PERFORMANCE ENHANCEMENT OF LONG HAUL ULTRA DENSE WDM SYSTEMS

Ph.D. Thesis

Submitted in fulfilment of the requirement for the award of degree

Of

DOCTOR OF PHILOSOPHY

Submitted by

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Certificate

I, **Yugnanda** hereby certify that the thesis entitled **"Performance Enhancement of Long Haul Ultra Dense WDM Systems"** submitted in partial fulfilment of requirement for award of degree of Doctor of Philosophy in Electronics and Communication Engineering Department Thapar University, Patiala, is a record of bonafide research work carried under the supervision of **Dr. R. S. Kaler** and **Dr. Enakshi Khular Sharma** (Delhi University, South Campus).

The matter presented in this thesis has not been submitted in part or in full to any other University or Institute for the award of any Degree or Diploma.

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Abstract

The burgeoning demand for broadband services such as database queries, home shopping, video-on-demand, remote education, telemedicine and video conferencing has pushed the existing networks to their limits. This demand was mainly fueled by the brisk proliferation of Personal Computers (PC) together with the exceptional increases in their storage capacity and processing capabilities and the widespread availability of the internet. Hence, the necessity, to develop high-speed optical technologies in order to construct large capacity networks arises. Two of the most popular multiplexing techniques available in the optical domain that are used in the building of such high capacity networks, are Wavelength Division Multiplexing (WDM) and Optical Time Division Multiplexing (OTDM). Dense Wavelength Division Multiplexing (DWDM) has drastically increased the capacity of optical transmission systems. Its inherent advantages have made it the current favorite multiplexing technology for optical networks. OTDM has made it possible to increase the bit rate transmissions on single wavelengths. Therefore, merging these two techniques to get very high-speed hybrid WDM/OTDM networks brings about the merits of both multiplexing technologies. These optical multiplexing technologies would solve the "fiber exhaust” problem and is expected to be the core technology in the all-optical networks of the future.

An optical fiber enables the transmission of many signals over long distances because of its huge transmission bandwidth (in THz) and low losses window of operation. Long Haul links are prone to losses and attenuation which forms the major limiting factor imposed by optical components or by fiber which degrades the system performance and limits the appreciable reach of the signals. In order to compensate for these effects, opto-electronic regenerators were used to perform the 3R of Reshaping, Retiming and Retransmitting the signal. Unfortunately it has also resulted in increased cost of the system. Therefore, Optical Amplifiers (OA) was introduced to boost the signals without going through the optical to electrical signal and vice versa conversions. Erbium Doped Fiber Amplifier (EDFA) was first modeled in 1987 by David Payne at University of Southampton, UK. It is a short length of erbium fiber which acts an amplifying media in the entire C band (1530nm-1570nm). In the scenario of DWDM channels, EDFA causes signal to noise ratio being differentially spread among the whole number of channels due to the various non-linear effects and phase noises

present in the optical amplifiers. Therefore, Hybrid Optical Amplifiers (HOA) which is formed by combinations of various Conventional Optical Amplifiers (COA) comes as possible solution to provide improved performance in terms of gain flatness and larger gain bandwidth for DWDM systems. Various advanced modulation formats can also aid in enhanced capacity systems. In this thesis, a step is made towards building, up scaled capacity WDM systems in a cost effective way. Such a system would require tailored and optimized real time parameters of the various components used throughout the complete system design.

Initially, the investigations are carried out using 64, 32 and 16 laser sources operating at wavelength from 1549.5nm with spacing of 0.4nm, 0.35nm, 0.25nm and 0.1nm and with different bit rates. It is found that the output power and BER is greatly affected by longer fiber links, higher bit rates and increased number of channels as inter channel crosstalk and other non-linearities comes into play. Therefore it is demonstrated for various cases the minimal allowed spacing which gives acceptable BER of 10^{-9} to 10^{-12} and Quality factor >15dB. With these guidelines more channels and larger distances coverage could be scaled. Further, a simplex OTDM system at (4 x 40Gbps) = 160Gbps is also characterized in terms of pulse width of the short pulses transmitted and the control power margin for the OTDM demultiplexer. The system is also optimized for the input power/channel. FWHM pulse width of 5ps serves optimum with control margin after 22dBm which degrades the performance. A 4 x 40Gbps RZ-DPSK high speed DWDM system was investigated for 110km reach.

Further, the number of channels is augmented and the system tested with various combinations of optical amplifiers (HOA) proposed for a DWDM system. It is reported that the Raman-EDFA HOA gives improved performance results as compared to Raman-SOA and EDFA-SOA amplifiers. A 160 x 2.488 Gbps DWDM system at 0.2nm channel spacing is evaluated with different HOA and COA. It is reported that Raman-EDFA provides Q factor >21dB with acceptable high output power of 10dBm. EDFA is reported to perform better than the other COA with Quality factor >18dB. The implemented DWDM system performs well with NRZ modulation format. At higher bit rate and higher channel systems, the RZ reportedly suffers from more dispersion and hence it gives reduced performance.

A 96 channel Ultra Dense DWDM system at 0.1nm is designed further and its performance is checked with Raman-EDFA for long haul applications. In the prospective of long haul communication system, it is recommended that 60 km is the optimum span distance of standard single mode fiber (SSMF) at which the proposed HOA achieves a 2070 km transmission distance with acceptable performance of Q factor >15dB. The EDFA obtained a maximum of 1794km with the same optimized span. The Dispersion Compensated Fiber length to correctly negate the dispersion effects is 9km. The HOA are also implemented on the combined capacity enhanced DWDM-OTDM systems to achieve the long distance performance with the established performance metric of BER $<10^{-9}$. A 320Gbps and 640Gbps system is implemented with HOA with different kinds of Raman fibers.

The HOA is implemented using different fibers like the Dispersion Shifted Fiber (DSF) and Dispersion Compensated Fiber (DCF). It is reported that Raman-EDFA HOA gives a higher system BER $<10^{-8}$ with DCF in the context of 640Gbps system. A high system output power > 6dBm is noted with 0dBm input power. The long distance transmission for both 320Gbps and 640 Gbps system topologies are notified. A distance of 345.044km for 8 x 4 x 10Gbps, 180.176km for 8 x 8 x 10Gbps and 184.02km for 16 x 4 x 10Gbps is reported. An orthogonal launch of the 640 Gbps system reports the repeater less single span distance of 207.02km.

Further, a high speed 16 x 10 Gbps DWDM is modulated with phase modulation schemes of DPSK (Differential Phase-Shift Keying) and DQPSK (Differential Quadrature Phase Shift Keying) modulated system at narrow channel spacing with different hybrid optical amplifiers. It is reported that for any of the combinations of HOA used in the scenario of lesser input power (<0dBm), the linear modulation schemes of NRZ and RZ is preferable. If the input channel power is >= 0dBm then DPSK and DQPSK could be used. Q factors > 30dB for NRZ > 29dB for RZ, 21dB for DQPSK and 18dB for DPSK is obtained. These phase modulated schemes are not prone to system nonlinearities that results due to the increased input power as the information is carried in phase and not amplitude.

The bandwidth efficient high capacity system with up to 640Gbps is investigated with different modulation formats and different kinds of fiber using the Raman-EDFA. It is reported that 8 x 8x 10Gbps DWDM-OTDM systems provide a highest ever reported gain >19dBm with HOA. The Noise Figure (NF) is minimum being around 5dB. The OSNR achieved is higher >20dB. A comparison with a different topology using 16 channels i.e. 16 x 4 x10Gbps system reportedly shows a HOA gain > 12dB and Q factor > 19.27dB. The HOA is observed to perform well even in the scenario of 640 Gbps with NRZ modulation. An extinction ratio of 18dB is noted for this case. A 320Gbps system with 8 x 4 x 10Gbps system reports a gain as high as 25dB with HOA is reported with Q factor >20dB. The high speed orthogonally launched 16 x 40Gbps DWDM system was also modulated with Duo binary and compared with simplex binary for single span reach distance.

Thus this thesis facilitates different proposed system implementations with newer configurations of Optical Amplifiers by tracking several system level challenges while acknowledging the limitations of existing system. Therefore, this study establishes the design and optimization of capacity enhanced Dense Wavelength Division Multiplexing with Hybrid Optical Amplifiers in the fiber optical communication system resulting in the aid of revolutionary growth of internet traffic for terrestrial fiber backbone networks.

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List of Publications/Project

The thesis includes the following:

1) **Project entitled**: "Capacity Enhancement in Long Haul Dense Wavelength Division Multiplexing System". **File Number: YSS/2015/002084, SCIENCE & ENGINEERING RESEARCH BOARD (SERB).**
2) Yugnanda, R. S. Kaler and E. K. Sharma, "Hybrid optical amplifier in high-speed duo-binary modulated hybrid DWDM-OTDM system," **Accepted for Oral presentation** to be presented 18 February, 2016, **Symposium: SPIE OPTO San Francisco, California, United States.**
3) Yugnanda, R. S. Kaler and E. K. Sharma, "Performance of Hybrid Optical Amplifier and Conventional Amplifier in the Scenario of Long Haul Ultra Dense Wavelength Division Multiplexed System", **World Congress on Engineering (WCE-2015), IAENG, London, UK, 1-3 July, 2015**.
4) Yugnanda, R. S. Kaler, E. K. Sharma, "Bandwidth Efficient High Speed Hybrid DWDM-OTDM System", Communicated to Optoelectronics and Advanced Materials - Rapid Communications.
5) Yugnanda and R. S. Kaler, "Optimization of Super Dense WDM Systems for Capacity Enhancement", OPTIK, International Journal of Light and Electron Optics, vol.123, pp 1497-1500, 2012. (IF: 0.769). **ELSEVIER**.
6) Yugnanda and R. S. Kaler, "Optical Time Division Multiplexing at 160Gbps using MZI Switching", OPTIK, International Journal of Light and Electron Optics,vol.122, pp 1981-1984, 2011. (IF: 0.769). **ELSEVIER**.
7) Yugnanda and R. S. Kaler, "Compensating Spectral Loss Variation in EDFA amplifiers for different Modulation Formats**"**, OPTIK, International Journal of Light and Electron Optics, vol.122, pp 435-439, 2011. (IF: 0.769). **ELSEVIER.**

Acknowledgement

"No journey is too long when the companions are good"

As I reach the end of this quite long yet fulfilling road to my Ph.D., it gives me immense pleasure and satisfaction to extend thanks and express my sincere gratitude to one and all who helped and supported me all through this journey.

I would like to offer my heartiest salutation to the Almighty God for that self-motivation, health and courage bestowed upon me in all the adversities and at every step and at every moment throughout the entire span of my studies. I would like extend special gratitude and deep appreciation to my parents who always encouraged me and kept up my spirits for the completion of the work.

The completion of any academic work is inconceivable without the expert guidance of my learned guides. I acknowledge and extend my deepest sense of gratitude to my revered guide **Dr. R. S. Kaler**, Deputy Director, Senior Professor, Department of Electronics and Communication Engineering, Thapar University, Patiala. Words are inadequate to extend my heartfelt thanks to **Dr. Enakshi Khular Sharma**, Delhi University, South Campus, whose indispensable help at most needed time and at every step of my work enabled me to complete the work. She is indeed my role model. Despite the various academic and official assignments, they devoted enough time and took great pains in discussing even in minute details of this work. Out of deep sense of gratefulness, I express my sincere thanks to **Dr. Sanjay Sharma**, Professor and Head, Department of Electronics and Communication Engineering, Thapar University, Patiala for continuous appreciation.

My heartfelt sincere appreciation goes to my husband, Mr. Vishal Puri, who has constantly supported me amidst this long and arduous journey filled with ups and downs. Special love to my son, Himanish for his non disturbing gestures and whose cute smile encouraged me to sail through all those disturbing and difficult moments during the course of my study. Finally I would also like to thank my parents-in-law for their patience and affection. Lastly I would also extend my thanks to my sister Dr. Sunanda whose moral support and spiritual enlightenment made me feel blessed.

Yugnanda

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List of Acronyms

DWDM	Dense Wavelength Division Multiplexing
OTDM	Optical Division Multiplexing
ISI	Inter Channel Interference
OA	Optical Amplifier
EDFA	Erbium Doped Fiber Amplifier
HOA	Hybrid Optical Amplifier
COA	Conventional Optical Amplifier
BER	Bit Error Rate
DPSK	Differential Phase-Shift Keying
DQPSK	Differential Quadrature Phase-Shift Keying
RA	Raman Amplifier
SSMF	Standard Single Mode Fiber
NF	Noise Figure
DCF	Dispersion Compensating Fiber
NF	Noise Figure
DSF	Dispersion Shifted Fiber
dB	Decibel
SPM	Self-Phase Modulation
FWM	Four Wave Mixing
XPM	Cross Phase Modulation
DRA	Distributed Raman Amplifier
OSNR	Optical Signal to Noise Ratio
FOM	Figure of Merit
Q Factor	Quality Factor
MLL	Mode Locked Laser
SW	Switching Window
CWDM	Coarse Wavelength Division Multiplexing
SOA	Semiconductor Optical Amplifier
SMZ	Symmetric McZhender Switch

O-E-O	Optical-Electrical-Optical
ASE	Amplified Spontaneous Noise
PMD	Polarization Mode Dispersion
HDWM	Highly Dense WDM
FWHM	Full Wave Half Maximum
LOA	Linear Optical Amplifier
LEAF	Large Effective Area Fiber
FEC	Forward Error Correction
AWG	Arrayed Waveguide Grating
SNR	Signal to Noise Ratio
PRBS	Pseudo- Random Bit Sequence
NRZ	Non Return to Zero
LP	Low Pass
ITU-T	International Telecommunication Union-Telecommunication
CW	Continuous Wave
Tx	Transmitter
Rx	Receiver
ODL	Optical Delay Line
UNI	Ultrafast Nonlinear Interferometer
TOADs	Terahertz optical Asymmetric Demultiplexers
SLALOM	Semiconductor Laser amplifier in Loop Mirror
OSA	Optical Spectrum Analyser
DRA	Distributed Raman Amplifier
R-E	Raman-EDFA
R-E-R	Raman-EDFA-Raman
E-R-E	EDFA-Raman-EDFA
R-S	Raman-SOA
R-S-R	Raman-SOA-Raman
BERT	BER Tester
PDCF	Pumped Dispersion Compensating Fiber
MZM	Mach-Zehnder Modulator

PDSF	Pumped Dispersion Shifted Fiber
PSMF	Pumped Single Mode Fiber
R-S	Raman-SOA
PC	Polarization Controller
FEC	Forward Error Control
DNRZ	Duo binary NRZ
DRZ	Duo binary RZ
Fs	Femto Second
LD	Laser Diode
f_c	Cut off Frequency
B	Bit Rate

List of Symbols

P_i	Input Signal Power
P_{out}	Output Signal Power
τ	Optical Time Delay
Δt	Pulse width/time delay
E_1, E_2	Energy in Valence and Conduction Band
c	Velocity of Light
h	Planck's Constant
λ	Wavelength
N	Carrier Level
G	Gain
ϕ	Phase
W	Switching Window
L	Length
Γ_s	Signal to core overlap
α_s	Rayleigh Scattering Coefficient
z	Fiber Propagation Step Size
A_{eff}	Effective Area
Π	Pi
a_{eff}	Effective Mode Area Normalized by Core Area
D	Dispersion

Chapter 1

Introduction

1.1 Introduction and Motivation

In the fast growing information world, we see an obdurate demand for networks of ever increasing system capacities which maintain low cost [1]. It is one of the mandatory features of modern communication networks to be, always, one of the fast moving technologies. Many rapid progress factors such as growth of internet and e-business, advanced technical applications, developing and changing templates of usage, has put a high demand of bandwidth and capacity on the existing optical network. It has become necessary to develop optical technologies that can handle these extremely high capacities given the vast available bandwidth of the fiber transmission medium. The bandwidth of Standard Single Mode Fiber (SSMF) is 53THz occupying the bandwidth of 1280nm-1650nm. An optical fiber is one of the mediums offering large bandwidth (~THz) for better performance. Initially, the optical fiber was restricted to large attenuation but currently different make and types of optical fibers exist which offer low attenuation losses (0.2dB/km) and which can be efficiently utilized in various multi-terabit and bandwidth efficient applications [2].

In order to accommodate large growing bandwidth requirements, high capacity bandwidth efficient Dense Wavelength Division Multiplexed (DWDM) transmission systems are required in the backbone networks. DWDM fulfills the requisite to increase the transmission capacity by expanding the useable bandwidth band, increasing the bit rate and narrowing down the inter channel spacing [3]. Since 1990, DWDM and Erbium Doped Fiber Amplifier (EDFA) technologies have known to increase the system capacities.

DWDM is defined as an optical multiplexing technique which carries in multiple wavelengths or optical carriers corresponding to different user data into a single fiber [4]. Earlier WDM systems were initiated in 1980s when only two largely spaced channels belonging to two different wavelengths i.e. 1310 nm and 1550 nm were used. In early 1990s, the second generation of Wavelength Division Multiplexing (WDM) was presented, in which more than six optical channels were processed. This was known as narrow-band WDM system since the channels were located over the wavelength grid with reduced channel spacing (i.e. 400 GHz). The optical communication system with reduced channel spacing was still under research in order to find ways to efficiently utilize the bandwidth for cost effective solutions. In the beginning of 1990s, DWDM systems were developed with 20 to 50 channels and with 100GHz to 200GHz inter channel spacing. By late 1990s, the great evolution of DWDM systems was observed with high transmission capacity (160 channels) at low channel spacing of 50GHz which corresponds to wavelength spacing of 0.4nm in the 1550nm band [5].

Besides the booming DWDM technology, another optical multiplexing technique of Optical Time-Division-Multiplexing (OTDM) served as a boon to achieve the ultra-high-speed all-optical networks which were much essential in this era of multimedia applications. OTDM systems proved to have manifold advantages over wavelength-division-multiplexed (WDM) systems. To enlist a few, as high bit rate to bandwidth ratio, higher bit rates per user wavelength etc. WDM system, in its domain, also has its own advantages of virtually multiplexing any bit rate or modulation format for signals, regardless of any coherency requirement. It proved to be a transparent system which allows flexibility in multiplexing signals from various independent systems [6]. Overcoming disadvantages of the established multiplexing techniques and combining their advantages resulted in an overall high capacity system [7].

High capacity systems are also prone to transmission losses which are inherent to any communication system. Even in a fiber optic link, the attenuation poses severe limitations on the system performance. Initially, electric regenerators were in use to account for loss management and to perform the Regeneration, Reshaping and Retiming (3R). However, these had a relatively high cost and complexity and were bounded by the drive electronics. The advent of Optical Amplifiers (OA) to amplify and condition the optical signal directly without the tedious O-E-O conversions significantly improved the quality of output signal. Therefore, the electric regenerators were replaced and the existing systems were upgraded to use OA. Several types of OAs were developed during 1980s and soon their use for high capacity and long haul link applications became comprehensive. By 1986, OA were an important component of fiber optic cable links across the Atlantic and Pacific oceans [8]. OA can be used as a pre-amplifier (by placing it just after the transmitter) and as post-amplifier (by placing it just before the receiver) and as an inline amplifier (by placing in the mid link). There exist nonlinearities which affect single channel systems like the Self-Phase

Modulation (SPM) and others which affect multiple channel systems is Cross Phase Modulation (XPM) and the one which creates additional frequencies is Four Wave Mixing (FWM). These noise effects are embedded in the fiber transmission systems. The noise induced by Optical Amplifiers, restricts it to be used for high performance systems [9]. So, there is demand of optical amplifiers which shall provide better performance metrics (in terms of reduced nonlinearities, high Quality Factor (Q Factor), less crosstalk, gain flatness, larger gain bandwidth) for DWDM systems. These improved-upon optical amplifiers are required to compensate for attenuation and system incurred losses of signals in a WDM system [10]. At present, the hybrid amplifiers are promising and widely used technology for today's high speed broadband applications to enhance the system performance without using costly techniques [11]. Various conventional and advanced modulation formats add to increase the spectral efficiency for long haul optical links.

1.2 Dense Wavelength Division Multiplexed System

1.2.1 Types of WDM and its Generalized Schematic

The parallel transmission of a number of different wavelength/optical carriers in a single optical fiber is known as WDM [12]. Therefore, by using WDM, one can avail the tremendous bandwidth available by carving up the optical transmission spectrum into a number of non-coinciding wavelength bands. Each single wavelength supports a unique user channel which operates at any random bit rate. This brings about corresponding challenges such as the design aspect and development of tailor-made network architectures, algorithm and network conventions. Since WDM multiplies the throughput or the transmission capacity on a single fiber, the provision of such efficiency avoids the need to install new fibers in existing systems, thereby reducing the total fiber infrastructure cost. More importantly, its major attraction is that it provides room for expansion with increasing bandwidth requirements. Hence, its use is most widespread in backbone systems where there is a need for enormous capacity.

WDM is partitioned into conventional or coarse (CWDM) and dense (DWDM) system. Coarse WDM systems include up to eight channels in the C-band i.e. 1550nm of optical silica fiber. The denser counterpart of WDM utilizes the same transmission window but with the difference that the channels are densely packed. Channel spacing varies and some systems are capable of 12.5 GHz (0.1nm) spacing. These DWDM systems are termed as ultra-dense WDM systems (U-DWDM). The increased channel spacing for a CWDM as compared to DWDM allows for less intricate and thus cheaper system transceiver architectures. All the variants of WDM are based on the same idea of multiplexing many wavelengths of transmission in a single fiber. They differ in the considered inter channel spacing and the number of channels. This in turn judges the DWDM system capability to amplify the multiplexed signals in single optical fiber. Table1.1 depicts the different kinds of WDM systems. Most prominent wavelength bands in use are the Conventional Band (C) and the Long Wavelength Band (L).

Table 1.1 Types of WDM systems

Criterion	**Coarse WDM**	**DWDM/U-DWDM**
Channel Spacing	Large from 1.6nm(200GHz) to 25nm	Small ,Less than 100GHz to 12.5 GHz and lesser
No of Bands used	O,E ,S,C,L	C,L
Cost per Channel	Low	High
Number of Channels Delivered	10-15	Hundreds of channels possible
Best Application	Short Haul	Long Haul

Wavelength Division Multiplexing (WDM) is analogous to electrical Frequency Division Multiplexing in spectral terms but it has the distinction that each WDM channel effectively has access to the entire intensity modulation fiber bandwidth which with current technology is of the order of several gigahertzes. Figure 1.1 shows the generalized DWDM schematic. The following is the block overview and a precise description of the system block wise:

- Signal Generation— A continuous wave laser acts as a light source and provides a light beam with narrow bandwidth. The digital data is modulated by different modulators available and transmitted on a fiber link.
- Merging the user channels—DWDM system uses multiplexers to merge the user signals. The multiplexers induce inherent losses. This loss depends on number of channels and

the channel spacing and can be mitigated with optical amplifiers and appropriate optical narrow filters. OA boosts all the signals in the wavelength band simultaneously without the need for electrical conversion.

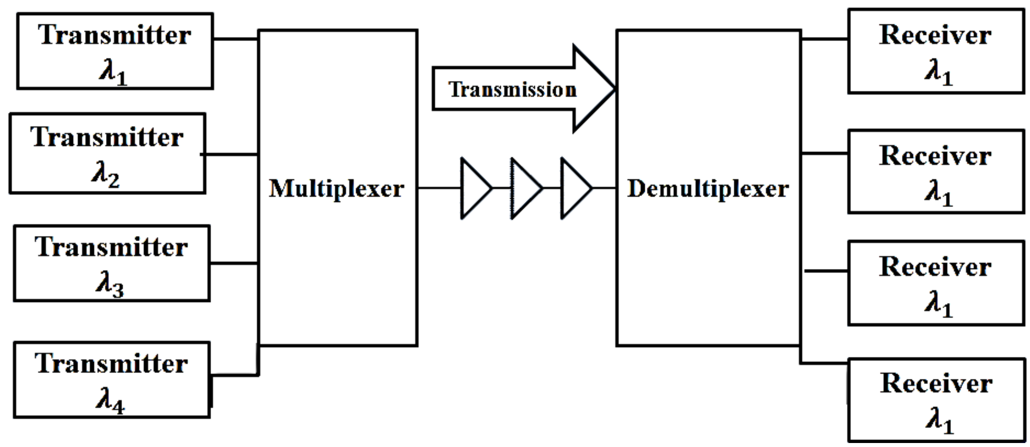

Figure 1.1 Wavelength Division Multiplexed Optical System

- Signal Transmission—The effects of Inter Symbol Interference (ISI), crosstalk and other signal losses and attenuations are inherent in fiber optic transmission. These inherent losses which affect the signal quality can be controlled by system parameters such as channel spacing, number and way of launch of signals and input power values per channel. Optical amplification after the transmitter, inline transmission and before the receiver may therefore be required.
- Demultiplexing—After receiving the signals, the multiplexed signals need to be demultiplexed or separated out to different individual wavelengths.
- Reception of the signals—After the demultiplexing the individual wavelengths are received by photo detectors.

Based on the above block functionalities, the DWDM fiber system needs to satisfy the following design requirements. On the transmit side, lasers with stable and narrow line width wavelengths should be used. In the link, the requirement is of an optical fiber that exhibits low loss and an Optical Amplifier which has large gain-bandwidth product. At the reception the PIN/APD photo detectors and optical demultiplexer using matched filters or diffractive elements (Arrayed Waveguide Grating) along with certain other optical inline components such as Optical cross-connects and Optical add/drop multiplexers, forms the complete DWDM fiber transmission system.

1.2.2 DWDM Design Parameters

WDM is an upcoming technology for increasing the capacity of fiber optic transmission systems. The DWDM system design demands from the expertise of the design engineer to tailor effectively various optical and electrical parameters which can ascertain stable operations of the Wavelength Division Multiplexed network [13].

Various design parameters are as follows:

Channel Width and Spacing: The number of user channels, the wavelength of the selected channel specific to the different bands of operation (centre frequencies), the pulse width of the pulses, the channel width and the inter channel spacing are pivotal parameters in the design of DWDM systems. Normally, the spectral width of the channel should be such that system gets non- overlapping channels. The operating centre frequency both of the transmitter and the receiver channels must be the same [14]. The channel line width, the wavelength bands of operation, bit rate, the different fiber type and the link length determine the amount of dispersion. To avoid the crosstalk and the inter channel interference, channel spacing should allow for a frequency deviation due to frequency drifts in the laser, filters and amplifiers.

Wavelength Launch and Input Power: In DWDM systems where each wavelength is used as a separate channel, it is imperative to consider the transmitter stability and reliability, receiver structure, amplifier and other active/passive optical components on the optical path between transmitter and receiver. DWDM system requires very high accuracy of wavelengths transmitted. For this, the power/channel is an important criterion. It should be uniform over the spectral bandwidth of the transmitted signals. The power/channel cannot be an arbitrary number, because as the coupled power increases, it directly impacts the nonlinear phenomena. The power budget, power penalty, extinction ratios and receiver sensitivity helps to determine the power/channel to get signals with high quality factor (Q factor) at the receiver. The transmission optical filter makes a lot of improvement in the system performance as it reduces the channel spectral occupancy and introduces controlled ISI even in narrower spaced systems. The orthogonal polarization launch of adjacent channels decreases the channel crosstalk and improves the system performance.

Channel bit rates and modulation types: The bit rate per channel and the modulation technique are parameters that determine the limits of channel width and channel separation, as well as channel performance, e.g. Bit Error Rate (BER), cross-talk, Optical Signal to Noise Ratio (OSNR), Figure of Merit (FOM), Q factor etc. [15]. The various advanced optical modulation schemes CSRZ, DQPSK, RZ-DPSK, Duo-binary etc. supports high bit rate transmissions in DWDM systems.

Channel Performance: The BER and Quality Factor is a performance metric specified for WDM systems. The WDM systems should be such designed so that signal fidelity is maintained. Mostly, the performance is judged by the value of the BER which is 10^{-9} to 10^{-12} for optical networks [16]. BER is an important figure of merit (FOM) and performance metric for WDM networks. The network designs ought to adhere to quality.

Channel Dispersion and Losses: The signal transmission in DWDM systems through fibers and various WDM components introduces a very harmful effect of dispersion or optical pulse widening. This causes the gross loss of power as the pulse spreads. The dispersion of the link is calculated based on the frequency distribution of each channel around the centre frequencies, the user channels transmitted, the overall fiber optical link lengths, the channel spacing, the various losses incurred and the dispersive features of all optical devices in the link. The receiver sensitivity is highly impacted by the signal integrity which is adversely affected by increased dispersion in the link [17]. The power penalty is a measure which relates to the additional input power level required to boost up the signal so that system fidelity is maintained along with the BER requirements of the system. Typical power penalty values in the range of 2-3dB exist for almost all the networks.

Optical Amplification: In DWDM systems, the optical amplifiers play a pivotal role in achieving global system capacities by overcoming attenuation and losses which should be carefully budgeted. The optical amplifier ought to be used to restore the intensity of the optical signal and to perform the 3R of Regeneration, Retiming and Reshaping. The existing amplifiers add a cost factor along with inducing noise in the system. The EDFAs restrict the number of channels and the wavelength range to be used as it operates best in the range of 1550 nm. The newer Raman amplifier with EDFA is a good consideration as the amplification range is not limited as in case of standalone EDFA but is decided by the pump frequency range of the Raman Amplifier. Wider stable and broader gain-bandwidth is achieved with Hybrid Optical Amplifiers (HOA) as against the other conventional optical amplifiers (COA).

Fiber Types and Transmission: The optical transmission is limited by nonlinear as well as linear effects in the system. Nonlinear effects of SPM, XPM and FWM and linear effects of amplifier spontaneous emission (ASE), attenuation, chromatic dispersion, and Polarization Mode Dispersion (PMD) effect the fiber transmission. The nonlinear effects are related to the refractive index change induced by input power levels. The contribution of the nonlinear effects to transmission is defined as the optical power density (power/effective area) times the distance of the fiber. Clearly, the higher the optical power and the longer the fiber distance, the greater is the nonlinear effect. Different kinds of fibers like the Dispersion Compensation Fiber (DCF) and Dispersion Shifted Fiber (DSF are used to mitigate the linear effects of dispersion. The only parameter that is manipulated is the optical input power. The total power of the received optical signal should be is greater than the receiver sensitivity to get acceptable performance limits.

1.2.3 Merits of DWDM System

Large Transmission Capacity: There is large scale growth in the transmission capacity of DWDM systems. Different values of base bit rates from 2.5 Gb/s and 10Gb/s etc. which are electrically supported, are optically multiplexed, so that the transmission capacity of the system is increased to more than 400 Gb/s and nearing Tb/s. Per wavelength base bit rates can be increased to greater than 40Gb/s by utilizing the time multiplexing of the optical wavelengths. It will result in booming the capacity in multichannel DWDM. DWDM combined with OTDM is indeed a critical technology for high capacity on chip, parallel operating different optical systems [18].

Transparent Transmissions and System Upgrade: The transparency/flexibility of DWDM systems to various modulation formats, various base bit rates/wavelength and protocols will enable carriers to tailor and render separate services to various customers in the same transmission fiber. The upgradability and expandability of DWDM networks are smooth, convenient and easy, therefore they permit to maximize the protection of the initial investment in the infrastructure. The different services of voice, data and image etc., all sent comfortably in the same optical link as multiplexed wavelengths in DWDM system, are independent of each other, and can bring great convenience to all other user at the same time. It can indeed support an optical super channel.

Long Haul Transmission: The Erbium Doped Fiber Amplifier is known to have a high gain, larger gain-bandwidth product etc. Almost the entire DWDM is covered in the amplification range of 1530-1565nm (C Band) of an EDFA. All the optical channels can be amplified at appropriate span distances and with reduced costs. Invent of Raman Amplification along with dispersion managed fiber spans has demonstrated DWDM over trans-pacific transmission distances [19].

System Flexibility: Optical in- line components such as optical cross connect (OXC) and optical add–drop multiplexers (OADM) and switches make the system flexible and expandable.

1.3 Optical Time Division Multiplexed System

OTDM is one of the established optical multiplexing techniques. The basic principle of OTDM is to increase the system capacity (achieving faster single channel rates) by multiplexing optical data channels in the temporal domain. The concept of OTDM was proposed around 1988 [20]. Initial experiments involved bit rates in the Gb/s range. Since then, OTDM transmission rates have increased significantly and their terabits per second transmission rates have been demonstrated. A process known as bit interleaving achieves OTDM and is basically an extension and expansion of the well-known technology of time division multiplexing [21]. Such high speed transmissions involve the complete signal processing, routing, switching and demultiplexing in optical domain only. This presents the challenge to investigate OTDM system for ultimate capacity limits on a single wavelength.

Generally, OTDM involves a process where short pulses are generated (usually using a Mode Locked Laser), modulated and then optically multiplexed into a high bit rate signal or a high speed signal. The control or the clock signal has the same wavelength as that of the data is both multiplexed. This timing clock is extracted from the signal and it further drives a time domain demultiplexer so that the original sub channels can be recovered [22]. The power, pulse width of the pulses transmitted and the wavelength of the optical signal ought to be optimized to suit the transmission characteristics of the fiber systems.

1.3.1. Generalized OTDM System

In WDM, the multiplexing is established in the frequency domain, whereas OTDM transmits in time domain. The multiple data channels are interleaved into a single high-speed data stream with minute control of their relative delay. The data is transmitted in the form of ultra-short duration optical pulses. An optical gate or a switch extracts the base rate sub-channel from the aggregate data stream at the receiver for subsequent processing. The essential component is the Mode Locked Laser (MLL) which generates short pulses. An input optical pulse train is split into N tributaries, each having different delays.

The time delay is T_{NB}=1/ (N*B), where N and B are the number of channels and the bit-rate of base input signal respectively [23]. Using an N: 1 combiner, the delay signals are recombined into one output of higher data-rate. By controlling the number of channels and the relative delays, a system with any high value of bit rate can be achieved. Each tributary has capacity of M Gbps, resulting in total capacity of N*M Gbps per wavelength. The important factor to be considered is that the input signal is in short pulses, the duration of which is less than the final bit-period $T_{NB.}$ The generalized schematic is shown in Figure 1.2.

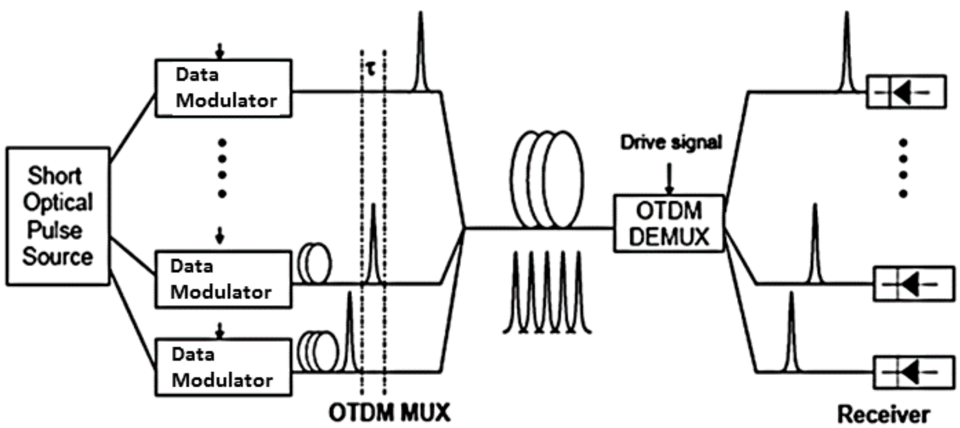

Figure.1.2.Generalized OTDM System

The OTDM Receiver is one of the most important parts of the system. Literature quotes comparison of many receiver configuration as in [24] [25] .Various switches like SAGNAC interferometer, Nonlinear Mirror Loop (NOLM) and Terahertz Optical Asymmetric Demultiplexer (TOAD) are few of the prevalent fiber based interferometric switches proposed for the OTDM demultiplexing. The Semiconductor Optical Amplifier-Symmetric Mach Zhender (SOA-SMZ) switch configuration is the best known OTDM demultiplexer. SOA forms the major building block due to its high extinction ratio and easy integratibility with other devices. The principle of operation is based on optically inducing refractive index change within the SOA by introducing the synchronized high power control pulses which change the differential phase resulting in output to be switched [26]. The 3dB couplers are used in the input and output of the switch. Rigorous analytical calculations on design of these couplers for various applications e.g. in power filters was done by Yasumoto et al. [27].

