

## **INFORMATION TO USERS**

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

**The quality of this reproduction is dependent upon the quality of the copy submitted.** Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

# **UMI**

A Bell & Howell Information Company  
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA  
313/761-4700 800/521-0600



7

**Survivable and Scaleable Multiwavelength Ring Network  
Architectures For Broad-band Fiber Optic Networks:  
An Experimental Demonstration**

by

Fatimah Shehadeh

A dissertation submitted to the Graduate Faculty in Engineering in partial  
fulfillment of the requirements for the degree of Doctor of Philosophy, The  
City University of New York.

1997

**UMI Number: 9721840**

---

**UMI Microform 9721840**  
**Copyright 1997, by UMI Company. All rights reserved.**  
**This microform edition is protected against unauthorized**  
**copying under Title 17, United States Code.**

---

**UMI**  
**300 North Zeeb Road**  
**Ann Arbor, MI 48103**

Approval page

This manuscript has been read and approved by the Graduate Faculty in  
Engineering in satisfaction of the dissertation requirement for the degree of  
Doctor of Philosophy.

|                 |                                  |
|-----------------|----------------------------------|
| <u>01-06-97</u> | <u>mali</u>                      |
| Date            | Chair of the Examining Committee |
| <u>1/6/97</u>   | <u>Grand J. Lowe</u>             |
| Date            | Executive officer                |

Prof Mohammed Ali

Rich Vodhanel (Bellcore)

Samir Ahmed

Ibrahim Habib

Roger Dorsinvil

Leonid Roytman

Janet Jackel (Bellcore)

Supervisory Committee

The City University of New York

## Abstract

### **Survivable and Scaleable Multiwavelength Ring Network Architectures For Broad-band Fiber Optic Networks: An Experimental Demonstration**

By

Fatimah Shehadeh

Advisor: Professor Mohammed Ali.

The explosive growth of on-line services, and the emergence of broadband services, require large and immediate increases in network capacity. Extensive research is being conducted in the fiber optic communication area to provide the required increase in bandwidth. The key element for the realization of this high capacity network is the Wavelength Division Multiplexing (WDM) technology, which allows many channels to propagate independently in the fiber. Another critical element is the Erbium-Doped-Fiber Amplifier (EDFA), to compensate for the losses suffered by these WDM devices and the transmission along the fiber,

The WDM devices studied in this work are provided by two different suppliers, each employing a different design technology. The two WDM technologies are compared in term of their insertion loss, polarization dependent loss, crosstalk, and accuracy of channel spacing.

EDFA, the second element studied, is characterized by large bandwidth, high gain, and non-uniform wavelength dependent gain. The last characteristic listed causes design problems for transmission systems when a chain of EDFAs is used. In this work, we demonstrate a simple technique to equalize the EDFA's gain, employing variable optical attenuators. The gain stability of the EDFA during the loss of input signals (due to network configuration changes or equipment failure), is also studied. Three stabilizing techniques requiring feedback are demonstrated and compared. In this study, both co- and counter-propagating control signals are used, as well as control of the pump power. A third stabilization scheme is introduced, based on saturating the amplifier without relying on feedback control. When this scheme is used, 1dB increase of one surviving channel is measured when 7 signals are lost, for the case of 3 EDFAs in cascade.

Finally, a ring network is built, employing optical nodes consisting of both WDM technologies and EDFAs to compensate for insertion losses. For this

work, signals were launched at 2.5 and 10Gb/s per channel, in an 8-node, 8 wavelength ring. Less than 1dB in system penalty is measured at the 8<sup>th</sup> node. We also, study the impact of laser misalignment on the cascaded WDM elements in such a ring. For  $\pm 0.3\text{nm}$  shift in signal wavelength, approximately 1.5dB is measured at the 8<sup>th</sup> node, for 10Gb/s transmission.

