Performance Analysis of DWDM Systems with Optical Add Drop Multiplexers and Optical Cross Connects

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Sanjeev Dewra

Registration No. 900906005

Supervisors

Dr. R.S. Kaler

&

Dr. Kuldip Singh

Department of Electronics and Communication Engineering

Thapar University,

Patiala -147004, Punjab, India

Certificate

I, **Sanjeev Dewra** hereby certify that the work which is being presented in this thesis entitled **“Performance Analysis of DWDM Systems with Optical Add Drop Multiplexers and Optical Cross Connects”** in fulfilment of requirements for the award of degree of Doctor of Philosophy in Electronics and Communication Engineering from Thapar University, Patiala is an authentic record of my own work carried under the supervision of **Dr. R.S Kaler and Dr. Kuldip Singh**.

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

Date: **(Sanjeev Dewra)**

Signature of the candidate

This is certified that above statement made by the candidate is correct to the best of my knowledge.

Supervisors:

Dr. R. S. Kaler	**Dr. Kuldip Singh**
Senior Professor & Dean (RPG)	Ex. Professor
ECED, Thapar University,	IIT-Roorkee
Patiala, Punjab, India.	

Abstract

This thesis deals with Performance analysis of Optical Add /drop multiplexers and optical Cross connects for Dense Wavelength Division Multiplexing system. It is essential to add/remove different channels in an optical communication system. The OADM provides flexibility and greater connectivity in the optical communication system. The OXC permits the system to be reconfigured on a channel by channel basis to optimize and exchange signals pattern, facilitate growth of network and increases network survivability. The sharing of system devices like OXADM, amplifiers and ROADM is permitted by the grouping of a multiple channels on a single fiber which results in cost savings. The Optical cross add drop multiplexer provides adding/dropping function and cross connecting signals similar to OADM and OXC in the optical system. Reconfigurable add drop multiplexer enables many channels which carry data to be added/dropped from optical fiber port without the need of optical-electrical-optical conversion. The designing and investigation of OXC, OADM using MZI-techniques, OADM based on FBG-circulator and ROADM based on DCE, PLC and WSS in fiber optical communication system is presented.

Firstly, an optical system performance in terms of crosstalk with OADM based on MZI, MZI-semiconductor optical amplifier and MZI-FBG techniques placed at 20 km point of a 40 km link obtained at 8 × 10 Gbps with 0.1 nm channel spacing has been evaluated and found that with the MZI-FBG based OADM, the signal can be transmitted with very less bit error rate and improved Quality value whereas MZI-SOA based OADM shows the worst results. The dense WDM system with optical add drop multiplexer placed at 35 km point of a 70 km link has also been investigated and is found that MZI-FBG based OADM and OADM based on MZI provide better results with covered transmission distance (150km) at channel spacing of 0.1 nm and 10 Gbps bit rate without using DCF and amplifier. It is observed that the worst case is with the MZI-SOA based OADM. In addition, it is observed that the MZI-based OADM is cost effective as compared to MZI–Semiconductor optical amplifier and MZI–Fiber Bragg grating based OADM. Further, unique architecture of an OADM based on FBG-Optical circulator has also been investigated for DWDM system with different modulators like Amplitude Modulator (AM), Mach-Zehnder (MZ) and Electro absorption (EA). This investigation has been done at 40 Gbps/ channel with ultra-narrow channel spacing of 0.1 nm. The maximum distance can be achieved

upto 70 km with acceptable BER performance using AM modulator. It is reduced to 50 and 30 km with MZ and EA respectively. It is also found that using Amplitude Modulator, the structure provides acceptable BER with 280 GHz maximum FBG bandwidth and 9 dB insertion loss, circulator insertion loss of 4.5 dB.

Further, the investigation of DWDM system based on OXCs using MZI, MZI-Semiconductor optical amplifier and MZI-Fiber Bragg grating techniques in the presence of crosstalk at 4x10 Gbps with 0.1nm channel spacing using standard single mode fiber has been done. To examine the optical communication system performance, the influence of increase in fiber length has been investigated. It is observed that the signal can be reached with minimum bit error rate using MZI-Fiber bragg grating based OXC and MZI based OXC up to 80 km whereas, the MZI-Semiconductor optical amplifier based OXC provides poor performance**.** The input-output power relationship shows improvement up to -14 dBm approximately in output power for MZI based OXC and MZI-FBG based OXC. It is observed that MZI based OXC architecture is cost efficient in comparison to MZI-SOA and MZI-FBG based OXC architectures.

In addition, this thesis gives an insight into the scope of integration of optical add/drop multiplexer and OXC. The performance of DWDM system using OXADM at 4 × 10 Gbps with 0.1 nm channel spacing and the effect of attenuation, insertion loss and crosstalk has been demonstrated and observed that the signal can be transmitted up to 85 km without amplification at 6 dB insertion loss with 50 dB attenuation. Further, it is analyzed that the system provides acceptable performance with maximum of −35 dB crosstalk at 70 dB insertion loss and 6 dB attenuation for the same transmitted distance. We show enhancement in distance of transmission at reduced channel spacing and high bit rate.

The thesis also highlights the investigative study of the effect of crosstalk in Dynamic Reconfigurable OADM based on Dynamic Channel Equalizer obtained with channel spacing of 100GHz at 40× 10 Gbps. The dynamic power transient with dynamic channel equalizer is also studied which equalizes the power variations with a single ROADM and observed that the signal with acceptable optical output power (-40 dBm) using dynamic ROADM based on Dynamic channel equalizer can be transmitted up to maximum distance of 220 km at 15 dB crosstalk**.** Further, the investigation of ROADM based on the Planar light wave circuit (PLC) and Wavelength Selective Switch (WSS) with 16 channels at bit rate of 10 Gbps with 100GHz channel spacing has been carried out. The dynamic power transients caused by addition or deletion of channels are mitigated using dynamic EDFA are also studied and analyzed that the signal with acceptable optical output power (-34 dBm) using dynamic ROADM based on PLC and WSS can be transmitted up to maximum distance of 462 km using three Dynamic EDFAs.

The evaluation of the number of nodes supported in optical communication system with minimum optical input power considering different topologies like bus, ring and hybrid using OADM at 10 Gb/s with 30 km distance between successive nodes in the presence of hybrid optical amplifier has been done. It is found that in bus topology, maximum numbers of 18 nodes are supported for -20 dBm signal input power. In ring topology, 30 nodes are supported for -30 dBm signal input power but in hybrid topology, at -20 dBm signals input power, the number of nodes supported for upper bus is 6 but for ring, the number of nodes supported is more than 10. We also investigated the number of nodes supported in optical network at different crosstalks with minimum optical input power for Ring, bus topologies using optical cross connects with protection schemes at 10 Gb/s in the presence of hybrid optical amplifier. It is found that in ring topology, more than 20 nodes are supported at -10 dBm input power and 8 nodes are supported at -20 dBm signal input power for -30 dB crosstalks. In bus topology, 16 nodes are supported at -10 dBm input power and 4 nodes are supported at -20 dBm input power for -30 dB crosstalks. The number of nodes supported in case of -50 dB and -70 dB crosstalks are more than 20 in both the bus and ring topologies.

List of Publications

The thesis include following research papers:

1. Sanjeev Dewra and R.S. Kaler,“Cross talk analysis in an optical network based on optical cross connects with different MZI techniques”, **Elsevier:** Optik-International Journal for Light and Electron Optics, Vol. 124, No. 1, pp. 55-59, January 2013.
2. Sanjeev Dewra and R.S. Kaler, “Performance analysis of optical network based on optical add drop multiplexers with different MZI techniques”, **Elsevier:** Optik-International Journal for Light and Electron Optics, Vol. 124, No. 4, pp.347-351, February 2013.
3. Sanjeev Dewra and R.S Kaler, “Performance evaluation of an optical network based on optical cross add drop multiplexer”, **OSA:** Journal of optical technology, Vol.80, No. 8, pp.502-505, August.2013.
4. Sanjeev Dewra and R.S Kaler, “Performance evaluation of optical add drop multiplexers with Mach-Zehnder interferometer techniques for dense wavelength division multiplexed system”, **OSA:** Journal of optical technology, Vol.80, No. 9, pp.526-531, September. 2013.

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(Sanjeev Dewra)

Table of Contents

Chapter 1 Introduction

Chapter 2 Literature Review

Chapter 3 Designing of low cost Optical Add Drop Multiplexer and OXC using Different Techniques

Chapter 4 Designing of Integrated Optical Cross Add Drop Multiplexer

Chapter 5 Designing of Reconfigurable Optical Add Drop Multiplexer to Increase Flexibility of Optical Network

Chapter 6 Performance of different topologies and explore protection schemes in these topologies to enhance survivability

Chapter 7 Conclusions, Recommendations and Future Scope

List of Figures

List of Tables

List of Symbols

P_i	Input signal power
P_o	Output signal power
η	Coupler’s coupling coefficient
Δ_{Φ}	Propagation phase difference between the two arms
T_1 &T_2	Power transmission of the upper and lower arm
Δ_{Φ}	Sum of a constant term
λ_{Bragg}	Bragg resonance wavelength
η_{eff}	Effective mode index
Λ	Grating period
α_r, α_s	Optical losses associate with reference and signal paths
n	Index of refraction of medium wave travels
λ	Operating wavelength
d	Optical path length
G_1, G_2	Gain of the amplifiers
$\emptyset$	Phase changes

List of Acronyms

APS	Automatic Protection Switching
AVC	Active-vertical-coupler
AWG	Arrayed waveguide grating
BS	Broadcast selective
BOXCs	Bidirectional optical cross connects
BER	Bit error rate
D-ROADM	Dynamic Reconfigurable ROADM
DCF	Dispersion compensating fiber
EDFA	Erbium doped fiber amplifier
FBGs	Fiber Bragg gratings
GDR	Group-delay ripple
HWA	Hierarchical waveband assignment
IS-BOXC’s	Independently switchable bidirectional optical cross connects
MC-OXCs	Multicast Capable Optical Cross Connects
MMI	Multimode imaging
MZI	Mach–Zehnder interferometer
NZDSF	Nonzero dispersion shifted fibers
OAMP	Optical amplifiers
OADM	Optical add/drop elements
OEO	Optical-electrical-optical
OXC	Optical cross connects
OXADM	Optical cross add drop multiplexer
WDM	Wavelength division multiplexing
RZ	Return-to-zero
RWA	Routing and wavelength assignment
ROADM	Reconfigurable optical Add drop multiplexer
SHR	Self-Healing Rings
SMF	Single mode fiber
SNR	Signal-to-noise ratio ultra long- haul (ULH) networks

ULH	Ultra long-haul
UHC	Ultrahigh-capacity
WSS	Wavelength Selective Switch
WRS	Wavelength-routing switch
WSXC	Wavelength-selective cross connect
WBS	Waveband switching
WSPXC	Wavelength-selective photonic cross-connects
WIXC	Wavelength-interchanging cross connect
WSOXCs	Wavelength-selective optical cross connects

Chapter 1

Introduction

1.1 Introduction and Overview

There has been always a demand for increased capacity of transmission of information. The scientists and engineers continuously pursue technological routes for achieving this goal. The technological advances ever since the invention of the laser in 1960 have indeed revolutionized the area of telecommunication and networking [1]. As compared to radio waves and microwaves, a high intensity, directionality, mono chromaticity light waves with less variance which are used for carrying the waves to transport huge information [2]. In optical transmission system, the active devices such as LASERs and PIN/APD detectors are placed at opposite sides. LASERs are transmitting devices that convert electrical signals into light signals. This transformation process or variations achieved by modulating a continuous light signal or using a component which produces modulated light [3], [4]. In 1990s, the wavelength division multiplexing (WDM) systems revolutionized the fiber optic communications industry by supporting high data rate over optical fiber [5]. A DWDM optical n/w involves a variety of branching components like wavelength multiplexers/de-multiplexers, gain flattened EDFAs with associated components, semiconductor optical amplifier, add-drop multiplexers, dispersion compensators, band pass filters, FBT-coupler, isolator and circulator etc [6]. If any of these components/devices could be realized in an all-fiber form it could be easily introduced in a link with a relatively lower insertion loss etc. [7]. In the network, Optical Add/Drop Multiplexers are components which offer proficiency to add/drop signals and are placed at locations supporting bidirectional pair of fiber and permit dropping and adding a number of wavelengths, thus decreasing optical-electrical-optical conversions, without disturbing the signals which are transmitted clearly via the node. Both in linear and ring network architectures, an OADM can be used and works in fixed or reconfigurable mode. Different technologies of OXC solutions were recommended and depending on the switching technologies and architectures used, OXCs are usually categorized in two core classes: transparent and opaque [8]. In transparent cross connect; the signals are transferred via an optical switches without the necessity of optical-electrical-optical convertor, thus proposing clearness to different protocols and bit rates. Opaque cross connects are fabricated by optical switches which are bounded by optical-electrical-optical conversions and this imposes the necessity of costly optical-electrical-optical interfaces [8].

1.2 Development of DWDM Technology

In 1980s,WDM evolved with two broadly spaced wavelengths that are in the regions 1310 nm and 1550 nm so it is also known as wideband WDM. The second generation WDM came into existence in 1990s and it is known as narrowband WDM, where eight channels were used at a channel spacing of about 400 GHz in the window of 1550nm and DWDM systems were evolving 16 to 40 channels at an interval of 100 to 200 GHz [9]. In the late 1990s, 64 to 160 channels were evolved in DWDM system at 50 or 25 GHz channel spacing [4].The growth and design of lasers and optical amplifiers are the main aspect of first-generation WDM. In the optical layer, the second generation wavelength division multiplexing is proficient of creating connection oriented light paths by utilizing optical add/drop and optical cross connect elements. Both bus and ring topology can be realized with OADM and OXC. Depending upon virtual topology, the light paths are activated and accomplished and with respect to traffic changes, the virtual topology can be dynamically reconfigured. The second-generation wavelength division multiplexing evolves the growth of OXC and OADM, wavelength convertor, routing, network control and management and so on [8]**.**

1.3 Components of a typical WDM Network

The accomplishment of optical networks requires various passive and active components to split, combine, add/drop, attenuate and amplify optical power at unlike wavelengths [10]. The network can be classified into two types: single hop and multi hop. There is a requirement of dynamic coordination between nodes in a single hop network. For an occurrence of packet transmission, sending node and receiving node to be tuned at similar wavelength for the packet's transmission period. In a single-hop environment, to send and receive packets rapidly, the source and destination are tuned to different channels quickly. As compared to transmission time of packet, the tuning time for transmitter and receiver is relatively extensive and the tunable range for transmitter and receiver is small. So, for efficiently coordinating the data transmissions, development of protocols is the main issue in designing the architectures of single-hop network [11]. In a multi hop environment, a node is provided with one or more channels to which its sources and destinations are to be tuned. To get better performance of network, such assignments are changed infrequently. The connectivity between two nodes is established by having intermediate routing nodes. To route a packets amongst the WDM channels, intermediate nodes are accountable as a packet sent out from source channels and at last gets it to the destination channels, after multi hopping via middle nodes. A different number of multi hop architectures are feasible, with respect to operational properties like ease of routing and the characteristics of performance like number of hops that should be traversed, proficient link usage and average delay of packets [8]. Passive components have fixed application in WDM networks since they need not require any external control for their operation. Such passive components are used to combine, tap off and split optical signals. To get a large degree of flexibility of network, the performance of active components can be electronically controlled. The active components consist of tunable sources, add/drop multiplexer, variable attenuators, amplifiers and tunable optical filters. As transmitter side has a sequence of tunable separately modulated sources of light or fixed-wavelengths, each source emits signal at a specific wavelength. So a multiplexer is required to combine optical signals coming out from light sources and couple the optical signals onto a fiber. Within the network, a variety of specialized components and various categories of optical amplifiers are there. The distance between optical amplifiers is known as a span. A demultiplexer is needed to separate the signals into suitable wavelengths at the receiving end [10].

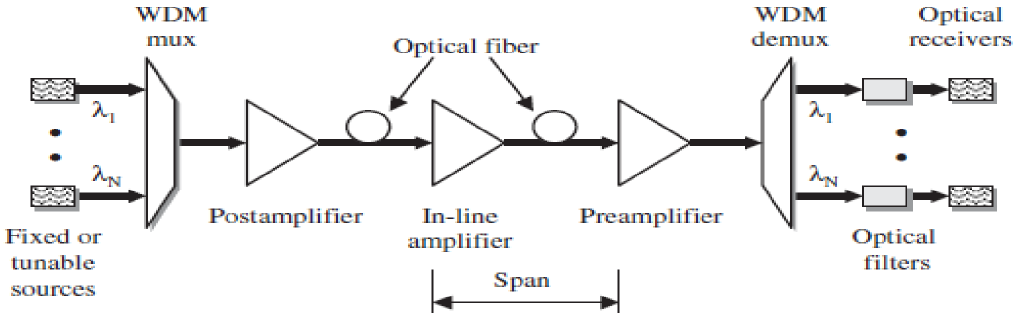

Figure 1.1 Components of a typical WDM network

1.4 Switching Elements

In any network, switching elements are important components. There are two types of switching depending on the signal carriers viz., electronic switching and optical switching. As per the switching point of view; cell switching and circuit switching are two fundamental classes. In optical system, circuit switching corresponds to wavelength routing & cell switching is optical burst and packet switching. In addition, when the transparency of optical signal is considered then two categories of switching one is opaque switching and other is transparent switching are taken into account. Combination of Boolean function is performed by Logic switching in which the data input to the device that controls the device state. Relational switching is to develop compatibility between input and output. The compatibility is a function of control signals which is given to the device & is independent to the data input contents [8].

1.4.1 OADMs

The OADM is a device that removes the particular wavelength λ_i from the multiple wavelengths λ_1, λ_2, --λ_i, --λ_N which are multiplexed on an incoming fiber, adds that particular wavelength with data content on the transmission fiber and bypasses all other wavelengths. Moreover, the OADM can be defined as a device that:

(a) Demultiplexes some wavelengths from an incoming fiber and drops them locally with or without optoelectronic conversion

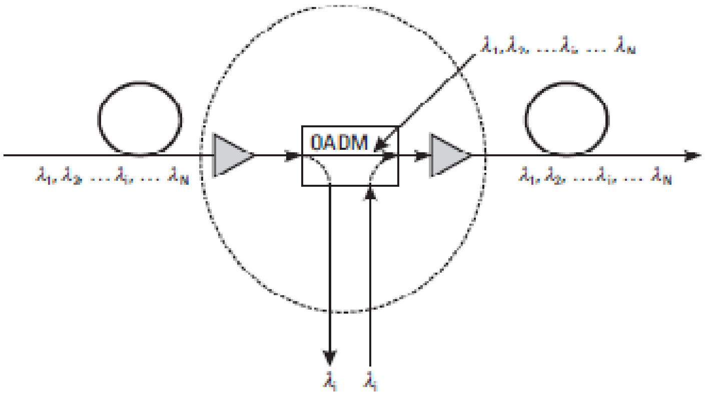

Figure 1.2 OADM principles.

(b) Bypasses the other wavelengths arriving from the incoming fiber to an outgoing fiber;

(c) Adds wavelengths locally on outgoing fiber via a multiplexer or a combiner;

(d) Demultiplexing and multiplexing the bypassed wavelength with the dropped wavelengths and/or with the added wavelengths is often required [12]. Service providers provide greater flexibility by the introduction of ROADM technologies which offers any wavelength to any node connectivity (known as "any to- any") without the requirement of pre defined traffic demands. The DWDM networks employ one of the following ROADM technologies: Pluggable ROADM, Remotely reconfigurable ROADM and Dynamic Reconfigurable ROADM (D-ROADM). Pluggable ROADM uses optical switches to enable remote activation and deactivation of predefined wavelengths and fixed OADM filters whereas remotely reconfigurable ROADM uses a first generation electromechanical switch, second generation Planar Light wave Circuit (PLC) or wavelength blocker subsystems in a Broadcast and Select (B&S) architecture. The third-generation technology is Dynamic Reconfigurable ROADM (D-ROADM) that uses Wavelength Selective Switch (WSS) as subsystem with four or eight add/drop ports [13]. There are two examples of fully-reconfigurable OADMs that are commonly used i.e., broadcast and wavelength selective architectures. The WS design employ wavelength dernultiplexing/multiplexing and switches interconnecting add/drop and express ports, whereas the BS depends on passive couplers/splitters and tunable filters. The design of BS provides superior features such as drop and continues, superior filter concatenation performance and better scalability in terms of add/drop proportion [8].

1.5 Optical Switches

An active switch offers wavelength reuse and also supports N^2 synchronized connections via itself as passive router. But the active star has further improvement over the passive router in terms of its direction-finding medium that can be dynamically reconfigured on demand. Though the active switch is not as fault-tolerant as the passive star & requires external power but router does not require any external power [14]. The active switch as shown in Fig 1.3 is referred to as WRS, WSXC or simply optical cross connect. Before entering the mux stage, the active switch can be improved with an extra capability of wavelength converter. A switch prepared with wavelength-convertor ability is more proficient than a Wavelength routing switch which is also known as WIXC [15].

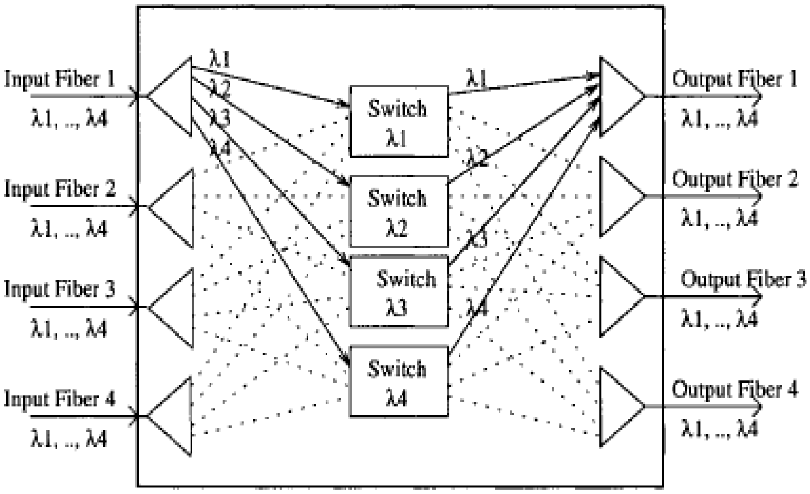

Figure 1.3 4 x 4 active switch [6].

1.5.1 Categories of Wavelength Switches (routers)

There are three categories of routers viz., Non-reconfigurable switches, Wavelength-Independent Reconfigurable switches and Wavelength-Selective Reconfigurable Switches. Non-reconfigurable switches that transmit each wavelength of input port to a fixed set of O/P ports. Once the switch is built, switches cannot be altered. Wavelength-Independent Reconfigurable switches have I/O patterns that can be reconfigured. These input-output patterns do not depend on the wavelength. Wavelength-Selective Reconfigurable Switches are generalized switches that combine the characteristics of Non-reconfigurable switches and Wavelength-Independent Reconfigurable switches [16].

1.5.2 Optical Cross-Connect

The optical cross connect switches the signals from I/P to O/P ports. These cross connects are treated to be wavelength insensitive i.e., unable to demultiplex unlike wavelengths on input fiber. As shown in Fig. 1.4, 2 x 2 cross element is a basic cross connect that transfer signals from two I/P ports to two O/P ports and has two states: bar state and cross state. In the first state, the signals routed from the upper I/P port to the upper O/P port & the signals routed from the lower I/P port to the lower O/P port. In the cross state, the signals routed from the upper I/P port to the lower O/P port and the signals routed from the lower I/P port to the upper O/P port.

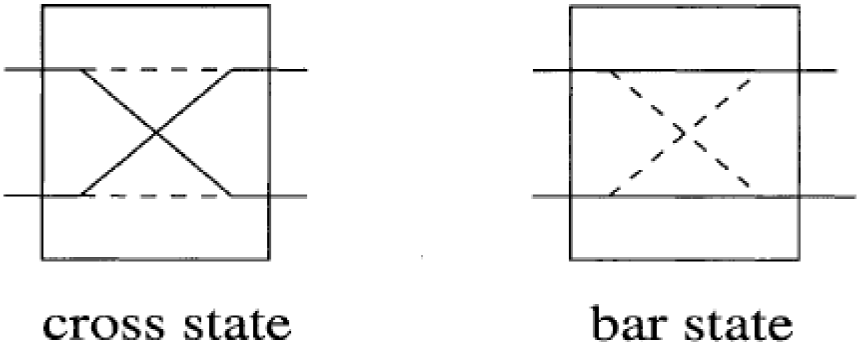

Figure 1.4 2x2 cross connects elements in cross and bar state.

The features of OXC and OADM are ideally similar, but in addition, the OXC provide:
(1) Rigorously non blocking connection b/w I/P and O/P ports.
(2) Span protection, ring protection and capabilities of bus restoration [8].

1.6 OXADM

In optical network, a recently discovered device called Optical cross add drop multiplexer. In metropolitan ring and bus configurations, OXADM which evolves the combination of OXC and OADM is used to enhance flexibility and effectiveness of optical n/w. In ring & bus topology, the OXADM acting as a node provides the features such as routing, supervision, multiplexing, survivability and termination. The main function of OXADM is to reconfigure the optical path while implementing add/ drop functions [17].

1.7 Protection Schemes

Schemes of Protection can be categorized into ring and bus protection. The schemes of ring protection include APS and SHR. Both ring & bus protection can be classified into two types one is path protection & other is link protection. In the path protection, whenever connection failure occurs to its primary path then the signals are rerouted via a backup route. The working and protection paths must be link disjoint so that no single link failure can affect these paths. On the other hand, the signals are rerouted around the failed link in link protection. Whereas path protection corresponds to well-organized employment of primary resources & end to end propagation delay for the recovered route, link protection provides faster protection switching time [18].

1.8 Conclusion

In this chapter, we have outlined the DWDM system using optical network components like OADM, OXC, OXADM and ROADM. Optical Add/Drop Multiplexers (OADMs) are elements that provide capability to add and drop traffic in the network. They are located at sites supporting one or two fiber pairs and enable a no. of wavelength channels to be dropped & added, thereby reducing the no. of needless optoelectronic conversions, without affecting the traffic that is transmitted transparently via node. A number of OXC solutions based on different technologies have been proposed to date and depending on the switching technology and the architecture used. An optical cross connect switches optical signals from I/P ports to O/P ports. These types of elements are usually considered to be wavelength insensitive. Optical cross add drop multiplexer is designed with a combined concept of optical cross connect (OXC) & optical add drop multiplexer which is potentially used to increase efficiency and flexibility of optical system particularly in metropolitan ring and bus configuration. The main function of OXADM is to reconfigure the optical channel path while implementing add/remove function simultaneously. The reconfigurable optical Add Drop Multiplexer (ROADM) remotely controls wavelengths which are added/dropped or passed via node. In a Dense wavelength Division Multiplexing System, the ROADM is competent of add/remove or pass through any or all wavelengths.

Chapter 2

Literature Review

2.1 Introduction

In DWDM system, OXC and OADMs are the main elements for the broadband Internet era. To route and multiplex channels into or out of SMF, OADM is used in dense WDM networks. The add/drop refers the ability of component to add new channels to an existing multi channel Wavelength Division Multiplexing system & to remove channels. An optical add/drop multiplexer may be considered to be a particular type of OXC. A traditional optical add/drop multiplexer comprises of three stages: demultiplexer, multiplexer and a technique of reconfiguring the paths between demux/mux and has ports for adding and removing the channels. The demux separates the channels in a link onto ports. The reconfiguration can be carried out by switches that send the channels to the mux or to drop ports. The mux multiplexes the wavelengths into a single fiber. In an optical system, an OXC is a component that is used by carriers to switch signals at a high-speed.

2.2 Literature Survey

2.2.1 Designing issues of Optical cross connects and Optical add drop multiplexers using different techniques

The Optical Cross Connect is an optical switch, completely non-blocking and considered to meet the premier performance and reliability needs in the applications with compact size, low power, low optical loss and fast switching speeds provides a stage to support existing technologies such as 10 Gbps as well as technologies with 40 Gbps and 100 Gbps transport. An OADM can be considered to be a particular type of optical cross-connect. OADM is cost effective solution in the optical domain with the minimum amount of electronics. OXCs and OADMs have been demonstrated using different Mach–Zehnder interferometers (MZIs) techniques i.e MZI, MZI-SOA and MZI-FBG. In addition FBG-circulator based OADM has also been analyzed. Crosstalk is an important issue for the designing of OADM and OXC which degrades performance of network. Crosstalk originates in OADM and OXC due to component imperfections.

Yikai Su et al. [19] investigated 40-Gbps return-to-zero (RZ) signal transmission in an optical system equipped with WS OXC. The research is performed in a recirculating loop setup that consists of 4100 km spans of transmission fiber. WS optical cross connect is placed inside the loop to imitate cascaded WS optical cross connects and studied various effects of degradation in the network, mainly those of node loss and optical filtering. Measurements of quality value of the received signal were carried out at different transmission distances and loss conditions of WS optical cross connect. Quality value of 15.5 dB was measured at distance 1200 km with two cascaded WS optical cross connect (WSOXCs) of which the node loss is 17 dB.

Chun-Kit Chan et al. [20] proposed and demonstrated an effective managerial scheme to observe the optical path routing at the OXCs in all optical transport systems. Due to failure in the cross connect, without monitoring light source and tapping off the power at the channels, any error in optical path can be detected. It can facilitate the system management in the optical layer of all optical and reconfigurable transport networks**.**

Hideki Maeda et al. [21] demonstrated a new reconfigurable WS optical cross connect features such as wide flat pass band and high cascadability. It is investigated by 10 Gbps x 8-channel wavelength division multiplexing transmission with an interval of 0.8 nm over 4000 km. The electrical SNR degradation caused by using optical cross connects is negligible in the end of transmission line. In the transmission line with an eight-unit OXC cascade, the bandwidths yielding 3-dB SNR degradation for the proposed OXCs and conventional OXCs were 0.6 and 0.1 nm respectively. The proposed optical cross connects have wide pass band and nearly no narrowing compared to the 0.8 nm interval between the channels.

Yunfeng Shen et al. [22] studied that in WDM optical system, the effect of coherent and noncoherent crosstalk on the signal transmitting via OXC nodes. Depending on the relationship between the time interval of one bit of the signal and propagation delay differences, coherent crosstalk may originate noise when fluctuation of signal power occurs. Since it can be a coherent combination of crosstalk contributions, a very high noise power may be caused by incoherent crosstalk. The requirements of crosstalk are then achieved for devices utilized in wavelength division multiplexing optical systems with dissimilar scales.

Ernesto Ciaramella [23] demonstrated Wavelength Granularity to reduce the complexity of OXC. In order to switch a large amount of channels, optical cross connects should have more complex structures. To cope with this, proposed to introduce optical granularity: if WDM signals with the same source–destination pair were assigned a group of adjacent wavelengths, they could be optically routed by OXC's as a single channel. This modifies usual routing and wavelength assignment, but reduces the number of optical components in OXC's and also makes it easier to configure and modify connections. Advantages are similar to those that might come from increasing electrical granularity, if this option were not limited by transmission impairments.

Haitham S. Hamza et al. [24] proposed new strictly non blocking Multicast Capable OXCs structures that develop the potential of MWCs. Multi-wavelength converters are capable of replicating a signal on an I/P channel to numerous O/P channels and investigated two families of Multicast Capable OXCs based on use of Full and Limited-range multi-wavelength converters and presented a no. of structures in each of the two families. Proposed structures present a trade-off b/w switching complexity, conversion cost and signal failure.

Jungho Kim et al. [25] developed IS-BOXC's that switch each bidirectional signal, both independently and simultaneously will be required and proposed new structures of IS-BOXC's using two dissimilar unidirectional OXC. The proposed independently switchable bidirectional OXCs suitably suppresses the RIN caused by optical reflection and Rayleigh backscattering.

Xiangnong Wu et al. [26] presented model of intra band crosstalk in an N × N FBG- circulator based OXC analytically and results showed that the coherent crosstalk of worst case is 22–26 dB more than non-coherent crosstalk, based on the 2 x 2 optical cross connect switching state. Moreover, a unique design of OXC with better performance of intra band crosstalk was proposed.

Fangfang Yan et al. [27] investigated the 4-stage multicast system which uses two multicast stages that is called 4(2 m)-stage multicast system and derived the conditions for sufficient WSNB and RNB of 4(2 m)-stage multicast system. The wide-sense non blocking and rearrange able non blocking situation are also offered for multicast request with restricted degree. 4(2 m)-stage multicast system requires at least O ($N^{3/2}$) cross points to be WSNB & RNB, which is a lower bound than the three-stage Clos network with two multicast stages & the same bound with the four-stage system with three multicast stages and designed full & partial MC-OXCs using 4(2m)-stage multicast system. In reducing splitting loss, the proposed WSNB full MC-OXC with two multicast stages is power proficient and cost effective as compared to the one accomplishing three multicast stages. Further, Partial MC-OXC using one multicast stage is proposed to decrease the splitting loss and cost of multicast. The RNB MC-OXCs with one or two multicast stages provide improved performance with respect of cross points, multicast cost & splitting loss than their WSNB counterparts.