The control block in the OTDM system is introduced which consists of several splitters and delay blocks. They detect the required channel and allow the switch to be open for the duration of the pulse width. Basically, SOA-SMZ implements an optical gate switch. The output of the interferometric switch consists of switching and reflective ports which outputs the data only. The control signal is held back by use of a 90^0 polarizer in the switch. 160Gbps OTDM is investigated in [28] using SOA demultiplexer. SOA-SMZ is shown in Figure 1.3.

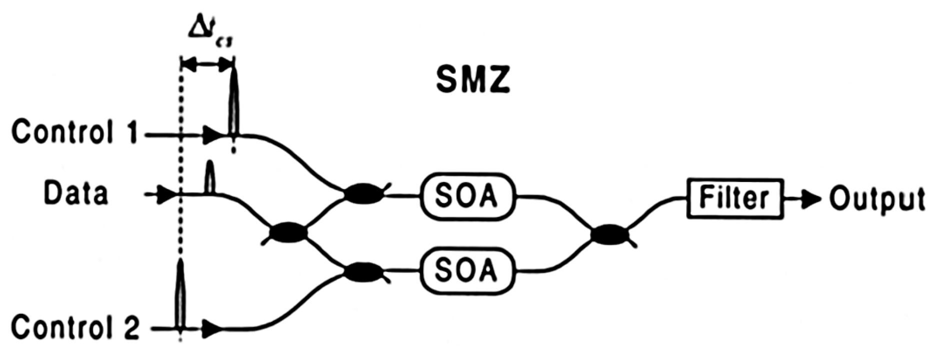

Figure.1.3. SOA-SMZ Switch (OTDM Demultiplexer)

1.4 DWDM using OTDM for Capacity Enhancement

The WDM is easy to implement but it is limited in speed by the electronic drivers. On the other hand, OTDM scales up to high bit rates by combining data into time slots. Optical multiplexing is easy to implement but the OTDM demultiplexing is quite complicated as regarding the clock recovery etc. The advantages of WDM and OTDM can be combined to maximize their advantages and reduce their individual disadvantages. The resulting system is a high capacity optical system [23]. Figure 1.4 shows the N channels on a single wavelength, at a base rate of 10 Gb/s that are combined together in the optical temporal domain forming a 40 Gb/s OTDM channel.

The hybrid system consists of M wavelengths incorporating the same temporal multiplex, thereby resulting in aggregate of M * N *10Gbps system capacity [29]. The idea of DWDM using OTDM to increase per channel wavelength offers a flexible approach to increase the overall capacity of the present day DWDM based optical networks. Judging and calculating the fiber number to be included in an optical network aids in the system performance [30]. High capacity hybrid DWDM-OTDM system performance is evaluated by Goyal *et al*. [31].

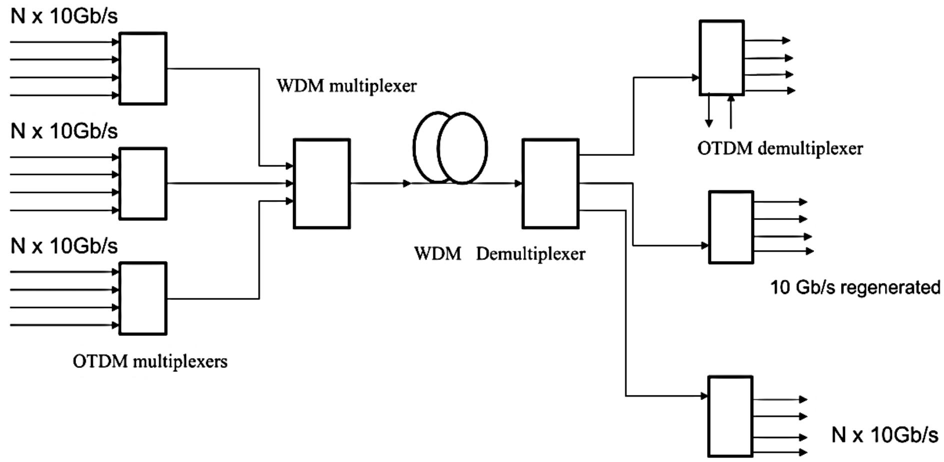

Figure 1.4.Hybrid DWDM /OTDM System

1.5 Optical Amplifiers

All the optical signals are simultaneously amplified without actually doing the complex and expensive O-E-O conversions by the Optical amplifiers. The large gain bandwidth of optical amplifiers enables propagation of many parallel channels on the wavelength grid, thereby, resulting in high capacity WDM systems. The most deployed amplifier with its amplification window in the C band is the erbium doped fiber amplifier (EDFA). It can therefore, amplify huge number of WDM channels spread out in the C band. A high power EDFA working in saturation region performs quite well in DWDM systems [32]. Since the EDFA is restricted to 1530-1565nm band, therefore, there is an essential requirement to improve the dynamic performance of current amplifiers so as to sufficiently increase the gain-bandwidth product and reduce the noise characteristics.

1.5.1 Principle of Optical Amplifiers

The basis of Optical Amplification is the principle of stimulated emission. It occurs, when incident photon with energy $E=E_2-E_1= hc/\lambda$ (Plank constant=h, velocity of light =c and wavelength of light = λ) interacts with electron energy state in E_2, causing it to return back into lower state (E1) with creation of second photon as shown in Figure 1.5 [33]. The incident and emitted photons are emitted in the same direction with the same phase/frequency and hence the amplification occurs. Population inversion is when $N_2 > N_1$, where N_2 and N_1

are the population density of atoms in the excited state E_2 and lower state E_1 respectively. Optical amplification is achieved by usage of an external pump.

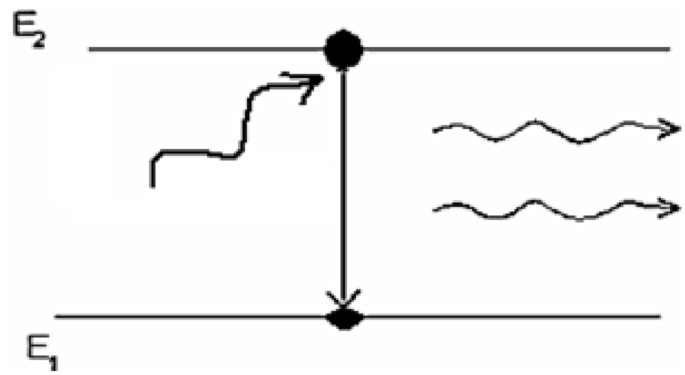

Figure 1.5. Optical Stimulated Emission

1.5.2 Conventional Optical Amplifiers

Optical amplifiers are categorized as SOA, EDFA and Raman based on whether they are semiconductor based (such as Semiconductor optical amplifiers) or fiber based (such as Erbium Doped or Raman Amplifier). As already mentioned all the Optical Amplifiers are based on stimulated emission in a laser [34].

Semiconductor Optical Amplifier (SOA)

A semiconductor optical amplifier (SOA) has a gain medium formed at the p-n junction of a semiconductor device. This is different from the laser diode because in that the anti-reflection coatings replace the end mirrors, as has been shown in Figure 1.6 [35]. The weak input signal traverses through the active region of the SOA. The injected current causes the population inversion and the input signal stimulates the transitions of electrons, thereby, emitting photons with the same energy resulting in a stronger signal. SOA offers broadband gain and therefore is used in spite of the fact that it suffers from strong crosstalk induced at high input powers due to its strong polarization dependency.

Erbium Doped Fiber Amplifier (EDFA)

Rare-earth elements like erbium, ytterbium etc., are doped into optical fibers to make them broad band fiber amplifiers. Amplifier operating wavelength and gain bandwidth is decided by the dopants in the fiber. An EDFA is widely used fiber amplifier, as it is capable of amplifying all the wavelengths ranging from 1520 nm to 1600 nm when pumped with 980nm [36] [37] [38]. The pump lasers, short length EDF (in meters) and wavelength selective coupler are three basic components of EDFA, as shown in Figure 1.7. The EDFA is easy to couple, it is polarization independent and availability of high-power pump lasers has made the EDFA the first choice in current DWDM optical systems.

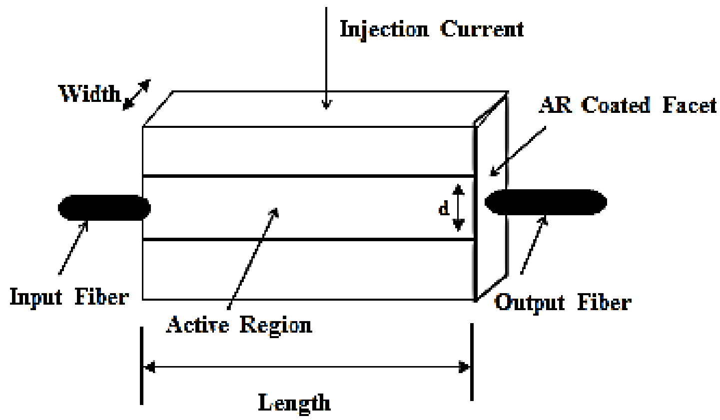

Figure 1.6. Schematic of Semiconductor Optical Amplifier

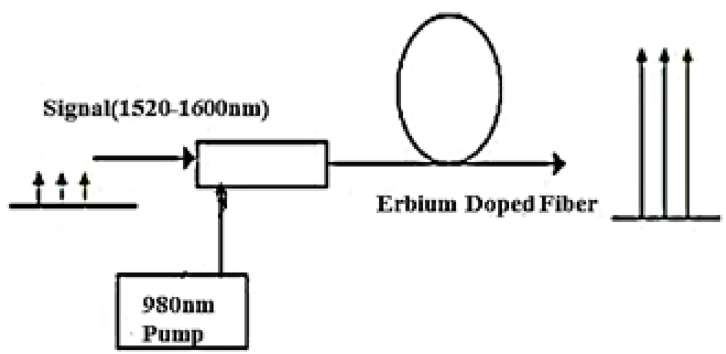

Figure 1.7: Erbium Doped Fiber Amplifier.

RAMAN Amplifier (RA)

When the fiber is used as a gain medium it results in a cost effective solution which is the Raman Amplifier. The optical amplification is performed with correct choice of pump power and wavelength [39]. The biggest advantage of Raman Amplification is that broad gain over spread spectra is achieved by appropriately selecting the pump power and pump wavelengths. When the optical medium is irradiated by intense monochromatic light, the scattered light shows a new wavelength in addition to the original signal. Figure 1.8 shows the Quantum mechanical process. The incident photon of frequency f_{p} excites molecule from ground state to the virtual state. The molecule soon falls down to the intermediate state, thereby, releasing Stokes photon with frequency $f_{s.}$ The energy difference between the virtual and the intermediate level is smaller than that of between the ground and the virtual state, hence $f_{s.} <$

fp. The anti- stokes photon has a higher frequency (f_a) than incident photon as is clear form figure below.

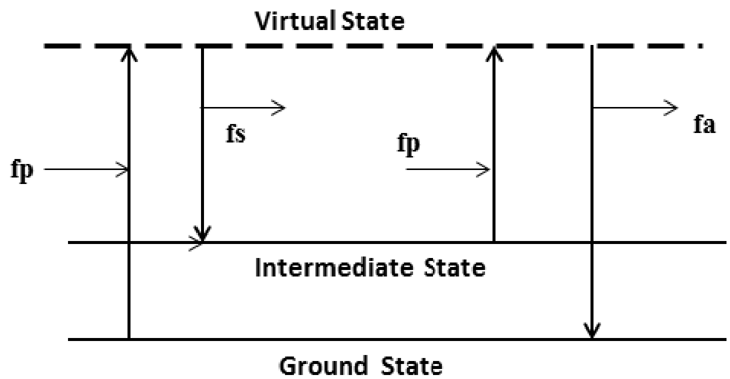

Fig. 1.8: Quantum mechanical process of Raman scattering

The optical amplification occurs in the transmission fiber itself and is distributed along the transmission line in distributed Raman Amplifier or is centered on lumped portion in discrete Raman Amplifier. Optical signals are amplified up to manifolds in the optical-fiber. The RA amplifiers have broad gain bandwidth (up to 112nm) and they can be employed on existing fiber, which reduces the cost. They are also known to reduce the effective span loss and improve the noise characteristics of the transit signal by boosting it up. RA combination with EDFA achieves very broad optical gain flattened bandwidth. The high power pump availability (> 500mW) and the decision of pump wavelength being shorter than the signal wavelength to be amplified, (frequency difference of 13.2THz [40]), results in highly amplified signal.

The Raman Amplifier has become very impressive and cost effective as there is no bondage for any specific fiber type. Moreover, by proper choice of the wavelengths of the pump used and pump power, the broadened gain region (100nm) can be obtained. The gain obtained is flat over the wavelength range making its use in WDM systems quite a mandatory step. The Figure 1.9 shows the Raman Amplifier.

The Figure 1.10 indicates that with the use of Raman Amplifier the signal power level maintains a substantial value to give a high value of OSNR. The power of the signal throughout the transmission does not drop down to too low a value of noise floor level nor does it shoots up to cause nonlinear effects. Therefore, as against the EDFA for which the signal rapidly falls just before the amplifier to the noise floor level and suddenly increases after the amplifier to meet the consequences of nonlinear effects the RA performs better. The lumped EDFA performs poorly as compared to the distributed Raman Amplifier.

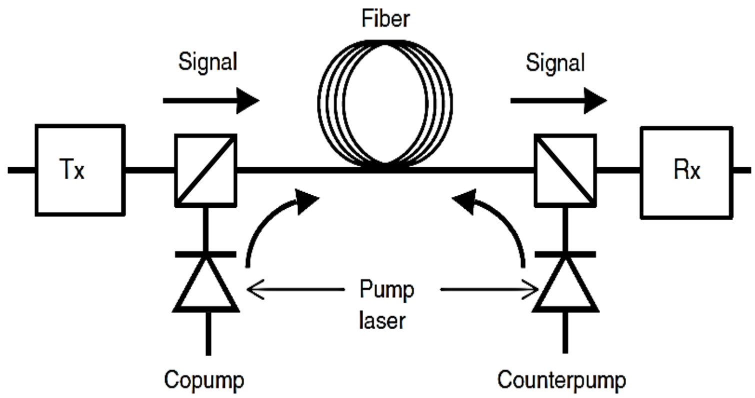

Figure 1.9: Raman Fiber Amplifier

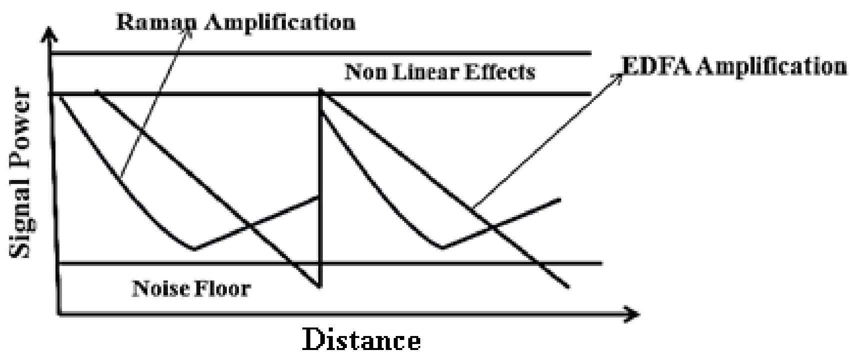

Figure 1.10: Signal Power Level with Raman and without Raman Amplifier

1.5.3 Hybrid Optical Amplifier

The current scenario of requirement of large capacity in the transmission bandwidth region beyond C band, into the L and the S bands have made it necessary to employ a combination of various Conventional Optical Amplifiers [41]. Usually, the combination of more than one optical amplifier in any configuration is called Hybrid Optical Amplifier (HOA). The net gain of the Raman-EDFA HOA (G_{Hybrid}) is the total of two individual gains of Raman and EDFA respectively [30]. Gain partitioning in hybrid amplifier is as shown in Figure 1.11. The Figure has gain and wavelength on Y and X axis respectively. The gains are in dB. The net gain for Raman-EDFA HOA is $G_{Hybrid} = G_{EDFA} + G_{Raman}$ [30]. It is seen from the figure that, some part of the wavelength band is efficiently amplified by EDFA with high gain and the other is amplified by Raman. Over the whole wavelength grid, single amplifier shows large variation. But if the Raman amplifier is combined with EDFA in any configuration (cascaded or parallel) then the large gain flatness can be achieved even with highest possible gain.

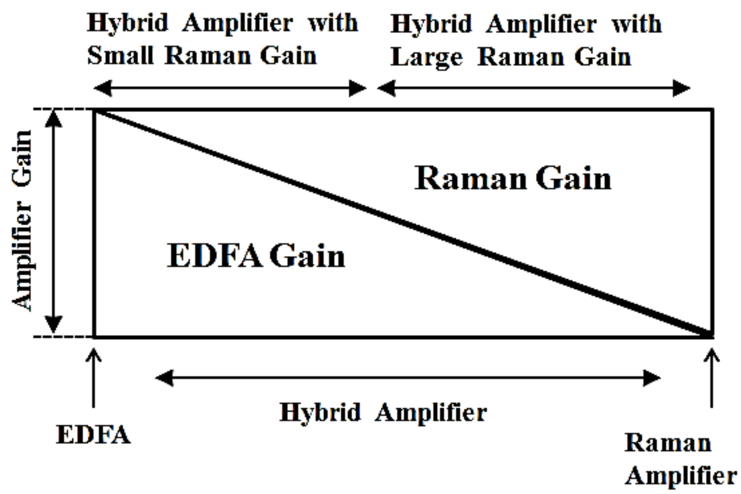

Figure 1.11: Gain partitioning in Raman-EDFA hybrid amplifier

It is, therefore, attractive to make as much use of the EDFA gain as much as possible and use other means of amplification beyond the EDFA bandwidth. The hybrid combinations of EDFA and Raman amplifier have been used to extend the seamless bandwidth of discrete amplifiers up to 80nm [42], 100nm [43] etc. Various optimization techniques of hybrid Raman and EDFA have been noted for increasing the broadband amplification [44], [45]. Thus a combination of DWDM with the hybrid amplifiers together in a system offers cost effective, reliable, flexible and a secure system. Widespread use of fiber optics (DWDM) in Radio Frequency (RF) applications offers yet more high performance systems [46].

1.6 Opical Code Patterns

The choice of correct optical code pattern or the modulation format offers high bandwidth efficiency in the high bit rate DWDM systems. The viability of the standard Non return Zero (NRZ) and Return Zero (RZ) modulation formats is already established. The sensitivity performance in the scenario of very narrow channel spacing amongst larger number of DWDM channels using conventional NRZ and RZ is the present trend.

To push the capacity of the current DWDM systems to higher levels the advanced phase modulation formats is in wider use. These phase modulation schemes carry information in their optical phases. They are known to be restricted by complicated phase recovery modules at the receiver. Hence, differential phase modulation schemes of Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) are in use which employs balanced detection. The Figure 1.12 depicts the DPSK system. It is known to carry the information in phase of 0 and Π.

The use of balanced detection allows for the requirement of 3dB lesser OSNR to reach a specific BER. The pattern dependent non linear losses is greatly reduced with these differential phase schemes as the power is present evenly in all the bit slots. Moreover the enhanced spectral efficiency is obtained from DQPSK wherein information is coded in phase difference of coded signals.

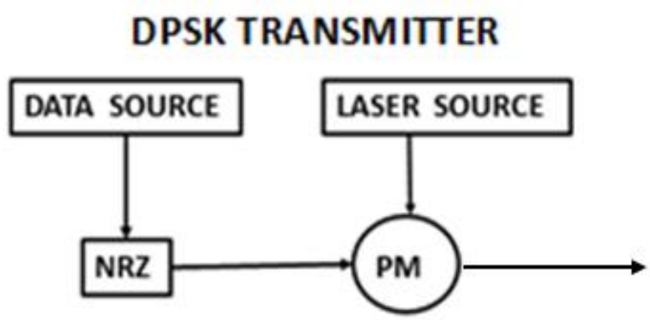

Figure 1.12 DPSK Transmitter

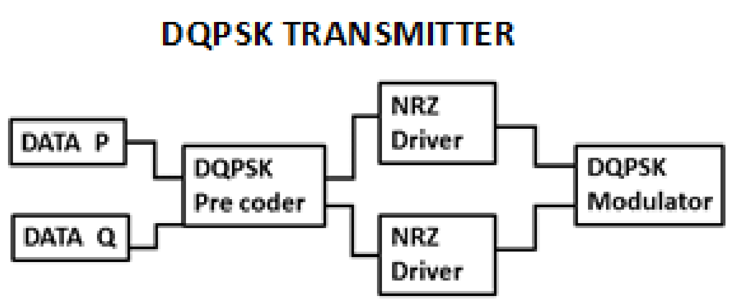

Figure 1.13 DQPSK Transmitter

DQPSK format used here includes 4 phase states of (0, Π/2, Π and 3Π/2). The two bits of information is encoded with each code symbol making the bit rate to be two fold of the symbol rate. Figure 1.13 depicts DPSK and DQPSK transmitters. Duo binary is yet another modulation scheme to materialize higher repeater less distances in Highly Dense Wavelength Division Multiplexed systems (HDWDM). It is known to offer dispersion immunity to the transmitted signal and offers improvement over conventional signaling (NRZ/RZ) [116]. This reduces the overall cost of the system by avoiding the need of any dispersion compensation modules in the mid link transmissions. An ideal duo binary signal is generated when a binary NRZ is passed through delay and add circuit along with a band limiting filter with band width which equals half of the bit rate. The filter greatly reduces the spectral components which could otherwise increase the non- linear distortions within the band of the receiver. Figure 1.14 depicts the duo binary filter. If the filter is employed with half of the bit rate, the dispersion distance is substantially increased.

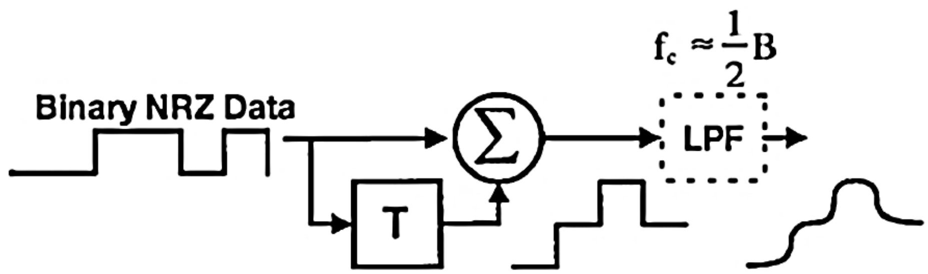

Figure 1.14 Duo binary Filter

1.7 Summary

The DWDM system is introduced with brief overview of the system blocks and their functionalities. DWDM types based on the inter channel separation are also explained. Further, an OTDM system with its receiver configuration is also discussed. From the system perspective, the various configurations of conventional optical and hybrid optical amplifiers are explained. As compared to the electro-optic regenerators, the optical amplifiers are more reliable, flexible, and can be used to amplify all the DWDM signals simultaneously with cost effective solutions. We believe that the hybrid optical amplifier should be regarded a best contender for future high-capacity DWDM system which can amplify broad gain bandwidth and can efficiently utilize all the fiber bandwidth. The implementation of hybrid optical amplifier in combined DWDM with OTDM is a sure winner to achieve long haul and high capacity optical systems. The optical code patterns of DPSK, DQPSK and duo binary are also introduced in the scenario of narrow spaced DWDM.

Chapter 2

Literature Review, Objectives and Outline

2.1 Introduction

The rapidly growing capacity requirements and a step towards framing “super channels” with capacities nearing terabit per second has generated renewed interest in devising ways and methodologies to achieve the same. Keeping in mind the cost effectiveness, the only solution that one foresees is the optical multiplexing domain. WDM comes as an instantaneous solution to accommodate the large expanding optical networks [3]. System investigation and optimization becomes a crucial step towards attaining a high fidelity WDM system [47] [48]. Such a system optimization takes into account the basic features pertaining to the inter channel spacing, bit rates, distance of the transmission, system nonlinear effects and linear effects, input power per channel and many more.

The support system to sustain the bit rate streams in excess of 40Gbps per wavelength is met by OTDM. The advent of hybrid schemes involving both DWDM and OTDM demand critical examination of network functionalities and scalability [49]. Further, the ingrained feature of such high capacity claims that the transmitter channels be densely packed with spacing less than 50 GHz. This would in turn lead to crosstalk at transmitter level and it could be overcome by using appropriate filters to cut down spectral overlap.

Transmission losses are imbibed in any optical communication link. To evade the use of electronic regenerators which makes the system unreliable and costly, the commencement of optical amplification offers multiple benefits over electronic regeneration. The bit rates are not limited by the electronic drive circuitry, rather it can be increased to as high as 80Gbps per wavelength by using optical time multiplexing techniques. Moreover, a system with combined data rates on different channels is also flexible with Optical Amplifier. Optical amplifiers being compliant to WDM eludes the requirement of any infrastructural modifications in the existing transmission links. This is very important feature which furnishes the realization of DWDM systems wherein the terabit/sec data rates have been already demonstrated [50].

The optical code patterns in the back-bone networks were the traditional NRZ and RZ [51]. But to reach record capacity levels and long distance applications, advanced modulation formats have become an intense need. Tera-bit transmission with channel spacing of 50GHz using advanced modulation is already established [52].

The system scenarios to device a high capacity network limits by either the channel spacing not being <50 GHz or by the count of channels. The main aim of this presented work was persuaded by the idea of designing and optimizing large number of channels which are closely spaced by taking into account the real time system parameters. The target is to get reduced system degradations and losses and incorporating optical amplifiers and its hybrid versions in capacity enhanced systems. Keeping this in mind the concerned literature survey was done to frame the objectives to improve upon the existing gaps and improvise on the current trends.

2.2 Literature Survey

2.2.1. DWDM system at narrow wavelength spacing to enhance the capacity

The transmission capacity of WDM system can generally be augmented by i) extending the useable bandwidth, ii) transmitting the wavelengths with narrow spacing, iii) increasing the number of the channels, iv) increasing bit rate per wavelength [3]. The reduction in channel spacing basically allows more number of channels to be transmitted in the same available band which implies no extra cost factor is required in laying of extra optical fibers to increase the capacity.

In 2009, Bobrovs *et al.* [48] demonstrated the minimal allowed spacing as one of the best criterion to enhance the capacity of (Highly Dense WDM) HDWDM system. It was implicitly proved that for a 2.5 Gb/s Highly Dense WDM system, the minimum allowed channel spacing ought to be more than 0.2nm (25GHz). It was also reported that 0.3nm (37.5GHz) serves as the higher limit for a 10Gbps system. These recommendations were useful in designing DWDM systems. The performance was evaluated by calculating BER and with the use of eye diagrams. A BER of $2.8e^{-11}$was reported for a 16 channel system with inter channel spacing of 0.3nm. The distance covered was only 40km as the link was presented without any mid link amplification to avoid any nonlinear losses.

Kaler *et al*. [53] studied the effect of signal to noise ratio for system attaining 1.28Tb/s capacity with spectral efficiency of 0.4bits/s/Hz. The impact of SNR on the number of channels, inter channel spacing and fiber length was presented. SNR improved with widened channel spacing as the effect of XPM marked a decrease. The channel spacing considered were from 0.8nm (100GHz) to 0.2nm. Similarly, with increased number of channels from 16 to 128, the SNR had a decreasing trend. Irrespective of the number of channels, if the inter channel spacing is more, the SNR becomes independent of increased number of channels and shows no variations even with 128channels. The dependence of SNR over short span links was negligible.

In 2004, Jansen *et al*. [54] demonstrated the transmission of 16 x 40Gbps = 640Gbps signals over 800km of Standard Single Mode Fiber. The inter channel spacing was 100GHz or 0.8nm. In 2011, Udalcovs *et al*. [55] reported a combined modulation three channel system and studied the response with varying channel spacing. One of the experiments stated by Jianjun Yu [56] stated the transmission of 20 x 112Gbps capacity based on orthogonal transmission of adjacent signals at spacing of 100GHz. This experiment indicated poor performance for long haul applications with only 10^{-4} BER being achieved. The total OSNR achieved for the 20 channels transmitted was 22.5dB. In yet another experiment, a ten channel DWDM system was presented with spacing of 30.8GHz for 100km of uncompensated single span SSMF [57]. The channel spacing was decided as being 1.1 times of the baud rate used.

Capacity enhancement was also achieved by increasing the per channel bit rates. This was made possible by clubbing OTDM with WDM and transmitting these high bit rates channels as densely as possible. DWDM using OTDM thus benefits from both the bandwidth utility and high capacity. Pieper, in 1998 [58] established 4 x 40Gbps OTDM transmission on a standard DSF fiber of 100km with inter channel spacing of 2nm. The system performance was judged with eye diagrams which is the most suitable form to measure results in a digital transmission [59]. It was reported that the OTDM performance largely depended on the pulse width of the transmitted pulses. For 160Gbps transmission the optimum pulse width was 4ps with 250 GHz separation. This avoided any FWM crosstalk to occur.

In 2006, Weber [60] described various OTDM high speed experiments and described in detail about the system set up and its various requirements. It was cited that the pulse source used in OTDM system transmission should generate short pulses with pulse width being less than the total bit period of the multiplexed signals. For the high capacity, 160Gbps, DPSK experiment, 1.4ps FWHM pulse width pulses were transmitted. The OTDM demultiplexer was the optical gate based on XPM in SOA. This was the preferred choice than the fiber based optical gate switches as they could be easily be integrated with other components.

Toliver *et al*. [61] compared the interferometric switching gate configurations for OTDM demultiplexing. It was concluded that SOA based SMZ switch exhibited the minimum switching window, minimum required power, flat top switching etc. Based on the conclusions Hirooka [62] performed the high capacity 640Gbps OTDM-DPSK transmission using SOA-SMZ switch. Corresponding 640Gbps, the switching gate of 1.5ps was realized and BER attained was 10^{-9} with extinction ratio >15dB. It was concluded that with SMZ switch as a demultiplexer, ultra-fast switching with minimum power requirement can be realized. The mathematical analyses of the OTDM with its BER calculations were performed by Ghassemlooy [63]. Razali Ngah [64] reported that SMZ switch is totally self-synchronized and no external clock recovery module was required. At the transmitter side the Optical Fiber Delay Lines (OFDL) was used to align or synchronize the control and the data signals to be given to the SOA-SMZ switch.

2.2.2. DWDM system with Optical Amplifiers at Narrow Wavelength Spacing

The conventional Optical Amplifiers EDFA, SOA and Raman have been in use for the WDM systems since their inception. The advent of EDFA, way back in 1990, brought about a revolution in WDM systems by replacing frequent use of costly electrical regenerators. EDFA employed in WDM systems act as lumped amplifiers providing lumped gain at a point in the fiber transmission link. As compared to the semiconductor based amplifier (SOA), the fiber based amplifiers work well as they are free from inherent non- linearities offered by the semiconductor material.

The EDFA being a discrete amplifier makes the signal see both the ends of noise floor (when intensity reduces) and peak power level prone to severe non linearities. Therefore, demand is to obtain amplifiers which sustain the power level of the signal throughout the transmission which is possible by having a large gain-bandwidth product. After the commercial availability of high power pumps for Raman Amplifier, it comes as a solution to achieve high capacity systems. The hybrid combination of the Conventional Optical Amplifier results in various Hybrid Optical Amplifiers. The Raman–EDFA hybrid amplifier is, especially, prominent as it utilizes the high power amplification efficiency of EDFA with flat gain and low noise characteristics of Raman [65]. The beginning of use of Hybrid Optical Amplifiers in general reduced the system impairments, increased the long haul applicability and provided a broadened bandwidth with a flat gain on it.

Hasan *et al*. [65] reported that the system performance of a real time WDM network can be improved by the use of a Hybrid Optical Amplifier (HOA). A 4×40 Gbps DWDM system with channel spacing of 50GHz (0.4nm) was implemented. The various proposed schemes of Hybrid Optical Amplifier positioning were compared on the system level with standalone Raman unit with respect to criteria of noise figure, gain and cost. It was reported that Raman-EDFA HOA provided a cost effective solution by giving better outcomes. It enabled 200km transmission with input power of 5dBm with acceptable BER of 10^{-10}.

Chang *et al.* [66] stated after comparing the EDFA and Raman-EDFA HOA that HOA was a better competitor with EDFA with respect to obtained low noise figure(NF), high OSNR, acceptable Quality factor and high output optical power. HOA was highly recommended as a substitute for increased performance as an inline amplifier. Q factor >18dB was found with HOA for an 80 channel system with 0.4nm spacing.

Jardim *et al*. [67] used eight channels WDM system with 0.5nm spacing and optimized the Hybrid Raman-EDFA by properly choosing the pump wavelengths of RA and input power levels of the EDFA, thereby, avoiding the gain saturation. It was concluded that two pumps were sufficient to achieve the global gain values.

Raman amplification was explored using different kinds of fibers. The different fibers designs have a huge impact on Raman amplification. A larger effective area fiber on one hand reduces the non linearities, and on the other hand, a small effective area fiber increases the Raman Amplification efficiency. Hansen *et al*. [68] implemented 25 channels WDM with 0.8nm spacing using in band DSF fibers. The authors also reported the experiment with 49 WDM channels with 0.4nm spacing. DSFs are reported to be a suitable choice for Raman amplification owing to its good Raman efficiency and equitable pump power requirements. Quality factor of 16.3dB was observed corresponding 3×10^{-11} of BER. Hence HOA performed within acceptable limits in the Zero Dispersion region. Carena *et al*. [69] reported that due to the non-linearity difference between the SSMF and NZDSF, single mode fiber offered large span distances to be covered.

Dispersion Compensating Fiber (DCF) used for Raman Amplification brings in two benefits of dispersion compensation as well as amplification. Lee *et al*. [70] carried out comparison of various configurations of DCF pumped Raman /EDFA hybrid amplifier using single pump and introduced concept of residual pumping. Out of the three proposed configurations, the Type 1 is Raman /EDFA in cascaded EDFA with residual pump after DCF, the Type 2 is Raman /EDFA in cascaded EDFA with residual pump before the DCF and the Type 3 is Raman assisted EDFA. The first and second type indicated high small signal gains of 21dB with less NF of 7dB. In [71] Raman only and Hybrid Raman/EDFA was compared to Type I proposed configuration. Raman exhibited a small signal gain of 5dB as against 21 dB by the hybrid type. Hence, significant gain enhancement with effectual gain-bandwidth was achieved.