## Acknowledgment

I wouldn't have participated in this exciting work, if it weren't for my advisor professor Mohammed Ali, who introduced me to the optical networking group at Bellcore. He is greatly appreciated for his ideas and support of my thesis work. Rich Vodhanel (Bellcore), my co-mentor, provided me with guidance, teaching and training. He is deeply thanked for his support for the best three years of my life. Chris Gibbons (Bellcore) is a great technician, whose help was essential. Tet Suzaki (NEC) is appreciated for his help and valuable comments on the 10Gb/s experiments. Nat Denkin (Lucent Technologies) proved to be a great friend. His help in the English language is highly valued. I thank also, my supervisor, Joe Kunz of Lucent Technologies, for his encouragement giving me the chance to write my thesis while on the job.

Finally, I thank my parents, my brother and my sister for their support and encouragement during my graduate study.

## TABLE OF CONTENTS

|                                                                                      |     |
|--------------------------------------------------------------------------------------|-----|
| Abstract                                                                             | iii |
| Acknowledgment                                                                       | vi  |
| List of tables                                                                       | ix  |
| List of figures                                                                      | x   |
| Chapter 1 Introduction                                                               |     |
| 1.1 Introduction                                                                     | 1   |
| 1.2 Thesis Statement                                                                 | 4   |
| Chapter 2 Self-Healing WDM ring network architectures                                |     |
| 2.1 Introduction                                                                     | 8   |
| 2.2 Self-Healing ring                                                                | 8   |
| 2.2.1 Two-fiber Unidirectional Ring                                                  | 9   |
| 2.2.2 Four Fiber Bi-directional Ring                                                 | 11  |
| 2.2.3 Upgrade from SONET fiber ring to WDM                                           | 12  |
| Chapter 3 Critical Technologies for WDM ring Network:<br>Components Characterization |     |
| 3.1 Introduction                                                                     | 16  |

|                                              |    |
|----------------------------------------------|----|
| - 3.2 Key enabling Technologies              | 17 |
| 3.2.1 Light sources and modulators           | 17 |
| 3.2.2 Wavelength Division Multiplexers (WDM) | 27 |
| a) Phase Arrayed Waveguide (PAW)             | 29 |
| b) Multilayer Interference Filters           | 30 |
| 3.2.3 Erbium-Doped Fiber Amplifier (EDFA)    | 32 |
| 3.2.4 Optical switches                       | 37 |

Chapter 4 Performance Analysis of individual components:  
their impact on overall system performance.

|                                                                                                                                |    |
|--------------------------------------------------------------------------------------------------------------------------------|----|
| 4.1 Introduction                                                                                                               | 39 |
| 4.2 Design approach for an optical network layer                                                                               | 39 |
| 4.3 Performance analysis/assessment of EDFA cascade with multiwavelength<br>handling capabilities                              | 40 |
| 4.3.1 Introduction                                                                                                             | 40 |
| 4.3.2 EDFA gain equalization                                                                                                   | 41 |
| 4.3.3 Gain control and WDM output stabilization of EDFA                                                                        | 50 |
| 4.4 External modulation chirp and laser frequency misalignment and their<br>impact on the overall WDM ring network performance | 60 |
| 4.5 WDM Cross-connects and its impact on the WDM ring<br>network transmission performance.                                     | 61 |

Chapter 5 WDM ring network implementation:  
end-to-end system performance

|                                                           |    |
|-----------------------------------------------------------|----|
| 5.1 Introduction                                          | 67 |
| 5.2 WDM Ring Network Experiment                           | 67 |
| 5.3 System Impairment due to laser misalignment and chirp | 75 |

Chapter 6 Conclusion

|                |    |
|----------------|----|
| 6.1 Conclusion | 81 |
|----------------|----|

|            |    |
|------------|----|
| References | 84 |
|------------|----|

- List of Tables:

|                                                                           |    |
|---------------------------------------------------------------------------|----|
| Table 4.1 EDFA WDM outputs with and without pump control                  | 52 |
| Table 4.2 EDFA WDM outputs with and without co-propagating control signal | 54 |
| Table 4.3 EDFA WDM outputs with and without counter-propagating signal    | 54 |
| Table 5.1 Summary of PAW and MI WDM components                            | 71 |