Yang Wang et al. [28] introduced WBS to collect multiple channels collectively as a band & switch the group using a single port. Inspite of using the T-OXCs, waveband switching systems uses MG-Optical cross connects to switch the signals at distinct granularities. Briefly reviewed and discussed the development in the designing of multi-granular optical cross-connect architecture, wavelength assignment algorithms, routing and protection schemes in waveband switching system. Two new schemes are proposed for solving problem of waveband assignment & protection of waveband. First scheme demonstrated the parameters like express signals and degree of node can affect the efficiency of switching of waveband. For saving ports, a new HWA algorithm is then proposed which takes the parameters of wave banding into consideration. Second scheme introduced the concept of band-segment & explore band-segment based protection schemes to attain objective of port reduction, the sharing of resources & survivability in waveband switching systems. Simulation results showed that the proposed hierarchical waveband assignment scheme results in a presentable approach, named as balanced path routing with heavy-signals first waveband assignment up to 18% in terms of reduction in port. When the proposed concept of band-segment is proficiently adopted in waveband switching systems then the protection and the sharing of resources can be achieved without sacrificing port saving.

Jade and Wang [29] investigated a unique technique for Semiconductor Optical Amplifier–Mach–Zehnder interferometer switches that combine a pump-probe quantity with an interferometer bias scan. This enables optimal bias recognition & superior perceptive of switching dynamics.

R. J. S. Pedersen et al. [30] showed the allowable fluctuation of center frequency (AFCF) for a grating based Mach–Zehnder interferometer OADM may not be restricted by the transfer function from the I/P to the drop port, but moderately by the transfer function from the add to the drop port or the I/P to the O/P port and the considerable bandwidth is determined by the bandwidth in which the coherent crosstalk is satisfactorily low and demonstrated the crosstalk reduces the AFCF by a factor of 2 for the commercially available device and showed an excellent prediction of the penalty due to coherent crosstalk based on measured transfer functions in comparison of directly measured penalties.

Y. K. Chen et al. [31] proposed and demonstrated three kinds of low-crosstalk and compact OADMs based on a multiport optical circulator with fiber Bragg gratings. For the multiport optical circulator (MOC)-based structure, there is a major crosstalk reduction of about 37 and 16 dB on the dropped and added channels respectively and examined bit-error rate performance and both intra band and inter band crosstalk-induced power penalties of this multiport optical circulator-based optical cross add drop multiplexer in a 10-Gbps network demonstration.

An Vu Tran et al. [32] proposed 3 new OADM techniques with simple & compact design and excellent crosstalk performance. The optical add drop multiplexer uses a single MOC & either one or two narrow-band FBGs, based on the crosstalk conditions.

A. Tzanakaki et al. [33] simulated the WDM system using optical add drop multiplexers and in the optical filtering linked with them, enhances the performance of networks with nonlinear effects. This is due to that cyclic filtering assists in eliminating the spectral broadening imposed by the Kerr nonlinearity and therefore eliminates the penalty associated and results recognized the optimum operating regimes in terms of filter bandwidths and power for optical add drop multiplexer-chain WDM networks.

Christos Riziotis et al. [34] optimized the performance of optical add-drop multiplexer comprises three steps of optimization. First, to reduce the extinction ratio of the unwanted mode at the null coupler waist, the waveguide asymmetry (V_2/V_1 ratio) should be optimized in order. Second, in order to further reduce the above mentioned extinction ratio, the coupler taper shape should be optimized. Third, to give negligible back reflections at I/P port and reduce radiation losses, the grating tilt angle & relative width can be also optimized.

Riziotis and Zervas [35] considered the performance of FBG based optical add drop multiplexer using theoretical simulations of system. The implications of the non optimum spectral features of coupler-based optical add/drop multiplexer are compared with other filter configurations.

Sarah D. Dods et al. [36] examined the impact of coherent and non-coherent homodyne crosstalk in WDM ring & bus systems using ROADMs. It is extensively understood that in these networks, non-coherent homodyne crosstalk results in power penalties at the RX and showed that coherent homodyne crosstalk results in a range of possible received powers. The probability distribution of power penalties is observed by Monte Carlo simulation. By increasing the crosstalk within each OADM and no. of WDM channels, probabilities of large power penalties also increases. Though, the power penalty distribution does not affect the no. of nodes through which a signal is transmitted.

M. Irfan Anis et al. [37] investigated the effect on the performance of OADM based n/w by shifting dissimilar filters at the receiver side and calculated the average bit error rate and with the help of eye diagram, analyzed the response of the filter & compared the results with ideal filter in optical add drop multiplexer cased environment. With the help of optical add/drop multiplexer, the system resources can be used efficiently and provide security to network and direction-finding character for add and remove channel. For this optical add/drop multiplexer can be designed based on ring architecture of four nodes transmitting at 10 Gb/s connected with four unidirectional non linear mode fiber span of 10 Km.

Mário J. N. Lima et al. [38] reported an examination of the homodyne/heterodyne crosstalk of Mach-Zehnder Interferometer-Fiber Bragg Gratings based Optical add drop multiplexer in WDM systems. Two different categories of gratings are considered with average refractive index perturbations, one non-uniform and negative and second one is constant and equal to zero. To reduce the homodyne or heterodyne crosstalk, two architectures of the referred category are proposed.

Daniel Pastor et al. [39] analyzed the effect of the FBGs-based optical add/drop multiplexers out band dispersion on bypassed adjacent channels to the dropped channel when it is moving subcarrier modulated signals. The results show a disadvantage in terms of additional harmonic and inter modulation distortion.

Xiang Liu [40] investigated the feasibility of transmitting 40-Gbps optical duo binary signals over transparent dense WDM systems with 50-GHz channel spacing and multiple OADMs. While the duo binary format is tolerant to pass band narrowing, from concatenated filtering by the OADMs, it is very sensitive to the GDR associated with this filtering and showed that GDR must be carefully controlled, e.g. by group-delay ripple compensation, before 40-Gb/s duo binary signals can be effectively used in dense WDM systems originally designed for 10-Gb/s traffic.

Christos Riziotis et al. [41] proposed a unique arrangement of an interferometric component, based on a full-cycle coupler architecture associated with a FBG symmetrically located into the waist of uniform coupler, using as an OADM with simultaneously optimized add & remove actions. Using theoretical simulations, the component performance was characterized at 40 Gbps wavelength division multiplexing system and compared directly with other optical add/drop multiplexer architectures.

Geoffrey A. Cranch et al. [42] described multiplexing techniques for interferometric fiber sensors based on TDM and DWDM using OADMs. The outcomes of an experimental set up is presented and discussed the noise sources in the network, dynamic range & a characterization of the distributed feedback fiber laser source noise and showed the crosstalk in the experimental set up to be b/w -47 & -76 dB based on the method involved. The multiplexing technique demonstrated the prospective to deal with minimum 192 interferometric sensors via two fibers depends on a network with six channels with less than 20 rad/ Hz phase resolution.

2.2.2 Optical cross add drop multiplexer for DWDM System

OXADM is an optical component that provides the capabilities of add/remove function and cross connecting signals in the system, similar to optical add drop multiplexer & optical cross connect. The component is mainly designed having better characteristics in support of advancing flexibility of system, reliability and effectiveness. The main purpose of cross add/drop multiplexer is to reconfigure the channel path while implementing add/remove function concurrently. OXADM is also able to perform restoration functions for point-to-point, ring and bus topologies.

Mohammad Syuhaimi Ab-Rahman et al. [43] designed OXADM with a joint concept of OXC and OADM that is used to enhance the effectiveness and flexibility of the system mainly in metropolitan bus and ring arrangement. The Optical cross add drop multiplexer node concentrates on providing functionalities of routing, multiplexing, supervision, transport, survivability and extinction in the optical layer for both ring and bus topologies. The designed 4-channel Optical cross add drop multiplexer component is estimated to get highest operational loss of 6 dB for each channel. Optical cross add drop multiplexer also provide survivability via restoration against losses in terms of linear, multiplex and ring protection to both configurations. Deprivation is estimated at 2 dB in O/P power w.r.t ordinary condition in ring protection foundation. The performance was carried out at 2.5 Gb/s with bit error rate $1x10^{-10}$ for linear protection whereas for ring protection, bit error rate of $1x10^{-19}$ and $1x10^{-13}$ were used. As per the proportion of system failure and span variation Optical SNR is calculated. The technique involved the characterizing and constructing of two optical cross add drop multiplexer.

Mohammad Syuhaimi Ab-Rahman et al. [44] described the current approach towards advancement in optical survivability technique by introducing the new channel reconfigurable component. The first proposal of hybrid OADM/optical cross connects /Multiplexer will be named as OXADM that presents the concept of accumulation, filtering, add/drop function, cross connecting, multiplexing and u-turn mechanism in a single device structural design. With these features, three restoration schemes have been developed to form a hybrid mechanism that is activated according to the degree and position of failures. The optical cross add drop multiplexing highlights on providing survivability via restoration against fault such as cable cut, power decreased & not responding the Erbium doped fiber amplifier in terms of multiplex protection, linear protection & ring protection that is also known as u-turn protection. The limitation has also been discussed as the results are compared with previous device such as OXC.

Mohammad Syuhaimi Ab-Rahman et al. [45] described a current component called as OXADM that has prospective use in Coarse Wavelength Division Multiplexing metro area systems. The component is the combined concept of OADM and OXC b/w two main communication lines in order to execute the channel direction-finding operation. To make it re-configurable, MEMS switches are included in the device. The component can be used in ring, point to point or bus topology which offers the features like routing, multiplexing, transport, supervision and restoration of processed customer digital signals mostly in the domain of optics. While implementing add & remove functions concurrently, the channels on each optical trunk can be switched b/w each other. The investigation of MUX has been done at 2.5 Gb/s (OC- 48) with bit error rate less than 10^{-9}. The highest length is achieved by OXADMs is 71 km without amplification at 6 dB insertion loss. A comparison between optical cross add drop multiplexing with the earlier components like TRN, Optical cross connect and OXN has also been done.

Mohammad Syuhaimi Ab-Rahman [46] described the second generation of optical switching devices that enhance the flexibility, reliability, capacity & also survivability of the transmission-line system used for digital system. The accumulation character has extended their use in management of channel and restoration systems in comparison with conventional components like optical add/drop multiplexer and Optical Cross Connect. The optical cross add/drop multiplexer prototype network highlights on providing survivability via restoration against losses, like breakdown of fiber in optical layer with ring topology in terms of linear protection and ring protection with two restoration methods. The method of Hybrid restoration with optical cross add/drop multiplexer enables the integration of ring, linear and multiplex protection in single system and it will be enabled as per the degree and types of failure analytically and experimentally. The maximum cascaded optical cross add/drop multiplexer based on the number of operational channels and I/O ports are also measured. The outcomes are then compared with conventional components; optical cross connect and optical add/drop multiplexer.

Muhammad Syuhaimi Bin Ab-Rahman et al. [47] investigated the Optical Cross Add Drop Multiplexer device that increases the capacity, flexibility and reliability of the transmission line system used for digital transmission. An Optical Cross Add Drop Multiplexer prototype network highlights on providing survivability via restoration against losses like breakdown of cable in optical layer with ring topology. To ensure data flow constantly in terms of linear protection and ring protection, two categories of restoration techniques have been proposed and described the modeling of optical cross add drop multiplexer analytically and also demonstrated their drawbacks as compared with conventional optical cross connect device.

Mohammad Syuhaimi Ab-Rahman et al. [48] investigated a current optical component model called as cross add drop multiplexer that has prospective application in Continuous WDM metro systems. The component uses the combination concepts of OADM and OXC b/w two main trunk lines in order to employ the channel direction-finding process. To make it re-configurable, MEMS switches are integrated in the component. With exceptional characteristics, the component is mainly constructed to recover system effectiveness, flexibility and survivability. The component can be used in different topologies like ring, bus and point to point to provide features like routing, multiplexing, transport, supervision and restoration of customer digital signals processed predominantly in the era of optics. While implementing add & remove functions concurrently, channels on each optical lines can be switched b/w each other and the comparison b/w OXADM with the earlier components like OXN, TRN and optical cross connect has been studied. The drawback occurs in Optical Cross Add Drop Multiplexer as compared with optical cross connect is also calculated systematically in terms of scalability.

2.2.3 Designing of reconfigurable optical add drop multiplexer using different techniques

The flexibility of ROADM based optical systems translates to a number of advantages for the system operator including installation, simpler system planning and a basic process of adding new channels to the system. ROADMs play an important function in optical network reconfigurability and cost saving. ROADMs based on DCE, WSS and PLC has been implemented to give high performance and functionality to each network application.

Motoharu Matsuura et al. [49] presented a multi-carrier distributed Wavelength Division Multiplexing ring network based on ROADMs for applications of the metro system. The drop-add-drop system experiment offering 10 Gbps wavelength division multiplexing transmission was demonstrated. Further, the utilization efficiency of the carrier wavelengths distributed by the MCLS in the drop-add-drop network has been recovered and the carrier wavelength reuse technique was introduced to set the carrier extraction circuits in each access node. The blocking probabilities of the drop-add-drop networks are compared with & without carrier wavelength reuse to investigate the effect of carrier wavelength reuse. The outcomes revealed that wavelength reuse reduced the blocking probability. Moreover the advantages of the drop-add-drop system over the conventional Reconfigurable Optical Add Drop Multiplexing system in terms of power consumption and cost are also analyzed.

Volkan Kaman et al. [50] investigated the feasibility of dense WDM optical short-reach metropolitan system using dynamically reconfigurable 3-D MEMS system based WS-OXC. Full amplification of dense WDM at the high-capacity node is evaluated with low-cost narrow-band EDFA whose variation of channel gain is compensated per span using the inherent channel equalization means of the WS photonic cross-connects.

Li Ke-jia et al. [51] designed and analyzed the fundamental device of dense WDM network, reconfigurable OADM utilized many tunable filters categorized by their tuning schemes. An electro-optically tunable reconfigurable OADM made-up on x-cut, y-propagation Ti: LiNbO3 waveguides, the electrodes converted the two polarizations of definite channels with effect of electro-optic and therefore realized the add and remove function combined with two polarization beam splitters.

Sorin Tibuleac et al. [52] investigated the Reconfigurable OADM based on 1× N Wavelength selective switches are evolving to sustain dense WDM systems with elevated capability and more flexibility in channel direction-finding. Different wavelength-selective switches techniques can be engaged to give steerable and colorless features for bus or ring topologies. Enhancement in specifications of Wavelength selective switch modules operating at 50 GHz wavelength interval have enabled 40 Gbps bit rates via wide Reconfigurable optical add/drop multiplexers networks. The similar reconfigurable OADM are also expected to hold 100 Gbps transmission in the near future. Optical SNR or quality value penalties can be induced by pass band narrowing, imperfect isolation across the signal PDL, B.W, insertion loss and other effects. The effect of these impairments depends on the transmitter and Rx types and on the WSS characteristics. Main transmission impairments like crosstalk, band pass narrowing, PDL and I.L are measured experimentally and numerical simulations for modulation formats and common data rates. Temporal fluctuations implications during power setting throughout a reconfigurable optical add/drop multiplexers network are also discussed.

Chen-Mu Tsai et al. [53] proposed a bi-directional reconfigurable technique of multi wavelength-selective OADM. To construct a bi-directional reconfigurable OADM with small range of wavelength tuned, the suggested applied FBGs and multiport optical circulators that could treat with wavelengths without the receiving signal having channel-interleaved. Furthermore, it was simpler & more flexible to expand wavelengths by the cascade of additional fiber Bragg gratings.

Zhuoran Wang et al. [54] reported the development of a unique optical multicast method 1 to 4 and 2 to 4 configurations using OXC matrix based on active-vertical-coupler. With 0.5 dB E.L per split of signal, firstly a 1 to 4 broadcast experiment has been carried out. Input signals with two channels are then fed into one row of optical cross point switch to evaluate the effect of

WDM on 1 to 4 multicast switching. Finally, combination of 1 to 4 and 2 to 4 expanded 2 to N multicast is also obtained with an N value up to 4. In different configurations, the switched signal quality, switching features and SNR ratio have been evaluated. Penalty of power < 4.5 dB are found in worst case switched signals in the 2 to 4 configuration. The outcomes confirmed the excellent multicast switching features nearly free from power splitting loss in this component.

V. Kaman et al. [55] reviewed the deployment and planning of reconfigurable optical carrier networks which requires next generation reconfigurable optical add-drop multiplexing which can support unlimited access of add drop with higher flexibility, a cost-effective multi-degree reconfigurable optical add-drop multiplexing that can support 100% add drop capacity of traffic with minimum pre-planning. Further, capability of this ROADM to share, distribute and therefore reduces the requirement for local resources like regeneration, wavelength-conversion, broadcast and multicast cards to the minimum possible required to save the overall n/w level is discussed.

Kiyo Ishii et al. [56] proposed an efficient ROADM ring connecting node structure that uses routing of waveband; it obtains a small footprint and exceptional cost effectiveness. The Planar Lightwave circuit technologies are used to implement the component and their performances were demonstrated in experiments.

Jonathan Homa et al. [57] explored the relationship between ROADM's and wavelength selective switches. ROADM is standard nodal subsystem for providing flexibility in modern multichannel fiber optical communication system. WSS is the predominant technique used to implement ROADMs. In modern multichannel fiber optical communication systems, the ROADMs are being used to provide automated provisioning of wavelengths. They accelerate provisioning time, reduce costs and remove human error from manual reconfiguration. Further, a range of structures for Reconfigurable optical add/drop multiplexers are rising to fulfill needs for two-degree versus multi degree nodes, edge versus core system applications, fixed vs colorless add/drop. Therefore, to enable the ROADM architectures, a wide range of WSS engines are required.

J. M. Tang et al. [58] described 3 categories of ROADM as per the fundamental switching schemes: Type I consists of a single large switch; Type II is composed of a no. of small switches aligned in parallel; and Type III has a single optical switch and only one channel being added and removed. A theoretical routing power model taken into consideration different ROADM structures and dynamic traffic is developed to investigate the wavelength routing ability of ROADMs of various types in optical communication systems. Simulative results showed that different types of ROADM vary considerably in their wavelength routing abilities. It is also found that Type I provides the highest ability of wavelength routing and least susceptibility among three ROADM structures whereas Type III offers ability of lowest wavelength routing and the highest susceptibility to dynamic traffic. A set of practically applicable criterion is recognized on constructing the optimal ROADMs to maximize the flexibility of ROADM-based system.

C.A. Al Sayeed et al. [59] proposed ROADMs which will play a major function in next-generation optical communication systems. Existing ROADM subsystems are suffering from either high I.L's or high manufacturing costs especially for the express channels that are preventing their rapid development in systems. The ROADM structure that integrates the best characteristics of the latest available ROADM structures is investigated. The proposed ROADM structure denoted as a Hybrid ROADM exhibits a lower I.L than existing ROADMs. Also it offers simplification and is a cost effective solution. To compare the performance of the proposed Hybrid ROADM in opposition to currently available ROADM structures, a metro system test bed has been configured. The obtained results indicated that the better performance is shown by the Hybrid ROADM in metro systems than available ROADM subsystems and also Hybrid ROADM reduces the overall system operating cost.

Zheng Wang et.al [60] addresses the problem of reducing power excursions in amplified wavelength division multiplexed networks with ROADM and WSS. In dynamic network loading scenarios, conventional WSS control leads to transient power excursions across the chain. Two WSS control strategies are considered: an integral-control and a modified integral-coordinated control for tracking. For both algorithms, convergence at an isolated node is shown to depend on the optical amplifier nonlinear gain coupling quantified by its Lipschitz constant. In a chain network with independently controlled ROADM nodes, the modified WSS control effectively decouples the nodes and reduces WSS transient power excursions across the chain. The bounds on these reductions are quantified analytically with respect to the $L2$ norm, by applying

Lyapunov analysis techniques for the interconnected chain system. Numerical results that verify and compare the two WSS control strategies are provided by implementation on a Transparent Optical Mesh (ATOM) platform for two realistic dynamic network loading scenarios.

2.2.4 Optical network topologies and protection schemes to enhance Survivability

Optical fiber has become the transmission medium of choice, the topologies are once again receiving considerable interest in the research community. Optical technologies can meet bandwidth needs with cost-effectiveness. The purpose is to explore topologies and architectures to enhance communication capabilities of future communication networks. Optical Cross Connect and Optical Add Drop Multiplexer provide survivability via restoration and shared protection against failure path that can be used in bus and ring topologies.

Tim Gyselings et al. [61] presented the effect of a crosstalk analysis of four optical wavelengths WDM cross-connect topologies. An optimum set of parameters are determined to diminish the total crosstalk. The scalability of the topologies is presented in terms of wavelengths and input fibers. The four topologies are compared in terms of crosstalk which is function of the number of cascaded OCXs.

Yatindra Nath Singh et.al [62] observed the use of Semiconductor Optical Amplifiers and Distributed Fiber Amplifiers in several topologies like bus, star, tree etc. Doped Fiber amplifiers are suitable to bus and ring based systems. Optical Amplifier will play major component in all the future communication system and their estimation in system needs to be further investigated.

Rachna asthana et.al [63] reviewed protection and restoration schemes. The path protection schemes give improved resource utilization at the cost of more computational density, whereas link protection can be provided once and for all in optical layer protection schemes. The physical level failure is to be recovered in the optical layer schemes to avoid the severe problem of fault multiplication in the higher layer. Higher layer schemes can be used to recover higher layer node failures or single link failure in the higher layers.

Table 2.1 Work reported on Optical Components using different techniques

Authors	Optical Component/Technique	Channel spacing	References
Chun-Kit Chan et al.	Conventional OXC’s	0.8nm	[20]
R. J. S. Pedersen et al.	OADM	1.1nm	[30]
A. Tzanakaki et al.	OADMs,	0.8nm	[33]
Yunfeng Shen et al.	OXC	0.8nm	[22]
S.K. Park et al.	Bidirectional optical cross connect	0.8nm	[64]
Jungho Kim et al	Bidirectional wavelength OXC	0.4nm	[25]
Hideki Maeda et al.	Wavelength-selective OXC	0.8nm	[21]
P. S. Andre et al.	Tunable OADM based on FBGs	0.8nm	[65]
Riziotis et al.	Bragg grating-based OADMs	0.5nm	[35]
S.K. Narayan khedkar et al.	FBG based OADM	0.8nm	[66]
An. Vu Tran et al.	Bidirectional OADM	>0.1nm	[67]
Hai Yuan et al	Bidirectional OXC using FBG and Optical circulators	0.2nm	[68]
P. T. Neves et al.	MZI-FBGs based OADM	1nm	[69]
Yuta Goebuchi et al.	Wavelength-selective switch based ROADM	1nm	[70]
M.S. Ab-Rahman et al.	OXADM	20nm	[45]
R. Kaler et. al.	Arrayed waveguide grating based OXC	0.1nm	[71]
Mahiuddin et al.	FBG based OADM	0.8nm	[72]
M. S. Ab-Rahman et al.	OXADM	20nm	[73]
Wei Hong et al.	ROADM and an OXC structures based on microring resonators	20nm	[74]

2.3 Gaps in Present Study

This section lists the common limitations encountered while dealing with OADM and OXCs. This would make the reader realize the importance of these drawbacks and elucidate the reasons for attempts to arrive at solutions to these problems.

One of the most significant issues is cost of the add/drop multiplexer & optical cross connects. Low cost OXC & OADM are yet to be implemented and also the effect of crosstalk due to OXC and OADM is yet to be overcome. Very limited work has been carried out to study the feasibility of a DWDM optical network based on an OXCs using different techniques, so that optimization can be done by avoiding the hardware costs involved. The impact of crosstalk on bit error rate and Quality of signal using these techniques has not been properly investigated.

Till now, investigation of DWDM system using OXADM has been carried out at low bit rate and higher channel spacing. The high data rate signals are required to be transmitted to a large distance with reduced interval. Implementation of OADM and OXC in a single architecture is not readily available [75]. Even limited work had been carried out for the comparison among different techniques based on OADMs in terms of cost, bit rate, interval between channels and covered distances. Using these techniques, the impact of crosstalk on BER and Quality of signal has not been properly investigated [76]. So as to improve survivability of optical system, more work needs to be carried out to implement different topologies by using OADM and OXC with protection schemes [77], [78].

2.4 Objectives

The investigation will concentrate on performance analysis of DWDM system with the following main objectives:-

1. To propose the design of low cost optical add drop multiplexer and OXC using different techniques to enhance the performance of DWDM systems.
2. To propose the design of integrated optical cross add drop multiplexer to increase efficiency of optical network.
3. To investigate techniques to design reconfigurable optical add drop multiplexer to increase flexibility of optical network.

4. To investigate performance of different topologies using optical add drop multiplexer and optical cross Connect and explore protection schemes in these topologies to enhance survivability.

2.5 Outline of Thesis

The thesis has been organized into seven chapters. Contents of each chapter are briefly described as under:

Chapter 1 introduces the introduction to optical add drop multiplexers & optical cross connects. Further the organization of thesis is presented.

Chapter 2 of this dissertation gives a comprehensive literature review of different designing techniques of optical add drop multiplexers & optical cross connects enhancing the performance of optical communication system. The objectives of the thesis are crystallized.

Chapter 3 deals with the first objective of the thesis which is to propose the design of low cost OXC & optical add drop multiplexer using different techniques to enhance the performance of DWDM systems. Optical add drop multiplexer and optical cross connects using different MZI techniques, OADM using bidirectional Fiber Bragg Grating-Optical circulator (FBG-OC) have been designed and implemented in optical system.

Chapter 4 deals with the second objective of the thesis which is to propose the design of integrated optical cross add drop multiplexer to increase effectiveness of optical system. The proposed design of integrated optical cross add drop multiplexer is the combined concept of optical cross connect and optical add drop multiplexer used to increase flexibility of optical system.

Chapter 5 deals with the third objective of the thesis which is to investigate techniques to design reconfigurable optical add drop multiplexer to increase flexibility of optical network. ROADM based on Dynamic Channel Equalizer, planer Light wave circuit and wavelength selective switch techniques are proposed and implemented to increase the flexibility of optical network.

Chapter 6 deals with the fourth objective of the thesis which is to investigate performance of different topologies using optical cross connect & optical add drop multiplexer and explore protection schemes in these topologies to enhance survivability. Finally Ring, bus and hybrid topologies are investigated using optical cross connect and optical add drop multiplexer and explored protection schemes in bus and ring topologies. The effectiveness of topologies is evaluated in terms of no. of nodes supported.

Finally, chapter 7 covers the summary/conclusion drawn; recommendations on the basis of results obtained in chapter’s three to six. In thesis, the performance of dense wavelength division multiplexed system is enhanced in terms of quality factor, Bit error rate & received optical power. The simulation results indicate that the proposed scheme effectively improves the performance of an optical communication system. Finally the scope of future work has been presented.

Chapter 3

Designing of low cost OADM and OXC using different techniques

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3.1 Introduction

This chapter focuses on the designing of low cost optical add drop multiplexer & optical cross connects using different techniques to enhance the performance of DWDM systems which is the first objective of the thesis. As we have discussed in previous chapter that the work is done on studying the feasibility of a DWDM network using OXCs & OADMs, but few work has been carried out to simulate the designing of optical add drop multiplexer & optical cross connects using various techniques. The effect of crosstalk on bit error rate & quality value using these techniques has not been analyzed accurately. All these measures have been taken in this chapter, to have the assessment of signal evolution as it passes via the dense WDM transmission. Optical add/drop multiplexer and optical cross connects using different MZI techniques, OADM using Fiber Bragg Grating-Optical circulator (FBG-OC) have been designed and implemented in an optical system.

3.2 Design of Optical add drop multiplexers & Optical Cross Connects

To facilitate better connectivity and elasticity of the system, Optical add/drop multiplexer is the main component in an optical communication system. Due to some characteristics such as small size, selectivity and simple to fixed with fiber systems, devices based on Fibers grating appear to be promising candidates for optical add drop multiplexers. Reduction of crosstalk is the main technical issue for design of optical add drop multiplexer that can strictly degrade system performance [79]. In OADMs, crosstalk arises through the imperfection of component that restricts the performance of the network [80]. Crosstalk at the similar channel as the input is usually known as homodyne crosstalk that cannot be removed by filtering [81]. In the ring network, optical add drop multiplexer can be introduced to compose proficient utilization of system capability, system security and channel direction-finding [82]. In WDM system, Optical add/drop multiplexer is used for routing and multiplexing the dissimilar channels that carry wavelength of light from a SMF. For the manufacturing of optical n/w, OADM is a category of optical device that is commonly used [83]. An Optical add/drop multiplexer may be well thought out to be certain kind of OXCs. In WDM networks, cross connect node is an important component of the system [84]. Such OXC's, having no. of I/P or O/P ports M at operating channels N, must be capable to control each I/P channel to any O/P port. Different types of schemes have been proposed to establish this goal. In Mach–Zehnder interferometer based optical cross connect, the Mach–Zehnder interferometer is used in which two 3 dB couplers are cascaded and is reported as an 8×8 rigorously non blocking OXC using MMI-based generalized MZI realized in the silica-on-silicon planar waveguide structure. In Mach–Zehnder interferometer-fiber Bragg grating based OXC, the Mach–Zehnder interferometer is used & within two arms of couplers, two similar fiber Bragg gratings are positioned, similar is described as an narrative design of 2×2 multi channel OXCs based on OADMs and switches [85]. In Mach–Zehnder interferometer-semiconductor optical amplifier based Optical cross connect, within two arms of couplers the Mach–Zehnder interferometer is used, two similar semiconductor optical amplifiers are situated and is represented as Semiconductor optical amplifier-MZI switches that consists of two semiconductor optical amplifiers and also located at the relevant upper and lower arms of Mach–Zehnder interferometer, while two 3-dB couplers engaged at the I/P and the O/P of the Mach–Zehnder interferometer to complete the interferometric arrangement. Interferometer is an optical instrument that splits a wave into two waves using a beam splitter, delays them by asymmetrical distances, forward them using mirrors, recombine them using another beam splitter and then detect the strength of their superposition. Intensity sensitive to phase change is given by [86]

$$\Phi = 2\pi \mathrm{nd}/\lambda \tag{3.1}$$

where $\mathrm{n} =$ index of refraction of medium wave travels, $\mathrm{d} =$ is the optical path length and λ is operating wavelength. The change in phase is converted into an intensity change using interferometric schemes.

Let output fields of the signal and reference arms to be [87]

$$\mathrm{E_r} = \mathrm{E_a}\sqrt{\alpha_\mathrm{r}\mathrm{k_1\ \ k_2}}\cos(\mathrm{w_o\ t} + \Phi_\mathrm{r}) \tag{3.2}$$

$$\mathrm{E_s} = \mathrm{E_O}\sqrt{\alpha_\mathrm{s}(1-\mathrm{k_1})(1-\mathrm{k_2})}\cos(\mathrm{w_o t} + \Phi_\mathrm{s}) \tag{3.3}$$

The output intensity of the interferometer:

$$\mathrm{I} =< \mathrm{E_r^2} > +< \mathrm{E_s^2} > +2 < \mathrm{E_r E_s} > \tag{3.4}$$

$$= \mathrm{I_O}[\alpha_r k_1 k_2 + \alpha_s(1-k_1)(1-k_2)$$
$$+2\sqrt{\alpha_s\alpha_r k_1 k_2(1-k_1)(1-k_2)}\cos(\Phi_r\Phi_s) \quad (3.5)$$

where $< >$ denote a time average over a period $> 2\pi/w_{o,}$ α_r and $\alpha_s$are optical loss associate with reference and signal paths respectively, k_1 and k_2 are constants.

The ratio of O/P signal (P_o) to the I/P signal (P_i) is given by [87]

$$\frac{P_o}{P_i} = \frac{1}{8}\{G_1 + G_2 - 2\sqrt{G_1 G_2}\cos(\Phi_1 - \Phi_2)\} \quad (3.6)$$

where G_1, G_2 were the gains of the amplifiers and Φ_1, Φ_2 were phase changes induced by nonlinear effects in the two amplifiers.

$$P_{out} = P_o((1-\eta)^2 T_1 + \eta^2 T_2 - 2\eta(1-\eta)\sqrt{T_1 T_2}\cos(\Delta_\Phi)) \quad (3.7)$$

where η is the coupling coefficient of coupler, P_o is the incident power, Δ_Φ is the propagation phase difference between two arms, T_1 and T_2 are the power transmission of the higher and lower arms respectively. Δ_Φ is the sum of a constant term that builds in phase difference between the two arms.

The impact of crosstalk is quantified by the power penalty parameter that is generally defined as the external power required at the receiver. The optical received power can be calculated by the following equation [88]

$$P_{received} = -10\log(1 - \text{crosstalk}) \quad (3.8)$$

3.3 OADM with different Mach-Zehnder Interferometer techniques

Like Synchronous Optical Networking Add/Drop Multiplexers, OADM elements provide the ability to add and remove traffic in the system. They allow the no. of wavelengths to be removed and added by minimizing the no. of useless optical-electrical-optical conversions without disturbing the traffic that is transmitted evidently via the port and are located at the sites that support bi-directional pairs of fiber [89]. Based on different optical devices, various kinds of optical add/drop multiplexers have been established. Depending on OADM and switches, these devices include MZIs that are used to add & remove channels as illustrated in narrative 2×2 multi channel OXCs [85]. MZI with fiber Bragg grating in which two fiber Bragg gratings are positioned in the opposite arms of Mach–Zehnder interferometer [90] and Mach–Zehnder interferometer with SOA in which two semiconductor optical amplifiers are positioned in arms of Mach–Zehnder interferometer [91].

In terms of crosstalk, the performance of an optical system based on optical add/drop multiplexer with MZI, Mach–Zehnder interferometer–Fiber Bragg Grating and Mach–Zehnder interferometer–semiconductor optical amplifier techniques received at 8×10 Gb/s with 0.1 nm interval DWDM transmission located at the 20 km point of a 40 km link is investigated.