The advanced multiplexing technique of combining OTDM with DWDM is the best option to increase the overall system capacity. The literature below indicates such hybrid systems which are restricted by use of EDFA only. Poboril [72] suggested the topology design of combining WDM with OTDM. Different component level parameters were discussed .The amplifier used was only the EDFA. Gousia *et al*. [73] realized the wavelength parallel bus architecture merging the WDM and TDM technique. It was reported that such a multiplexing would yield high scalability, high spectral efficiency and bandwidth elasticity. It was restricted with use of an inline EDFA only. Schuh *et al*. [74] reportedly used a dual stage EDFA for signal amplification of 3 x 80km of fiber. Four DWDM channels, (each enhanced to 160Gbps by using fiber based interleaver), were spaced 400GHz apart. Delfyett *et al*. [75] stated about the unique marriage of WDM with TDM which results in state of art peak value capacity and high performance systems.

Ahsan [76] reported the self-restoring hybrid PON architecture implemented with the Semiconductor Optical Amplifiers (SOAs). The use of HOA , the Raman/EDFA was reported in combined WDM-TDM [77] by Shapiro *et al*. Sixteen WDM channels with 100GHz spacing were transmitted with both inline EDFA and Raman/EDFA and the performance was compared in a symmetric dispersion regime.

2.2.3. Increased transmission distance in DWDM by overcoming fiber impairments

The need for long and ultra-long distances to be covered by DWDM systems is imperative in commercialized telecommunication networks. Islam [78] talks about deployment of Raman Amplifiers in the futuristic networks for long haul networks. Since RA can be used in C, S or

L bands depending on the pump wavelengths, hence, 20 channels S Band DWDM system spaced by 200GHz was implemented over 10 spans of SSMF covering a total of 867km.

Chung *et al*. [79] corroborated a long-haul communication of 1040 km of SSMF on a 16 channel DWDM using the hybrid amplifiers of Raman and linear optical amplifiers (LOA). The LOA used was the SOA which constituted the HOA used. The single span was of 80km with span loss of 16dB. It was observed that after 1040 km transmission the acceptable Q factor obtained was between 12.7 dB to 14.5 dB. A flattened gain of nearing 35dB was obtained with RA with LOA.

Schuh *et al*. [74] reported error free 3 x 80 km transmission in 4 x160Gbps DWDM/OTDM transmission. BER < 10^{-9} was obtained after 240km reach of Tera Light TM Fiber. In [77], 2000km with repeater spacing of 80km was reported in Raman assisted transmission. Downie *et al*. [80] reported a distance of 1200km (using 12 spans of 100km) for 40Gbps direct detection DWDM system at 100GHz spacing without any inline dispersion compensation. A LEAF fiber was used to carry out the transmissions with only EDFAs.

Hurley *et al*. [81] used again only EDFAs for a 38 channel DWDM system spaced at 50 GHz. The distances up to 1500km with fixed pre-compensation and 900km without any inline compensation was achieved in the Corning (LEAF) optical fiber with 100km spans with each span having a loss of 20dB. Only EDFA with fixed power configuration was used in such a way that average power per span was optimal for transmissions.

Seo *et al*. [82] used 16 channels DWDM with 200GHz spacing between the channels. These were transmitted over 5 x 80 km distance using the linear optical amplifier in combination with DRA, the distributed Raman fiber amplifier. The linear Optical Amplifier was a gain clamped SOA. The combined gain of 20 dB with NF < 2.7 dB was notified.

Suzuki *et al*. [83] transmitted 100 channels with 25GHz channel spacing with even and odd channels being orthogonally polarized. Four spans of dispersion shifted fiber (DSF) each span being of 80km (4 x 80km) in the C band transmission was successfully established. It was rightly concluded that Q factor achieved with backward pumping is 2dB greater than the one achieved with forward pumping. The Q factor was greater than 11.6dB without any Forward Error Correction (FEC) being used.

Gavioli *et al*. [57] conducted ultra-narrow spaced ten channel transmission over different kinds of fiber, SSMF and the NZ-DSF and by employing narrow channel filtering at the transmitter. The single span length was 100km with the EDFA. A total of 2300km over SSMF was attained as against only 800km reached by NZDSF. A comment on use of LEAF was quoted as being 40% more efficient than NZDSF.

Chandrasekhar *et al*. [52] demonstrated terabit transmission over 16 x 80 km of SSMF spans. 25 DWDM channels spaced at 50GHz channel spacing were divided into even and odd channels and differently modulated and separately multiplexed using Arrayed Waveguide Grating. A total reach of 1280 km was achieved including designed bandwidth efficient Reconfigurable Optical Add Drop Multiplexer every 320 km.

The quest to reach higher distances with gain flattened amplifiers had started way back in 1999 when Hiroji Masuda [84] transmitted 14 DWDM channels over 67nm of bandwidth with the use of novel HOA. A 900km distance was covered with BER of 10^{-9} with the low noise hybrid Raman amplifier with EDFA. It was concluded that due to the flattened gain characteristics all the channels experience the same gain and obtain larger distances as compared to the EDFA stand-alone unit.

2.2.4. Modulation formats for super DWDM System

The demand for high capacity DWDM systems and side by side the low cost infrastructure demand for end to end transmissions have led to emphasis on the modulation format that renders high bandwidth spectral efficiency. The individual channels in a system can be transmitted with same optical code pattern or with a mix of transmitting formats with the end capacity being the measure for it. Bosco *et al*. [85] compared RZ, NRZ and CSRZ modulation on a DWDM system with narrow spacing between the channels. To study the effects of various system parameters only 3 channels at 0.4nm was considered. The non-compliance of RZ and CSRZ below 0.8nm spacing at higher DWDM system was shown. It was suggested that the introduction of transmission filter improved the RZ performance and allowed Carrier Suppressed RZ transmission at 0.4nm with penalty of 0.5dB only. It was also claimed that orthogonal polarization of adjacent channels could make both RZ and NRZ possible at 0.4nm spacing. It was concluded that a tight transmission filter effectively would turn RZ into an approximate NRZ and CSRZ pulses into duo binary coded pulses. Gabriel [86] talks about various amplitude and phase modulation schemes necessary for high bit rate DWDM systems. It was stated that to achieve larger distances and better OSNR, DPSK was a good candidate. The effect of bit rate on the modulation format used was extensively quoted.

All the back -bone networks mostly work with NRZ and RZ formats. The applicability of these was studied way back in 1997 by Breuer *et al.* [87]. A dispersion managed 40Gb/s TDM system was tested with NRZ and RZ formats. It was concluded that 50% duty cycle RZ was superior to NRZ in achieving 1200km as against 400km distance by NRZ. Mastuda *et al***.** [88] compared NRZ and RZ in a single line experiment with in line amplification over long distances on a zero dispersion regime. Since higher order dispersion and accumulated ASE due to the inline amplifiers affected the overall system performance, NRZ performed better covering 6000km than RZ which covered 4400km (reference at BER = 10^{-9}) because of its less dispersive features. Bobrovs *et al*. [89] studied 8 WDM channels transmission with 100GHz spacing and analyzed the nonlinear effects on NRZ and RZ modulation schemes. FWM was seen to occur more with NRZ in zero dispersion regime as compared to RZ.
Takeshi *et al*. [90] compared NRZ and RZ modulation pattern in 75GHz densely spaced, 120 channel DWDM systems. Single and parallel polarization state was assumed for all the transmitting channels. NRZ was opted as the best choice for distances lesser than 1000km because of the ease of the transmitter and the receiver designs. The transmission was independent on the type of fiber used. Carrier suppressed RZ was opted as the best candidate for systems using fibers with larger dispersion. The IM-DPSK format outperformed, as longer transmission distances (>2000km) independent on the fiber type could be achieved, even when it needed complex designs of transmitter and the receiver. The complex design refers to inclusion of a phase modulator, the differential modulator and the intensity modulator for transmitting the IM-DPSK signal.

Jaworski [91] illustrated that although no specific guidelines are there for the use of any specific modulation format but these are decided and are based on the required capacity and speed keeping in mind the vulnerability of system to certain nonlinear effects. NRZ was the all-time suitable candidate reaching 0.4b/s/Hz spectral efficiency. RZ increased receiver sensitivity over NRZ but had poor spectral efficiency. Duo binary–PSK was dispersion tolerant but was more sensitive to Kerr non-linearity. DPSK and DQPSK format offered 3dB receiver sensitivity improvements and also enhanced the transmission distance amidst the ASE limitations. Gnauck *et al*. [92] dedicatedly talks about optical phase shift transmission systems, the DPSK and its capability to cover long haul distances. It was demonstrated that DPSK is more sound to fiber nonlinear effects and it offers 3dB lesser OSNR requirement to attain an acceptable value of BER (10^{-9} to 10^{-12}). Though the receiver design gets complicated by presence of the delay line interferometric demodulator, but still it's a tradeoff between performance and the cost. Aihan [93] focused on dispersion managed systems to enhance the system performance. It was reported that RZ and CS-RZ were more robust apart from being anti-nonlinear and anti-PDM.

2.3 Gaps in Present Study

The relentless demand of increasing system capacities within limited bandwidth due to the ever increasing internet traffic loads have regenerated the demand to device transmission networks with the capability of serving many user channels simultaneously, thereby maintaining the system quality. Increased bit rates per wavelength and transmitting them with ultra-narrow channel spacing demands basic sensitivity analysis of various system components such as multiplexers, optical amplifiers and demultiplexer etc. Reaching maximum capacity limits also expects system design and intensive optimization in terms of number of transmitting signals, optimal modulation formats, bit rate, link length, input power per channel, channel spacing, transmitter and receiver filters, and launch of signals in terms of polarization, fiber linear and nonlinear effects etc.

Lastly, the advent of hybrid optical amplifiers (HOA) and their applicability on the Ultra DWDM system is crucial in terms of attaining long haul communication links. HOA are known to offer a broadband amplification regime with gain flatness over the entire wavelength band. DWDM system, especially the high bit rate ones, using OTDM to multiplex into high bit rates incorporated with HOA at ultra-narrow channel spacing need to be designed and optimized to enhance the system capacity at low system cost. In order to achieve such a system design, it is of utmost importance to propose and design and optimize newer DWDM systems with controlled parameters and with more number of high bit rate channels at ultra-narrow spacing. The acceptable performance metrics of BER, Q factor, Figure of Merit (spectral efficiency defined as bit rate to channel spacing) etc. need to be achieved with these newer designs aiming at minimum system constraints and losses.

Table 2.1 Previous Related work in DWDM

Author/Year	**Channel Spacing**	**No. of Channels**	**Amplifier**	**Modulation Format**	**Distance**	**Bit rate / BER /Q Factor**
Bobrovs ,2010 [18]	0.3nm(10Gbps)/ 0.2nm(2.5Gbps)	2	-	NRZ/RZ	40km	10^{-9}
Jansen,2004 [54]	0.8nm	16	EDFA	RZ	800km	40Gbps / 10^{-6}
Bosco,2002 [85]	0.4nm/0.6nm	3	EDFA	RZ/NRZ/CS-RZ	-	42.65Gbps
Kamal,2002 [53]	0.4nm	32	EDFA	NRZ	250km	10Gbps / 10^{-12}
Chang,2006 [66]	0.4nm	16	EDFA/HOA	-	80km SPAN	10Gbps / 10^{-12}
Suzuki,2003 [83]	0.2nm	100	Raman	NRZ	320km	10Gbps / 10^{-12}
Downie,2010 [80]	0.8nm	40	EDFA	DPSK	1200km	43Gbps / 15dB
Hurley,2006 [81]	0.4nm	38	EDFA	Duo-binary	1500km	10.7Gbps / 20dB
Lee,2003 [82]	1.6nm	16	SOA-RAMAN	NRZ	400km	10Gbps / 20dB
Kim,2005 [79]	0.8nm	16	SOA-RAMAN	NRZ	1040km	10Gbps / 15dB
Jaworski,2003 [91]	-	4	EDFA	RZ-DPSK	320km	40Gbps
Ivananovs,2007 [89]	0.4nm	8	EDFA	NRZ/RZ	100km	10Gbps
Sapiro,2004 [77]	0.8nm	4	EDFA	RZ	160km	40Gbps / 10^{-9}
Haris,2006 [109]	0.8nm	8	Raman-EDFA	Duo-binary	240km	10Gbps / 10^{-9}
Takeshi,2002 [90]	0.6nm	120	Raman-EDFA	DPSK	100x6,8,12 km	40Gbsp / 15dB
Schuh,2002 [74]	3.2nm	4 x 16 OTDM	EDFA	RZ	240km	40Gbps / 10^{-9}

The Table 2.1 enlists all the relevant work done at a glance with various system parameters for different WDM systems.

The gaps in the current systems are summarized here under.

[1] The existing WDM systems focusses on wider channel spacing (>0.4nm to 1.6nm). The potential of WDM system with decreased channel spacing needs to be investigated more in minimal allowed bandwidth supporting maximum number of USER channels.

[2] The performance and evaluation of cost effective Hybrid Optical Amplifiers for Ultra-DWDM has not been studied so far.

[3] DWDM using OTDM for capacity enhancement is little explored.

[4] There is increased scope of implementation of Hybrid Amplifiers in DWDM using OTDM which is not yet reported to the fullest.

[5] Improvements in achieving Long Haul Links both in U-DWDM and DWDM using OTDM using Hybrid Optical Amplifiers is yet to be explored in depth.

2.4 Objectives Framed

After the thorough study of the literature concerned and understanding of the ongoing trends, the following objectives are proposed:

[1] To investigate Super DWDM system at narrow wavelength spacing (<=25 GHz) to enhance the capacity.

[2] To investigate Super DWDM system with optical amplifiers at Narrow Wavelength Spacing.

[3] To increase the transmission distance in Super DWDM systems by overcoming the fiber transmission impairments.

[4] To determine the optimized modulation format for Super DWDM Systems.

2.5 Contribution of Thesis

The basic aim and contribution of the work presented in this thesis is to propose high capacity U-DWDM or the Super DWDM system with increased number of channels and at reduced narrower channel spacing. Another innovative capacity enhanced bandwidth efficient DWDM using OTDM is also proposed. From application point of view the various Hybrid Amplifiers proposed are implemented on the designed and optimized DWDM systems which yield enhanced capacity. Various kinds of fibers are used to check for the maximum transmission performance of the proposed systems. Finally, the modulation formats are verified at all the system levels presented.

The major contribution of the thesis can be enlisted as follows.

[1] The proposed U-DWDM System offered large bandwidth efficiency with large number of channels which are transmitted over long transmission distance. (The parameters were optimized for the designed systems using OPTSIM).

[2] The proposed DWDM using Optical Time Division Multiplexing system, of increased capacity up to 16 x 4 x 10Gbps with narrow channel spacing allows many users on a single wavelength and many wavelengths to be closely spaced to each other.

[3] Implementing the Gain Flattened Hybrid Optical Amplifiers (HOA) in U-DWDM and in high speed DWDM using Optical Time Division Multiplexed Systems. This will achieve very long haul fiber links by overcoming system losses.

[4] Investigation of the above system with various existing modulation schemes.

2.6 Organization of Thesis

Based on the objectives and the literature survey the aim of the thesis is to design high speed, bandwidth efficient U-DWDM system to enhance capacity with minimal bandwidth, maximum approachable distance and acceptable performance metrics. The thesis has been organized into seven chapters as follows:

Chapter 1: An introduction and overview of the basics of WDM, its design parameters etc. is presented in this chapter. The basic OTDM system technology is also introduced. Apart from this various conventional optical amplifiers and their types are also discussed here.

Chapter 2: A detailed literature review of DWDM and Optical Time Division Multiplexing and their hybrid system and of optical amplifiers is presented. Further, the problem formulation, loop-holes in existing system and objectives are presented.

Chapter 3: The first objective i.e., to investigate Super DWDM systems at lesser channel spacing to enhance the capacity is encompassed here. DWDM systems are proposed and the allowable and acceptable limits to bit rates, channel spacing and overall link distance are optimized for maximum capacity enhancement. A 4 x 4 Optical Time Division Multiplexed system is also introduced with RZ-DPSK modulation so that further DWDM systems using OTDM could be better designed to get bandwidth limited high speed systems.

Chapter4: Application of the designed Hybrid Optical Amplifiers on the proposed DWDM and on the combined high capacity DWDM with Optical Time Division Multiplexed system to maximize the distance is presented here. First a 160 x 2.488Gbps DWDM system is investigated with varying input power values for different combinations of Conventional and Hybrid Amplifiers. With minimum utilization of bandwidth Raman-EDFA HOA provides improved gain and quality of signal even for 96 optical channels covering 33.3nm bandwidth. A high bit rate DWDM is investigated with HOA for an 8 x 8 x 10Gbps system. Further the impact of using different kinds of fibers on Raman amplification is also investigated.

Chapter 5: The third objective of maximizing the propagation distance with minimum transmission impairments is presented. Using the proposed 96channels DWDM System at 0.1nm spacing a record length of 2070 km is achieved with single span of 60km of SSMF. To overcome the system impairments high speed 16 x 4 x 10Gbps system is investigated with orthogonal (polarization) launch of even and odd channels. A single repeater less distance of 207 km is noted for this case. The OSNR performance with a different topology of 8 x 8 x 10Gbps is also quoted .The maximum distance reached for all, 4 x 4 x 10Gbps, 8 x 4 x 10Gbps, 8 x 8 x 10Gbps and 16 x 4 x 10Gbps is reported.

Chapter 6: The fourth objective to investigate the modulation formats for the proposed systems is presented. Various back- bone modulation formats to increase the overall capacity of the designed system are investigated. This includes, NRZ, RZ, NRZ-RC, RZ-RC, DPSK, DQPSK, Duo binary formats.

Chapter 7: This chapter summarizes the work undertaken and presents the conclusions drawn and recommendations given on the basis of results obtained in Chapters three to six.

Chapter 3

DWDM System at Narrow Wavelength Spacing for Capacity Enhancement

3.1 Introduction

This chapter deals with the first objective to investigate the Dense Wavelength Division Multiplexed (DWDM) System at narrower spaced channels for capacity enhancement. Large capacity DWDM systems are designed and the performance is investigated in terms of received eye diagram, bit error rate and Q factor. Real time system parameters are used for the investigations so that maximum number of channels at minimal channel spacing and at higher bit rate per channel could be achieved. Further, high bit rate DWDM system is investigated by using the concept of single wavelength, Optical Time Division Multiplexing (OTDM), to increase the bit rate per transmitted wavelength and hence the capacity within the minimum occupied bandwidth. The system is investigated in terms of the input signal power per channel, control signal power level and the pulse width of transmission. Both the optical multiplexing techniques are separately investigated to optimize and maximize their individual performances. An enhanced capacity of 4 x 40Gbps RZ-DPSK DWDM system is investigated for maximum of 110km in a simple system without the amplifiers.

3.2 Investigation of Ultra-DWDM System for Capacity Enhancement

3.2.1 Various 64 x 10Gbps, 32 x 10Gbps and 16 x 10Gbps DWDM Systems

The relentless demand for capacity for ever growing internet traffic has motivated the network design engineers to create a niche in the system design. This is possible by rigorous investigations keeping in mind the pivotal system parameters. Especially, to meet the long haul link requirements, every single block from transmitter to the receiver needs to be carefully designed and optimized with real time parameters.

Generally, to reach high capacities (i) number of channels can be increased, (ii) bit rate per channel can be augmented, (iii) channel spacing can be reduced. Increased bit rate per channel demands maintaining high SNR throughout to meet the acceptable transmission performance. With increased number of channels the useable bandwidth increases and this demands optical amplifiers to amplify the entire wavelength band. Narrow channel spacing is feasible at the cost of low bit rate per channel. This, in turn, demands multiplexers and demultiplexers that operate in narrow band domain. Therefore, all the three enlisted factors for high capacity come with one or the other technical issues. While designing, all the system issues are kept in mind.

International Telecommunication Union-Telecommunication (ITU-T) has set standardized channel spacing available for commercial DWDM systems [94]. The previously existing system as in [7] [12] [95] etc. come either with more number of channels but are limited by large channel spacing or vice versa. Abdelsalam *et al.* [23] proposed a hybrid of WDM and OTDM transmitting 200Gbps using 4 x 10 x 5Gbps signals. Ghassemlooy *et al*. [26] showcased the performance of 1 x 4 OTDM as related to the pulse width of the transmitted pulse and the switching window. Unfortunately, the literature about DWDM was limited by the minimum allowed channel spacing for the various bit rates, different number of channels in the system. So, this objective focusses on resolving system issues and making a simple designed DWDM system (refers to reduced complexity). DWDM systems with different capacities are proposed at narrow channel spacing and with high spectral efficiency. The system performance is explored with allowable channels, bit rate/channel and inter channel spacing supporting maximum of 80km transmission without the use of any inline amplifiers.

3.2.2 DWDM System Design

The simulative block diagram is made using OPTSIM. The system under investigation includes transmitters with 64, 32 and 16 channels. The single channel transmitter consists of a digital data source which is the PRBS digital data generator of degree 7, NRZ encoder, a Continuous Wave (CW) source of laser and a $LiNbO_3$ Mach-Zhender Modulator (MZM). The peak power of laser per user channel is 1mW. Since, bit rates in excess of 2.5Gbps are considered, use of external modulation is a better approach to significantly reduce the laser internal chirp on the optical signals. The bit rate is kept as a variable with values of 5Gbps, 10Gbps, 15Gbps, and 20Gbps. Some investigations also adhere to bit rates of 12.5Gbps.

The first channel is centered at 1549.5nm with different channel spacing forming an equally spaced spectrum. The bandwidth occupied by considered 64 channel system at 0.1nm, 0.2nm, 0.3nm and 0.4nm spacing is 6.3nm, 12.6nm, 18.9nm and 25.2nm respectively. Similarly, for a 32 channel system with 0.1nm spacing, it is 3.1nm, for 0.2nm it is 6.2nm, for 0.3nm it is 9.3nm and goes on. The multiplexed signals passes through the ideal multiplexer and further the signal is transmitted over single span length up to 80km without the use of any amplifiers.

The SSMF is of 75μm^2 effective area with dispersive slope of 0.09 ps/ (nm^2 .km) and has a standard attenuation of 0.25dB/km. In this investigation amplifiers are not used to reduce system non linearities as only the transmitter parameter are optimized and investigated. At the reception, the optical Gaussian Filter filters out the optical power within the definite wavelength band. The bandwidth of the Gaussian Filter is based on 50% value of the spacing at which the channels are transmitted.

Finally, a photo detector performs the optical to electrical conversion with use of Low pass (LP) Bessel filter. A Bessel Filter produces minimum overshoot when compared to other available filters. Bessel Filter uses bandwidth which is 70% of the bit rate. The PIN photo detector used has responsivity of 0.875A/W. The minimum dark current is 0.1nA. The PIN is preferred over APD as the latter requires high bias voltage and it displays temperature instability. PIN is more economical and requires lesser complex circuitry.

Eventually, the digital data evaluation is carried by plotting of eye diagrams [96] and by Q factor analysis. The eye diagram serves as an optimum tool to access the system performance. Such a visual display gives at a glance, judgment of the received SNR and a wider eye opening is indicative of good system performance. Figure 3.1 shows the DWDM system set up.

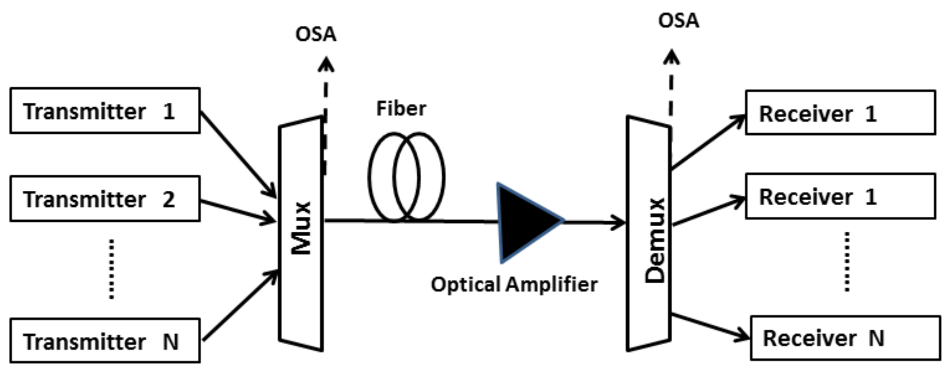

Figure 3.1 DWDM System Setup, OSA: Optical Spectrum Analyzer

The block schematic of single channel transmitter is shown in Figure 3.2. The simulation is based on solving complex differential equations taking into consideration the linear and the prevalent nonlinearities induced by the system. The wave lengths are transmitted as time domain samples over the complete band of wavelengths used. The simulative environment supports the TDSS (Time Domain Split Step) method to simulate both the dispersive and nonlinear losses incurred in to the system.

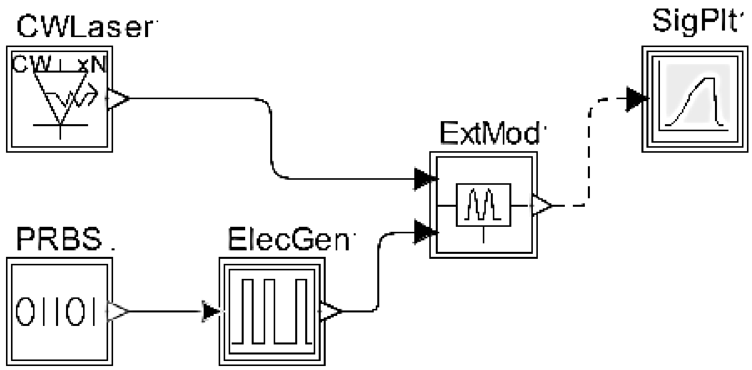

Figure 3.2 Single DWDM Channel Transmitter

3.2.3 Results and Discussion

Increasing the number of channels in DWDM system, with narrowing of the inter channel spacing yields different quality of the signal and eye diagrams indicating the different levels of performance. The output power and the bit error rates are considerably affected by longer lengths of the fiber, high bit rates per channel and by increased count of the channels. For a 32 channel system covering a 3.1nm band width with spacing as 12.5GHz (0.1nm), the BER observed for single span repeater less distance up to 80km is shown in Figure 3.3. It is observed that as the bit rates per user data transmission increases from 5Gbps to 12.5Gbps, the BER subsequently worsens.

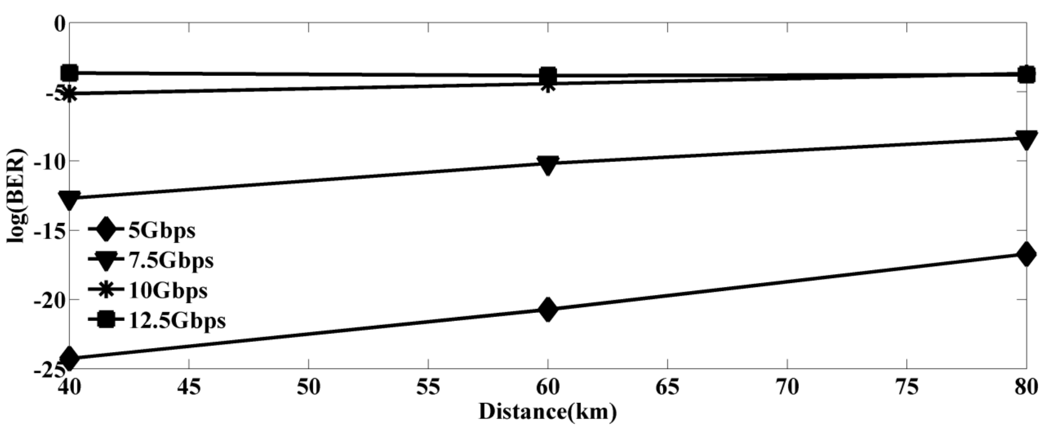

Figure 3.3 BER versus Distance for 32 channels, 0.1nm spaced DWDM System

This can be attributed to the fact that at narrow spacing with more number of transmitted bits per second causes huge spectral overlap even if narrow filters are employed. Also, with increase in distance, the onset of nonlinear effects causes a low BER performance. Moreover, the single span distance increase causes little variation in the BER especially at

12.5Gbps. More or less low power levels is obtained though out the distance covered. This is explained as for input powers of 0dBm at distances of 80km, there are combined effects of non-linear effects and huge crosstalk. So, overall deteriorated performance is observed. Acceptable BER (10^{-9} to 10^{-12}) is observed for bit rates equal to and below 7.5Gbps as shown below.

Further optimization of number of channels with bit rates is also done. Figure 3.4 indicates the resulted BER for varying number of channels at 0.1nm spaced DWDM system over 60km single span length. The system is tested for different bit rates. The constant poor BER at 10Gbps is reported at minimal distance of 60km (chosen after simulative iterations) for channels up to 64 as seen by the straight line at 10^{-5}. As explained earlier, as the bit rates are increased, all the channels performance degrades with respect to output power received.

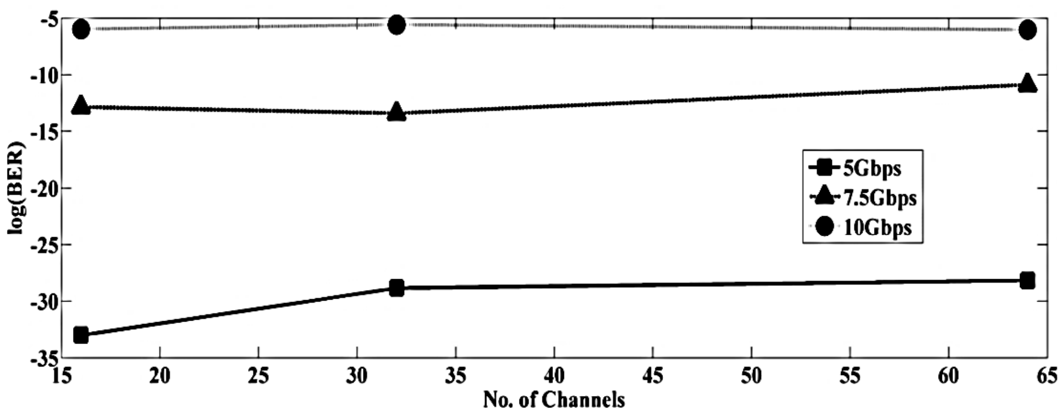

Figure 3.4 BER versus Number of Channels for 0.1nm spaced, 60km, DWDM System

All the channels considered i.e.16, 32 and 64 channels U-DWDM system perform excellently well at 0.1nm spacing at 5Gbps bit rate. The eye diagrams for 16, 32 and 64 channel DWDM channel at 0.1nm spacing, 5Gbps bit rate covering span 80 km is shown as below in Figure 3.5. Wide opened eye diagram gives good BER and a sustainable communication link. It is observed that all the eye diagrams display quite a wide eye opening. The 64 channel system exhibits lesser eye opening as compared to the 32 channel and 16 channel systems. The BER obtained at 0.1nm spacing in 16 x 5Gbps, 32 x 5Gbps and 64 x 5Gbps system is $3.95e^{-10}$, $5.5e^{-8}$ and $1.2e^{-7}$ respectively. As the bit rate increases to 10Gbps the eye opening reduces e.g. in a 64 channel system a BER of only $7.59e^{-3}$ is obtained at 0.1nm which is poor. But as the spacing is increased to 0.25nm, BER significantly improved to $9.16e^{-9}$. For a 64 x10Gbps system nominal spacing ought to be =>0.2nm.

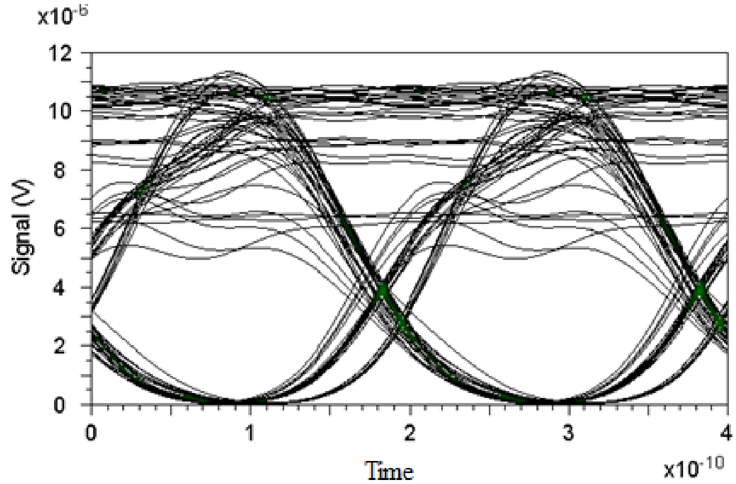

Figure 3.5 a) Eye Diagram: 64 channel, 0.1nm spaced, 80km, and 5Gbps DWDM system

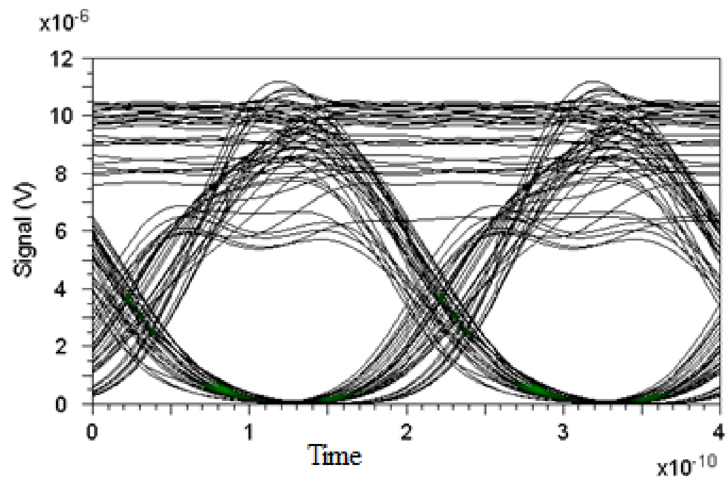

Figure 3.5 b) Eye Diagram: 32channel .0.1nm spaced, 80km, 5Gbps DWDM System

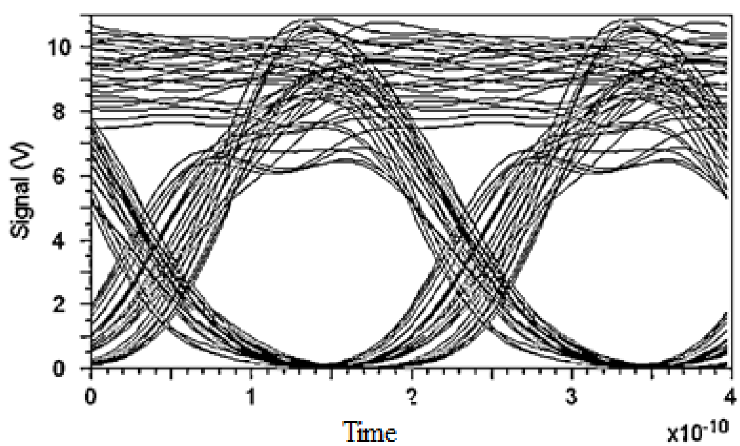

Figure 3.5 c) Eye Diagram: 16 channel, 0.1nm spaced, 80km, 5Gbps DWDM System

The 64 channel spectrum obtained after the multiplexer at 0.25nm spaced DWDM system is shown in Figure 3.6.