List of figures:

|                                                                                                                               |    |
|-------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1 Optical layer                                                                                                      | 5  |
| Figure 2.1 Unidirectional self-healing WDM ring network with a hub and N-1 local offices                                      | 10 |
| Figure 2.2 Optical component a) at local office, b) at hub office                                                             | 14 |
| Figure 2.3 Four-fiber bi-directional SHR                                                                                      | 15 |
| Figure 3.1 Schematic representation a) DFB, b) DBR                                                                            | 19 |
| Figure 3.2 Structure of six-channel selectable laser                                                                          | 22 |
| Figure 3.3 Comparing external and direct modulation schemes                                                                   | 23 |
| Figure 3.4 Schematic structure of Mach-Zehnder interferometer type modulator                                                  | 23 |
| Figure 3.5 Frequency response of 83km of standard fiber, using LN modulator                                                   | 25 |
| Figure 3.6 Resonant frequencies to calculate the chirp parameter and dispersion factor                                        | 27 |
| Figure 3.7 Schematic representation of a phased array demultiplexer (a), and magnification of the output focusing coupler (b) | 30 |
| Figure 3.8 Structure of a multilayer interference cavity thin film based multiplexer                                          | 31 |
| Figure 3.9 Transmission and reflection of an MI filter                                                                        | 32 |
| Figure 3.10 Energy level diagram corresponding to three-level system                                                          | 34 |
| Figure 3.11 Basic EDFA device architectures: a) forward pumping, b) backward pumping, c) bi-directional pumping.              | 36 |
| Figure 3.12 Optical switch construction                                                                                       | 38 |

|                                                                                                                                                                 |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.1 Experimental setup for gain equalization measurements                                                                                                | 43 |
| Figure 4.2 Equalized internal gain of eight wavelengths versus signal input power, for a pump of 27.5 mW                                                        | 44 |
| Figure 4.3 EDFA output with and without input signals, $P_p = 27.5\text{mW}$ , $P_{\text{tot}} = -8.5\text{dBm}$                                                | 45 |
| Figure 4.4 Optical spectrum measured at the output of the W-ADM showing the light equalized output signals                                                      | 46 |
| Figure 4.5 Equalized internal gains at eight wavelengths versus pump power, for total input signal power a) $-8.5\text{dBm}$ , b) $-18.5\text{dBm}$             | 48 |
| Figure 4.6 Optical spectrum measured at the output of the W-ADM showing the light equalized output signals                                                      | 49 |
| Figure 4.7 Experimental setup for gain stabilization employing control signals.                                                                                 | 51 |
| Figure 4.8 Spectrum of one surviving channel, when four out of five are dropped, employing counter-propagating control signal technique for gain stabilization. | 53 |
| Figure 4.9 Power needed for control signal in co- and counter- propagating directions, and for 1480nm pump to stabilize WDM output levels.                      | 55 |
| Figure 4.10 The spectrum of transmission simulating 8 channels, when no saturation applied and the case when saturation is used. 6dB in output power is lost.   | 57 |
| Figure 4.11 Applying a saturating signal and observing the impact of dropping 7 channels on the system.                                                         | 58 |
| Figure 4.12 transient response for pulse width of 100ms.                                                                                                        | 59 |

|                                                                                                                                                                                                   |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.13 Setup used to measure transient response for 3 EDFAs in a WDM system.                                                                                                                 | 60 |
| Figure 4.14 Architecture of an 8-wavelength, 8x8 wavelength selective cross-connect.                                                                                                              | 63 |
| Figure 4.15 Transmission through a network of 8x8 WDM cross-connects (WSXC) was evaluated by routing a 2.5 Gb/s signal at $\lambda_1$ eight times through the WSXC.                               | 64 |
| Figure 4.16 Bit error results, $\bigcirc$ baseline, $\square$ transmission through 16 EDFAs and 16 de/mux filters, optical switch fabric removed, $\Delta$ transmission 8 times through the WSXC. | 65 |
| Figure 5.1 experimental setup for the ring measurements                                                                                                                                           | 68 |
| Figure 5.2 Passband evolution of the PAW and MI filters as they are cascaded.                                                                                                                     | 70 |
| Figure 5.3 The spectrum of 8 channels at the output of the eighth node.                                                                                                                           | 72 |
| Figure 5.4 The Bit-Error-Rate performance at 2.5 and 10 Gb/s rates for 8 node 8 channels ring experiment.                                                                                         | 73 |
| Figure 5.5 Eye diagram for channel eight as function of wavelength misalignment for 10 Gb/s.                                                                                                      | 74 |
| Figure 5.6 Laser misalignment penalty for 10Gb/s                                                                                                                                                  | 76 |
| Figure 5.7 SNR degradation for eight node ring network as $\lambda$ drifts from the filter's center.                                                                                              | 77 |
| Figure 5.8 BER vs. Optical SNR for 2.5 and 10GHz signals.                                                                                                                                         | 79 |
| Figure 5.9 System penalty function of chirp parameter $\alpha$                                                                                                                                    | 79 |



