INVESTIGATION ON 160 Gb/s DENSE WAVELENGTH DIVISION MULTIPLEXED SYSTEMS

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Master of Engineering (Electronics and Communication)

Submitted by

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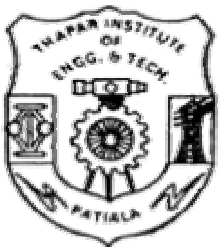

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ABSTRACT

The tremendous growth of Internet traffic has created increasing demand on high capacity optical communications networks. The optical transmission networks offer improved possibilities for dealing with ever growing demands on transmission bandwidth and system capacity. In the last 20 years, the optical transmission networks have become one of the most important part in the telecommunication hierarchy, whose seamless integration with conventional network applications and services forces a further development and a broader deployment of optical networks in all telecommunication areas.

Making a classification of different optical transmission networks, it can be distinguished between Access, Metro and Core (or back-bone) networks. This is the most convenient network classification made to the transmission distance or network diameter. Access networks as the base of the telecommunication hierarchy, are characterized by the interaction between numerous different network technologies based on different transmission media e.g. wire, wireless or fiber. These networks possess a small total capacity and inter-operational functionality between different transmission protocols (e.g. TCP/IP, ATM) and services (e.g. ISDN, DSL). The conventional wire based data transmission dominates the access area, making these networks to become a bottleneck of data transmission in the future. The implementation and deployment of optical networks in this region e.g. fiber-to-the-home (FTTH) and fiber-to-the-business (FTTB) would address the bottleneck problems, hence enabling an even broader bandwidth access than with conventional wire based technologies (e.g. DSL). But this is rather a question of deployment strategy and cost than of the achievable transmission performance. Metro area networks (MANs) accumulate the traffic from the access networks with different protocols and services, enabling its further transmission over longer distances. The MANs are based on optical transmission technologies and they are characterized by a limited transmission distance (< 200 km) and an increased network complexity. Furthermore, MANs have to deal with different communication protocols, thus requiring close interaction between the network management and transmission infrastructure, which results in the fact that the channel data rates used here are rather small (<10

Gb/s/ch, at the moment). The core networks connect numerous MANs over distances larger than 200 km. Basically, it can be distinguished between terrestrial and under-sea core networks. The under-sea networks are characterized by point-to-point transmission, ultra long-haul transmission distances (>1000 km), and specialized component characteristics (e.g. component life times and customized fiber types). The core networks possess an increased transmission capacity based on larger channel data rates. The upgrade of core networks represents the first step for a faster worldwide communication. The deployment of future optical networks and upgrade of existing ones will be governed by the growth of the traffic in all network areas. The question arising here, is what is the best transmission technology to be implemented in future systems. Dense wavelength division multiplexing (DWDM) networks has emerged as a very attractive option.

The focus of this work was set on 160 Gb/s based optical transmission systems with a varying number of channels in order to investigate the potential of 160 Gb/s technologies for the implementation in the next generation optical transmission networks. The results of this work can be used as design guidelines enabling a better understanding of propagation limitations in high bit rate transmission systems and give useful insights needed for the capacity upgrade of existing transmission lines. In this, we studied different components of DWDM transmission system and its configuration.

Then at 160 Gb/s channel data rate, single-channel and 16-channel DWDM system is designed and variation in the results are studied when fiber length and optical fiber attenuation is varied. NRZ- format is used for DWDM transmission system. Different results such as optical spectrum, electrical spectrum, electrical signal, eye-diagram, Q-Value, eye opening, eye-closure, OSNR etc. are observed to evaluate the performance of the system. Due to increase in optical attenuation and fiber length Q-value, eye opening and jitter decreases but bit error rate increases at received power. Thus, fiber attenuation describes the fact that optical power decreases exponentially when propagated in optical fibers.

DWDM system is limited by different impairments-linear and nonlinear impairments. Linear impairments include optical attenuation, chromatic dispersion and polarization mode dispersion. Nonlinear impairments include Kerr nonlinearities and scattering. Self-phase modulation, cross-phase modulation and four wave mixing is dominant in long-haul DWDM system and their random effect on 160 Gb/s DWDM is studied and different results are obtained to evaluate the impact of nonlinearities on the DWDM system. AOPMD component is used to stimulate PMD by taking into account of its frequency dependence. It reduces the statistical PMD behavior of fiber without any loss, dispersion or non-linearity. In order to vary the random effect of PMD on system performance, seed

parameter of AOPMD is varied. Q-Value and eye opening decreases with increase in seed parameter of AOPMD but OSNR increases.

The effect of Kerr nonlinearities on 160 Gb/s DWDM system and their impact on the performance of long-haul DWDM system is demonstrated in thesis. The Kerr effects occur because of the variation of refractive index of the fiber core with optical power. The Kerr effects degrade the DWDM long-haul system performance more significantly than scattering effects. Hence impairments due to scattering effects are ignored in DWDM systems. Simulation results show that the magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate. FWM efficiency is also a function of signal polarization.

Thus 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate. This tendency can be explained by a reduced complexity in realization and availability of required 160 Gb/s system components e.g. narrow-band filters on the one hand, and compatibility of 160 Gb/s data rates with existing transmission infrastructure on the other hand. The increased system capacity in 160 Gb/s DWDM system is enabled by implementation of some new sophisticated technologies, e.g. novel modulation formats, new fiber and amplifier types, which are becoming mature, because of the possibility to realize them using only electronics or some hybrid (electro-optics) solutions, which seems to be impossible at channel data rates e.g. 40 Gb/s.

The future of DWDM system is Ultra-dense wavelength division multiplexing system (UDWDM). Ultra-Dense Wavelength Division Multiplexing (UDWDM) is the science and technology of packing optical communication channels as closely as physically possible on a single optical fiber or any other optical medium. The development of 10 Gb/s UDWDM technology would enable continued advancement in fiber-optic transmission capacity without requiring dramatic upgrades in infrastructure.

CERTIFICATE

I hereby certify that the work being presented in the thesis entitled "Investigation on 160Gb/s Dense Wavelength Division Multiplexed Systems" in partial fulfillment of the requirement for the ward of degree of Master of engineering in Electronics And Communication engineering, is an authentic record of my own work carried out as requirements for the award of degree M.E. Electronics and Communication at Thapar Institute of Engineering & Technology (Deemed University), Patiala, under the guidance of Dr. R. S. Kaler Head ECED during January to June, 2006.

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This is to certify that the above statement made by the student is correct and true to the best of my knowledge and belief.

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The real spirit of achieving a goal is through the way of excellence and austerous discipline. I would have never succeeded in completing my task without the cooperation encouragement and help provided to me by various personalities.

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Above all, I render my gratitude to the **ALMIGHTY** who bestowed self-confidence, ability and strength in me to complete this work.

PLACE: T.I.E.T Patiala

(MANJINDER KAUR)

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LIST OF ABBREVIATIONS

AM	**Amplitude Modulated**
ATM	Asynchronous transfer mode
APD	Avalanche photodiode
AWG	Arrayed Wave Grating
BER	Bit Error Rate
CD	Chromatic Dispersion
CSO	Composite Second Order
CW	Continous Wave
CWDM	**Coarse Wavelength Division Multiplexer**
DFB	Distributed Feedback Laser
DGD	Differential Group Delay
DSL	Digital Scriber Line
DMUX	Demultiplexer
DWDM	Dense Wavelength Division Multiplexer
EAM	Elektroabsorption modulator
EDFA	Erbium Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FEC	Forward Error Correction
FTTB	Fiber-to-the- home
FTTH	Fiber-to-the-business
FP	Fabry Perot
FWHM	Full Width Half Maximum
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion
IP	Internet Protocol
ISI	Intersymbol Interference
LEDs	Light Emitting Diode
MANs	Metro Area Network
MEMs	**Micro-electrical mechanical systems**
MZI	Mach-Zehnder Interferometers
MZM	Mach-Zehnder Modulator

MUX	Multiplexer
NRZ	Non-return-to-Zero
NLSE	Non-linear Schrodinger Equation
OADM	Optical add /drop multiplexer
OSNR	Optical signal to noise ratio
OWAD	Optical Wavelength add drop
PCS	Personal cellular system
PIN	Positive-intrinsic-negative
PMD	Polarization mode dispersion
Q-Value	Quality factor
SBS	Stimulated Brilloin Scattering
SDH	Synchronous Digital Hierarchy
SOA	Semiconductor Optical amplifier
SONET	Synchronous Optical Network
SOP	State Of Polarization
SPM	Self-Phase Modulation
SSMF	**Standard Single Mode Fiber**
SRS	Stimulated Raman Scattering
TDSS	Time-Domain Split Step
TFF	Thin Film Resonant Cavity Filters
UDWDM	Ultra Dense Wavelength Division Multiplexer
UV	Ultra Violet
VBS	Variable Bandwidth Simulation
WDM	Wavelength Division Multiplexer
XPM	Cross Phase Modulation

1.1 INTRODUCTION

In the last few years, there has been enormous increase in telecommunications services that demand large amounts of bandwidth services such as interactive multimedia, video conferencing and streaming audio have made the capacity of the exiting optical fiber systems insufficient. Technologies such as Frame Relay and ATM are also adding to the need for capacity. Internet usage which will grow by 700 percent annually in coming years is threatening to telephone access networks [1]. Another significant cause of bandwidth demand is the carriers need to guarantee fall-safe network. As telecommunication has become more critical to businesses and individuals, service providers have been required to ensure that their networks are fault tolerant. During the past several years, a trend has developed through out the world to encourage competition in the telecommunication sector through government deregulation and market-driven economic stimulation. Moreover, while early competition among long distance carriers was based mainly on a strategy of price reduction, today's competitive advantage depends increasingly on maximizing the available capacity of network infrastructures and providing enhanced reliability. As the telecommunication has become more critical to businesses and individuals, service providers have been required to ensure that their networks are fault tolerant and impervious to outages. In many cases, telephone companies must include service level guarantees in business contracts, wit severe financial penalties should outages occur [1,2]. To meet these requirements, carriers have broadened route diversity, either through ring configurations or 1:1 point-to-point networks in which back-up capacity is provided on alternate fibers. Achieving 100% reliability however requires that spare capacity be set aside and dedicated only to a backup function. This potentially doubles the bandwidth need of an already strained and overloaded system. The growth of cellular and PCS is also placing more demand on fiber networks, which serve as the backbone even for wireless communications. At the same time carriers are enhancing network survivability, they must also accommodate growing customer demand for services such as video, high resolution graphics and large volume data processing that require large amounts of bandwidth [2]. Thus the deployment of future optical networks and upgrade of existing ones will be governed by the growth of

the traffic in all network areas. Taking a look on the traffic growth trends up to year 2006 illustrated in Figure 1.1, it can be observed that data based services and applications, e.g. internet or broad-band access represent the driving forces for the future capacity enlargement [2].

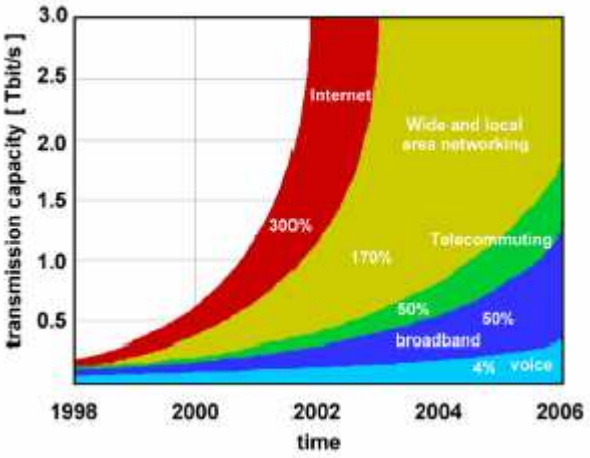


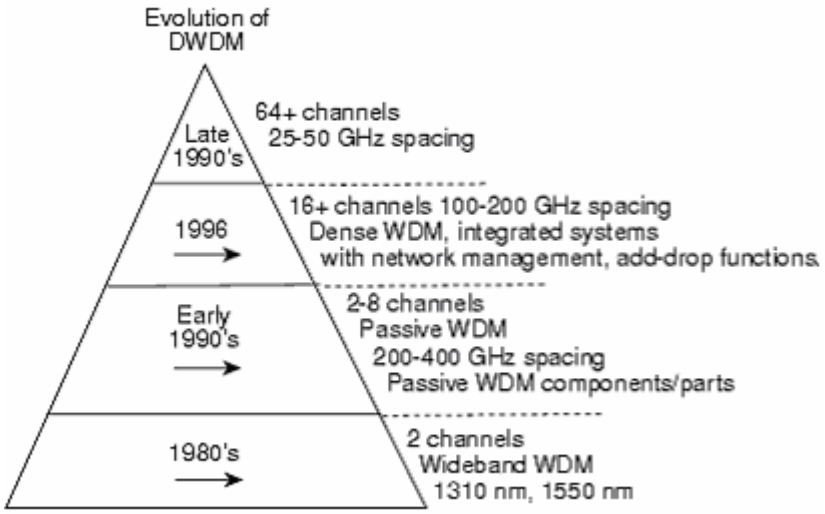
Figure 1.1 (Traffic growth trends)

1.2 EVOLUTION OF DWDM SYSTEM

Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm regions, sometimes called wideband WDM. The early 1990s saw a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels were now spaced at an interval of about 400 GHz in the 1550-nm window. Figure1.2 shows the evolution of DWDM. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz [2]. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add-drop functions, and management capabilities. Thus dense wavelength-division multiplexing (DWDM) revolutionized data transmission technology by increasing the capacity signal of embedded fiber [2,3]. This increase means that the incoming optical signals are assigned to specific (wavelengths) within a designated frequency band, then multiplexed onto one fiber. This process allows for multiple video, audio, and data channels to be transmitted over one fiber while

maintaining system performance and enhancing transport systems. This technology responds to the growing need for efficient and capable data transmission by working with different formats, such as, SONET/SDH while increasing bandwidth.

Figure 1.2 (Evolution of DWDM)



1.3 FEATURES OF DWDM

A powerful concept of an optical communication link is that many different wavelengths can be sent along a single fiber simultaneously in the 1300-to-1600-nm spectral band. The technology of combining a number of wavelengths on to the same fiber is known as dense wavelength division multiplexing or DWDM. The key features of DWDM are as follows: -

- **Capacity upgrade:** The classical application of DWDM has been to upgrade the capacity of exiting point-to-point fiber optic transmission links. If each wavelength supports an independent network signal of a few gigabits per second, then DWDM can increase the capacity of a fiber network dramatically [1-3].
- **Transparency:** An important aspect of DWDM is that each optical channel can carry any transmission format. Thus using different wavelengths, fast or slow asynchronous and synchronous digital data and analog information can be sent simultaneously and independently over the same fiber without the need for a common signal structure.
- **Wavelength routing:** In addition to using multiple wavelength to increase link capacity and flexibility, the use of wavelength-sensitive optical routing devices makes it possible to use wavelength as another dimension, in addition to time and space, in

designing communication networks and switches. Wavelength routed networks use the actual wavelength of a signal as the intermediate or final address.

- **Wavelength switching:** Wavelength-routed networks are based on a rigid fiber infrastructure, wavelength-switched architectures allow reconfiguration of the optical layer. Key components for implementing these networks include optical add/drop multiplexers, optical cross connects and wavelength converters.

1.4 COARSE WAVELENGTH DIVISION MULTIPLEXING

WDM system has been segmented into two parts, “dense” and “coarse” WDM. Dense WDM (DWDM) is generally held to be WDM with more than 8 active wavelengths per fiber, with systems with fewer active wavelengths being classed as coarse WDM (CWDM). DWDM systems are significantly more expensive than CWDM because the laser transmitters need to be significantly more stable than those needed for CWDM. CWDM is a lower-cost alternative to DWDM for short-haul (less than 31 miles) optical transport from the enterprise edge to the service provider metropolitan core [2,3]. Therefore, it is best suited for applications that have lower data- capacity requirements and for fiber spans that are 31 miles or less. As a result, lower-cost CWDM systems provide more economic benefits while providing the same security, reliability and equality as a DWDM system.

1.5 DWDM SYSTEM CONFIGURATION

Dense Wavelength Division Multiplexing (DWDM) is a fiber-optic transmission technique. DWDM is a technology that allows multiple information streams to be transmitted simultaneously over a single fiber. It involves the process of multiplexing many different wavelength signals onto a single fiber. Optical networks use Dense Wavelength Multiplexing as the underlying carrier. The most important components for a DWDM system are transmitters, receivers, fiber amplifiers, DWDM multiplexer, and DWDM demultiplexer [3]. These components allow a DWDM system to interface with other equipment and to implement optical solutions throughout the network. Figure 1.3 gives the structure of a typical DWDM system.

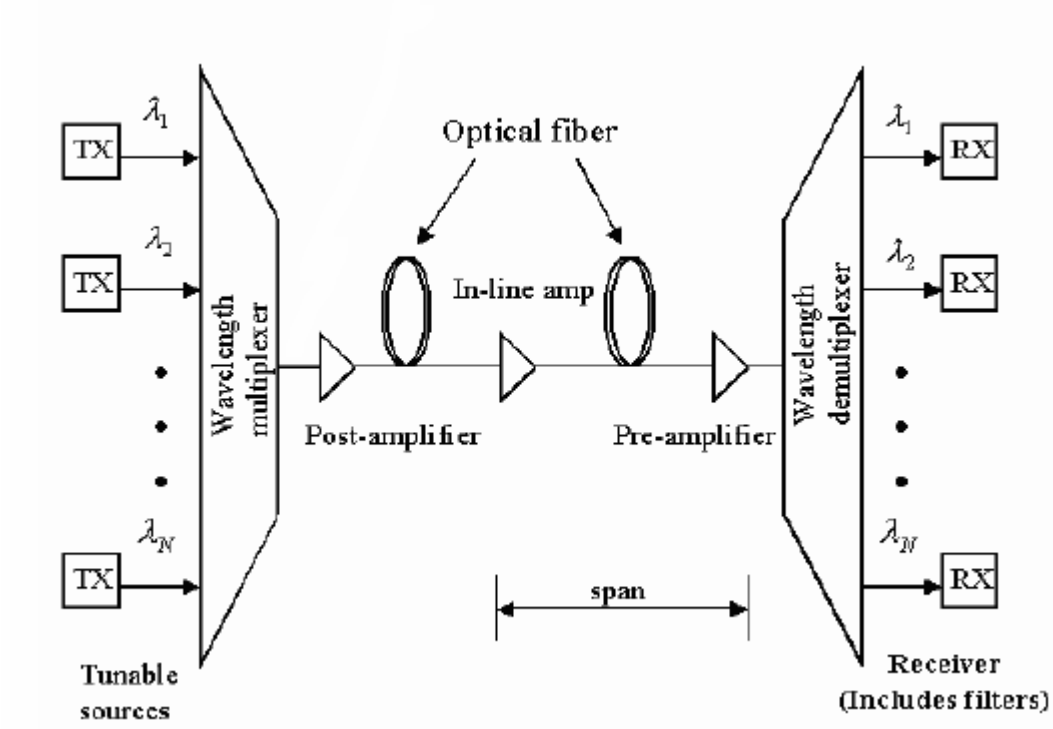


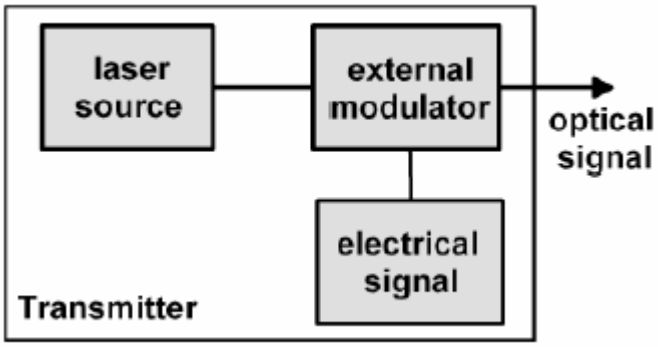
Figure 1.3 (Block diagram of DWDM)

1.5.1 OPTICAL TRANSMITTER

The transmitter generates a specific wavelength channel and these wavelengths are combined for transmission over the same fiber by a multiplexer. On transmitter side, lasers with precise and stable wavelengths are used. Light sources, or light emitters, are transmit-side devices that convert electrical signals to light pulses. The process of this conversion, or modulation, can be accomplished by externally modulating a continuous wave of light or by using a device that can generate modulated light directly. The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Its characteristics are often a strong limiting factor in the final performance of the optical link. Light emitting devices used in optical transmission must be compact, monochromatic, stable, and long lasting [3,4]. Two general types of light emitting devices are used in optical transmission, light-emitting diodes (LEDs) and laser diodes or semiconductor lasers. LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps, they exhibit a relatively wide spectrum width, and they transmit light in a relatively wide area. These inexpensive devices are often used in multimode fiber communications. Semiconductor lasers, on the other hand, have performance characteristics better suited to single-mode fiber applications. Two types of semiconductor lasers are widely used, monolithic Fabry-Perot lasers, and distributed

feedback (DFB) lasers. The latter type is particularly well suited for DWDM applications, as it emits a nearly monochromatic light, is capable of high speeds, has a favorable signal-to-noise ratio, and has superior linearity. The DFB laser represents the most important and most widely used single mode laser type in the 1550 nm region. . This wavelength range is compatible with EDFAs. DFB lasers are realized by the implementation of a Bragg grating structure inside the cavity between the reflecting surfaces of a Fabry-Perot (FP) laser [4]. Figure 1.4 shows transmitter setup with external modulation.

Figure 1.4 (Transmitter set up with external modulation)



External modulation can be realized with $LiNbO_3$-based Mach-Zehnder modulator (MZM) and InP-based elektroabsorption modulator (EAM).

1.5.2 OPTICAL FILTERS

Optical filters used are multiplexers (MUXs) and demultiplexers (DMUXs) in a WDM system and represent the key components for enabling dense WDM transmission systems. The function of wavelength multiplexer (MUX) is to combine the light output from different laser transmitters at different wavelengths. On other hand, the wavelength demultiplexer (DMUX) splits the wavelength division multiplexed signal into different wavelengths. These devices form critical elements of a WDM transmission system [4]. The basic technologies used for the fabrication of MUXs and DMUXs in DWDM systems are arrayed wave gratings (AWG), fiber Bragg gratings (FBG), dielectric thin film resonant cavity filters (TFF) and Mach-Zehnder interferometers (MZI).

1.5.2.1 THIN FILM FILTER (TFF)

Thin film resonant cavity filters (TFF) are today's major deployed commercial filter type in optical transmission systems characterized by low device costs and high reliability. TFF represent a special case of Fabry-Perot or etalon filters with multiple cavities, where the mirrors around the cavity are realized by using reflective dielectric thin film layers as shown in figure 1.5.

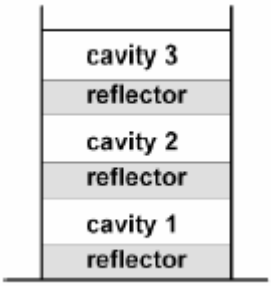


Figure 1.5(a) (TFF multilayer structure)

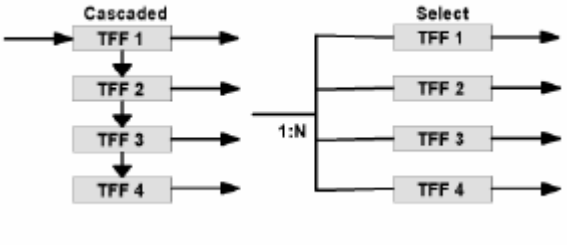


Figure 1.5(b) (TFF based DMUX)

Similar to external cavity lasers, the wavelengths passing through the reflective mirrors in TFF are determined by the length of the cavity. All the wavelengths transmitted through the thin film layers are superimposed. Multiple cavities are necessary in order to create a filter shape with flat top pass-band and sharp edges. For N channel functionality of MUX and DMUX, N TFF filter devices have to be combined. It can be distinguished between cascade and select architectures. In a DMUX realized as a cascade of TFF as shown in figure 1.5(b), a certain wavelength is passed through each TFF, while all other wavelengths are reflected into the following cascade [2-4]. The drawback of this concept is the varying filter loss at different wavelengths. In select-structure architecture (Fig. 1.5(b) right), all incoming wavelengths are broadcasted by a 1:N splitter to N filters. The filter loss is identical for different wavelengths, but larger than in cascaded structure and increases with the number of channels. The TFF-based MUXs and DMUXs are characterized by a small temperature drift coefficient (no active temperature control needed) and a flat-top filter response favorable for the use in DWDM systems. According to a large filtering loss for large number of channels, this technology is suitable for 50 GHz MUX and DMUX realizations with a low number of channels (N < 16).

1.5.2.2 MACH-ZENDER INTERFEROMETER (MZI)

Mach-Zehnder interferometer based filters (MZI) are interferometric devices in which the filtering is realized by the length variations in the MZI arms. A MZI-based filter consists of two 2x2 3-dB couplers at the input and output and MZI arms between them. The path difference between the MZI arms equals ΔL as shown in figure 1.6. The input signal is divided equally into both arms by the first 3-dB coupler. The signal in the upper arm is shifted by $\pi/2$ by the coupler compared to the signal in the lower arm. Additionally, a signal phase delay ΔL occurs in upper arm. After the second 3-dB coupler, signal from the upper arm experiences $\pi/2$ phase shift by the second coupler [4,5]. The drawbacks of the MZI concept are the insufficient channel separation, making additional filtering necessary, and the need for active temperature stabilization, reducing the reliability and increasing component cost.

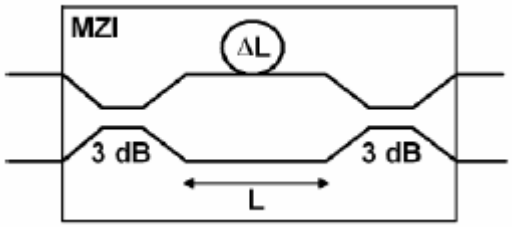


Figure 1.6 (MZI structure)

1.5.2.3 ARRAY WAVEGUIDE GRATING (AWG)

Figure 1.7 depicts the structure of an array waveguide grating (AWG) multiplexer or demultiplexer. The waveguides including the input and output couplers are all fabricated on a single silicon substrate. The number of inputs and outputs of the AWG is denoted by N. The size of the couplers and M X N respectively, where M is the number of nnected by the input and output couplers. Conside lexed signal λ_1, λ_2, λ_3.....λ_n at the inp input coupler splits the multiplexed signal into M p avels through the arrayed waveguides that includes a... length difference of each arrayed waveguide introduces wavelength dependent phase delays. The phase delay at each wavelength interferes in such a manner that each wavelength contributes to the maximum intensity, thus providing a converging wave through the DWDM output coupler. Finally, each wavelength is directed to an individual fiber.

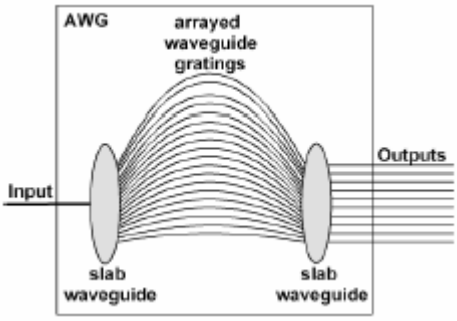


Figure 1.7(AWG structure (DMUX)

The drawback of this technology is related to phase errors arising from manufacturing imperfections and temperature variations.