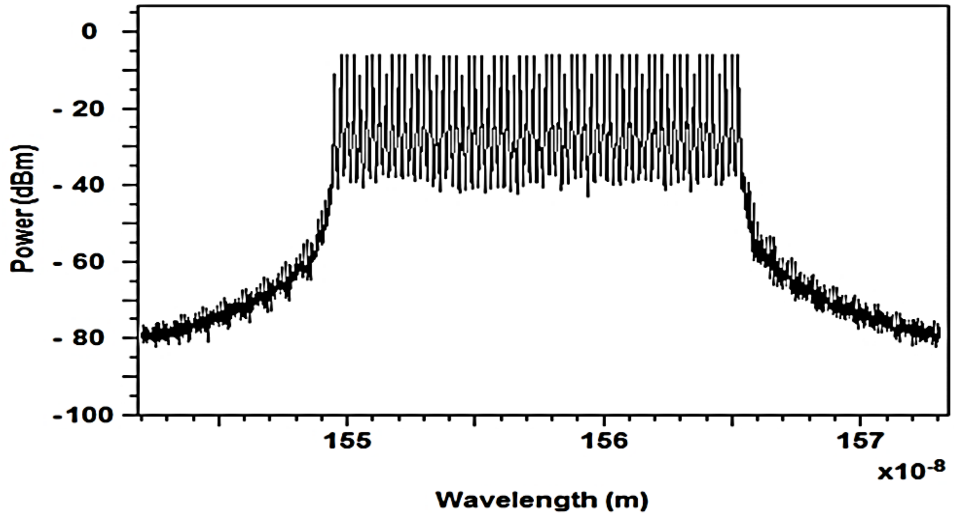

Figure 3.6 Optical Spectra of 64 channels, 0.25spaced, 10Gbps DWDM System

To get clear picture, the following analysis was done by transmitting 32 channels for a distance of 60km at different applied bit rates from 5Gbps, 7.5Gbps, 10Gbps and 12.5Gbps. The channel spacing was varied from 0.1nm to 0.4nm. Reduction of channel spacing worsens the bit error rate for different values of bit rates. BER is a performance criteria calculated from the eye diagram. There is remarkable decrease in performance at 0.1nm for bit rates higher than 5Gbps. This is evident from Figure 3.7given below.

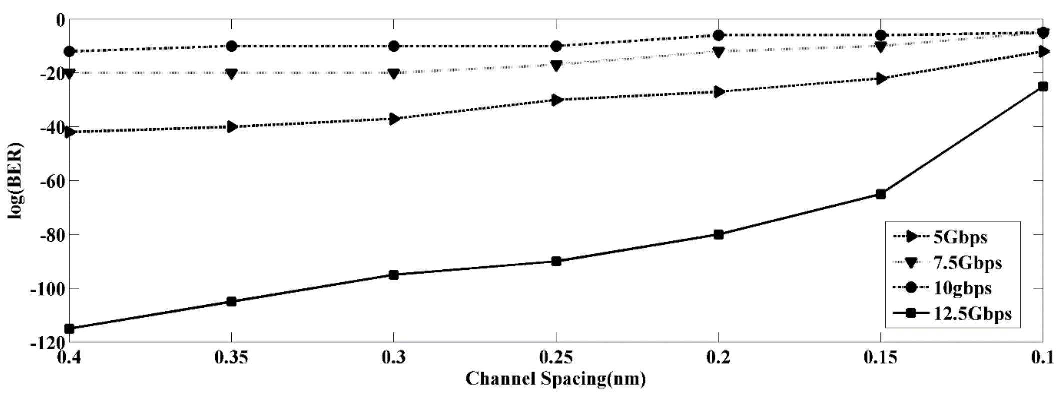

Figure 3.7 BER versus Channel Spacing at different bit rates

The feasibility of 10Gbps system is at spacing more than equal to 0.2nm e.g. for considered 32 channel system at 0.25nm channel spacing at 60km gives BER of $7.2e^{-8}$.

The BER is also studied at different single span distances as is shown in Figure 3.8.

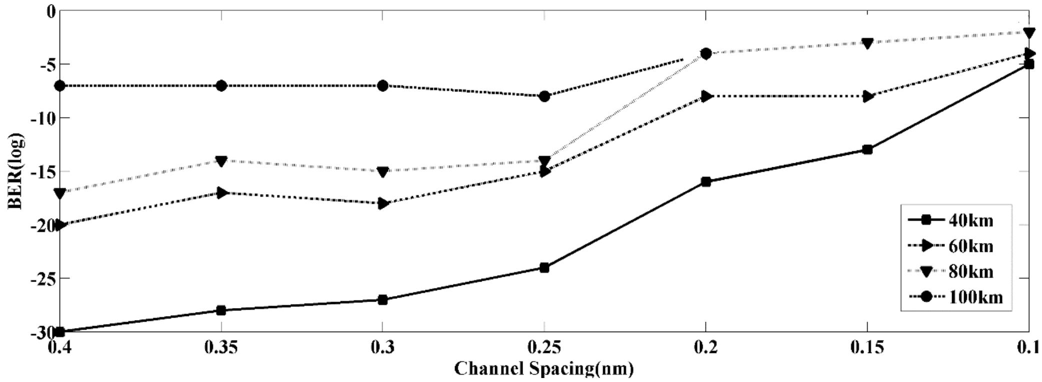

Figure 3.8 BER versus Channel Spacing at different single span length

For all distances lesser than equal to 60km reach, acceptable performance limits are obtained even at 0.1nm. BER values for 16 x 10Gbps, 32 x 10gbps and 64 x 10Gbps DWDM system 0.2nm spacing is 4.9e-9, 7.2e-8 and 2.1e-7 respectively. Therefore, at 10Gbps maximum reach is 60km at 0.2nm spacing. Beyond 60km the performance for the 10Gbps system degrades for > = 32channels. The calculated optimal distance for 0.1nm spaced, 5Gbps system is 80km. On the similar grounds, 30km is the appreciable reach obtained for 16 x 15Gbps, 32 x 15Gbps and 64 x 15gbps DWDM systems at 0.35nm spacing as the allowable spacing for acceptable performance for 15Gbps systems. For system at 20Gbps i.e. poor performance with BER <=e^{-3} is observed for span up to 25km even at spacing of 0.4nm. Further variation of BER for all the different group of channels at 10Gbps can be observed at one glance in Figure 3.9.

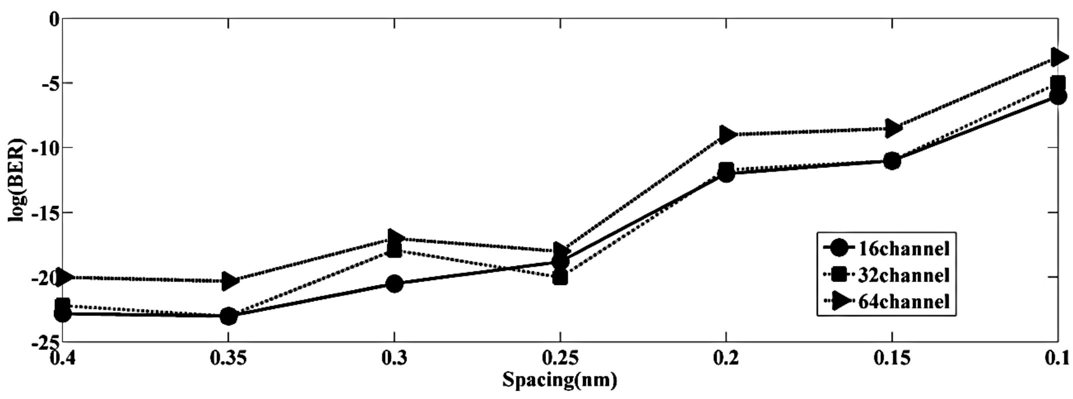

Figure 3.9 BER versus Channel Spacing at different number of channels

All the 160Gbps, 320Gbps and 640Gbps systems variation were studied at 60km for different channel spacing. The BER was noted and it was observed that with lesser spacing and higher number of channels, the BER indicated marked worsened performance. At 0.25nm spacing all the systems reported acceptable performance. The 64 channel system at 0.25nm gives a BER of $2.1e^{-7}$. Similarly, 32 channels noted similar BER reading of $7.2e^{-8}$. The 16 channel system reported a BER of $4.2e^{-9}$.

The eye diagram in Figure 3.10 a), b) and c) shows the wide eye opening obtained from 64, 32 and 16 channel systems at spacing of 0.25nm at 10Gbps data rate. The minimum spacing recommended for 10Gbps system is therefore equal to greater than 25GHz or 0.2nm. Above this the general performance decreases with BER falling below acceptable limits. Likewise further the boundary condition for systems with higher bit rates of up to 15 Gbps is also reported. The results and discussion above indicate the feasibility of DWDM system at 12.5GHz grid.

The improvement in performance is achieved not below 0.2nm spacing for 10Gbps DWDM systems. Whereas, at 0.1nm spacing, system below 7.5Gbps gives excellent results. The eye diagram at 5Gbps is already quoted for reference in Figure 3.5. As the bit rates are increased to 15Gbps, the bottom floor for the channel spacing becomes 0.35nm. Accordingly, the limits to single span distance are also reported.

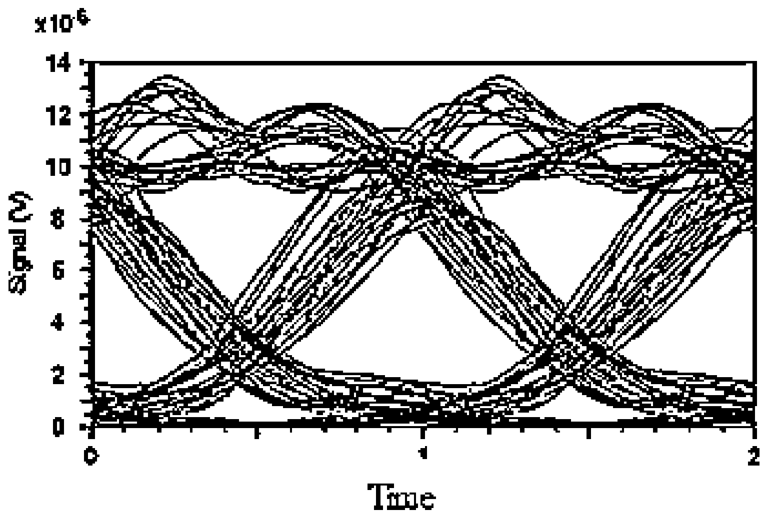

Figure 3.10 Eye Diagram: a) 64 channel, 0.25nm spaced, 60km, 10Gbps DWDM System

Figure 3.11 a) and b) indicates the eye diagram for 32 channels 0.35nm spaced, 30km, 15Gbps system and 32 channels 0.4nm spaced, 25km, 20Gbps DWDM system respectively for fair comparison. The eye opening reduces as the channel bit rates are increased or the channel spacing is reduced.

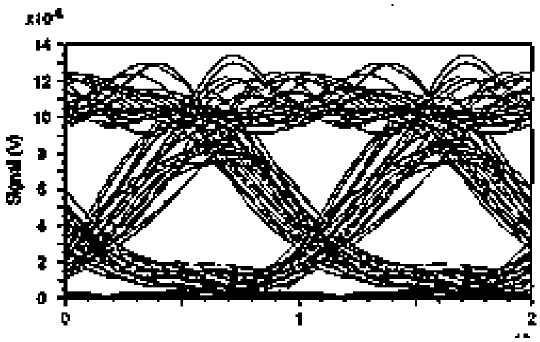

Figure 3.10b) Eye Diagram: 32 channel, 0.25nm spaced, 60km, 10Gbps DWDM System

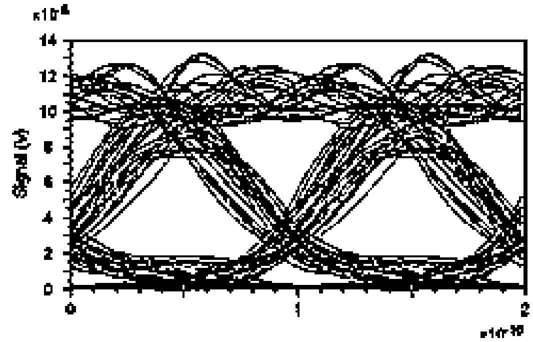

Figure 3.10c) Eye Diagram: 16 channel, 0.25nm spaced, 60km, 10Gbps DWDM System

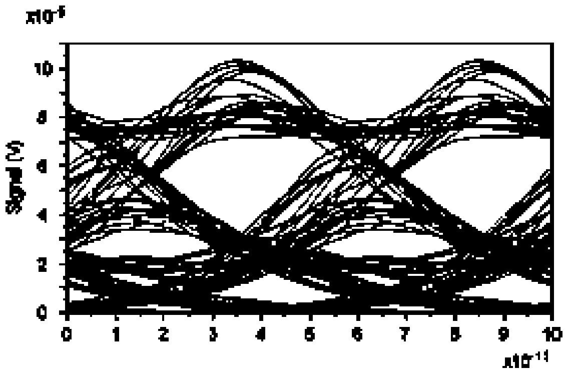

Figure 3.11a) Eye Diagram: 32 channel, 0.35nm spaced, 30km, 15Gbps DWDM System

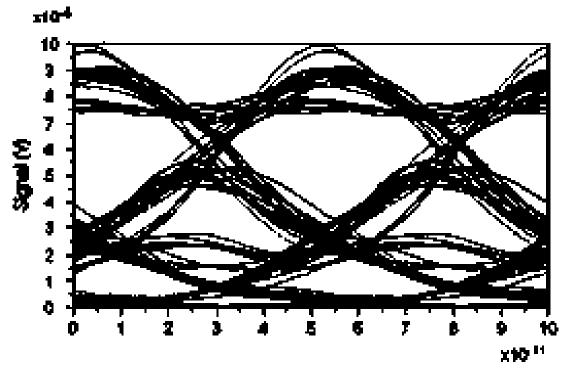

Figure 3.11 b) Eye Diagram: 32 channel, 0.4nm spaced, 25km, 20Gbps DWDM System

Table 3.1 gives BER values obtained with allowable values of optimized bit rates, channel spacing and number of channels.

Table 3.1 Optimized BER Readings for Designed DWDM System

No of channels **Bit rate**	**5gbps**	**10gbps**	**15gbps**	**20gbps**
16	0.1nm at 80km 3.95e-10	0.25nm at 60 km 4.9e-9	0.35 at 30km 2.8e-7	0.4 nm at 25km 1.96e-3
32	0.1nm at 80km 5.5e-8	0.25 nm at 60km 7.2 e-8	0.35 nm at 30km 5.08e-8	0.4nm at 25km 2.17e-3
64	0.1nm at 80km 1.2e-7	0.25nm at 60km 2.1e-7.	0.35 nm at 30km 9.2e-9	0.4nm at 25km 1.41e-2

3.3 Capacity Enhancement –High Speed DWDM Systems using OTDM

3.3.1 System Design and Concept

The main concept behind designing DWDM with OTDM is driven by the need of high capacity bandwidth limited systems. The requirement of high speed electronics at networks nodes limits per channel to be transmitted at high bit rates, hence limiting the capacity offered. The rate of transmission is always increasing ahead of the processing speed of the electronics involved. Hence, OTDM comes as a true solution offering increased bit rates per wavelength by using optical delay lines (ODL) [97]. These ODL creates optical multiplexing in temporal domain. The delay is set as reciprocal of total bit rate offered per wavelength i.e. 1/N*B, where N is number of delays (termed as sub-channels) and B is the base bit rate.

To illustrate, if a 10Gbps signal is delayed four times, the total bit rate is 40Gbps and therefore, the delay is 25ps between each of the sub channels, i.e. 25ps, 50ps etc. [98]. The first pulse is the clock with zero delay. The laser source employed is a MLL which generates short pulses. The pulse width has to be < 1/N*B or in other words lesser than the period of the multiplexed stream. Usually, the pulse width is taken as <40% of the time slot [99]. A 40Gbps PRBS of degree 7 is employed and each of the data stream is RZ modulated and later combined passively in a power combiner. These 40Gbps streams are bit interleaved to form 160Gbps OTDM System. Figure 3.12 shows the Single Wavelength OTDM Transmitter of 4 x 40Gbps system.

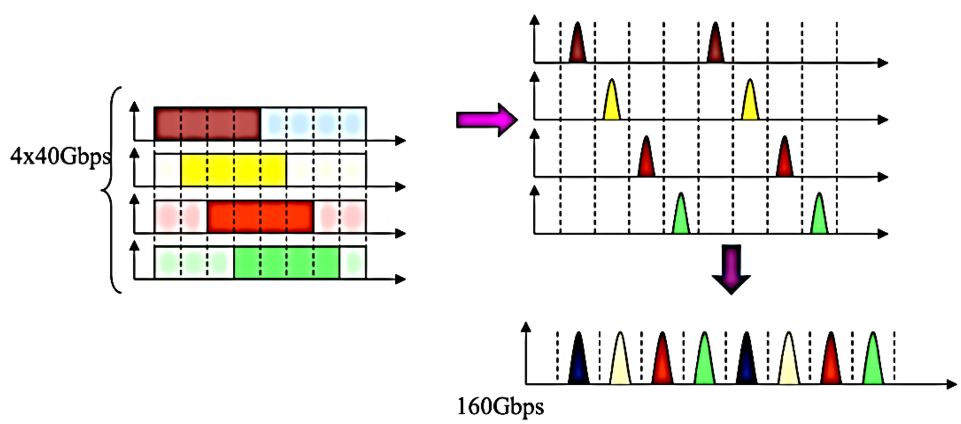

Figure 3.12 4x40Gbps DWDM/OTDM System

OTDM Demultiplexing demands ultra-fast response times and fast processing optical gates or switches to extract base tributary from the bit interleaved stream of data. Various switches were compared in [100] employing interferometric orientation with nonlinear elements like the TOADs, UNI, SHALOM etc. Every received channel requires one demultiplexing switch. The switch used need to have enough bandwidth to allow the data sampling to be performed in the used bit slot. The optical switches based on XPM together with an interferometric set up using the nonlinear SOA are judged as the best choice for demultiplexing. Appropriate positioning of the non- linear elements enable data signals to experience the differential response. The easy integrity, compactness and the requirement of lesser control power levels enables the interferometric switches to be employed for the demultiplexing of OTDM signals. Figure 3.13 shows the demultiplexer module which effectively includes combiners and splitters for combining and splitting the data pulses, two couplers which introduces the control pulses, two SOA which induces the differential phase shifts and polarization controllers at the end to allow only the data to be received at the compound receiver.

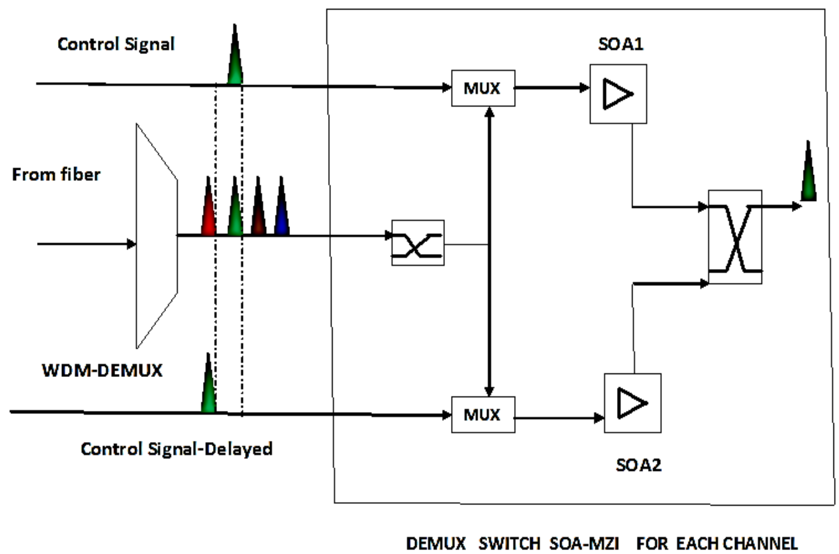

Figure 3.13 Symmetric Mach Zhender-SOA Demultiplexer

The control block provides synchronization based on proper timing delays to select the channel of interest and determines the switching window duration. The two control signals delayed by the switching window length causes differential phase shift to be induced in the SOA. The differential response causes the data pulses to be switched at the output port. Figure 3.14 indicates the control block in use in the demultiplexing operation. The working of the SOA-SMZ is basically based on the change in refractive index caused by critical synchronization of high power control pulses that change the optical phase of the data signals in the interferometric configuration. There is 90^0 phase difference between the launched data and the control signals.

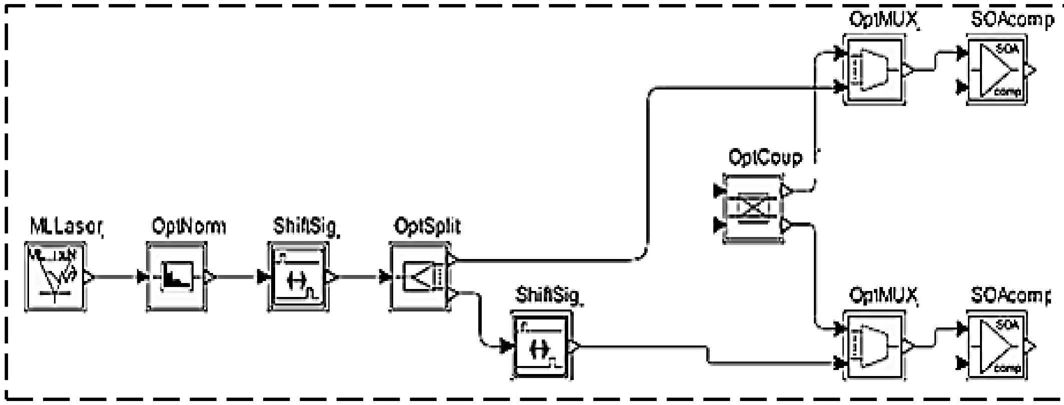

Figure 3.14 Control Block to set the Switching Window

The signal powers at the output of SMZ are given by the interferometric equations as in [63].

$$P_{out,1}(t) = 0.125P_{in}(t)\left[G_1(t) + G_2(t) - 2\sqrt{G_1(t) \times G_2(t)}\cos(\Delta\emptyset)\right] \quad (3.1)$$

$$P_{out,2}(t) = 0.125P_{in}(t)\left[G_1(t) + G_2(t) + 2\sqrt{G_1(t) \times G_2(t)}\,cos(\Delta\emptyset)\right] \quad (3.2)$$

$$W_i(t) = 0.125\left[G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)}\,cos(\Delta\emptyset)\right] \quad (3.3)$$

where $G_1(t)$ and $G_2(t)$ are the temporal gains of the SOA1 and SOA2 respectively which are placed in MZI manner and $\Delta\emptyset$ is the phase difference. These values are varying with respect to input power and phase difference between launching signals at the two input arms of SOA-MZI. If the control channel saturates SOA, then the temporal gain also saturates. Also various other parameter changes the temporal gain that is width or length of SOA etc.

The W_i (t) gives the switching window (SW) by normalising the output with respect to the input. Hence appropriately delayed control signals result in differential phase shifts when the switch is in balanced state and therefore output is switched out.

3.3.2 Conclusions and Discussion

At the wavelength of 1650nm, four OTDM sub channels give 160Gbps signal. The system is optimized in terms of input power variations, pulse width of the signal and the control power required. Their effect on the BER is investigated and suitable margins are drawn for acceptable performance. The FWHM pulse width of the signal is crucial for OTDM transmissions as it is bounded by the limit of being less than the total occupied bit slot to avoid any overlapping of these short pulses.

The distance covered is 100km of fiber length. Figure 3.15 shows the BER obtained with the variation of the input power from 5 to 10dBm. It is noted that with increase of the power of the input channel, the BER in excess of 10^{-20} is obtained for all the channels and it subsequently increases for the increased input power. Quality factor greater than 20dB is noted for all the OTDM channels. All the channels give acceptable performance in the input range per channel considered. Further, the pulse width is optimized and BER variation is studied. Pulse width is optimized based on a successive iterations. It is the runs iterative procedure used to optimize the parameter for simulative efficiency.

As expected the increase in pulse width improves the BER. This is explained as, the increase in pulse width (in time domain) implies decrease in the spectral overlap and hence the crosstalk. This in turn improves the performance.

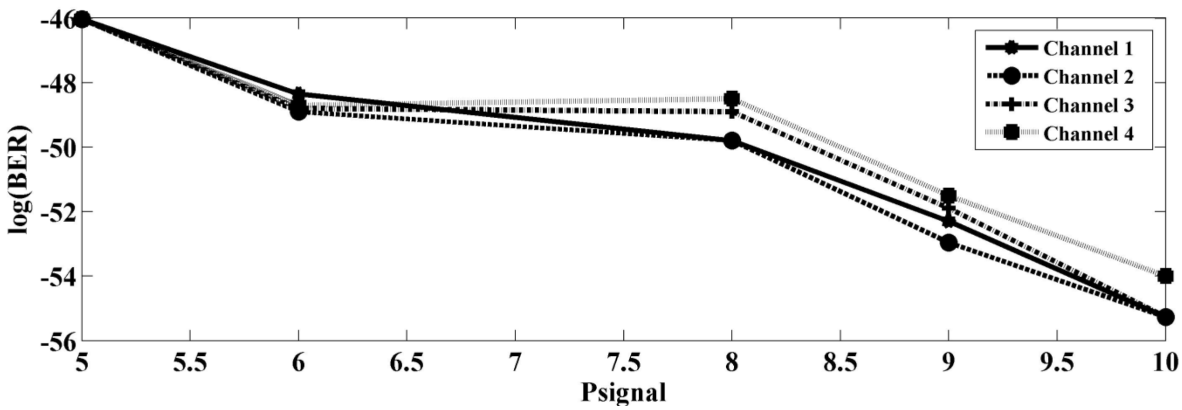

Figure 3.15 BER versus Power of Input signal for 160Gbps OTDM System

Next the control signal power of the control block is optimized. The control block suitably produces the delayed control signals to select the channel to be demultiplexed and decides the switching window duration. Effectively, it should take a value around 10 times more than the data signal value. In the absence of control pulses the SMZ is in balanced state. When no Control Pulses are present, the SMZ is balanced and the data signals undergo the similar gain and phases change in both the arms of the interferometer induced by the SOAs. Therefore, data signals emerge as it is, to the output port. When the high powered control signals, delayed by the switching window duration pass through the SOAs it causes gain and phase properties of both the SOAs to change sequentially causing the gain and phase differences in the data signals though XPM, resulting in the switched output. Therefore, the control signal optimized is shown in Figure 3.16.

It is reported that as the control power increase, the BER degrades above a certain value of 22dBm. As seen the BER worsens from 10^{-35} to 10^{-4} for channel 1. Channel 4 also indicates a similar drop of BER from 10^{-25} to 10^{-3}. Likewise the quality of the signal also drops. Similar trend is seen for all the channels considered. Usually as in [63], value > 90mW (>19.5dBm) of control power for 4-8ps pulses is considered optimum. Therefore, an optimum value of control power for 160Gbps system is not more than 22dBm with pulse width of 5ps for 25ps window.

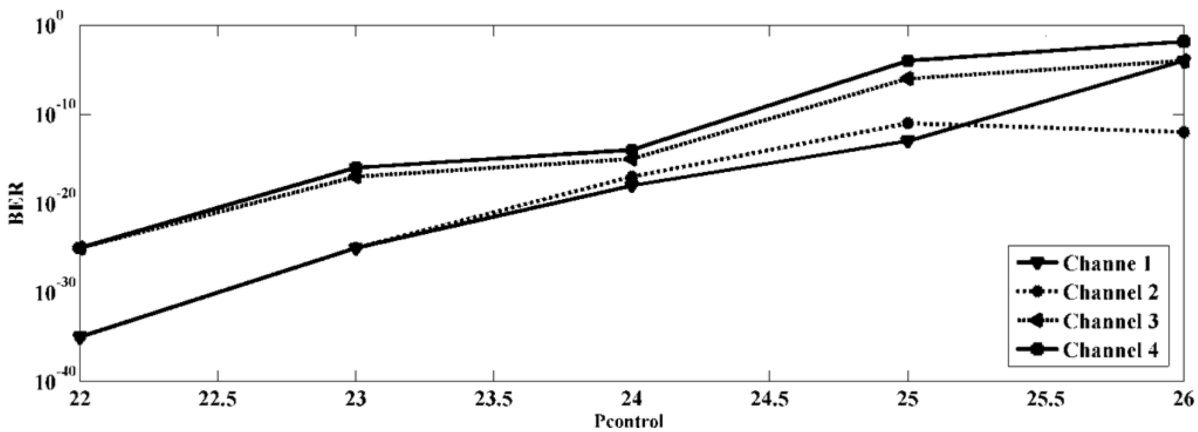

Figure 3.16 BER versus Power of Control signal for 160Gbps OTDM System

3.4 Modeling of 4 x 4 x 10Gbps RZ-DPSK DWDM/OTDM System

3.4.1 System Schematic and Results

The high speed bandwidth limited DWDM can be modeled by increasing per wavelength bit rate optically by using OTDM as discussed in above section. The need to change the fiber type is quite cumbersome when it comes to increasing the system capacities on already installed fiber systems. In the studies in [100] and [72-74], DWDM over OTDM is presented. They lag by the channel spacing constraint. We propose bandwidth efficient RZ-DPSK modulated 4 x 4 x 10Gbps system at 0.2nm spacing.

The system consists of 4 DWDM wavelengths spaced at 25GHz, with each wavelength being temporally delayed to include 4 users. This hybrid DWDM-OTDM system covers the bandwidth of 0.6nm from1550 nm to 1550.6 nm in 0.2 nm spacing. Figure 3.17 shows the single wavelength transmitter of 4 × 40 Gbps DWDM using OTDM System. A PRBS pattern generator with degree 7 acts as a data source. A MLL emits light beam with -10dBm power which is RZ-DPSK modulated. It is one of the most evitable modulation formats to achieve high speed optical networking. No dispersion compensation or amplifiers are initially used. With the pulse width of 4ps and each user being delayed by 25ps on a single wavelength, achieves single span transmission of 110km on a SSMF.

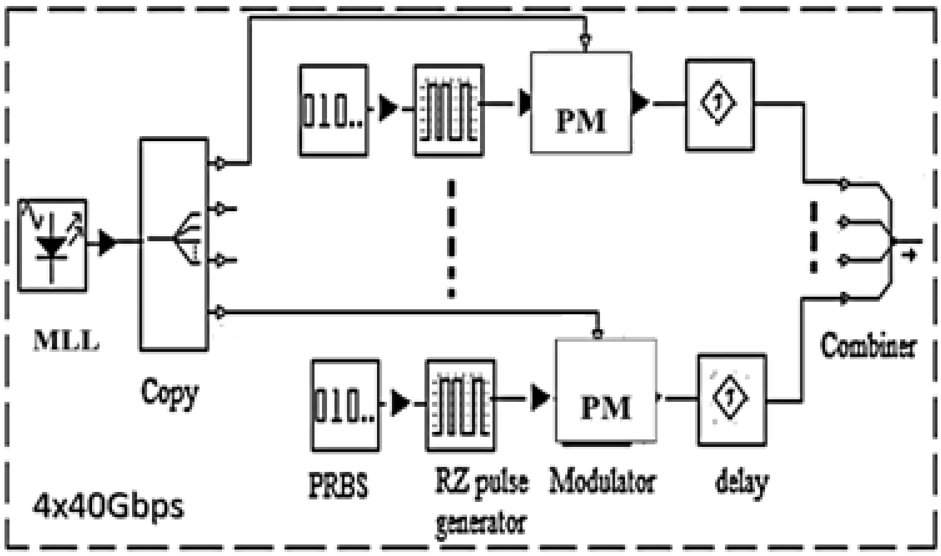

Figure 3.17 Single Wavelength Transmitters of 4x4x10Gbps DWDM/OTDM System

The composite signal is demultiplexed at the reception and further SOA-SMZ is employed to extract the 10Gbps base rate channel of interest. The SOA-SMZ demultiplexer was explained in the concerned sections above. A PIN photo detector is employed at the receiver to convert the optical to electrical signal and BER analyzer judges the system fidelity.

Figure 3.18 shows the BER obtained for single span distances for varying input power:-5dBm,-10dBm and -15dBm. The maximum Q factor of 21.6 dB is obtained corresponding to

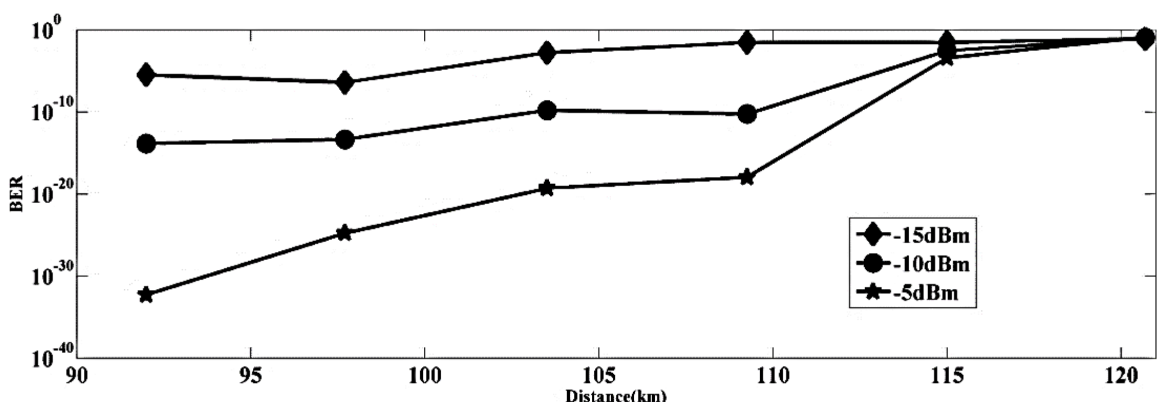

Figure 3.18 Performances of 160Gbps, RZ-DPSK DWDM/OTDM, 0.2nm Spaced System

BER of $7.4e^{-34}$ for input of -5dBm at 92km. As the distance increases to 110km, the Q factor gradually falls to 18.72dB. At high bit rates and with increase in input power the system performance decreases. For designed 160Gbps band efficient system the appropriate input power is optimized to -10dBm to achieve acceptable performance till the highest appreciable transmission reach is achieved.

3.5 Summary

In this chapter, ULTRA DENSE WDM system including 16, 32 and 64 channels is designed. These are investigated at different bit rates and channel spacing and single span distances. The minimal allowed channel spacing in HDWDM (Highly Dense WDM) is demonstrated. With the optimized combinations, acceptable results in terms of BER are framed. It is recommended that minimum channel spacing for 15Gbps, 64 channel systems is not less than 0.35nm for a single span of 30km giving BER of $9.2e^{-9}$. The minimum spacing for 10Gbps, 64 channel systems is not less than 0.25nm for a single span of 60km with acceptable BER of $10e^{-8}$. The 5 Gbps ,64 channel system gives acceptable results at spacing of 0.1nm for maximum up to single span of 80 km. Hence, a capacity up-to 960Gbps, 640Gbps and 320 Gbps is achieved in a planar system with no amplifiers by demonstrating the minimal allowable channel spacing for each case. The obtained benchmarks could serve to improve the DWDM system further.