# Chapter 1

## Introduction

### 1.1 Introduction

Driven by the emerging explosion of information exchange and the prospect of introducing broad-band integrated services digital network (B-ISDN), the capacity requirements of future transport networks will be demanding. Various estimates predict an increase in the traffic demands by the turn of the century by a factor of 10, or even more. In today's information infrastructure, the increased transport capacity requirements of telecommunication networks are met by the use of fiber-optics as single-channel, point-to-point transmission links, with all networking and service functions done electronically. To upgrade such an infrastructure, a core transport network is required to handle both narrow-band and broad-band services together in an efficient manner. This calls for not only high-capacity channels, but also transport channels with sufficient granularity to handle signals at all levels in the network. Electronics switching systems are seen to have a capacity limit in the region of a few tens of Gbit/sec. While it will no doubt be possible to increase this limit through the further development of high-speed electronic technology, there will be an increased price to pay. By careful layering of a future transport network, it may be possible to minimize cost by introducing a new optical network layer based on multiwavelength optical communication technology in the transport hierarchy, with optical switching controlled in an appropriate way through a network management system. Such

an optical layer can form the common underlying network for different overlying networks and could be made transparent to data rate and format and would be particularly suitable for bulk transport of high-bandwidth signals services.

The prospects for creating such multiwavelength optical networks that are transparent to signal format and bit rate are being investigated in several consortia activities and research programs around the world. The principle goal for these programs is to create the possibility of a "future proof" network in which the optical signals flowing through the network are uninterrupted by electronics from source to destination, and in which the character of the individual signals is determined by the terminal equipment attached to the network at the source and destination.

The envisioned multilayered network architecture satisfies these objectives by combining optical wavelength division-multiplexing (WDM) with synchronous optical networking (SONET) and asynchronous-transfer mode (ATM) networking. The principle feature of this network structure is that the optical transport layer, comprising the wavelength/space cross-connect switches (OXC's), allows large blocks of capacity to be routed around the network without the need for optoelectronic conversion and processing. The end-user services are supported by a layer of SONET and ATM electronic switches, which, in turn, are supported by the transparent optical WDM network layer.

Figure 1.1 shows the envisioned multilayer network architecture. As shown in the Fig., the optical network layer is segmented into local-exchange networks, that is the focus of this thesis, and a long distance network. Note that the WDM networking layer is

conceptually the same for both applications. However, the local-exchange network will, in general, comprise more variety of network architectures such as, broadcast stars, fixed wavelength routing, rings, and mesh-interconnected topologies.

One network architecture that is very powerful, as will be shown in this thesis, for high capacity local-exchange transport applications is the ring architecture. Specifically, self-healing ring networks that utilize wavelength-division multiplexing to provide survivable transport in the local-exchange network layer will be the focus of this thesis. Network survivability here denotes the capability for the network to recover from a single failure. Self-healing ring networks using electronic add-drop multiplexers (SONET ADMs) provide the required survivability, but are limited in capacity to about 10 Gb/s by the electronics, which may not be sufficient for many future interoffice network applications. The use of WDM technology provides a powerful mechanism to overcome this electronic capacity limitation while preserving the important survivability feature. This is particularly true when transmission and wavelength assignment are performed in a manner that does not require each node to detect and process all wavelengths traveling around the ring. The transparency and independence of the WDM channels permit vastly dissimilar bit rates to pass between different pairs of nodes, allowing network connectivity and transmission rates to be tailored and upgraded flexibly according to prevailing traffic patterns and evolving service demands. The WDM ring has the additional advantage that the electronics at each office can be sized to match the demand for traffic at that office. This is in contrast to an electronic ring, where the electronics at each office has the same capacity and is sized according to the total aggregate ring capacity. It is anticipated that these WDM networks may afford greater routing