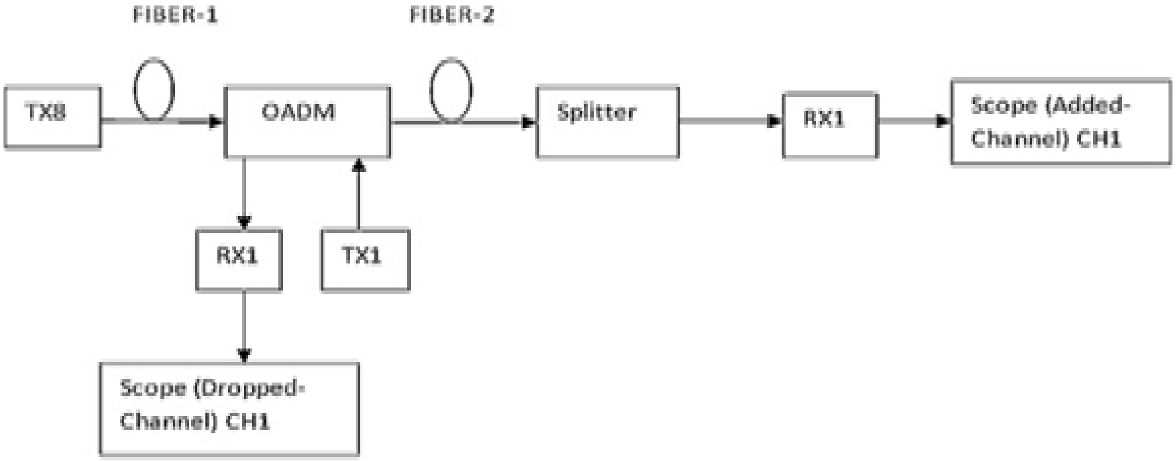


Figure 3.1 System model based on OADM

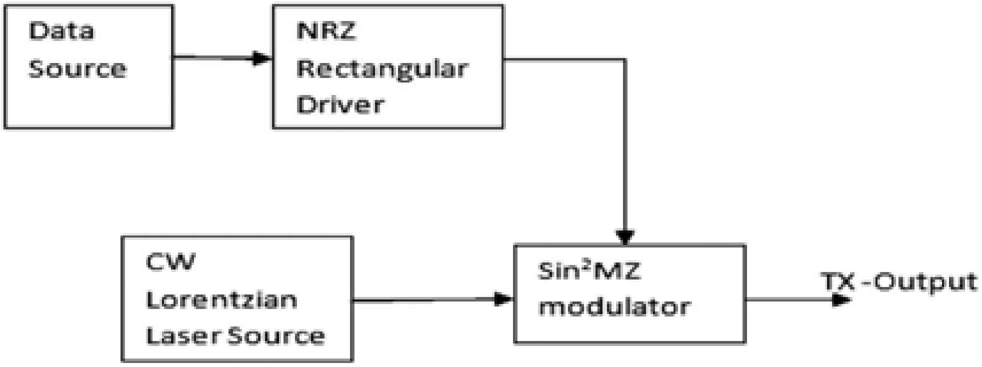


Figure 3.1(a) Single channel transmitter

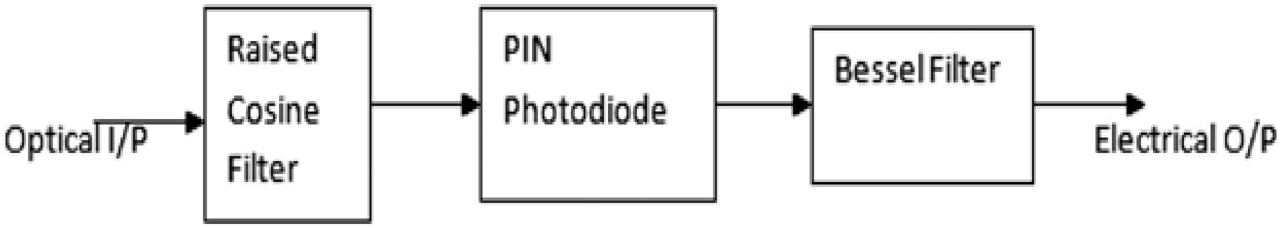


Figure 3.1(b) Single channel receiver

Transmitter, OADM and receiver are three stages of an optical transmission link as shown in Figure 3.1. An optical add/drop multiplexer has 4 ports named as input port, output port, add port and drop port. A channel having frequency 193.15 THz is added to the add port & similar frequency is dropped to the drop port. The single channel TX is as shown in Figure 3.1(a). Each transmitter consists of non-return to zero rectangular driver, data source, amplitude modulator, laser source. The source of data is modified by sequence and baud rate. The block of laser shows basic Continuous wave Lorentzian laser. The design has 8 center frequencies, 1 mW continuous wave power, ideal laser noise BW, 10 Full width at half max. laser random line widths and phase. Here modulation driver generates non return to zero rectangular data format with a signal dynamics that is low level −2.5 and high level +2.5. TXs are followed by a fiber of 20 km and an optical add/drop multiplexer in the circuit that has filter bandwidth 40 GHz, insertion loss 3 dB, bandwidth reference 18 and add/drop frequency 193.15 THz. An optical add/drop multiplexer crosstalk is varied via parametric run from −90 dB to −10 dB. In addition, it is followed by other link of fiber of 20 km, receiver and splitter. In Mach–Zehnder interferometer based OADM, the signal passes via VOA where 3 dB I.L is defined and then applied to the splitter, ideal dual arm MZI that has B.W 40 GHz, 25ps delay and tuning frequency 193.5 THz, 3 dB coupler & combiner. The signal is to be chosen from I/P port passes via splitter, BPF and lastly the signal is removed to the drop port of the optical add/drop multiplexer. To the add port, the signal passes via VOA where 3 dB I.L is defined and then fed to the combiner, splitter, BPF and again combiner. At last the O/P is taken from the O/P port and by making use of VOA b/w the propagating signals, crosstalk is defined b/w add/remove channels as shown in Figure 3.2.

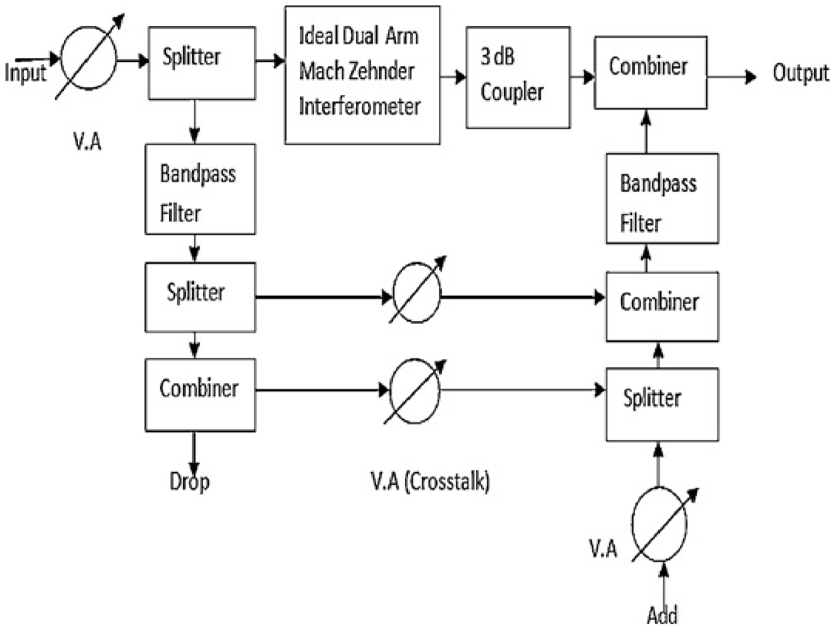


Figure 3.2 Structure of Optical add-drop multiplexer based on Mach-Zehnder Interferometer

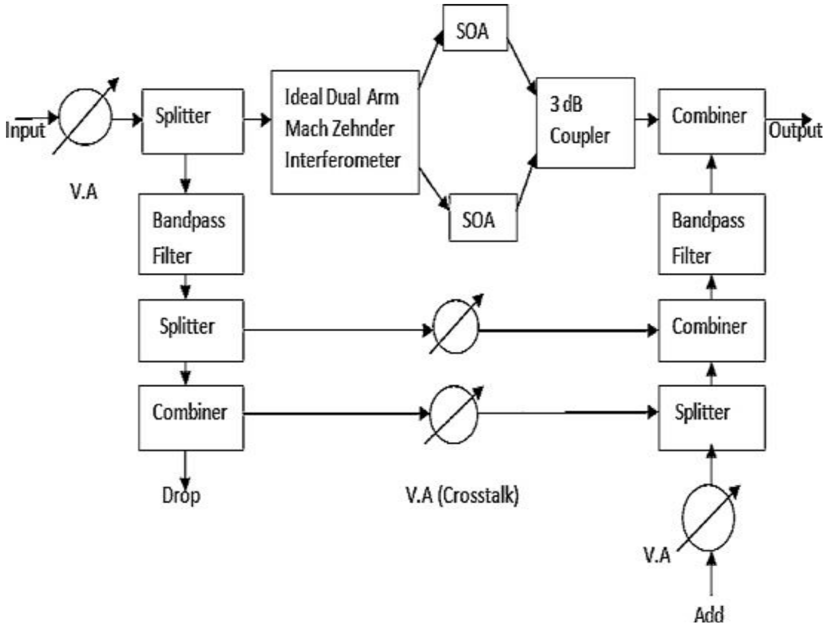


Figure 3.3 Structure of Optical add-drop multiplexer based on Mach-Zehnder Interferometer-SOA

Likewise, in Mach-Zehnder Interferometer–SOA based OADM, two similar semiconductor optical amplifiers are used in the opposite arms of Mach-Zehnder Interferometer with 3 dB coupler as depicted in Figure 3.3.

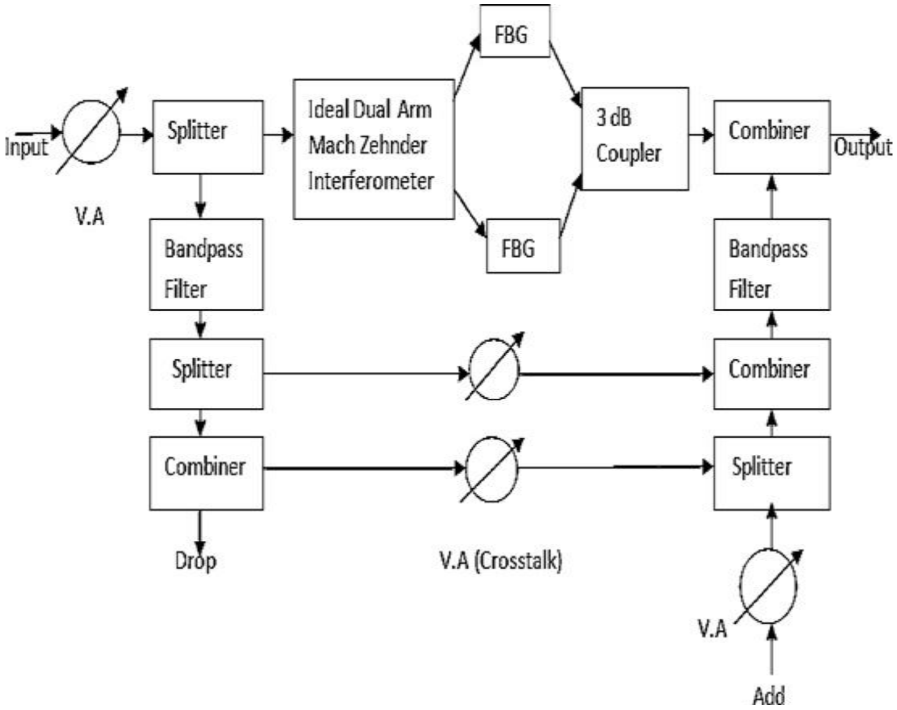


Figure 3.4 Structure of Optical add-drop multiplexer based on Mach-Zehnder Interferometer-FBG

In Mach-Zehnder Interferometer–Fiber Bragg grating based optical add drop multiplexer, two same ideal Fiber Bragg Gratings are used in the opposite arms of Mach-Zehnder Interferometer with 3 dB coupler as depicted in Figure 3.4. As shown in Figure 3.1(b), a single receiver consists of PIN photodiode, low pass Bessel filter and raised cosine filter. To detect a change in performance, electrical scopes are used.

Figure 3.5 depicts the quality value with crosstalk of Add channel-1 detected at the O/P port. It is clear that in case of Mach-Zehnder Interferometer based optical add/drop multiplexer and Mach-Zehnder Interferometer-fiber Bragg grating based optical add/drop multiplexer for Add channel, as the crosstalk increases from −90 to −10 dB, the quality value decreases. But in case of Mach-Zehnder Interferometer–semiconductor optical amplifier based optical add/drop multiplexer, the quality value remains at 6.020600 dB whereas in case of Mach-Zehnder Interferometer–Fiber Bragg grating based optical add drop multiplexer as crosstalk increases from −90 to −10 dB, the quality value decreases from 15.99 to 12.79 dB and is more in comparison of another techniques at high crosstalk.

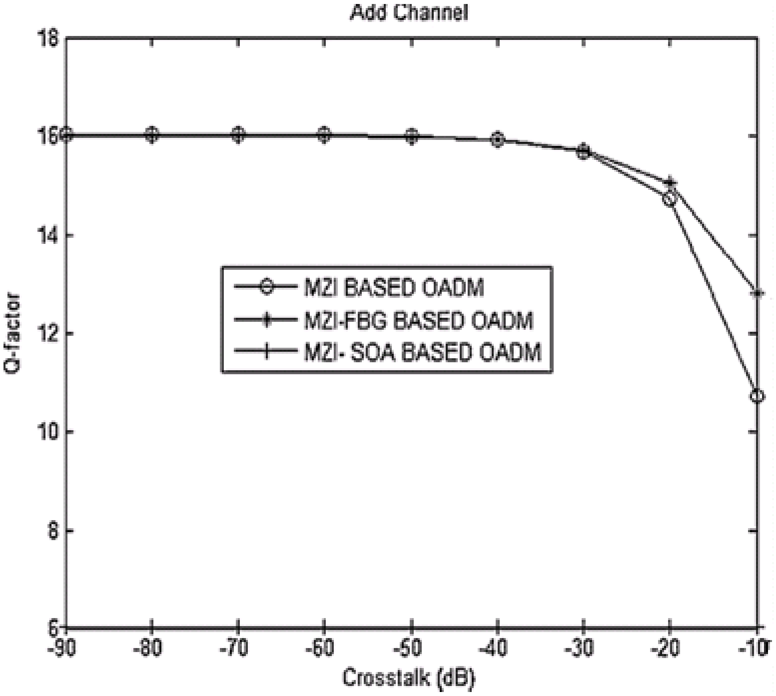


Figure 3.5 Quality factor vs. crosstalk of add channel at frequency 193.15 THz

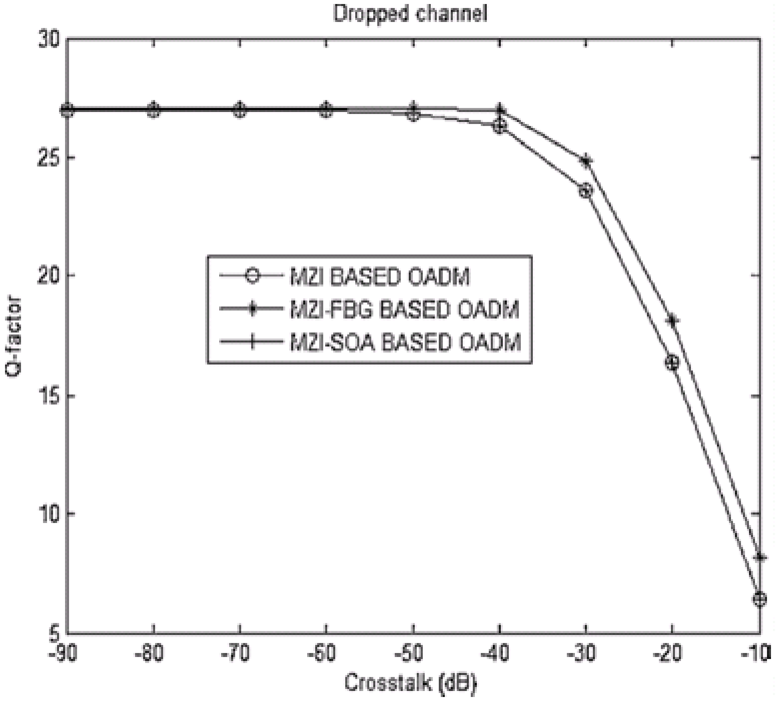


Figure 3.6 Quality factor vs. Crosstalk of drop channel at frequency 193.15 THz

As shown in figure 3.6, the quality value with crosstalk of channel 1 detected at the drop port. In this plot, the crosstalk varied from −90 to −10 dB, quality value in case of Mach-Zehnder Interferometer based optical add/drop multiplexer, Mach-Zehnder Interferometer–FBG based OADM and Mach-Zehnder Interferometer–SOA based optical add/drop multiplexer decreases. But in case of Mach-Zehnder Interferometer–Fiber Bragg grating, with similar crosstalk, the quality value decreases from 27.00 to 8.17 dB and is more in comparison of another techniques. The bit error rate at frequency 193.15 THz with crosstalk at O/P port is as shown in Figure 3.7. It is found that for Mach-Zehnder Interferometer-fiber Bragg grating based optical add/drop multiplexer, as the crosstalk increases from −90 to −10 dB, the bit error rate increases from 1.43181×10^{-10} to 8.21797×10^{-6} in the comparison of other but at the similar time it is less in comparison of another techniques at high crosstalk. As in case of MZI–FBG based OADM, a grating is directly induced into the Fiber's core which leads to low I.L whereas in MZI–SOA based OADM, SOAs have more nonlinear effects and insertion losses and therefore it is the worst case.

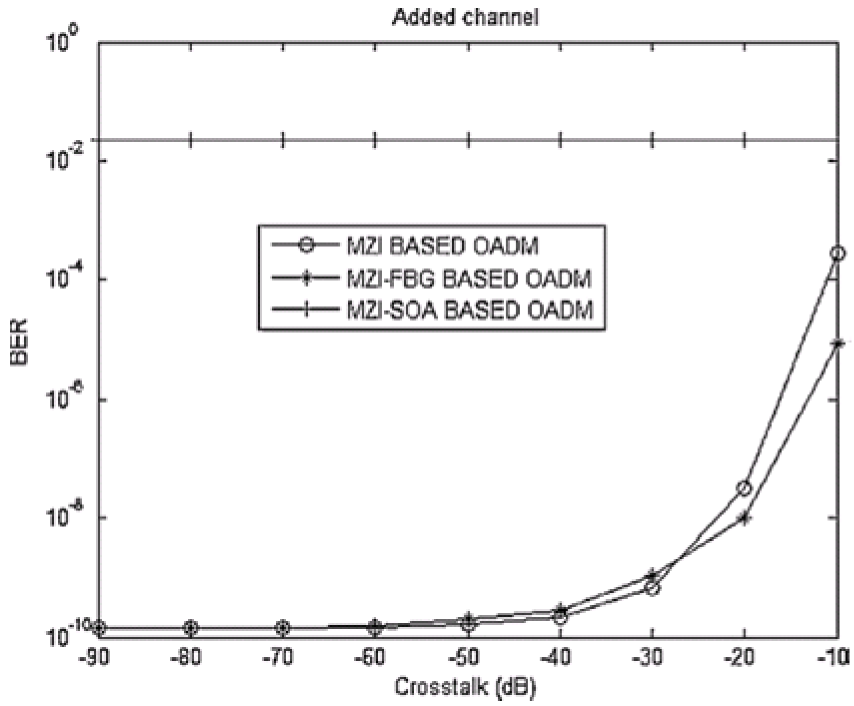


Figure 3.7 Bit error rate vs. Crosstalk of Add channel at frequency 193.15 THz

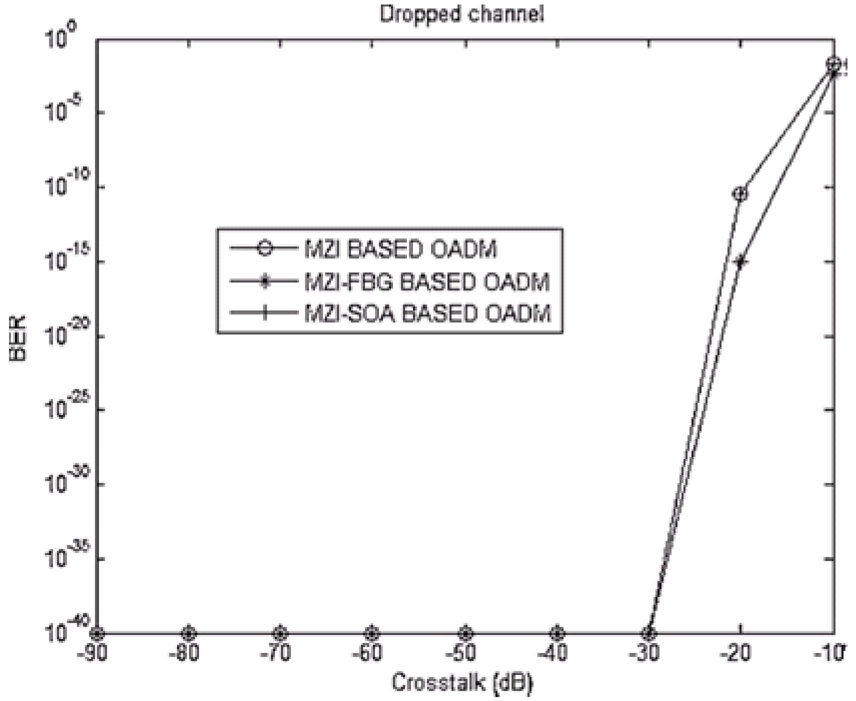


Figure 3.8 Bit error rate vs. Crosstalk of drop channel at frequency 193.15 THz

Figure 3.8 reveals the bit error rate with crosstalk level plot of frequency 193.15 THz at drop port. It is further found that bit error rate for Mach-Zehnder Interferometer–Fiber Bragg grating based optical add drop multiplexer remains at 1×10^{-40} as the level of crosstalk increases from −90 to −30 dB and increases from 8.4549×10^{-16} to 0.00419683 as the crosstalk increases from −20 to −10 dB.

We have also evaluated the three MZI techniques of OADM for dense WDM network & examine the impact of crosstalk obtained at 8 × 10 Gb/s with 0.1 nm interval. It is also found that Mach-Zehnder Interferometer–Fiber Bragg grating based optical add/drop multiplexer and Mach-Zehnder Interferometer-based optical add-drop multiplexer provide improved results with max. distance (150km) at interval of 0.1 nm and bit rate of 10 Gb/s without using Dispersion Compensating Fiber and amplifier and the worst case is observed with Mach-Zehnder Interferometer–SOA based optical add/drop multiplexer. The Optimization of Mach-Zehnder Interferometer-based optical add/drop multiplexer and Mach-Zehnder Interferometer–fiber Bragg grating-based optical add/drop multiplexer with interval is as depicted in figure. It is found that the system has been optimized at 0.1 nm for different parameters like tuning frequency, I.L, coupling ratio, interferometer B.W, delay, BPF stages, −3 dB two-sided B.W of BPF, Fiber Bragg grating reference frequency & crosstalk as described in Table 3.1.

Table 3.1 Optimized parameters

Insertion loss	3 dB
Interferometer bandwidth	40 GHz
Interferometer delay	25 ps
Interferometer tuning frequency	193.5 THz
Coupling ratio	50:50
Band pass filter no. of stages	15
−3 dB two sided bandwidth of band pass filter	40 GHz
FBG reference frequency	193.414 THz
Crosstalk	−20 dB

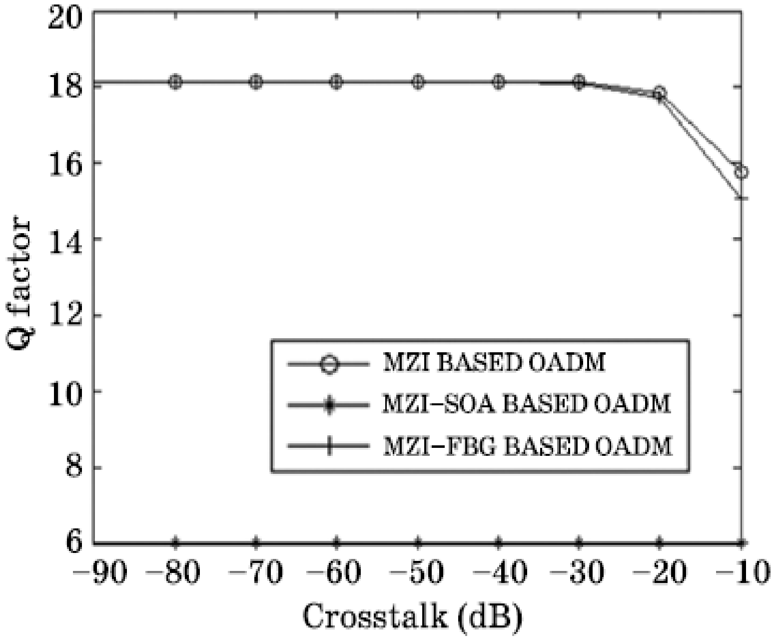


Figure 3.9 Q-factor vs. crosstalk of Add channel at frequency 193.15 THz for 70 km

As shown in figure 3.9, the quality value with crosstalk plot of Add channel channel–1 (193.15THz) detected at the O/P port. It is clear that in case of Mach-Zehnder Interferometer-based optical add-drop multiplexer and Mach-Zehnder Interferometer–FBG based optical add/drop multiplexer for Add channel, as the crosstalk level increases from −90 to −10 dB, the quality value of the signal decreases from 18.14 to 15.08 dB & from 18.13 to 15.74 dB respectively.

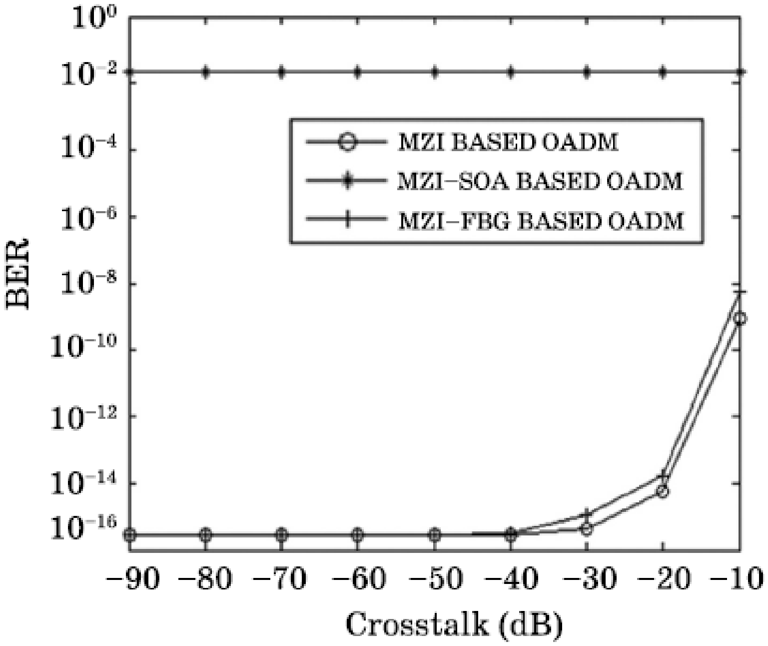


Figure 3.10 Bit error rate vs. crosstalk of Add channel at frequency 193.15 THz for 70 km.

Figure 3.10 depicts the bit error rate with crosstalk graph of frequency 193.15 THz at O/P port. It is found that the bit error rate for Mach-Zehnder Interferometer–FBG based optical add/drop multiplexer and Mach-Zehnder Interferometer based optical add/drop multiplexer increases from 2.67×10^{-16} to 5.83×10^{-9} and from 2.69×10^{-16} to 8.66×10^{-10} respectively as the crosstalk increases from −90 to −10 dB**.** As for Mach-Zehnder Interferometer–SOA based optical add/drop multiplexer, semiconductor optical amplifiers have more I.Ls and nonlinear effects such as XGM, XPM and FWM.

Figures 3.11 & 3.12 shows that as the transmission length increases from 70 to 150 km, degradation of bit error rate and quality value occurs. Degradation occurs due to continuous increase in span distance and amplified spontaneous emission noise. For given transmission length, the variation in quality value of 3 Mach-Zehnder Interferometer techniques at channel spacing 0.1 nm and −20 dB crosstalk for 10 Gb/s are from 17.86 to 16.19 dB for Mach-Zehnder Interferometer using optical add-drop multiplexer, from 17.72 to 16.19 dB for Mach-Zehnder

Interferometer–Fiber Bragg grating based OADM & remains at 6.02 dB for Mach-Zehnder Interferometer–semiconductor optical amplifier based optical add drop multiplexer as depicted in Figure 3.11.

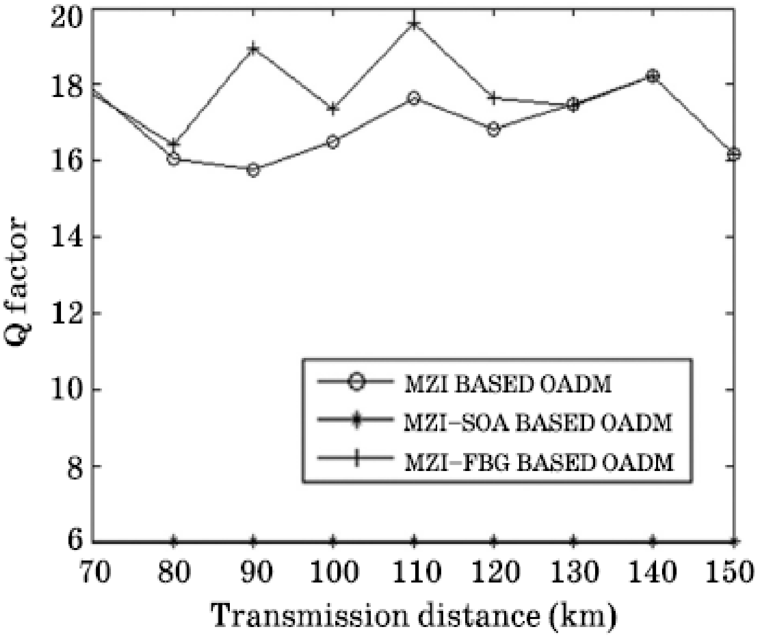


Figure 3.11 Q-factor vs. Transmission distance of add channel at frequency 193.15 THz at -20dB crosstalk

The plot b/w the bit error rate and transmission distance at the fiber is as depicted in Figure 3.12. For Mach-Zehnder Interferometer-based optical add/drop multiplexer and Mach-Zehnder Interferometer–FBG-based optical add/drop multiplexer, the bit error rate is low and these designs of optical add drop multiplexer indicate best performance as compared to Mach-Zehnder Interferometer–SOA based optical add/drop multiplexer. It is found that at the transmission distance of 150 km, Mach-Zehnder Interferometer-based optical add-drop multiplexer and Mach-Zehnder Interferometer–FBG based optical add/drop multiplexer provide both suitable bit error rate about 1.38×10^{-10} and also quality value as 16.19 dB.

Moreover, at dissimilar bit rates varying from 5 to 40 Gb/s the performance of three Mach-Zehnder Interferometer techniques is investigated. To achieve better results, 0.1 nm interval is used in this system. The variation of signal quality as a function of bit rate of single channel among 8 channels is as shown in Figure 3.13.

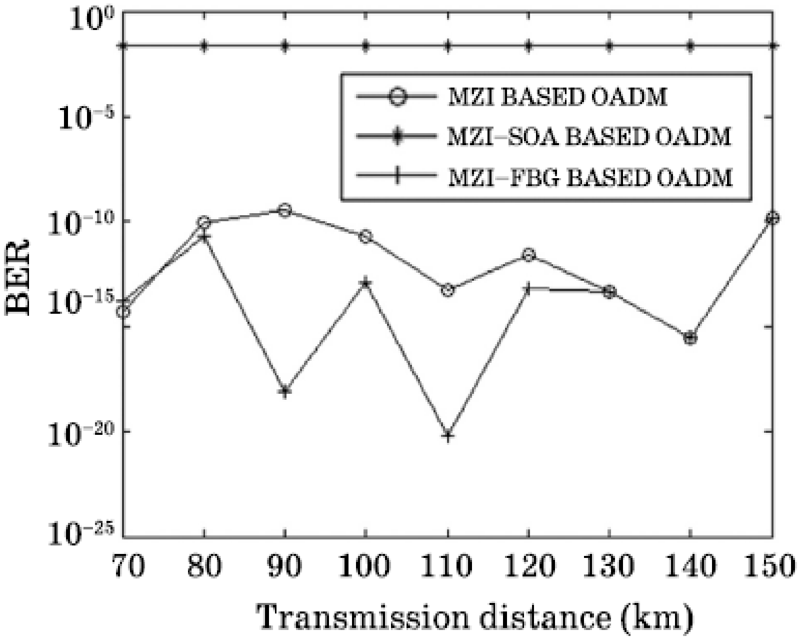


Figure 3.12 Bit error rate vs. transmission distance plot of add channel at frequency 193.15 THz at -20dB crosstalk

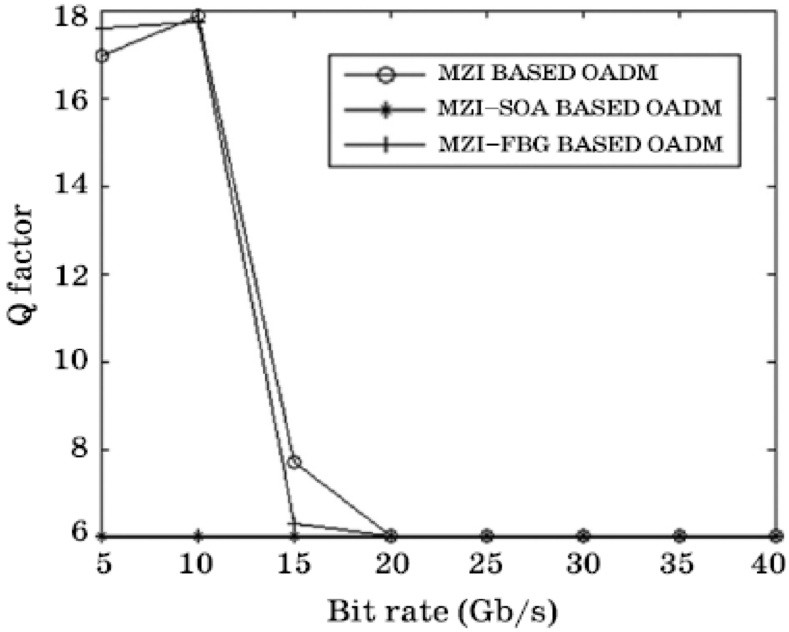


Figure 3.13 Q-factor vs. bit rate of Add channel at frequency 193.15 THz and -20dB crosstalk for 70 km

It is observed that again Mach-Zehnder Interferometer-based optical add-drop multiplexer and Mach-Zehnder Interferometer–FBG based optical add-drop multiplexer provide improved quality value 17.86 dB & 17.72 dB for 10 Gb/s bit rate. The variation in bit error rate vs. bit rate is as shown in Figure 3.14. It is observed that again Mach-Zehnder Interferometer-based optical add/drop multiplexer & Mach-Zehnder Interferometer–FBG based optical add/drop multiplexer provide suitable bit error rate 5.47×10^{-15} and 1.58×10^{-14} for 10 Gb/s bit rate.