Further, Single wavelength four channel OTDM system is simulated and optimized and the impact of signal power, pulse width and control signal power on BER is investigated. 160Gbps OTDM system with SOA-SMZ demultiplexing is implemented. The control using MZI switch strictly maintains the delay time between the adjacent channels. The parameters of pulse width of 5ps with control power till 22dBm and input power till 5dBm gives BER $>10^{-9}$. SOA integrated MZI switch used will be the keys to future OTDM transmission systems. Utilizing the above built optical time multiplexed system, a 4 x 4 x 10Gbps, RZ-DPSK DWDM system is modeled for maximum single span reach of 110km with BER $< 10^{-9}$. With these conclusions, further study investigates various amplifiers and their combinations on high channel, high capacity, narrow spaced, and bandwidth efficient systems.

Chapter 4

Optical Amplifiers for DWDM System at Narrow Wavelength Spacing

4.1 Introduction

This chapter presents the second objective to analyze the DWDM systems at narrow channel spacing with optical amplifiers. Various conventional amplifiers are used in the scenario of very large number of closely spaced WDM channels. Further, different combinations of these basic (COA) conventional optical amplifiers EDFA, SOA and RAMAN resulting in the hybrid combinations are also presented. HOA supports an increased channel DWDM system thereby preserving the bandwidth as they give excellent performance even at reduced channel spacing of 0.1nm. These proposed Hybrid Optical Amplifiers (HOA) achieves better performance with respect to the gain flatness and gain bandwidth product with better Quality factor, Bit Error Rate etc. even at 160 channel DWDM system.

Since the objective is to use amplifiers aiming at enhancing the capacity, hence increased bit rate DWDM using per channel Optical Time Division Multiplexing is also presented with proposed HOA, for the very first time. The 8 x 8 x 10Gbps bandwidth efficient system is implemented with Hybrid Optical Amplifier. A good performance with high optical to noise ratios and minimum noise figure is reported with the used hybrid optical amplifiers. The impact of Raman Amplification using different types of fibers are also investigated and it is shown that with appropriate choice of input power and pump powers, high quality of signal can be achieved on any fiber.

4.2 DWDM System with COA and HOA at Narrow Channel Spacing

The broad-band EDFA amplifies signals in the C band. Since it distinctly amplifies optical signals in each wavelength band, it tends to increase the system cost and its amplification is limited to C band signals [101]. SOAs also have emerged as appealing amplifiers as higher gains could be achieved along with longer single span distances [102]. Recently, Raman amplifiers have gathered huge attention as it is promising technology for high capacity and in long-haul optical communication links [103]. Raman amplification with high output power and EDFAs enable broadband amplification thereby also preserving the spectral shape.

In literature various experiments using COA and HOA are reported to cater to high gain-bandwidth product of the systems [43] [44]. Unfortunately, the use of amplifiers are restricted to WDM only (large channel spacing > 0.4nm). Expensive gain equalizing filters were used for achieving the broad flat gain. In this work various Hybrid Optical Amplifiers are used in scenario of DWDM system at ultra-narrow channel spacing without any costly module. The COA are used to draw a performance comparison. The original contribution is to provide Broad Band amplification in high speed DWDM systems enhancing the overall performance of the system unlike work presented in [53], [73], [79], [85] etc.

4.2.1 Simulation Setup with Conventional Optical Amplifiers (COA)

The simulative setup comprises 160 channels with 0.2nm (25GHz) spacing which are emitted from CW laser sources with -10dBm power per channel. The system set up is shown in Figure 4.1. Each of the channels are modulated by NRZ modulation formats individually and transmitted over a medium haul link. These laser beams are modulated by a $\sin^2$ amplitude modulator with an excess loss of 4dB. The simulated bitrate for large 160 cannel is at SONET/SDH 2.488 Gbps with a pseudorandom binary sequence of degree 7.

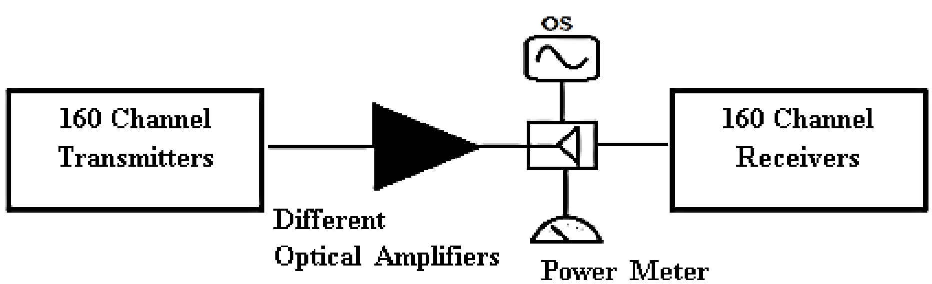

Figure 4.1 DWDM set up with 160 channels with different Optical Amplifiers

The spectrum covered is from 191THz to 195 THz (1537.39nm-1569.59nm). Each of the channels is amplified with different conventional optical amplifiers. A SOA, EDFA and RAMAN are deployed over a medium haul link. The transmission fiber used is the dispersion shifted anomalous fiber (DS). The SOA is assumed to have bias current of 100mA supporting carrier lifetime of 0.3ns. The confinement factor of 0.35 with input/output loss of 3dB is employed. The amplifier length is 250µm, width/ thickness is 3µm /0.8µm respectively. The Raman loss in Raman amplifier used is 0.25dB/km with reference frequency for dispersion at

1550nm. The Raman length is optimized to 12km with back-ward pump at wavelength of 1454nm with power of 550mW. The counter pump configuration is used as against the co-pumping as it leads to lesser noise coupling with signal. The signal power is less throughout the link while using a counter Raman pump and, therefore, its use is prevalent in long haul applications. The Erbium Doped Fiber Amplifier (EDFA) is assumed to have a flat gain shape with gain of 25dB with noise figure of 4.5dB. Various optimizations for the pump power and the number of the power pumps used present a flexible range in wavelength domain wherein flat gain can be achieved.

The receiver is the normal PIN photo detector for optical to electrical conversion. The dark current of 0.1nA and responsivity of 0.875A/W is employed. The BER and OSA (Optical Spectrum Analyzer) and the power meters are used as the end modules for results analysis and to view the spectrum obtained after the transmission. Figure 4.2 shows the optical spectra for the 160 channel DWDM spaced at 0.2nm spacing evenly spread across the occupied bandwidth of 31nm. The study in [121] depicts the transmission spectra of 60 channels with 200 GHz (1.6nm) spacing, which occupy 98nm bandwidth amplified by the Raman-EDFA. This current investigation is an improvement as the system deals with sending more number of channels in minimum required bandwidth by controlling the inter channel spacing. The wavelengths are spread across (C+L) band as against only C band as shown in [117].

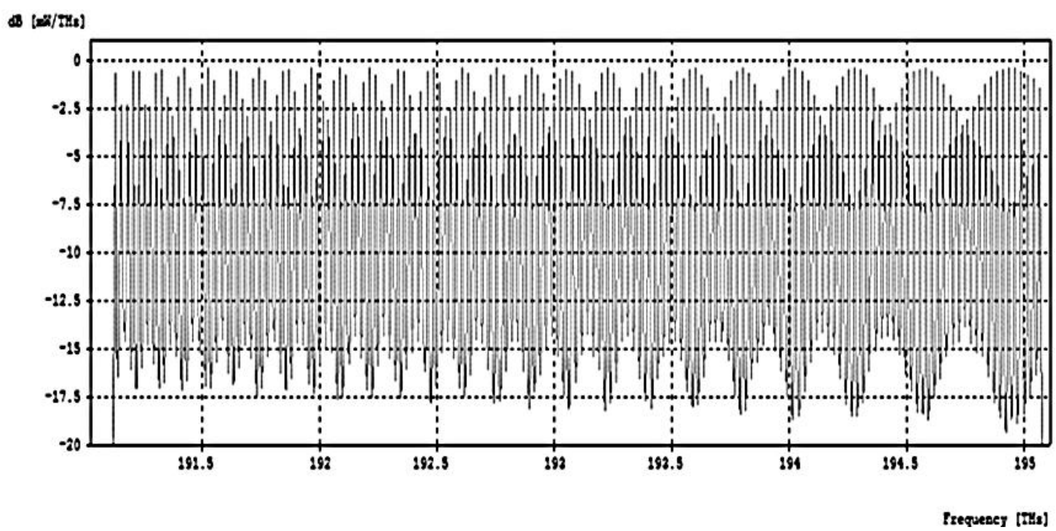

Figure.4.2 Optical Spectra of 160 Channels System

The Table 4.1 shows EDFA parameters, Table 4.2 indicates SOA parameters and Table 4.3 depicts RAMAN parameters.

Table 4.1 EDFA Parameters for 160 Channel System

EDFA Parameters	Value
Gain shape	Flat
Maximum small signal gain	25dB
Noise figure	4.5 dB

Table 4.2 SOA Parameters for 160 Channel Systems

SOA Parameters	Value
Amplifier length	250 µm
Active large width	3 µm
Active large thickness	0.8 µm
Confinement factor	0.35
Bias current	100 mA
Carrier lifetime	0.3 ns
Input/output insertion loss	3 dB

Table 4.3 RAMAN Parameters for 160 Channel Systems

Raman Parameters	Value
Raman fiber length(DCF)	12 Km
Raman loss	0.25 dB/Km
Pump wavelength	1454 nm
Pump power	550 mW
Reference frequency for dispersion	1550nm
Dispersion at Reference Frequency	2.15ps/nm/km
Operating Temperature	300K

4.2.2 DWDM System with Hybrid Optical Amplifiers (HOA)

The enormous bandwidth potential of DWDM network with proposed Hybrid Optical Amplifiers offer cost effective solution to the already existing optical networks. The conventional amplifier individually suffers from one or the other factor of gain non-flatness or the limited band of amplification etc. The HOAs are designed to overcome these disadvantages and also to minimize impairments resulting from the nonlinearities present in the fiber and to augment the transmission distances.

HOAs would also tend to increase the ability of optical communication systems in terms of increased channels and bandwidth, thereby, offering acceptable system performance at reduced channel spacing. Unfortunately, existing Hybrid Optical amplifiers are investigated for WDM system only (at large channel spacing). In this work, the HOAs are exploited for DWDM system at reduced channel spacing <25GHz. The original contribution of this work is to provide broad band amplification with bandwidth efficient DWDM system unlike any other reported work in concerned studies [104], [105], and [106].

To quote the special advantage of Raman Amplifier in making of a HOA is that any amplification band can be tailored by choosing right combination of the pump wavelengths. To add to it, different fibers like DSF and DCF can be used to implement the Raman Amplification. The most exhilarating possibility is to achieve the dispersion compensation and amplification simultaneously by using pumped DCF. In band amplification in zero dispersion regimes can be obtained by using pumped DSF.

In the following section, several configurations of optical amplifiers are proposed for an ultra-narrow DWDM system and performance is studied in terms of output power, the BER and the Q factor.

4.2.2.1 Different Configurations of HOA in DWDM System

Various configurations/Modes of Hybrid Optical Amplifiers are proposed with combinations of existing conventional amplifiers as shown in Figure 4.3. Mode I is the RAMAN-EDFA(R-E), Mode II is RAMAN-SOA(R-S), Mode III is RAMAN-EDFA-RAMAN(R-E-R) and Mode IV is RAMAN-SOA-RAMAN(R-S-R). Effectively, all these amplifiers are employed as pre amplifiers before the receivers to augment the signal power and to increase the receiver sensitivity.

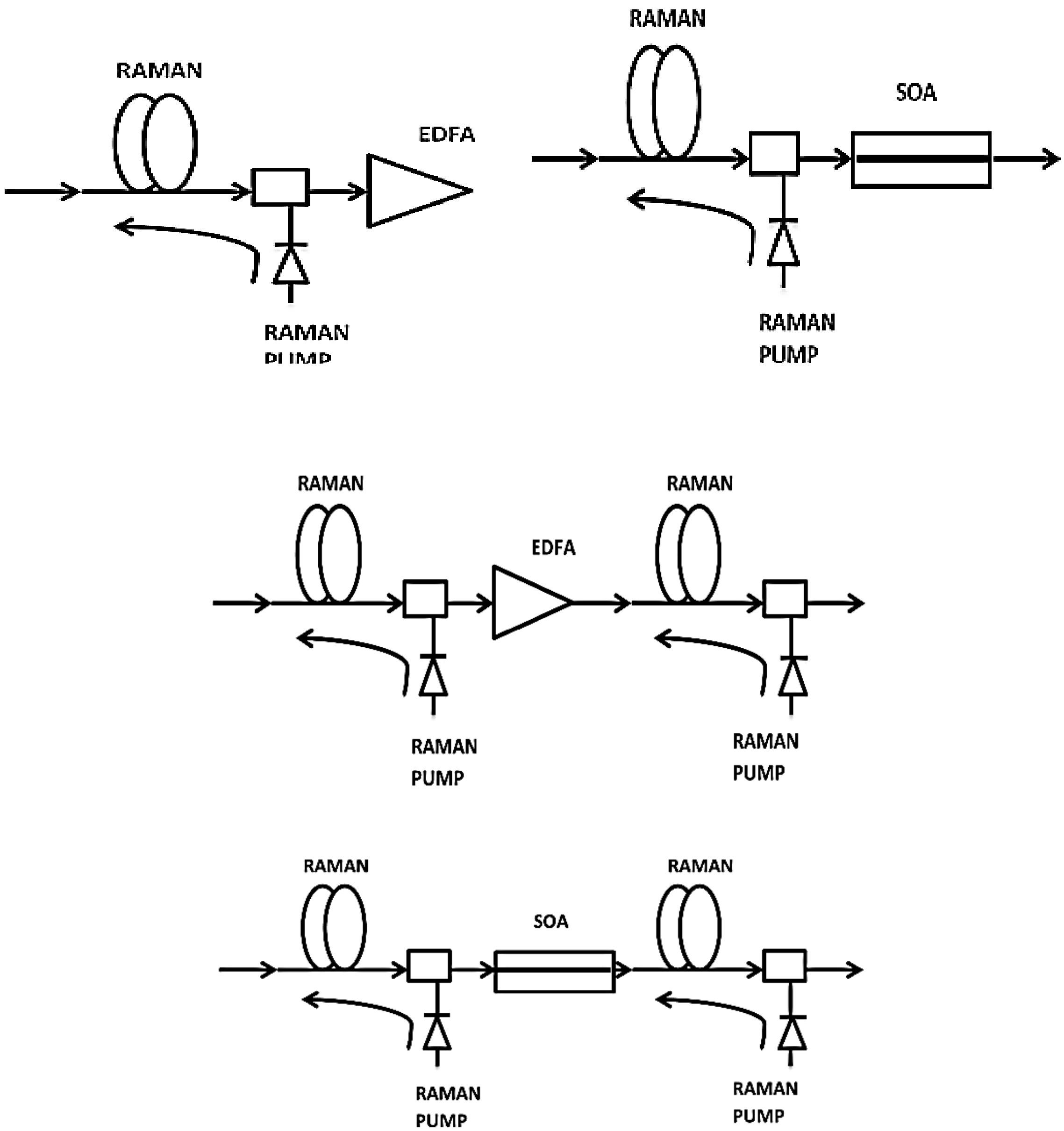

Figure 4.3 Various Configurations of HOA a) Mode I, b) Mode II, c) Mode III, d) Mode

In Mode I, the Raman Amplifier acts as the booster followed by the EDFA. Mode II, again, uses a Raman booster followed by the semiconductor optical amplifier (SOA). An EDFA is used as an inline amplifier between the two Raman Amplifiers in three stage amplification in Mode III. Mode IV includes the SOA mid link between the two Raman Amplifiers. DWDM channel with 160 CW laser beams is investigated with the proposed configurations of HOAs. A comparative assessment of performance is done on the designed 160 channel system using all the Conventional Amplifiers and the proposed Hybrid Amplifiers.

4.2.2.2 Gain Analysis of the proposed RAMAN-EDFA amplifier

Giles in [107] described the rate equation for the EDFA as a three level system. The EDFA gain is given as:

$$G_{EDFA} = G_{max}\left(L, \lambda_p, \lambda_s\right) = \exp\left[\mathrm{L}\frac{r_p(\lambda_p) - r(\lambda_s)}{1 + r_p(\lambda_p)}\right] \quad (4.1)$$

It indicates that G_{max} depends exponentially on pump wavelength (λp) and signal wavelength (λs). The dependence appears in the terms of cross-section ratios rp= $\sigma p_a/\sigma p_e$ (pump absorption/pump emission), r=$\sigma s_a/\sigma s_e$ (signal absorption/signal emission). The other parameters like the L= ($L_{amp.}$ Γs.σ_{se}. λs .N_T) has dependence on the wavelength of the signal. The length of the amplifier (L_{amp}) is constant and Γs indicates the signal to the core overlap.

In Raman amplification the power spectrum of the amplified optical signal is affected by co/counter Raman pumping, Rayleigh back- scattering and Raman ASE noise. As described earlier the counter propagating pump is preferred and is considered for the analysis. The set of two coupled equations govern the Raman-amplification process as has been described by including these effects [8].

$$\varepsilon \frac{dP_p}{dZ} = \frac{w_p}{w_s} g_R P_p P_s - \alpha_p P_p \quad (4.2)$$

Where α_s and α_p are the losses at stokes and pump wavelengths. The factor accounts for co /counter propagation Raman pumps with a +, - sign respectively. The signal gain is calculated as [8]

$$G_{Raman} = G(z) = \frac{P_s(z)}{P_s(0)} = \quad exp\left(g_R \int_0^z P_p(z)dz - \alpha_s z\right) \quad (4.3)$$

where Ps and Pp are the signal and pump power, respectively. The longitudinal position (along fiber) is denoted by z and Rayleigh scattering coefficient is α_s. Similarly the gain of SOA amplifier is given [122].

$$G_{SOA = \Gamma a[N(z,t) - N_0]} \quad (4.4)$$

In the investigations in [57] and [69] it was reported that the total gain for HOAs is a multiplication of individual amplifiers gain while placing in a cascaded manner.

Hence, total gain of proposed RAMAN-EDFA and Raman-SOA is:

$$G_{RE} = G_{Raman} \times G_{EDFA} \tag{4.5}$$

$$G_{RS} = G_{Raman} \times G_{SOA} \tag{4.6}$$

4.3 Results and Discussions

The performance of the proposed 160 DWDM, spaced at 25GHz is initially tested with different conventional amplifiers. The output power obtained with input of -10dBm is taken as a performance measure, along with the obtained Quality factor. Any specific value would have been picked for the performance comparison in the range from -20dBm to 5dBm. Figure 4.4 draws the comparison of EDFA, RAMAN and SOA amplifiers.

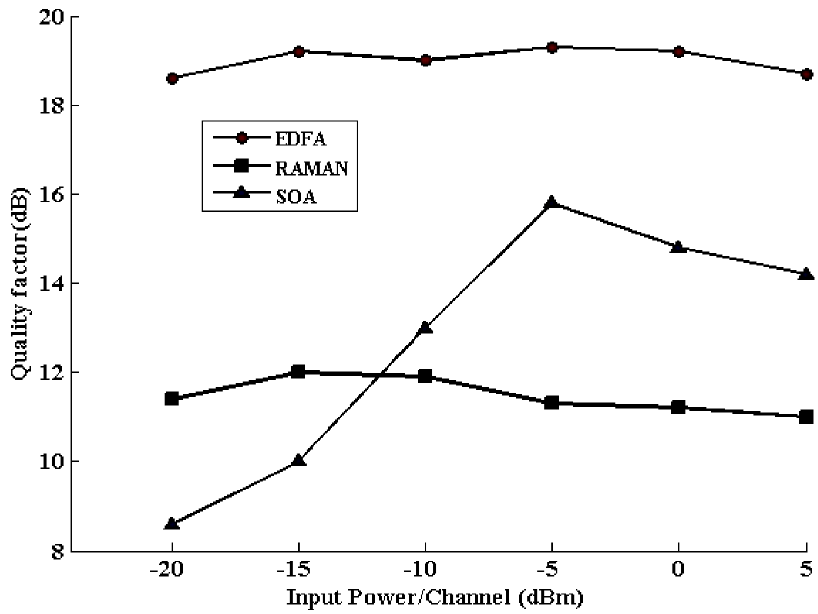

Figure 4.4 Quality Factor versus Input Power with COA in 160 Channels DWDM

It is observed that EDFA scores well as compared to other conventional optical amplifiers in the term of Q-factor (> 18 dB). The standalone Raman amplifier obtained a Quality factor >11dB as against SOA which shows marked variations from 8.5dB to 15dB. SOA is seen to degrade the system performance as the semiconductor material offers much nonlinearity as compared to fiber amplifiers. At higher input power/channel, the system induced crosstalk due to the high polarization of SOA waveguide adds to the low performance. EDFA performs the best as it is lesser prone to polarization effects owing to its circular symmetry in the fiber. Moreover, the amplification depends on erbium ion instead of molecular vibration and electrons [2]. As the input power increases from -20dBm to 5dBm it is observed that Quality of signal reduces.

Further, EDFA is also seen to give the output optical power > 9.8 dBm, which is very high value of the output obtained as against Raman and SOA which indicates comparatively lesser output power. High input/channel in the 160 channel system saturates the amplifier as is seen in the graphs below. Figure 4.5shows the high output power obtained for the input variations. Hence, it is observed that EDFA amongst the conventional optical amplifiers performs best as compared to the other optical amplifiers in the implemented 160 channel DWDM set up.

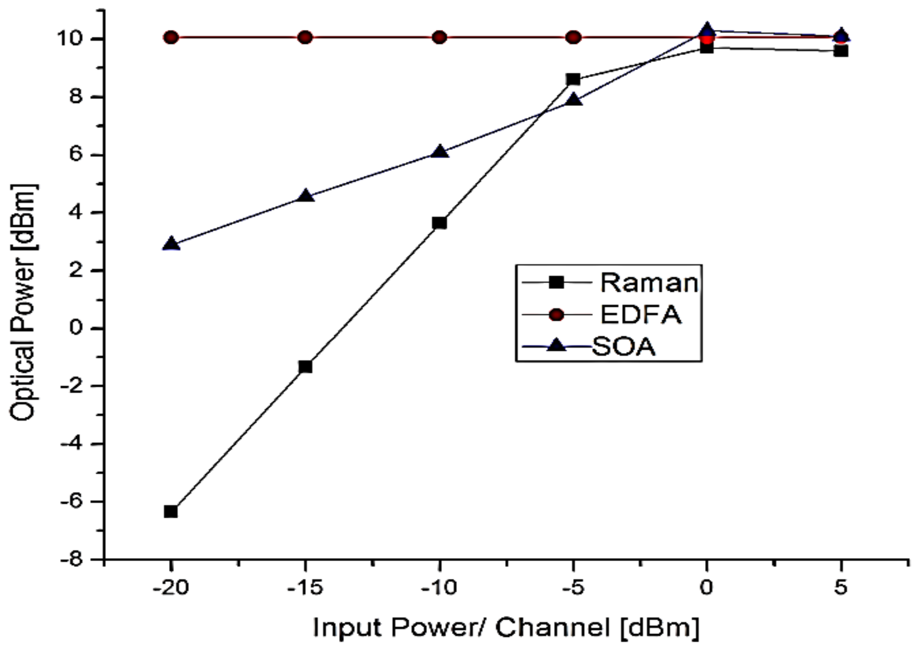

Figure 4.5.Optical Power versus Input Power with COA in160 Channels DWDM

Similar investigations are carried out with the proposed HOA combinations. The quality factor and output power obtained with different HOAs are studied. It is observed with the comparative analysis with various hybrid amplifiers that Raman-EDFA HOA gives a good tradeoff as compared to other hybrid combinations with Q factor varying from 20dB to 21.5dB. The Raman-EDFA-Raman has Quality factor of around 16dB, Raman-SOA indicates 13dB to 15dB variations and Raman-SOA-Raman shows Q factor from 11.5dB to 13dB (low and high peaks are measured). Figure 4.6, gives evidence of the same. It can be seen again that the presence of SOA degrades the system performance due to various non-linear effects. On the same grounds, the measured output power as against the input power also indicates the best performance with Mode I, RAMAN-EDFA HOA. It is observed that Mode II and Mode IV hybrid combinations including SOA gives least performance with respect to quality of signal as well as the received optical power. Both Mode I and Mode III i.e. R-E and R-E-R, is seen to perform well with Raman-EDFA (R-E) outperforming.

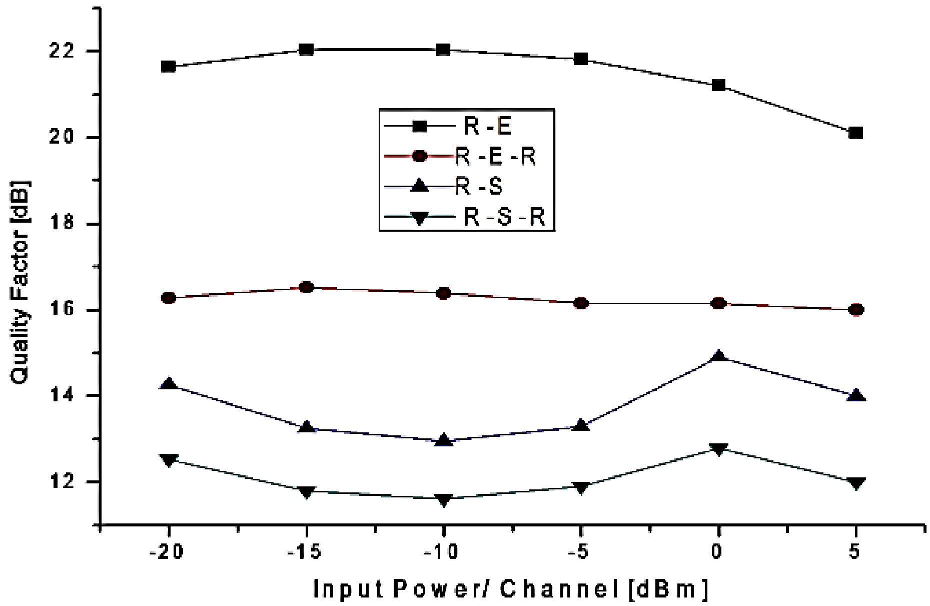

Figure 4.6 Quality Factor versus Input Power with HOA in 160 Channels DWDM

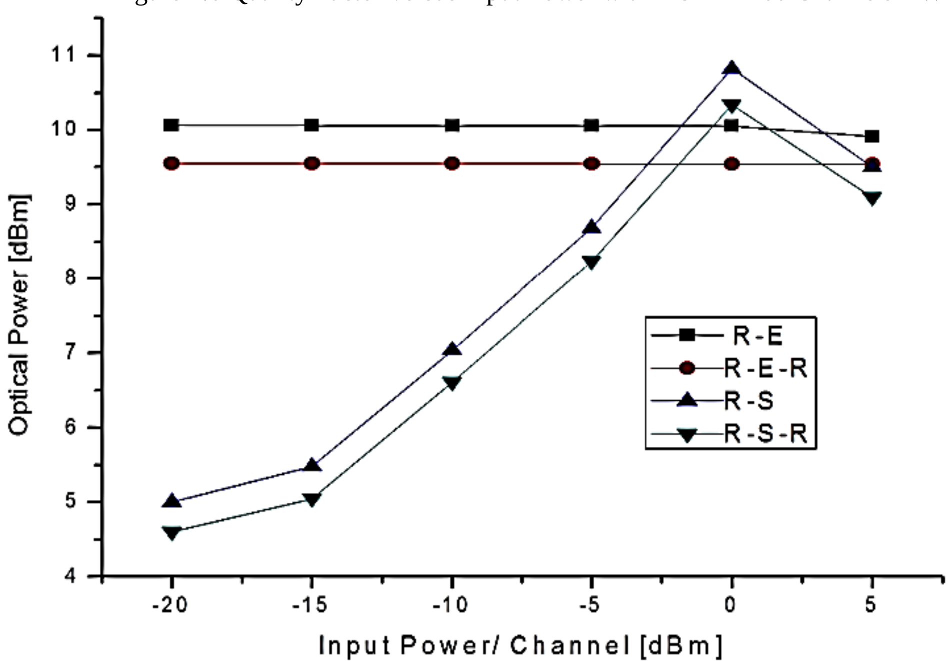

Figure 4.7 Quality Factor versus Input Power with HOA in 160 Channels DWDM

Figure 4.7, above, shows the comparison and it is seen that again Raman-EDFA provides better output optical power, almost 10dBm, as compared to other hybrid combinations with Raman-EDFA-Raman (R-E-R) with 9.5dBm as against Raman-SOA(R-S) and Raman-SOA-Raman(R-S-R) showing large variations from 5dBm to 9.5dBm and 4.5dBm to 9dBm respectively. As the power of input channel rises, the quality of the signal reduces due to the induced nonlinearities and conventionally the output power increases. The large variation in the output power in SOA as explained before is due to induced crosstalk at higher input powers. Table 4.1 enlists the obtained Q factor and output power at -10dBm of input at one glance for different proposed HOAs.

Table 4.4 Maximum Q Factor and Output Power for all HOA Modes

Configuration	Q Factor	Output Power
Raman-EDFA	21.5dB	10dBm
Raman-EDFA-Raman	16dB	9.5dBm
Raman-SOA	13dB	7dBm
Raman-SOA-Raman	12dB	6.5dBm

Hence, after the above analysis of both the conventional and hybrid optical amplifiers in the proposed 160 channel narrow spaced DWDM system, it is concluded that EDFA amongst the COAs performs the best with Q>18dB. On the other hand, the Mode I, Raman-EDFA offers best performance with Q>21dB. These implications are fruitful in designing systems with narrower spacing and for long haul links.

4.4 Raman-EDFA HOA in High Bit Rate DWDM Systems

As an application of the best judged Raman-EDFA HOA, it is therefore, investigated on proposed high bandwidth efficient, high speed DWDM system. High bit rate, narrow spaced DWDM system can be designed to enhance the system capacity with hybrid optical amplifiers. The per channel bit rate of the closely spaced wavelengths is increased by utilizing optical time division on each of them. In different studies in [31], [76] the systems are restricted to number of channels, bit rate and with the use of the conventional optical amplifier only, which are used to boost the signals. Raman-EDFA HOA comes as the supreme and cost effective solution to amplify the signals and render high capacities with reduced system offered non-linearities.

Eight closely spaced wavelengths at 0.2nm spacing embed per channel eight optical delays, and with base rate of 10Gbps, the total capacity of the newer proposed system is 8x8x10Gbps within a small bandwidth of 1.4nm. The system occupies the wavelength band from 1550 to 1551.4 nm with 0.2 nm spacing. The system set up is shown in Figure 4.8.

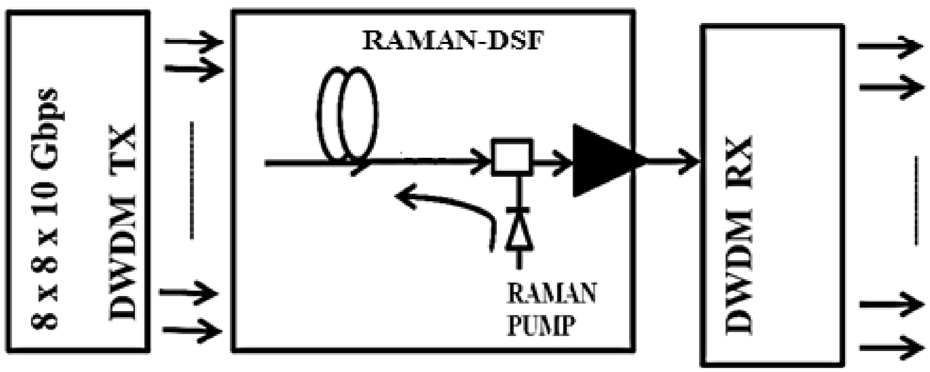

Figure 4.8. 8 x 80 Gbps DWDM with Raman-EDFA HOA

The single transmitter is same as in Figure 3.15 in Chapter 3. Mode Locked Lasers emits the -5dBm power per channel with wavelength starting at 1550nm. An optical time domain multiplex of eight sub channels, each at base rate of 10Gbps, increases the per channel bit rate to be 80Gbps. Features of creating an SHIFT is employed with the PRBS pattern generator output. According to this, output port of PRBS is rotated by a specified amount to ensure sufficient decorrelation in the output pattern for different user signals. As closely spaced higher bit rates channel can cause crosstalk so such decorrelation are often employed. A 3-dB pulse width of 5 ps drives a Mach Zhender Modulator. The first sub channel serves as the reference and the rest three are delayed by the time window specified as A ⁄ (N*B) which is 25ps for N=4 and B=10Gbps, where “A” is the sub channel number 0, 1, 2.

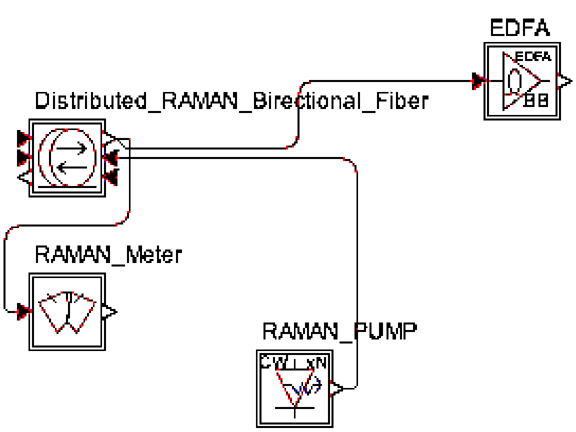

Figure 4.9 Schematic of Bidirectional Distributed Raman Amplifier

Figure 4.9 indicates the RSOFT schematic of the bidirectional fiber being used as a Distributed Raman Amplifier. The Raman-EDFA HOA is employed for the first time in high bit rate narrow spaced DWDM-OTDM system. A Hybrid Amplifier consists of backward pumped dispersion shifted fiber of 45.044km with a flat gain EDFA. The gain of EDFA is 20dB. The high power causes EDFAs to saturate, thereby, exhibiting non uniform gain [107]. The high pump power adds to the overall cost of the system. Therefore, for each set up of different channels DWDM, the realistic parameters must be carefully designed or chosen for broadband amplification. Table 4.5 lists Raman parameters for high bit rate DWDM system.

Table 4.5 Raman Parameters for High Bit Rate DWDM System

Raman Parameters	**Value**
Raman fiber length	45.044 Km
Raman loss	0.25 dB/Km
Pump wavelength	1453 nm
Pump power	500 mW
Reference frequency for dispersion	1550nm

Table 4.6 lists out the OSNR and the Noise Figure (NF) obtained for the entire spectrum occupied by the DWDM wavelengths.

Table 4.6 OSNR values and Noise Figure for proposed DWDM System

Wavelength [nm]	OSNR [dB]	Noise Figure [dB]
1550	32.7486	5.0547
1550.2	27.4309	5.05607
1550.4	25.9308	5.05867
1550.6	27.3053	5.04902
1550.8	21.0401	5.05051
1551	27.2797	5.05213
1551.2	25.5903	5.05455
1551.4	26.7115	5.05774

High value of OSNR with least noise figure is quoted for 640 Gbps capacity system's performance over 90.088Km (2 spans) of Raman amplifier fiber with minimum utilization of bandwidth. It can be observed from Figure 4.10 that the gain variation across the wavelength is quite uniform with the offered HOA and with a gain (> 19 dB) with very minimal variations of <0.02B. The Noise figure of around 5dB is reported. This value of Gain and NF is the best values ever reported for such high bit rate narrow spaced DWDM system.