flexibility, reduced life-cycle costs (powering, maintenance, etc.) and enhanced reliability (WDM networks use passive components) compared to rings using electronic ADMs, while providing substantially increased bandwidth to accommodate growth of future services.

## **1.2) Thesis statement**

This thesis examines the technological requirements and assesses the performance analysis and feasibility for implementing self-healing inter-office ring networks that utilize commercially available WDM technology, all-optical Add/Drop multiplexers (ADMs), all-optical protection ring using Erbium-doped Fiber Amplifiers (EDFAs), and optical switches to provide survivable transport in the local-exchange network layer.

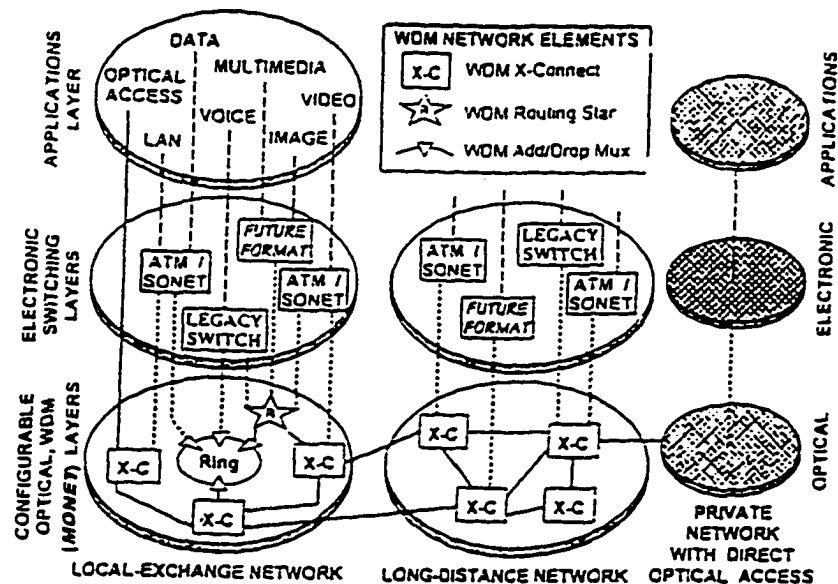


Figure 1.1 Optical layer.

The overall objective of this work is two fold:

- 1) To experimentally examine and analyze the performance of all the critical elements necessary for the implementation of high-capacity, scaleable, and survivable WDM ring networks. To achieve WDM ring network , a set of WDM network elements are needed. This includes WDM terminals, WDM repeaters (EDFAs), WDM ADMs, and optical

switches (basic WDM crossconnects and wavelength-converting WDM crossconnects). Basic WDM crossconnect allow for wavelength-selective spatial rearrangement of the paths with no wavelength translation. Wavelength/space WDM crossconnects allow for arbitrary wavelength and space rearrangement of the paths by including the wavelength conversion function in the network element. All of these components affect the transmission performance and each required an individual study of their characteristics before incorporation into an end-to-end transmission system. Consequently, performance requirements for each of these subsystem components and its isolated individual impact on the overall network performance will first be analyzed.

2) Using the above performance analysis tool, it will be possible to combine these components in any combination, to allow the important network elements and a variety of network architectures to be constructed. While most of our initial work will be in a laboratory setting, using prototype devices and subsystems, the ultimate goal of this thesis is to construct several laboratory testbeds. The laboratory testbed experiments will be designed to answer critical systems and technology questions, to demonstrate interworking of the network elements and subsystems, and to verify the technological feasibility of implementing the proposed WDM ring network architectures.