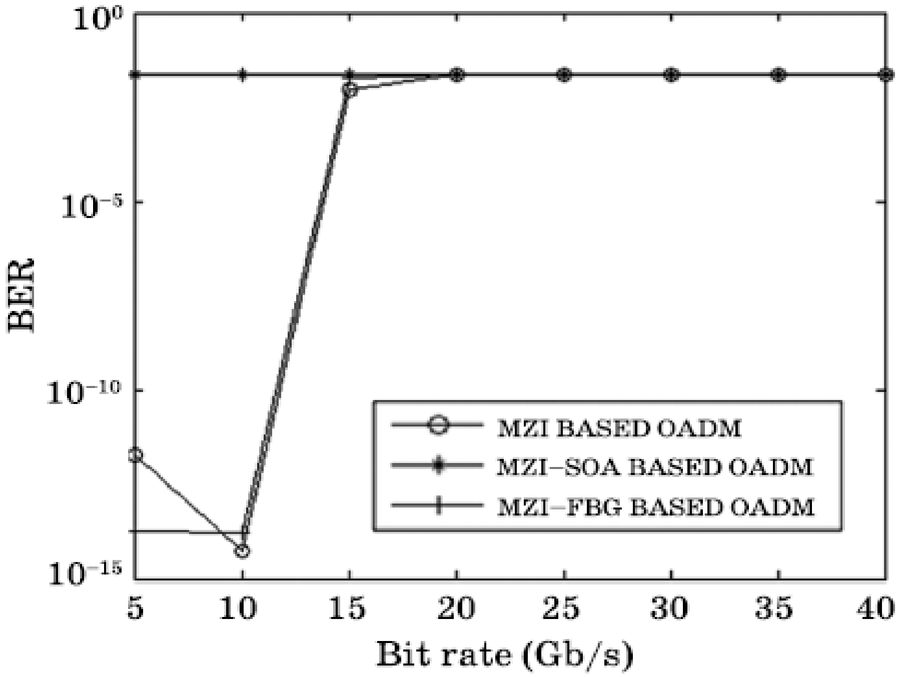


Figure 3.14 Bit error rate vs. bit rate of Add channel at frequency 193.15 THz and -20dB crosstalk

The variation in bit error rate & quality value as a function of channel spacing is as shown in Figure 3.15 and 3.16. It can be seen that again Mach-Zehnder Interferometer-based optical add-drop multiplexer & Mach-Zehnder Interferometer–FBG based optical add-drop multiplexer provide acceptable quality value and bit error rate for 0.1 nm channel spacing.

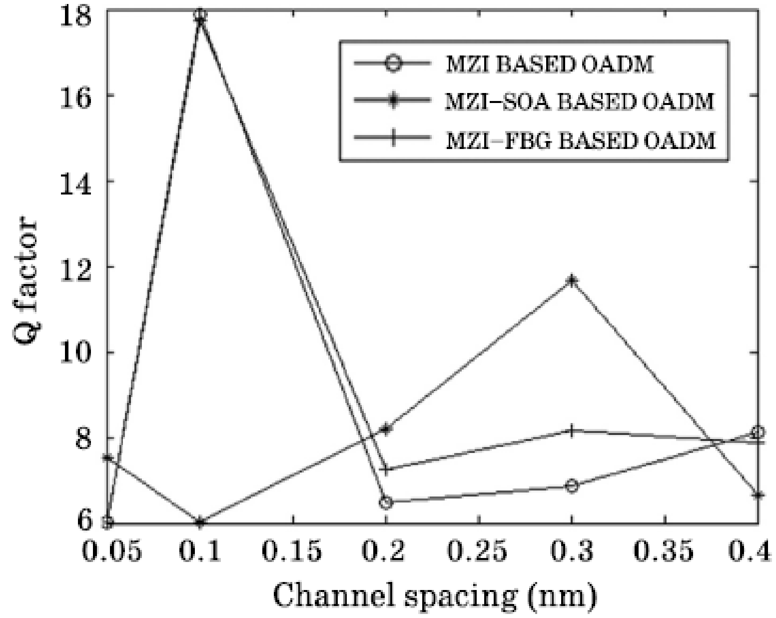


Figure 3.15 Q-factor vs. channel spacing plot of Add channel at frequency 193.15 THz and -20dB crosstalk and 10Gbps bit rate for 70 km

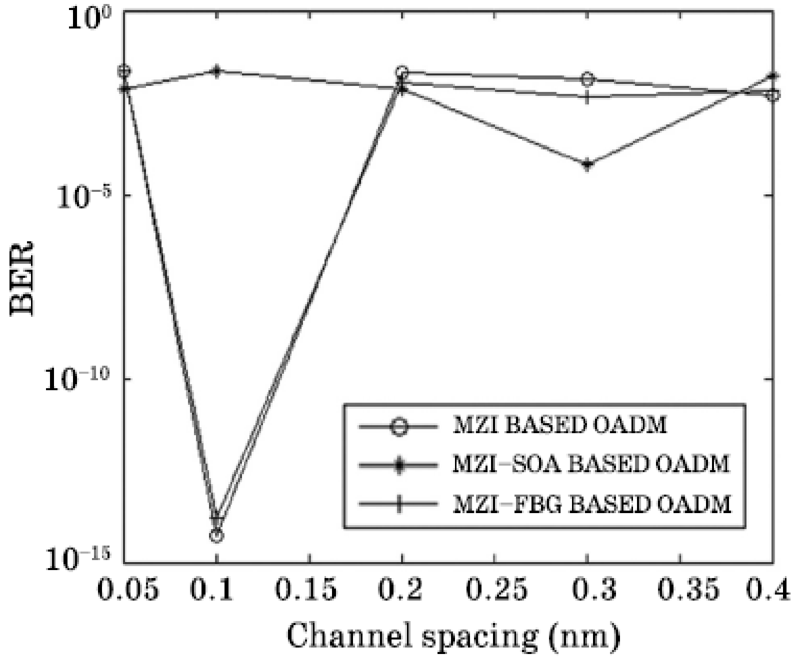
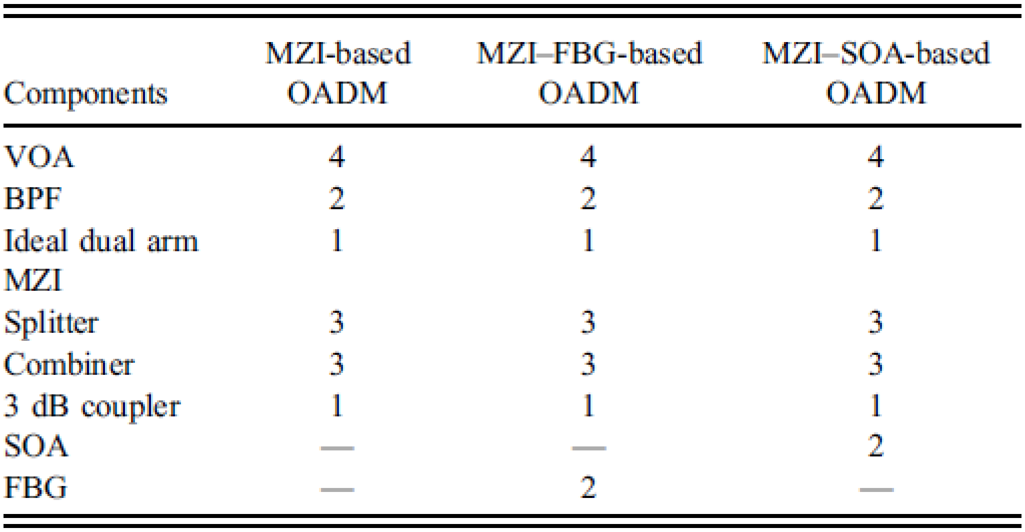


Figure 3.16 Bit error rate vs. channel spacing of Add channel at frequency 193.15 THz at -20dB crosstalk and 10Gb/s bit rate for 70 km

The system’s cost depends on the no. of equipments used that is the equipment of optical layer & equipment of network higher layer. As compared to other techniques, the structure of Mach-Zehnder Interferometer-based optical add/drop multiplexer is trouble-free & cost effective because it requires less no. of components as shown in Table 3.2.

Table 3.2 Number of Components Required



Components	MZI-based OADM	MZI–FBG-based OADM	MZI–SOA-based OADM
VOA	4	4	4
BPF	2	2	2
Ideal dual arm MZI	1	1	1
Splitter	3	3	3
Combiner	3	3	3
3 dB coupler	1	1	1
SOA	—	—	2
FBG	—	2	—

As compared to the structures of MZI-based optical add/drop multiplexer, Mach-Zehnder Interferometer–FBG and Mach-Zehnder Interferometer–SOA based optical add/drop multiplexer require incorporation of Fiber Bragg grating and semiconductor optical amplifiers that increases both the complexity and cost of the architecture.

3.4 Fiber Bragg grating-circulator based OADM

An optical add/drop multiplexer will play an important role in enabling better flexibility and connectivity in dense WDM network [92]. Due of their characteristics such as small size, low loss, spectral selectivity & cylindrical equilibrium permits easy coupling with optical fiber systems, Fiber Bragg grating based devices [93] seems to be promising for OADMs. Fiber gratings can be used in enormously narrow band filters, dispersion compensators [94], wavelength converters [95], add/drop multiplexers, phase conjugates and channel stabilized pump lasers [96]. If its wavelength is equal to Bragg resonance wavelength that is λ_{Bragg}, the propagating wave is reflected, otherwise the wave is transmitted. The relation between the grating spatial periodicity & the Bragg resonance wavelength is given by [97],

$$\lambda_{\mathrm{Bragg}} = 2\,\eta_{\mathrm{eff}}.\Lambda \qquad (3.9)$$

Here η_{eff} is effective mode index, λ_{Bragg} is Bragg resonance wavelength and Λ is grating period.

The unique structure of an optical add-drop multiplexer based on bidirectional Fiber Bragg Grating-Optical circulator has been investigated for DWDM system with different modulators like Amplitude Modulator, Mach-Zehnder and Electro absorption. The basic principle of all optical modulators is to modulate the optical carrier according to the data signal in the term of amplitude, frequency, phase etc. The general schematic of optical modulator is shown in Fig. 1.

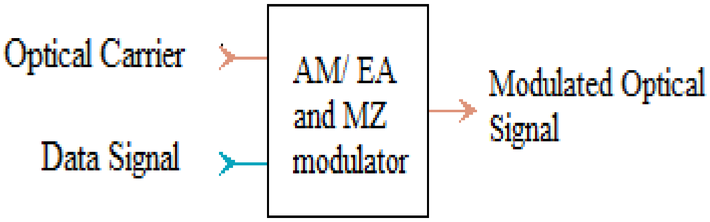


Figure 1.Schematic of optical modulator.

Amplitude Modulator:

The output signal $E_{\mathrm{out}}(t)$ is given by [85]

$$E_{\mathrm{out}}(t) = E_{\mathrm{in}}(t).\sqrt{d(t)} \qquad (3.10)$$

Where $E_{\mathrm{in}}(t)$ denotes the input optical signal. The power transfer function $d(t)$ is defined as:

$$d(t) = (1 - m) + m.\,\mathrm{data}(t) \qquad (3.11)$$

Where m is the Modulation Index and $\mathrm{data}(t)$ represents the electrical modulation signal. It is assumed that usually $\mathrm{data}(t)$ varies within the limits $0 \leq \mathrm{data}(t) \leq 1$ to ensure a power transfer function $d(t)$ larger than zero. If a negative power transfer function $d(t)$ would arise, $d(t)$ is internally clipped up to zero. The power of the output signal $P_{\mathrm{out}}(t) = |E_{\mathrm{out}}(t)|^2$ is given by:

$$P_{\mathrm{out}}(t) = P_{\mathrm{in}}(t).d(t) = P_{\mathrm{in}}(t).((1 - m) + m.\,\mathrm{data}(t)) \qquad (3.12)$$

With $P_{\mathrm{in}}(t) = |\mathrm{Ein}\ (t)|^{2}$ being the input power of the optical carrier.

Electro absorption Modulator:

The output signal $\mathrm{E_{out}(t)}$ is given by

$$\mathrm{E_{out}(t) = E_{in}(t).\sqrt{d(t)}.\exp\left(\frac{j\alpha}{2}\ln[d(t)]\right)} \qquad (3.13)$$

Where $\mathrm{E_{in}(t)}$ is the input optical signal and α denotes the chirp factor which couples the phase and amplitude changes of the optical wave. To represent the power transfer function $\mathrm{d(t)}$ power of the output signal $\mathrm{P_{out}(t)}$.

Table 3.3 Basic parameters and its considered values

Specification (Parameter)	**Value**
Modulation Index (m)	0.9
Chirp Factor (α)	0
Input power of the optical carrier (P_{in}(t))	1 mW

Mach-Zehnder modulator:

The behavior of such modulators depends on their design, and specifically the configuration of the electrodes with respect to the Lithium-Niobate crystal. With good design and manufacturing [86], the modulator will have a large extinction ratio and a low chirp (dynamic change in frequency under modulation). This version includes a choice on specifying the chirp (the optical frequency shifts during the leading and trailing edges of a pulse).

The optical power $\mathrm{P_{out}}$ at the O/P of MZM depends on the phase difference $\Delta\Phi$ b/w the two modulator branches.

$$\mathrm{P_{out}(t) = P_{in}(t).d(t) = P_{in}(t).\cos^2[\Delta\Phi(t)]} \qquad (3.14)$$

With

$$\Delta\Phi(\mathrm{t}) = \frac{\Delta\Phi_1(\mathrm{t}) - \Delta\Phi_2(\mathrm{t})}{2}$$

Where $\mathrm{d(t)}$ is the power transfer function and $\Delta\Phi_1(\mathrm{t})$ and $\Delta\Phi_2(\mathrm{t})$ are the phase changes in each branch caused by the applied modulation signal $\mathrm{data(t)}$.

Table 3.4 Basic specifications and its considered values

Specification (Parameter)	**Value**
Extinction ratio	30 dB
Symmetry Factor (A physical-design based parameter for specifying the chirp)	-1
ChirpSign (A physical-design based parameter for specifying the chirp. Takes the opposite sign of the AlphaFactor)	Positive

These specifications and models have been used in numerical simulations.

The DWDM system consists of three stages: transmitter, Bidirectional FBG-OC based OADM and receiver is shown in Figure 3.17. In OADMs, channel-1 with one frequency is added to the add port & similar frequency is removed to the drop port. Each TX consists of data source, laser source, non-return-to zero rectangular driver and optical amplitude modulator. The continuous wave laser source is used to generate an optical carrier having 1 mW of power and 10 MHz of line width which is fed to the modulator. Modulation driver generates the NRZ rectangular data signals with a signal dynamics (amplitude level variation) that is low level -2.5V & high level +2.5V. The pulses are then modulated using AM, Mach-Zehnder and Electro Absorption modulator individually at 40 Gbps of data signals.

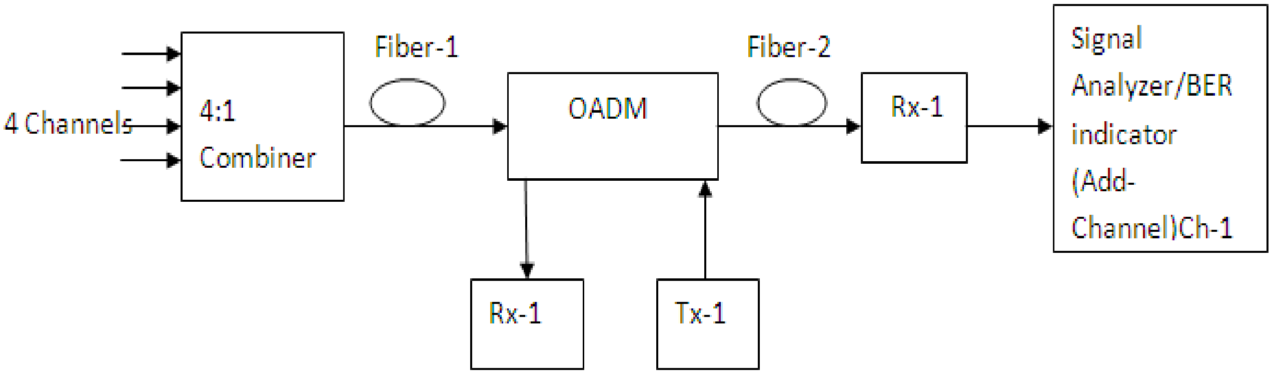


Figure 3.17 System Set up of FBG-OC based OADM

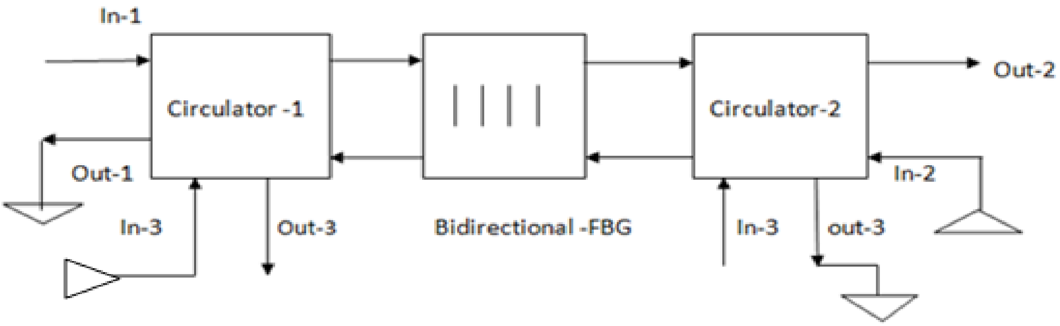


Figure 3.18 A typical Add/Drop multiplexer

The transmitters are followed by a 4:1 combiner which combines four optical input channels and consists of three cross couplers and a fiber link with effective area of core 80× 10^{-12} m^2 and the dispersion 16 ps/nm/km. For adding/dropping operation, the inline bidirectional OADM is used which consists of two circulators and bidirectional filter FBG. Bidirectional filter FBG includes two basic FBG filters and two multiplexer which reflect as well as transmit the wavelength with two bidirectional ports and allow transmission in both directions as shown in Fig 3.18. The parameters of FBG and circulator (such as circulator insertion loss, FBG I.L, FBG bandwidth) have been taken as variable. Other related fixed parameters are FBG & circulator rejection of 30 dB is used. In a 3-port circulator, I/P signal on port 1 is sent out on port 2, I/P signal on port 2 is sent out on port 3 and I/P signal on port 3 is sent out on port 1. An informational signal is added at the add port, reflected back via fiber Bragg grating & then passed via circulator 2. Another signal with the similar channel as the informational signal is entered at circulator 1. The receiver consist of raised cosine band pass filter with 0.2 raised cosine roll off, PIN photodiode with 1A/W responsivity, center frequency of 192.2 THz, zero dark current and low-pass Bessel filter. Signal Analyzer is used to examine the performance.

Fig. 3.19 shows the BER with transmission distance plot of Add Channel channel-1 (192.2 THz) detected at O/P port. In this case the insertion loss of FBG and circulator is taken as 0 dB with the FBG bandwidth of 40 GHz to check the impact of transmission distance. It is evident that the proposed network survives up to 70 Km transmission distance using A.M modulator giving acceptable BER of 8.90×10^{-12}. By using MZ and EA modulators, the network survives up to 50 Km and 30 Km distance for add Channel giving acceptable BER of 1.00×10^{-9} and 3.00×10^{-12}, after that the system performance is degraded since MZ and Electro Absorption modulators are lumped electrode devices whose speeds are restricted by the entire parasitic of the devices that limits the devices to very small length for high speed process and have more chirp.

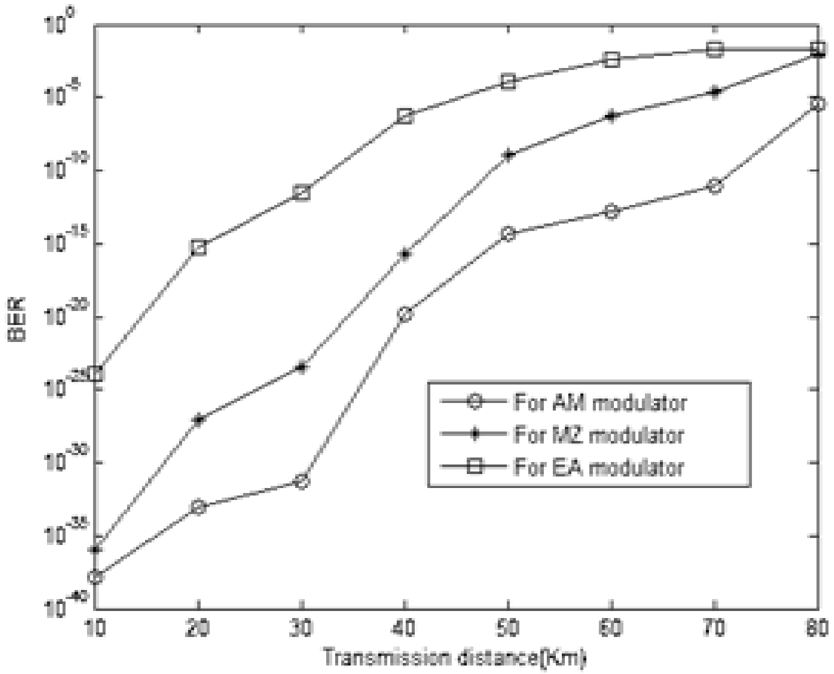


Figure 3.19 Bit error rate vs. Distance of Add channel at frequency 192.2 THz

Figure 3.20 depicts the bit error rate with FBG bandwidth at output port of frequency 192.2 THz for 30 Km distance. It is observed that the network can survive with larger FBG bandwidth up to 280 GHz for AM modulator with zero insertion loss of FBG and Circulator showing an acceptable BER 9.79 $\times 10^{-10}$. With MZ and EA modulator, the System Survive up to FBG bandwidth of 240 GHz and 200 GHz providing an acceptable BER of 8.51 $\times 10^{-10}$ and 9.26×10^{-10} respectively. After that the system performance is again degraded.

Figure 3.21 depicts the bit error rate with FBG insertion loss plot at O/P port of frequency 192.2 THz for 30 Km distance with zero insertion loss of circulator. It is observed that the network can tolerate maximum insertion loss of 9 dB for AM modulator showing an acceptable BER of 8.16 $\times 10^{-10}$. With MZ and EA modulators, the System can tolerate insertion loss up to 7 dB showing an acceptable BER of 7.24×10^{-10} and 6.53×10^{-10} respectively.

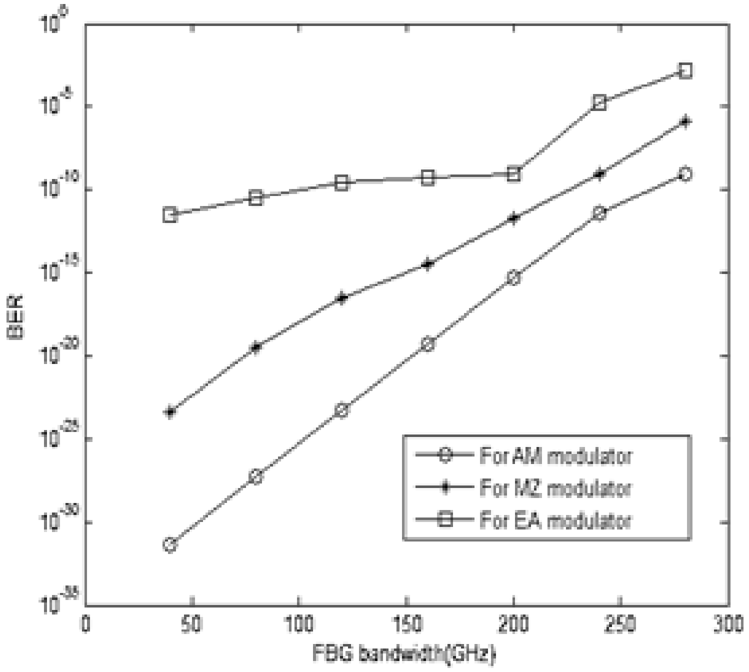


Figure 3.20 BER vs. FBG B.W of add channel at frequency 192.2 THz

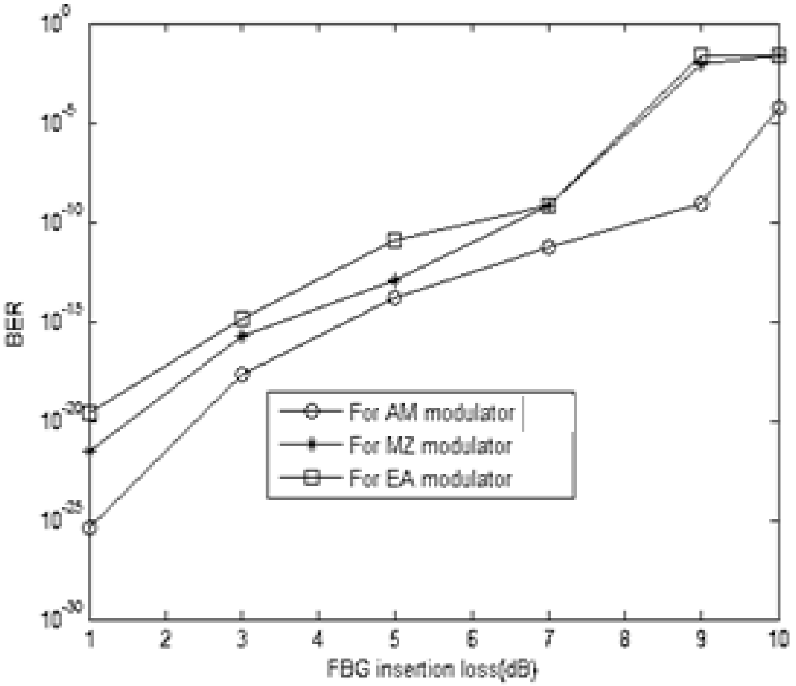


Figure 3.21 BER vs. FBG I.L of add channel at frequency 192.2 THz

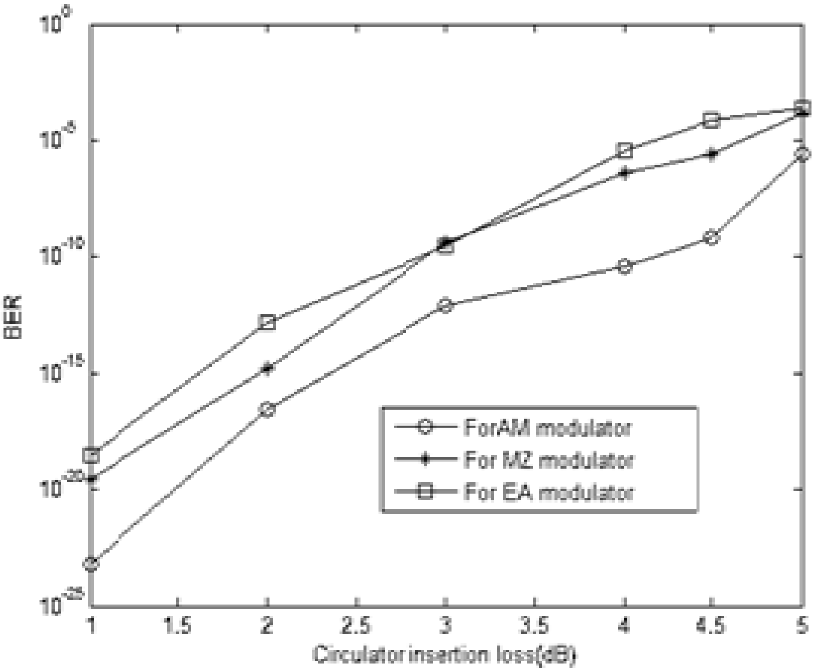


Figure 3.22 Bit error rate vs. Circulator I.L of add channel at frequency 192.2 THz.

Figure 3.22 depicts the bit error rate with circulator insertion loss at output port of frequency 192.2 THz for 30 Km distance with zero insertion loss of FBG. It is observed that the network can tolerate an insertion loss up to 4.5 dB for AM modulator showing an acceptable BER of 6.16 $\times 10^{-10}$. With MZ and Electro-absorption modulators, the system can tolerate an insertion loss up to 3 dB showing an acceptable BER of 4.24×10^{-10} and 3.14×10^{-10} respectively.

3.5 Crosstalk analysis in an optical network based on OXC with different Mach-Zehnder Interferometer techniques

In realistic systems, various signals and channels could control each other & causes major crosstalk in the OXC, has prevented the use of optical cross connects in profitable networks. Based on the cross-connecting state of the optical cross connect, the no. of contributions leaked from each signal with the similar channel as the signal measured is in random. Due to thermal and mechanical fluctuations, the differences in propagation delay and polarization states of the crosstalk contributions are also in random and drift w.r.t one another.

The effect of crosstalk in three basic cross connects based on MZI techniques obtained at 4x10 Gbps with 0.1nm interval DWDM transmission using standard SMF is also evaluated. Type-I is

MZI based OXC, Type-II is MZI-FBG based OXC & Type-III is MZI-SOA based OXC. The signal is transmitted with minimum bit error rate using MZI-Fiber Bragg grating based optical cross connect and Mach-Zehnder Interferometer based OXC up to 80Km. Figure 3.23 depicts simulation set up consists of transmitter, 2x2 an OXC and receiver. TXs are followed by a fiber i.e standard single mode fiber of dispersion 16 ps/nm/km, an EDFA in the circuit that has a flat gain shape and maximum small signal gain of 35 dB, fixed power of output 6.025dBm in both input ports**.** To provide the power difference of 3dB at input ports, an attenuator is used in the circuit.

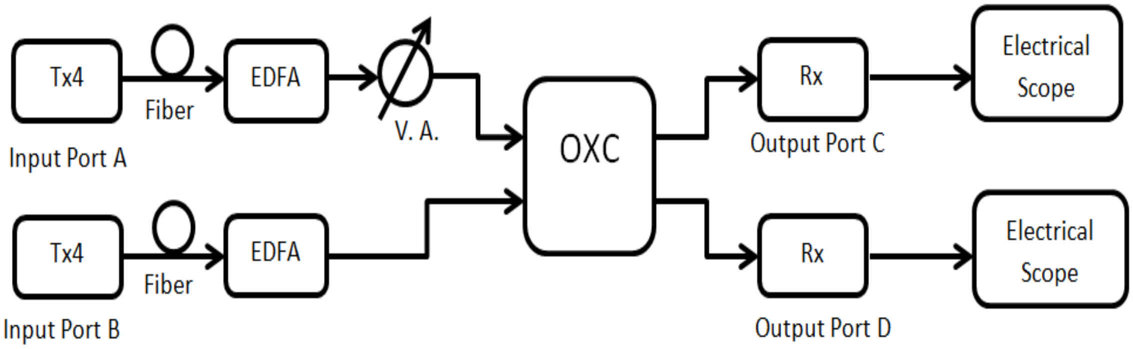


Figure 3.23 System model based on OXC

The cross connect has insertion loss 3 dB, the filter roll off 0.2, filter BW 50, I.L switch 0.5, interval 0.1 nm and crosstalk is from −100 to −10 dB. In Mach-Zehnder Interferometer based OXC, the signal passes via dissimilar sections such as VOA where 3 dB I.L is defined in both the I/P ports. Section of demux consists of raised cosine BPF with each wavelength passes the signal to the real switch that is 2 × 2 four OXC and then the optical mux multiplexes all the wavelengths to the O/P ports as depicted in Figure 3.24. With each real switch that is 2×2 OXC further passes the signals via variable attenuator where insertion loss (I.L) 0.5 is specific in the I/P ports & are applied to the combiners and splitters. The crosstalk is defined by making use of variable attenuator b/w the propagating signals & lastly the signals passes via Mach-Zehnder Interferometer switch where two 3 dB couplers are used as depicted in Figure 3.25.