1.5.2.4 FIBER BRAGG GRATING (FBG)

Fiber Bragg grating (FBG) structures are characterized by a periodic perturbation of the refractive index over structure length as shown in figure 1.8. The grating patterns exploit photosensitivity of germanium doped silica fibers. Exposing a fiber to ultra violet (UV) light causes refractive index changes in the fiber core. The change of the refractive index needed to obtain gratings is quite small ($\approx 10^{-4}$). The distance between two adjacent gratings is called grating period Δ, determining which wavelength will be reflected by the grating according to:

$$\lambda Bragg = 2neff\Delta$$

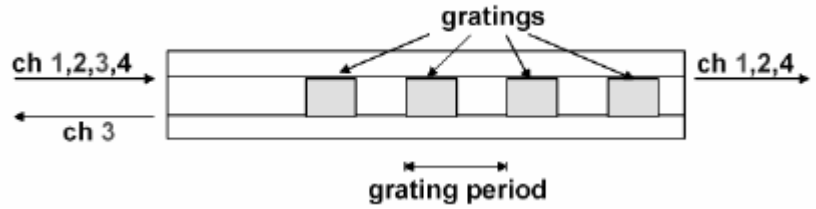
where n_{eff} represents the effective refractive index. The reflected wavelength is called Bragg wavelength. Due to the fact that the reflection of the grating is not ideal, a small amount of power leaks through the grating, resulting in optical losses. Depending on the grating period, it can be distinguished between short-and long-period gratings. FBGs in MUX and DMUX devices are short-period gratings. Long-period gratings are used in erbium doped amplifiers (EDFAs) for tailoring the amplifier spectrum. FBG-based MUX (Add-Drop filters) and DMUX devices possess a flat-top passband shape. Further advantages of FBGs are lower losses compared to other filter devices, a high wavelength accuracy and high adjacent channel separation [5]. Temperature stabilization in FBGs is passive, because FBGs can be integrated in combination with a material with a negative temperature expansion coefficient. The drawbacks of FBGs are a large chromatic dispersion and dispersion ripples due to grating inaccuracies as well as the need for additional components (e.g. circulators, couplers) for the separation of channels, resulting in large costs due to a hybrid design. Chromatic dispersion of a FBG-based filter is proportional to the difference of delay times at different wavelengths. In most filters type, the variations of the time delay are larger at the edges of the filter passband and they are less critical as long as the channel spectral width is much smaller than the passband width of the filter, but in FBG-based filters large delay time variations occur in the passband, resulting in an increased chromatic dispersion and dispersion ripple [2]. FBGs can be used for implementation in MUX and DMUX devices at 50 GHz channel spacing with a

smaller number of channels (N < 8), because of the increased complexity regarding fabrication and packaging.

Figure 1.8 (FBG structure)

1.5.3 OPTICAL AMPLIFIER

Optical amplifiers represent one of the crucial components in an optical transmission system. Despite of the minimum attenuation at 1.55 μm (theoretically, 0.16 dB/km), fiber losses significantly limit the transmission performance with increased transmission distance (>20 km). Optical amplification can be realized using different amplifier concepts and mechanisms e.g. semiconductor optical amplifiers (SOA), rare-earth doped fiber amplifiers (e.g. erbium, holmium, thelium, samarium) or more recently Raman amplifiers. All these amplifier types are based upon different physical mechanisms resulting in different device characteristics and implementation areas [3-5]. The rare-earth doped fiber amplifiers provide optical amplification in the wavelength region from 0.5-3.5 μm. The most important representative of these amplifier type are erbium doped



fiber amplifiers (EDFAs), which is today's widely used amplifier type in optical transmission systems due to the fact that it provides an efficient optical amplification in the 1.55 μm region. EDFAs are silica based optical fibers that are doped with erbium. This rare earth element has the appropriate energy levels in its atomic structure for amplifying light at 1550 nm. A 980 nm "pump" laser is used to inject energy into the doped fiber. When a weak signal at 1310 nm or 1550 nm enters the fiber, the light stimulates the rare earth atoms to release their stored energy as additional 1310 nm or 1550 nm light. This process continues as the signal passes down the fiber, continually growing stronger. Figure 1.9 illustrates Erbium-doped fiber amplifiers:

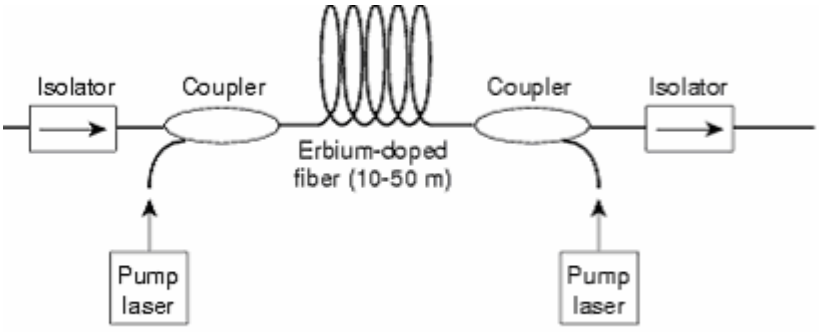


Figure 1.9 (Erbium doped fiber amplifier)

The photons amplify the incoming signal optically, boosting the wavelength, and avoiding almost all of the active components. The output power of the EDFA is large, and thus, fewer amplifiers may be needed in any given system design. The amplification process is independent of the data rate. The key performance parameters of optical

amplifiers are gain, gain flatness, noise level, and output power. EDFAs are typically capable of gains of 30 dB or more and output power of +17 dB or more. The target parameters when selecting an EDFA, however, are low noise and flat gain. Gain should be flat because all signals must be amplified uniformly [5]. While the signal gain provided with EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters. Such filters are often built into modern EDFAs. Low noise is a requirement because noise, along with signal, is amplified. Because this effect is cumulative, and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated and, therefore, the length of a single fiber link. In practice, signals can travel for up to 120 km between amplifiers. At longer distances of 600 to 1000 km (372 to 620 mi) the signal must be regenerated. That is because the optical amplifier merely amplifies the signals and does not perform the 3R functions (reshape, retime, and retransmit). EDFAs are available for the C-band and the L-band.

1.5.4 OPTICAL ADD /DROP MULTIPLEXER (OADM)

Between multiplexing and demultiplexing points in a DWDM system, as shown in figure 1.10, there is an area in which multiple wavelengths exist. It is often desirable to be able to remove or insert one or more wavelengths at some point along this span. An optical add/drop multiplexer (OADM) performs this function. Rather than combining or separating all wavelengths, the OADM can remove some while passing others on. OADMs are a key part of moving toward the goal of all-optical networks [4,5].

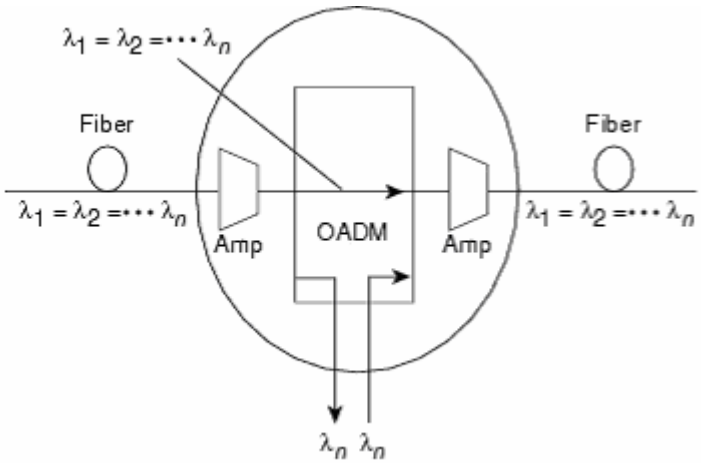


FIGURE 1.10 (Optical add/drop multiplexer)

There are two general types of OADMs. The first generation is a fixed device that is physically configured to drop specific predetermined wavelengths while adding others. In the simplest OADM, wavelengths to be added and dropped are pre-selected, these devices are referred to as being i.e. fixed as shown in figure 1.11(a). Fixed OADMs are

simple, protocol independent, bit rate transparent and low cost devices. No network management is required to set up a wavelength to be dropped or added. Because the wavelengths within each device are predetermined, significant pre-deployment network planning is required to specify what wavelengths are to be dropped where. Once designed, the system is permanently static unless the network operator is willing to perform an out-of-service upgrade. In addition, fixed OADMs have loss factors of 4 - 6 dB (each dB of loss translates to a cost for additional amplification equipment). The fixed OADM can introduce an inventory problem of extraordinary magnitude if one demands complete flexibility in delivering wavelengths [6]. This problem is governed by the number of permutations of wavelengths and the number of drops at each site a calculation of factorial magnitude. Clearly this is not a feasible solution for network providers or equipment manufacturers. Instead, manufacturers have limited the number and the locations of the wavelengths that can be dropped in the network. For all of the above reasons, fixed OADMs are becoming obsolete.

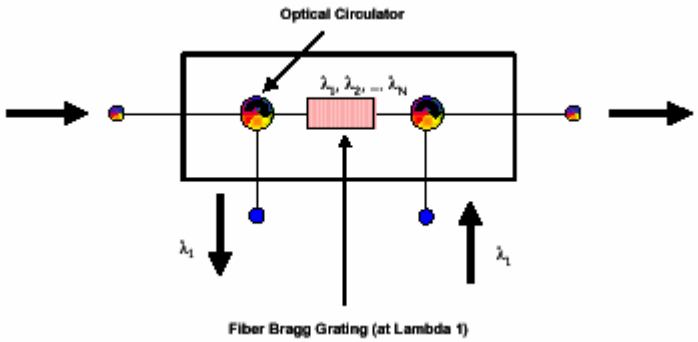


Figure 1.11(a) (fixed OADM)

The second generation is reconfigurable and capable of dynamically selecting which wavelengths are added and dropped. The emerging generation of OADMs, meaning those currently under development and in field trials, is configurable in that any given wavelength can be dropped and inserted at any given site. The switches can be micro-electrical mechanical systems (MEMs), bubble jet, thermal optical or liquid crystal-based. The system can be designed so that it is scalable and upgradeable to higher OADM channel counts. And, when fully configured to add and drop all the wavelengths

on a given fiber, a configurable OADM becomes a DWDM device [5-7]. Configurable OADMs are easy to provision, and the reconfiguration can be done in-service as shown in figure 1.11(b).

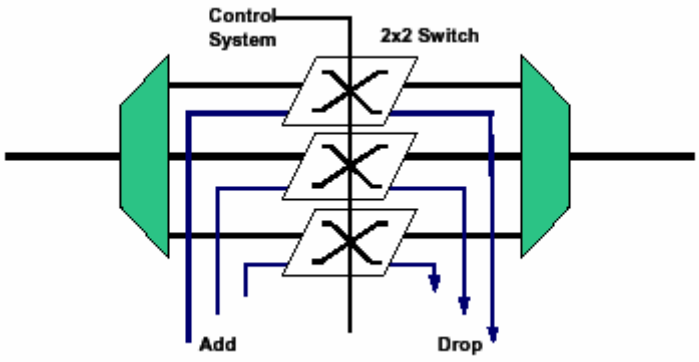


Figure 1.11(b) (Reconfigurable OADM)

1.5.5 OPTICAL RECEIVER

On the receive end, it is necessary to recover the signals transmitted at different wavelengths on the fiber. Because photodetectors are by nature wideband devices, the optical signals are demultiplexed before reaching the detector. Two types of photodetectors are widely deployed, the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). PIN photodiodes work on principles similar to, but in the reverse of, LEDs. That is, light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship. APDs are similar devices to PIN photodiodes, but provide gain through an amplification process. One photon acting on the device releases many electrons. PIN photodiodes have many advantages, including low cost and reliability, but APDs have higher received sensitivity and accuracy [7,8]. However, APDs are more expensive than PIN photodiodes, they can have very high current requirements, and they are temperature sensitive.

1.6 DWDM IMPAIRMENTS

The performance of a lightwave system is an important consideration in the design of a DWDM long-haul link. DWDM system is becoming more and more complex due to the higher demand for system capacity. Therefore, different system impairments such as

noise, chromatic dispersion, fiber nonlinearities and polarization effects must be taken into account [8]. Hence, a system model should be devised to analyze and study the impact of these impairments. The propagation of optical fields in dielectric fibers can be described by Maxwell's equations:

$$\Delta \text{ X } \text{E} = - \partial B / \partial t$$
$$\Delta XH = J + \partial D / \partial t$$
$$\Delta . D = \rho_{\text{f}}$$
$$\Delta . B = 0$$

where E and H are the electric and magnetic field vectors and D and B are the electric and magnetic flux densities. J represents the current density vector and ρ_{f} is the charge density. The flux densities D and B are caused by the propagation of E and H inside the medium.

$$\nabla^2 \text{E} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = -\mu_0 \frac{\partial^2 P(E)}{\partial t^2}$$

P is the polarization of the medium, which is dependent on the electrical field and in a weak nonlinear medium it can be expressed by a Taylor polynomial:

$$P \approx \varepsilon_0 \left\{ \underbrace{\chi^{(1)} E}_{P_L} + \underbrace{\chi^{(2)} : EE + \chi^{(3)} : EEE}_{P_{NL}} \right\}$$

where the parameter $\chi^{(1)}$ is the susceptibility of the medium. The term $\chi^{(1)}$ is the linear susceptibility describing the linear part (PL) of polarization. The nonlinear part (PNL) is determined by the second and third order tensors $\chi^{(2,3)}$, which determine the nonlinear behavior of the medium. $\chi^{(2)}$ can be neglected in optical fibers because of the inversion symmetry at the molecular level [8]. Thus, $\chi^{(3)}$ governs the nonlinearities in the fiber. The real part of $\chi^{(3)}$ is responsible for the Kerr effect and the imaginary part for the stimulated processes [9]. Considering x-polarized light propagation in z direction, the electric field of the signal is given by:

$$E = e_x F(x,y) \frac{1}{2} A(z,t) \exp(j\omega_0 t - j\beta(\omega) z) + c.c$$

where F(x, y) is the modal distribution of the fundamental fiber mode, A (z, t) is the field amplitude, ω_0 the carrier frequency and $\beta(\omega)$ is the propagating constant given by:

$$\beta(\omega) \approx \beta_0 + \beta_0(\Delta\omega) + \frac{\beta_2}{2}(\Delta\omega)^2 + \frac{\beta_3}{6}(\Delta\omega)^3$$

Thus, the scalar propagation equation can be derived by applying the slowly varying envelope and rotating wave approximations yielding partial differential equation known as the nonlinear Schrödinger equation (NLSE):

$$\frac{\partial}{\partial z}A(z,t) = \underbrace{-\frac{\alpha}{2}A(z,t)}_{attenuation} + \underbrace{j\frac{\beta_2}{2}\frac{\partial^2}{\partial T^2}A(z,t)}_{1.orderGVD} + \underbrace{\frac{\beta_3}{6}\frac{\partial^3}{\partial T^3}A(z,t)}_{2.orderGVD} - \underbrace{\frac{\gamma}{\omega_0}\frac{\partial}{\partial t}\left(|A(z,t)|^2 A(z,t)\right)}_{self-steepening}$$

$$\underbrace{-j\gamma|A(z,t)|^2 A(z,t)}_{KerrEffect} \underbrace{-j\gamma T_R\frac{\partial}{\partial T}|A(z,t)|^2 A(z,t)}_{SRS}$$

where α represents the fiber attenuation, T is measured with the frame of reference moving with the pulse at group velocity Vg (T=t-z/Vg), T_R refers to the slope of the Raman gain, and is the nonlinear coefficient of the fiber. The terms on the right side of Equation above describe the fiber propagation limitations divided in two groups: the linear - attenuation and GVDs - and nonlinear – Kerr effect, self-steepening and stimulated Raman scattering (SRS) - group. In the following chapters, these effects will be further described. The self-steepening is a higher order nonlinear effect, which originates from the intensity dependence of the group velocity. Since it occurs only for ultra-short optical pulses with widths smaller than 1 ps, this effect is not considered in investigations presented in this work [9].

1.6.1 LINEAR IMPAIRMENTS

The linear impairments comprise fiber attenuation, chromatic dispersion (GVD) and polarization mode dispersion (PMD). These linear characteristics dominate the behavior of an optical transmission system in the low power transmission region and in interaction with nonlinear effect in high power region limit the maximum transmission distance of the system.

1.6.1.1 FIBER ATTENUATION

The light propagation in optical fibers is characterized by reflections on the core-cladding boundary. These reflections are caused by difference between the refractive indices of the

core and the cladding [9,10]. The signal propagation in an optical fiber is always accompanied by loss of the input power P (0, t). The signal power after propagation through a fiber length z is given by:

$$P(z,t) = P(0,t).\exp(-\alpha z)$$

The parameter α is called fiber attenuation and represents a sum of different losses in the fiber. The fiber attenuation describes the fact that optical signal power decreases exponentially when propagated in optical fiber. The conventionally used unit for α is [dB/km]:

$$\alpha[dB/km] = -\frac{10}{z}\log_{10}\left(\frac{P(z,t)}{P(0,t)}\right) = 4.343.\alpha[km^{-1}]$$

The attenuation exhibited by the optical fiber is dependent on the wavelength of the propagating signal. The total loss is caused fundamentally by three different mechanisms: material absorption, Rayleigh scattering and waveguide imperfections. Considering material absorption, it can be differentiated between intrinsic and extrinsic absorption losses. The intrinsic losses are caused by the absorption of the incoming light by electron and molecular-vibrational resonances [10].

1.6.1.2 CHROMATIC DISPERSION (GVD)

One of the most important features of the optical transmission is the signal broadening during propagation of different spectral components in an optical fiber. This phenomenon known as chromatic dispersion refers to propagation time differences in the fiber. Chromatic dispersion represents the fact that different colors or wavelengths travel at different speeds, even within the same mode. This can be understood as a frequency dependence of the refractive mode index that causes different spectral components of the pulse to propagate at different group velocities. Accordingly, chromatic dispersion is known as group-velocity dispersion (GVD). The consequence of chromatic dispersion is the broadening of the single pulse and interference between adjacent pulses known as inter-symbol-interference (ISI).

The chromatic dispersion can be understood as the sum of material and waveguide dispersion. Material dispersion occurs due to the changes of the refractive index of optical fiber with optical frequency. This effect can be understood as the interaction between the propagating optical field and the electrons and molecules of the fiber material resulting in a frequency dependent change of the refractive index. Waveguide dispersion is the consequence of the frequency dependent mode propagation constant at the code-cladding interface [11].

1.6.1.3 POLARIZATION MODE DISPERSION (PMD)

Polarization mode dispersion (PMD) is another complex optical effect that can occur in single-mode optical fibers. Single-mode fibers support two perpendicular polarizations of the original transmitted signal. If were perfectly round and free from all stresses, both polarization modes would propagate at exactly the same speed, resulting in zero PMD. However, practical fibers are not perfect, thus, the two perpendicular polarizations may travel at different speeds and, consequently, arrive at the end of the fiber at different times. Figure 1.12 illustrates this condition.

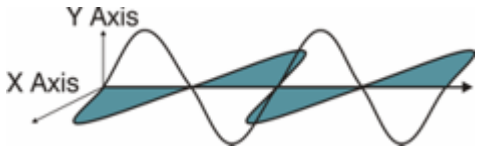


Figure 1.12 (Illustrates PMD)

The fiber is said to have a fast axis, and a slow axis. The difference in arrival times, normalized with length, is known as PMD ($ps/km^{0.5}$). Excessive levels of PMD, combined with laser chirp and chromatic dispersion, can produce time-varying composite second order (CSO) distortion in amplitude modulated (AM) video systems. Like chromatic dispersion, PMD causes digital transmitted pulses to spread out as the polarization modes arrive at their destination at different times. For digital high bit rate transmission, this can lead to bit errors at the receiver or limit receiver sensitivity. Considering the pulse propagation in the fiber. The axes are not necessarily in the vertical and horizontal planes. In fact, their random orientation depends upon the stresses in the fiber. The light polarized along one of the axes experiences a different refractive index than light polarized along the other axis. This effect is known as birefringence. As the index of refraction is a measure of how fast light moves through the material, the linear-polarized light launched into one principal axis travels through the fiber faster than the

light launched into the other axis. It also means that the relative phase of the light in the two axes changes as it propagates along the fiber [11,12]. This phase difference changes the overall state of polarization (SOP) of the light leaving the fiber. An optical pulse with the polarization aligned with one of the principal axes emerges at the fiber output in the same state of polarization without any PMD impact. For a pulse with randomly oriented polarization, one part of the pulse is transmitted along one of the principal axes, and the other part is transmitted along the other principal axis. The received pulse becomes broadened, because the two parts arrive with a delay time ½ , called differential group delay (DGD).

1.6.2 NONLINEAR PROCESSES

In addition to PMD, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects accumulate. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing [12]. Basically, the nonlinear processes can be divided into in-elastic and elastic (parametric) processes as shown in figure 4.10. The in-elastic processes are dependent on the imaginary part of $\chi^{(3)}$ and become evident above some specific power threshold level. The elastic processes known as Kerr nonlinearities are characterized by the dependence on the real part of $\chi^{(3)}$. The Kerr nonlinearities are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) which become important at increased channel bit rates. Stimulated Raman Scattering (SRS) and Stimulated Brilloin Scattering (SBS) are inelastic processes.

1.6.2.1 KERR NONLINEARITIES

The Kerr nonlinearities belong to the group of elastic parametric nonlinear processes in which the transmission fiber plays a passive role. The Kerr nonlinearities are characterized by the power dependent fiber refractive index. XPM and FWM are multichannel nonlinearities. SPM is single-channel nonlinearities. The fiber non-linearity which affects only the phase of the propagating signal is called the self-phase modulation (SPM). SPM is a single-channel effect and the interaction of SPM with fiber dispersion results in pulse broadening or eye closure at the receiver the pulse spreading caused by

SPM depends on channel power, fiber length and dispersion. The SPM effects can be minimized by keeping the non-linear phase shift O_{NL} <<1. The effect of SPM can be reduced by optimizing the channel power and by using a good dispersion map in a DWDM long-haul lightwave link [13].

Cross-phase modulation (XPM) is similar to SPM, where the intensity modulation of one carrier modulates the phases of other co-propagating carriers. XPM is multi-channel effect. The magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate. Larger the channel spacing yields less XPM. XPM arises, when the phase of one optical carrier is modulated by other DWDM channels [12-14]. The phase is converted to intensity noise due to fiber dispersion leading to nonlinear interaction between the optical carriers. The impact of XPM can be minimized by employing proper dispersion management techniques. The XPM effect is always accompanied by the SPM effect. For a separation of XPM from SPM, an efficient method is the ”pump-probe” method, in which an intensity modulated channel (pump) with a large channel power distorts a CW-probe channel is used.

Four-wave mixing (FWM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components. For example when two waves co-propagate at frequencies fp and fq through a fiber, the mixing of these two waves result in two new waves at the frequencies 2fp-fq and 2fq-fp. In general, the number of mixing products in N channel DWDM system is ½ (N^3-N^2). The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate. FWM efficiency is also a function of signal polarization. It can be seen that low dispersion fiber have a higher FWM efficiency than high dispersion fibers and efficiency decreases with increase in channel spacing.

1.6.2.2 SCATTERING PROCESSES

The second mechanism that cause fiber nonlinearities is the scattering phenomena, which product Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering. SRS is an interaction between the light and vibration of silica molecules. The incident light wave

scattered by molecules undergoes shift in the frequency, called the stokes frequency. Thus if two optical waves separated by stokes frequency are co-injected into a Raman active medium, then the lower frequency wave (called the probe wave) gets amplified at the expense of the higher frequency wave (called the pump wave). The process of this amplification is known as stimulated Raman scattering and affects the performance of multiwavelength transmission system [14]. SRS causes power transfer from the shorter wavelength channels to the longer wavelength channels, thus leading to crosstalk at the subcarrier frequencies. In DWDM system, each wavelength is modulated by a set of RF subcarrier frequencies. Hence, SRS crosstalk terms at the subcarrier frequencies are generated by the SRS interaction between the sub-carriers and optical carriers through modulated gain. Thus by decreasing the channel spacing and / or channel power will decrease the effects of SRS, but system design should adopt trade-off between the channel spacing and power.

SBS arises due to the interaction of light with the vibrational modes of the fiber. The incident light wave is scattered into a lightwave of lower frequency (or longer wavelength) by an amount $f_B = 2nV_S/l$ where n is refractive index, V_S is the velocity of sound in air and l is the signal wavelength. SBS converts the transmitted signal in the fiber to a backward scattered wave, thus limiting the maximum power that can be launched into fiber. SBS power threshold is increased by using SBS suppression techniques. First, the effect of SBS can be countered by broadening the laser optical spectrum above the Brillouin linewidth. The SBS threshold is strongly dependent on the linewidth of the optical source with narrow linewidth sources having considerably lower SBS thresholds. Extremely narrow linewidth lasers (e.g. less than 10 MHz wide), often used in conjunction with external modulators, can have SBS thresholds of +4 to +6 dBm at 1550 nm. The SBS threshold increases proportionally as the optical linewidth increases [32]. Broadening the effective spectral width of the optical source minimizes SBS.

1.7 INTRODUCTION TO OPTSIM

In this thesis, we have used the optical simulation tool known as optsim (Version3.6.0) for simulation of Dense Wavelength Division Multiplexing System. Optsim is a high-end optical system simulator for professional engineering and cutting-edge research of WDM, CATV and other emerging optical systems. Optsim is defined to combine the greatest

possible accuracy and modelling power along with extreme ease-of-use on UNIX and Windows NT operating systems. Optsim includes the latest simulation algorithms to guarantee the highest possible accuracy and real-world results. Optsim includes an extensive component model library of the most commonly used components for the engineering of electro-optical systems, with particular emphasis on WDM and digital CATV systems. It also supports innovative optical approaches such as quasi-RZ and dispersion-managed solition systems. Optsim is exclusively developed, marketed and supported worldwide by RSOFT Design Group, with Headquarters in North America, and entirely focused on productivity tools for telecom and datacom engineering and components. Optical fiber simulation is based on the time domain split-step (TDSS) method. This method takes into account all linear and non-linear effects. This method is one of the most accurate methods available in the field of optical fiber propagation simulation. However, there are instances when a full, non-linear TDSS simulation is not required, for example during the investigation of the effects of varying many of the system's free parameters. This procedure could involve impracticably long simulation times. In order to optimize both the accuracy and the computational effort, optsim supports an incremental simulation approach with two different simulation techniques:

(a) **Spectral propagation technique**: In this simulation, only the power spectrum is propagated and all the linear effects are considered. In this simulation only the optical components are simulated.

(b) **Variable bandwidth simulation technique:** in this simulation technique, the full vector signal is propagated, all linear and non-linear effects are considered. In this technique all system components are simulated.

1.8 LITERATURE SURVEY

From literature survey we observed that, DWDM is really just the first step on the road to full optical networking [1]. An all-optical network implies that the service provider will have optical access to traffic at various nodes in the network just as they have access today in the SONET layer for SONET traffic [2-3]. Optical Wavelength Add/Drop (OWAD) is that capability in which Wavelengths are added or dropped to/from a fiber

without fully separating out all of the signals individually [2], [5], [8]. But ultimate bandwidth management flexibility will come with a cross-connect capability on the optical layer [4]. Combined with OWAD and DWDM, the optical cross-connect will permit a flexible, high-capacity, efficient optical network with full optical bandwidth management. DWDM systems are bit-rate and format independent [5]. They can accept any combination of interface rates (e.g., synchronous, asynchronous, OC- 3/STM-1, OC-12/STM-4, OC-4WSTM- 16 or OC-192/STM-64) on the same fiber-at the same time. If a carrier operates both an ATM and a SONET network, the ATM signal would not have to be multiplexed up to the SONET rate to be carried on the DWDM network. Since the optical layer carries signals "as is" without any additional multiplexing, carriers can quickly introduce ATM or IP without deploying an overlay network. An important benefit of dense wavelength division multiplexing system is that any type of cargo can be carried on the "highway"[1-7].

These networks based on dense wavelength division multiplexing system and optical path technologies are expected to realize flexible, transparent and cost effective transport networks with a large transmission capacity [3], [5], [9]. It allows a single fiber to carry several wavelengths very far, while sharing the expensive equipment. However, these cutting technologies require the careful placement of amplifiers and the other network elements to ensure error free propagation of the signal and to minimize the costs [4]. In practice, it is common to use a set of constraints to ensure the valid configurations for the deployment. It is however, non-trivial to identify the optimal configuration under all constraints [8,9].

Dense wavelength division multiplexing system using erbium-doped fiber amplifier is the dominant technology in the optical fiber transmission systems [5]. The unified DWDM transmission in the optical fiber transmission model for systems incorporating cascaded optical amplifiers and a realistic demultiplexing (DMUX) characteristic with a periodic transfer function can be used to evaluate the Bit error rate (BER) accounting for influence of Non-Gaussian detected Amplified Spontaneous Noise (ASE) noise, noise correlation between the stochastic optical amplifiers [6]. This model can also be used to compare to

the Gaussian receiver model in realistic design cases to provide important information as well as the validity of the Gaussian model [6].