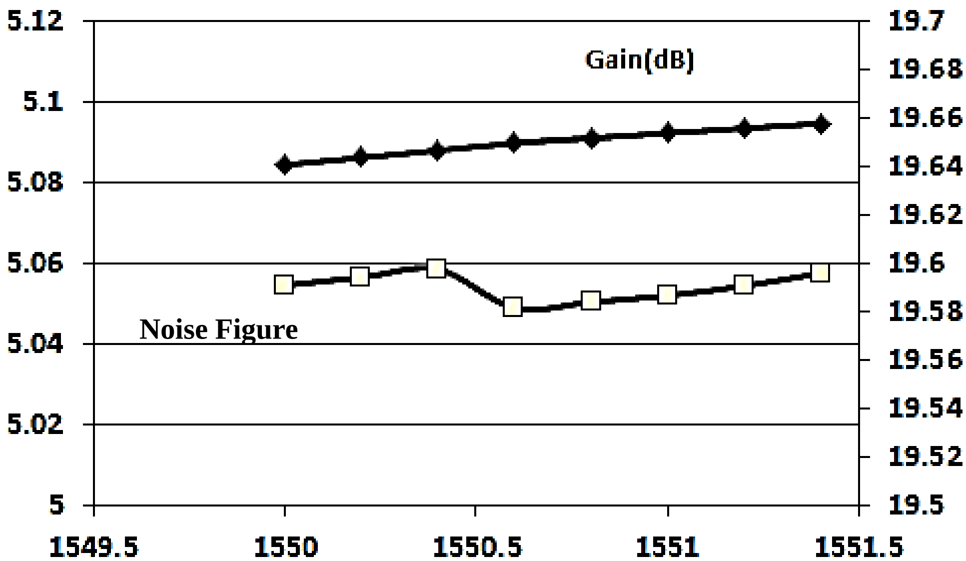

Figure 4.10 GAIN and Noise Figure for proposed DWDM System

Further, the output was observed for 640Gbps, bandwidth efficient system at much reduced spacing of 0.1nm .The averaged output from -21dBm to -23dBm is noted for the entire 0.7nm occupied bandwidth spectrum from 1550nm to 1550.7nm as in Figure 4.11.

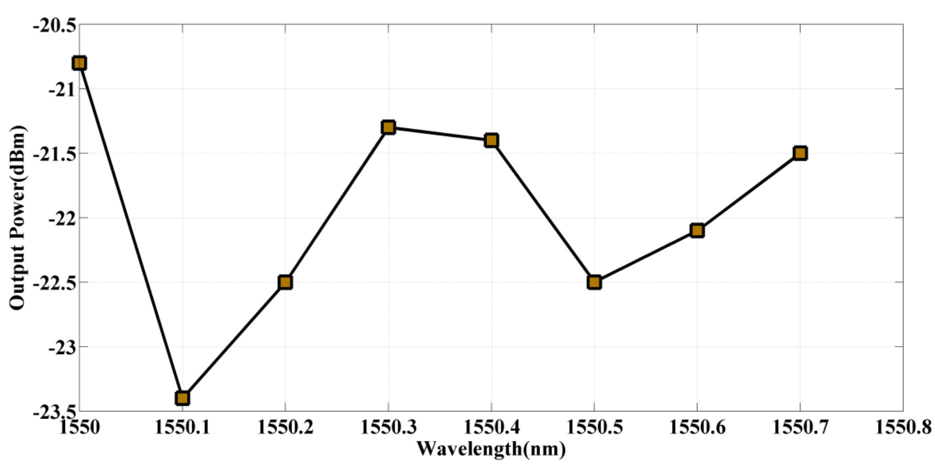

Figure 4.11 Output Power obtained for 0.1nm spaced 640Gbps System

4.5 Impact on RAMAN Amplification using different kinds of Fibers

The impact of using different kinds of fibers for Raman Amplification in the scenario of designed 8 x 4 x 10Gbps high speed DWDM systems is studied. The Raman Amplifier can be modeled with different gain mediums with fibers having different core areas. The non linearities can be reduced by using large effective area fibers (LEAF) and on the other hand, less area fibers give a better Raman efficiency and higher gains for the used Raman pump.

The Raman Gain is calculated as in [40]:

$$G_{r=\exp\left(\frac{g_r}{A_{eff}}P_p L_{eff}\right)} \quad (4.7)$$

where $g_{r:}$ Raman Gain Coefficient

$P_{p:}$ Pump Power

$L_{eff:}$ Effective Length

A_{eff}: Effective Area

The effective area depends is given as in [40]:

$$A_{eff=a_{eff\,\pi\left(\frac{dia}{2}\right)^2}} \quad (4.8)$$

where a_{eff} is the effective mode area normalized by the core area. A_{eff} depends upon the diameter of the fiber .Table 4.7 lists out the diameters and total areas considered for different kinds of fibers.

Table 4.7: Effective Area of various RAMAN Fiber Medium

a_{eff}	1.425 (SMF)	1.425 (DSF)	0.4 (DCF)
dia	8.2e^{-6}	7e^{-6}	8.2e^{-6}
A_{eff}	**75 μm^2**	**55 μm^2**	**21 μm^2**
Wavelength	Optical Band in use	1550nm	1312nm

The Pumped SMF (PSMF) with 75μm^2, Pumped DSF (PDSF) with 55 μm^2 and Pumped DCF (PDCF) with 21 μm^2 are tabulated. Pumped DCF as Raman Amplifier offers double benefit of amplification and dispersion compensation as mentioned earlier. The Gain and NF is studied at different pump powers for different kinds of fibers. Transmitter and Receiver parameters are same as used in previous section. It is observed that maximum gain is observed for PDCF throughout, for the different values of pump powers used.

Its reduced effective area offers more Raman amplification efficiency as compared to when the higher effective areas fiber is used. A gain of around 30dB is noticed for PDCF, 22.93dB for PDSF and >10dB with SMF at 0.5W pump power. Minimum gain is obtained when pumped SMF is used at any given pump power as in Figure 4.12. PDSF is a good choice as it offers moderate gains. With increase of pump power till 0.5W the gain seems to increase gradually. For all the three configurations considered a low noise figure (NF) till <5dB is noted.

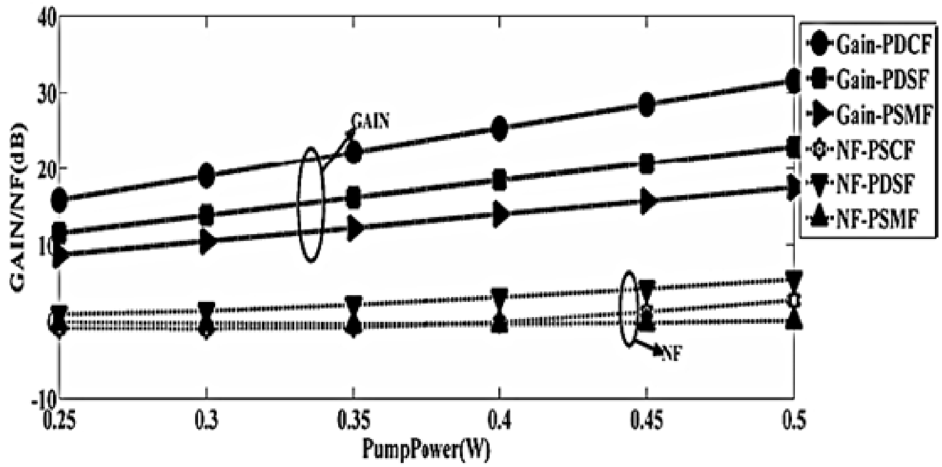

Figure 4.12 Gain/NF with different fiber mediums for RAMAN Amplification

As shown in Figure 4.13, a flat gain is spread across the entire wavelength stretch covering 1.5nm, calculated at 0.35W pump power. It re-signifies the above iterated fact that PDCF gives the maximum gain.

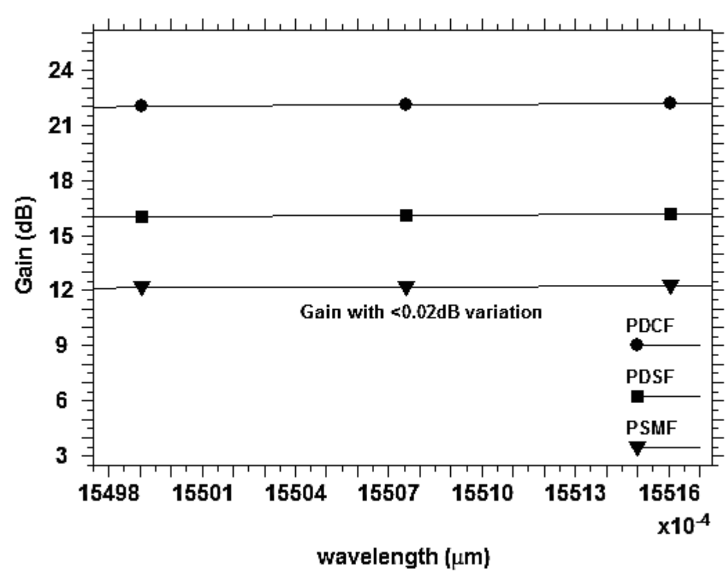

Figure 4.13 Flat Gain with Raman-EDFA HOA with different fiber mediums for 8 x 4 x 10Gbps

PDCF reports a gain of 22.204dB, while PDSF notices a gain of 16.166dB and PSMF reports the least gain of 12.2dB in 8 x 4 x 10Gbps DWDM System. Thus Raman Gain offered by 21 μm^2 fiber is almost 30% more than offered by 55 μm^2 fiber.

The lesser effective core area fiber offers more gain, but it is also accompanied with increased indulgence of Raman Noise. The maximum, reachable transmission distance is calculated with both discrete PDCF and PDSF. It is observed that there is a difference of 22.044km with different Aeff areas. The total transmission distance of 323.02km of PDCF as against 345.044km of PDSF is obtained. The Raman noise along with system attenuation becomes prominent and decreases the received signal quality for longer reach transmission. The performance of PDSF is evaluated on 8 x 4 x 10Gbps at 345.044km transmission link by varying the pump power from 0.25W to 0.55W at different input powers of -15dBm , -10dBm and -5dBm as shown in Figure 4.14. It is seen that with the increase in the pump power, the quality of signals show a gradual increase for input power till -10dBm. Further increment of input power/channel with increased pump power causes rapid downfall in the obtained quality factor. This can be attributed to the fact that increased non linearity with increased Raman noise induces the sudden fall in the Quality of signal.

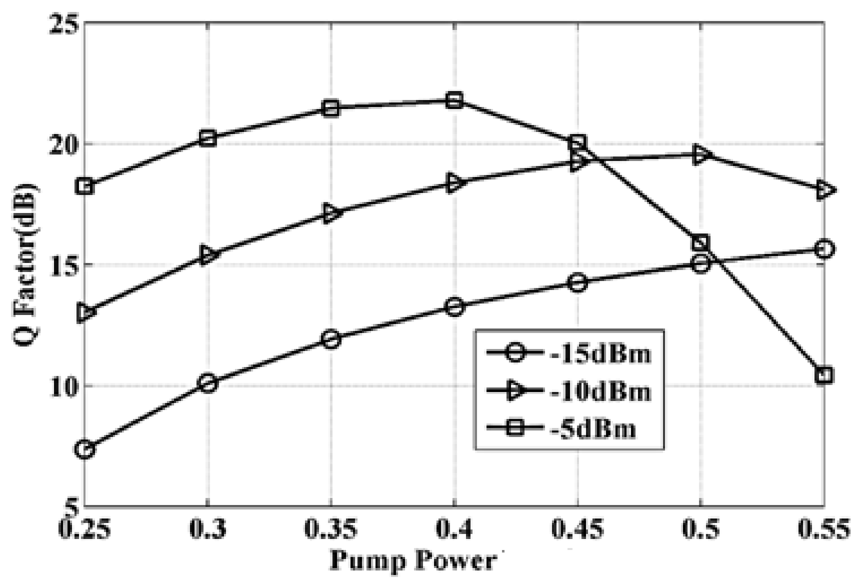

Figure 4.14 Q factor versus Pump Power for PDSF 8x4x10Gbps DWDM System

The Q factor varies from 18.22dB to maximum 21.78 dB before the downfall after 0.45W of pump power at -5dBm of input power. A maximum Q factor of 15.64dB and 18.09dB is reported at -15dBm and -10dBm respectively at 0.55W pump power.

It can be concluded that right combination with optimized values of input power/channel with chosen pump power yields high Q factor >15dB.

4.6 Summary

It is observed that EDFA amongst the conventional amplifiers and Raman-EDFA amongst the hybrid amplifiers score the best output performance. The Raman-EDFA HOA offers an excellent quality signal with Q factor>21dB as against the EDFA giving >18dB of Quality Factor. To validate the performance of the best judged, flat gain, optimized Raman-EDFA, investigations were also carried from application point of view on the highly bandwidth efficient proposed, high bit rate DWDM system at 0.2nm spacing.

An 8x80Gbps DWDM system is designed and implemented with Raman-EDFA. The highest ever gain of >19dB and lowest ever values of Noise Figure~5dB with OSNR>21dB is notified for high capacity 640Gbps DWDM system at narrow channel spacing. Reduction of the channel spacing to 0.1nm reduces the bandwidth occupancy to only 0.7nm hosting high capacity DWDM system with acceptable output power levels. Further, the impact of using different kinds of fibers with different core effective area on Raman Amplification is studied on the designed 8x80Gbps System. PDCF gives ten times more gain as compared to other fibers. It is reported that with correct match of the input power/channel with appropriate pump power, a high quality signal with Q factor as high as >20dB can be obtained for the proposed high speed DWDM system at channel spacing of 0.2nm.

Further, the designed amplifiers would be further investigated with the prospects of proposed DWDM systems supporting long haul links.

Chapter 5

Long Haul DWDM System at Narrow Wavelength Spacing

5.1 Introduction

In the previous Chapters various amplifiers and their hybrid combinations were introduced in narrow spaced DWDM systems. The simpler designed system with amplifiers served to increase the capacity. This chapter fulfils objective 3 and focusses on ultra-narrow DWDM system to achieve long haul communication links. Various literature studies viz. [108], [42], [54], [79], [81] and [82] discuss the establishment of long haul links with various individual and combinations of SOA, RAMAN and EDFA amplifiers. But all these quoted studies lag either in the number of channels transmitted or the wavelength spacing between them.

Therefore, the present work is an improvement over the previous quoted studies in terms of both increased number of channels and reduced channel spaced wavelengths. Raman-EDFA combination is shown to achieve long haul fiber link using Raman-EDFA hybrid amplifier at ultra-narrow spacing. The covered appreciable distance is also noted with conventional EDFA to draw a comparative performance. The high speed, DWDM system with 8 x 4 x 10Gbps, 8 x 8 x 10gbps and 16 x 4 x 10Gbps systems are also presented showcasing the maximum reachable repeater less transmission. The designed systems aim to transmit maximum data with minimum useable bandwidth there-by achieving the enhanced capacity.

5.2 Very Long Haul DWDM System

To achieve long optical links, a flat gain spread over the entire broad gain bandwidth and presence of high output power are criteria taken into account. Lee [108] had set up 16 channels with spacing of 200GHz (1.6nm) to get a reachability of 5 spans of 80 km each using combination of inline SOA with Raman Amplifier. Chung et al [79] transmitted 16 channels spaced at 0.8nm for a distance of 1040km using inline EDFA with Raman Amplifier. Haris *et al* [109] established repeater less 240km transmission by transmitting 8 channels using only Raman amplifier to maintain high OSNR throughout. Downie [80] increased the number of channels to 38 in the red end of the C band and covered 1500km distance without use of any inline dispersion compensation methods. The channel spacing was 50GHz.

It was observed that existing system had the limitation of lesser number of channels as well as wider channel spacing > (25GHz) = 0.2nm. The following section presents ultra-narrow DWDM systems with long appreciable transmission distances.

5.2.1 Proposed System Details

The system setup for long haul communication using proposed Hybrid Raman-EDFA and conventional EDFA is shown in Figure 5.1.

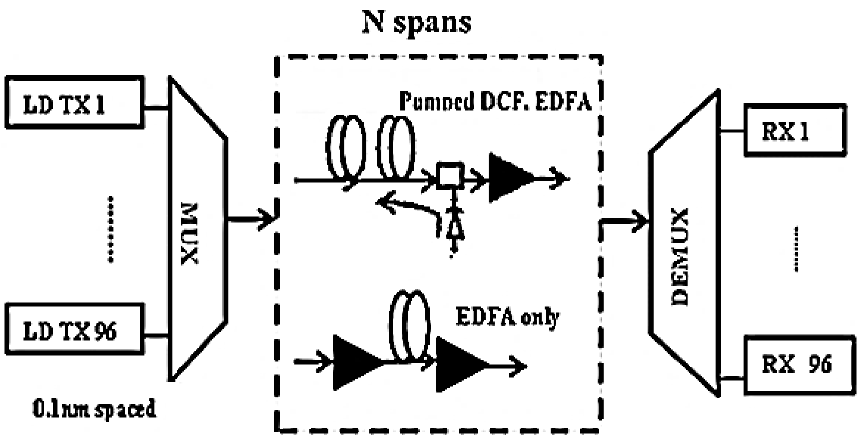

Figure 5.1 Long Haul 0.1nm spaced DWDM

Each DWDM transmitter transmits 96 x 2.488Gbps optical channels spaced at 12.5 GHz (0.1 nm) starting from 1536nm. The data stream from a Pseudo Random Binary Sequence (PRBS) generator with degree 7, (2^7-1) using a NRZ pre-coder drives an amplitude modulator. The pseudo random binary sequence generator sequence is rotated between each of the output ports so as to decorrelate them from each other for all the 96 user channels.

Each input probe is optimized and launched with power of -10dBm to balance the OSNR (optical signal to noise ratio) and nonlinear effects. We consider a long haul system composed of Nspans. The total span comprises of the Standard Single Mode Fiber (SSMF) and the small dispersion compensating module.

The fiber length parameters are L_{span} for the Standard Single Mode Fiber (SSMF) and L_{DCF} for the Dispersion Compensated Fiber (DCF). DCF is used to compensate for the link dispersion.

The total link length is given as below [2].

$$L_{total} = N_{span} (L_{span} + L_{DCF}) \quad (5.1)$$

The loss of 0.25dB/km exists in Raman pumped DCF with pump wavelength at 1449nm and pump power of 600mW. The effective area of DCF is 21µm^2 [112]. A pumped DCF establishes amplification and dispersion compensation in one entity as also quoted in [110]. Each span has SSMF with dispersion of 16ps/nm-km and DCF with negative dispersion of 106.56ps/nm-km and an EDFA. EDFA has fixed gain of 22dB and noise figure of 4dB. The DWDM system with conventional amplifier includes SSMF followed by two stages EDFA with DCF for dispersion compensation. The Length of DCF for dispersion compensation is based on the following equation [2].

$$L_{DCF} = -\frac{D_{span}}{D_{DCF}} L_{span} \qquad (5.2)$$

where Dspan and D_{DCF} are dispersion values for SSMF and DCF considered. Mynbaev in [2] has used the following equation to get the length of DCF and SSMF.

$$\frac{L_{span}}{L_{DCF}} = 6.66 \qquad (5.3)$$

Using the above two equation the dispersion can be adjusted as

$$D_{DCF} = -6.66\, D_{span} \qquad (5.4)$$

For the analysis, the first channel is taken after the demultiplexer. The receiver includes PIN photo detector with dark current of 0.1nA and with responsivity of 0.875 A/W. The Table 5.1 below enlists the various combinations of DCF and SMF lengths. The span cases are a random pick from a study in [111]. The present work is an improvement over the quoted literature as reduced spacing is considered for long haul links. Iteratively, all the combinations for a single span are implemented to judge for the best combination. The DCF mounted effectively, compensates the dispersion incurred by the standard single mode fiber.

Table 5.1 Different variation of SSMF and DCF

Cases	**SSMF (km)**	**DCF (km)**
1	24	3.6
2	36	5.4
3	48	7.2
4	60	9.0
5	72	10.8
6	84	12.6

5.2.2 Results and Discussion

The proposed DWDM system is tested under varying span cases as in Table 5.1. With different span cases the maximum approachable distance $L_{approach}$ as the function of L_{span} is calculated to get Q factor >15dB for BER < 10^{-9}. It is observed that the span case 4 corresponding to SSMF length of 60km gives maximal approachable distance.

Table 5.2 and Table 5.3 lists out all the spans and maximum distances reached for both Raman-EDFA and EDFA. All the cases considered, reach different number of spans to achieve the target of >15dB Q factor and acceptable BER. After the case 4, the number of spans starts to reduce. So, to calculate the long haul distance span case 4 is considered. The Q factors and BER values are quoted for the 96 channel U-DWDM system.

Table 5.2 L approach with EDFA with target Q >15dB

Cases	Spans	$A_{pproach}$(km)	Q factor	BER
1	18	496.8	15.52	1.30×10^{-9}
2	24	993.6	15.47	2.19×10^{-9}
3	21	1159.2	15.41	$2.7\text{x}10^{-9}$
4	26	1794	15.73	2.4×10^{-9}
5	21	1738.8	15.5	1.02×10^{-9}
6	17	1642.2	15.63	1.09×10^{-9}

The total appreciable distance reached is 2070km obtained with maximum number of 30 spans with Raman-EDFA Hybrid Optical Amplifier. For comparison the maximum distance obtained with Raman-EDFA HOA and that of distance obtained with EDFA standalone (1794km) for this span case is also reported. We observe that the total distance achieved with EDFA is 276km lesser as compared to distance achieved with Raman-EDFA HOA. The Raman Amplifier along with the high output power EDFA allows for higher and flat gain for the extended transmission distances.

Table 5.3 L approach with Raman-EDFA with target Q >15dB

Case	Spans	$L_{approach}$(km)	Q factor	BER
1	21	579.6	15.10	5.07×10^{-9}
2	26	1076.4	15.19	3.92×10^{-9}
3	23	1269.6	15.31	1.7×10^{-9}
4	30	2070	15.43	1.61×10^{-9}
5	25	1904.4	15.16	1.19×10^{-9}
6	19	1835.4	15.21	1.06×10^{-9}

Figure 5.2 shows the results of the maximum approachable distance $L_{approach}$ for both the conventional EDFA and Hybrid Raman-EDFA as a function of L_{span} given a target Q factor > 15 dB, bit rate < 10^{-9}. It is observed that all the different span cases give target quality of signal but after the span case 4, corresponding to 60km of SSMF, the distance covered starts to decrease.

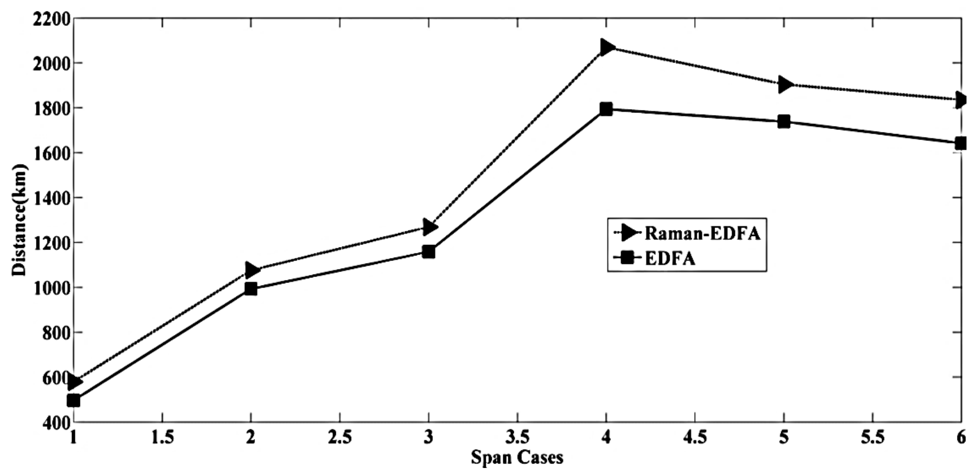

Figure 5.2 Maximum Approachable distance versus different span

It is recommended from these results that Raman-EDFA can be used in long haul communication at optimal span distance (L_{span}) for better performance. Hence, hybrid Raman-EDFA does serve to increase the overall capacity of the U-DWDM system with maximized channels at very dense channel spacing whilst increasing the distance of transmission.

5.3 Overcoming Transmission Impairments in High Speed DWDM systems

5.3.1 Transmission using Orthogonal Polarization of Adjacent Channels

Orthogonally transmitting adjacent channels centered at narrow spacing reduces the possible inter channel interference. Therefore, using the concept of orthogonally transmitting the adjacent wavelengths facilitates high bit rate transmission successfully over larger distances. The high bit rate per channel is achieved by optically time multiplexing single wavelength channels with intra channel shift incorporated to avoid any crosstalk. Combining both concepts in the scenario of 16 x 4 x 10Gbps yields better performance with high Quality factor and longer achievable distance.

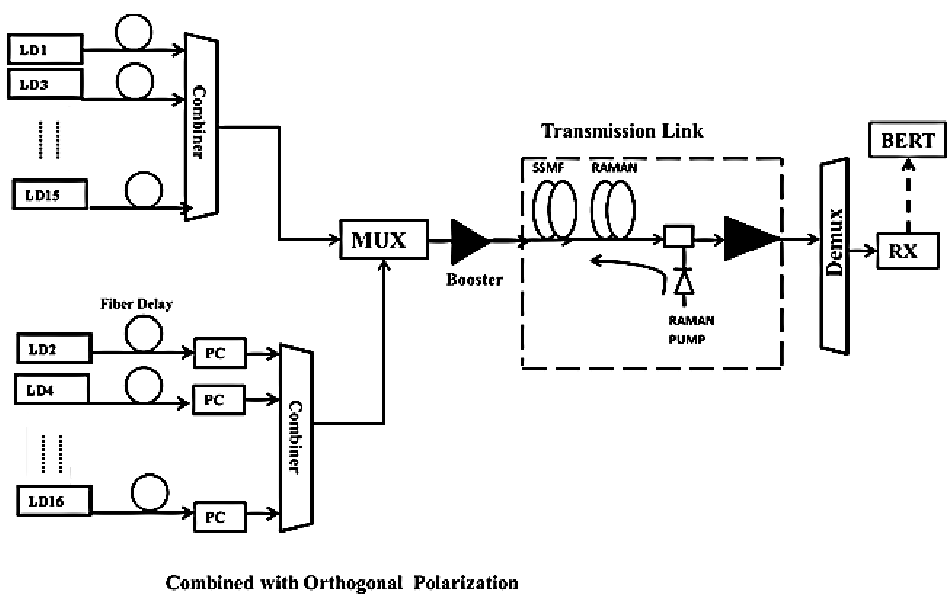

Figure 5.3 High Speed 16 x 4 x 10Gbps DWDM with orthogonal launch of input signals

Sixteen closely spaced DWDM wavelengths at the spacing of 0.2nm, starting from 1550nm, covering the bandwidth of 3.1nm are multiplexed as shown in Figure 5.3. Per channel bit rate is increased to 40Gbps by suitably incorporating optical delay lines. NRZ coding is used to modulate the PRBS (2^7-1) binary sequence using the MZM without any Forward Error Control (FEC). Power/Channel is normalized to -5dBm. The SHIFT introduced per PRBS is "(2^7-1)/Number of optical delays" i.e.32 bits. Every even channel is orthogonally launched using a PC (Polarization Controller). Channels 2, 4, 6…….16 and channels 1, 3….15 are both separately combined via a passive combiner before finally multiplexing them to the fiber. Raman pump wavelength is at 1451nm with pump power of 550mW.

Followed by a booster is the discrete RAMAN-EDFA HOA, with Raman Fiber being a "pumped dispersion compensated fiber" with length optimized to 27.027km. The transmission link in the above figure comprises of single span comprising of 180km of SSMF. Hence, the total single span distance covered by the high speed 640Gbps system is 207.02km.To draw the comparison with appreciable distance reach without the orthogonal launch, the above topology system design is retransmitted with parallel polarization with the same ITU-T compliant channels. It is observed that it spans a distance of 184.02km. A good 23km is enhanced with 90^0 polarizations. This span reach could be enhanced more with increased pump power source. Most commercial available pump is limited from 250mW to 550mW.

The Figure 5.4 compares the Q factor obtained for 640Gbps high speed DWDM system with and without the polarization launch transmitters for the same 184.02km. The available Raman pump with power of 0.55W at 1451 nm is used. It is observed that for the same span covered, the orthogonally polarized system offers a far better quality of signal as compared to its parallel polarized counterpart. For any given distance e.g. at 115km, the Q factor is at 25.72dB as against 20.90dB for the latter case. Similarly, as the distance increases to 184.02km, the Q factor notifies a value of 21dB as against 19.27dB for parallel sent channels.

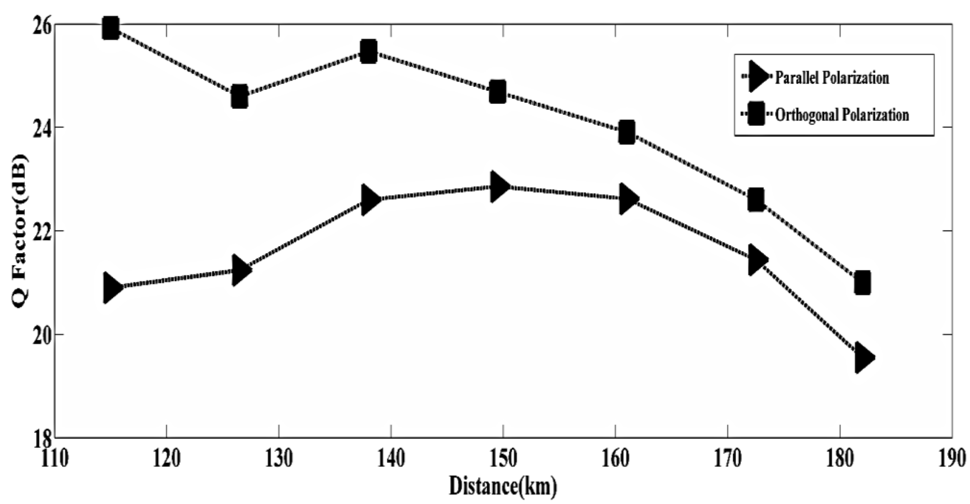

Figure 5.4 640Gbps DWDM system with Parallel and Orthogonal Polarization

The Table 5.4 at a glance gives strong evidence of high performance achieved for both the cases considered.

Table 5.4 Comparison of 640Gbps DWDM System with Parallel and Orthogonal Polarization

Polarization	BER	Q Factor(dB)	Eye Closure(dB)
Parallel	$1.83e^{-20}$	19.27	2.5
Orthogonal	$1.87e^{-32}$	21.44	2.03

The variation of Q factor with increased distance is measured for the 16 x 4 x 10Gbps orthogonally polarized system at different pump powers from 0.45W to 0.65W at 1451nm. It is observed that for any pump power, with increase in distance the Q factor tends to reduce. To quote for a specific 207.02km at 0.65W Raman pump, Q factor of 14dB and eye closure of 2.6dB is reported. Likewise for the same distance, with the pump power of 0.55W the Q factor observed is more of 15.17dB. Similarly, the Q factor >16dB is noted with pump power of 0.45dB. Appropriate pump power of 0.55W for maximum distance of 207.02km is therefore, recommended for 640Gbps polarized DWDM system with Q factor >15dB.

It is clear from the Figure 5.5 that increased pump power values also decrease the Q values and hence the output quality. Hence for long reach optical links an optimum pump value determines the best quality of the received signal.

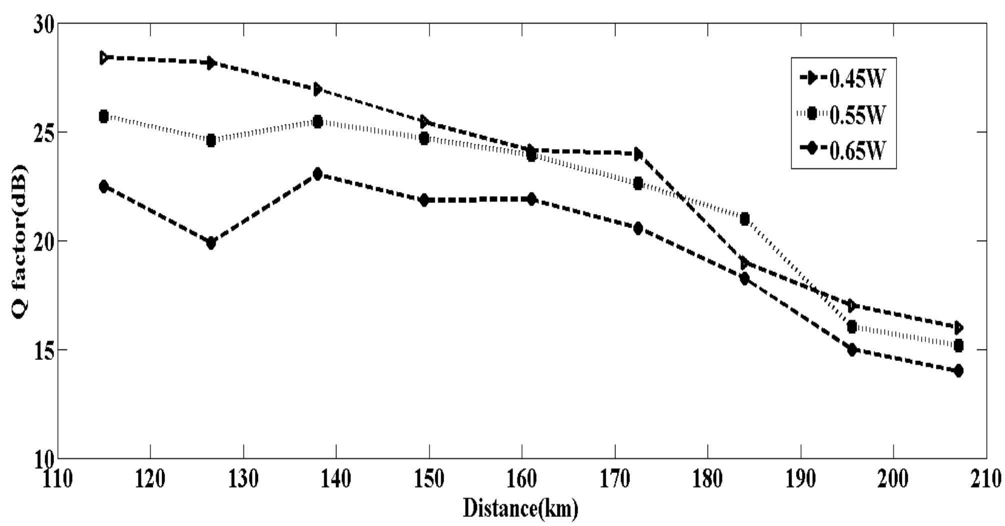

Figure 5.5 Performance Investigation with various Raman Pump Powers

The eye diagram below in Figure 5.6 a), b) and c) shows the output signal levels obtained after the maximum transmission of 207.02km with various pump powers of 0.45W, 0.55W and 0.65 W respectively. It is evident from the following diagrams that the varying eye openings and power level varies at the received signal as the pump power is varied. The increased pump power increases the eye closure. The high pump power with high input powers are also reported to hamper the output performance as it adds in the non- linear effects and the increased Raman noise. Therefor the careful optimization of the Raman pump power tailored at a specific wavelength for minimal input power per channel increases the maximal reach of the designed system.