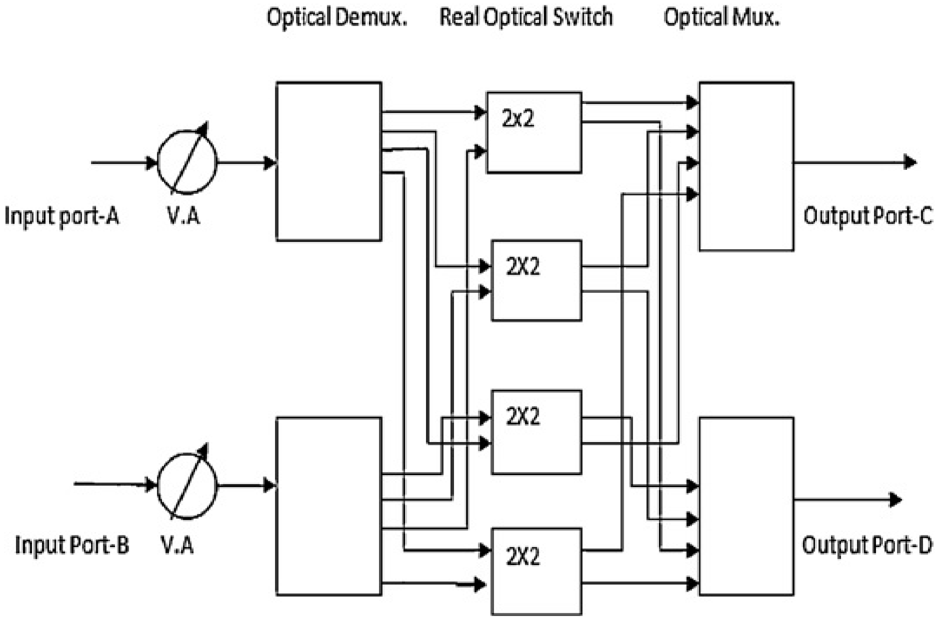


Figure 3.24 Structure of Optical cross connect

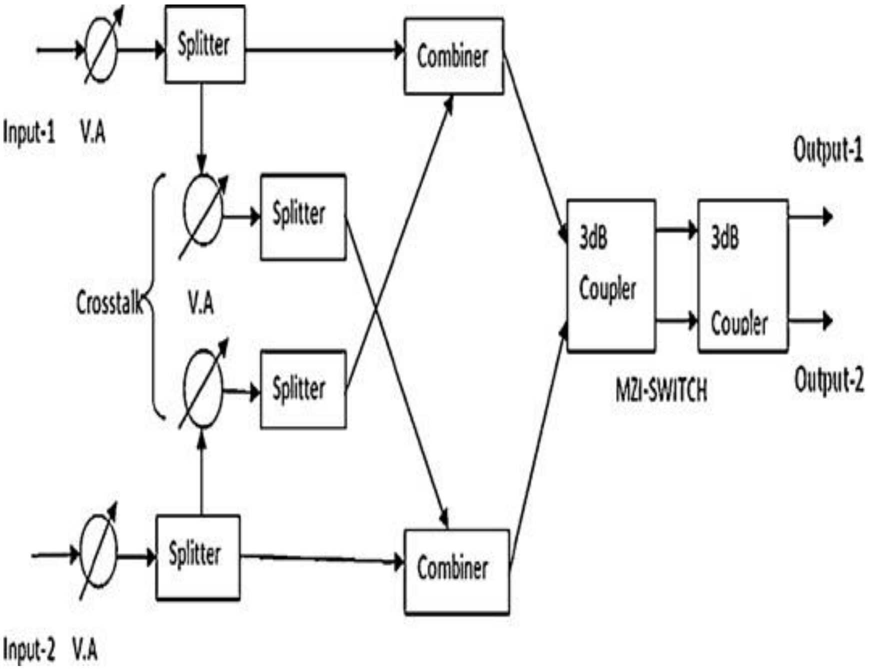


Figure 3.25 Real optical switch (2×2) based on Mach-Zehnder Interferometer

Likewise, In Mach-Zehnder Interferometer-SOA based OXC, two identical semiconductor optical amplifiers are used in the opposite arms of couplers as depicted in Figure 3.26.

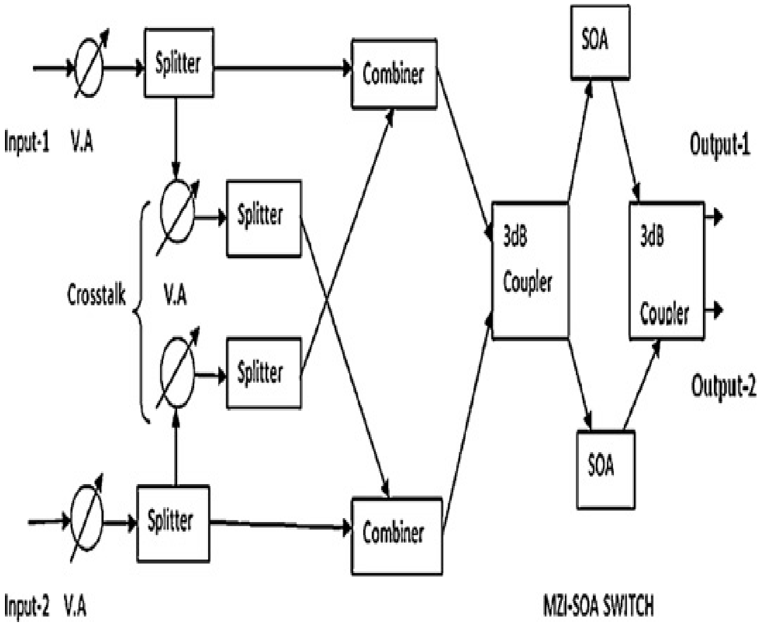


Figure 3.26 Real optical switch (2×2) based on Mach-Zehnder Interferometer-SOA.

In Mach-Zehnder Interferometer-FBG based OXC, two similar ideal Fiber Bragg gratings are used in opposite arms as shown in Figure 3.27.

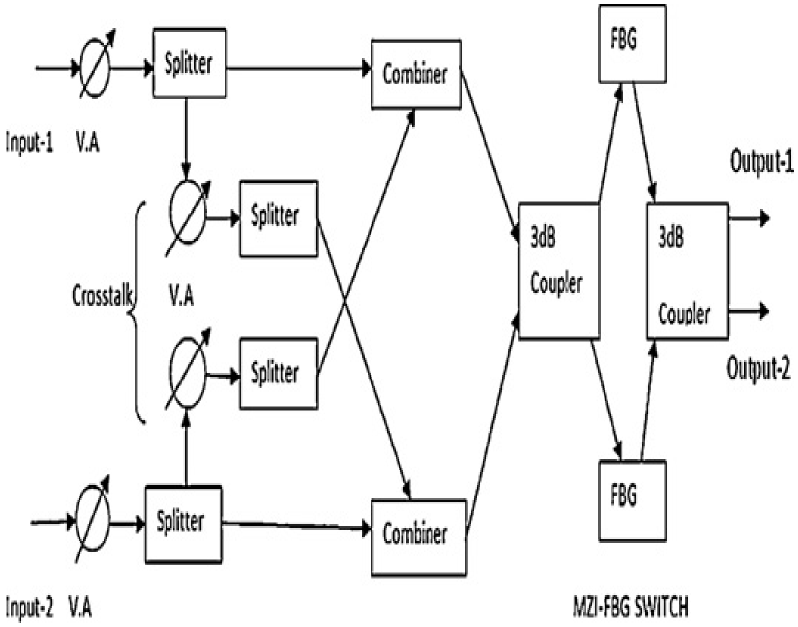


Figure 3.27 Real optical switch (2×2) based on Mach-Zehnder Interferometer-FBG.

As OXC is in bar state, single RX consists of optical raised cosine filter, low pass Bessel filter and PIN photodiode. To examine change in performance, electrical scopes are used. Optical filter element implements a raised cosine transfer function filter having BPF synthesis, 0.2 raised cosine roll off, 1 as raised cosine exponent, 192.95 THz center frequency and 40 GHz bandwidth. PIN photodiode has parameters such as 193.0 THz/1553.32 nm reference frequency, 1 A/W responsivity, 0.7981 quantum efficiency and zero dark current that is used to identify the signal that is converted into electrical signal. The filter has 5 poles and has 8 GHz B.W.

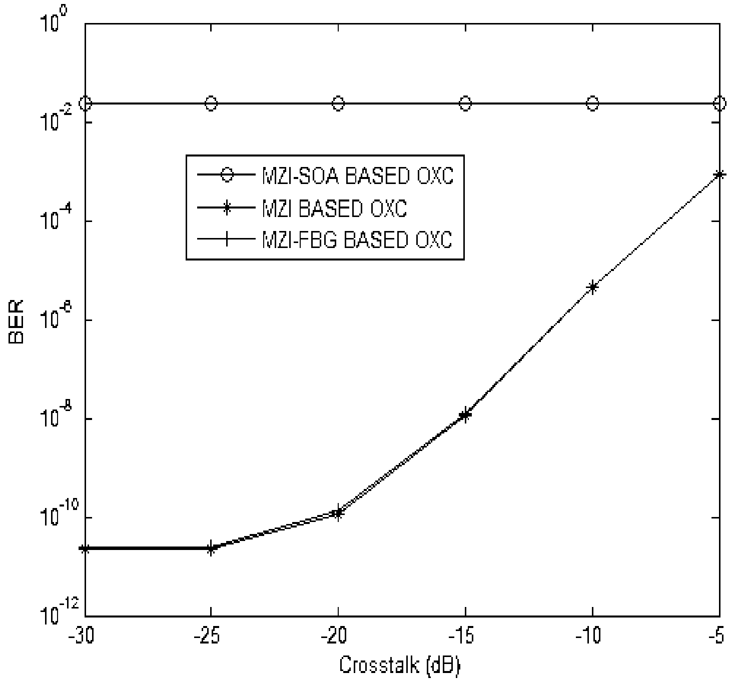


Figure 3.28 Bit error rate vs. Crosstalk plot at frequency 192.95 THz of output port C for 80Km.

Figure 3.28 & Figure 3.29 shows BER versus Crosstalk plot at output port C & output port D with channel frequency of 192.95THz. It is observed that the BER for Type-I and Type-II increases as the level of crosstalk increases from -30 to -5 dB for 80 km distance as compared to Type-III. In case of Type-III, semiconductor optical amplifiers have more nonlinear effects and insertion losses.

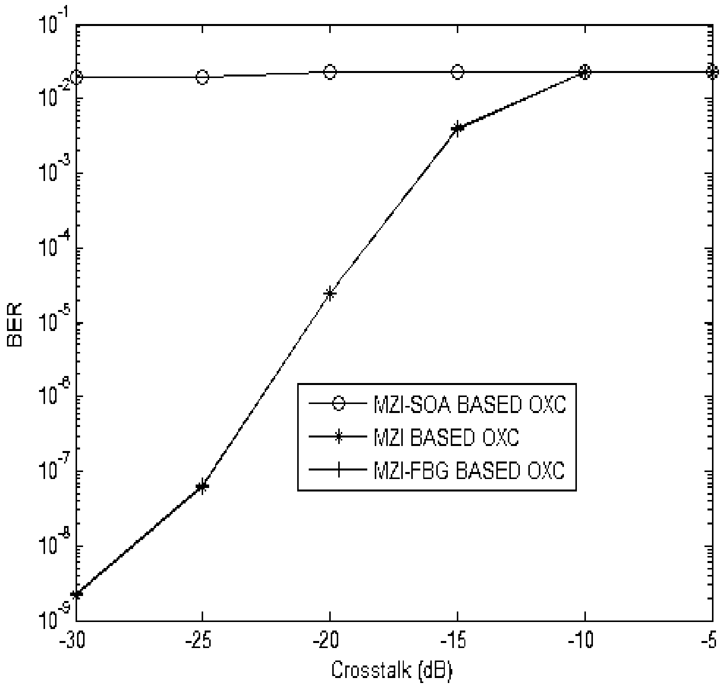


Figure 3.29 Bit error rate vs. Crosstalk plot at frequency 192.95 THz of output port D for 80 km.

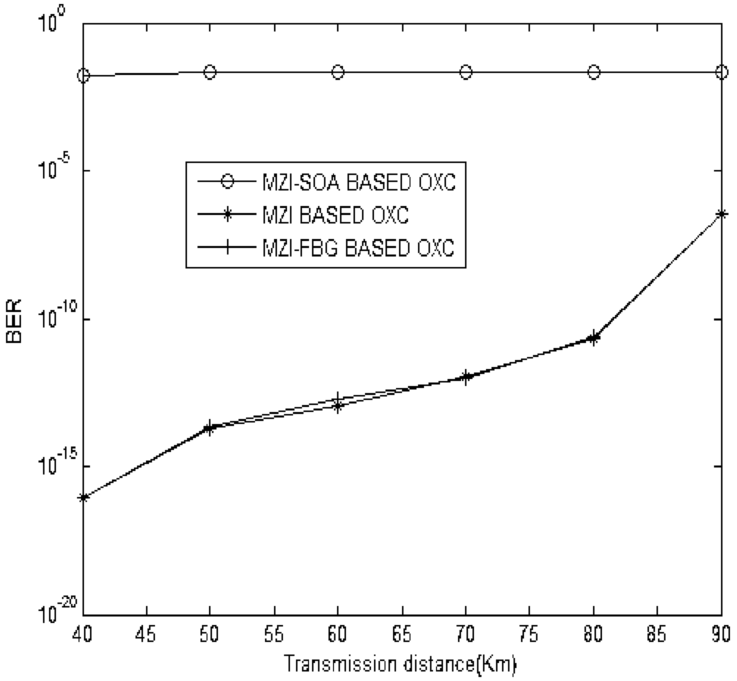


Figure 3.30 Bit error rate vs. Transmission Distance plot at frequency192.95 THz of output port C for -30 dB crosstalk

Figure 3.30 depicts bit error rate versus Transmission distance plot at output port C at channel frequency of 192.95THz. It is found that Mach-Zehnder Interferometer based OXC and Mach-Zehnder Interferometer-Fiber Bragg grating based optical cross connect provides suitable bit error rate i.e. from 9.18 x 10^{-17} to 2.16 x 10^{-11} and 9.36 x 10^{-17} to 2.37 x 10^{-11} at -30 dB crosstalk as distance increases from 40 to 80 km as compared to Type-III. After this distance the performance is below acceptable limit.

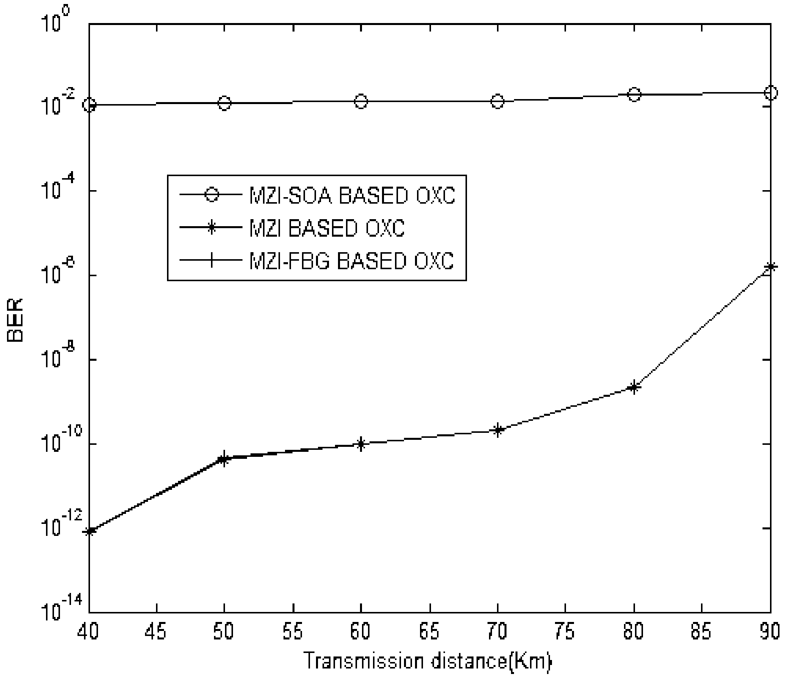


Figure 3.31 Bit error rate vs. Transmission Distance at frequency 192.95 THz of output port D for -30 dB crosstalk

Figure 3.31 shows bit error rate vs. Transmission distance plot at output port D for -30dB crosstalk at channel frequency of 192.95THz. It is observed that Type-I and Type-II OXC provides acceptable BER i.e. from 8.19333×10^{-13} to 2.13881×10^{-9} and 7.89409×10^{-13} to 2.2553×10^{-9} at -30 dB crosstalk as distance increases from 40 to 80 km as compared to Type-III OXC. After this distance the performance is degraded. It is evaluated that the signal can be transmitted successfully with an suitable bit error rate with Type-I and Type-II OXC at -30 dB crosstalk as compared to Type-III OXC up to a distance of 80 km.

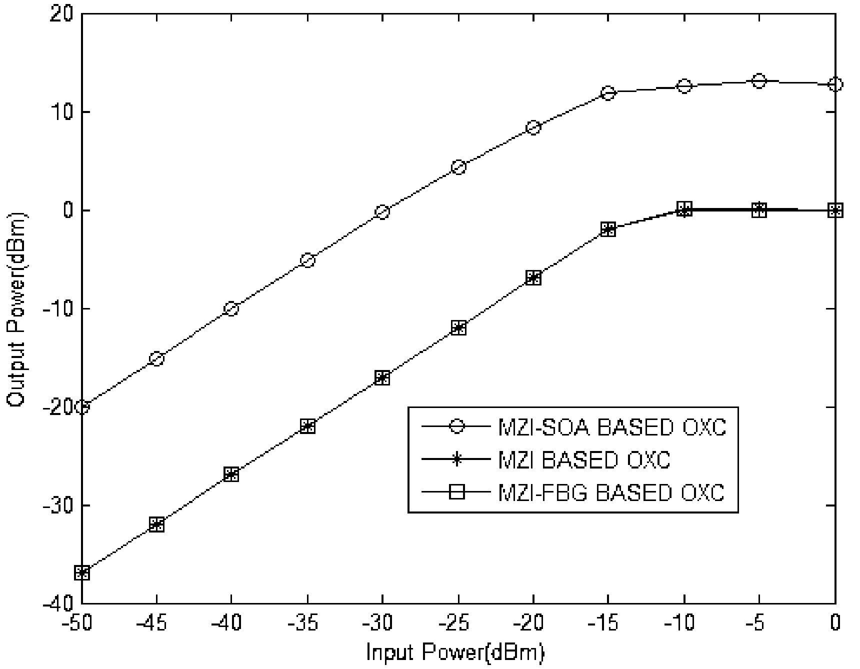


Figure 3.32 Output power vs. Input power plot at -30dB crosstalk for 80 KM distance of output port C

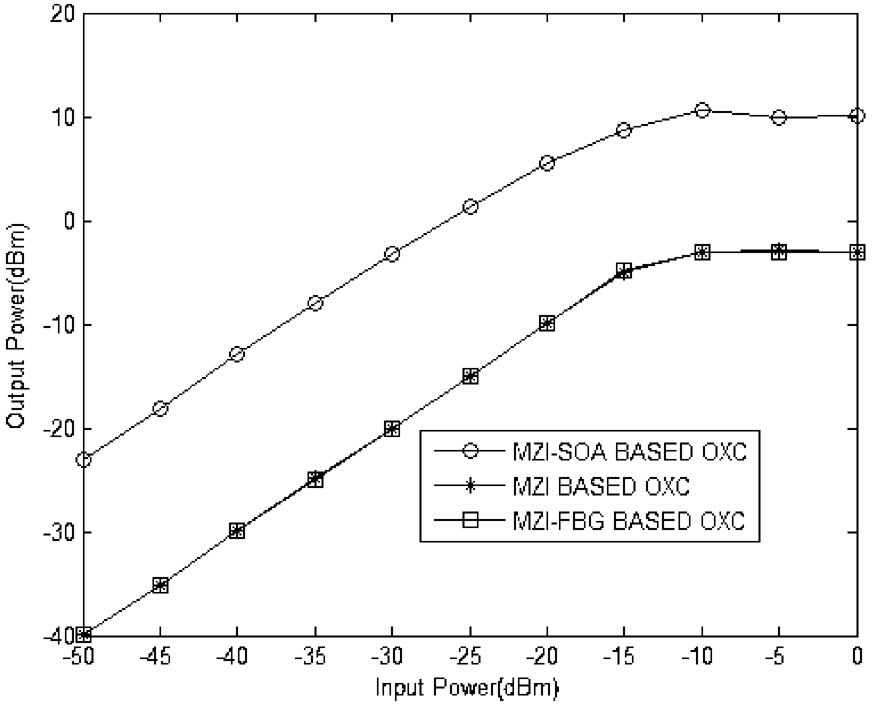


Figure 3.33 Output power vs. Input power plot at -30dB crosstalk for 80 km distance of output port D

Figure 3.32 and 3.33 shows the O/P power vs. I/P power plot at -30 dB crosstalk for 80 km distance. It is observed that the output power at port C for Type-I is -32.099 dBm and for Type-II it is -32.103 dBm for the input power level of -45dBm. For port D the output power for Type-I is -35.139 dBm and for Type-II it is -35.148 dBm for the input power level of -45 dBm.The Type-III is having worst performance in terms of output power. At port C for the input power of -45dBm, the output power is only -15.154 dBm and for port D it is -18.193 dBm only.

The system's cost depends on the number of equipments used that is higher layer tool and optical layer tool. The structure of Type-I OXC is trouble-free and cost effective because in it less number of components are required. Its total approximate cost is quite less as compared to other two types. Whereas, Type-II and Type-III OXC structures require couple of FBG's and SOA's, which add to the cost and complexity of the design as compared to Type-I formation.

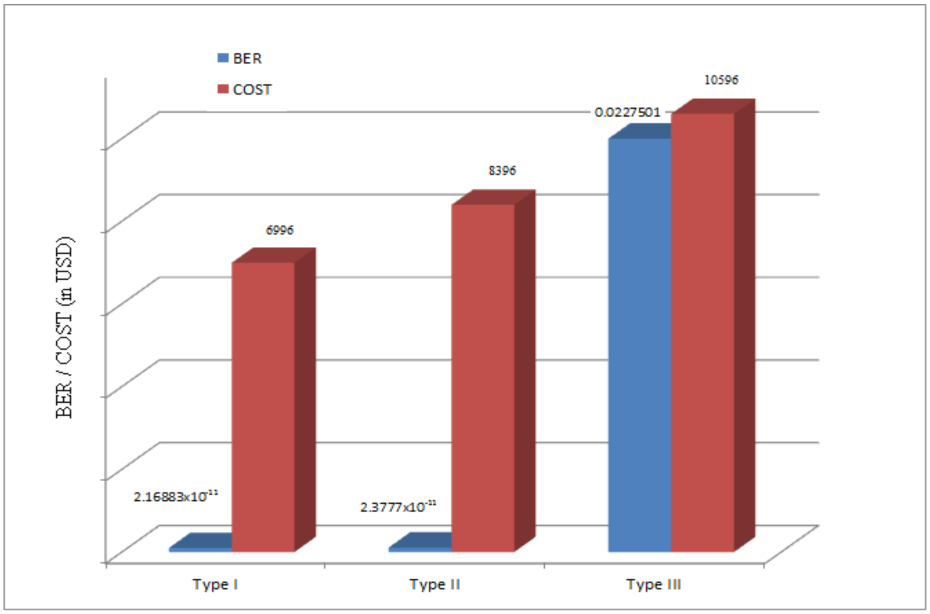


Figure 3.34 BER and Cost approximation

Figure 3.34 shows the BER and Cost approximation for the described architectures. The BER is plotted for -30 dB crosstalk at output port C with a distance of 80 km from the transmitter, with a channel frequency of 192.95 THz. BER of Type-I and Type-II are in the acceptable limits whereas BER of Type-III is beyond acceptable limit. Cost of the system is presented in USD with approximated cost of the components used. The cost of Type-I is minimum, whereas the cost of Type-III is more than others. Therefore Type-I is better due to minimum BER and Minimum cost.

3.6 Conclusions

In this chapter, we have outlined OADM & OXC with different MZI techniques. It is found that the signal can be transmitted via MZI using optical add/drop multiplexer and MZI–Fiber Bragg grating with optical add drop multiplexer efficiently with improved performance in comparison of other techniques. As crosstalk increases, signal quality decreases but at the similar time, in Mach-Zehnder Interferometer–Fiber Bragg grating based optical add/drop multiplexer; quality value is large with highest crosstalk level in comparison of another techniques. The signal can also be transmitted effectively with very small bit error rate with Mach-Zehnder Interferometer–FBG based optical add drop multiplexer at max. crosstalk for add and remove channels in comparison of another techniques. The worst case is the Mach-Zehnder Interferometer–semiconductor optical amplifier based optical add drop multiplexer as seen from the results as far as quality value and bit error rate are concerned for add and remove channels.

Therefore, whole analysis of network using OADM with dissimilar techniques is completed here, which proves that Mach-Zehnder Interferometer–FBG based optical add/drop multiplexer is useful as the main backbone in our current communications. We have also evaluated the three Mach-Zehnder Interferometer techniques of OADM and investigated the impact of crosstalk with optical add drop multiplexer located at the 35 km point of a 70 km link. It is found that Mach-Zehnder Interferometer based optical add drop multiplexer & Mach-Zehnder Interferometer–fiber Bragg grating based optical add/drop multiplexer have best performance among the three techniques in the terms of quality value & BER. We describe maximum length of 150 km achieved by Mach-Zehnder Interferometer-based optical add/drop multiplexer & Mach-Zehnder Interferometer–fiber Bragg grating based optical add drop multiplexer at acceptable bit error rate (1.38×10^{-10}) and quality value (16.19 dB).

It is illustrated that the Mach-Zehnder Interferometer based optical add drop multiplexer system has low cost in comparison of other techniques. We have also investigated the structure of Bidirectional FBG–Optical Circulator based OADM for high speed DWDM networks with 0.1nm of interval. Three kinds of modulators have been used and further compared with respect to the variation of performance parameters including FBG bandwidth, insertion loss of FBG and optical circulator. Using MZ and Electro-absorption modulators, the transmission distance is restricted to 50 km and 30 km while it is increased to 70 km when the AM is utilized. It is observed that using AM modulator; the signal can be communicated up to 70 km with an acceptable BER. Moreover, it is also found that proposed system provides suitable performance with maximum FBG bandwidth of 280 GHz, FBG insertion loss of 9 dB, circulator insertion loss of 4.5 dB for Amplitude Modulator. It is also found that the signal can be transmitted up to 80Km through Type-I and Type-II optical cross connect effectively with superior performance as compared to Type-III OXC. The signal can be transmitted effectively with an acceptable bit error rate that is $2.16883 \times 10^{-11}$and 2.3777×10^{-11} at output port C, 2.13881×10^{-9} and 2.2553×10^{-9} at output port D, with Type-I and Type-II OXC at -30 dB crosstalk as compared to Type-III OXC up to a distance of 80 km. The input-output power relationship shows improvement up to -14dBm approximately in output power for Type-I and Type-II OXCs hence our system becomes more efficient and consumes lesser power. Thus, the entire investigation of the system based on OXCs with unlike MZI techniques with the variations of distances is done here, it is also observed that the Type-I OXC structure has low cost in comparison of other techniques which proves that Type-I and Type-II OXC are valuable as the major backbone in our present infrastructure.

Chapter 4

Designing of integrated optical cross add drop multiplexer

4.1 Introduction

This chapter is based on the designing of integrated OXADM to increase efficiency of system which is related to the second objective of this research work. The proposed design of integrated OXADM is the combined concept of OXC and OADM that is used to increase the flexibility of optical system. The work reported in [45**]** using OXADM is restricted to a bit rate of 2.5Gbps for the interval of 20 nm. We extended this research work to higher bit rate of 10 Gbps to verify the performance in terms of crosstalk, bit error rate, I.L & attenuation for different lengths.

4.2 Optical cross add drop multiplexer

It is essential to add/remove dissimilar channels in a Dense WDM optical system and optical add drop multiplexer facilitates better flexibility of the system [98]. Optical cross connects permit the system to optimize and exchange traffic patterns on a channel-by-channel basis, progress of network growth and improve system survivability [99]. Similar to Optical Add Drop Multiplexer and Optical Cross connects, the optical cross add/remove multiplexer has ability to add/remove different wavelengths and cross connecting traffic in the optical system [100]. A wavelength Demux, a Mux and a switching subsystem are three subsystems of OXADM. At least two distinct wavelengths each with a data rate of 2.5 Gbps is likely to handle by every OXADM. It is an integrated component that consists of 4 OADM & two 2 × 2 realistic optical switches [101]. OXADMs are used in a variety of point-to-point carrier distribution applications. Each OXADM handles minimum two separate channels with a granularity of 2.5 Gbps. The optical cross add drop multiplexer is used as a wavelength splitter in which a particular channel is redirect from the main communication line as the other channels are combined and producing a multiplexed signal towards their receivers. OXADM is able to meet multiple functions such as implementation of add/drop functions, wavelength routing, optical node termination, multiplexing and restoration design for point-to-point, bus or ring networks [99]. The OXADM can also used as single optical device like Mux, Demux, OXC, OADM, wavelength roundabout and wavelength selective coupler. To overcome the various functions in DWDM system, OXADM can used to be worldwide and with a high dependability.

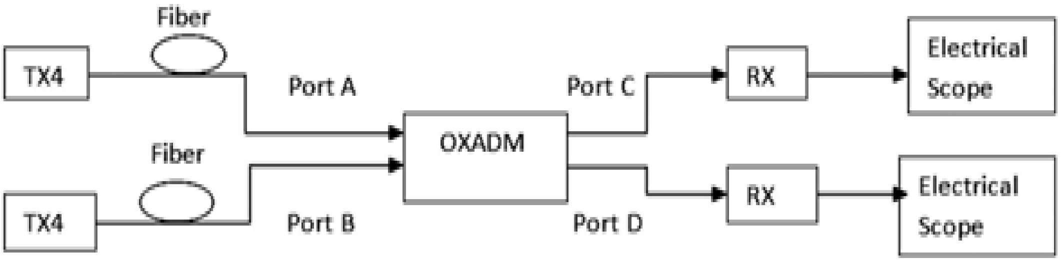


Figure 4.1 OXADM System setup

The signal may start off at one boundary of the system and depart the system at other point. The wavelengths can surpass along any route through optical elements like Optical cross connects and Optical add Drop Multiplexer. The transmitter, OXADM and receiver are three stages of our proposed network as shown in Fig. 4.1. Each transmitter consists of non-return to zero rectangular driver, data source, amplitude modulator and laser resource. The block of laser shows basic Continuous wave Lorentzian laser. The modulation driver generates non return to zero rectangular data format. TXs are followed by a fiber of dispersion 16 ps/nm/km. Optical raised cosine filter with 192.95 THz centre frequency, PIN photodiode with 193 THz reference frequency and low-pass Bessel filter are parts of a receiver. To observe the performance of system, electrical scopes are used.

Fig. 4.2 depicts the structural design of Optical cross Add Drop Multiplexer. The OXADM consists of two inputs (A & B) and two O/P (C & D) ports. Both I/P ports A& B are linked with 4 wavelengths separately.

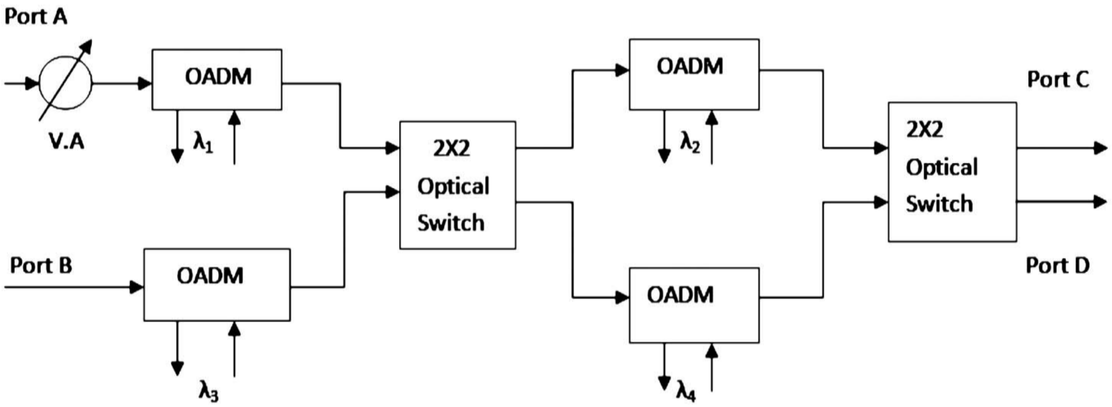


Figure 4.2 Architecture of OXADM

The bi-directional functions can be performed by optical cross add drop multiplexer's and have an asymmetrical architecture. The OXADM offers add/remove and routing functions like OADM and OXC. It comprises VOA, OADMs and 2 × 2 realistic optical switches. The optical signal power is reduced by variable attenuator which is added to the port A of OXADM. The wavelength routing function between two different routes is performed by 2 × 2 optical switches. In this design, realistic switches are used that provides improved performance than MEMS optical switches.