From literature survey, we observe that optical signal transmission over long-span standard single mode fiber links with 40 Gb/s suffers strong restriction [8], [9], [11]. This is a typical scenario with high relevance for optical submarine transmission systems, but it can also be encountered for selected links in terrestrial networks where, for example, topological constraints make placement of equipment expensive [10]. It can become a question of high topical interest to meet this challenge. Due to the strong signal attenuation in such long-span configurations, the signal quality suffers from low optical SNR (OSNR) at the receiver [10]. Because of the broad signal spectra, this problem becomes more and more challenging for the increasing channel data rates of future dense wavelength division multiplexing (DWDM) systems [11]. Currently, systems operating at channel data rates of 40 Gb/s are installed, and the first 160-Gb/s systems are being tested under field conditions. Upgrading the channel data rate is one approach to reduce costs in order to meet the decreasing revenues per bit. The paper demonstrates the 8 x 160 Gb/s DWDM system led to 1.28 Tb/s capacity [12, 13]. With the increasing demand for transmission capacity on optical fiber trunk lines, ultra-long 160Gb/s per channel all optical transmission systems are now becoming very attractive, as they offer high signal spectral efficiency and large capacity with a smaller number of channels, at potentially lower cost [14], [16]. However, design of typical terrestrial transmission systems at 160 Gb/s line rate with 100 km amplifier spacing is challenging, since the launched power into both the transmission fiber and the dispersion compensation fiber is limited due to non-linearity related impairments [14]. The low dispersion tolerance of 160-Gb/s signals is also an important issue [15]. The dispersion slope of the transmission fiber and the dispersion compensating modules must be matched to yield a net accumulated dispersion for all DWDM channels [15].

For all exponential growth laws in an optical fiber, physical limits must be considered, which have become difficult to elucidate due to nonlinear nature of light in an optical fiber [15]. Optical fiber technology makes polarization mode dispersion the ultimate limiting factor for high speed long distance optical fiber transmission [16]. The polarization effects play a critical role toward the performance of high speed lightwave systems [19,20]. These effects can be classified into polarization mode dispersion (PMD), polarization dependent loss (PDL) and polarization dependent gain (PDG) [19]. The PMD arises from the fiber birefringence due to imperfect fiber core geometry [21]. The PDL occurs when the

insertion loss of a passive component is dependent on the state of polarization of the signal [21]. The amplifier gain can also be polarization dependent (PDG). Although the effects of PDL and PDG are minimal, PMD has a severe effect on the performance of a 160 Gb/s lightwave system, leading to significant performance degradation in long-haul links [23-24]. Management of PMD in long-haul lightwave systems involves optimizing both the accumulated as well as dispersion slope mismatch within the acceptable limits. The use of dispersion managed cables (DMCs) would be an ideal strategy to minimize the PMD in under sea long-haul links [22]. Different dispersion compensation technologies have been developed during recent years for terrestrial high speed long hauls systems [23-27]. These technologies are based on dispersion compensation fibers, fiber gratings and virtual image phased arrays [24].

The Kerr effects occur because of the variation of refractive index of the fiber core with optical power. The Kerr effects degrade the DWDM long-haul system performance more significantly than scattering effects. Hence impairments due to scattering effects are ignored in DWDM systems [25,28]. A reduced model can be used to describe the SPM limited fiber transmission in dispersion managed lightwave systems [25]. By introducing a new figure of merit, the maximum transmission distance versus optical power, the first-order performance estimation of WDM systems can be established [26]. The fiber four wave mixing (FWM) effect can also be described in the zero dispersion wavelength region. Hence, the phase matching characteristics, where the first order chromatic dispersion is zero, show that the FWM light is generated efficiently at some particular combinations of the input light wavelengths [27]. The derivation of the zero-dispersion wavelength region along the fiber length can play an important role in determining FWM behavior [28,29]. Another strategy to reduce these effects in multichannel transmission systems is based on unequal channel spacing. The effects of launched power and polarization can be an important consideration in the design of these systems with launch power greater than a few mill-watts in the fiber with low chromatic dispersion [30].

1.9 GAPS IN DWDM SYSTEM

The main gaps in DWDM system are:

1. There is need for further enhancing the capacity of DWDM system to reduce costs in order to meet the decreasing revenues per bit.
2. The present system is exploited up to 40 Gb/s linearly like optical attenuation, chromatic dispersion and polarization mode dispersion.
3. The present system is exploited up to 40 Gb/s nonlinearly like self-phase modulation, cross phase modulation, four wave mixing, stimulated Raman scattering and stimulated Brillouin scattering.

Thus the impairments of DWDM system have not been exploited fully.

1.10 THESIS OBJECTIVES

The main objective of the thesis is:

1. Study of DWDM components-optical transmitters, optical filters, optical amplifiers etc.
2. To design a single channel 160Gb/s DWDM transmission system.
3. To design (16 x 160 GB/s) 2.56 Tb/s DWDM transmission system.
4. Analyze the performance of single channel and 16-channel 160Gb/s based DWDM transmission system by varying different parameters. For this we took various results like eye diagram, optical spectrum and calculate Q-Value, eye opening, bit error rate, eye closure and jitter etc.
5. Finally, we analyze the different DWDM system impairments-polarization mode dispersion and Kerr effect that includes self-phase modulation, cross-phase modulation and four wave mixing.

1.11 THESIS ORGANIZATION

This thesis is divided into five chapters. First chapter describes the dense wavelength division multiplexing system technique. Difference between DWDM and CWDM is discussed in this chapter. Features of DWDM system and its configuration are also described in this chapter. DWDM components such as optical transmitter, optical filters, optical add / drop filters and optical receivers etc. are discussed in this chapter. Different DWDM impairments are discussed in this chapter. This chapter also describes the fiber optics simulation tool known as Optsim that includes different simulation techniques for designing the system set up.

Second chapter describes the design of single-channel 160 Gb/s DWDM transmission system. With optimized system settings, the total performance of 160 Gb/s based transmission system with different fiber length and attenuation is analyzed. The performance of the single-channel dense wavelength division multiplexing (DWDM) is

evaluated using optical spectrum analyzer, electrical spectrum analyzer and electrical scope in terms of optical spectrum, electrical spectrum and eye-diagrams.

In third chapter, we further increase the number of channels from single to 16-channel using same 160 GB/s bit rate and DWDM system is designed and thus the capacity increased to (16 x 160 GB/s) 2.56 Tb/s. Such high capacity system is investigated. After designing the system, optical spectrum is determined both at the input and output. To analyze the performance of the designed system, different parameters are varied and impact of their variation is studied through different simulation results obtained.

Fourth chapter describes linear effects. Linear effects include attenuation, chromatic dispersion and polarization mode dispersion. Impact of PMD on 160 Gb/s DWDM system is studied and different simulation results are analyzed regarding eye diagram, optical spectrum, Q-value, differential group delay and OSNR etc.

Fifth chapter describes the impact of Kerr Nonlinearities on 160Gb/s DWDM system. The system set up for SPM, XPM and four wave mixing is designed separately.

Finally sixth chapter gives conclusion and future scope of work.

CHAPTER-2

160Gb/s SINGLE CHANNEL INVESTIGATION

2.1 ABSTRACT

This chapter reports the transmission of single-channel DWDM system at 160 Gb/s channel data rate.160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate. 160 Gb/s single-channel DWDM system is designed and results are studied by varying fiber length and optical fiber attenuation. NRZ- modulation format is used for DWDM transmission system. The focus of this work was set on 160 Gb/s based optical transmission to investigate the potential of 160 Gb/s technologies for the implementation in the next generation optical transmission networks. Due to increase in optical attenuation and fiber length Q-value, eye opening and jitter decreases but bit error rate increases at received power. Thus, fiber attenuation describes the fact that optical power decreases exponentially when propagated in optical fibers.

KEYWORDS: DWDM, NRZ, Attenuation, Fiber Length, Q-Value, BER and OSNR

2.2 INTRODUCTION

The realization and the field implementation of 160 Gb/s single channel transmission systems will be the first step to a deployment of 160 Gb/s based and spectrally efficient DWDM transmission systems. A 160 Gb/s single channel transmission, combination with OTDM-techniques efficiently replace today's 10Gb/s and 40 Gb/s DWDM systems. Accordingly, the optimization of component characteristics and system settings in 160 Gb/s single channel transmissions is required [23]. In order to deliver sufficient rules for a future system design, it would be necessary to consider not just characteristics of single transmission components (e.g. fibers, amplifiers, modulators), but also the interaction of different components and their interplay with different transmission limitations. In this chapter, 160Gb/s single-channel DWDM transmission system is designed. In this chapter, optimization of transmission settings and design rules for the implementation of 160 Gb/s single channel systems are presented. The system setting optimization is provided for NRZ modulation formats considering effects of different system characteristics, e.g. fiber length, dispersion, input powers and attenuation in transmission and dispersion compensating fibers. With this optimized system setting, the total performance of 160 Gb/s based transmission system with different, fiber length and attenuation is analyzed [23-25]. The performance of the single-channel dense wavelength division multiplexing (DWDM) is evaluated using optical spectrum analyzer, electrical spectrum analyzer and electrical scope in terms of optical spectrum, electrical spectrum and eye-diagrams. For different values of attenuation, fiber length and dispersion DWDM system is simulated

and peak power, peak frequency, peak-to-peak amplitude, bit-error rate (BER), eye opening, eye-closure, Q-value and jitter is evaluated. Bit-error (BER) at received optical power and Q-value is evaluated. Superimposed diagrams are also obtained for different values of attenuation, fiber length and dispersion [24].

It has been observed that, during the decade, several telecommunication networks have been utilized the fiber optic medium as the backbone of their interoffice and long haul networks to meet the growing demand for bandwidth requirements [23,24]. The long-haul transmission systems include terrestrial as well as undersea lightwave links. Furthermore, the terrestrial links are classified into long haul systems and ultra long haul systems [23]. The distance in lightwave links may vary from a few thousands of kilometers to several thousands of kilometers. The first generation optical networks utilized lightwave links operating at 10 Gb/s in the 1550 nm window of a low loss single mode fiber [22,24,27]. As the demand for bandwidth increased, different ways of increasing the capacity of a network were explored. First, network operators or carriers increased the data rate from 10 Gb/s to 40 Gb/s by using an electrical time division multiplexing scheme [23]. However, ETDM poses a severe limitation with high speed electronics beyond 10Gb/s. as an alternative to ETDM, the optical time division scheme was considered, but it was the wavelength division multiplexing scheme that offered a practical solution to increase the capacity of lightwave system [24]. 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate [25]. This tendency can be explained by a reduced complexity in realization and availability of required 160 Gb/s system components e.g. narrow-band filters on the one hand, and compatibility of 160 Gb/s data rates with existing transmission infrastructure on the other hand [26]. The increased system capacity in 160 Gb/s experiments is enabled by implementation of some new sophisticated technologies, e.g. novel modulation formats, new fiber and amplifier types, which are becoming mature, because of the possibility to realize them using only electronics or some hybrid (electro-optics) solutions, which seems to be impossible at channel data rates e.g. 40 Gb/s [24].

In this chapter, we design a single-channel 160 Gb/s system and thus the optimization of transmission settings and design rules for the implementation of 160 Gb/s single channel systems are presented. The system setting optimization is provided for NRZ signal modulation formats considering effects of different system characteristics, e.g. fiber length, dispersion, input powers and attenuation in transmission and dispersion

compensating fibers. With this optimized system setting, the total performance of 160 Gb/s based transmission system with different fiber length and attenuation is analyzed. The performance of the single-channel dense wavelength division multiplexing (DWDM) is evaluated using optical spectrum analyzer, electrical spectrum analyzer and electrical scope in terms of optical spectrum, electrical spectrum and eye-diagrams.

This chapter is organized into five sections. First section and second section gives the introduction of the chapter, literature survey and thesis organization. Third section describes the system set up of single-channel 160 Gb/s system. In Fourth section, we vary the parameters such as attenuation and fiber length and different results as optical spectrum, eye-diagram, electrical spectrum are taken to show the performance of the system and then these different results obtained are discussed in this section. For different values of attenuation, fiber length and dispersion DWDM system is simulated and peak power, peak frequency, peak-to-peak amplitude, bit-error rate (BER), eye opening, eye-closure, Q-value and jitter is evaluated. Bit-error (BER) at received optical power and Q-value is evaluated. Superimposed diagrams are also obtained for different values of attenuation, fiber length and dispersion. Finally conclusion of the chapter is given at the end of the chapter.

2.3 SYSTEM SET UP

Single-channel 160Gb/s DWDM transmission over standard single mode fiber (SSMF) with non return-to-zero (NRZ) modulation format is illustrated [26]. The DWDM terminal equipment of the 160 Gb/s single channel DWDM system that was used for transmission is schematically in figure2.1.

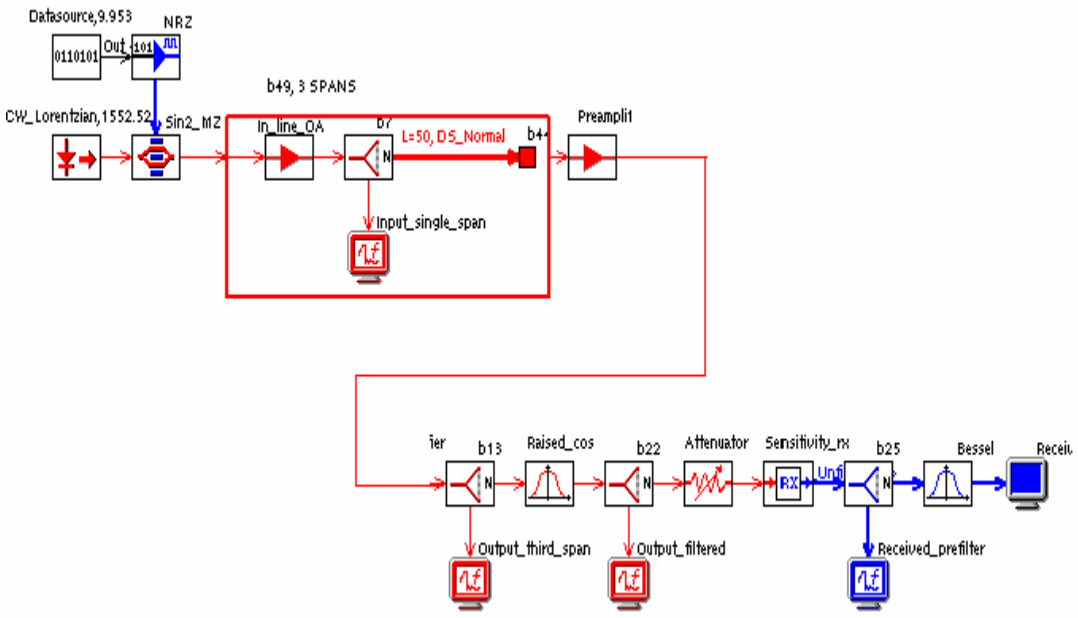


Figure 2.1 (Set up of 1x 160-Gb/s DWDM used for transmission)

The transmitter composed of data source, electrical driver, laser source, amplitude modulator and optical link section. Data source (pseudo-random bit sequence generator), stimulates a pseudo-random or a deterministic logical signal generator of arbitrary level (number of bits per symbol) [27]. Data source is customized by baud rate, sequence, logical signal level (number of bits per symbol) and period length.

In 160 Gb/s single-channel DWDM transmission system, data source has 160Gb/s bit rate and number of bit for each symbol is set at 1. As, baud rate is defined as bit rate per bit per symbol so its baud rate is set at 160Gbaud/s [27]. Sequence selected for data source for generation of bit sequence is pseudo random sequence with pseudo-random sequence degree 7. Thus, the period length of the pseudo-random sequence becomes 2^7-1 bits. The logical signal is then passed to the driver which converts the logical signal, a binary sequence of zeros and ones into an electrical signal. In this transmitter set up NRZ modulation format is used. Laser source provides transmission at 1552.52nm laser

emission frequency. In this CW lorentzian laser is implemented as this implements a simplified continuous wave (CW) laser. Laser phase noise is taken into account by generating a Lorentzian emission line shape whose FWHM (Full Width Half Maximum) i.e. power spectrum width at half maximum is specified at 10 MHz. The output from driver and laser source is passed to amplitude modulator. The Sin^2 shaped transfer function is typical for the Mach-Zehnder external modulators based on electro-optic effect in the $LiNbO_3$ devices. For this model, the chirping factor is included. In DWDM system Mach-Zehnder external modulators is used. So, in this transmission Sin^2 shaped transfer function is set with maximum transmissivity offset voltage at 2.5 V and chirp factor is taken to be zero. Maximum transmissivity offset voltage is the value of the electrical input corresponding to maximum transmission state [27,28]. Ideally, this value is 0 V, but often the modulators are slightly unbalanced in the absence of any applied electric field, so a biasing voltage must be applied to compensate this offset. The optical signal from Mach- Zehnder external modulator is passed through the optical link section. The optical link section is composed of three spans of 50 Km standard single mode fiber (SSMF), optical amplifier for i.e. in-line EDFA for loss compensation and splice component (b4) is used to implement a connection point for fibers with different parameters (different type of fibers). Splice component has a graphical utility only; it has no functions except allowing optical lines to be connected in arbitrary shapes, by putting a splice on each vertex. It is used also in the iterated components because this is a fictitious optical component with one optical output, useful to draw a period of optical link. The iteration function (b49) is needed to draw links that are intrinsically periodic. In such situations by creating a single period of link- having a single optical input and a single optical output and iterating it a number of times. Thus iteration function is extremely useful when describing periodic optical network in a very compact form for long haul optical system. These long haul network are often designed as a periodic structure since they are made up of sequence of fibers of nearly equal length followed by optical amplifiers together with other elements such as optical splitter and optical spectrum analyzer [28].

Receiver section of 160 GB/s DWDM transmission system is composed of optical filter, optical attenuator, sensitivity receiver and electrical filter as shown in figure 2.1. Signal

after passing through optical link section is received at the receiver. 160 GB/s DWDM system is simulated using raised cosine optical filter. The optical raised cosine filter is useful in many simulations where the exact shape of the filters are not know in details, and one wants to describe filters simply with their central frequency and passband [28-30]. In DWDM set up, filter center frequency f_0 is 193.1[THz], bandwidth B_W is 60GHz, roll off parameter R_0 is set at 0.5 and raised cosine exponent α is set at 1. The electrical signal is filtered with electrical filter of kind low pass Bessel transfer function in the set up. Then sensitivity optical receiver simulates a complete optical receiver (inclusive of photodetector, amplifier and post detection filter). It is based on receiver sensitivity specification. It also performs BER semi-analytical evaluation. At receiver, measurements are made with the help of optical spectrum analyzer, electrical spectrum analyzer and electrical scope. In Electrical spectrum analyzer, electrical spectrum is estimated using the method of modified periodograms, i.e. sectioning the entire data sequence into a number of parts each containing N_P samples, where N_P is computed in order to obtain the number of points requested by the Number of Spectrum Points over the displayed Bandwidth parameter i.e. taken to be 500 points. Electrical scope is help to obtained eye diagram and from the eye diagram determine the value of eye opening, eye closure, Q-factor and jitter. Now, after setting the required parameters of 160Gb/s single channel DWDM system, there are certain parameters that can be varied and different results can be obtained and analyzed [29].

2.4 Simulation Results and Discussion

In this chapter, 160Gb/s single-channel NRZ DWDM transmission system is deigned. We observe that at the transmitter the optical spectrum is obtained using three filters-ideal, lorentzian and rectangular is wide free from any type of distortion as shown in figure 2.2. We get optimum value of peak- frequency, peak power and OSNR at channel #1 as shown in table 1. The power 3.97984[mW] is evaluated in range [193.036, 193.164] [THz]. To view that the system works accurately parameter like fiber length and attenuation is varied.

Keeping the fiber length constant at 50 Km for three spans, power attenuation of the fiber is varied from 23 dB to 33dB. Firstly, we observe is eye diagram for different values of optical power attenuation, we obtained that Q-value reduces from 28.6 dB to 15.184 dB

and its graph is show in figure 2.6 with maximum value30, minimum value is 15.2341 and peak-to-peak amplitude is 14.7659. Then eye opening also decreases from 3.69468e-005 [a.u] to 2.05354e-005 [a.u] as shown in table 2. If the attenuation is further increased above 33db, eye closure will increased and the effect of distortion will increase. Nextly, the electrical spectrum for different values of optical attenuation is varied i.e. 23dB, 27dB, 30dB, and 33dB are superimposed using ideal filter as shown in figure 2.4. We observe that peak frequency and peak power decreases with increase in optical attenuation as shown in table 3. BER at received power versus optical attenuation graph shown in figure 2.5 indicates that BER remains constant up to 30 dB and then increases suddenly. From the graph we calculated that maximum value is 3.79813e-009, minimum value is 1e-040, peak-to-peak amplitude is 3.79813e-009, mean is 5.6972e-010, standard deviation is 1.05736e-009 and variance is 1.118e-018. Thus fiber attenuation describes the fact that optical power decreases exponentially when propagated in optical fibers.

Now, another parameter we vary is fiber length i.e. fiber transmission distance from 50Km to 150Km for three span keeping attenuation constant at 23 dB. We firstly, observe the eye diagram and analyze the Q-value, eye opening, bit error rate eye closure and jitter with increase in fiber transmission distance. If fiber length is increased above 150Km eye closure will increased. Then at different values of fiber length, optical spectrum obtained is superimposed in one diagram observe that peak power decreases from 40.81 to 39.78 as shown in figure 2.8. Similarly, electrical spectrum for different values are superimposed and that peak power and peak frequency decreases with increase in each value but with slight difference as shown in figure 2.9. Next, we obtain the graph between BER Vs received power when fiber length is varied as shown in figure 2.10. BER increases from 0.01 to 0.025. And from the graph peak-to-peak amplitude for each value is calculated and observes that peak-to-peak amplitude also increases from 0.010 at 50Km to 0.0237 at 150Km for three spans. Thus we find that the effect of distortion and noise is minimum in single-channel 160 GB/s NRZ DWDM transmission system.

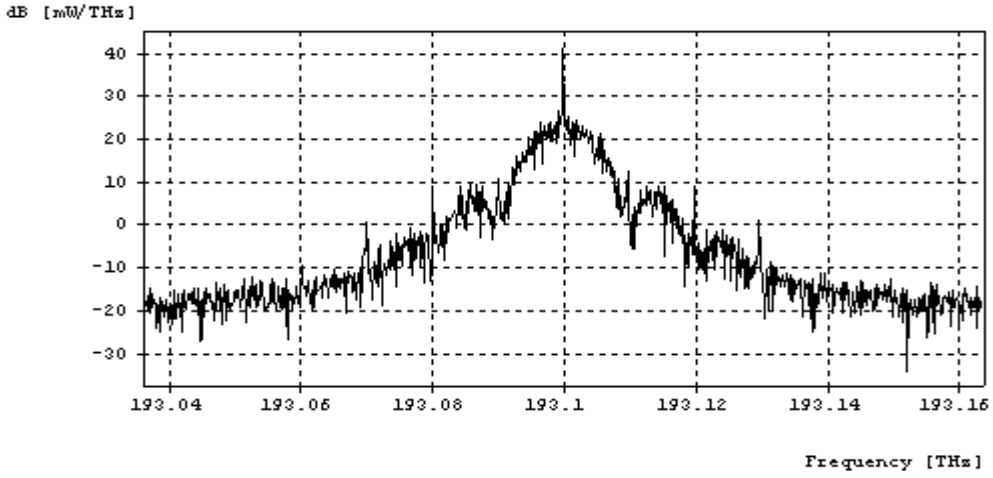


Figure 2.2 (a) (Optical spectrum of 1 x 160-Gb/s DWDM transmitter with ideal filter)

Filter type	**Peak frequency**	**Peak power**	**OSNR**
Ideal filter	193.1[THz]	41.22814dB[mW/THz]	NIL

Lorentzian filter	193.1[THz]	5.154282[dBm]	25.095619[dB]
Rectangular filter	193.1[THz]	5.664891[dBm]	44.092834[dB]

Table 1 (Analysis of Optical spectrum of 1 x 160-Gb/s DWDM transmitter using three filters)

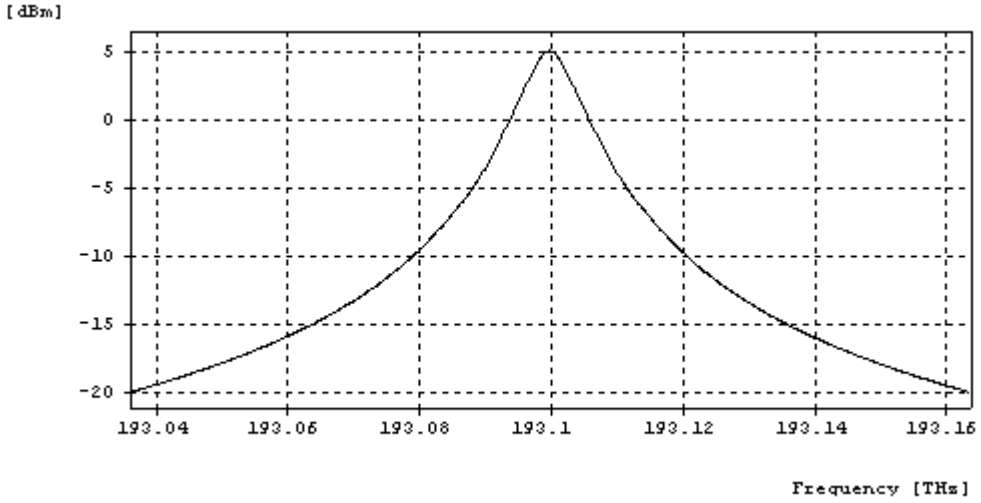


Figure 2.2 (b) (Optical spectrum of 1 x 160-Gb/s DWDM transmitter with Lorentzian filter)

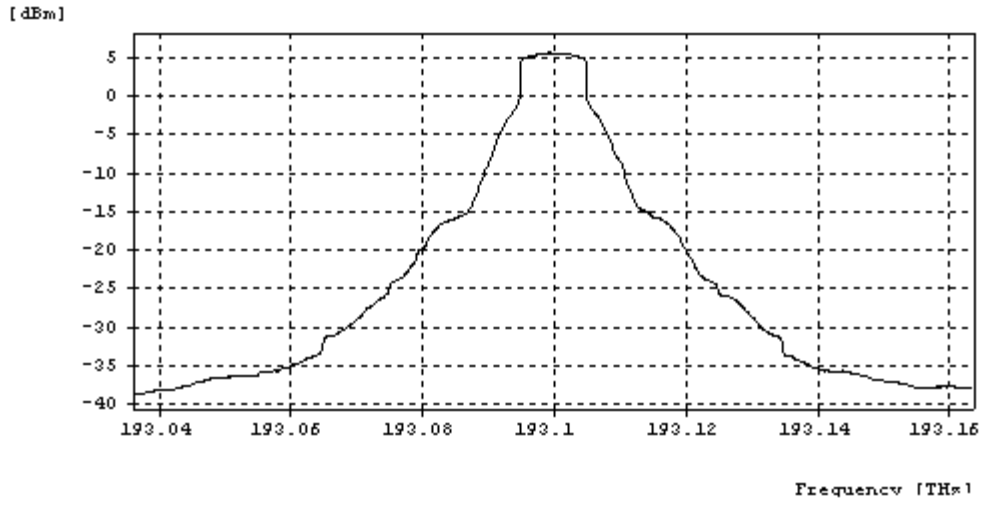


Figure 2.2(c) (Optical spectrum of 1 x 160-Gb/s DWDM transmitter with rectangular filter)