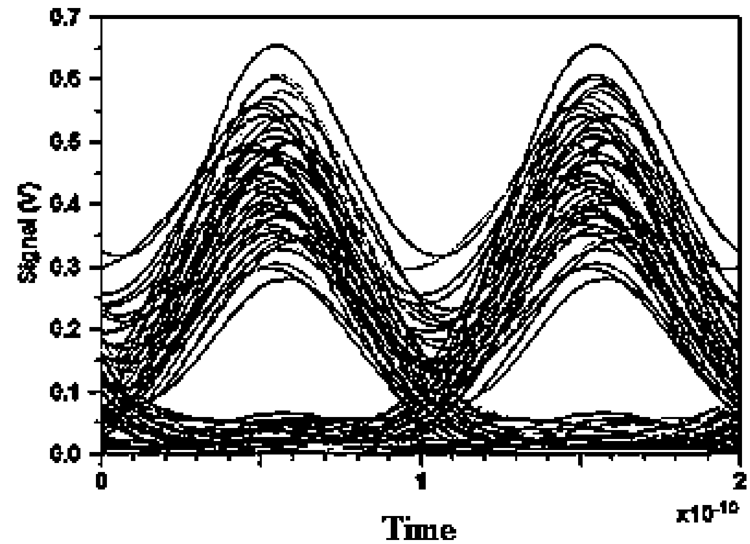

Figure 5.6 a) Eye Diagram: Maximum Span Covered with 0.45W Pump Power

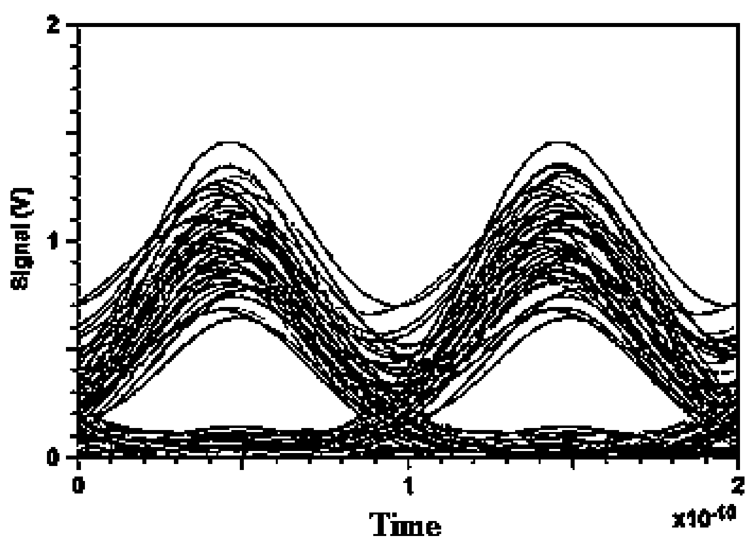

Figure 5.6 b) Eye Diagram: Maximum Span Covered with 0.55W Pump Power

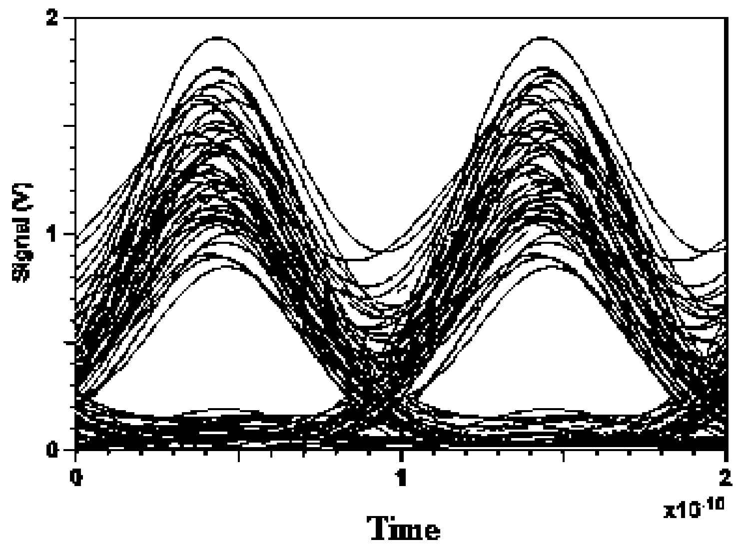

Figure 5.6 c) Eye Diagram: Maximum Span Covered with 0.65W Pump Power

Further, other proposed topologies 8 x 4 x 10Gbps DWDM system reported a distance of 345.044km with quality factor of 20dB and highest ever gain reported of 25.178dB for such high speed networks. In Chapter 3, 8 x 80Gbps DWDM topology was quoted. The performance evaluation in terms of approachable distance with appreciable BER was conducted here. Both 8 x 8 x 10Gbps and 16 x 4 x 10Gbps cover 180.176km and 184.02km respectively. Described above is the increased transmission up to 207.02km in 16 x 4 x 10Gbps system with orthogonal polarization.

The 8 x 8 x 10Gbps system employs a Distributed Raman Amplifier (DRA) of length 45.044 km of pumped dispersion shifted fiber used as single span. It is noted that as the number of single span increases, it causes the OSNR performance to decrease, as shown in Figure 5.7. It can be observed that after 4^{th} span (i.e. after 180.176km) the OSNR degrades to its unacceptable value due to induced nonlinearities, losses etc. If the threshold OSNR is assumed as 20dB for performance investigation then the extended reach of the system up to around 200km can be considered.

The Table 5.5 shows the Q factors and Gain achieved with maximum reachable distance for different implemented bandwidth efficient systems all at 0.2nm spacing.

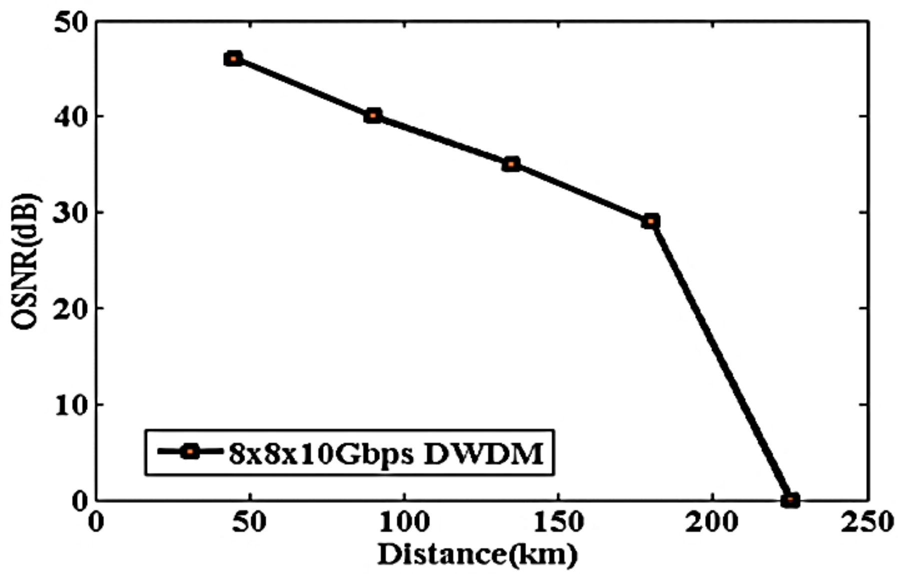

Figure 5.7 OSNR versus Distance in 8x8x10Gbps DWDM System

From the reported results it is recommended that narrowband DWDM systems give excellent performance if a hybrid Raman-EDFA is used as pre amplifier. In the scenario of 8 x 8 x 10Gbps, 8 x 4 x 10Gbps and 16 x 4 x 10Gbps proposed high speed and bandwidth efficient DWDM systems it can be truly recommended that these narrow spaced systems can reach a large transmission distance achieving good performance metric.

Table 5.5 Performance evaluation of various High Speed DWDM Systems

DWDM	**Capacity**	**Span**	**Q factor**	**Gain(HOA)**
4 x 4 x10	160 Gbps	362.296km	17dB	26dB
8 x 4 x 10	320 Gbps	345.044 km	20dB	25.178dB
8 x 8 x 10	640 Gbps	180.1761km	15.8dB	19dB
16 x 4 x10	640 Gbps	184.02km Polarized* 207.02km	19.27dB Polarized*21.44dB	>12dB

Orthogonally transmitting the signals help overcoming the transmitter induced impairments and by use of optimum pump power levels larger distances can be optimized.

5.4 Summary

The work presented here signifies the ultra-narrow DWDM systems in very long haul applications. 96 closely spaced channels at 0.1nm spacing are transmitted over 30 spans covering the distance of 2070km using the proposed hybrid optical RAMAN-EDFA amplifier. In order to draw the comparison, EDFA standalone transmission is also conducted. The total reachable distance reported using 26 spans makes it 1794km. This is 276km lesser than that achieved by Hybrid Amplifiers. The single optimized SSSF span is of 60km with DCF component of 9km.

Further, the high speed DWDM systems are also implemented to see the maximum coverage without using any expensive modules throughout the transmission. The 0.2nm spaced 16 x 4 x 10 Gbps systems are modeled employing orthogonal launch of adjacent channels which reduced the system impairments and for larger distances. The distances covered with 8 x 4 x 10Gbps, 8 x 8 x 10Gbps and 16 x 4 x 10Gbps are 345.044km, 180.02km and 207.02 km respectively. Highly acceptable performance is recorded with Q factor nearing 20dB with optimized Raman pump with 0.55W power at 1451nm for 16 x 4 x 10Gbps system.

The 8 x 8 x 10gbps system reported maximum ever reported OSNR value of almost 30dB in the scenario of 640Gbps high speed DWDM systems.

Having investigated the various proposed DWDM systems at 0.2nm and 0.1nm channel spacing, the next work focusses on implementing designed DWDM systems with various modulation formats to adjudge the best one.

Chapter 6

DWDM System using various Modulation Formats

6.1 Introduction

The previous Chapters focused on modeling of various narrow and ultra-narrow spaced DWDM systems with/without use of amplifiers for high speed long haul applications. The present Chapter covers the last objective aiming at investigating the super DWDM system, using various simple and advanced modulation formats. Evaluation of different modulation formats at base bit rates from 10Gbps to high speed DWDM systems with 40Gbps are carried out in this Chapter. Initially, a 16 channel system is evaluated with phase modulation schemes of QPSK and DQPSK and its performance compared with NRZ and RZ formats. Further, the 160 channels DWDM system is investigated with NRZ, RZ, NRZ-RC and RZ-RC modulation formats. All the investigations are carried out at narrow channel spacing. The high speed DWDM system 16 x 40Gbps is also investigated with duo binary modulation with Hybrid Amplifiers at reduced spacing for the first time. The performance is judged with the BER, Q factor and Eye Diagrams.

6.2 Narrow DWDM System with Different Modulation Formats

The modulation format characterizes the coding of data on the optical signal. The detailed comparison of different modulation formats appears in [113]. It is quoted that the NRZ format poses more dispersion tolerance but suffers from nonlinear effects. RZ offers nonlinear tolerance and along with phase modulation formats exhibits more robustness. Udalcovs [114] concluded that NRZ-OOK would give higher spectral efficiency achieving long link performance. Sharma in [115] checked for robustness of NRZ, RZ, CSRZ and CRZ modulation on 40Gbps fiber links. The studies in [116], [117], [118], and [119] investigated DWDM channels limited by the number of transmitted channels and restricted to only RZ/NRZ modulation with EDFA alone. Previous studies in [80], [88], [90], and [85] etc. all aims at DWDM systems analysis with different simple and advanced phase modulation restricted to either lesser number of channels or limited by wavelength spacing. We extend the work by investigating the systems at reduced spacing with different modulation formats and HOAs.

6.2.1. System Schematic

The deleterious effects of dispersion and non linearities must be managed to achieve transmission over appreciable distances and to obtain an acceptable performance of the system. Therefore, robustness of the optical code pattern is important.

The DWDM system investigated, includes 16 x 10 Gbps Continuous Wave lasers (CW) lasers which are transmitted with channels spaced at 0.2nm as shown in Figure 6.1. The bandwidth covered is 3.1nm starting from 1550nm. These are modulated with various optical code patterns viz. NRZ, RZ, Differential PSK (DPSK), Differential Quadrature PSK (DQPSK), individually and are transmitted over a Dispersion Shifted (DS) anomalous fiber over a medium haul link. The various configurations of the proposed hybrid amplifiers based on conventional amplifiers (Chapter 4) viz, Raman-EDFA, EDFA-SOA and Raman-SOA are used to amplify the differently modulated signals. This is done to observe the best combination of HOA and the launch power thresholds which can give a good performance at reduced channel spaced DWDM signals transmitted with different signaling formats.

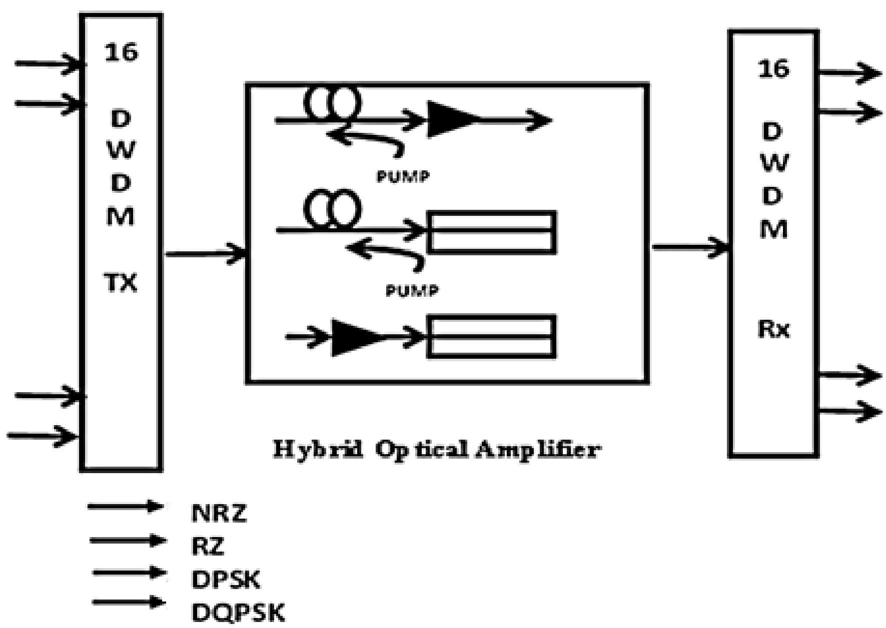

Figure 6.1 Investigations of 16 DWDM Systems with different modulation formats

The amplifiers are optimized to give almost a flattened gain. The Raman provides lumped amplification in the last segment of the transmission link (discrete amplifier). The loss in Raman amplifier used is 0.25 dB/km with reference frequency for dispersion at 1550nm.

The Raman length is optimized to 12km with commercially available backward Raman pump unit with power of 400mW at 1454nm which is used for all the proposed configurations. The EDFA used is assumed to have a flat gain shape with noise figure of 4.5dB. The SOA is assumed to have bias current of 100mA supporting carrier lifetime of 0.3ns. The receivers are appropriate to the different modulation formats used. It includes the normal PIN photo detector with responsivity of 0.85 A/W and minimum dark current of 0.1nA.

6.2.2 Results and Conclusions

Various configurations of Hybrid Optical Amplifiers Raman-EDFA, EDFA-SOA and Raman-SOA are placed in the implemented DWDM system and the performance of the system with different optical code patterns is evaluated in terms of optical signal quality received, for the varied input power levels. The first channel of DWDM system is analyzed for its transmission performance with different modulation formats.

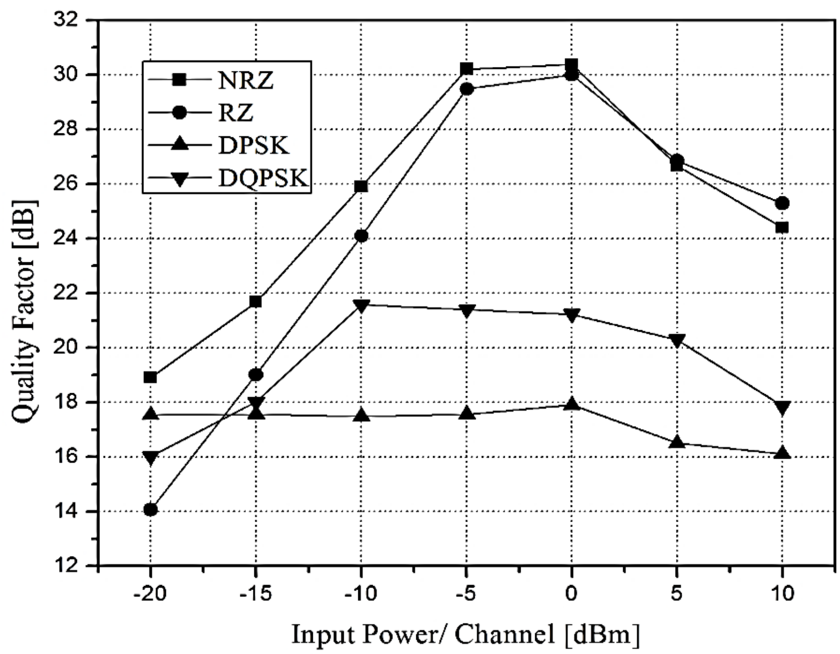

Figure 6.2 Q Factor versus P_{Input} /Channel with Raman-EDFA with different modulation

Figure 6.2 depicts the optical signal quality of the first channel received when Raman-EDFA hybrid amplifier is employed as an inline amplifier with signals being differently modulated with NRZ, RZ, DQPSK and DPSK modulation formats. The input power is varied from very low -20 dBm to high 10dBm. It is observed that the quality factor peaks at 30.2dB for NRZ and at 29.4dB for RZ till 0dBm of input power and thereafter there is a decrease in quality of signal to 25dB and 24.3dB for NRZ and RZ, respectively. DQPSK and DPSK demonstrate the advantage of a maintained signal quality even at higher input power >=0dBm with variation of quality factor being <4dB and < 2dB for DQPSK and DPSK respectively. These phase modulation formats are more immune to nonlinearities (which comes with increased input power) as compared to the NRZ and RZ and this is evident form the more or less stable curves obtained. Since the information is carried in the phase transitions, rather than by the amplitude variations, the fluctuations in the output power are less in case of phase modulated signals even at high input power as compared to the simple NRZ and RZ case.

Further, in Figure 6.3 the 16 DWDM channels are tested with the next configuration of hybrid amplifier, the EDFA-SOA. It is observed that the Q factor peaks at 27dB for NRZ and 25dB for RZ at -10dBm of input power and there is a drastic decrease in the quality factor which drops down to around 16dB and 14.5dB for NRZ and RZ respectively at 0dBm of input power. Whereas, DPSK and DQPSK schemes indicate minimal variation of <2dB and <1dB respectively for input >=0dBm. Since the SOA is more affected at higher input powers due to the nonlinearities there is a rapid fall in the quality just after -10dBm. Apart from the high nonlinear response of this waveguide device, the polarization dependency causes high induced crosstalk resulting in reduced performance.

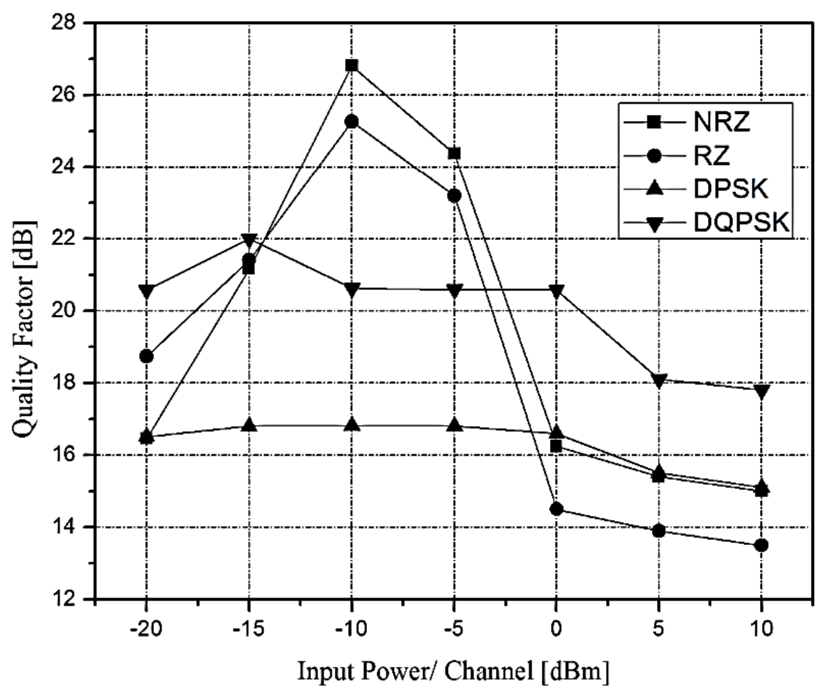

Figure 6.3 Q Factor versus P $_{input}$/Channel with EDFA-SOA with different modulation

Figure 6.4 also indicates the similar behavior when Raman-SOA hybrid amplifier is used in the implemented DWDM system. The NRZ shows quality factor peak at 24.5dB and RZ peaks at 24dB. The quality of signal rapidly falls off with this hybrid optical amplifier just at -15dBm and -10dBm for NRZ and RZ, respectively because of the presence of the SOA which is more prone to non linearities being a semiconductor amplifier. It is observed that again DPSK and DQPSK maintain the quality of the signal throughout the input signal variation from -20dBm to 10dBm with minimum variation in the output quality of signal.

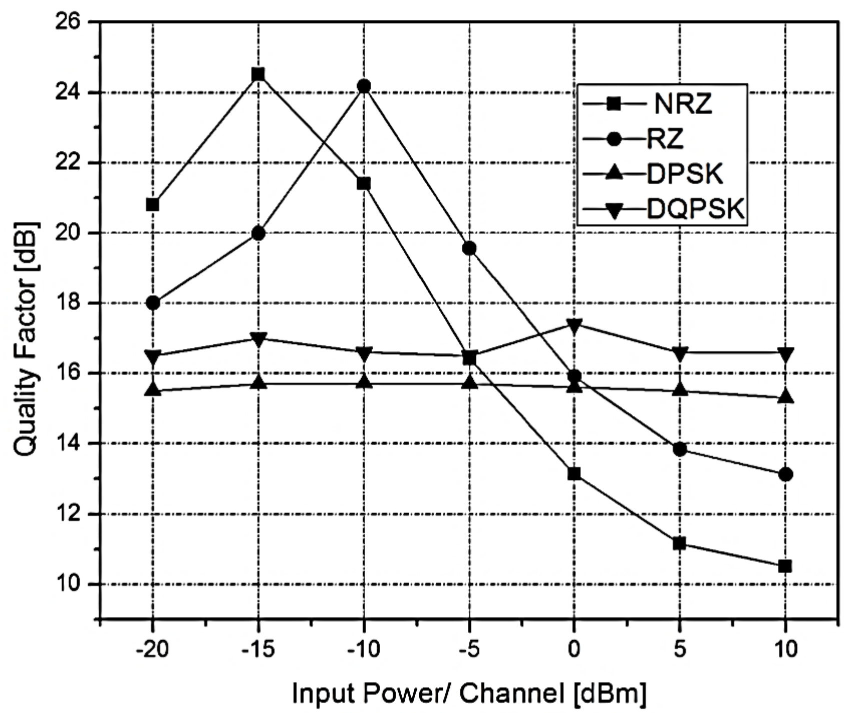

Figure 6.4 Q Factor versus P_{input}/Channel with Raman-SOA with different modulation

It is observed that for all the combinations of the proposed amplifiers used for the 160Gbps DWDM system, in the scenario of less input power/channel i.e., < = 0dBm for Raman-EDFA and <= -10dBm for EDFA-SOA and Raman-SOA, the NRZ and RZ modulation format is preferable. On the other hand in the scenario of higher input power/channel, > = 0dBm for all the configurations of the hybrid amplifiers, the DPSK and DQPSK modulation formats is seen to demonstrate a stable quality of signal with minimal variation of the Q Factor. It is also observed that amongst all the hybrid optical inline amplifiers employed, the Raman-EDFA performs the best and Raman-SOA performs the worst in DWDM scenario at narrow spacing with different modulation formats. Figure 6.5 shows the eye diagrams for NRZ and RZ for the three combinations of HOAs.

1)

2)

3)

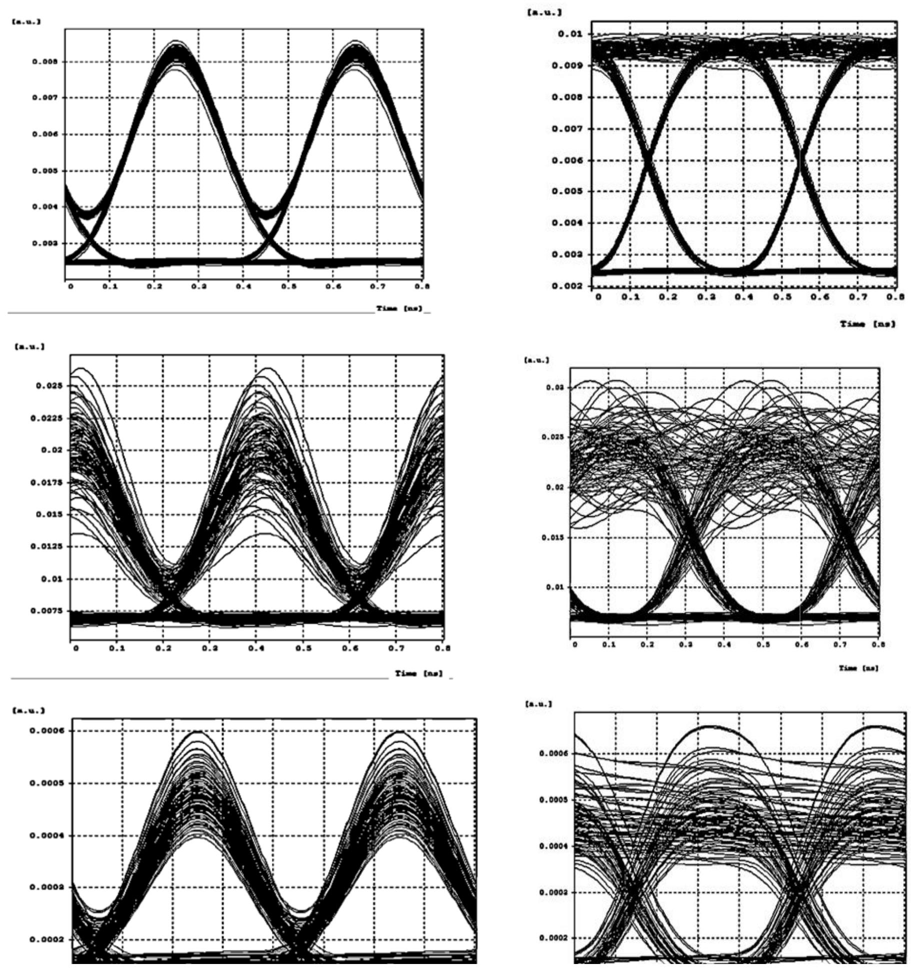

Figure 6.5 Eye Diagrams for RZ (Left) and NRZ (Right) for 1) R-E, 2) E-S, 3) R-S

The Table 6.1 at a glance shows the maximum Q factors obtained for the DWDW system with all the configurations of the proposed Hybrid Amplifiers used with different modulation formats. It also indicates (in brackets) the input threshold where the maximum is obtained for each amplifier for NRZ and RZ formats. The Q factor for DPSK and DQPSK modulation formats is taken with 0dBm of input power level. This, in turn indicates the appropriate input power suitable for typical kinds of hybrid amplifiers employed in 16- DWDM scenarios.

The 160 channels covering C+L band was explained in Chapter 4. The various optical modulation formats viz. NRZ, RZ, NRZ-RC and RZ-RC are compared by using Raman-EDFA HOA and EDFA conventional optical amplifier. The performance was evaluated in terms of Q-factor and received output optical power.

Table 6.1 Q factor for different modulation formats using all HOAs

HOA	NRZ Q(dB)	RZ Q(dB)	DQPSK Q(dB)	DPSK Q(dB)
RAMAN-EDFA	30.2 (0dBm)	29.4 (0dBm)	21	18
EDFA-SOA	27 (-10dBm)	25 (-10dBm)	20.8	16.8
RAMAN-SOA	24.5 (-15dBm)	24 (-10dBm)	17.5	15.8

Figure 6.6 shows the investigation of the first channel received at the output while using an inline Raman-EDFA (HOA) hybrid optical amplifier for different modulation formats. It is reported that Raman-EDFA gives better performance results when NRZ modulation format is used. It gives a Q factor at peak >21.5dB at input of -10dBm. The RZ modulation gives Q factor peak at 19.75dBm. The NRZ-RC peaks at 19.5dB and RZ-RC shows highest at 18.5dB. At higher bit rates and more number of channels the NRZ format scores better than RZ as, RZ is more prone to dispersion and SPM (Self Phase Modulation) owing to the fact that it occupies double the modulation bandwidth and it has high peak power.

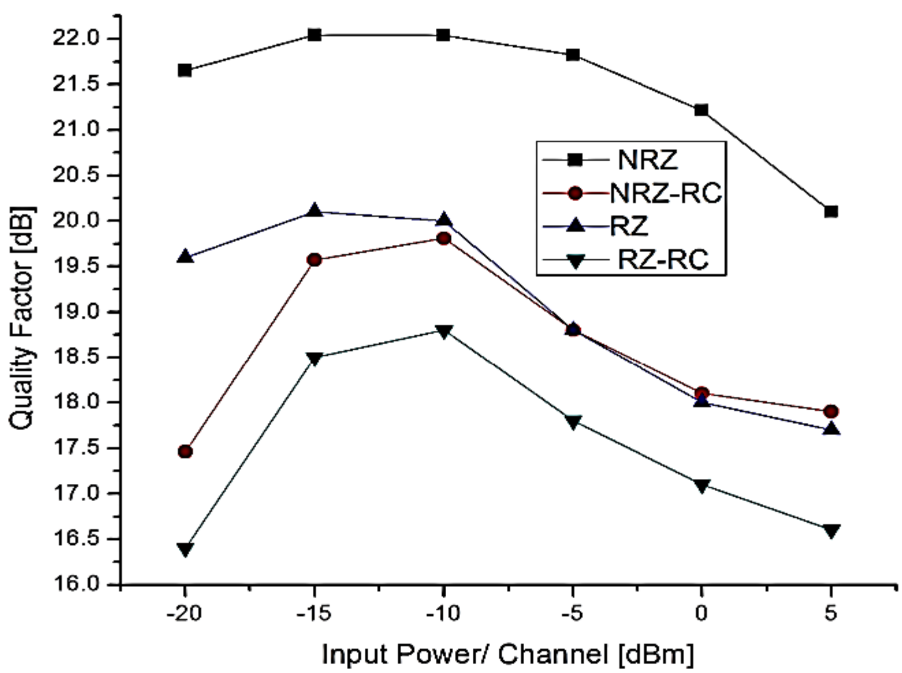

Figure 6.6 The160 channel DWDM with various modulation formats using Raman-EDFA

Due to the cumulative effects of ASE and Raman noise, the much expected rapid downfall in Quality factor is observed after -10Bm of input. In the case of EDFA conventional amplifier, the NRZ shows good results with Quality factor >18dB, as shown in Figure 6.7, as against >16dB, 12dB and 11dB for RZ, NRZ-RC and RZ-RC respectively at -10dBm of input power.

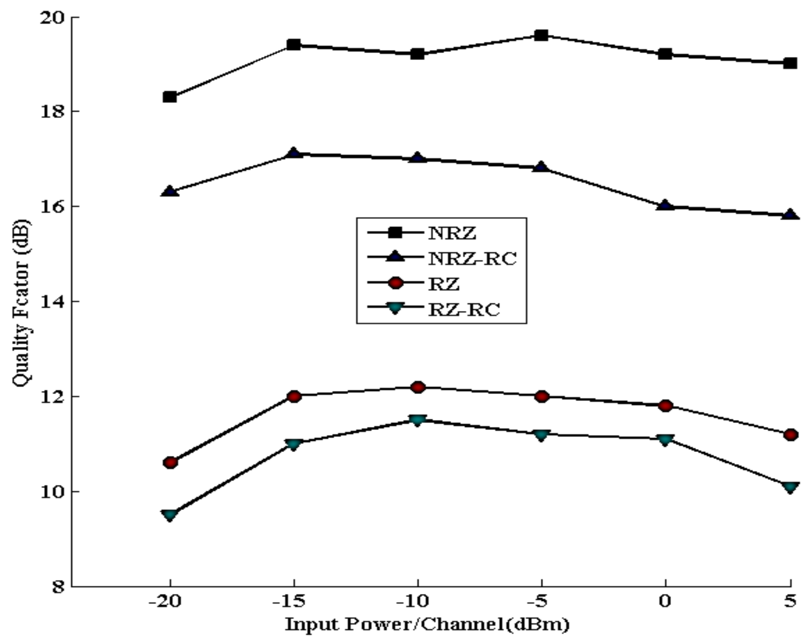

Figure 6.7 The160 channel DWDM with various modulation formats using EDFA

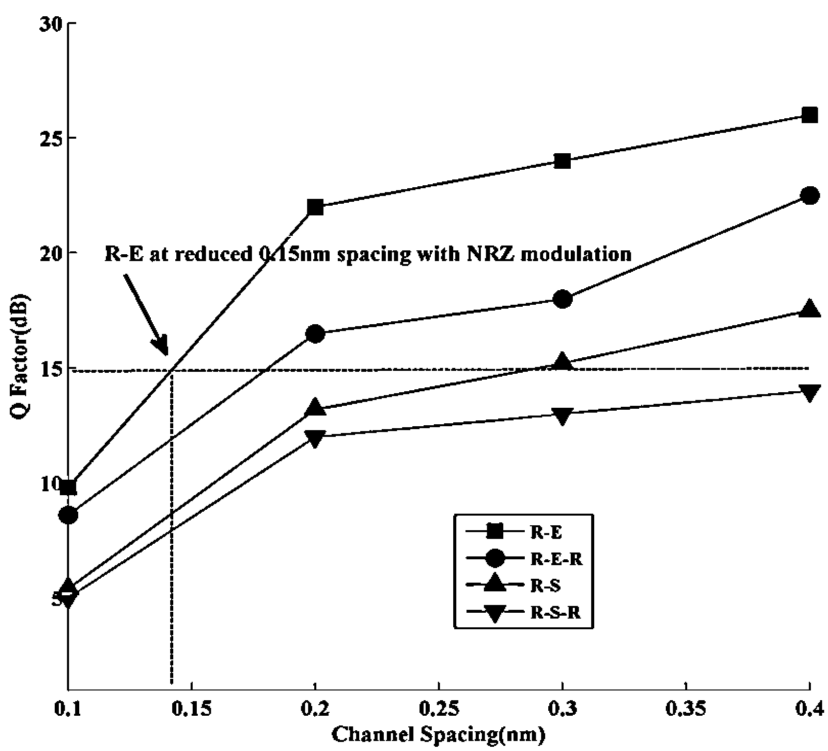

Figure 6.8 Raman-EDFA at reduced channel spacing with NRZ

Figure 6.8 indicates that with the appropriate optimization, the Raman-EDFA performs well even at reduced channel spacing in the scenario of 160 channels. Q Factor of 15dB is noticed at spacing <0.15nm. The Table 6.2 below summarizes the comparison of various states of art schemes and the investigation currently carried out. It is concluded that the investigation using proposed hybrid amplifiers with NRZ format give improvement in terms of Quality factor in a DWDM system with more number of channels implemented with reduced channel spacing. As mention in Chapter 3, a high output power is achieved in DWDM system covering both C and the L band using HOA. It is observed that good performance of UDWDM using Hybrid Amplifiers with suitable modulation format can be achieved with proper optimization of parameters.

Table 6.2 Comparison of State of Art Schemes with Current Investigation

Formats	**Amplifier**	**Band**	**Channels**	**Spacing**	**Q**	**State of Art Scheme**
-	Hybrid/ EDFA	C	80	0.4nm	19dB	[119]
NRZ,RZ,CSRZ	EDFA	C	3	0.4nm	-	[85]
NRZ	Hybrid	C	100	varying	25dB	[117]
RZ,NRZ,RZ-RC,NRZ-RC	Hybrid/ EDFA	C+L	160	0.2nm 0.15nm	21dB 15dB	Current Investigation

6.3 High Speed Duo binary Modulated 16 x 40Gbps DWDM system

The repeater less transmission in a DWDM system reduces the overall cost and simplifies the transmission system. Especially, when SSMF has to be deployed for transmission, owing to its large local dispersive element, the maximum reach of transmission is important. To combat the dispersion usually DCF is employed. But duo binary modulation offers advantage of dispersion tolerance for long link distances. The literature presents DWDM system investigations with duo binary modulation for long span distances using conventional amplifiers. Till now, high speed bandwidth efficient DWDM networks employing Optical Time Division Multiplexing at narrow channel spacing (0.2nm) with hybrid Raman-EDFA is not yet reported. Haris *et al*. [109] reported 8 x 10Gbps duo binary transmission at 0.8nm spacing over SSMF. Kaiser *et al.* presented 225km SSMF transmission using Raman amplification [110]. In this section previous work is extended by employing hybrid amplification in scenario of 16 x 40Gbps at reduced channel spacing.