The BER in terms of I.L, attenuation and crosstalk for DWDM system for different transmission lengths with optical cross add drop multiplexer have been evaluated. Bit Error Rate is recorded at the first channel to investigate the performance of the system

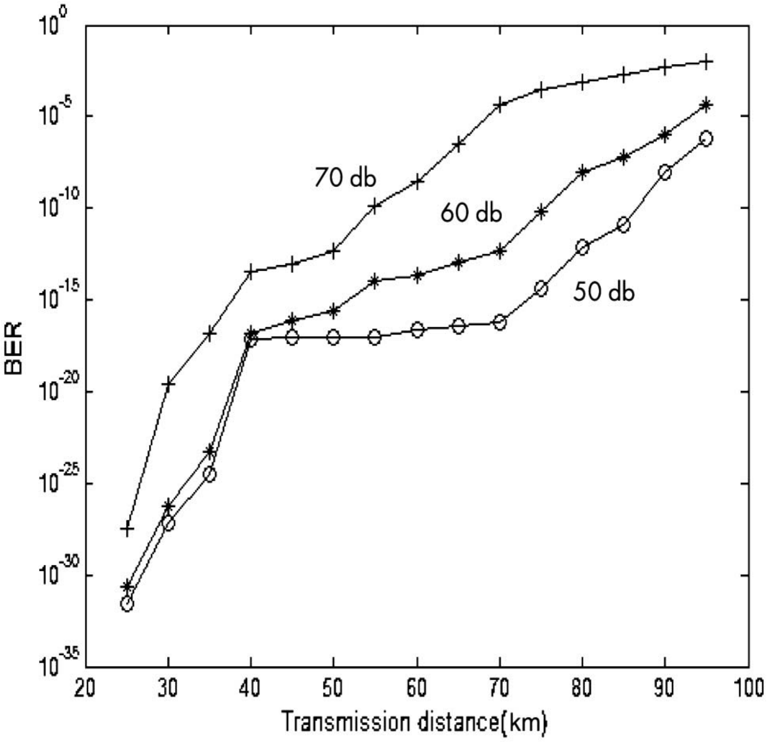


Figure 4.3 Bit Error Rate vs. transmission distance for different attenuations at 6 dB I.L and −100 dB crosstalk

Fig. 4.3 shows the Bit Error Rate vs. transmission distance at different attenuations. The maximum transmission distance obtained is 85 km without amplification at an insertion loss of 6 dB and crosstalk −100 dB with attenuation of 50 dB while at 60 & 70 dB attenuations the distance achieved is 75 and 55 km respectively. If the attenuation increases, it is obvious that the distance achieved by Optical Cross Add Drop Multiplexer decreases. It is observed that the acceptable Bit Error Rate of 1.326 × 10^{-11} is obtained at a distance of 85 km without amplification. The Bit Error Rate goes to unacceptable level (>10^{-9}) as the length is increased beyond 85 km.

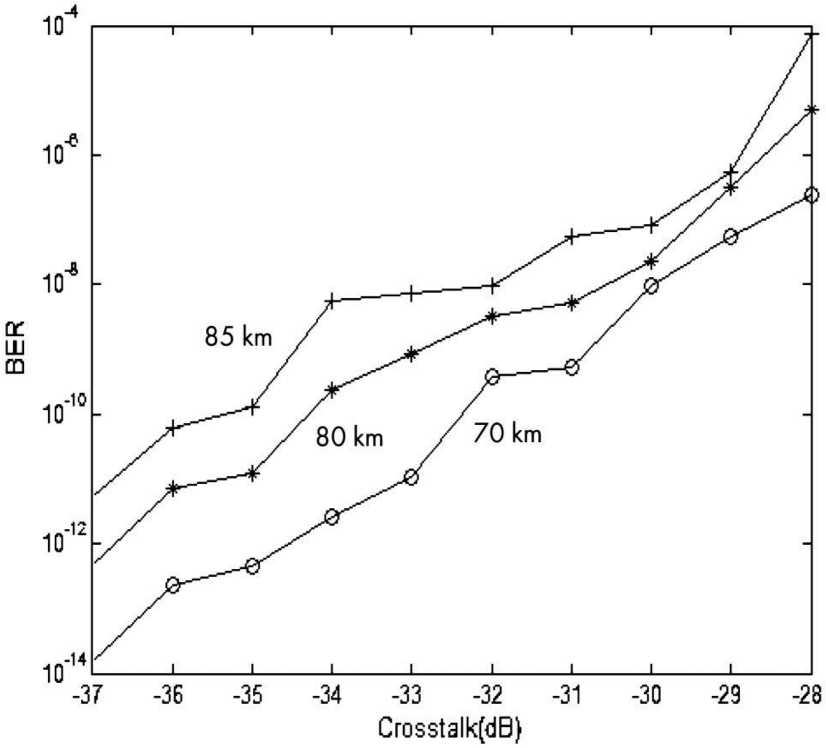


Figure.4.4 Bit Error Rate vs. crosstalk for different lengths at 6 dB attenuation and 70 dB I.L

Figure 4.4 shows graph of Bit Error Rate vs. crosstalk for dissimilar lengths. It is found that at 70 km the OXADM provides superior outcome at an I.L of 70 dB & attenuation of 6 dB up to max. crosstalk of −31 dB. The transmission length of 80 & 85 km have been covered with acceptable Bit Error Rate for the crosstalk of −33 and −35 dB respectively.

Figure 4.5 depicts the Bit Error Rate vs. I.L performance for different lengths for Optical Cross Add Drop Multiplexer. According to transmission distance max. value of I.L can be defined. For the acceptable I.L are 84 dB with Bit Error Rate of 8.1873 × 10^{-10} for 70 km length and 72 dB with Bit Error Rate of 9.364 × 10^{-10} for 75 km length.

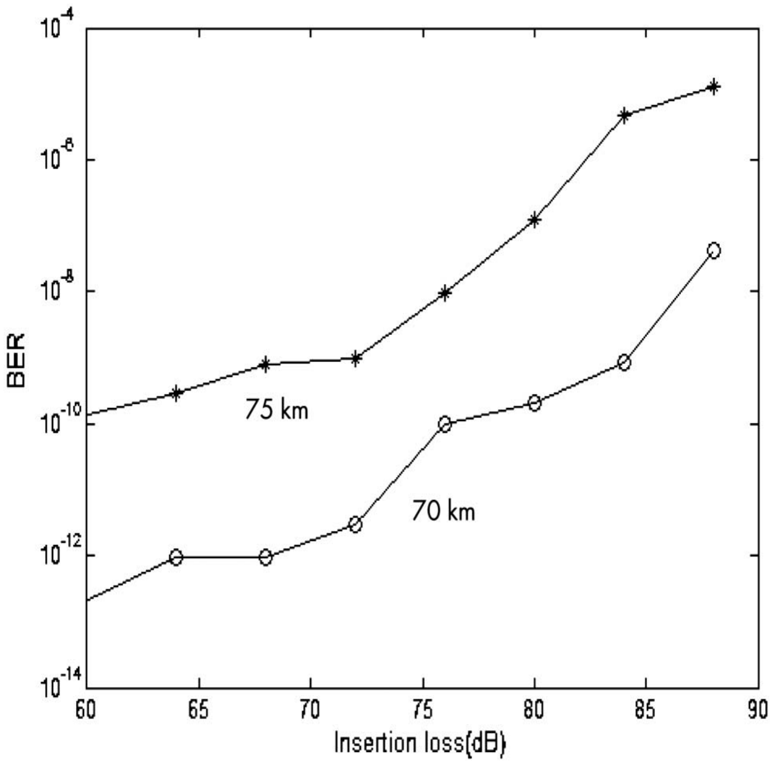


Figure 4.5 Bit Error Rate vs. I.L for different lengths at 50 dB attenuation and −100 dB crosstalk

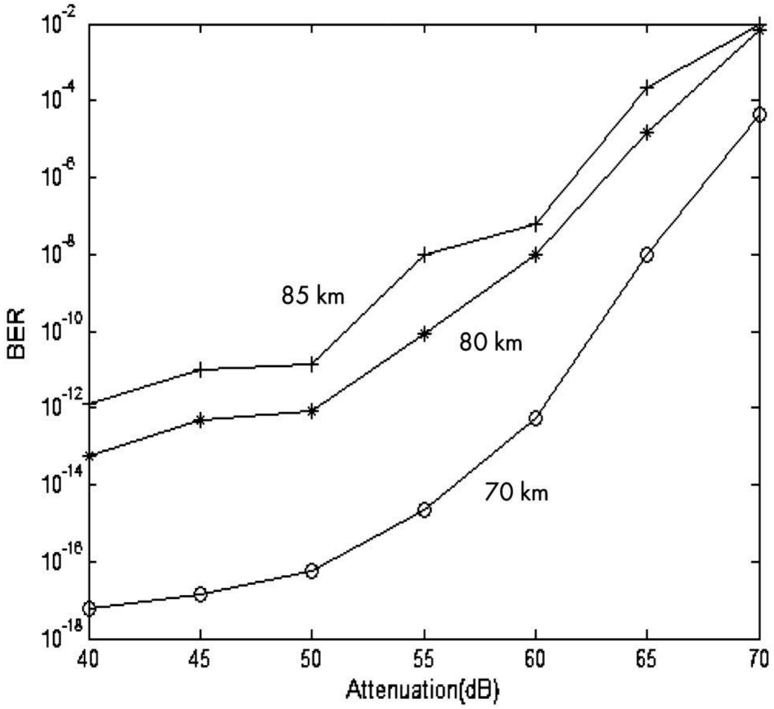


Figure 4.6 Bit Error Rate vs. attenuation for different lengths at 6 dB I.L and −100 dB crosstalk

Fig. 4.6 depicts the Bit Error Rate vs. attenuation graph for different lengths. The acceptable attenuation is 60 dB with corresponding Bit Error Rate of 5.226×10^{-13} for 70 km length , 55 dB with corresponding Bit Error Rate of 8.453×10^{-11} for 80 km length & 50 dB with corresponding BER of 1.326×10^{-11} for 85 km length.

4.3 Conclusions

In this chapter, we investigated the performance of optical Dense WDM system based on Optical cross Add Drop Multiplexer. The system performance is analyzed with OXADM in terms of Bit Error Rate at dissimilar attenuation, crosstalk and I.L's for dissimilar transmission lengths. It is observed that the maximum transmission length obtained is 85 km without amplification at I.L 6 dB with an attenuation of 50 dB using OXADM. For 85 km distance, the system provides adequate Bit Error Rate with maximum crosstalk of −35 dB at an I.L of 70 & 6 dB attenuation. At high bit rates & narrow interval, we show enhancement in transmission distance.

Chapter 5

Designing of reconfigurable optical add drop multiplexer to increase flexibility of optical network.

5.1 Introduction

This Chapter deals with the design of reconfigurable OADM to increase flexibility of network which is the third objective of the research work. ROADM based on Dynamic Channel Equalizer, planner Light wave circuit & wavelength selective switch techniques are proposed and implemented in this chapter. The designing of optical cross add drop multiplexer at high bit rate 10 Gbps and reduced interval of 0.1nm is discussed in previous chapter. The effect of crosstalk has been investigated to calculate the performance of optical communication system in terms of received optical power. The dynamic power transient with dynamic channel equalizer is also studied which equalizes the power variations with a single ROADM. The transient effects are mitigating using the Dynamic EDFA component with the surviving channels.

5.2 Reconfigurable optical add drop multiplexer

The Reconfigurable Optical Add Drop Multiplexer remotely controls wavelengths which are added/removed or passed via node [102]. Without optical-electrical-optical conversion, the Reconfigurable OADM enables multiple channels carrying data to be added/removed from a transmission optical fiber port. Reconfigurable OADM has ability to dynamically allocate accessible n/w bandwidth to individual users without disturbing the signals. Also it equalizes the power levels of the different wavelengths that make it advantageous in optical communication systems. The optical add-drop n/w based on Reconfigurable OADM is valuable for migrating or improvement of existing n/ws [103].

5.3 Dynamic Reconfigurable Optical Add/Drop Multiplexer using Dynamic Channel Equalizer in an optical communication system.

In Dense WDM System, ROADM is competent of add/drop or pass through any or all channels. ROADM offers flexibility on the provisioning of channels apart from how the network changes [104]. Two-degree and multi degree are two types of ROADMs, where the degree refers to the no. of fibers incoming & outgoing the ROADM node. A two-degree ROADM is similar to a position on a highway with off & on ramps to fall off & allow local traffic. ROADM terminates an incoming fiber, add & remove specified channels & blocks these channels from propagating. It also equalizes the collective traffic of added/expressed channels & provides an outlet for the traffic headed for the proceeding ROADM node. A Multidegree ROADM is similar to an exchange where highways assemble. For interconnecting rings or web networking, ROADM is used. From the multiple fibers incoming & exiting the multidegree node, it accepts and rearranges wavelengths as well as adding/removing local channel traffic [105].

The transmitter section consists of 5 bands each of which consists of 8 channels resulting in 40 channels as shown in Figure 5.1. 40 channels with different Centre frequencies are fed through the multiplexers to the input port of ROADM**.** The band represents a laser array which consists of user defined number of on-off keying transmitters. Band spacing and channel spacing of ROADM is 1THz and 100GHz. Band1 has center frequency ranging from 193.1 to 193.8 THz. Every transmitter includes NRZ coder, Modulator, Data Source and a Continuous Wave Laser. Data source produces a binary series of data stream which is customized by baud rate, sequence type. The optical amplitude modulator receives the O/P from the driver & laser source. The NRZ rectangular data format type is generated by the modulation driver. The power controlled amplifiers are used which have a maximum gain of 20 dB and noise figure of 4dB at the input and add port of the ROADM. The ROADM adds and drops the group of wavelengths dynamically. The response time of ROADM is 3×10^{-4}sec and crosstalk varying from 15 dB to 35 dB. The signal duration of ROADM is equal to time step.

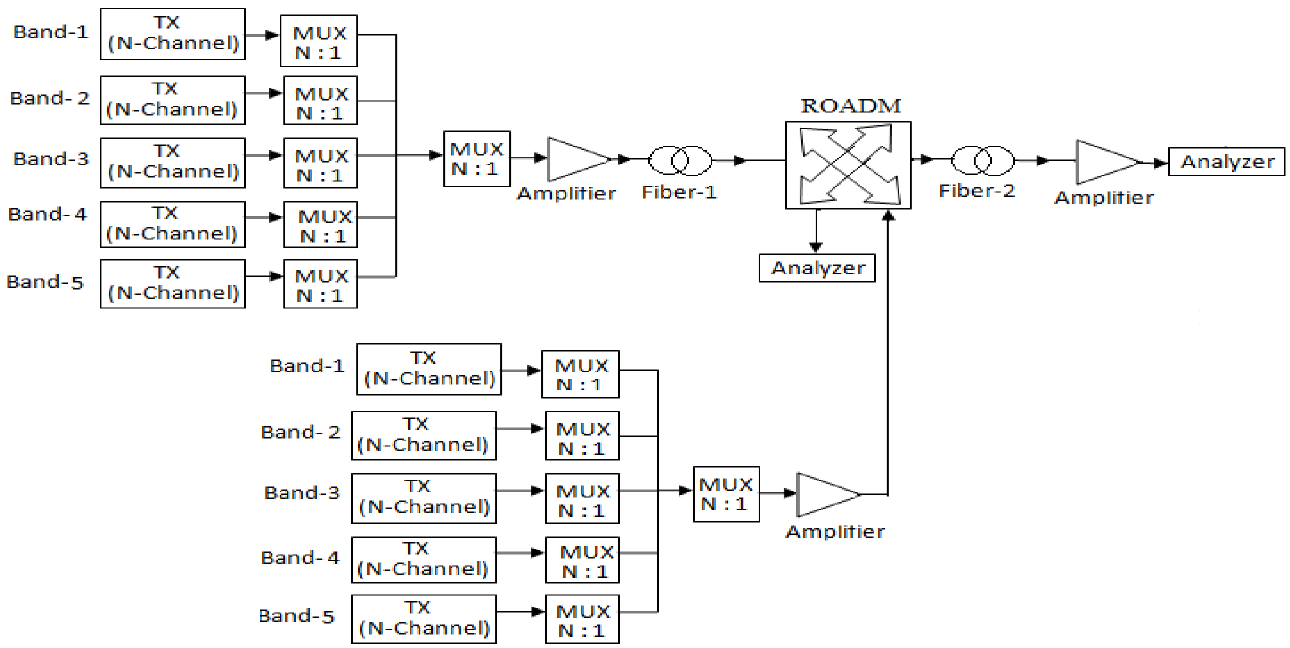


Figure 5.1 System Set up of Reconfigurable add drop multiplexer based on Dynamic Channel Equalizer

The ROADM model includes a DCE with max. attenuation 10dB, power threshold 1×10^{-6} W, integral gain 1.5 & integration time 4×10^{-4} sec. All three parts (add, drop & VOA-array) as shown in fig. 5.2 are modeled on the per channel level, taking into account crosstalk & finite switching time. The Dynamic channel equalizer is a VOA-array with proportional integral (PI) Controller. The common control line manages the 2x2 switches and variable optical attenuators located within the reconfigurable add module in the Dynamic ROADM architecture. The power levels b/w different express & add channels are balanced by dynamic power-balancing system developed by variable optical attenuator. Separation of Mux/Demux & switching functions enable to study both per-band (group of channels) or per channel ROADM-functionality using the same switch matrix model. The signal duration parameter enables to use this module in both the multi iterative simulations with sampled blocks, in power transient analysis using parameterized signals & special interactive simulation (sweep). The Amplifier after the ROADM is saturable type amplifier with gain 20dB; saturation power 10^{-3}w and noise figure 4 dB. The final results in terms of optical output power are obtained on the analyzer**.**

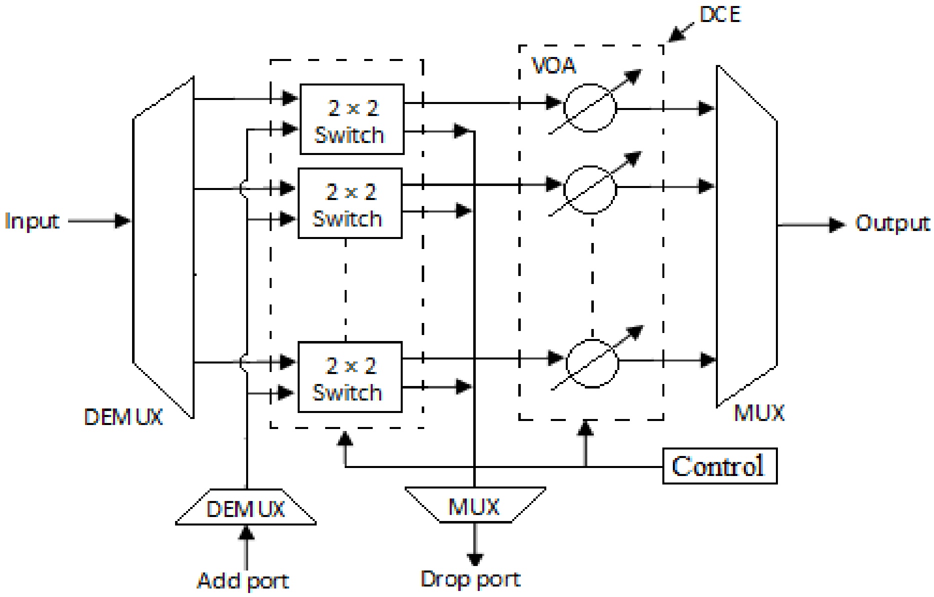


Figure 5.2 Architecture of ROADM using Dynamic Channel Equalizer

To illustrate the performance of ROADM, received O/P power is recorded at first band at 40×10 Gbps with 100 GHz channel spacing. The O/P optical power vs. transmission distance before amplifier without DCE at different crosstalks is shown in Fig. 5.3. It is found that the received optical O/P power decreases with increase in transmission distance. It is also evident that the reachable distance in case of 15 dB and 35 dB crosstalk is 120 km and 40 km respectively with optical O/P power of -39.1dBm**.** For 25 dB crosstalk the reachable distance is 60 km with acceptable optical O/P power of -37 dBm. As crosstalk of ROADM increases, the transmission distance decreases.

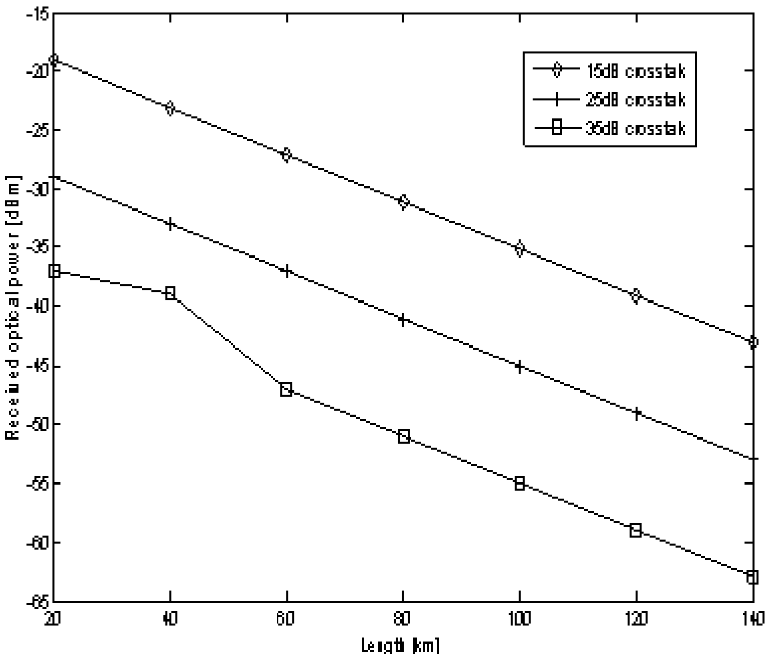


Figure 5.3 Received optical power vs. transmission distance before amplifier without DCE

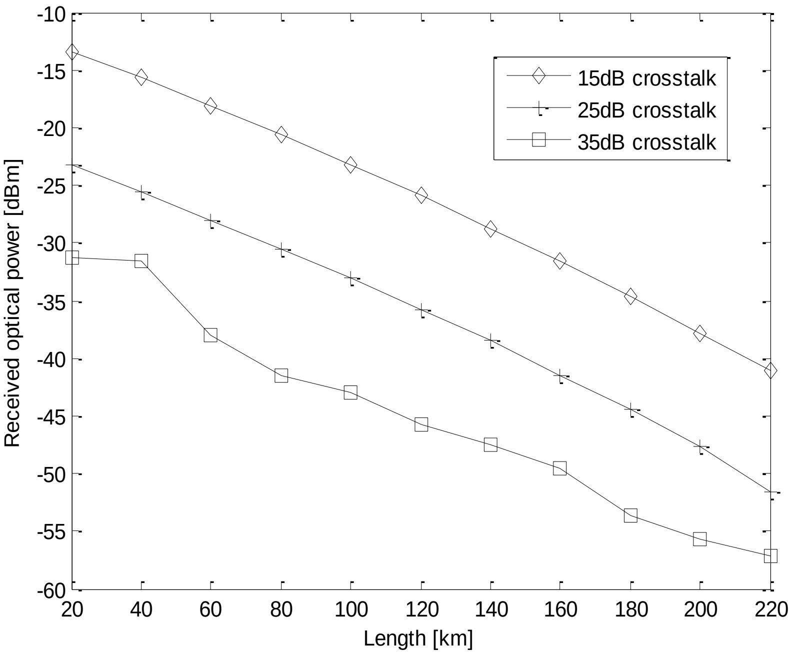


Figure 5.4 Received optical power vs. transmission distance after amplifier without DCE

Fig. 5.4 reveals that after amplifier without Dynamic channel Equalizer, the maximum reachable distance at 15 dB, 25 dB and 35 dB crosstalk is 200 km , 140 km, 60 km with acceptable optical output power of -37.8 dBm, -38.5 dBm and -38 dBm.

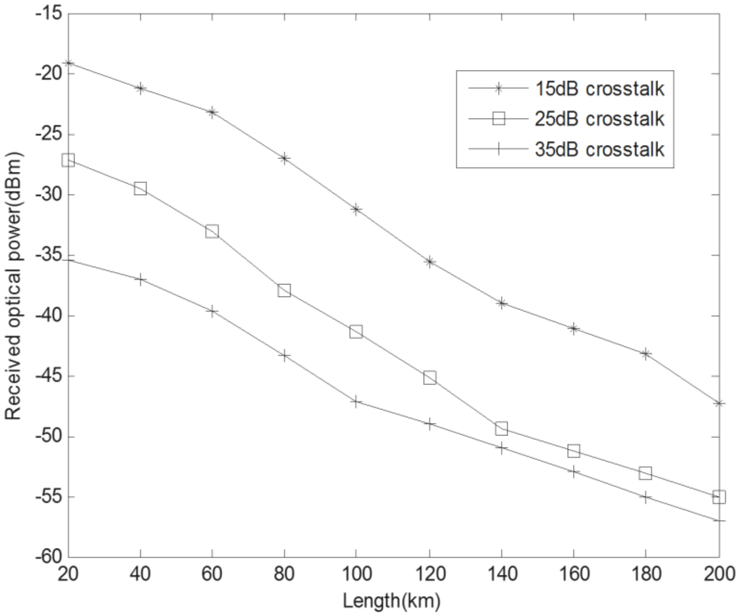


Figure 5.5 Received optical power vs. transmission distance before amplifier with DCE

Fig. 5.5 depicts the received power vs. transmission distance before amplifier with Dynamic channel Equalizer at different crosstalks. The maximum reachable distances before amplifier with DCE at 15 dB, 25 dB and 35 dB crosstalk are 140 km, 80 km and 60 km with acceptable optical output power of -39.02 dBm, -37.90 dBm and -39.70 dBm.

As seen in Fig. 5.6, the O/P signals approaching out of the DCE based ROADM are sufficiently powerful to reach maximum transmission distance after amplifier at 15 dB, 25 dB & 35 dB crosstalk are 220 km, 160 km and 100 km with acceptable optical output power of -39.5 dBm, -38 dBm and -37.6 dBm .

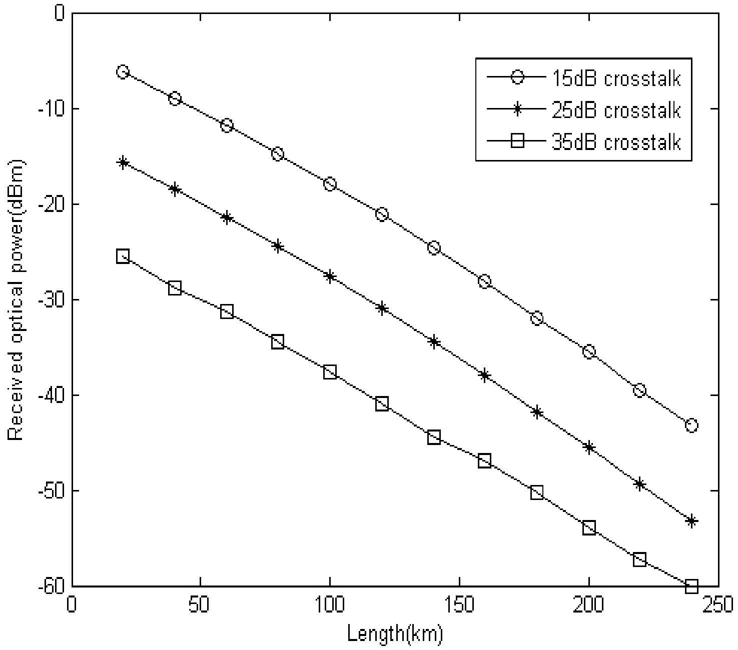


Figure 5.6 Received optical power vs. transmission distance after amplifier with DCE

Fig. 5.7 shows the dynamic transient power response using single Reconfigurable Optical Add Drop Multiplexer which dynamically add and drop the multiple wavelengths due to which major inequality in the optical power levels and also SNR among the multiple wavelengths occur. So to avoid such situations, Dynamic channel Equalizer is used to equalize power levels among different wavelengths. It is also observed from the response that there are less power variations among the channels using a single ROADM which yields to improvement in performance of the system.

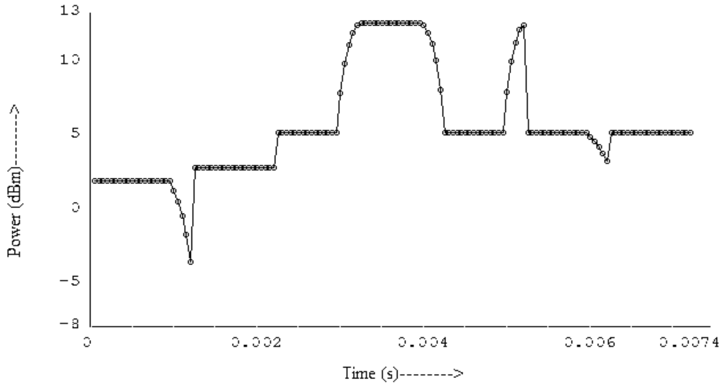


Figure 5.7 Dynamic transient power response

5.4 Reconfigurable optical Add drop multiplexer based on PLC and WSS

WSS is the heart i.e. critical enabler of ROADM. In a WSS based ROADM network, the Wavelength Selective Switches can add/ drop optical signals or pass through without optical-electrical-optical conversion [106]. As the Planar Lightwave circuit technology adds the feature of loss wavelength filters with high performance switches based on thermo optic effect in MZI, therefore it is preferably suited to wavelength switching functions. Planar Light wave Circuit is a solid-state technology with low-cost nonhermetic packaging & low costs due to lack of critical optical alignments [107]. The transmitter, ROADM and receiver are the three stages of the simulation set up. The transmitter section consists of sixteen channels, whose frequency ranges from 193.1 to 194.6 THz. Each channel operates at its own frequency range. Every transmitter includes NRZ coder, Modulator, Data Source and a Continuous Wave Laser. Data source produces a binary series of data stream which is customized by baud rate, sequence type. The optical amplitude modulator receives the O/P from the driver & laser source. The NRZ rectangular data format type is generated by the modulation driver. The sixteen channels are spaced at 100 GHz and each channel is having 4mW input power. The Emission frequency of first channel is 193.1THz. The simulation set up is shown in Fig. 5.8

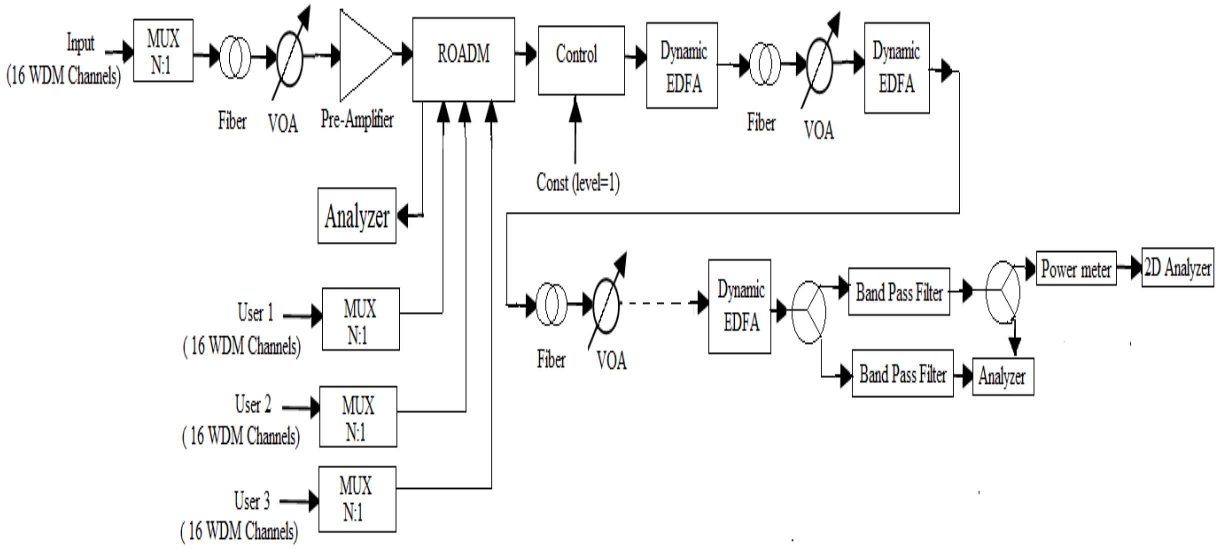


Figure 5.8 System set up of ROADM based on PLC & WSS

This set up illustrates the system performance due to the dynamic traffic changes. It supports 16 WDM channels and provides colorless add drop ports. The ROADM is used to add/drop and switch channels. This causes dynamic power changes (as the no. of transmitted channels varies or the power of the add & drop channels is different). The impact of these transients can be mitigated with a single feed forward (constant input power). This is shown by observing the power variation for surviving channel with or without Control Scheme at the receiver. The Control Scheme simulates a non ideal optical switch or gate, a drive of 0 turns the switch off, a drive of 1 turns it on. The preamplifier is power controlled amplifier with maximum gain of 20 dB and noise figure of 5dB. The variations in operating conditions that are frequently encountered in practical WDM networks can be cope up with the dynamic EDFA. The dynamic EDFA utilizes a passive Gain Equalizing filter which is followed by a variable optical attenuator of 4dB for automatic power control of an EDFA. The fiber length of EDFA is 16 m. The forward pump power and pump wavelength are 200 mW and 980 nm.