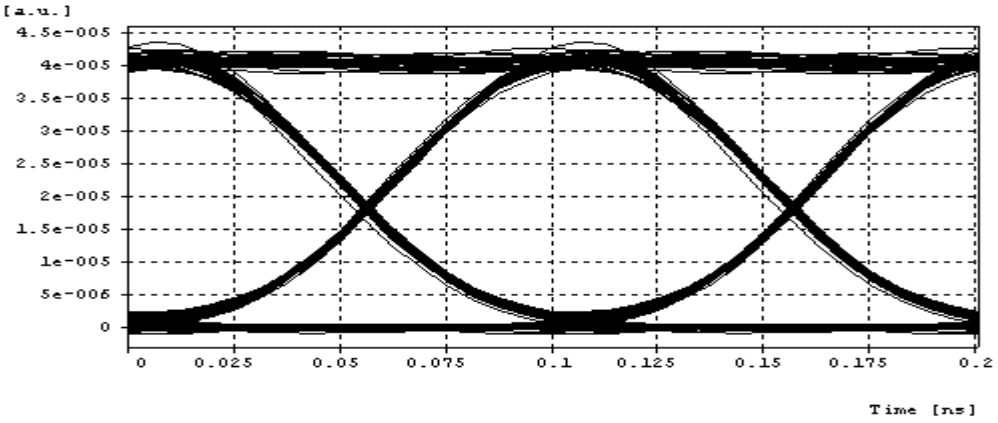
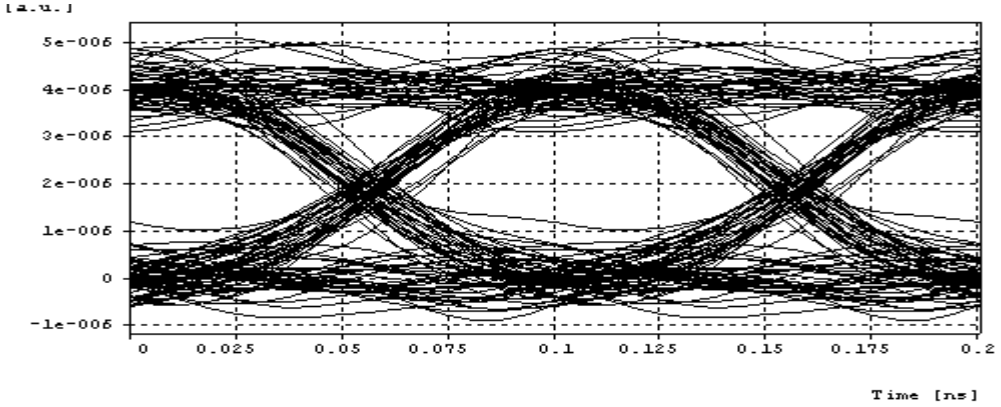


Figure 2.3 (a) (Eye diagram with attenuation at 23 dB)
Figure 2.3 (b) (Eye diagram with attenuation at 33 dB)



Attenuation	***Q-value***	***Eye opening***	***Bit error rate***	***Jitter***
23[dB]	*28.605657[dB]*	*3.69468e-005[a.u.]*	*1e-040*	**0.0173862[ns]**
27[dB]	*25.824818[dB]*	*1.38101e-005[a.u.]*	*1e-040*	**0.0156681[ns]**
33[dB]	*15.184115[dB]*	*2.05354e-006[a.u.]*	*4.97428e-009*	*0.0197604[ns]*

Table 2 (Analysis of eye diagram of single channel DWDM at different values of attenuation)

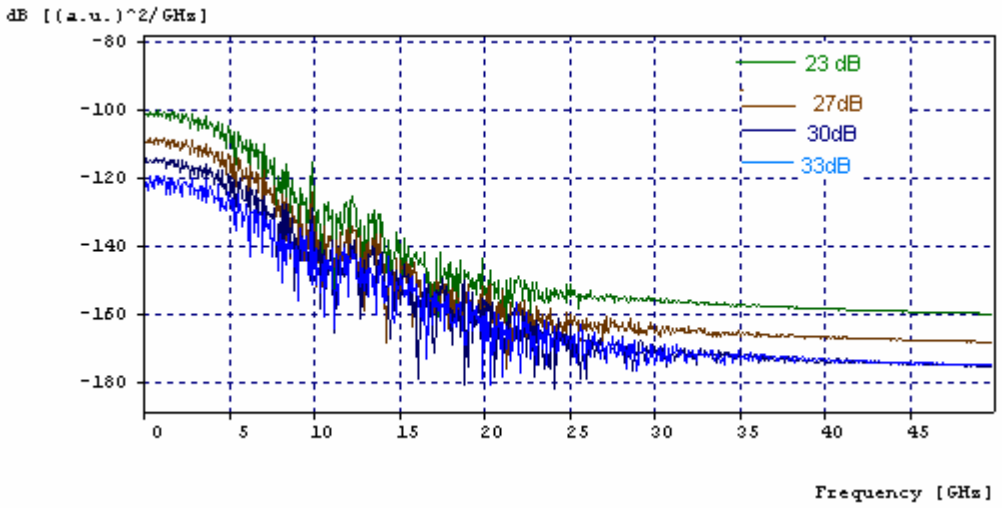
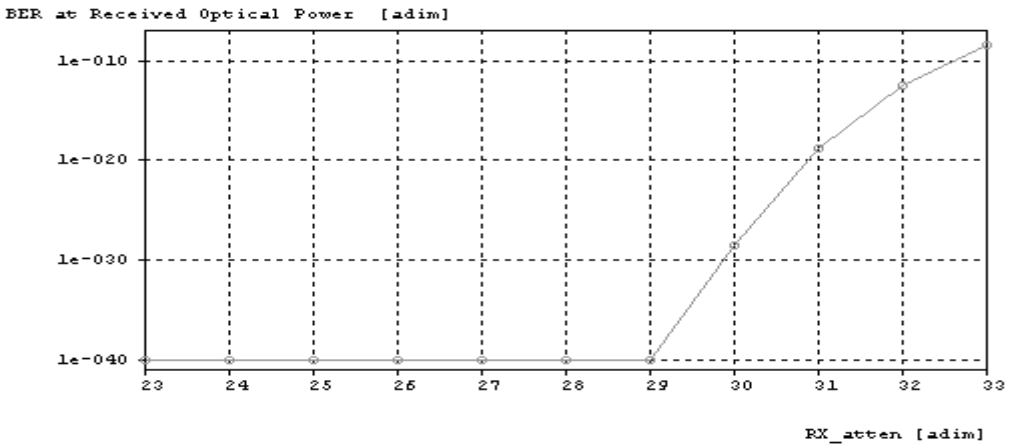


Figure 2.4 (Electrical spectrum when attenuation is varied from 23dB to 33dB

ATTENUATION(dB)	Peak frequency (GHz)	Peak power
23	7.10719	-110.24
27	7.10517	-118.354
30	6.32618	-124.40
33	5.54517	-131.41

Table 3 (Analysis of electrical spectrum when attenuation is varied in single channel 160 GB/s DWDM system)

Figure 2.5 (BER at received power versus optical attenuation)



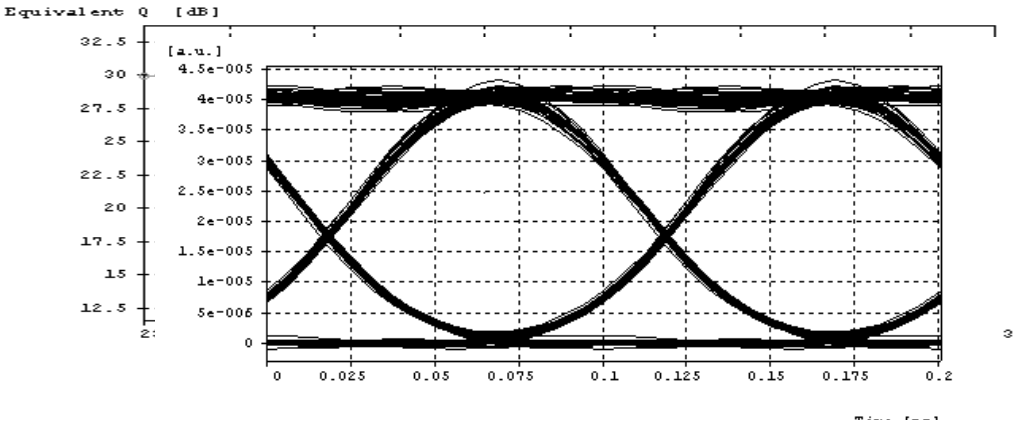


Figure 2.7 (a)(Eye diagram at 50 Km fiber length)

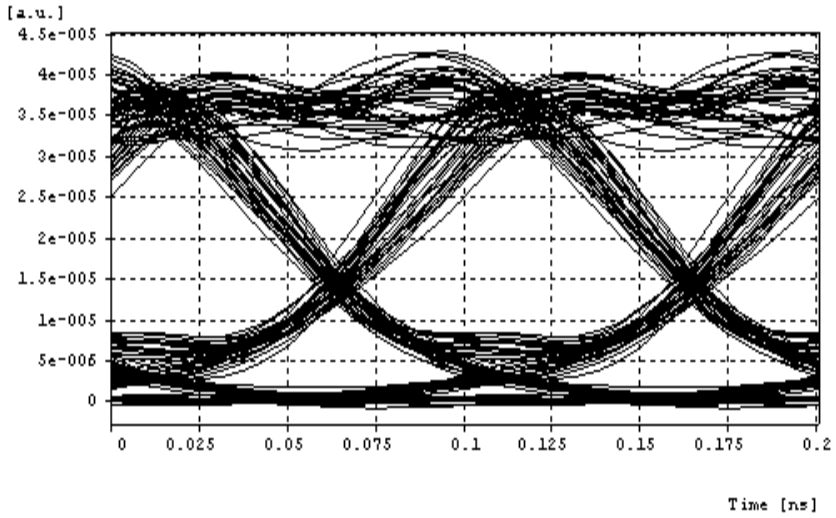


Figure 2.7 (b)(Eye diagram at 150 Km fiber length)

Fiber length	***Q-value***	***Eye opening***	***Bit error rate***	***Jitter***
50 Km	*29.740905[dB]*	*3.71942e-005[a.u.]*	*1e-040*	0.0170882[ns]
100 Km	*22.089505[dB]*	*3.17938e-005[a.u.]*	*1.14887e-035*	*0.0165742[ns]*
150 Km	*17.427230[dB]*	*2.3778e-005[a.u.]*	*5.24166e-014*	*0.0204015[ns]*

Table 4 (Analysis of eye diagram when fiber length is varied in single channel DWDM system)

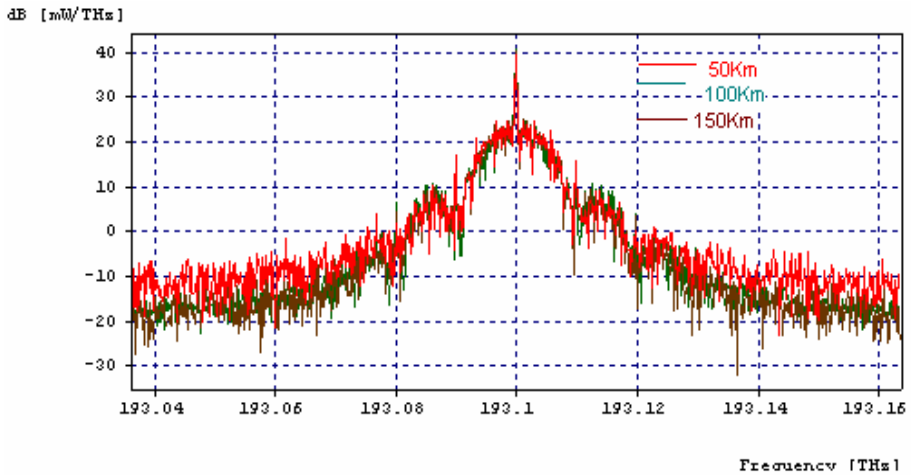


Figure 2.8 (Optical spectrum when fiber length is varied from 50Km to 150Km)

FIBER LENGTH (Km)	PEAK FREQUENCY (THz)	PEAK POWER dB(mW/THz)
50	193.1	40.816086
100	193.1	40.372181
150	193.1	39.781326

Table 5 (Analysis of optical spectrum when fiber length is varied in single-channel 160Gb/s DWDM system)

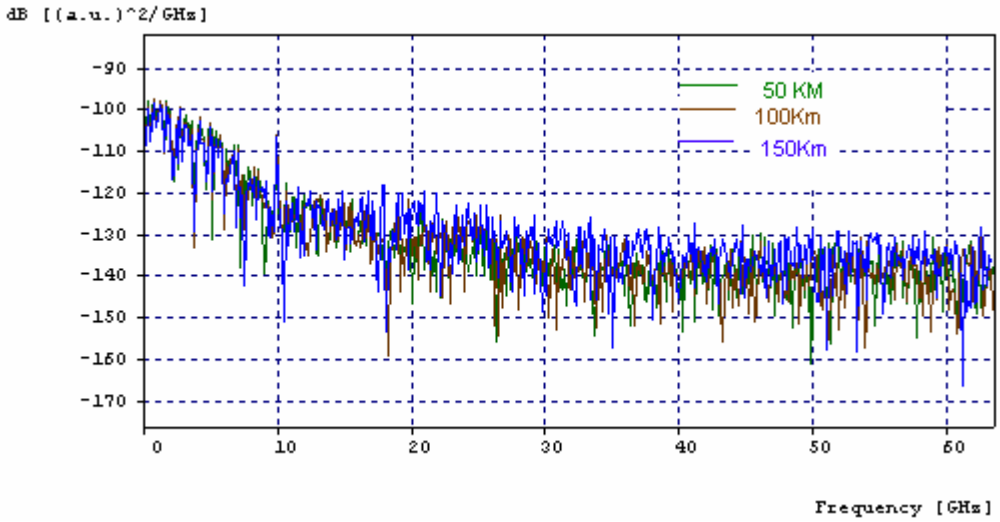


Figure 2.9 (Electrical spectrum when fiber length is varied from 50Km to 150Km)

Fiber length (Km)	Peak frequency (GHz)	Peak power
50	2.55001	-97.164360
100	1.65751	-98.939891
150	0.765002	-101.827057

Table 6 (Analysis of electrical spectrum when fiber length is varied in single-channel 160 Gb/s DWDM system)

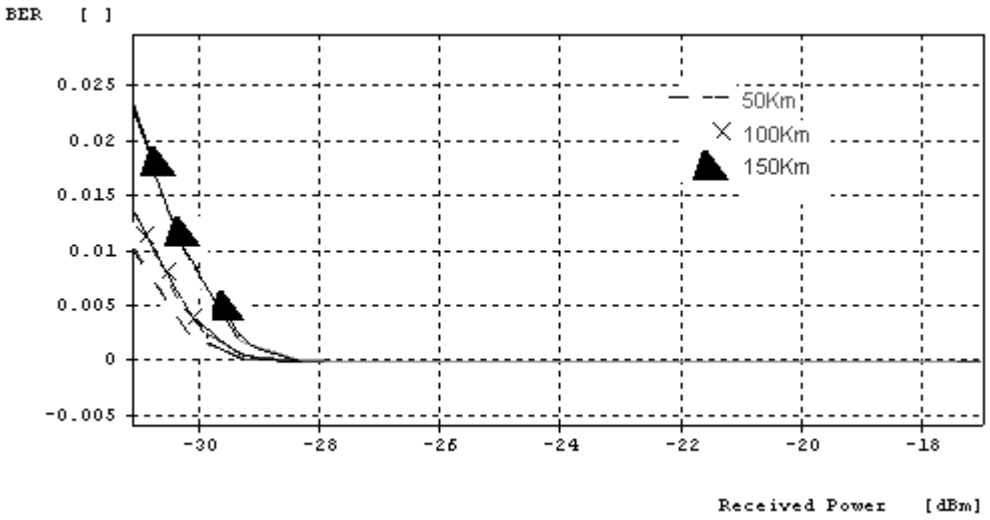


Figure 2.10 (BER versus received power when fiber length is varied from 50Km to 150Km)

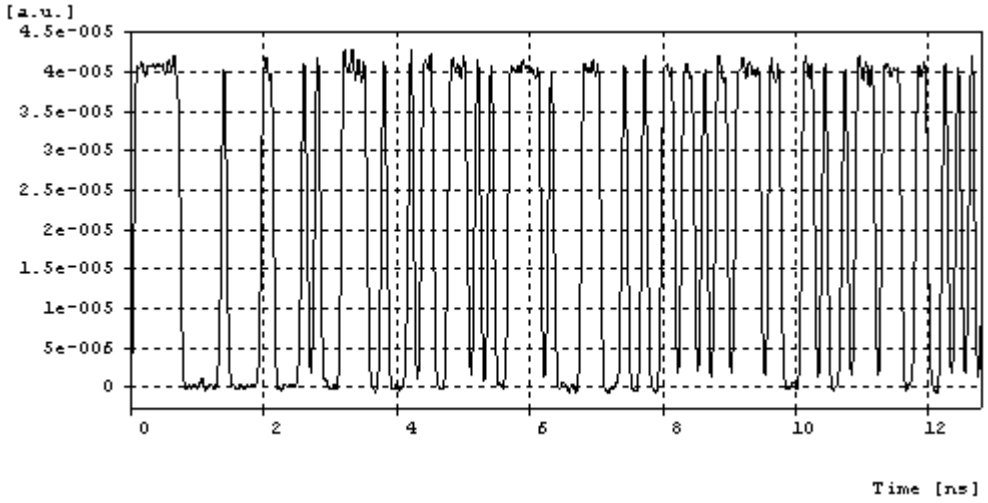


Figure 2.11(Electrical signal when fiber length is 50Km)

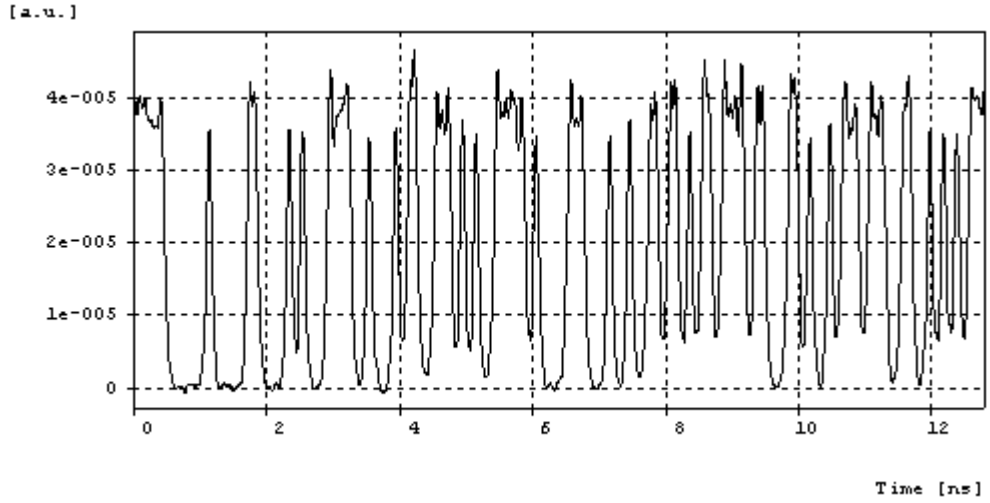


Figure 2.12 (Electrical signal when fiber length is 150Km)

Fiber length (Km)	**Maximum value [a.u.]**	**Minimum value [a.u.]**	**Peak-to-peak amplitude [a.u]**
50	4.28985e-005	-5.78439e-007	4.34769e-005
100	4.35577e-005	-8.09291e-007	4.4367e-005
150	4.67801e005	-5.10375e-007	4.72905e-00

Table 7 (Analysis of electrical signal when fiber length is varied in single-channel 160 GB/s DWDM system)

2.5 CONCLUSION

In this chapter, 160Gb/s single-channel NRZ DWDM transmission system is deigned over three spans of 50 Km standard single mode fiber. To view that the system works accurately parameter like fiber length and attenuation is varied. Keeping the fiber length constant at 50 Km for three spans, attenuation is varied from 23 dB to 33dB. Thus eye opening decreases. If the attenuation is further increased above 33db, eye closure will increased and the effect of distortion will increase. Thus fiber attenuation describes the fact that optical power decreases exponentially when propagated in optical fibers. When fiber length is varied, we observe the eye diagram and analyze the Q-value, eye opening, bit error rate eye closure and jitter with increase in fiber transmission distance from it. Thus we find that the effect of distortion and noise is minimum in single-channel 160 GB/s NRZ DWDM transmission system. Thus we conclude that 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate due to reduced complexity in realization and availability of required 160 Gb/s system components.

CHAPTER-3

DWDM TRANSMISSION AT (16 X 160GB/s) 2.56 Tb/s

3.1 ABSTRACT

This chapter reports on the field transmission of 16 x 160Gb/s over standard single mode fiber links. It gives an overview of the key technologies applied for the realization of 16x160 Gb/s (2.56 Tb/s) dense wavelength division multiplexing (DWDM) system demonstrator and summarizes long-haul simulated transmission with terabit per second capacity over SSMF fiber infrastructure. In this chapter, fiber length and optical attenuation is varied to study the performance of the system and system is evaluated in terms of Q-Value, eye-opening, optical spectrum, Electrical spectrum and eye diagram. With increase in attenuation and fiber length Q-Value and eye-opening decreases but optical signal to noise ratio increases for both lorentzian and rectangular filter. In 16-channel 160 Gb/s DWDM system transmission fiber length and optimum value of attenuation reduces as compared to single channel system due to increase in number of channels. 16-channel 160 Gb/s DWDM system provide capacity up to 2.56 Tb/s and thus large information can be transferred to the receiver.

KEYWORDS: DWDM, Fiber Length, optical attenuation, OSNR, Q-Value and BER.

3.2 INTRODUCTION

After investigation of 160 Gb/s single channel transmission characteristics the next step into the direction of future transmission systems is made considering multi-channel 160 Gb/s systems employing the dense wavelength division multiplexing (WDM) technique [24]. The numerical investigations taking into account various transmission aspects were performed in order to determine and describe the capacity upgrade mechanisms that could enable a better utilization of the available system bandwidth. In this chapter, 16-channel dense wavelength division multiplexing system is designed with bit rate at 160Gb/s. 16 x 160 Gb/s DWDM system led to 2.56Tb/s capacity [25,26]. Such high capacity system is investigated. The investigations presented in this chapter are made considering parameters of already available system components for intensity modulated direct detection systems. In order to concentrate on transmission effects and characterize

system behavior, the investigated transmission lines do not contain any sophisticated technologies, e.g. super FEC codes or orthogonal polarization between adjacent channels. Thus 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate. This tendency can be explained by a reduced complexity in realization and availability of required 160 Gb/s system components e.g. narrow-band filters on the one hand, and compatibility of 160 Gb/s data rates with existing transmission infrastructure on the other hand [27]. The increased system capacity in 160 Gb/s DWDM system is enabled by implementation of some new sophisticated technologies, e.g. novel modulation formats, new fiber and amplifier types, which are becoming mature, because of the possibility to realize them using only electronics or some hybrid (electro-optics) solutions, which seems to be impossible at channel data rates e.g. 40 Gb/s [30].

We observe that, optical signal transmission over long-span standard single mode fiber links with 40 Gb/s suffers strong restrictions [27,29,30]. This is a typical scenario with high relevance for optical submarine transmission systems, but it can also be encountered for selected links in terrestrial networks where, for example, topological constraints make placement of equipment expensive [29]. It can become a question of high topical interest to meet this challenge. Due to the strong signal attenuation in such long-span configurations, the signal quality suffers from low optical SNR (OSNR) at the receiver [30]. Because of the broad signal spectra, this problem becomes more and more challenging for the increasing channel data rates of future dense wavelength division multiplexing (DWDM) systems [26-30]. Currently, systems operating at channel data rates of 40 Gb/s are installed, and the first 160-Gb/s systems are being tested under field conditions [31-34]. Upgrading the channel data rate is one approach to reduce costs in order to meet the decreasing revenues per bit [31]. The paper demonstrates the 8 x 160 Gb/s DWDM system led to 1.28 Tb/s capacity [31,32]. With the increasing demand for transmission capacity on optical fiber trunk lines, ultra-long 160Gb/s per channel all optical transmission systems are now becoming very attractive [35,37,39], as they offer high signal spectral efficiency and large capacity with a smaller number of channels, at potentially lower cost [33], [34]. However, design of typical terrestrial transmission systems at 160 Gb/s line rate with 100 km amplifier spacing is challenging, since the launched power into both the transmission fiber and the dispersion compensation fiber is limited due to non-linearity related impairments [40-42]. The low dispersion tolerance of 160-Gb/s signals is also an important issue [43]. The dispersion slope of the transmission fiber and the dispersion compensating modules must be matched to yield a net accumulated dispersion for all DWDM channels [45-47].

In this chapter, we design a 16-channel 160 Gb/s DWDM transmission system. 16 x 160 Gb/s DWDM system led to 2.56Tb/s capacity. Such high capacity system is investigated. The investigations presented in this chapter are made considering parameters of already available system components for intensity modulated direct detection systems. Non-return-to-zero (NRZ) modulation format is used for this design. 16-channel transmitter and 16-channel receiver both are designed as compound component. After designing the

system, optical spectrum is determined both at the input and output. To analyze the performance of the designed system, different parameters are varied and impact of their variation is studied through different simulation results obtained.

This chapter is organized into five sections. First and second section gives the introduction of the chapter, literature survey and thesis organization. Third section describes the system set up of 16 x 160 Gb/s DWDM system and led to 2.56 Tb/s capacity. In Fourth section, we vary the parameters such as attenuation and fiber length and different results as optical spectrum, eye-diagram, electrical spectrum are taken to show the performance of the system and then these different results obtained are discussed in this section. For different values of attenuation, fiber length and dispersion DWDM system is simulated and peak power, peak frequency, peak-to-peak amplitude, bit-error rate (BER), eye opening, eye-closure, Q-value and jitter is evaluated. Bit-error (BER) at received optical power and Q-value is evaluated. Superimposed diagrams are also obtained for different values of attenuation, fiber length and dispersion. Finally, conclusion is given at the end of the chapter.

3.3 SYSTEM SET UP

16 X 160 Gb/s DWDM transmission system is shown in figure 3.1. The set up consist of 16-channel transmitter (WDM_Tx_16ch). 16-channel transmitter is the compound component consist of 16 single channel transmitter optically combined with the help of optical combiner [33]. The set of 16-channel transmitter compound component is shown in figure 3.2. Each single channel transmitter compound component is composed of data source, laser source, amplitude modulator and driver as explained in chapter-2. Modulation format used in electrical driver is non-return-to-zero (NRZ) [34].

In this set, CW lorentzian laser source is used. Thus, the output from the driver and laser source is passed to Mach-Zender external amplitude ($\sin^2$-shaped) modulator with maximum transmissivity offset voltage at 2.5V. Single channel transmitter component is shown in figure 3.3. Thus the transmitter consist of 16 laser sources with wavelength ranging from 193.035 THz to 193.785 THz, channel spacing is set at 50GHz, PRBS

(pseudo-random bit sequence generator) sequence degree is set 9. Thus the period length of pseudo-random sequence becomes 2^9-1 bits.

The logical signal from each data source is passed to its respective driver which converts logical input signal into electrical signal. The output from each driver and laser source is modulated using its respective Mach-Zender modulator [37]. The output from each modulator is combined using optical combiner to produce one output (optical_output) of 16-channel transmitter [37]. Complete set up formed for 16 x 160Gb/s dense wavelength division multiplexing system is shown in figure 3.1. Thus the capacity of (16 X 160 Gb/s) DWDM transmission system has increased to 2.56 Tb/s. So, more users can be accommodated and lot of information can be transferred to the receiver [35].