Specifically, this work report here the successful transmission performance of an eight-wavelength, 8-node WDM ring network at 2.5 Gb/s and 10 Gb/s data rates per channel, giving total network capacities of 20 Gb/s and 80 Gb/s. To the best of our knowledge, this is the largest WDM ring experiment with the highest capacity yet reported. In a WDM network, an optical signal may pass through many nodes en route to the final

destination. Signal degradation can occur at each node due to finite filter passbands and filter misalignment, added crosstalk signals, added EDFA amplifier spontaneous emission (ASE) noise, and wavelength dependent gain. The main objective of this work is to investigate the accumulation of these optical degradations in an 8-node, 8-wavelength WDM ring network with data rates of 2.5 and 10 Gb/s per channel.

## **Chapter 2**

### **Self-Healing WDM Ring Network Architectures**

#### **2.1) Introduction**

This chapter investigates self-healing ring networks that utilize wavelength-division multiplexing (WDM) to provide survivable transport without resorting to high speed electronic Add-Drop Multiplexers (ADM) [1]. In SONET rings [2] using electronic ADM the aggregate capacity of the ring is limited by the line rate of the transmission link connecting the ADMs, which in commercial practice is currently 2.5 Gb/s with 10 Gb/s in the near future. A WDM ring that uses WDM drop-and-add multiplexers offers the possibility to increase the aggregate ring capacity by a factor roughly equal to the number of wavelengths, without increasing the electronic multiplexer and transmission line rates beyond 10 Gb/s. Transparency is another advantage of WDM systems, where channels at vastly different bit rates can pass between different pairs of nodes, allowing network connectivity and transmission rates to be tailored and upgraded flexibly according to prevailing traffic patterns and evolving service demands.

#### **2.2) Self-Healing Ring:**

A self-healing ring is a network architecture that connects a set of central-offices in a physical ring topology with bandwidth sharing and a self-healing capability to network

component failures [3]. These failures include a variety of individual faults such as electronic ADM failure, fiber cuts, and transmitter failures [4]. The self-healing ring architectures can be divided generally into two categories: uni-directional and bi-directional self-healing rings. Both types of WDM rings can be designed to be consistent with present SONET standards [5,6,7], allowing graceful upgrades from electronic SONET rings to WDM SONET rings.

#### 2.2.1) Uni-directional Self-Healing Ring (SHR)

A uni-directional SHR requires two fibers, one working to carry the transmission signals, and another protection path to recover from any failure on the working fiber. Figure 2.1 shows a two-fiber uni-directional WDM ring network supporting switch consolidation where  $N-1$  local offices are originating homing traffic flow converging to a single hub. Transmission on both fiber is identical except for direction of propagation; the counter-propagating signal provides network survivability during a cable cut. Each of the  $N-1$  local offices is assigned a unique wavelength for transmission to, and receiving from, the hub. Figure 2.2(a) illustrates a block of the equipment needed at each local office. The optical part consists of two optical amplifiers, one in each direction, followed by an optical add/drop filter to handle the traffic directed to and from the office. The electronic part consists of a single SONET ADM in the terminal mode, where optical-to-electrical and electrical-to-optical conversion takes place. The two transmitters at each end of the ADM are arranged to continuously transmit signals into the ring in opposite directions. A multiplexer at the ADM receives both signals (working and protection) compares their