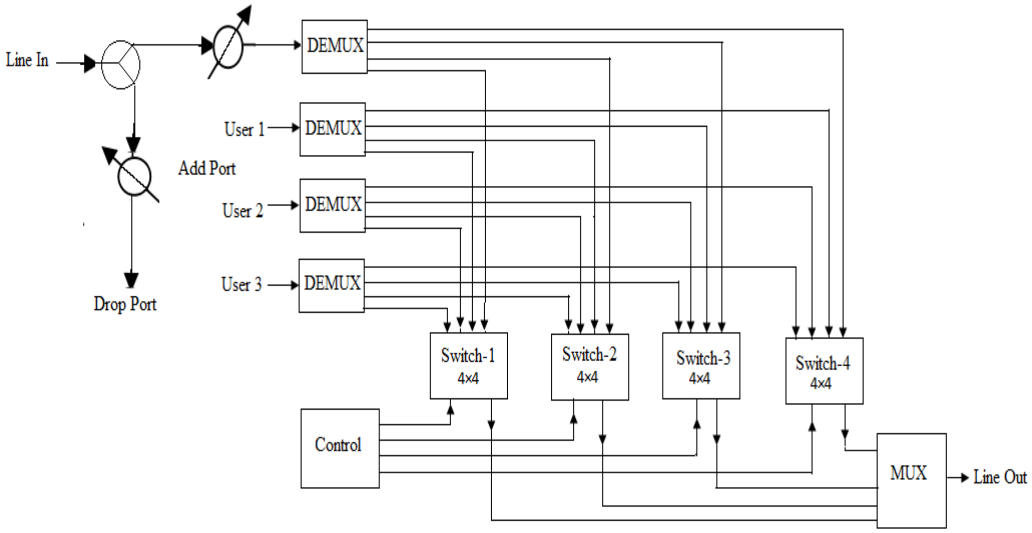


Figure 5.9 Architecture of ROADM using PLC and WSS

Fig. 5.9 shows the architecture of ROADM using PLC and WSS. The technologies of our proposed structural design depends on multiplexers & demultiplexers, 4× 4 optical switches and variable optical attenuator(VOA). The Line-In input port receives the incoming optical signals , the part of which is diverted towards drop port. The demultiplexer separates the rest of input signal into N channels. The multiplexing, demultiplexing & switching of channels b/w one or multiple input fiber ports and one or more O/P fiber ports is accomplished by the WSS. The dynamic power transients are obtained at the analyzer whereas the received optical power is received via power meter at the 2D analyzer.

To illustrate the performance of ROADM based on PLC & WSS, the impact of dynamic transients is studied by utilizing dynamic EDFA's which equalizes the power variations among the channels and received optical output power is recorded at first channel obtained at 16×10 Gbps with 100 GHz channel spacing. Fig. 5.10 to 5.12 depicts the Dynamic transient response after three, five and seven dynamic EDFA's with the surviving channels. The variations in number of EDFA's in the network affect the dynamic power transients. The power variations are more with less number of dynamic EDFA's. The method based on Dynamic EDFA's where heads and tails are joined to the beginning and end of a traffic block to mitigate the impacts of power transients on networks is proposed. The more number of dynamic EDFA's, significantly reduces the EDFA optical power transients. Whenever channels are added or dropped into optical networks, the performance is limited by the power transients. The total number of EDFAs in the network decides the dynamic character like speed, duration and amplitude of such power transients. The power in the existing channels may go beyond the threshold if some channels are dropped; above this the fiber nonlinearities cannot be neglected. The power in the existing ones diminishes if the channels are added and may drop below the receiver sensitivity.

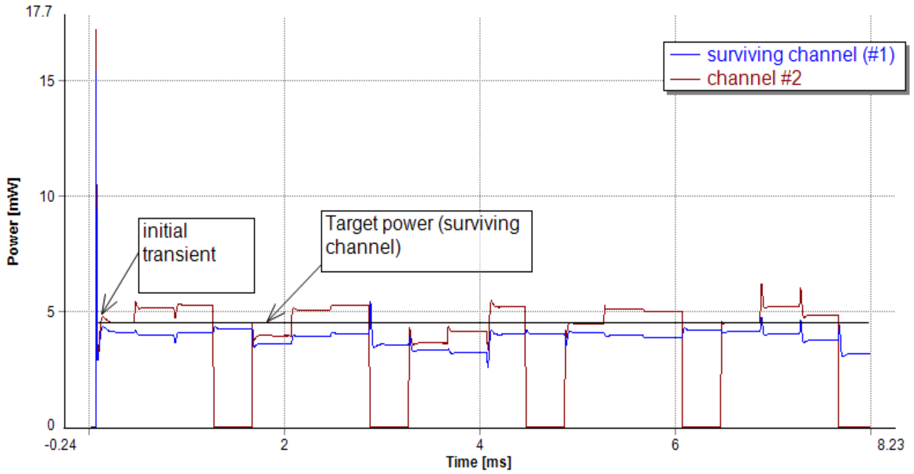


Figure 5.10 Dynamic transient response after three dynamic EDFA

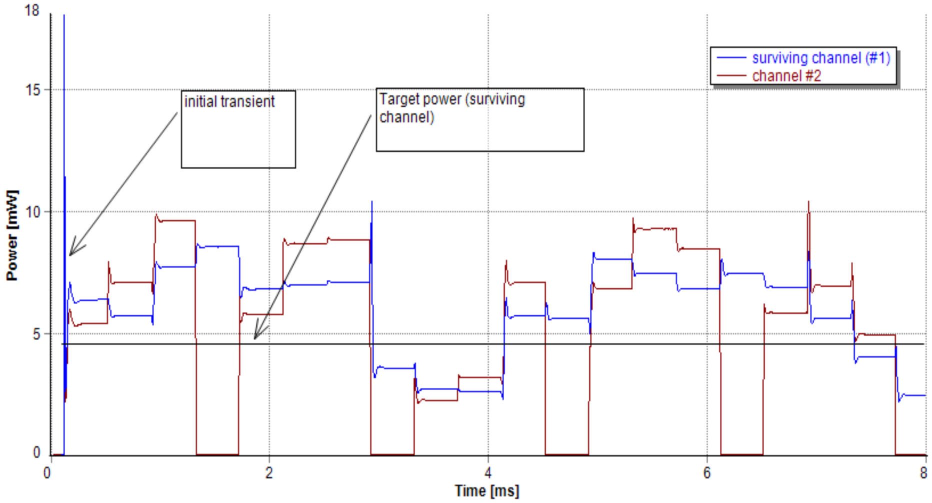


Figure 5.11 Dynamic transient response after five dynamic EDFA

The power of the surviving channels increases or decreases due to cross saturation in the amplifiers when channels are add/drop by network's reconfiguration or failure. Power excursion of surviving channels can cause signal distortion by nonlinear effects or degradation of optical signal to noise ratio (OSNR).

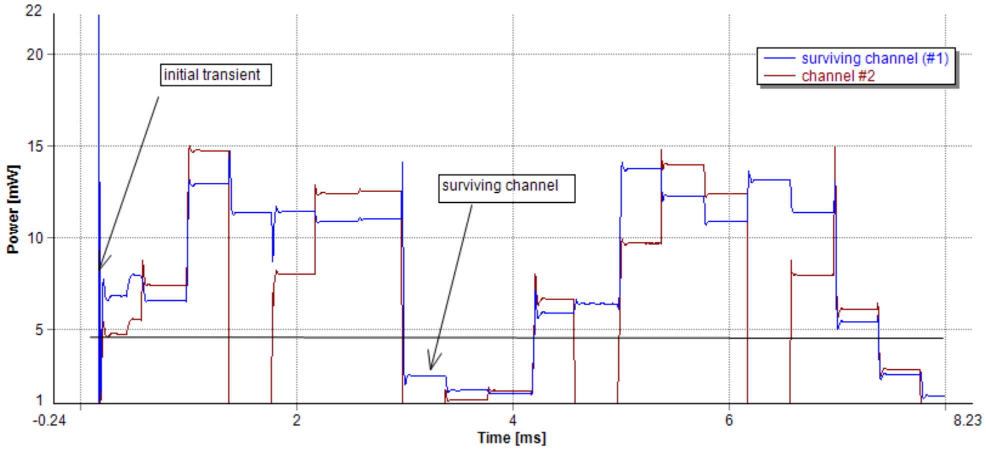


Figure 5.12 Dynamic transient response after seven dynamic EDFA

The more number of dynamic EDFA's in chain causes the increase in the amplitude of transients and reduction in power transients. Dynamic EDFA do not need the adding up of expensive electro-optic components or high-power lasers.

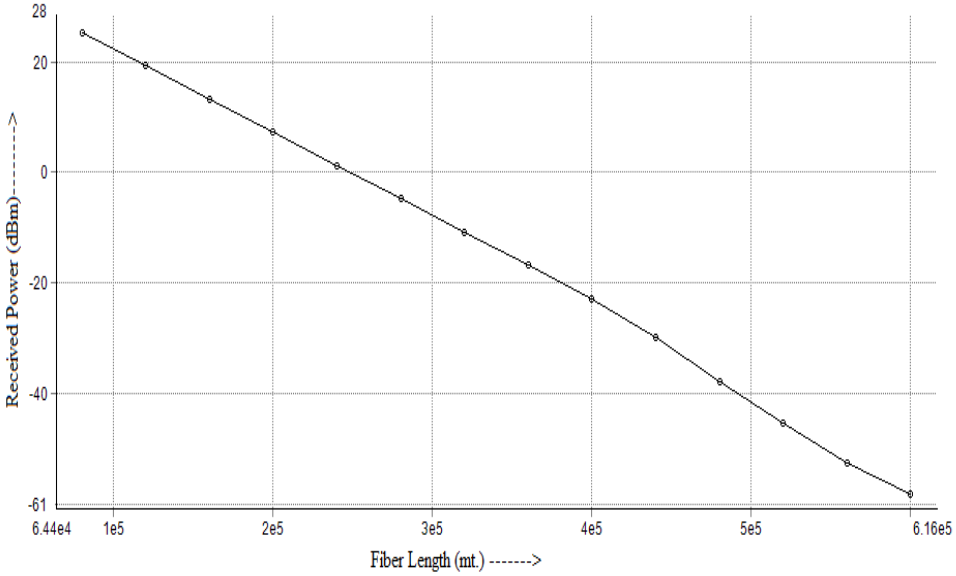


Figure 5.13 Received power vs. fiber length

The Received power vs. fiber length graph is depicted in fig. 5.13. As we increase the length of fiber, received power decreases. The signal can be transmitted with acceptable optical output power (-34 dBm) using dynamic ROADM based on PLC and WSS up to maximum transmission distance of 462 km with three EDFA's.

5.5 Conclusions

In this chapter, we have outlined the reconfigurable add drop multiplexer based on Dynamic Channel Equalizer, Wavelength selective switch & planar lightwave circuit. The performance of Dynamic ROADM based on DCE is obtained for 40× 10 Gbps with 100GHz channel spacing. To evaluate the performance of optical communication system, the effect of crosstalk has been observed in terms of received optical power. DCE is used to equalize power levels among different wavelengths. It is observed in the system also that the maximum transmission distance covered with Dynamic channel Equalizer is 220 km after the amplifier and 140 km before the amplifier at minimum crosstalk (15 dB) respectively. However at maximum crosstalk (35 dB) the transmission distance varies as 100 km after the amplifier and 60 km before the amplifier.

The performance of ROADM based on PLC and WSS is obtained for 16×10 Gbps with 100 GHz channel spacing. We evaluated the power transient effects caused by the addition or deletion of channels. The add-drop of the channels causes transient effects in the surviving channels. Such transient effects are mitigating using the Dynamic EDFA component with the surviving channels. It is observed that with the acceptable optical output power of (-34 dBm) the signal can be reached up to maximum transmission distance of 462 km with three dynamic EDFA’s.

Chapter 6

Performance of different topologies and explore protection schemes in these topologies to enhance survivability

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6.1 Introduction

This chapter investigates the performance of different topologies using optical add drop multiplexer & optical cross connect & explores protection schemes in these topologies to enhance survivability which is the fourth objective of this research work. The performance of ring, bus and hybrid topologies at 10 Gb/s with 30 km distance between successive nodes are investigated at minimum optical input power. The effectiveness of topologies is analyzed in terms of no. of nodes supported. We have also evaluated the different topologies using protection schemes. If breakdown occurs in working fiber, optical cross connect switches the affected signal to the protection path. To achieve the maximum transmission distance between nodes, the inline hybrid optical amplifiers are used. The gain equations of Raman and EDFA are also analyzed to estimate the net gain of hybrid optical amplifier, which is an addition of both amplifier gains.

6.2 Optical Topologies with the placement of Hybrid Optical Amplifier

Optical DWDM bus and ring networks are becoming important due to their simplify network management, potential to significantly increase total network capacity and improve reliability, [108]. By using OADMs situated at large traffic points in the network the trends in the optical transport layer migrates from point-to-point DWDM links to optical ring networks. The DWDM channels can be dropped at each OADM node in these topologies and can also evidently bypass the node without requiring expensive optoelectronic conversions [109]. The metropolitan networks are formerly growing from simple point to point links into ring structures by optical OADMs based on latest technology advancements, while in long-haul systems, the OADM-chain architectures are widely utilized [110]. The filter concatenation possessions are considered to be major performance restrictive factor in ring architectures or metro OADM-chain [111]. As far as the long transmission distance is concerned, it is utmost important to boost the signals. At present, various optical amplifiers are available to amplify the optical signals but the hybrid optical amplifier is the best alternative than others.

In general, Erbium doped fiber amplifier has been used as inline amplifier and booster to transmit signals over thousands of kilometers and Fiber Raman amplifiers (FRA) improves the noise figure, eliminates noise accumulation and decrease the nonlinear effects of optical fiber systems [112], [113]. By cascading two amplifiers, general performance can be improved and this is known as hybrid optical amplifier. Hybrid amplifiers provides better performance with flat gain. To estimate the net gain of cascaded hybrid Raman-EDFA, it is necessary to calculate individual gain of Raman and EDFA first. Giles *et al.* calculated the three level EDFA gain from the associated rate equations as [114]:

$$G_{EDFA} = G_{max}(L, \lambda_{p,} \lambda_s) = \exp\left[\left(\frac{r_P(\lambda_p) - r(\lambda_s)}{1 + r_p(\lambda_p)}\right) L\right] \qquad (6.1)$$

where G_{max} depends up on λ_p (pump wavelength), λ_s (signal wavelength), cross-section ratio $r_p(\lambda_p) = \sigma_{pa}/\sigma_{pe}$ (pump absorption/pump emission) and $r(\lambda_s) = \sigma_{sa}/\sigma_{se}$ (signal absorption/signal emission).

The parameter $L = (L_{amp}.\Gamma_s.\sigma_{se}.\lambda_s.N_T)$ varies with signal wavelength, where, L_{amp} is the physical length of the amplifier, N_T is the transparency of carrier density and Γ_s is the signal to core overlap.

In a Raman amplifier, the power spectrum of the optical signal is affected by Raman pumping (only counter-propagation is considered here), Raman amplified spontaneous emission (ASE) noise and Rayleigh back- scattering. The pump power does not remain constant along the Raman fiber length. When these effects are included, the Raman amplification process is governed by the set of two coupled equations and gain [115].

$$G_{Raman} = G(z) = \frac{P_s(z)}{P_s(0)} = \exp\left(g_R \int_0^z P_p(z)dz - \alpha_s z\right) \qquad (6.2)$$

Where P_s and P_p is the signal and pump power respectively, α_s is Rayleigh scattering coefficient & z is longitudinal position along the fibre.

For hybrid optical amplifiers, the total gain is the addition (in case of decibel) of the individual gains of the cascaded amplifiers, as also reported in [116]. Then the total gain of the Raman-EDFA is given as:

$$G_{\mathrm{Hybrid}} = G_{\mathrm{EDFA}} + G_{\mathrm{Raman}} \tag{6.3}$$

Fig. 6.1 depicts the schematic set up for the bus topology. It consists of twenty nodes in which one channel is added & another channel is removed. Each user is linked to bus via the optical add drop multiplexer. Each user is linked to another user by SMF of 30 km length. To continue propagation of information from transmitter users the assignment of one hybrid optical amplifier is made in the start of each segment. After the required number of nodes, Hybrid optical amplifiers are used in bus topology. The first hybrid optical amplifier is used after first node and further placement of hybrid optical amplifiers is done after four nodes. The hybrid optical amplifier module consists of combination of Raman and EDFA amplifier. The Raman amplifier is operating at a temperature of 300K with single pumping and consists of counter-propagating Raman pump unit with pump power 20 dB, pump frequency 206.35 THz, pump wavelength 1451.77nm & pump attenuation of 1.2 dB/Km. The EDFA has flat Gain shape and noise figure with a 25 dB fixed Gain. The node consists of TX1, an OADM and RX1. The optical add drop multiplexer adjoin new channels at distinct wavelengths & drops preceding channels. Each TX comprises a laser source, a data source, an electrical driver & an optical modulator. The format type of data source is NRZ type at 10 Gbits/s. The binary series is converted into the electrical signal by the electrical driver.

The simulation is performed with a 2.3 THz B.W and a center frequency of 193.35THz. The study of results is made by optical power meter and electrical scope attached to each node.

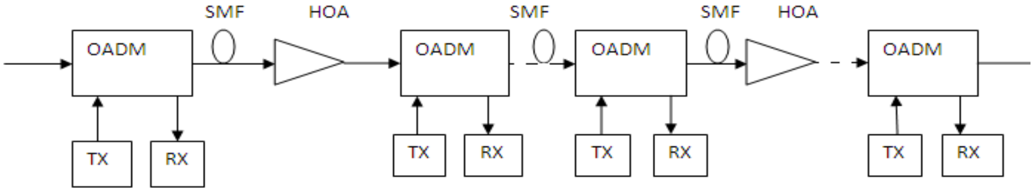

Figure 6.1. Simulation setup for the bus topology with OADM based on Hybrid optical amplifiers.

The ring network topology consists of forty nodes with one wavelength added and another wavelength dropped. The length of fiber is 30 km and hybrid optical amplifier follows the node as depicted in Figure 6.2. The hybrid optical amplifier module is same as it describes in the bus topology. The placement of first hybrid optical amplifier is done after first node and further placement of hybrid optical amplifiers is done after four nodes & so on. The study of results is made by using electrical scope & optical power meter attached to each node. Further, the user consists of TX1, an OADM and RX1. The forty nodes used f1, f2, f3, ----f40 frequencies. In the ring topology all these frequencies are used in spherical manner that is at the node1 the frequency f1is added and frequency f40 is removed. The frequency f2 is added & frequency f1 is removed at the node 2 & so on. Simulation of the ring topology is carried out with the bit rate of 10 Gb/s & center frequency of 193.4THz.

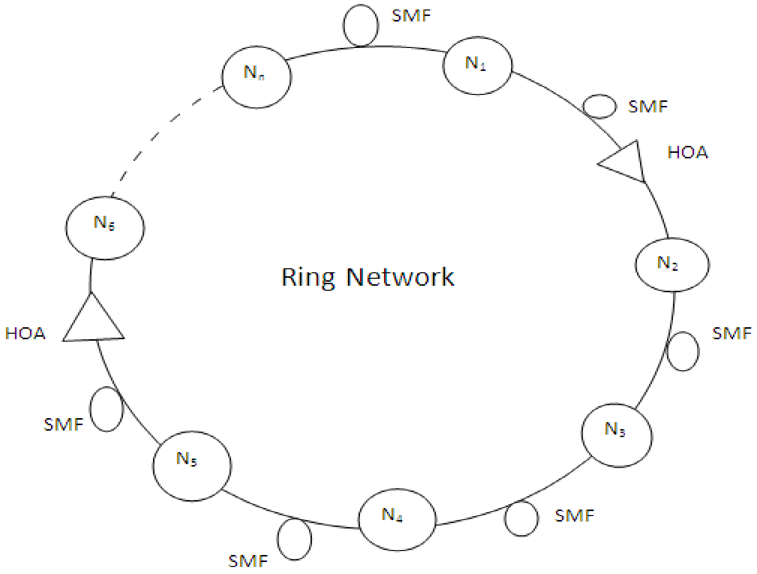

Figure 6.2 System setup for the ring topology with OADM using Hybrid optical amplifiers.

The hybrid network topology consisting of two bus topologies i.e. upper bus and lower bus and two ring topologies i.e. upper ring & lower ring. These two topologies are connected with the hub (2x2 optical switches) as shown in Figure 6.3. Each bus & ring topology consists of ten nodes. Therefore, hybrid network topology incorporates twenty nodes. The placement of first hybrid optical amplifier is done after first node and further placement of hybrid optical amplifiers is done after four nodes and so on in each topology. In hybrid network topology, the node consists of TX1, an OADM and RX1. Adding and dropping of different wavelengths are done in the same fashion as in bus and ring topologies. The simulation of the hybrid topology is carried out with the 193.35 THz center frequency and the bit rate of 10 Gb/s.

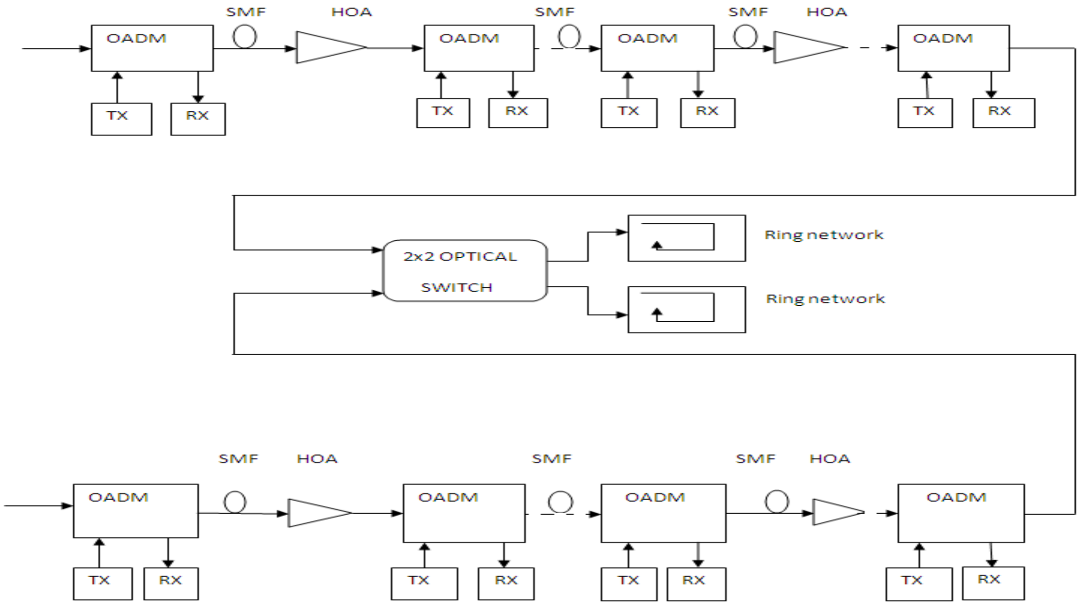

Figure 6.3 System setup for the Hybrid topology with OADM using Hybrid optical amplifiers

For the bus topology, the simulation is carried out with twenty nodes by using five hybrid optical amplifiers only for different optical input powers. At −30 dBm optical I/P power, no users are supported & signal quality reduces with reduction in the optical input power as shown in Figure 6.4. Because of increase in the amplified spontaneous emission noise power, the quality of the received signal reduces. The cause of amplified spontaneous emission noise power is fewer at 0 dBm & −10 dBm optical input power. Thus the maximum supported users are more than 20. But at -20 dBm optical I/P power, 18 users are supported. This is due to again increase in the amplified spontaneous emission noise power. At −30 dBm optical I/P power, the impact of amplified spontaneous emission noise power is moderately high. Therefore, signal quality in bus topology continues to decrease. At high values of optical I/P power, a major gain variation occurs. So the gain of the hybrid optical amplifier decreases, which causes power penalty. It is also analyzed that the optical O/P power continuously reduces from transmitting users to different receivers as shown in Figure 6.5.

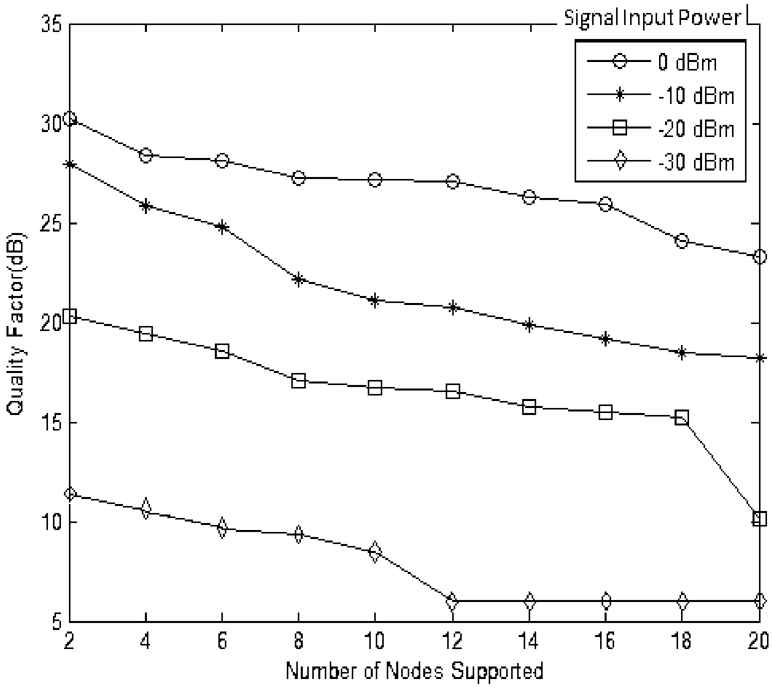

Figure 6.4 Quality factor vs. supported nodes at different optical input powers for the bus topology using HOA

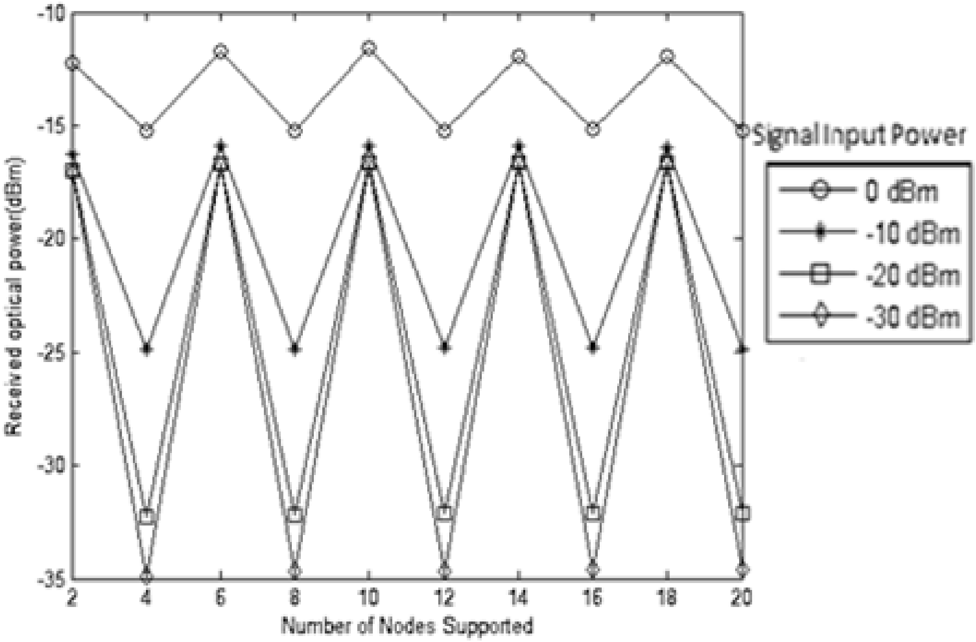

Figure 6.5 Received optical power vs. supported nodes at different optical input power for bus topology using HOA.

As per the equation number (6.3), the gain is one of the important parameter to observe the performance of hybrid amplifier in optical network topologies. The gain values are plotted for 0 dBm and -20 dBm powers at input. For better clarity we have calculated the gain at selected nodes of bus topology. From Figure 6.6**,** it can be observed that the hybrid amplifier provides sufficient amount of gain to recognize the optical signal, in the term of Q-factor at its acceptable range at any used network nodes.

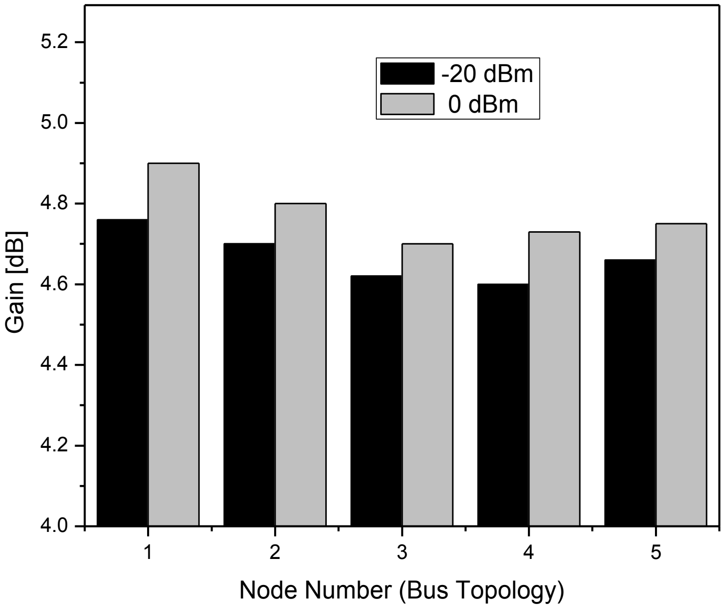

Figure 6.6 Gain vs selected nodes of bus topologies at different input power.

By using only ten hybrid optical amplifiers, the two span simulation is performed for dissimilar I/P optical powers for the ring topology. The results for quality of signal vs. number of nodes supported for different I/P powers & received optical powers are observed as shown in Fig 6.7 and 6.8. It is found that the quality of signal at −30 dBm optical I/P power decreases for 30 nodes as shown Figure 6.7. It is observed that adequate optical O/P power is available at all nodes for different I/P optical powers as shown in Figure 6.8. There is sufficient quality achieved for all nodes at all I/P signal powers. Two spans are permitted to examine the performance of a ring topology. The sufficient quality & power is observed for a large number of users as shown in Figure 6.7 & 6.8 in the simulation of two spans.

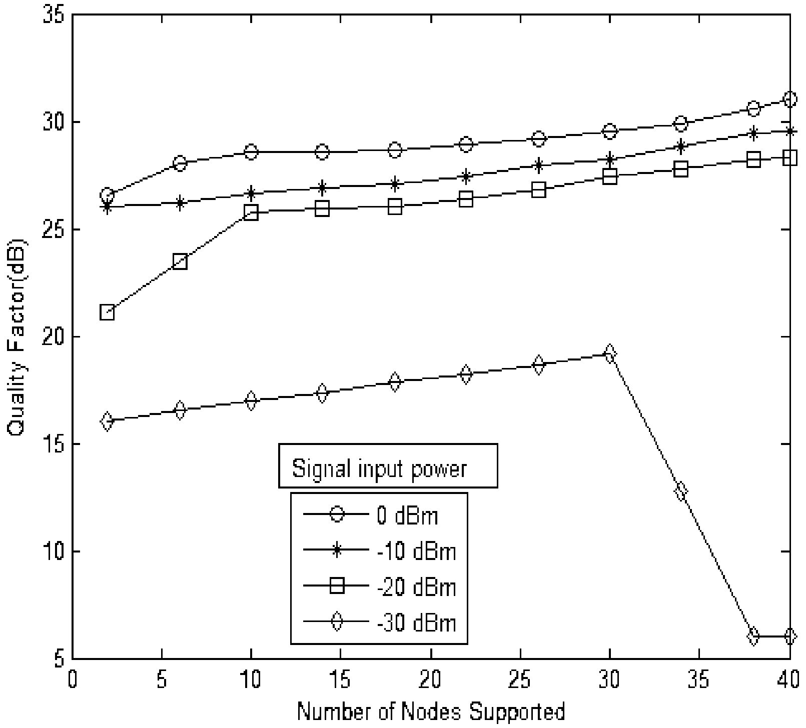

Figure 6.7 Quality factor vs. supported nodes at different input signal power for ring topology using HOA.

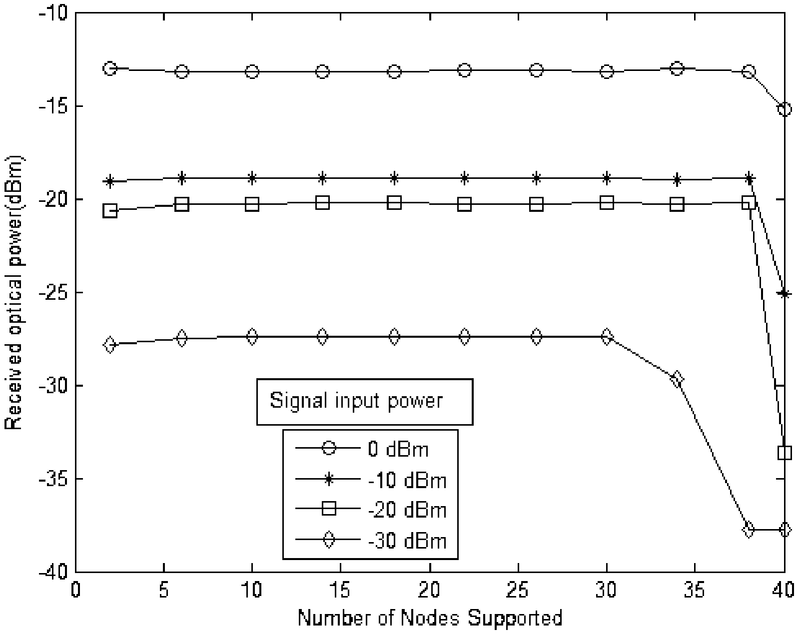

Figure 6.8 Received optical power vs. supported nodes at different input signal power for ring topology using HOA.

The hybrid topology incorporates two bus topologies i.e. upper bus and lower bus and two ring topologies i.e. upper ring and lower ring. These two topologies are connected with the hub (2x 2 optical switch). The simulation of hybrid network topology is performed for twenty nodes by using six hybrid optical amplifiers. No users are supported in the upper bus and ring topology at −30 dBm input power as shown in Figure 6.9 & the signal quality reduces with a reduction in the input optical power. The increase in ASE noise power reduces the quality of the output optical signal. The cause of ASE noise power is less at 0 & −10 dBm optical I/P powers. Hence the max. users supported are more than 10 for upper bus & ring. But at -20 dBm I/P signal power, 6 nodes are supported for upper bus but for upper ring, more than 10 nodes are supported.