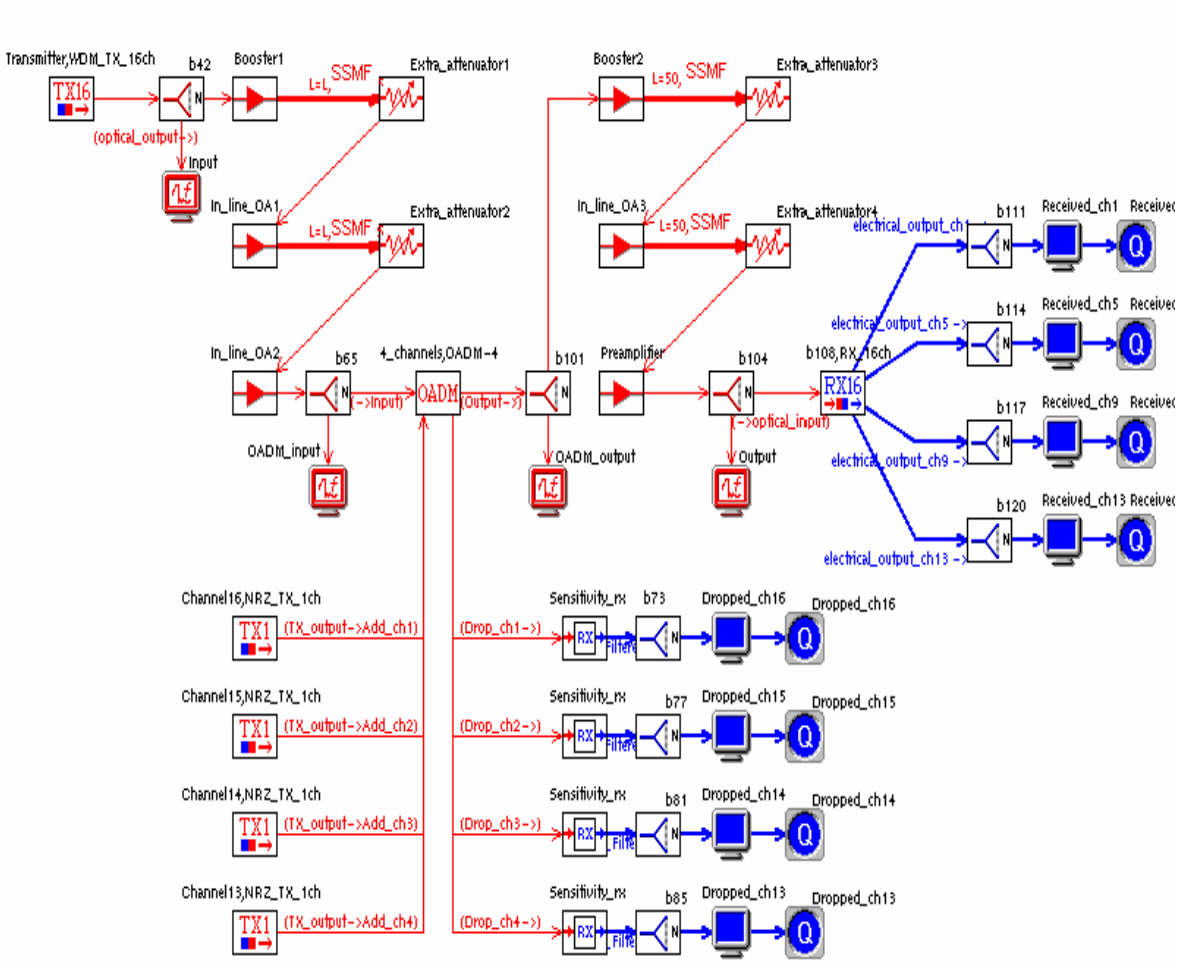


Figure 3.1 (System set for 16 X 160 Gb/s DWDM transmission system)

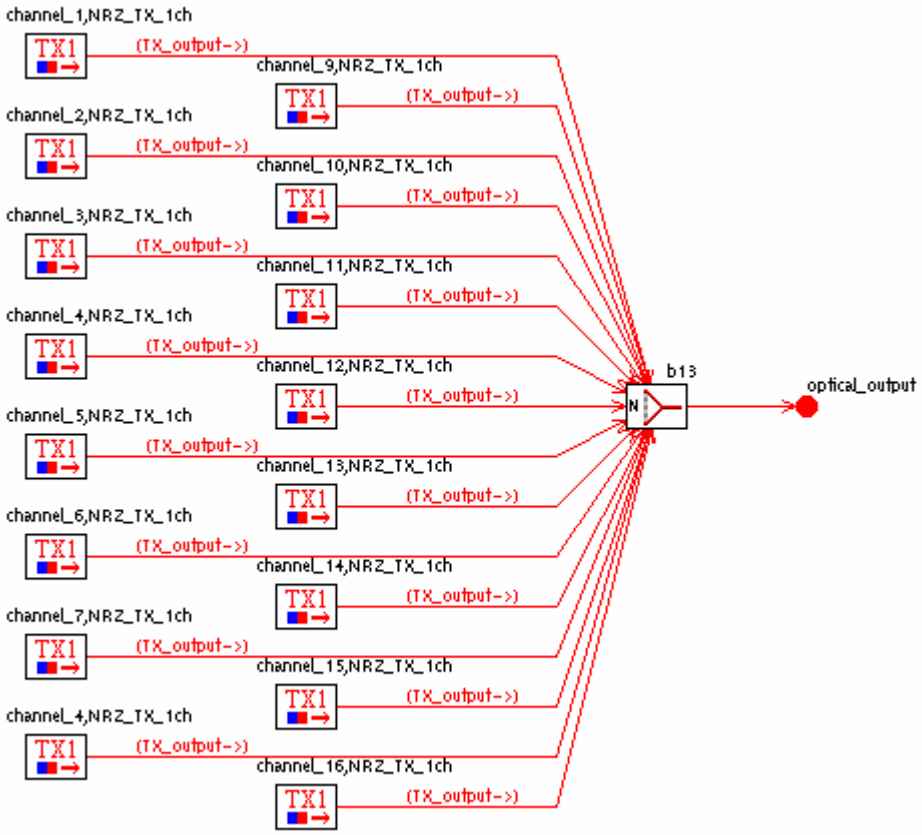


Figure 3.2 (16-channel NRZ transmitter)

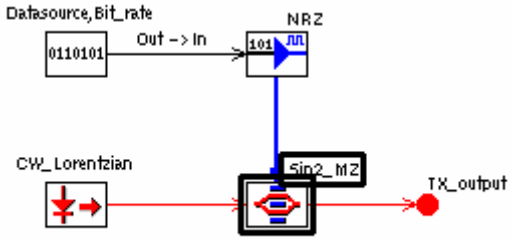


Figure 3.3 (Single-channel NRZ transmitter)

From the transmitter section optical signal is launched into 200 Km SSMF fiber link. In-line EDFA is used for loss compensation [38]. Along the fiber link, after 100 km four channel optical add drop multiplexer (OADM) is used to select and to add four channels.

The dropped channels are detected by receivers with appropriate electrical filtering. The added channels are propagating together with other ones and detected at the end of fiber link. In OADM, if given at the input port a WDM aggregate, the selected channel is dropped and available at the drop port [38]. Another channel at the same frequency may be added using the add port. The drop operation is implemented using an optical notch filter. The transfer function of the notch filter is the complementary of a Multiple-Stage Lorentzian bandpass filter and has the same bandwidth [37-39]. Four channel optical add drop multiplexer (OADM) compound component is shown in figure 3.4.

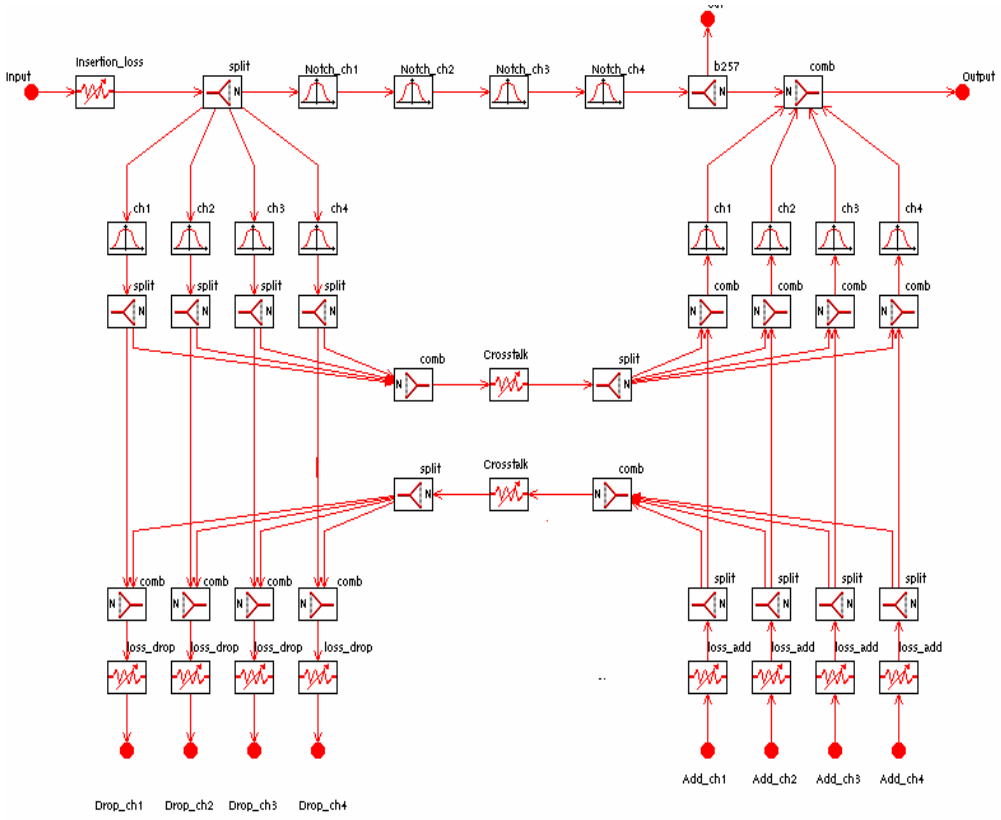


Figure 3.4 (4-channel OADM)

At receiver 16-channel receiver is used to receive all the information of 16-channel. 16-channel DWDM receiver compound component is shown in figure 3.5 that is composed of 16 single channel receiver. Single channel receiver composed of optical raised cosine filter, PIN photodiode with no noise and responsivity 1A/W and electrical filter is of kind

Bessel filter and is shown in figure 3.6. Thus each 16-channel DWDM receiver composed of optical raised cosine filter, PIN photodiode and Bessel filter [40].

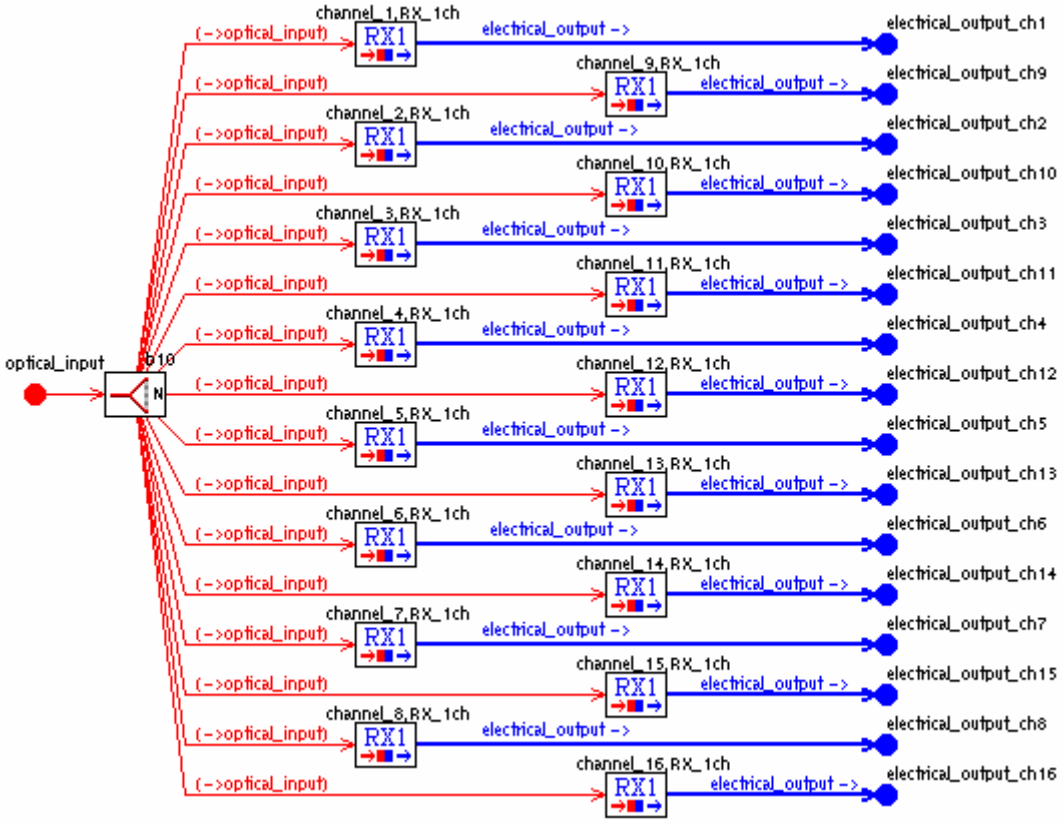


Figure 3.5 (16-channel DWDM receiver)

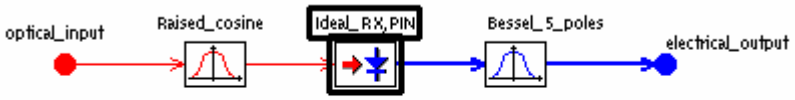


Figure 3.6 (Single-channel receiver)

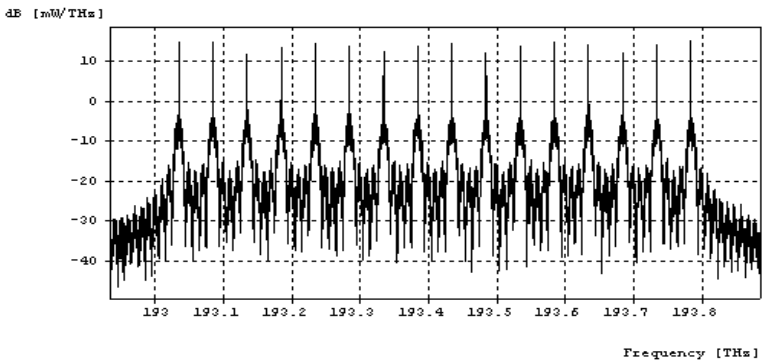
3.4 Simulation results and discussion

In this chapter, 16 X 160 Gb/s NRZ DWDM transmission system is designed. Here the channels are increased from single to sixteen channels. In this 16-channel transmitter and 16-channel receiver is designed as compound component. 4-channel OADM is also

designed so that any four channels can be added or dropped. At the transmitter the optical spectrum is observed using ideal, lorentzian and rectangular filter as shown in figure 3.7 and peak-to-peak amplitude, peak frequency, peak power is evaluated in each filter as shown in table 8. At OADM multiplexer we observe the optical spectrum at input and output. We observe that at the output peak frequency and peak power decreases and the power 0.0801149[mW] is evaluated in the range [192.934, 193.886] [THz]. The peak power reduces from 6.29 [mW] to 5.86 [mW] then input optical spectrum as shown in figure 3.8. Thus eye diagram of dropped channel-19 from OADM is evaluated in terms of Q-value, bit error rate, eye opening, eye closure, jitter etc as shown in figure 3.9. We observe that eye diagram after dropped is still wide. Then we analyzed the electrical spectrum of dropped channel-13 as shown in figure 3.10 and thus the peak frequency is 2.1009[GHz] and peak power is -71.935574[dB] from the graph is evaluated.

Next, we evaluate the performance of 16-channel DWDM system by varying the parameter i.e. fiber length and attenuation. Fiber length is varied from 20Km to 80 Km keeping all other parameters constant. Eye diagram is observed for each value of fiber length and from it Q-value, eye opening, eye closure, average eye opening, bit error rate and jitter is calculated. For 80 Km eye diagram has eye opening reduces to 1.12249e-005 and Q-value also decreases as fiber length increases as shown in figure 3.17 and thus we obtain that maximum value is 18.9143, minimum value is 7.92431 and peak-to-peak amplitude is 10.99. At receiver, 16-channel DWDM system optical spectrum is obtained using lorentzian and rectangular filter and all the 16-channel OSNR is evaluated and observe that OSNR increases with increase in fiber length as shown in figure 3.14.

Next, we vary the attenuation from 3dB to 35 dB and fiber length is kept constant at 50 Km. In this, we observe eye diagram, at 20 dB eye opening reduces to 6.71991e-005. At 35 dB eye diagram closure is more than eye opening that is 21.419916. And there is lot of distortion as shown in figure 3.18. Q-value versus optical attenuation graph show that Q-value decreases up to 25 dB then it remains constant as shown in figure 3.19. Eye opening also decreases with increase optical spectrum up to 25 dB and then it remains constant as eye diagram has lot of distortion as shown in figure 3.20. From the graph, we



evaluated that maximum value is 20.037, minimum value is 6.0206 and peak-to-peak amplitude is 14.0164. Then we obtain electrical spectrum for all the values of optical attenuation i.e. 3, 20, 35 dB and superimpose them on one diagram as shown in figure 3.21and evaluate peak power and peak frequency. We observe that peak power decreases with increase in optical attenuation.

Figure 3.7 (a) (Optical spectrum at 16-channel transmitter when ideal filter used)

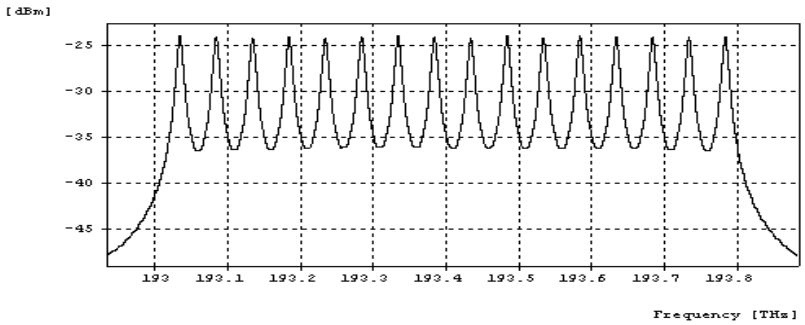


Figure 3.7 (b) (Optical spectrum at 16-channel transmitter when Lorentzian filter used)

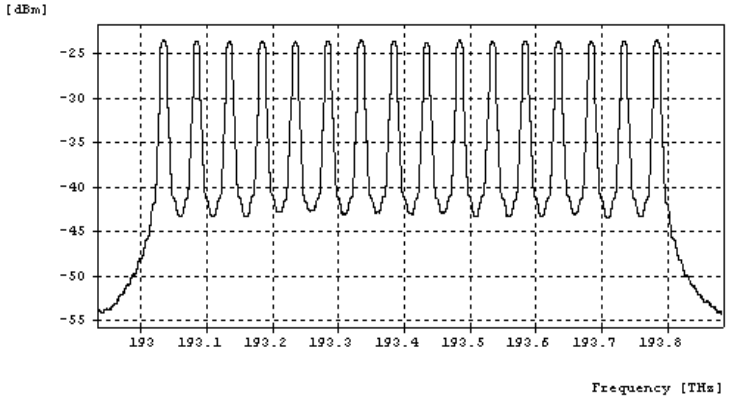
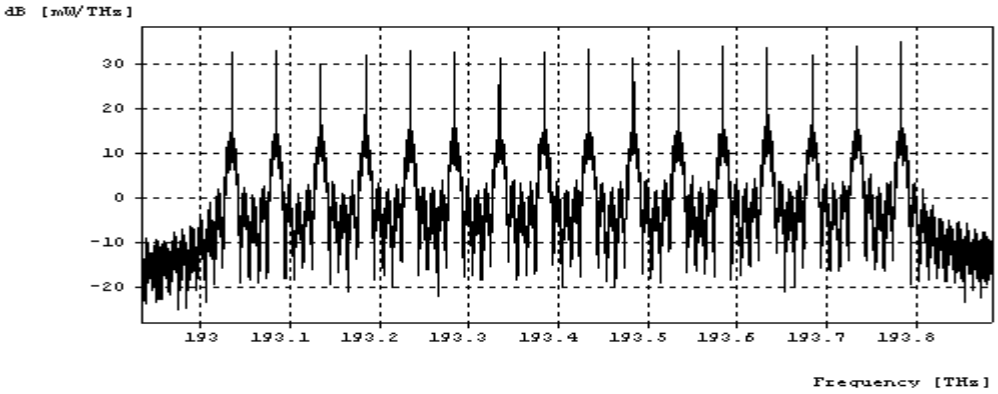


Figure 3.7 (c) (Optical spectrum at 16-channel transmitter when rectangular filter used)

Filter type	Peak frequency	Peak power
Ideal filter	193.785[THz]	15.330402dB[mW/THz]
Lorentzian filter	193.085[THz]	-23.8752dB[mW/THz]
Rectangular filter	193.035[THz]	-23.374800dB[mW/THz]

Table 8 (Analysis of optical spectrum in 16 x 160 Gb/s DWDM system using three filters)

Figure 3.8 (a)(Optical spectrum at OADM input)



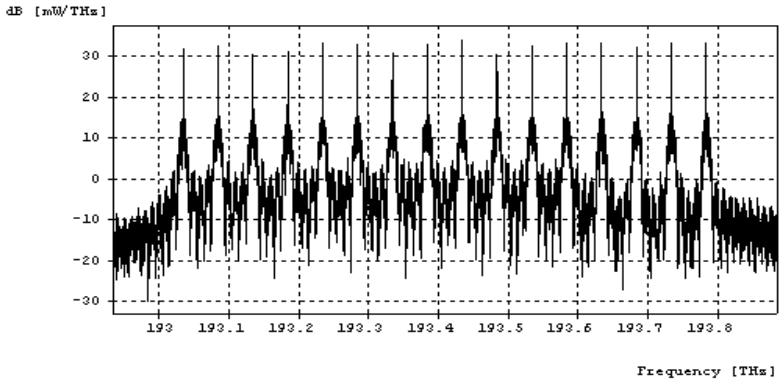


Figure 3.8 (b) (Optical spectrum at OADM output)

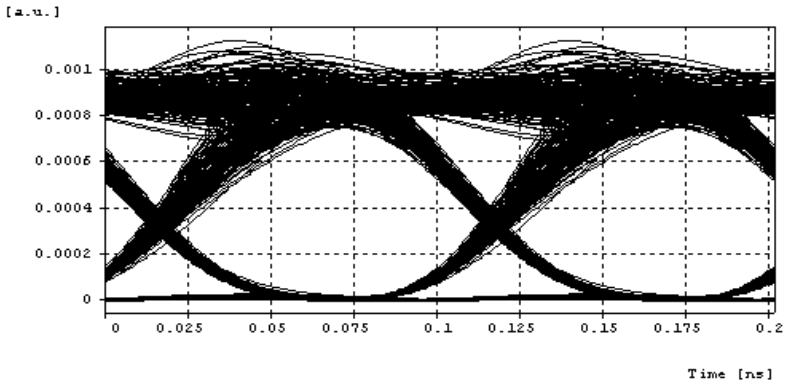


Figure 3.9 (Eye diagram of dropped channel-13 from OADM)

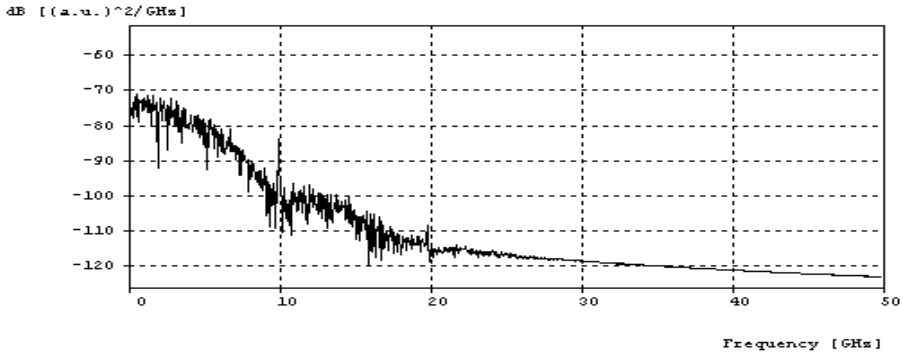


Figure 3.10 (Electrical spectrum of dropped channel-13 from OADM)

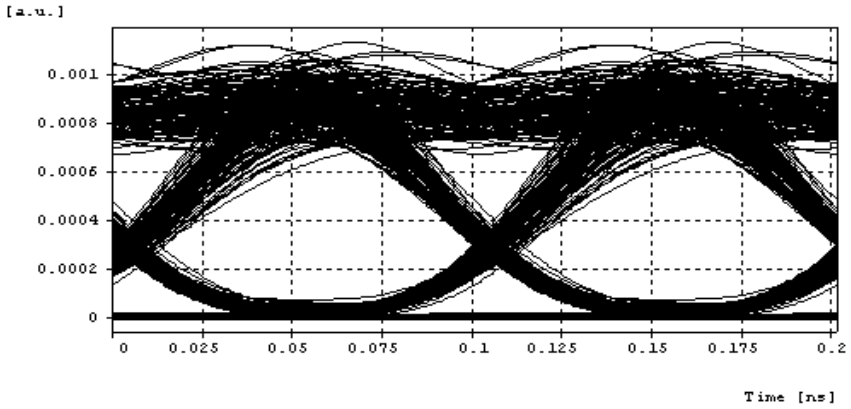


Figure 3.11(a) (Eye diagram for received channel-9 when fiber length is 20Km)

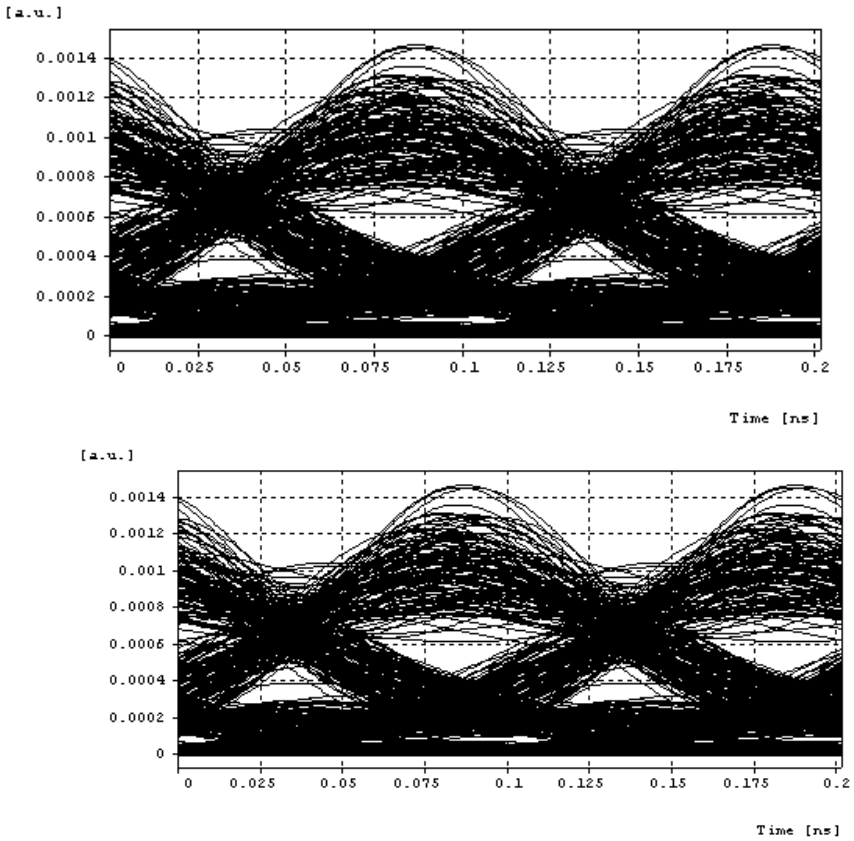


Figure 3.11(b) (Eye diagram for received channel-9 when fiber length is 50Km)

Figure 3.11(c) (Eye diagram for received channel-9 when fiber length is 70Km)

Fiber length	***Q-value***	***Eye-opening***	***Bit error rate***	***Jitter***
20 Km	*18.949800[dB]*	*0.00058078*	*3.08789e-019*	*0.0185409*
50 km	*0.0185409[dB]*	*0.000348116*	*3.70719e-008*	*0.0280313*
70 km	*10.190408[dB]*	*9.18393e-005*	*0.000676568*	*0.0287952*
80 km	*2.48995[dB]*	*1.12249e-005*	*0.00638033*	*0.0287813*

Table 9(Analysis of eye diagram when fiber length is varied)