6.3.1 Numerical Simulation Set Up

The proposed 16 x 4 x 10Gbps system is investigated with Duo binary-NRZ signaling which gives better performance over longer reachable distances using SMF pumped Raman Amplifier with EDFA. The investigations of duo binary format using HOA in scenario of high speed DWDM/OTDM systems are examined at narrow spacing for the first time. The high speed DWDM systems designed in previous chapters used DCF pumped RA. In the current investigation a PSMF is used.

The duo binary format is proved to give a better performance over long haul applications as it provides spectral occupancy band limited to half of the bit rate. Figure 6.9 shows the block schematic used in the system design. The inset shows the, reduce spectral occupancy of the duo binary modulated signal as compared to simple NRZ signaling. By employing the correct electric transmitter filter response, all the spectral components can be suppressed beyond the half bit rate which could otherwise experience phase distortions affecting the receiver performance. An investigation in [116] also quotes duo binary filter approximated as a low pass filter with cut off as B/4.

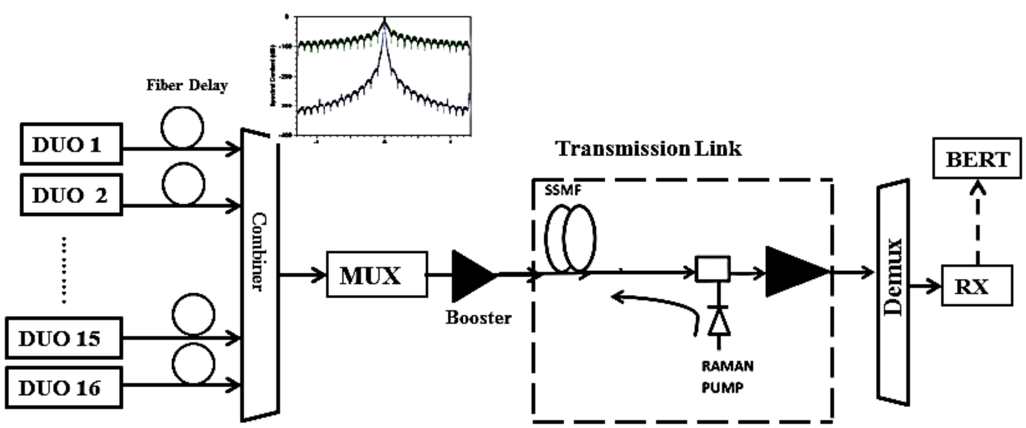

Figure 6.9 16 x 40Gbps DWDM with duo binary transmission

Figure 6.10 ahead, shows the single channel duo binary transmitter. The ideal duo binary NRZ is generated by using a delay and add circuit followed by a band limited with cut off =

B/2, where B is the base bit rate, i.e. centered at 5GHz. This causes finite rise time and fall time between levels. The use of filter improves the dispersion limited transmission distance. The short pulses generated by MLL laser are Duo-NRZ modulated and further delayed by optical delay lines (ODL) to carry 40Gbps per wavelengths. The composite signal further is transmitted and amplified by the Raman pumped SSMF of 119km. The Raman pump at 1454nm with 550mW is employed followed by an EDFA with fixed gain of 25dB and NF of 4dB. At the reception, the normal PIN photo detector used has a responsivity of 0.875 A/W and minimum dark current of 0.1 nA.

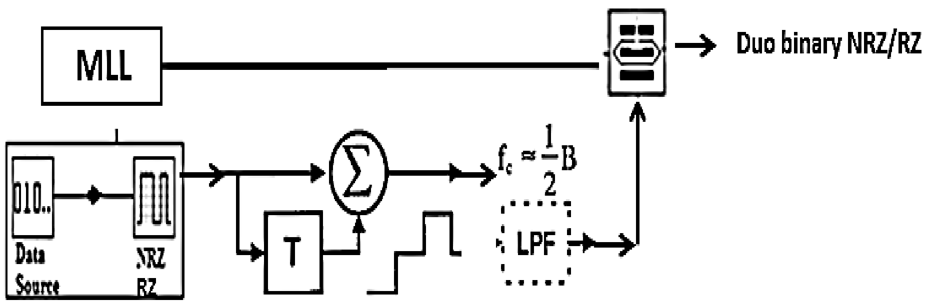

Figure 6.10 Single Channel Duo binary transmitter

6.3.2 Results

The transmitted spectrum obtained after HOA inline amplification in the 0.2nm spaced 16 x 40 Gbps is shown in Figure 6.11. The sixteen peaks at 0dBm of input /channel just after the amplification is observed. The Raman-EDFA HOA reports a gain of 21.375dB.

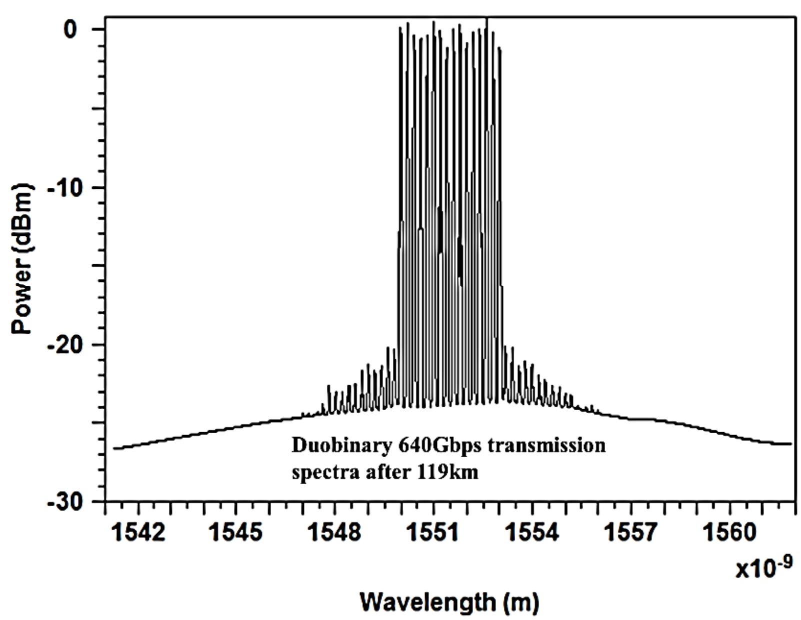

Figure 6.11 Received spectra after HOA at 0.2nm 640Gbps DWDM System

To quantify the system performance with hybrid Raman-EDFA amplification the system is examined with different per channel input power of -5dBm and 0dBm. The received power around 6dBm for 0dBm input and around 3.2 dBm for -5dBm of input is received as shown in Figure 6.12 ahead. These are good acceptable levels of output across the entire transmission band. With no costly dispersion controlling components and no special system design, duo binary modulated signals transmitted over repeater less 119km gives good received output power level across all the channels spread across 3.1nm bandwidth.

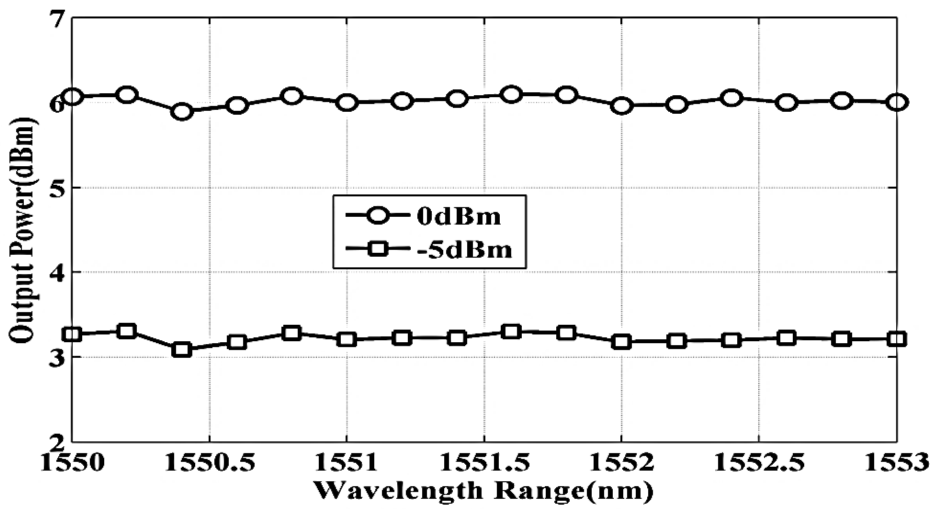

Figure 6.12 Received output power across the entire transmission band

Further, to draw a comparison, simple binary and duo binary for the same transmission distance is compared for different launch powers from -10dBm to +10dBm. The Q factor shows an improvement of 2.60dB e.g. at 0dBm input per channel. A high Q factor nearing 18dB is observed for duo binary as against around 15dB with binary signaling. The graph in Figure 6.13 shows evidence of high spectral efficiency with use of duo binary signaling is achieved, as Q is maintained for higher input powers till +6dBm.

A value of 16.20dB is reported as against 13.94dB of Q obtained at +4Bm after which the performance falls rapidly to unacceptable levels. Hence, in the scenario of high speed 640 Gbps the nonlinear duo binary signaling limit for repeater less 119km, requires 6dBm of optical power. A forward SNR of 20dB is obtained for the system investigated.

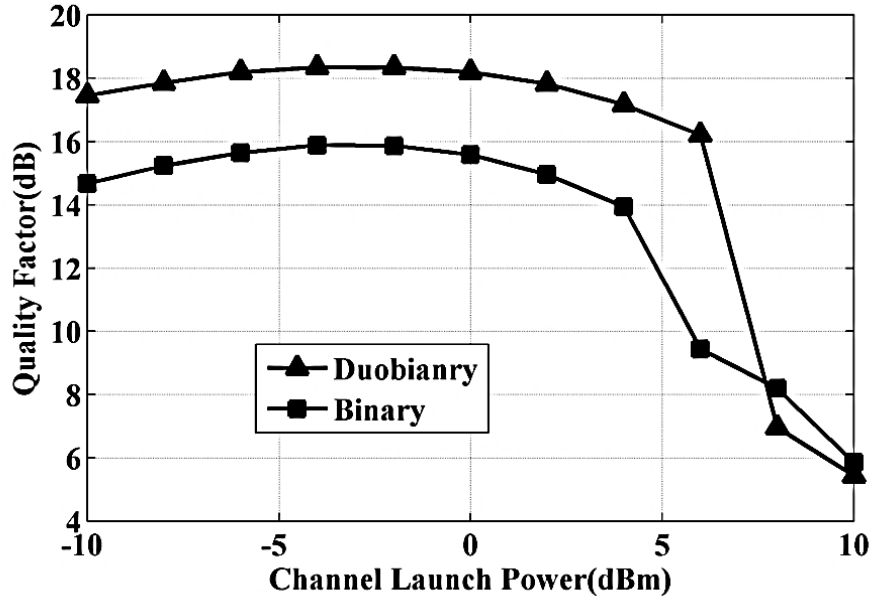

Figure 6.13 Q factor versus Input power/Channel with Duo binary and binary Signaling

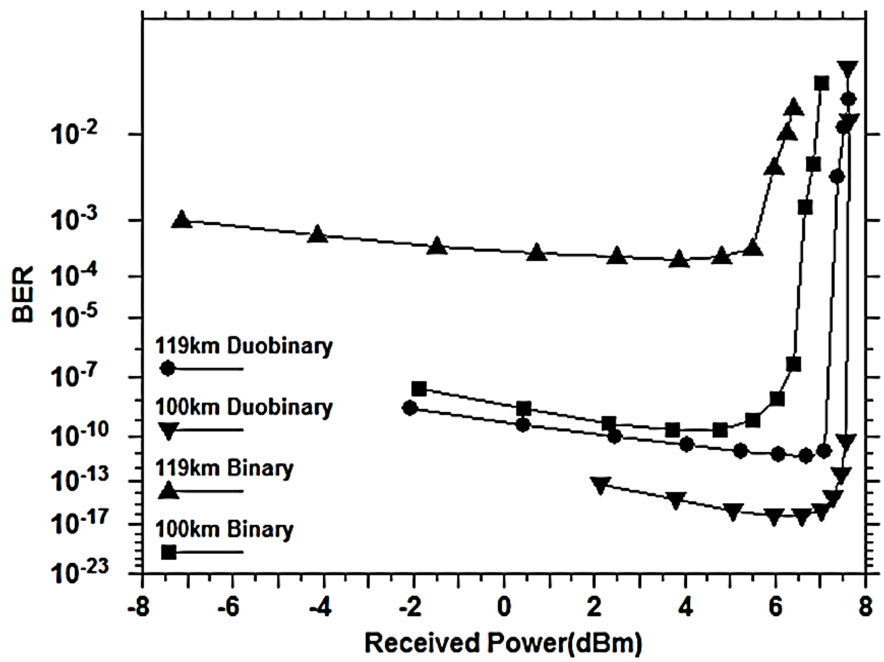

Figure 6.14 BER versus Received Power for binary and Duo binary Signaling

Figure 6.14 indicates the BER versus the received optical power for 119km and 100km of Duo binary and binary transmission respectively. It shows that duo binary is more resilient to chromatic dispersion in the SSSMF transmission as compared to a simple binary signaling format. BER< e^{-12} with high received power is obtained for maximum 119km reach with duo binary and comparatively poorer performance is observed with binary signaling which makes system dispersion limited to <100km. The eye diagram obtained after 119km transmission is shown below in Figure 6.15.

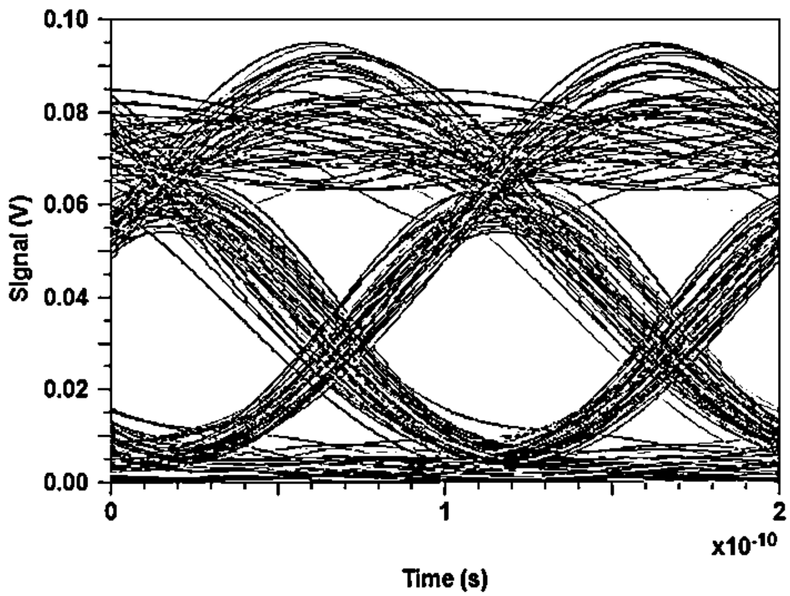

Figure 6.15 Received Eye Diagram with Duo binary Signaling after 119km

6.4 Spectral Loss Compensation in EDFAs using different Modulations

6.4.1 Simulation Setup and Results

Figure 6.16 depicts the simulative schematic of the technique implemented to control the spectral losses in a system containing an EDFA amplifier chain. The transmitter section includes a PRBS generator of degree 7 followed by the electrical driver which acts as RZ raised cosine, NRZ raised cosine and Manchester raised cosine rectangular driver. The external Mach-Zhender modulator exhibits insertion loss of 5dB with 30dB extinction ratio and 0.5 chirp factor. LP Bessel Filter is employed as electrical filter.

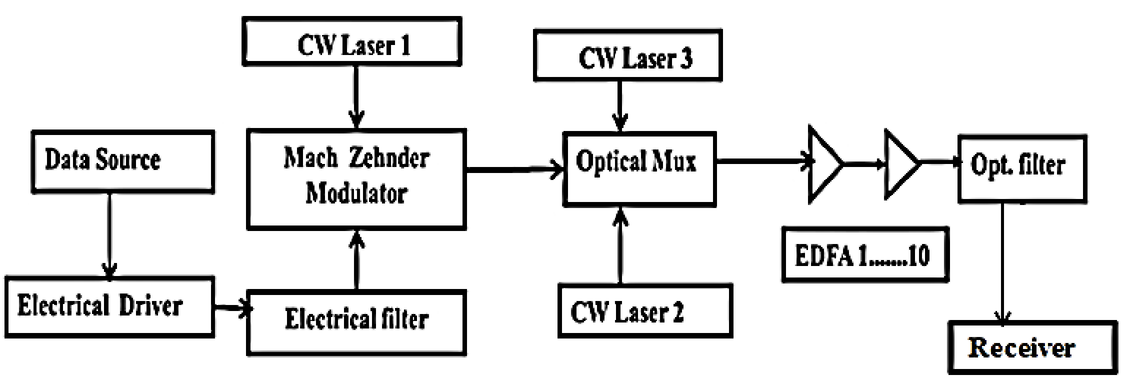

Figure 6.16 Compensating Spectral Losses with Different Modulation Formats

CW Laser1 is at 1550 nm wavelength with 20mW peak power, Laser 2 is centered at 1557 nm with 5mW peak power and Laser 3 operates at 980 nm having a power of 100mW. A chain of 10 EDFAs are considered each with length 10 m, meta stable life time of 10 ms. Compound optical receiver comprising of the photo detector, the preamplifier, and the post amplifier/filter is used to output the decoded electrical signal.

The investigations are carried out with NRZ-RC, RZ-RC and Manchester–RC modulation formats. Figure 6.17 reveals the power spectrum plots measured after the electrical generator, at the output of electric filter and the output of receiver. The investigations reveal that the highest power levels are produced at the output with the minimum noise in case of NRZ raised cosine data format. It is also observed that the NRZ – RC produces least noisy spikes after the electrical filter. On the other hand, the Manchester raised cosine exhibits lesser spikes after the chain of EDFA amplifiers, when compared to RZ raised cosine format. It is evident that the received signal quality with the minimum nonlinearities and least spectral loss variations are obtained with NRZ raised cosine than in case of Manchester raised cosine and RZ raised cosine modulation formats.

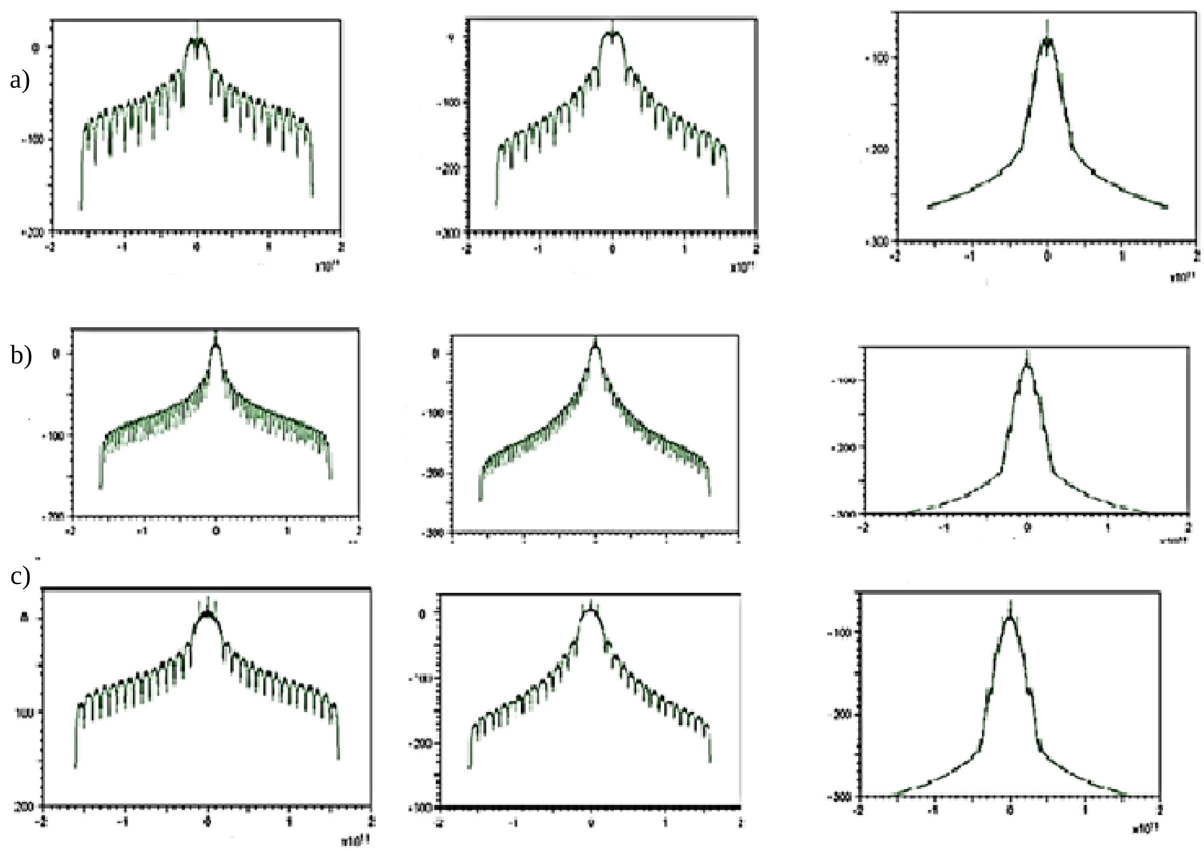

Figure 6.17 Power Spectrum: a) Manchester RC, b) NRZ- RC, c) RZ -RC

The eye diagrams obtained are shown in Figure 6.18 ahead. The eye diagrams are noted after the electrical driver, electrical filter, and external modulator and at the output of the receiver. It is observed that the eye diagram is distorted both for RZ raised cosine and Manchester raised cosine formats. Nevertheless, no distortions are obtained for NRZ raised cosine signals measured at all the three instants. The robustness of NRZ, RZ and Manchester raised cosine modulation formats at 10 Gbps for optical long haul link on the amplifier noise variations has been investigated in a link consisting of the chain of EDFA amplifiers.

Therefore, it is reported that in a link consisting of EDFA amplifiers, the NRZ –RC provides highest power levels with minimum losses indicated by reduction in noisy spikes at the output of receiver. Moreover, its robustness over dispersive SMF link is justified by wide eye opening in comparison with RZ and Manchester raised cosine modulation.

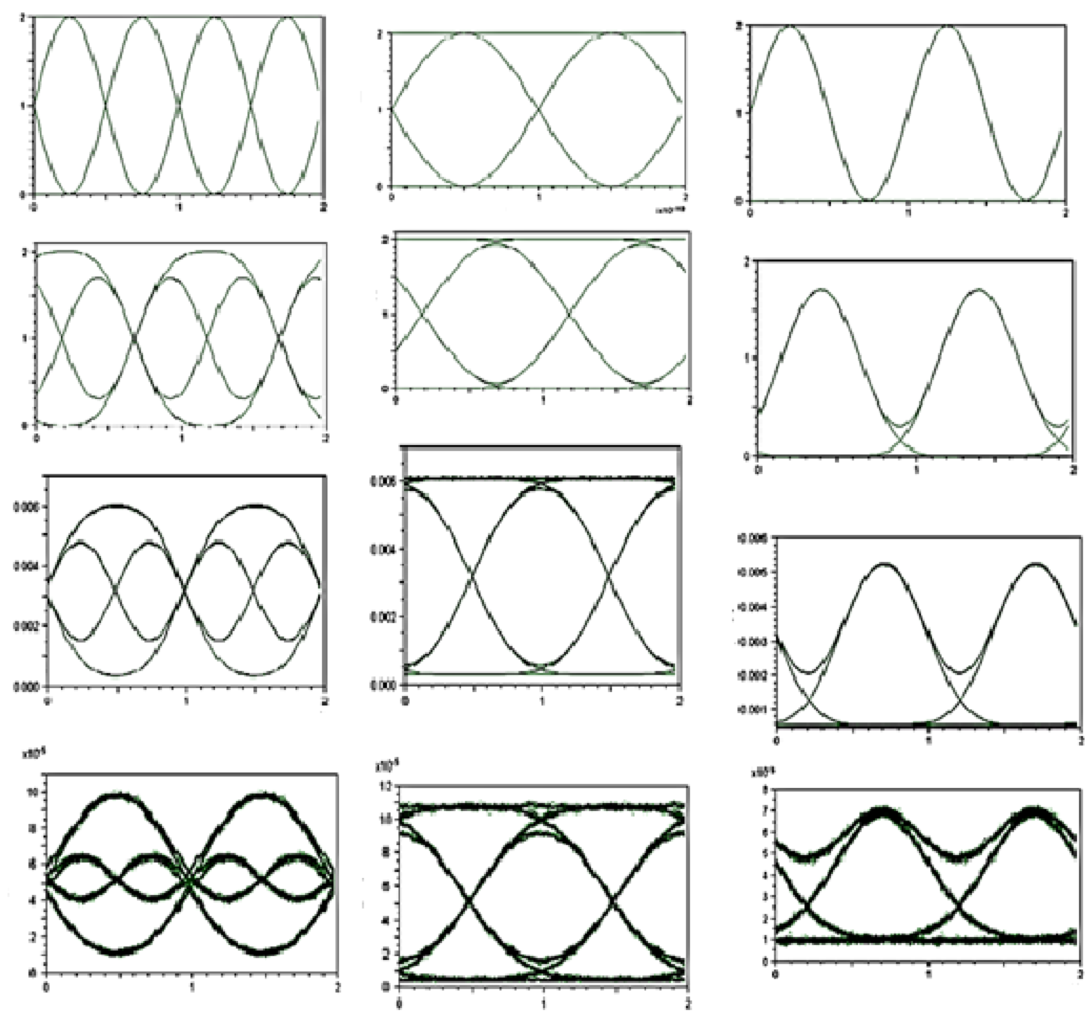

Figure 6.18 Eye Diagram :(Left) Manchester, (Middle) NRZ, (Right) RZ Raised Cosine

6.5 Summary

This Chapter accomplishes investigation of the various proposed DWDM systems at narrow channel spacing with various modulation formats. The 16 channel DWDM system is transmitted with DPSK and DQPSK modulation formats. It is reported that at higher input power /channel of > 0dBm, the phase modulated formats gives a stable performance as compared to the NRZ and RZ format which shows a drop down of quality as the input power increases. The system is analyzed with various proposed HOA. The RAMAN-EDFA HOA reports a maximum of 21dB and 18dB for DQPSK and DPSK formats respectively. A lesser value of Q of 20.5dB and 16.5dB is noted with EDFA-SOA for DQPSK and DPSK respectively. Similarly, 17.2dB for DQPSK and 15.5dB for DPSK is reported with Raman-SOA.

Further, C+L band 160 channels transmitted with simplex and raised cosine formats are also examined with conventional inline EDFA and Hybrid Raman-EDFA. A Q factor of > 21dB is noted with HOA and >18dB is reported from EDFA. The Raman EDFA works effectively even in the scenario of reduced channel spacing (<0.15nm) obtaining Q factor of 15dB. Next the spectral loss variations in a system with chain of EDFA amplifiers using various modulation formats are also reported. NRZ-RC signaling performs well in such a link with widest eye opening and minimum noisy spikes.

Finally, 16 x 4 x 10Gbps DWDM system is investigated with duo binary signaling obtaining quality factor >18dB. The HOA offers a gain of 21.375dB for the channels transmitted. The received output power is a highest reported in the scenario of high speed 640Gbps system.

Chapter 7

Conclusions, Recommendations and Future Scope

7.1 Conclusions

The enhanced capacity DWDM System is the key technology to meet the unprecedented demand of ever growing e-traffic and cater to the end-user bandwidth demands. The bandwidth efficient, high speed, large capacity DWDM system is designed and investigated at ultra-narrow channel spacing. The current scenario of the DWDM systems lag either in the number of transmitted channels or in the inter channel spacing and, moreover, they embed only rare-earth-doped amplifiers. Therefore, this thesis focusses on augmenting the user channels sent over minimum bandwidth without employing costly inline equipments. The bit streams in excess of 40Gbps per channel are managed by using Optical Time Division in combination with Dense Wavelength Division Multiplexed Systems. The use of the proposed hybrid combinations of the conventional amplifiers in the designed high speed DWDM systems gives a cost effective capacity enhanced, long haul fiber optic systems. The systems functionality and flexibility at narrow channel spacing is achieved.

The conclusions of the work done according to the assigned objectives are summarized as under:

1) Various DWDM systems at narrow and ultra-narrow channel-spacing are investigated with a simple design (without any inline amplification module) to draw boundary conditions for the minimal allowable channel spacing for 5Gbps, 10Gbps, 15Gbps and 20Gbps DWDM systems. The 16, 32 and 64 channels are considered. The overall performance is adjudged by plotting BER and related eye diagrams. It is reported that the minimum channel spacing for 15Gbps, 64 channel systems should not be less than 0.35nm for a single span of 30km giving BER of $9.2e^{-9}$. The minimum spacing for 10Gbps, 64 channel systems is not less than 0.25nm for a single span of 60km with acceptable BER of $10e^{-8}$. The 5Gbps, 64 channel system gives acceptable results at spacing of 0.1nm for maximum up to single span of 80km. Therefore, an enhanced capacity up-to 960Gbps, 640Gbps and 320Gbps is achieved in a planar system demonstrating the minimal allowable channel

spacing for each case. The obtained benchmarks could serve to improve the DWDM system further.

The high speed network is proposed using optical time division multiplexing on DWDM wavelengths and it is investigated on the threshold values of the pulse width, the input power/channel and the control power of the demultiplexer. The 5ps FWHM pulse width from a MLL laser with control power till 22dBm and input power till 5dBm gives BER >$10e^{-9}$. The SOA integrated MZI switch for demultiplexing ought to be the future for OTDM transmission systems. The increased reachability of 110km in high speed 4 x 4 x 10Gbps DWDM-RZ-DPSK systems is reported with Q factor of 18.72dB.

2) The different combinations of conventional optical amplifiers resulting in hybrid optical amplifiers (HOA) are proposed. These are implemented as pre amplifiers to give a cost effective long haul DWDM systems. The investigation of 160 channel DWDM systems is carried out with Raman-EDFA-Raman, Raman-EDFA, Raman-SOA and Raman-SOA-Raman HOA along with the conventional standalone EDFA, RAMAN and SOA amplifiers in the 0.2nm spaced system. EDFA amongst the Conventional Optical Amplifiers performs the best with Q factor >18dB and RAMAN-EDFA amongst the HOA out performs with excellent Q factor >21dB.

   To validate the performance of the best judged, flat gain, optimized Raman-EDFA HOA, investigations are also carried from application point of view on the highly bandwidth efficient proposed, high bit rate DWDM system at 0.2nm spacing. An 8x8x10Gbps DWDM system is designed and implemented with Raman-EDFA. The highest ever gain of >19dB and lowest ever values of Noise Figure~5dB with OSNR>21dB is notified for high capacity 640Gbps DWDM system at narrow channel spacing. The proposed system at 0.1nm spacing also reported acceptable output power levels. Further, an 8x4x10Gbps DWDM system is also investigated with different kinds of RAMAN fibers. It is reported that with correct match of the input power/channel with the RAMAN pump power, a high quality signal with Q factor as high as >20dB can be achieved.

3) The DWDM system is also significantly presented with Raman-EDFA in a 0.1nm spaced 96 channels system for long haul applications. Optimum of 30 spans is reported of SSMF with 9km of DCF making it a long haul transmission of 2070 km with excellent performance of BER < $10e^{-15}$. The rare-earth doped EDFA reported much lesser with 26 spans making it 1794km of link distance.

   The bandwidth efficient 8x4x10Gbps, 8x8x10Gbps and 16x4x10gbps reported single span distance of 345.044km, 180.02km, and 184.02km respectively with good OSNR performance (>26dB). The even and odd orthogonal launch of channels for the system considered aids in longer span reach ability (207.02km). Such investigations of these high speed DWDM systems with Hybrid Optical Amplifiers at narrow spacing for long haul applications are noted for the first time.

4) Various implemented systems are investigated in the scenario of different linear and phase modulation schemes. The 16 channel DWDM system is transmitted with DPSK and DQPSK modulation formats. It is reported that at higher input power/channel (>0dBm), these phase modulated formats gives a stable performance throughout as compared to the NRZ and RZ formats. The RAMAN-EDFA HOA reports a maximum of 21dB and 18dB for DQPSK and DPSK formats respectively.

   The C+L band 160 channels transmitted with simple and raised cosine formats are also examined with conventional EDFA and Hybrid Raman-EDFA. The Q factor of > 21dB is noted with HOA. The compliance of using Raman-EDFA with different modulation formats can revolutionize the ULTRA-DWDM domain with very good performance over long haul and large capacity applications.

   The successful investigation of DUO-Binary NRZ and RZ is carried out for 640Gbps system using the Raman-EDFA HOA. A high quality factor >18 dB with BER < $1e^{-15}$ is observed. The HOA gives a gain of 21.375dB with SNR of 20dB for all the channels transmitted. The received output power is a high > 5dBm, highest reported in the scenario of high speed 640Gbps systems. A comparison of duo binary and binary signaling revealed that dispersion limited distance was increased with duo binary format.

Hence the work summarized above establishes the large capacity, high speed DWDM systems with Hybrid Optical Amplifiers and different modulation formats at narrow channel spacing. The results and the newer designed systems would pave ways for the system design engineers to create a niche in the optical domain.

7.2 Recommendations

The possible recommendations based on the results obtained from the work presented are as follows.

1) The implemented DWDM system with EDFA and proposed Hybrid Amplifiers are a feasible cost effective architecture for DWDM systems with a support of maximum number of channels at ultra-narrow channel spacing. At such narrow spacing these can be used as the backbone for achieving high capacity systems designed in both L and C band to meet the increasing capacity of the future optical networks.
2) The proposed Raman-EDFA HOA can be a perfect choice even in high speed communication systems using optical time division multiplexing with DWDM. The high speed, band width efficient systems designed with HOA not only reduces the cost of the system, but also supports high bit stream per wavelength with minimum system impairments.
3) The reported results also indicate that in cost effective DWDM system with designed Raman-EDFA HOA, the maximum appreciable transmission distance is 2070 km that is made possible for 96 channel DWDM system at 12.5GHz of channel spacing. Therefore, these systems are strongly recommended for high capacity long haul DWDM as compared to multi pump amplifiers or the costly electronic regenerators.
4) The system is feasible with any type of modulation formats and performs well. The performance can be enhanced by employing Duo binary and other phase modulation schemes.
5) The system performance in terms of cost effectiveness, obtained system gain, Quality factor, output power received, number of channels transmitted and the

inter-channel spacing outperforms the current existing scenario of the optical systems and therefore are recommended in practical optical networks.

7.3 Future Scope

No research is unending. Therefore, the future scope of the work done is enlisted below.

1) Near future aims at still larger capacity, bandwidth efficient and long haul systems with per channel base rate of 40Gbps or more. Commercially, the high speed systems with per channel bit rate > 80Gbps is yet to be made viable.
2) The combination of various hybrid amplifiers with rare earth dopants like Er+ and Yb+ in the bandwidth efficient narrow DWDM is still to be explored.
3) The research work can be extended by using residual pumping (single pump for both the Raman and EDFA amplifiers) which can further reduce the cost of the system.
4) A combined DWDM system with OTDM with varied combinations of various bit rates and modulation formats in split band (C+L+S Band) with HOA all in one system is yet to be explored. (COMBINED SUPER SYSTEMS).
5) Further the number of channels beyond 16 x 4 x 10Gbps can be extended for an increased potential and a system with unequal channel spacing could be considered.

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