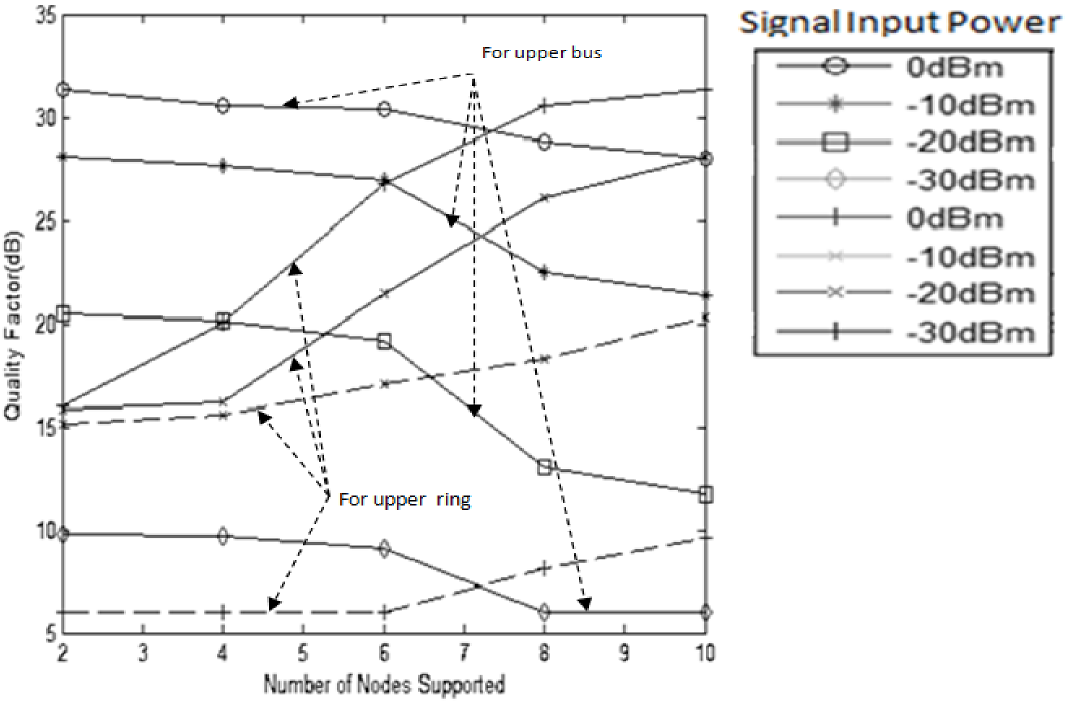

Figure 6.9 Quality factor vs. supported nodes at different signal input power for hybrid topology using HOA.

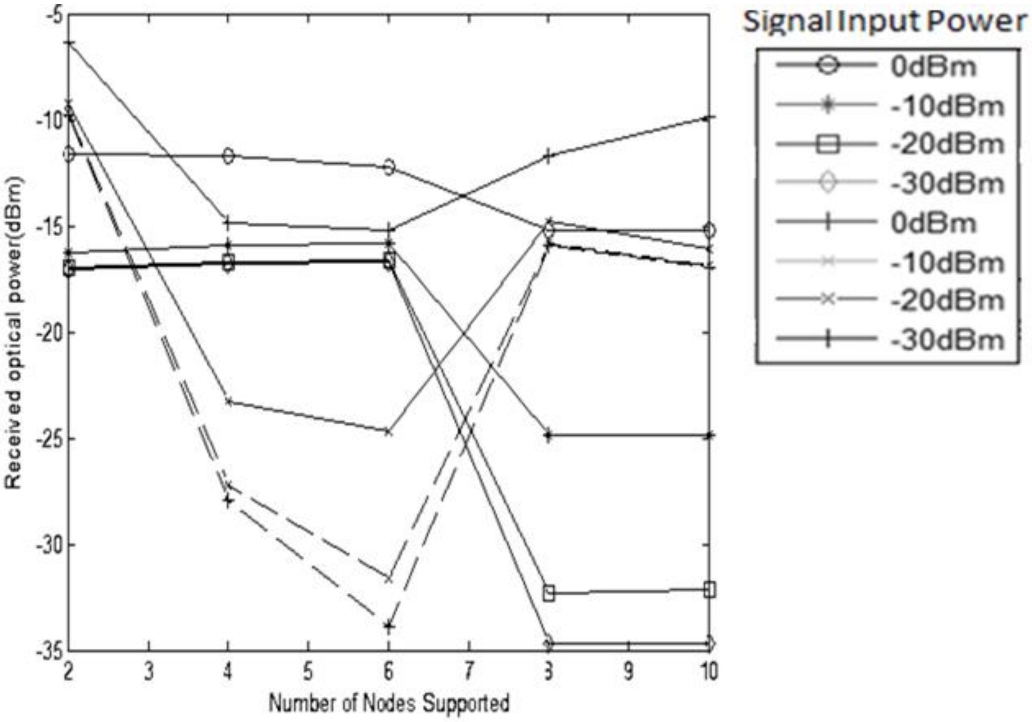

Figure 6.10 Received optical power vs. supported nodes at different input signal power for hybrid topology using HOA.

For the upper bus, the impact of amplified spontaneous emission noise power is moderately high at −30 dBm I/P optical power. At 0 dBm I/P signal power, considerable gain variation occurs. Thus the gain of the hybrid optical amplifier drops, hence causing power penalty. It is also analyzed that the O/P optical power decreases with the decrease in I/P signal power as depicted in Figure 6.10. The optical O/P power decreases from transmitting node to receiver node caused by the non uniform allocation of power among the nodes in the upper bus. For the upper ring, enough O/P optical power is obtained at the O/P for all users for different optical powers.

6.3 Protection scheme in bus and ring Topologies using Hybrid RAMAN-EDFA Amplifier

In a protection scheme whenever a link breakdown occurs, the signal will be passed to the alternative routes. The node in which breakdown occurs will switch the signals to protection path. By choosing a path between the redundant transceivers, protection is achieved by optical cross connect switches. In this means, the breakdown of transceivers as well as other optical components is protected [18].

Figure 6.11 depicts the schematic set up for the bus network topology. The bus network consists of twenty nodes. Every node is linked to bus throughout the optical cross connects. Every node is joined to each other by single mode fiber of 30 km length. In order to maintain the propagation of information from transmitter users, one hybrid optical amplifier is placed at the start of each segment. The first hybrid optical amplifier is used after first node and further placement of hybrid optical amplifiers is done after four nodes. The hybrid optical amplifier consists of Raman and EDFA amplifier. The Raman amplifier is operating at a temperature of 300 K with single pumping and consists of counter propagating Raman pump unit with pump power 20 dB, pump frequency 206.35 THz, pump wavelength 1451.77nm & pump attenuation of 1.2 dB/km. The EDFA has flat Gain shape and noise figure with a 25 dB fixed Gain. Each node consists of TX1, RX1 and an OXC. Each transmitter composed of a data source, an electrical driver, a laser source & modulator. The format of data source is NRZ type at 10 Gbits/s. The binary sequence is converted into the electrical signal by electrical driver. The data is converted into optical signal using CW laser. The NRZ rectangular type data format is generated by Modulation driver. Sin^{2}Mach–Zehnder modulator is used to modulate the pulses. The simulation is carried out with a B.W of 2.3 THz & a center frequency of 193.35THz. The analysis of results has been carried out by electrical scope and optical power meter attached to each node.

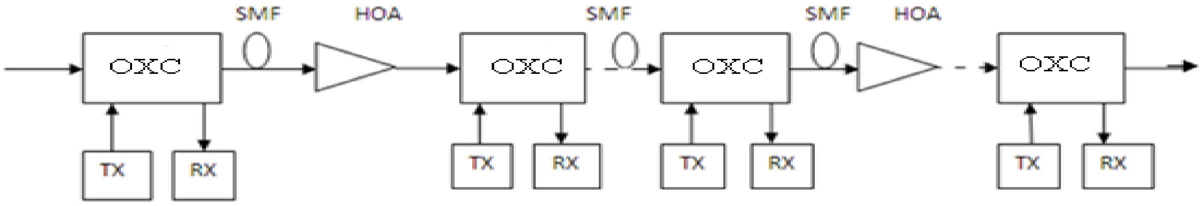

Figure 6.11. Simulation setup for the bus topology with OXC using Hybrid optical amplifier.

The ring network consisting of twenty nodes using optical cross connects as shown in Fig. 6.12. The placement of first hybrid optical amplifier is done after first node and further placement of hybrid optical amplifiers is done after four nodes and so on. Further, the node consists of transmitter, an Optical cross connects (OXC) & receiver. The f1, f2, ----f20 frequencies are used by twenty nodes. The simulation of the ring topology is carried out with the bit rate of 10Gb/s & center frequency of 193.4THz.

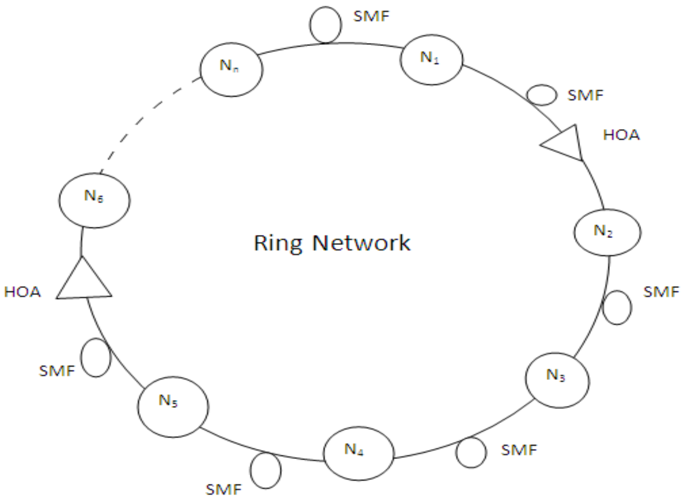

Figure 6.12 System setup for the ring network topology with OXC using Hybrid optical amplifiers

The schematic set up for the bus topology using linear protection scheme is shown in Fig 6.13. In a bus topology, 1+1 is a type of network protection technique. The signal is transmitted respectively on a working and a protection fiber in 1+1 technique. The receiver can make a decision to acknowledge the copy of signal based on the signal quality at the receiver side.

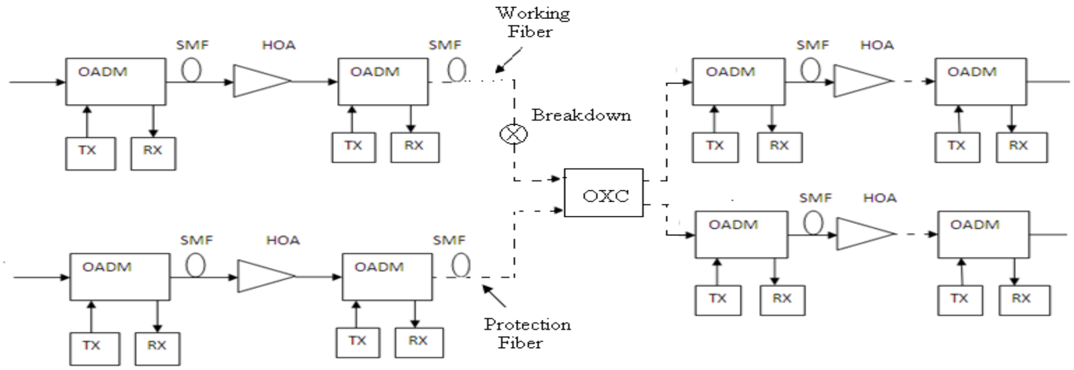

Figure 6.13 System setup for the bus topology using protection scheme

The System setup for the ring topology using ring protection scheme is shown in Fig. 6.14. A particular protection path is used to keep the signal in 1+1 architecture. The link at the beginning of the path is stable in this architecture. The switching at the tail end occurs and traffic is sent over two similar routes and the destination or the receiving end selects the better of these two signals in this architecture. In case of any breakdown, the destination switches onto the protection path.

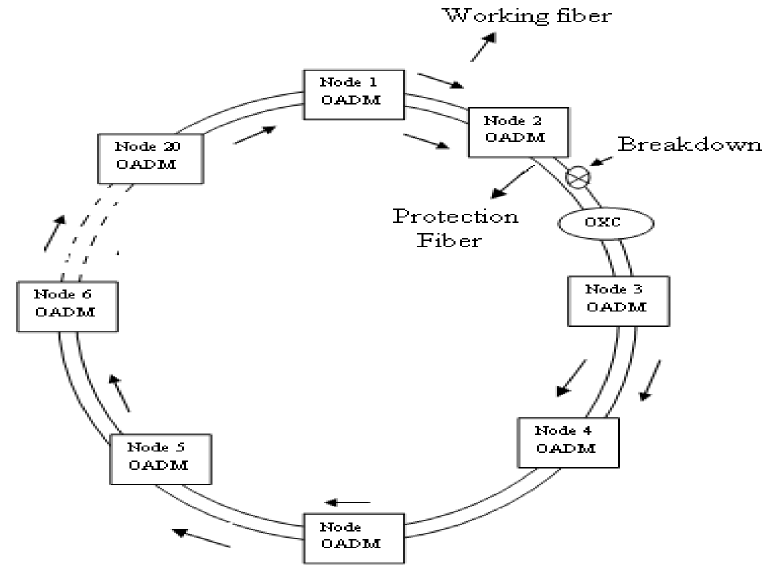

Figure 6.14 System setup for the ring topology using protection scheme

The simulation is carried out for different low input powers and crosstalks for the bus topology with twenty nodes using hybrid optical amplifiers. The Quality factor vs. supported nodes at -10 dBm optical input power for different crosstalks is as shown in Fig.6.15. The maximum users supported are 16 at -10 dBm input signal power at -30 dB crosstalks. Fig. 6.16 depicts the Quality factor vs. supported nodes for the bus topology at -20 dBm input signal power. The supported users are 4 at -30 dB crosstalk & more than 20 users are supported in case of -50 dB and -70 dB crosstalk. With decrease in the optical input power, signal quality decreases. The quality of the O/P optical signal reduces caused by increase in amplified spontaneous emission noise power.

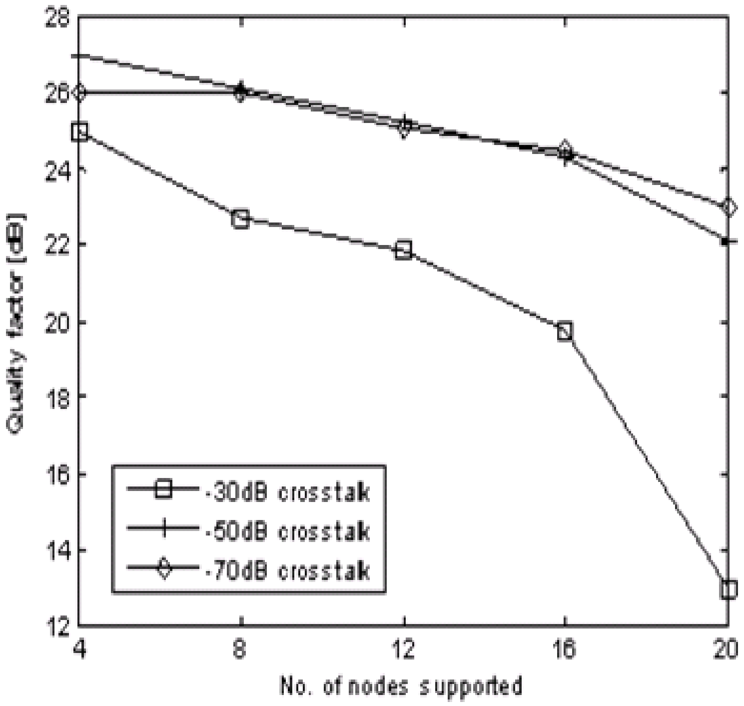

Figure 6.15 Quality factor vs. supported nodes for the bus topology at -10dBm signal input power

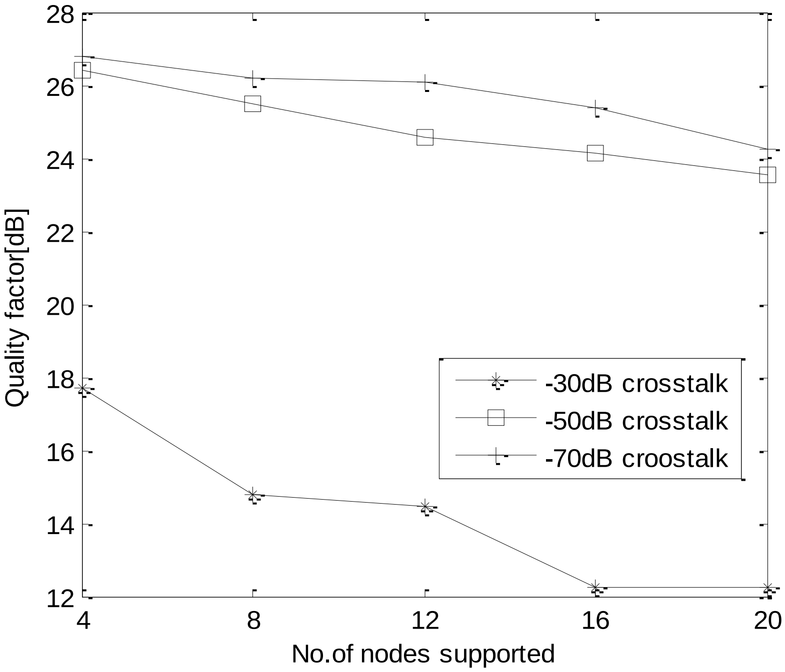

Figure 6.16 Quality factor vs. supported nodes for the bus topology at -20 dBm signal input power

Fig.6.17 shows the quality of signal vs. supported users at -10 dBm input power for ring topology. It is observed that more than 20 users are supported for -30 dB, -50 dB & -70 dB crosstalk.

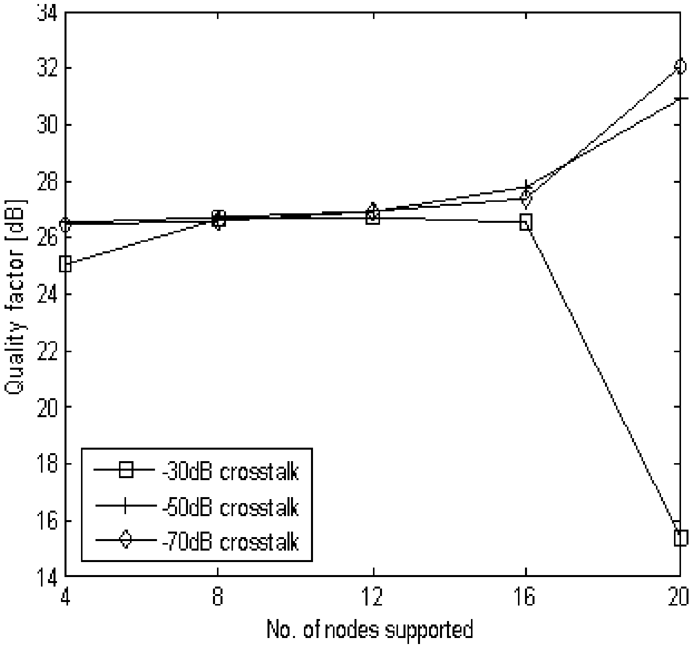

Figure 6.17 Quality factor vs. supported nodes for the ring topology at -10 dBm input signal power

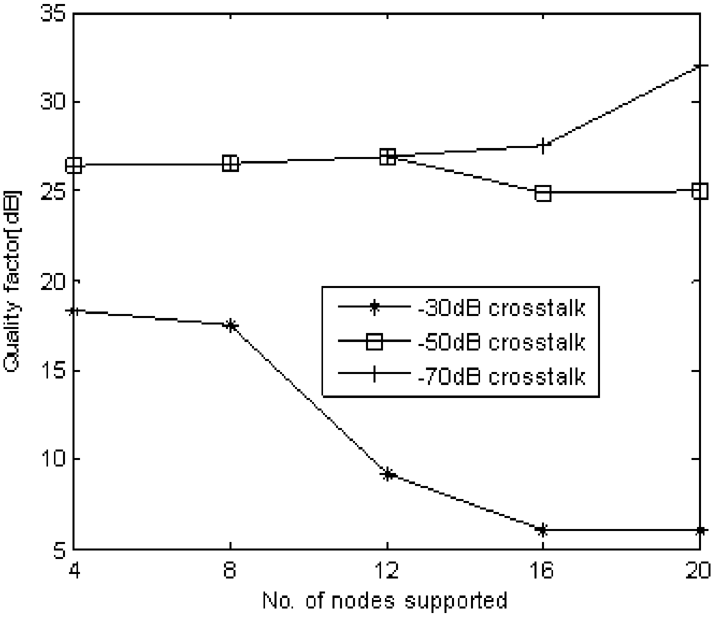

Figure 6.18 Quality factor vs. supported nodes for the ring topology at -20 dBm signal input power

The quality factor vs. supported users for ring topology at -20 dBm input signal power depicts in Fig. 6.18. The maximum supported nodes are 8 at -30 dB crosstalk. In case of -50 dB & -70 dB crosstalk more than 20 nodes are supported.

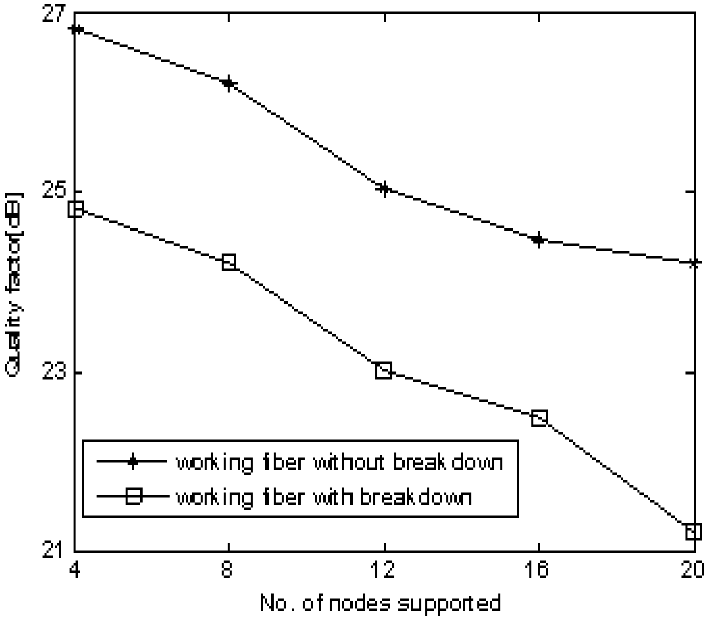

Figure 6.19 Quality factor vs. supported nodes with protection scheme for bus topology

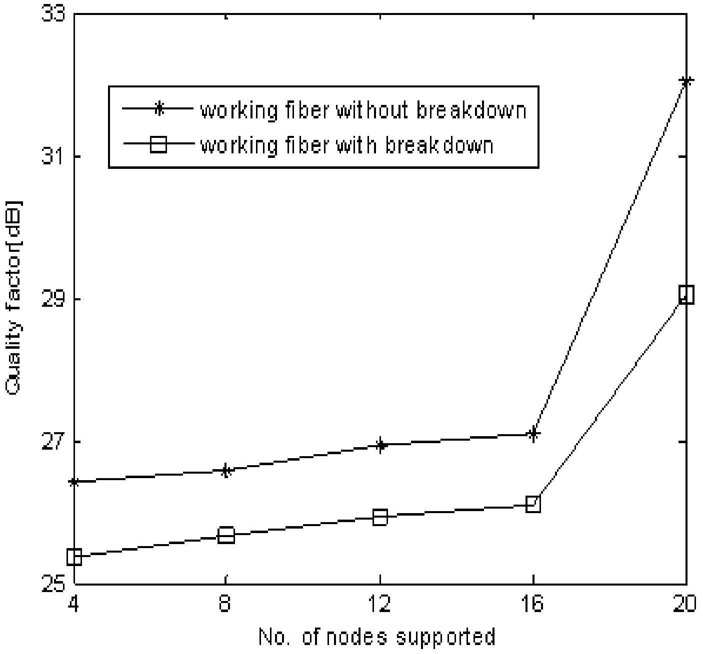

Fig.6.20 Quality factor vs. supported nodes with protection scheme for ring topology.

Fig.6.19 & 6.20 show the Quality factor vs. supported nodes with protection scheme for bus and Ring topology at -70 dB crosstalk with 30 km fiber length between two nodes for working and protection fiber. Few changes in quality factor were found which shows no degradation in the quality factor with and without breakdown.

6.4 Conclusions

In this chapter, we have outlined the different topologies with optical add drop multiplexer & optical cross connect & explore protection schemes in these topologies to enhance survivability. It is concluded that for the simulation of twenty nodes of bus topology, no user is supported at -30 dBm I/P signal power but at low I/P optical power of -20 dBm, 18 nodes are supported at signal power above -20 dBm and the supported users are more than 20. In ring topology, 30 nodes are supported at low optical I/P power of -30 dBm and at other signal I/P power above -30 dBm, supported users are more than 40 for the simulation of Forty nodes and for Twenty nodes hybrid topology, the signal quality reduces with a reduction in the I/P power & at −30 dBm optical I/P power, no users are supported in the upper bus & ring. But at -20 dBm I/P signal power, supported nodes for upper bus is 6 but for upper ring, the supported users is more than 10. In all these topologies, the received power decreases with the decrease in optical power.

We have also evaluated the different topologies using protection schemes. In ring topology, 8 nodes are supported and in bus topology 4 nodes are supported at -20dBm input signal power for -30dB crosstalks. The number of users supported in case of -50 dB and -70 dB crosstalks are more than 20 in both the bus and ring topology. If breakdown occurs in working fiber, optical cross connect switches the affected signal to the protection path.

Chapter 7

Conclusions, Recommendations and Future scope

7.1 Conclusions

This thesis presents the Performance Analysis of DWDM Systems with OADM & Optical Cross Connects. The motivation and objective of this thesis is to do an in depth analysis of the characteristics of OADMs and OXCs. The simulation of OADMs and OXCs has been carried out and the outcomes presented have been validated using theoretical work. The outcomes obtained from this study are summarized are as follows:

1. The optical communication system with Optical Add Drop Multiplexer located at 20 km point of a 40 km link using three MZI techniques obtained at 10 Gbps with 0.1 nm interval is demonstrated. The results are obtained for NRZ rectangular modulated data signal. OADM based on MZI–Fiber Bragg Grating shows the better results as compared to other techniques. OADM based on MZI-FBG, Quality value is more with max. crosstalk in comparison of other techniques. Also the signal is successfully transmitted with a very low Bit Error Rate with OADM based on MZI–FBG. OADM based on Mach Zehnder Interferometer–SOA shows the worst results in terms of Quality factor and Bit Error Rate.
2. The investigation of the optical communication system with OADMs located at the 35 km point of 70 km link using three MZI techniques obtained at 8 ×10 Gbps with 0.1 nm interval has been done. With respect to crosstalk, the MZI based OADM & MZI–FBG based OADM show better results in the terms of quality factor and bit error rate. The maximum distance achieved is 150 Km using OADM based MZI & MZI–FBG at acceptable Bit Error Rate (1.38×10^{-10}) and quality factor (16.19 dB). OADM based on MZI is cost effective solution as compared to other techniques. The acceptable Bit Error Rate and Quality factor is achieved with OADM based on MZI and MZI–FBG.
3. The structure of Bidirectional FBG–Optical Circulator based OADM for DWDM system with 0.1nm of interval has been investigated. Three kinds of modulators are compared in terms of FBG bandwidth, I.L of FBG & optical circulator. Using Mach Zehnder and Electro Absorption modulators, the transmission distance is restricted to 50 Km and 30 Km while it is increased to 70 Km in case of Amplitude Modulator. Using AM

modulator, the signal travels the distance of 70 km with an acceptable BER. The proposed system shows adequate performance with maximum FBG bandwidth of 280 GHz, FBG insertion loss of 9 dB, circulator insertion loss of 4.5 dB for Amplitude Modulator.

4. The dense wavelength division multiplexing system based on OXCs using different techniques at 10 Gbps with 0.1 nm interval is also evaluated. The signal is successfully transmitted with an acceptable Bit Error Rate i.e $2.16883 \times 10^{-11}$and 2.3777×10^{-11}at output port C, $2.13881 \times 10^{-9}$and 2.2553×10^{-9}at output port D, with Type-I and Type-II OXC at -30 dB crosstalk as compared to Type-III OXC up to a distance of 80 km. The Type-III OXC shows the worst results as far as BER is concerned. The input-output power relationship shows improvement up to -14 dBm approximately in output power for Type-I and Type-II OXCs hence our system becomes more efficient and consumes lesser power. It is also observed that the Type-I OXC system is a cost effective solution among the three cases.
5. The Dense Wavelength Division Multiplexing system with OXADM has been analyzed with the mutual concept of OADM and OXC. The performance is investigated by evaluating the bit error rate at different I.L's, attenuation and crosstalk for different lengths. The transmission distance of 85 km without amplification at I.L 6 dB with an attenuation of 50 dB is achieved by OXADM. For 85 Km transmission distance, the system provides adequate Bit Error Rate with maximum crosstalk of -35 dB at an I.L of 70 and 6dB attenuation.
6. The performance of Dynamic Reconfigurable Optical Add/Drop Multiplexer based on Dynamic Channel Equalizer is obtained for 40× 10 Gbps with 100GHz channel spacing. The effect of crosstalk has been investigated to calculate the performance of optical transmission system in terms of received power. Since DCE equalizes power levels among different channels. It is observed in the system also that the max. transmission distance covered with Dynamic channel Equalizer is 220 Km after the amplifier and 140 Km before the amplifier at minimum crosstalk (15 dB) respectively. However at maximum crosstalk (35 dB) the transmission distance varies as 100 Km after the amplifier and 60 km before the amplifier.

7. The performance of Reconfigurable Optical Add/Drop Multiplexer based on PLC and WSS is obtained for 16× 10 Gbps with 100 GHz channel spacing. We evaluated the power transient effects caused by the addition or deletion of channels. The add-drop of the channels causes transient effects in the surviving channels. Such transient effects are mitigating using the Dynamic EDFA component with the surviving channels. It is found that the signal can be transmitted with adequate optical output power (-34 dBm) up to maximum transmission distance of 462 km with three dynamic EDFA's.
8. In bus topology, no user is supported at -30 dBm I/P signal power but at low I/P optical power of -20 dBm, 18 nodes are supported and at signal power above -20 dBm, the supported users are more than 20. In ring topology, 30 nodes are supported at low optical I/P power of -30 dBm and at other signal I/P power above -30 dBm, supported users are more than 40 for the simulation of forty nodes and for twenty nodes hybrid topology, the signal quality reduces with a reduction in the I/P power & at −30 dBm optical I/P power, no users are supported in the upper bus and ring. But at -20 dBm I/P signal power, supported nodes for upper bus is 6 but for upper ring, the supported users are more than 10. In all these topologies, the O/P optical power reduces with the reduction in optical power.
9. The simulation of twenty nodes of bus and Ring topology using protection scheme has also been carried out. In ring topology, 8 nodes are supported and in bus topology 4 nodes are supported at -20 dBm input signal power for -30 dB crosstalks. The number of users supported in case of -50 dB and -70 dB crosstalks are more than 20 in both the bus and ring topology. If breakdown occurs in working fiber, optical cross connect switches the affected signal to the protection path.

7.2 Recommendations

1. The proposed architecture of DWDM system with Mach Zehnder Interferometer based OADM & OXC and Mach Zehnder Interferometer–Fiber Bragg Grating based OADM & OXC show the better results among the different techniques. The results achieved have shown that Mach Zehnder Interferometer based OADM and MZI–Fiber Bragg Grating based OADM techniques perform better results in terms of transmission distance, bit error rate and quality of signal. The strong points of the proposed techniques are:

simplicity and cost-effectiveness in terms of less number of components required. Hence this low cost MZI based OADM can be recommended for DWDM transmission system as compared to other techniques.

2. The proposed structure of bidirectional FBG-optical circulator based OADM can be employed for high speed DWDM systems. The circulator and FBG parameters can be recommended for the design of optimized Bidirectional FBG-optical circulator for DWDM system.
3. The proposed ROADM based on different techniques such as DCE, PLC, WSS and combined concept of OADM & OXC i.e OXADM can also be applied to more number of channels. Therefore with this approach, high bit rate & less channel spacing are achieved and applicable for DWDM system.
4. The Hybrid (RAMAN-EDFA) optical amplifier can also be applicable for low signal input power to support large number of users in different topologies like bus, Ring and hybrid network. The Protection schemes in different topologies can be recommended to improve the survivability of optical DWDM system.

7.3 Scope for Future work

1. The OADM and OXC with different techniques have been investigated. The performance can be enhanced by Optimization of Semiconductor optical amplifier, Fiber Bragg Gratings and circulators.
2. The performance of DWDM system with OXADM i.e the combined concept of OADM and OXC operations can be improved by increasing the number of channels. Also the results can be extended for the higher bit rates.
3. The reconfigurable add drop multiplexer based on Dynamic Channel Equalizer, Wavelength selective switch and Planar Lightwave circuit is investigated to evaluate the performance of optical communication system. Since channel spacing is also a major concern. Work can be carried out with lesser channel spacing. The work must progress for the mitigation of power transients using dynamic EDFA component with the surviving channels.
4. The different topologies have been studied with OADM and OXC. The simulation results can be extended by increasing the no. of nodes supported in the system.

Protection schemes can be explored in the network topologies to enhance the performance of the system.

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