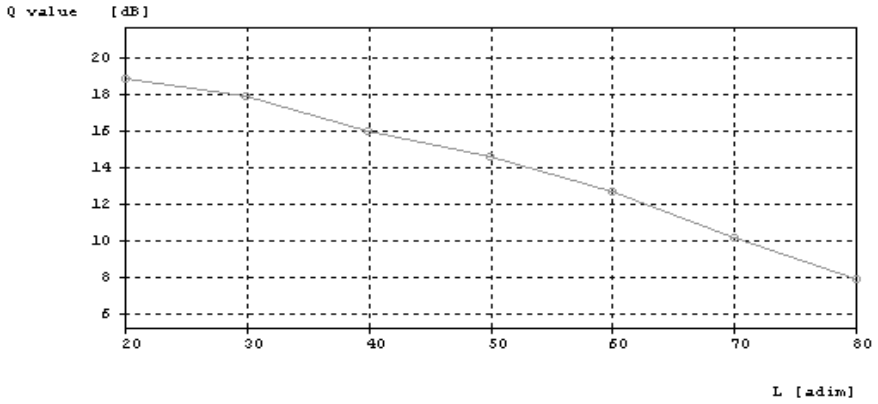


Figure 3.12 (Q-value versus fiber length)

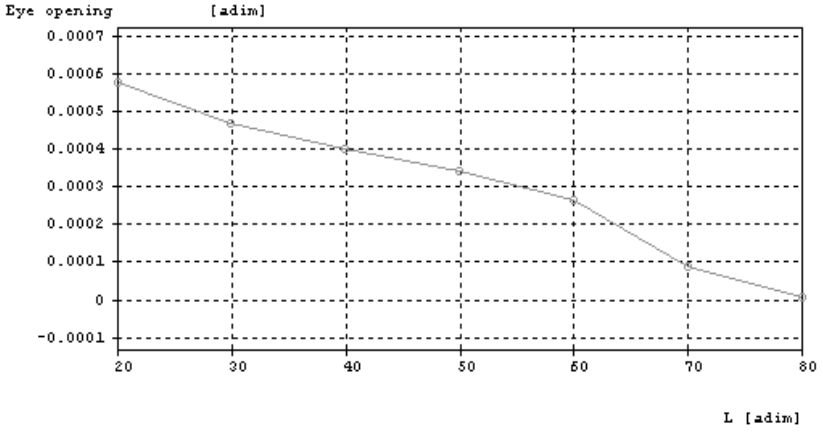


Figure 3.13 (Eye opening versus fiber length)

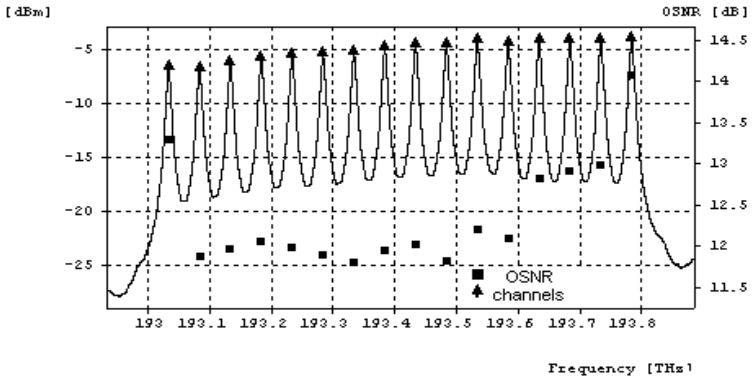
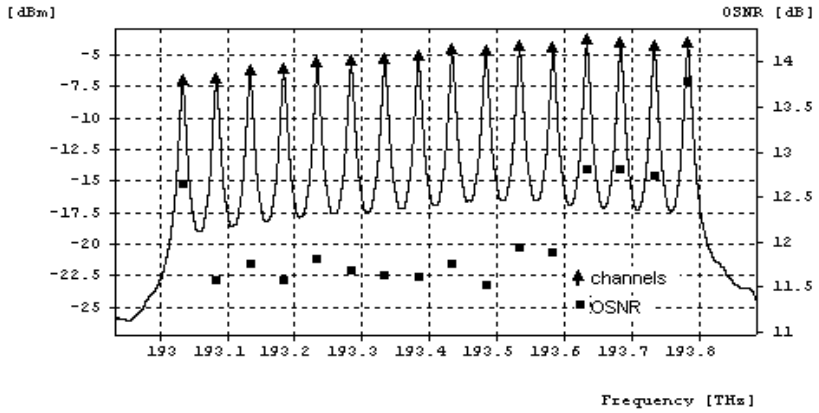


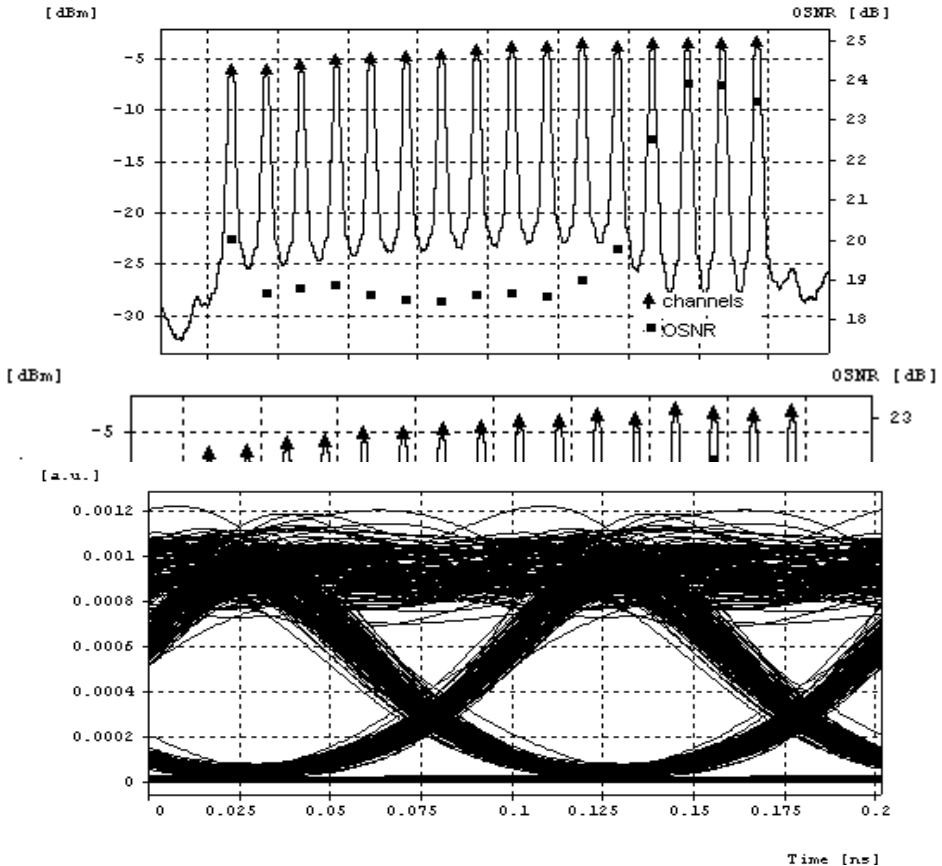
Figure 3.14(Optical spectrum at receiver when fiber length is 50Km with lorentzian filter)

Figure 3.15 (Optical spectrum at receiver when fiber length is 80Km with



lorentzian filter)

Figure 3.16 (Optical spectrum at receiver when fiber length is 50Km with



Fig

Figure 3.18 (a) (Eye diagram at attenuation is at 3 dB)
Figure 3.18 (b) (Eye diagram at attenuation is at 20 dB)

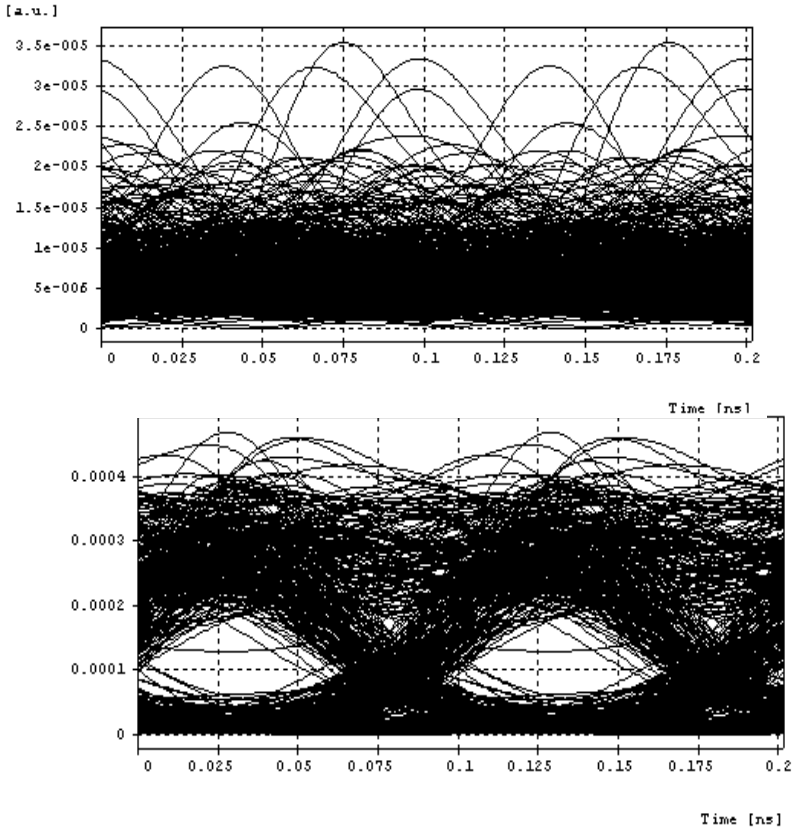
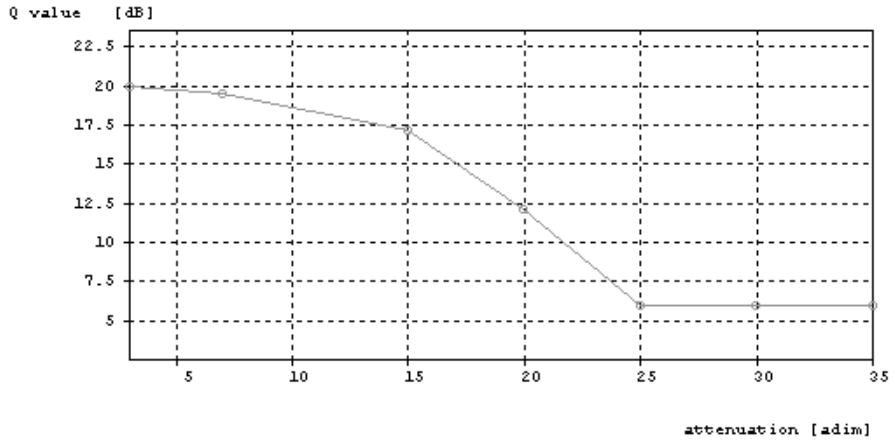


Figure 3.18 (c) (Eye diagram when attenuation at 35 dB)

Attenuation (dB)	Q-value [dB]	**Bit error rate**	**Eye opening**	Jitter
3	20.0243	7.8504e-023	0.000650471	0.019057
20	12.176258	3.46606e-005	6.71991e-005	0.0203999
35	6.020600	0.0227501	4.00473e-008	0.0245126

Table 10 (Analysis of eye diagram when attenuation is varied in 16 x 160 Gb/s DWDM system)

Figure 3.19(Q-Value versus attenuation)



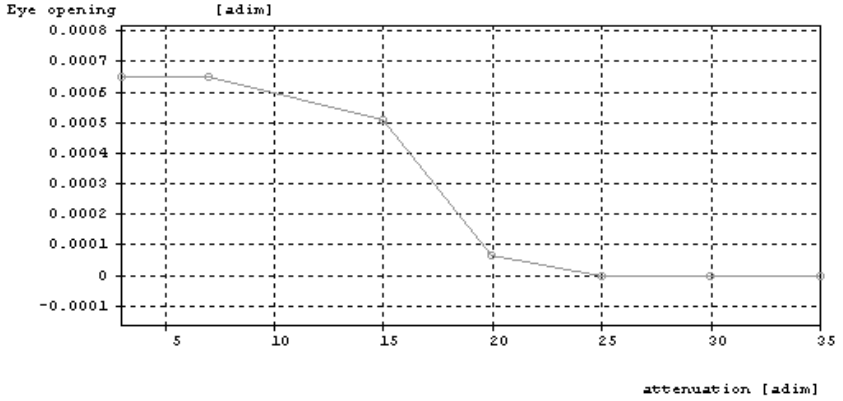
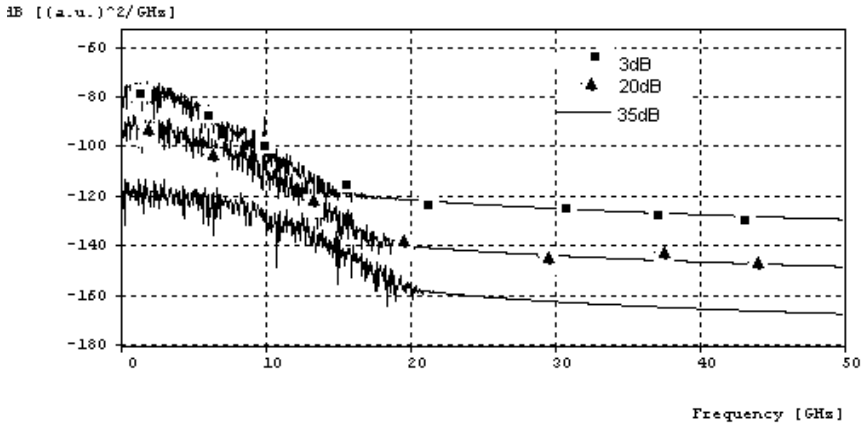


Figure 3.20 (Eye opening versus attenuation)

Figure 3.21 (Electrical spectrum when attenuation is varied)



5.5 CONCLUSION

In this chapter, 16 X 160 Gb/s NRZ DWDM transmission system is designed. Here the channels are increased from single to sixteen channels. In this 16-channel transmitter and 16-channel receiver is designed as compound component. 4-channel OADM is also designed so that any four channels can be added or dropped. At the transmitter the optical spectrum is observed using ideal, lorentzian and rectangular filter and peak-to-peak amplitude, peak frequency, peak power is evaluated in each filter. At OADM multiplexer we observe the optical spectrum at input and output. We observe that at the output peak frequency and peak power decreases then input optical spectrum. Thus eye diagram of dropped channel-19 from OADM is evaluated in terms of Q-value, bit error rate, eye opening, eye closure, jitter etc. We observe that eye diagram after dropped is still wide. OSNR increases with increase in fiber length. Q-value Vs optical attenuation graph show that Q-value decreases up to 25 dB then it remain constant. Eye opening also decreases with increase optical spectrum up to 25 dB and then it remains constant as eye diagram has lot of distortion.

In single-channel 160Gb/s optimum value of attenuation is 23 dB. In this we have wide eye diagram. But, in 16-channel 160Gb/s DWDM system optimum value is 3 dB and has eye opening small. If we compare fiber length, in that fiber length is varied up to 150 Km but in 16-channel it is just varied up to 80 Km. at 80 Km eye opening is less as compared to eye opening at 150 Km in single–channel. But 16-channel 160 Gb/s DWDM system provide capacity up to 2.56 Tb/s and thus large information can be transferred to the receiver. It is also compatible with optical components without any sophisticated techniques such as super FEC codes or orthogonal polarization between adjacent channels. 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate. This tendency can be explained by a reduced complexity in realization and availability of required 160 Gb/s system components e.g. narrow-band filters on the one hand, and compatibility of 160 Gb/s data rates with existing transmission infrastructure on the other hand. The increased system capacity in 160 Gb/s DWDM system is enabled by implementation of some new sophisticated technologies, e.g. novel modulation formats, new fiber and amplifier types, which are becoming mature, because of the possibility to realize them using only electronics or some hybrid

(electro-optics) solutions, which seems to be impossible at channel data rates e.g. 40 Gb/s.

CHAPTER-4

POLARIZATION MODE DISPERSION

4.1 ABSTRACT

This chapter demonstrates the effect of polarization mode dispersion in 160 Gb/s single-channel DWDM systems. AOPMD component is used to stimulate PMD by taking into account of its frequency dependence. It reduces the statistical PMD behavior of fiber without any loss, dispersion or non-linearity. In order to vary the random effect of PMD on system performance, seed parameter of AOPMD is varied. Q-Value and eye opening shows decreases with increase in seed parameter of AOPMD but OSNR increases. Peak power decreases in output optical spectrum as compared to input optical spectrum.

KEYWORDS: DWDM, PMD, Q-Value, Seed Parameter, AOPMD and DGD

4.2 INTRODUCTION

Polarization mode dispersion (PMD) is another complex optical effect that can occur in single-mode optical fibers. Single-mode fibers support two perpendicular polarizations of the original transmitted signal. If were perfectly round and free from all stresses, both polarization modes would propagate at exactly the same speed, resulting in zero PMD [13-15]. However, practical fibers are not perfect, thus, the two perpendicular polarizations may travel at different speeds and, consequently, arrive at the end of the fiber at different times. Excessive levels of PMD, combined with laser chirp and chromatic dispersion, can produce time-varying composite second order (CSO) distortion in amplitude modulated (AM) video systems. Like chromatic dispersion, PMD causes digital transmitted pulses to spread out as the polarization modes arrive at their destination at different times. For digital high bit rate transmission, this can lead to bit errors at the receiver or limit receiver sensitivity. For a pulse with randomly oriented polarization, one part of the pulse is transmitted along one of the principal axes, and the other part is transmitted along the other principal axis. The received pulse becomes broadened, because the two parts arrive with a delay time ½ , called differential group delay (DGD).

It has been observed, that recent progress in optical fiber technology makes polarization mode dispersion the ultimate limiting factor for high speed long distance optical fiber transmission [15, 16,19]. The polarization effects play a critical role toward the performance of high speed lightwave systems [15]. These effects can be classified into polarization mode dispersion (PMD), polarization dependent loss (PDL) and polarization dependent gain (PDG)[16]. The PMD arises from the fiber birefringence due to imperfect fiber core geometry. The PDL occurs when the insertion loss of a passive component is dependent on the state of polarization of the signal [17-19]. The amplifier gain can also be

polarization dependent (PDG). Although the effects of PDL and PDG are minimal, PMD has a severe effect on the performance of a 160 Gb/s lightwave system, leading to significant performance degradation in long-haul links [18].

Management of PMD in long-haul lightwave systems involves optimizing both the accumulated as well as dispersion slope mismatch within the acceptable limits [19,20,22]. The use of dispersion managed cables (DMCs) would be an ideal strategy to minimize the PMD in under sea long-haul links [21]. Different dispersion compensation technologies have been developed during recent years for terrestrial high speed long hauls systems [22,25]. These technologies are based on dispersion compensation fibers, fiber gratings and virtual image phased arrays [23]. In typical long haul DWDM system, dispersion maps are utilized to optimize the accumulated dispersion [24]. The dispersion maps are two-dimensional maps which depict the accumulated dispersion versus the transmission distance [26,27,29]. These maps are quite useful and help the system designer to optimize the system performance by appropriately placing the dispersion compensators ina link [30].

In this chapter, we have investigated the effect of PMD on 160 Gb/s DWDM system. For this 160 Gb/s single-channel DWDM system is designed. PMD has a severe effect on the performance of a 160 Gb/s lightwave system, leading to significant performance degradation in long-haul links. Performance of the system is evaluated in terms of optical spectrum, optical signal to noise ratio, eye-diagram, Q-Value, eye-opening and differential group delay.
This chapter is organized into five sections. First and second section includes introduction of polarization mode dispersion, its literature survey and chapter organization. Third section describes the effect of PMD on 160 Gb/s DWDM system. For this 160 Gb/s single-channel DWDM system is designed. In fourth section, system is simulated by varying the seed parameter of AOPMD and different results have been taken such as eye-diagram, optical spectrum, Q-value and DGD graph and effect of these on DWDM system have been discussed. Finally conclusion of chapter is given.

4.3 SYSTEM SETUP

To determine the effect of PMD on DWDM system, 160Gb/s single channel DWDM system is taken as shown in figure 4.1. The logical signal from data source is passed through driver of NRZ modulation format. The electrical filter used is Bessel filter [13]. CW lorentzian laser source is used at 1550 nm emission frequency. The output from filter and laser source is modulated using $\sin^2$ modulator (Mach-Zender modulator). The optical signal is passed over 100Km of standard single mode fiber. AOPMD component is used to stimulate PMD by taking into account of its frequency dependence [14-17]. It reduces the statistical PMD behavior of fiber without any loss, dispersion or non-linearity. In order to vary the random effect of PMD on system performance, seed parameter of AOPMD is varied from 1 to 25. Seed parameter is an integer value that defines the seed for the statistical process used in PMD model. At the end of simulation it

displays the Q-factor versus seed parameter. Moreover value of differential group delay (DGD) obtained for each statistically case is directly available as output of AOPMD [18]. After simulation, we also obtain input as well output optical spectrum using ideal, lorentzian and rectangular filter and from it we calculated optical signal to noise ratio [19]. OSNR graph is obtained with increase in seed parameter and determines the impact of PMD on the performance of the DWDM system [20].

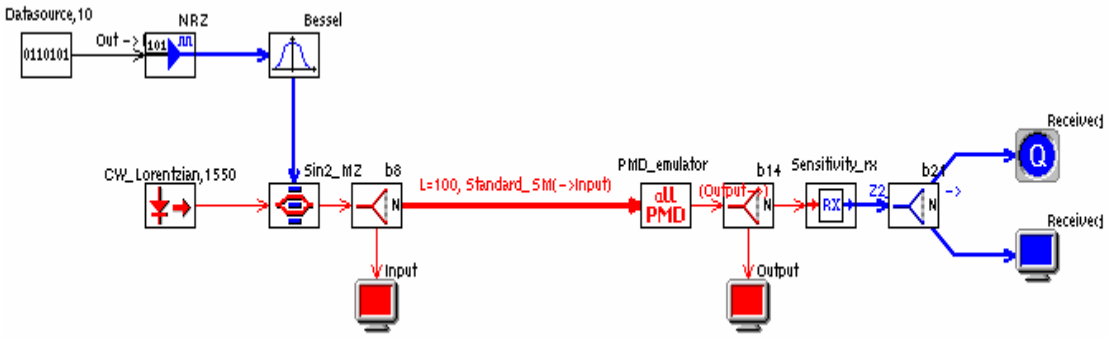


Figure 4.1 (Impact of PMD on DWDM system)

4.4 SIMULATION RESULTS AND DISCUSSION

In order to vary the random effect of PMD on system performance, seed parameter of AOPMD block is varied from 1 to 25. The input optical spectrum is obtained at the transmitter using ideal, lorentzian and rectangular filter as shown in figure 4.2. From the graph of input optical spectrum using lorentzian and rectangular filter OSNR is calculated and shown in figure using the square symbol. Delta symbol shows the channel. When we observe the graph 4.2 (b) and 4.2 (c), we found that in input optical spectrum obtained using lorentzian filter that OSNR value is 39.51 but in input optical spectrum using rectangular filter OSNR value increases to 49. As compared to input optical spectrum using ideal filter, peak power and peak frequency decreases as shown in table 6. Figure 4.3 shows the output optical spectrum using ideal. With increase in seed parameter, peak power decreases slightly i.e. with very minimal difference in all the three spectrums as shown in figure 4.3. Another observation is that with increase in seed parameter OSNR value increases. Its maximum value obtained is 31.7104, minimum value is 31.5924 and peak-to-peak amplitude is 0.118023 as shown in figure 4.4.

In the eye-diagram, we observe that with increase in seed parameter Q-value and eye-opening has lot of variation as shown in graph 4.5 and 4.6. Q-value has maximum value equal to 15.9145, minimum value is 7.24797 and peak-to-peak amplitude is 8.66657.

Mean value in range [1, 25] is 12.8926, standard deviation in range [1,25] is 2.0473, and variance in range [1,25] is 4.19146. Similarly, Maximum value is 4.9211e-006, Minimum value is 4.91144e-006 and peak-to-peak amplitude is 9.6602e-009 for eye opening versus seed parameter. Figure 4.7 shows the graph between differential group delay versus seed parameter. This shows that, DGD varies randomly with increase in seed parameter. Its Maximum value is 273.116, Minimum value is 30.9331 and peak-to-peak amplitude is 242.183 as obtained from the graph.

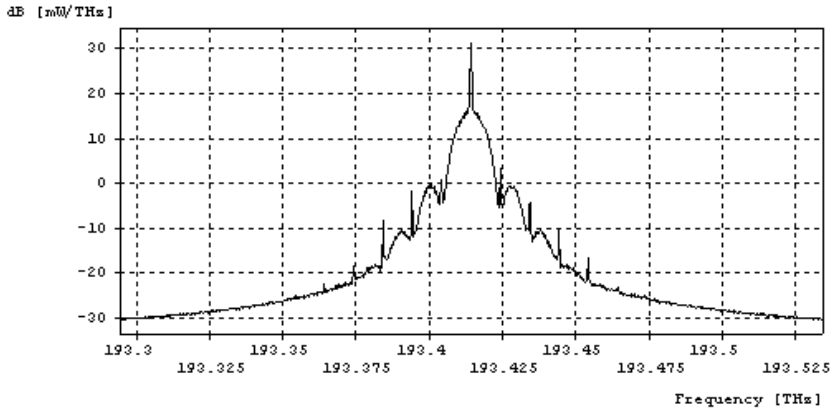


Figure 4.2 (a) (Input optical spectrum when ideal filter is used)

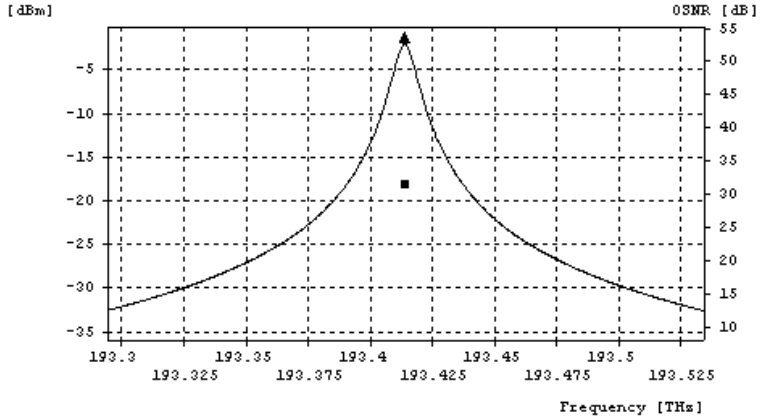


Figure 4.2 (b) (Input optical spectrum when lorentzian filter is used)

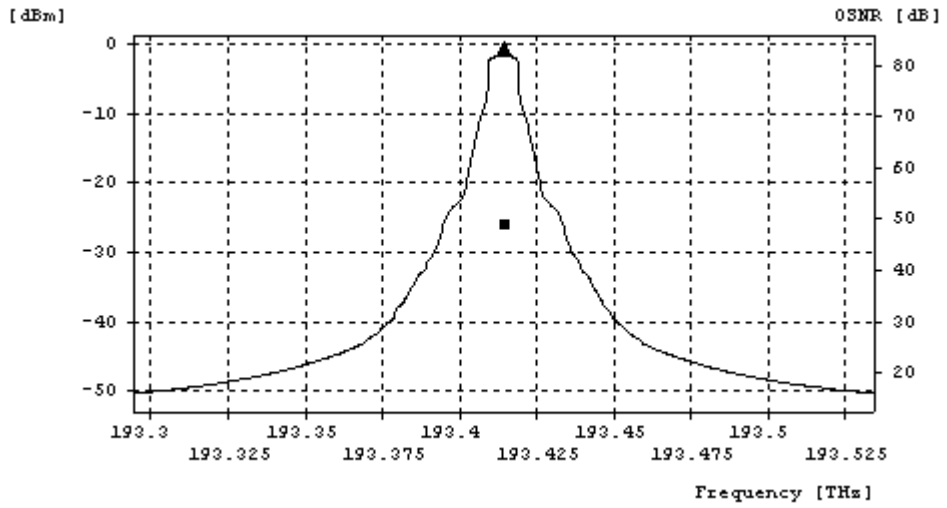


Figure 4.2 (c) (Input optical spectrum when rectangular filter is used)

Type of filter	Peak frequency	Peak power	OSNR
Ideal	193.415[THz]	31.274677dB[mW/THz]	NIL
Lorentzian	193.414[THz]	-1.868459[mW/THz]	31.513407
Rectangular	193.412[THz]	-1.353603[mW/THz]	49.008238

Table 11 (Analysis of input spectrum to study impact of PMD on DWDM system)

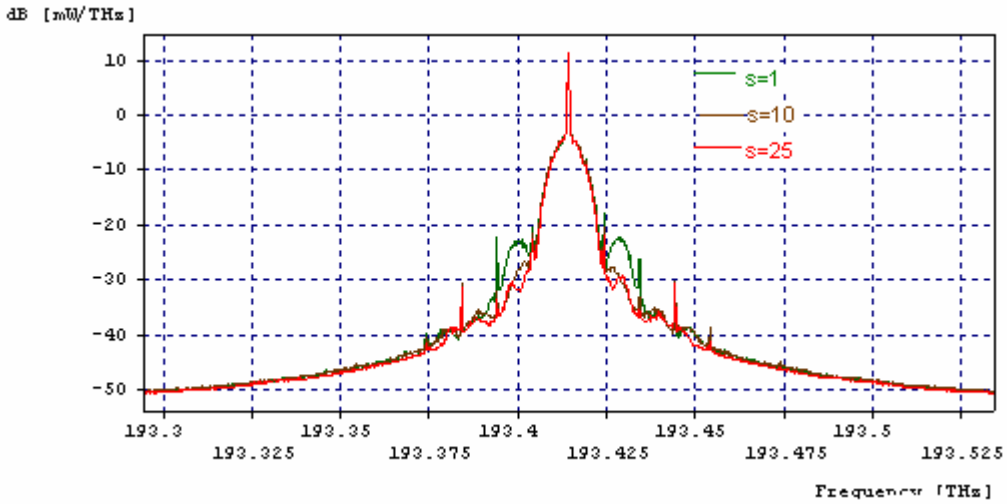


Figure 4.3 (Output optical spectrum when seed parameter is varied)

Seed parameter	**Peak frequency**	**Peak power**
1	193.415 [THz]	11.300062dB[mW/THz]
10	193.415 [THz]	11.297400dB[mW/THz]
25	193.415 [THz]	11.291031 dB[mW/THz]

Table 12 (Analysis of optical spectrum when seed parameter is varied using ideal filter)

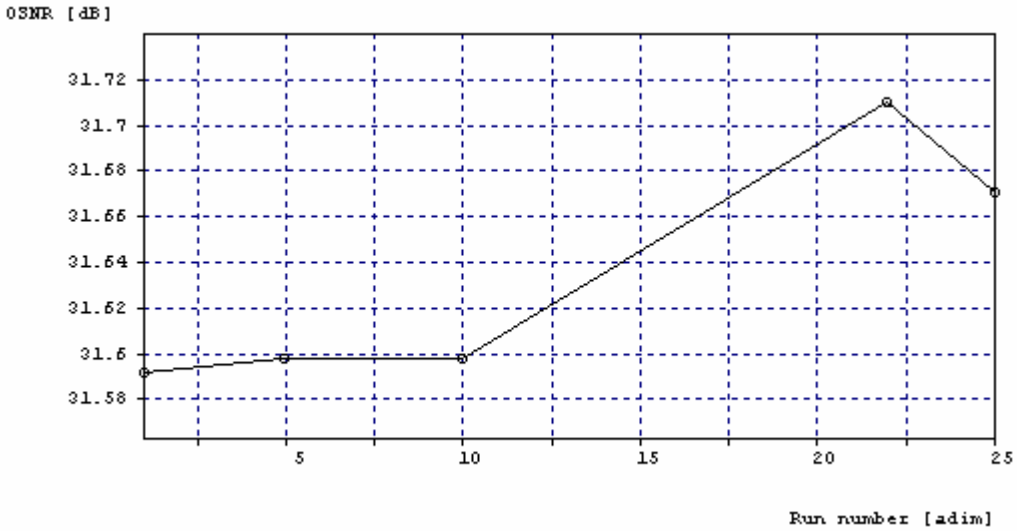


Figure 4.4 (OSNR Vs seed parameter)

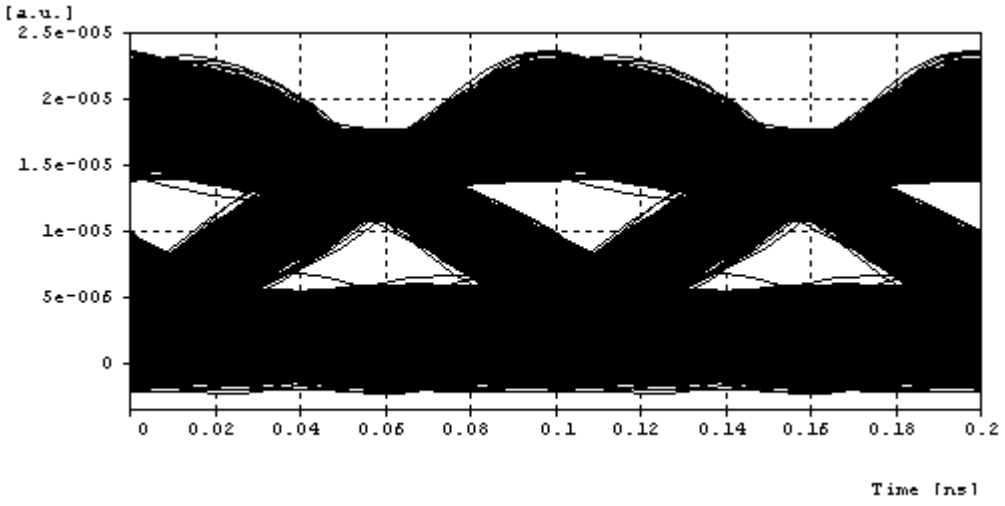


Figure 4.5 (a) (Eye diagram when seed parameter is 1)

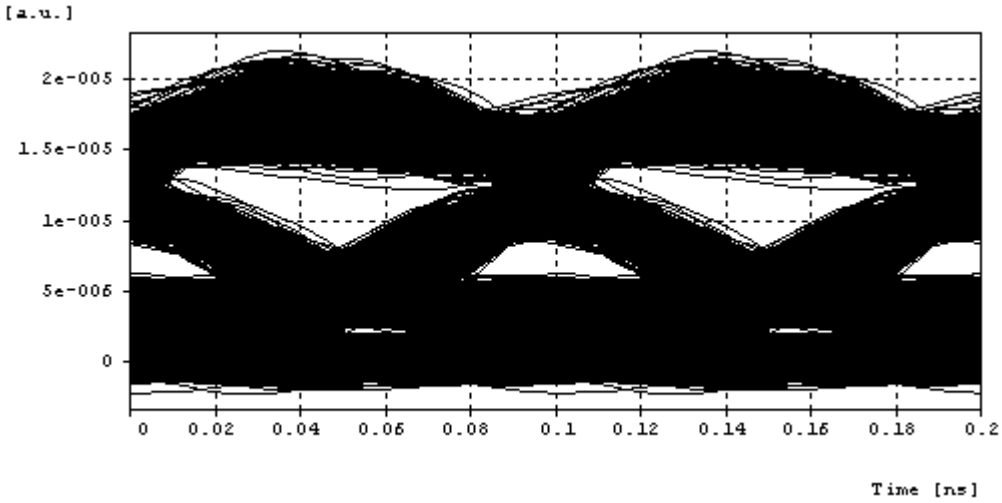


Figure 4.5 (b) (Eye diagram when seed parameter is 10)

Seed parameter	***Q-value [dB]***	***Bit error rate***	***Eye opening***	***Eye closure***	***Jitter***
1	*12.612*	*9.66e-006*	*4.47e-006*	*4.330358*	*0.0284539*
10	*9.641*	*0.0012*	*2.34755e-005*	*6.753368*	*0.0277977*

Table 13 (Analysis of eye diagram when seed parameter is varied)

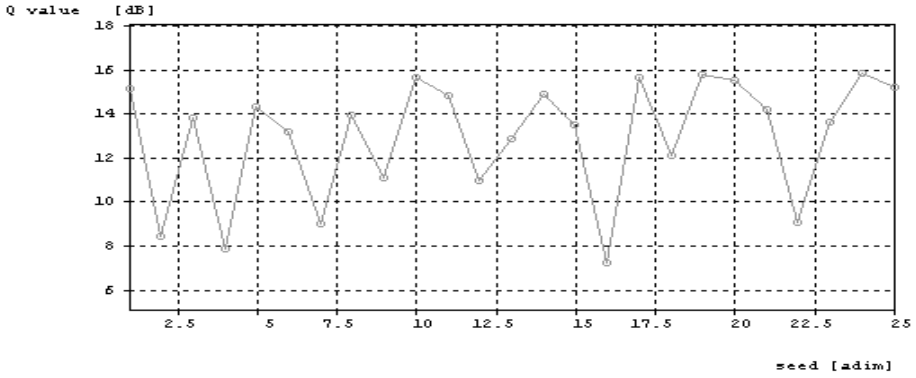


Figure 4.6 (Q-value versus seed parameter)

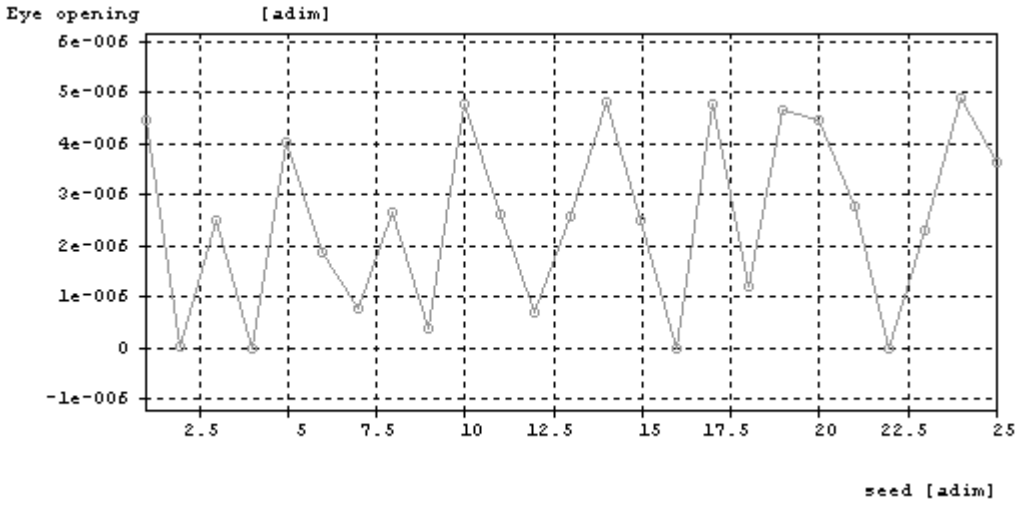


Figure 4.7 (Eye opening Vs seed parameter)

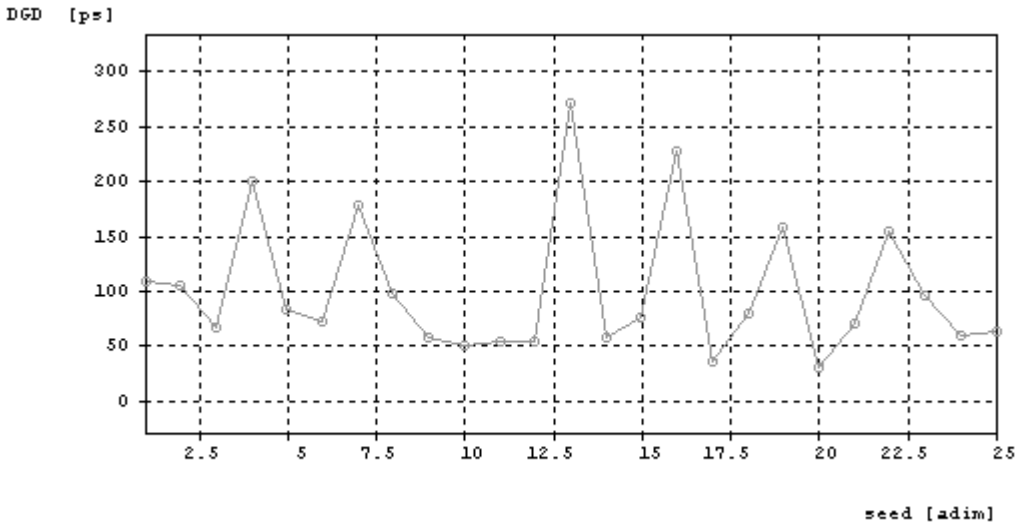


Figure 4.8 (DGD Vs seed parameter)

4.5 CONCLUSION

In this chapter effect of polarization mode dispersion is determined on single-channel 160 Gb/s system by varying the seed parameter. The effect of PMD is roughly estimated

through differential group delay parameter. To vary the random effect of PMD on system performance, seed parameter of AOPMD is varied and observe that peak power varies slightly in the output optical spectrum using ideal, lorentzian, and rectangular filters. OSNR increases with increase in seed parameter up to 20 and after it decreases. Q-Value, eye-opening and eye-closure graphs also show large variations with increase in seed parameter. Differential group delay (DGD) also varies due to random effect of PMD on system performance. DWDM system is more effected by non-linear impairments. The effect of PMD can be reduced by PMD dispersion compensation schemes.

CHAPTER 5

KERR NONLINEARITIES

5.1 ABSTRACT

This chapter demonstrates the effect of Kerr nonlinearities on 160 Gb/s DWDM system and look at their impact on the performance of long-haul DWDM system. The Kerr effects occur because of the variation of refractive index of the fiber core with optical power. The Kerr effects degrade the DWDM long-haul system performance more significantly than scattering effects. Hence impairments due to scattering effects are ignored in DWDM systems. Simulation results show that the magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate. FWM efficiency is also a function of signal polarization.

KEYWORDS: DWDM, SPM, XPM, FWM, and Optical power

5.2 INTRODUCTION

The nonlinear effects degrade the system performance. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects accumulate [35]. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing. The Kerr nonlinearities are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) which become important at increased channel bit rates. XPM and FWM are multi-channel nonlinearities. SPM is single-channel nonlinearities. To examine the impact of SPM, XPM and FWM the set up is designed and thus, to show the dependency of SPM, XPM and FWM on dispersion value, 160 Gb/s single-channel NRZ system is designed [35, 36]. FWM efficiency is also a function of signal polarization and the effect of polarization can be seen in the system using the extra component called polarizer. The optical spectrum clearly shows the impact of FWM on 160 Gb/s system as spectrum gets widened.

It has been observed that, the information capacity of a lightwave is ultimately limited by the nonlinear interactions between the information signals and the fiber medium [35-37]. These optical nonlinear interactions can lead to interference, distortion and attenuation of the signals, resulting in system degradation [37]. The nonlinear effects in fibers can be broadly classified into two categories: stimulated scattering effects and Kerr effects. The scattering effects are due to the interaction of light waves with molecular or sound waves in fiber. The scattering effects include Brillouin scattering (SBS) and Stimulated Raman Scattering (SRS) [38].

The SRS causes a power transfer between WDM channels, but it can be mitigated by the gain equalization schemes [34]. The impact of SBS in a long-haul DWDM system is not

critical due to lower channel power, but it is an important consideration in cable television transmission systems [36]. The Kerr effects occur because of the variation of refractive index of the fiber core with optical power. The Kerr effects degrade the DWDM long-haul system performance more significantly than scattering effects [35,37,39]. Hence impairments due to scattering effects, are ignored in DWDM systems [37, 38]. The fiber non-linearity which affects only the phase of the propagating signal is called the self-phase modulation (SPM)[39,40]. SPM is a single-channel effect and the interaction of SPM with fiber dispersion results in pulse broadening or eye closure at the receiver. The pulse spreading caused by SPM depends on channel power, fiber length and dispersion [40]. Cross-phase modulation (XPM) is similar to SPM, where the intensity modulation of one carrier modulates the phases of other co-propagating carriers [41-43]. XPM is multi-channel effect. The magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate [42]. Larger the channel spacing yields less XPM [35,41,42]. Four-wave mixing (FWM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components [43]. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate [44,45,50].

In this chapter, we determine the impact of Kerr nonlinearities on 160 Gb/s DWDM system. Separate system set ups are designed for each Kerr nonlinearities and then different results have been obtained to determine the performance of 160 Gb/s system. Optical spectrum, eye-diagram, Q-value, OSNR, eye opening and optical power are evaluated from the simulation for each Kerr nonlinearities.

This chapter is organized into six sections. First and Second section gives the introduction of the chapter, literature survey and thesis organization. Third section describes the impact of self-phase modulation on 160 Gb/s DWDM system and to examine the dependency of self-phase modulation on dispersion value, 160 Gb/s single channel NRZ system is designed. Thus, dispersion value is varied to obtain different results. In fourth section, to show the dependency of XPM on dispersion value multichannel system is designed and different results have been taken to show the impact. In fifth section, DWDM set up is designed to show the dependency of FWM on dispersion value. Sixth section gives conclusion of whole chapter.

5.3 SYSTEM SETUP FOR SPM

The fiber non-linearity which affects only the phase of the propagating signal is called the self-phase modulation (SPM). SPM is a single-channel effect and the interaction of SPM with fiber dispersion results in pulse broadening or eye closure at the receiver. The pulse spreading caused by SPM depends on channel power, fiber length and dispersion. Now, to examine the dependency of self-phase modulation on dispersion value, 160 Gb/s single channel NRZ system is designed as shown in figure 5.1. Dispersion values are varied from –10 to 10 ps/nm/Km [41]. The power at each span is set to 10 dBm. The fiber grating is used to compensate over fiber span L Km length the accumulated dispersion and its slope [42]. It a passive device with a flat modulus frequency response and a group delay corresponding to a given total dispersion and dispersion slope. With help of optical spectrum analyzer, electrical scope and Q-estimator simulation results are taken which shows the dependency of SPM on dispersion value. Before transmission over the optical

fiber link results obtained such as eye diagram, Q-value versus dispersion and eye opening Vs dispersion etc are shown below. When dispersion is varied from -10 to 10 ps/nm/Km, at transmitter side all eye diagrams are wide even Q-value versus dispersion and eye opening versus dispersion are straight line i.e. there is no effect of dispersion [43].

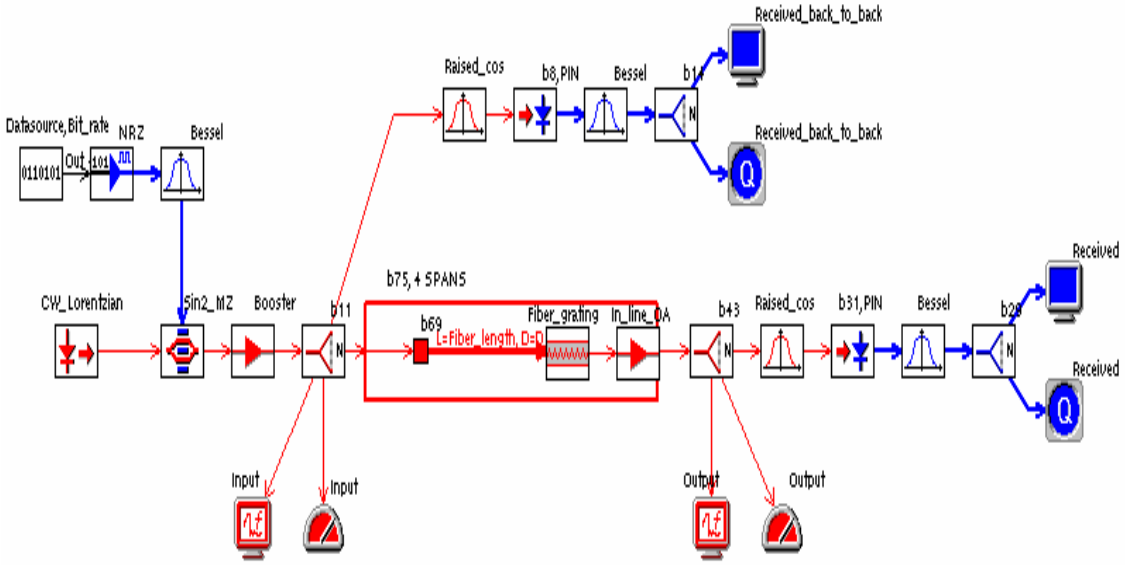


Figure 5.1 (Impact of dispersion value on SPM)

5.3.1 Simulation results and discussion for SPM

After simulation, different results are obtained. Firstly, we observe the results obtained before transmission over fiber link. Before transmission eye-diagram obtained is wide as shown in figure 5.2. Even Q-Value, eye opening is also constant for different values of dispersion as sho[illegible]on. But after transmission ove creases with increase in dispe increase in dispersion as sho lation results that, when D<0, t er frequency components of th bined effects of fiber nonlinear urs when the fiber dispersion D>0, it results in pulse narrowing or compression. Thus eye opening reduces and eye closure increases as shown in figure. The effect of SPM can be reduced by optimizing the channel power and by using a good dispersion map in a DWDM long-haul lightwave link [46].

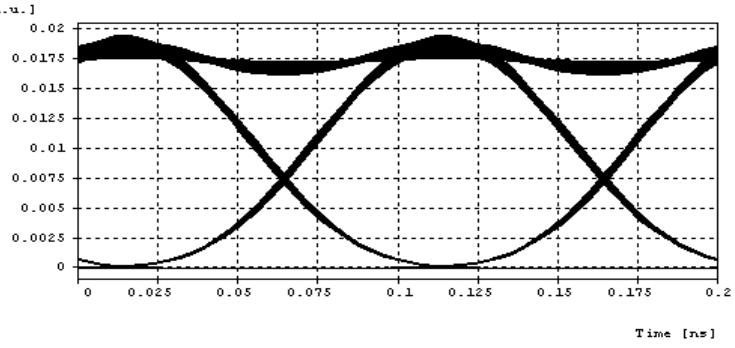


Figure 5.2 (Eye diagram before transmission)
Figure 5.3 (Q-Value before transmission)

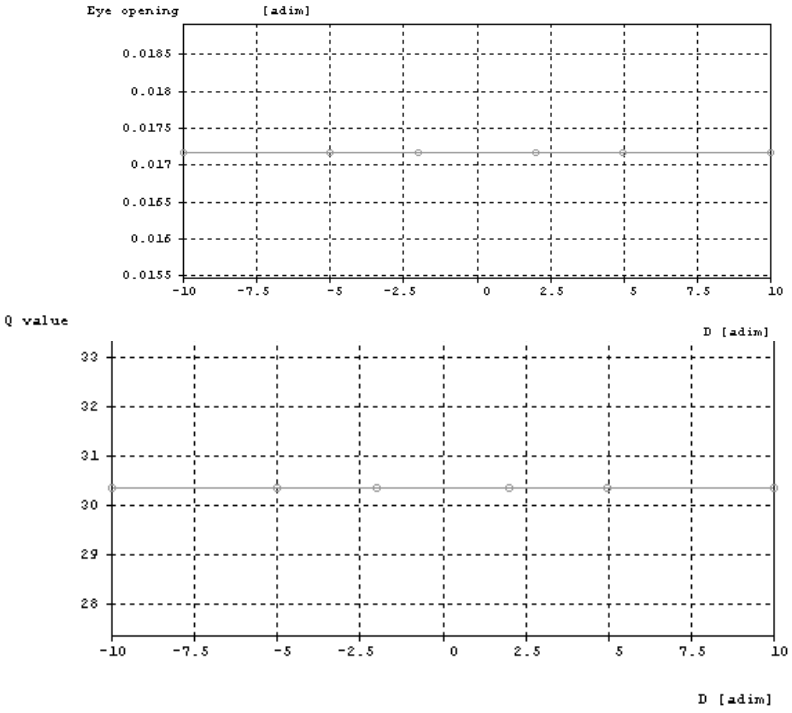


Figure 5.4 (Eye opening before transmission)

Figure 5.5 (Q-Value Vs dispersion at receiver)

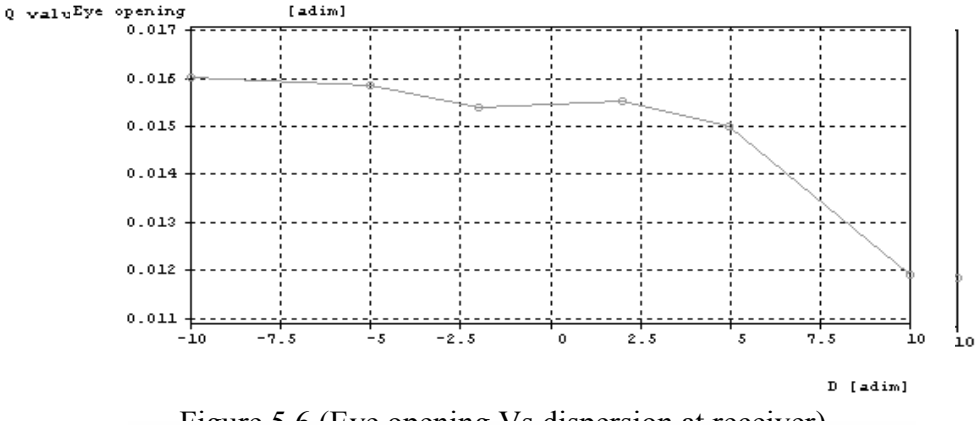


Figure 5.6 (Eye opening Vs dispersion at receiver)

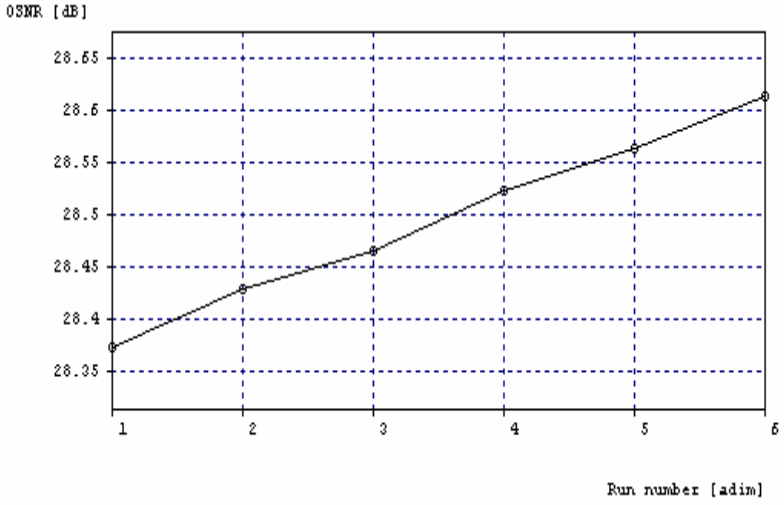


Figure 5.7 (OSNR Vs dispersion at receiver)

Figure 5.8 (a) (Eye diagram at D=-10ps/nm/Km at receiver)

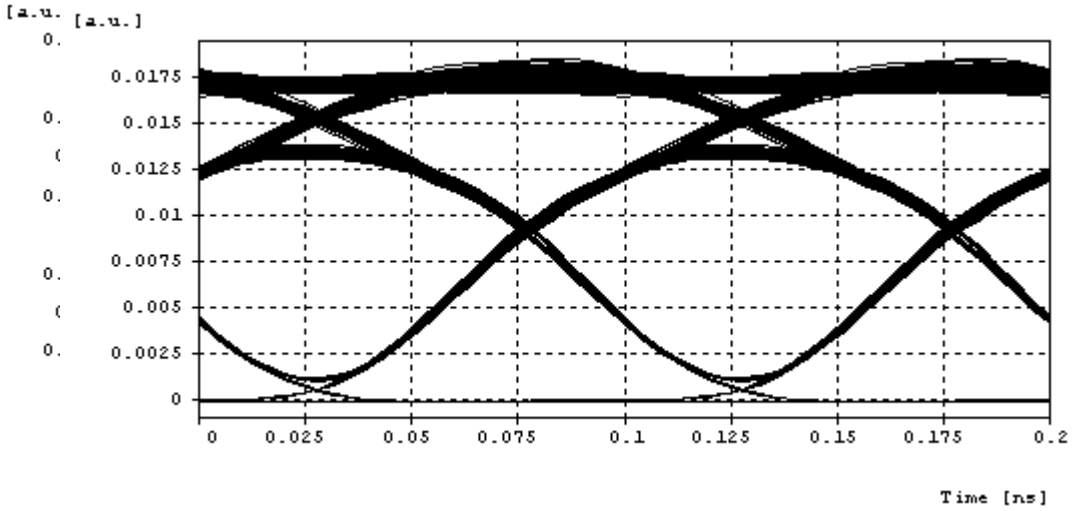


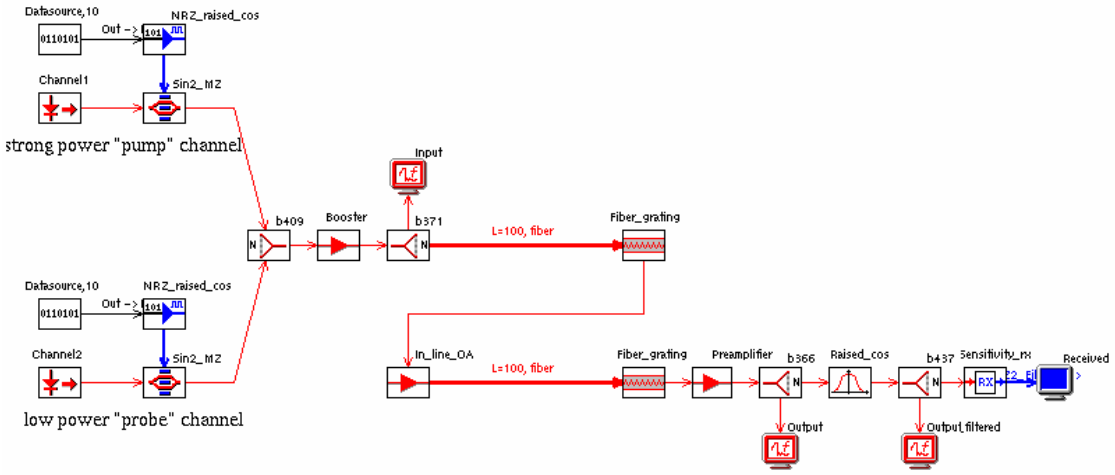
Figure 5.8 (b) (Eye diagram at D=10ps/nm/Km at receiver)

Dispersion	Q-Value [dB]	Bit Error Rate	Eye opening	Jitter
-10	26.7972	1e-040	0.16039	0.01666
-2	30.889	1e-040	0.01596	0.01849
2	33.0042	1e-040	0.01554	0.02206
10	18.6577	1.84e-01	0.01192	0.02657

Table 14 (Analysis of eye diagram at receiver when dispersion is varied)

5.4 SYSTEM SETUP FOR XPM

Cross-phase modulation (XPM) is similar to SPM, where the intensity modulation of one carrier modulates the phases of other co-propagating carriers. XPM is multi-channel effect. The magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate. Larger the channel spacing yields less XPM. XPM arises, when the phase of one optical carrier is modulated by other DWDM channels [47]. The impact of XPM can be minimized by employing proper dispersion management techniques. The XPM effect is always accompanied by the SPM effect. For a separation of XPM from SPM, an efficient method is the ”pump-probe” method, in which an intensity modulated channel (pump) with a large channel power distorts a CW-probe channel is used. To show the



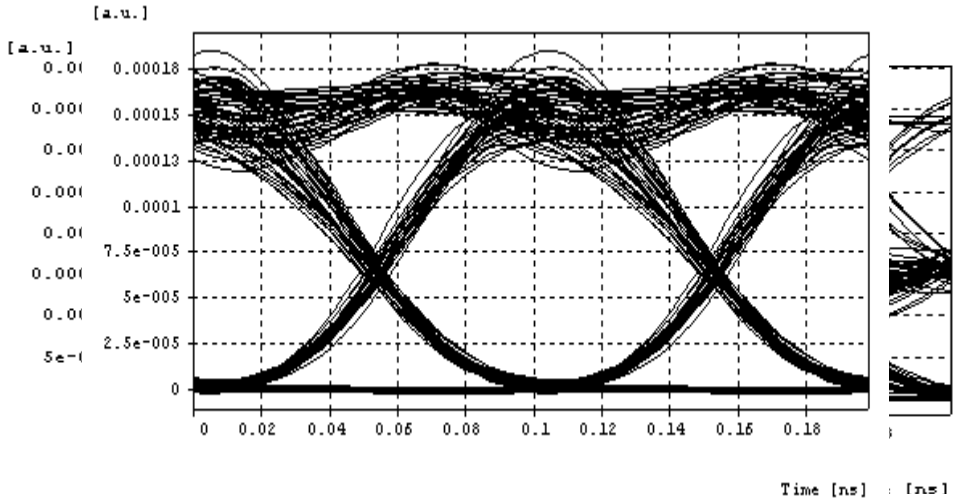
dependency of XPM on dispersion value, it is varied from 0 to 4 ps/nm/Km. Set up is shown in figure 5.9 in which two DWDM channels are launched over two DS fiber span of 100 Km each. In order to focus on XPM, one of the two channels-"the probe" has lower power and sent along the link together with stronger "pump" channel. Both probe and pump channel are modulated by NRZ signals at 160Gb/s [47,48]. The effects of XPM are visible as enlargement of received probe spectrum and distortion in eye diagram as shown in figure .Now, after simulation, different results have been obtained to see the impact of dispersion on XPM. Eye diagram, optical spectrum have been observed for different values of dispersion and these results are shown below:

Figure 5.9 (Impact of dispersion on XPM)

5.4.1 Simulation results and discussion for XPM

To examine the performance of the system, results have been taken after simulation eye-diagrams are observed which shows that when dispersion value is 0, we get worst eye diagram as shown in figure 5.10 (a). But when dispersion value is 4, eye diagram is wide as shown in figure 5.11 (b). Then, we observe the optical spectrum. In input optical spectrum, we get two peaks but due to increase in dispersion value we can see the impact of XPM and thus at zero dispersion there is enlargement of probe spectrum but not at dispersion value 4 as shown in figure 5.12. We get required spectrum at dispersion value 4 and free from distortion. Thus, this point is tolerable point.

Figure 5.10 (a) (Eye diagram when D=0)
Figure 5.10 (b) (Eye diagram when D=4)



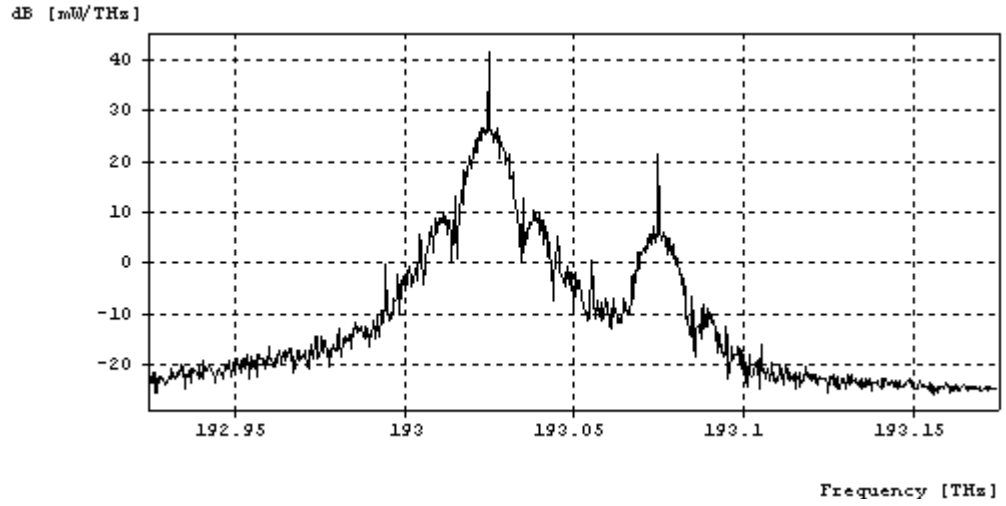


Figure 5.11 (a) (Input spectrum at transmitter)

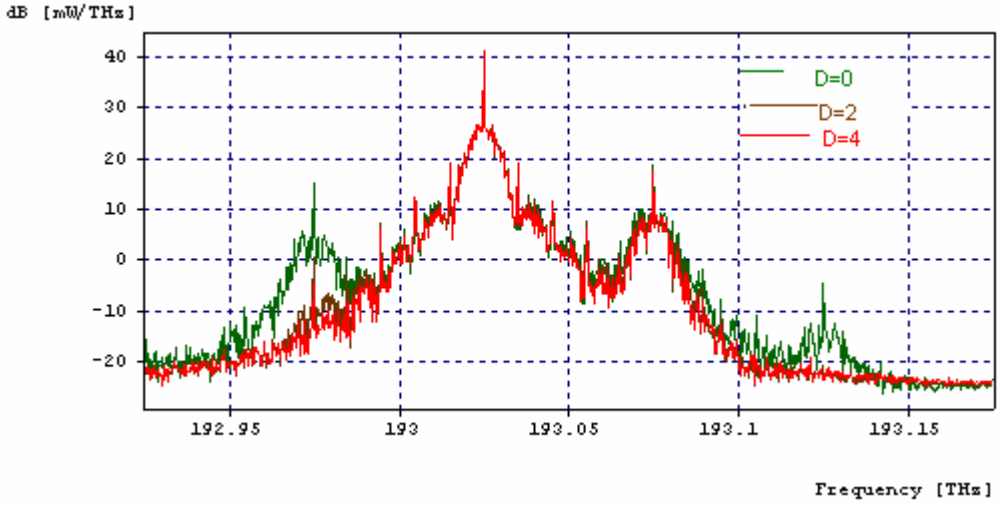


Figure 5.11 (b) (Output spectrum at receiver when dispersion is varied)

5.5 SYSTEM SETUP FOR FWM

Four-wave mixing (FWM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components [47-50]. For example, when two waves co-propagate at frequencies fp and fq through a fiber, the mixing of these two waves result in two new waves at the frequencies 2fp-fq and 2fq-fp. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate [47,48]. FWM efficiency is also a function of signal polarization. In FWM efficiency versus channel spacing for different dispersion values, it can be seen that low dispersion fiber have a higher FWM efficiency than high dispersion fibers and efficiency decreases with increase in channel spacing [48]. DWDM set up is designed to show the dependency of FWM on dispersion value as shown in figure 5.12. Two DWDM channel are launched over two DS fiber span of 100 Km each. Dispersion is compensated at each span. Fiber dispersion value is varied from 0 to 4 ps/nm/Km [49]. The optical power spectrum of received signal shows the FWM product decrease with increasing dispersion as shown in figure 5.13.

Figure 5.12 (Impact of dispersion on FWM)

5.5.1 Simulation results and discussion for FWM

At transmitter input optical spectrum achieved is shown in figure 5.14 (a) has two waves at frequencies fp and fq. But in optical spectrum as shown in figure 5.14(b) two new waves at frequencies 2fp-fq and 2fq-fpare achieved and spectrum broadened at different values of dispersion. Even the optical power decreases with increase in dispersion in FWM as shown in figure 5.14.

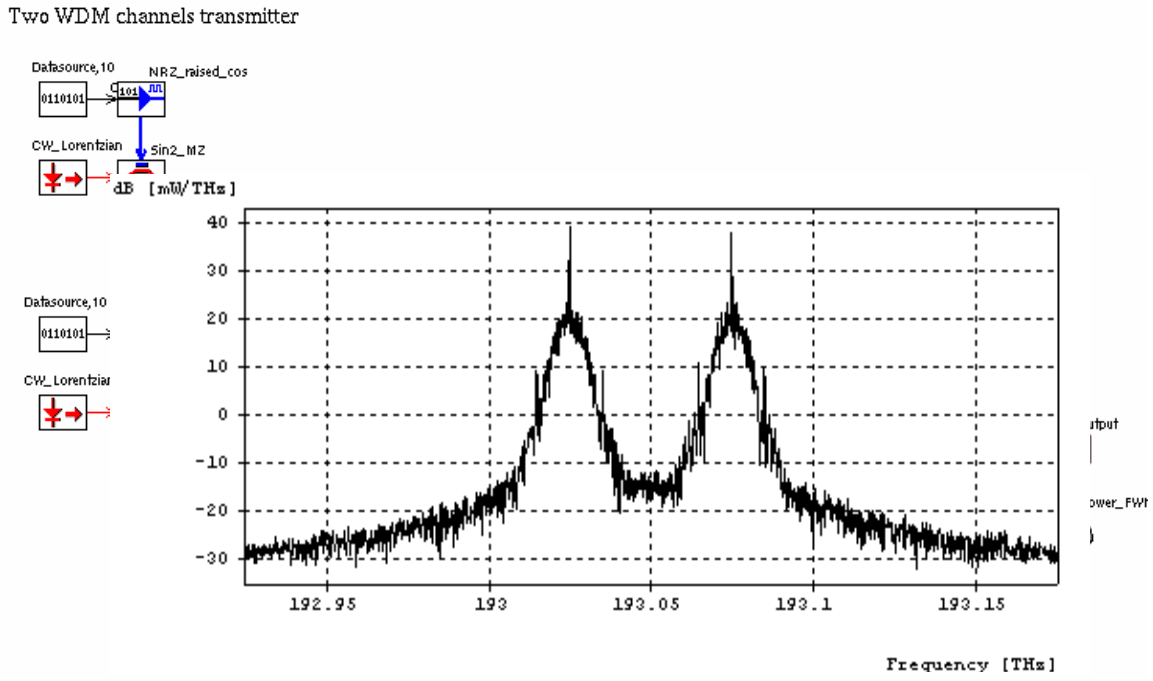


Figure5.13 (a) (Input spectrum at transmitter for FWM)

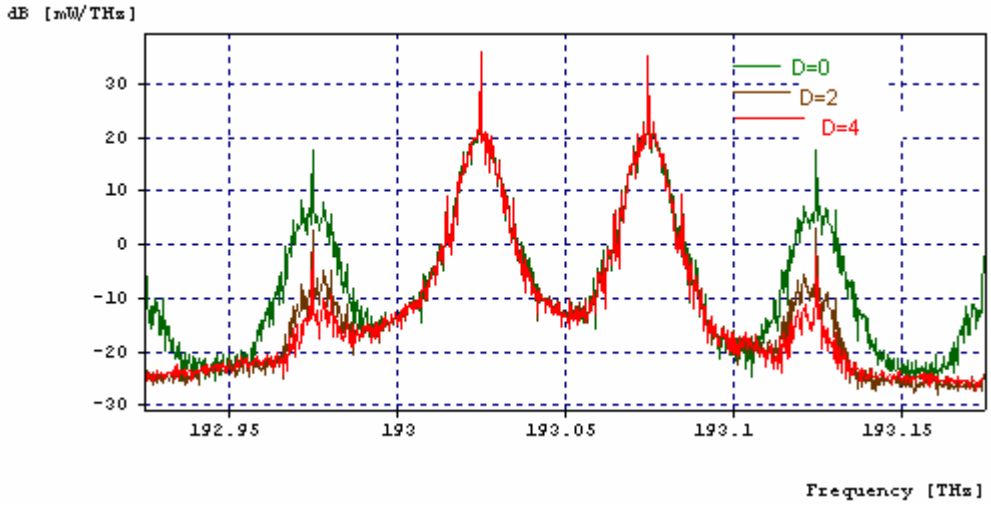


Figure 5.13 (b) (Output spectrum at receiver for FWM)

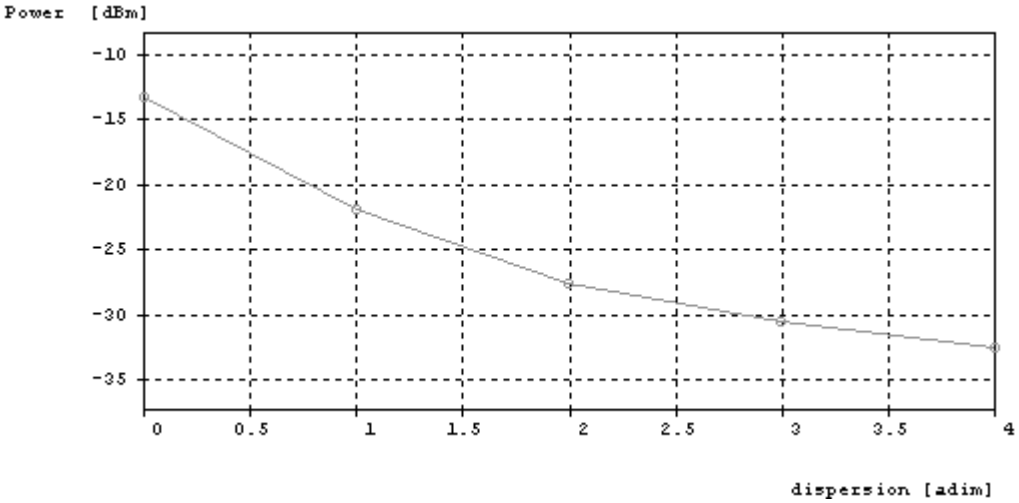


Figure 5.14 (Optical power spectrum versus dispersion)

5.6 CONCLUSION

Nonlinear effects become important in DWDM system when optical power is high. To show the dependency of SPM on dispersion value, 160 Gb/s single-channel NRZ system is designed and observe that when D<0, the higher frequency components travel slower than the lower frequency components of the pulse. Hence, the pulse is broadened by the combined effects of fiber nonlinearity and dispersion. Similarly, the opposite phenomenon occurs when the fiber dispersion D>0, it results in pulse narrowing or compression. Thus, eye opening reduces and eye closure increases. XPM is multi-channel effect. The magnitude of XPM depends on fiber dispersion, fiber length, channel spacing and bit rate. To show the dependency of XPM on dispersion value, it is varied from 0 to 4 ps/nm/Km. The effects of XPM are visible as enlargement of received probe spectrum and distortion in eye diagram. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate. FWM efficiency is also a function of signal polarization. FWM products are maximum when

polarization are aligned and nearly completely reduced to zero when two polarizations are orthogonal. The effect of SPM can be reduced by optimizing the channel power and by using a good dispersion. But impairment due to FWM can be minimized by spacing the channels unequally, ensuring that no mixing products fall on any of the channels, along the use of appropriate dispersion management.

6.1 CONCLUSION

The worldwide demand for bandwidth is soaring, driven by increasing Internet usage. To meet this demand, telephone companies are working on ways to implement dense wavelength-division multiplexing, a technology designed to wring more bandwidth out of fiber-optic cable. Dense wavelength-division multiplexing (DWDM) could be described as trying to solve rush-hour traffic congestion by adding more lanes to the free-way without making it any bigger. DWDM increases the number of communication channels within a fiber-optic cable, thereby letting service providers obtain much more bandwidth without installing expensive new cable. The technology increases transmission speeds up to 16 times, to as much as 40 Gbps, where bottlenecks exist now. Speeds could increase to as much as 80 Gbps next year. More bandwidth for carriers could mean better Internet and intranet performance, faster data transmission, more robust multimedia applications, and, theoretically, stable or lower access rates.

SONET and SDH take a Time Division Multiplexed (TDM) electrical signal and convert it to an optical signal ensuring it meets their exact criteria. That signal is then sent out over a single fiber into the network. Dense Wave Division Multiplexing (DWDM) combines multiple signals carrying SONET or SDH (or, in reality, any format) onto one single fiber. It does this by first assigning incoming optical signals to specific frequencies (wavelength, lambda) within a designated frequency band. Then it multiplexes the resulting signals together and sends them out onto one fiber. Because incoming signals are never terminated in the optical layer, the interface can be bit-rate and format independent.

DWDM is really just the first step on the road to full optical networking. An all-optical network implies that the service provider will have optical access to traffic at various nodes in the network just as they have access today in the SONET layer for SONET traffic. Optical Wavelength Add/Drop (OWAD) is that capability. Wavelengths are added or dropped to/from a fiber without fully separating out all of the signals individually. But ultimate bandwidth management flexibility will come with a cross-connect capability on

the optical layer. Combined with OWAD and DWDM, the optical cross-connect will permit a flexible, high-capacity, efficient optical network with full optical bandwidth management.

Since DWDM combines multiple optical signals together onto one fiber, they can be amplified as a group and transported over that single fiber thus increasing the fiber's capacity. Each signal carried can be at a different rate (OC-3/12/24, etc.) and a different format (SONET/SDH, ATM, Data, etc.). For example, a DWDM network with a mix of SONET signals operating at the over a DWDM infrastructure can achieve capacities of 160 Gb/s and beyond. Thus DWDM system can carries up to 80 wavelengths on one fiber. At maximum configuration (eight fibers, each carrying 400 Gb/s), service providers could transmit 90,000 volumes of an encyclopedia in one second on a single fiber. The system supports SONET/SDH signal input of OC-48/STM-16 (for a total of 200 Gb/s), or up to 40 wavelengths of OC-192/STM-64 (for a total of 400 Gb/s), or a combination of both. This DWDM system is the first to support a simultaneous mix of these speed rates over one fiber, giving service providers more flexibility as they increase network capacity.

DWDM systems are bit-rate and format independent. They can accept any combination of interface rates (e.g., synchronous, asynchronous, OC- 3/STM-1, OC-12/STM-4, OC-4WSTM- 16 or OC-192/STM-64) on the same fiber-at the same time. If a carrier operates both an ATM and a SONET network, the ATM signal would not have to be multiplexed up to the SONET rate to be carried on the DWDM network. Since the optical layer carries signals "as is" without any additional multiplexing, carriers can quickly introduce ATM or IP without deploying an overlay network. An important benefit of dense wavelength division multiplexing system is that any type of cargo can be carried on the "highway."

Since the development and deployment of optical transmission networks offer improved possibilities for dealing with ever growing demands on transmission bandwidth and system capacity. The deployment of future optical networks and upgrade of existing ones will be governed by the growth of the traffic in all network areas. The capacity and traffic needs of new transmission services were expected to require the upgrade of existing networks to system capacities up to 3 Tbit/s. The question arising here, is what is the best transmission technology to be implemented in future systems. The key technology for providing a better exploitation of the existing transmission infrastructure is dense wavelength division multiplexing (DWDM). Thus in order to achieve maximum transmission performance and spectral efficiency, highest channel data rate should be employed and thus it will led to increase in overall system capacity. In this thesis work, I designed single-channel NRZ DWDM transmission system at 160 Gb/s channel data rate using. After simulation we observed that eye diagram is wide and there is less effect of

dispersion. Then fiber transmission length and attenuation is varied. We observed that eye opening value decreases with increase in fiber length and attenuation. Bit error at received power first remain constant upto 30 dB then suddenly increases and Q-value also decreases with increase in attenuation. During the analysis of electrical signal obtained after simulation it is observed that peak-to-peak amplitude increases slightly with increase parameter values. When fiber length is varied, there is small increase in bit error rate with increase in received power. Thus we find that the effect of distortion and noise is minimum in single-channel 160 GB/s NRZ DWDM transmission system. Thus, we conclude that 160 Gb/s shows the best transmission potential as compared to 10 Gb/s and 40 Gb/s channel data rate due to reduced complexity in realization and availability of required 160 Gb/s system components.

After evaluating single channel 160 Gb/s system, 16 x 160 Gb/s NRZ DWDM transmission is designed. In this 16-channel transmitter and 16-channel receiver is designed as compound component of the system. 4-channel optical add/ drop multiplexer is used so that the service provider will have optical access to traffic at various nodes in the network. Wavelengths are added or dropped to/from a fiber without fully separating out all of the signals individually. In this we observed that eye opening reduces with increase in fiber length and thus eye closure increases. Q-Value also reduces with increase in fiber length. Thus, mean standard deviation and variance is evaluated for them. Then the optical spectrum at the receiver OSNR is evaluated at each channel (i.e. at all 16 channels) and observed that OSNR increases with increase in frequency and power at different fiber length using lorentzian and rectangular filter. Electrical spectrum is obtained by varying attenuation and observed that peak power and peak frequency decreases with increase in attenuation. Thus 16 x 160 Gb/s DWDM system provide 2.56 Tb/s capacity. In single-channel 160Gb/s optimum value of attenuation is 23 dB. In this we have wide eye diagram. But, in 16-channel 160Gb/s DWDM system optimum value is 3 dB and has eye opening small. In single channel 160Gb/s DWDM system fiber length is varied up to 150 Km but in 16-channel it is just varied up to 80 Km. At 80 Km eye opening is less as compared to eye opening at 150 Km in single –channel. But 16-channel 160 Gb/s DWDM system provide capacity up to 2.56 Tb/s and thus, large information can be transferred to the receiver.

Different system impairments-linear effects and nonlinear effects are studied. Linear effects such as attenuation, chromatic dispersion and polarization mode dispersion effects the DWDM system. Due to the impact of polarization mode dispersion there is large variation in Q-value and eye opening. There is also large variation in differential group

delay (DGD) due to PMD. This lead to worse performance of DWDM system. Then we compare the simulation results of 160 Gb/s DWDM system with 40 Gb/s DWDM system and observe that 40 Gb/s system suffers more from PMD. But effect of PMD is less severe on 160 Gb/s DWDM system as variation in output optical spectrum is very small with increase in seed parameter. The effect of PMD can be reduced by PMD dispersion compensation schemes. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects accumulate. The nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM. The scattering effects include stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The SRS causes a power transfer between DWDM channels, but it can be mitigated by the gain equalization schemes. The impact of SBS in long-haul DWDM system is not critical due to lower channel power. The kerr effects occur because of variation of refractive index of the fiber core with optical power. The kerr effects degrade the DWDM system performance more significantly than the scattering effects. The effect of SPM can be reduced by optimizing the channel power and by using a good dispersion map in a DWDM long-haul lightwave link. But impairment due to FWM can be minimized by spacing the channels unequally, ensuring that no mixing products fall on any of the channels, along the use of appropriate dispersion management. Also, the fiber with a large effective area has proven to be quite effective in reducing the FWM products.

Thus 160 Gb/s based systems can enable an improved system capacity and an enhanced spectral efficiency, which seems to be necessary for future transmission systems, because the increasing bandwidth demands make the better utilization of existing system bandwidth an important target for the future design works. Better bandwidth utilization does not mean increased spectral efficiency at any cost, e.g. with a significant reduction of transmission distance or an increased complexity of transmission line. It is rather the introduction of novel transmission technologies, e.g. modulation formats, sophisticated filtering methods and dispersion compensation schemes, which are characterized by a compatibility with the existing transmission line infrastructure and by a reduced complexity enabling a straightforward system upgrade from lower channel date rates.

6.2 FUTURE SCOPE OF WORK

The future of DWDM system is Ultra-dense wavelength division multiplexing system (UDWDM). Ultra-Dense Wavelength Division Multiplexing (UDWDM) is the science and technology of packing optical communication channels as closely as physically possible on a single optical fiber or any other optical medium. While the UDWDM concept originated in long-haul fiber-optic communications, it is also expected to be a key enabling technology for future massively parallel computing systems. Currently, much research in optical communications is focused on increasing the bit-rate of individual optical channels from 10 Gb/s to 160 Gb/s. This “high-speed” approach faces serious obstacles due to fiber chromatic dispersion (CD) and polarization-mode

dispersion (PMD) since the dispersion penalty scales roughly as $(\text{bitrate})^2$. An alternative equally valid approach for increasing transmission capacity, which however has not received as much attention, is to scale DWDM channel spacing to ultra-dense dimensions of ~ 10 GHz, while keeping the bit rate fixed at 10 Gb/s. This latter approach is known as Ultra-dense WDM (UDWDM). The development of 10 Gb/s UDWDM technology would enable continued advancement in fiber-optic transmission capacity without requiring dramatic upgrades in infrastructure (i.e. new fiber, Raman distributed amplification, per-channel PMD compensation, etc.) as would be needed for 160 Gb/s systems. Moreover, 10 Gb/s UDWDM may be the only practical way for Si-based optical interconnects to approach the capacity of optical fiber since Si-based optoelectronic devices are unlikely to ever attain speeds greater than 10 Gb/s.

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