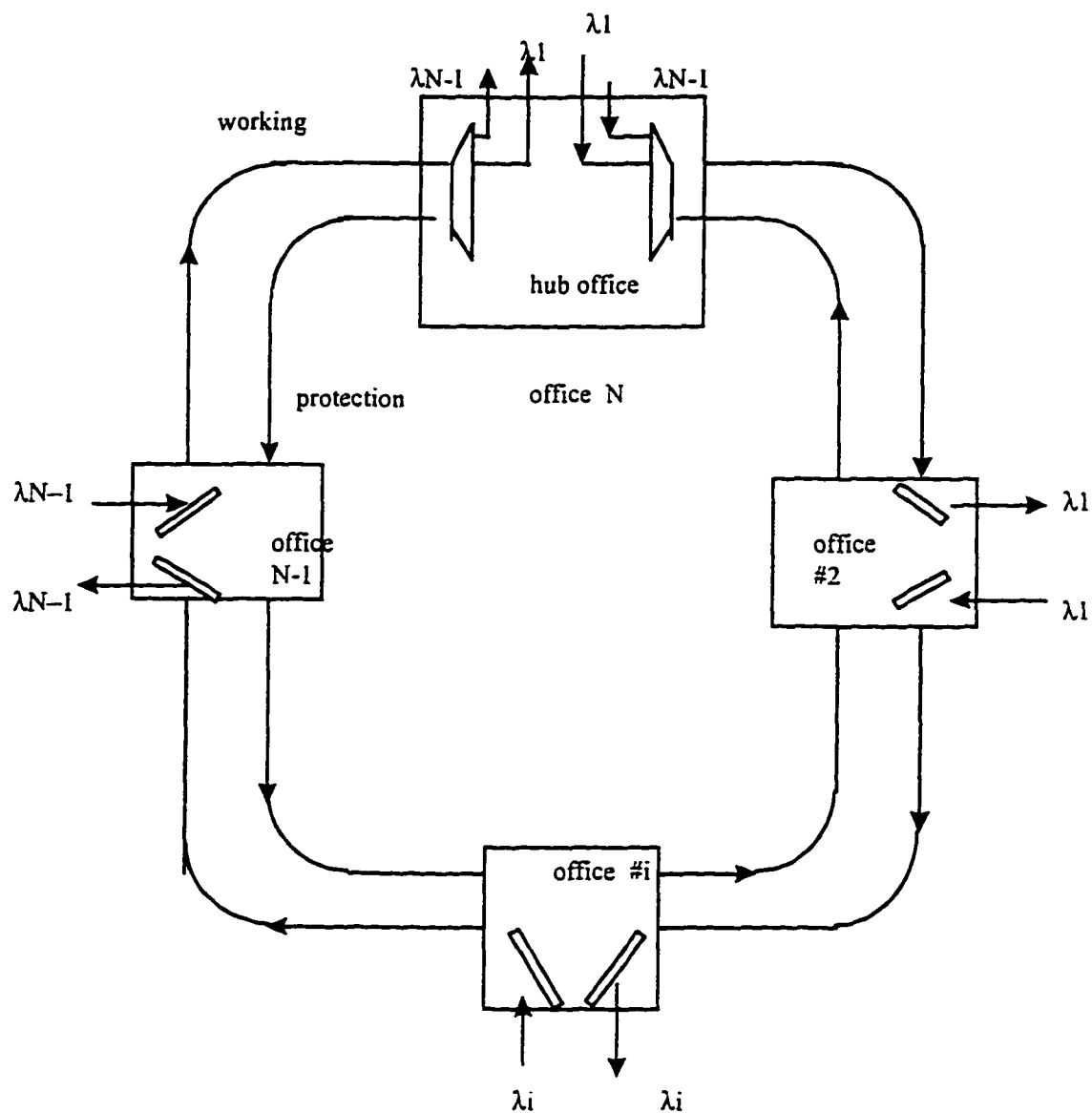


Figure 2.1 Uni-directional self-healing WDM ring network with a hub and an N-1 local offices [3].

quality, selects one of them for normal operation or the other to recover from a network failure due to cable cut.

Figure 2.2(b) shows a block diagram of the equipment needed at the hub office. The equipment consists of two optical fiber amplifiers, one in

each direction, followed by redundant wavelength demultiplexers and an array of  $N-1$  SONET ADMs, each in the terminal mode. The output signals from the SONET ADM array are multiplexed using redundant wavelength multiplexers, one for the working ring and one for the protection ring, and sent over the fibers with the signal at each wavelength intended for a different local office.

### 2.2.2) Bi-Directional Self-Healing WDM Ring Networks

A bi-directional self-healing WDM ring architecture is appropriate for connecting a set of broadband switches with full mesh traffic pattern, since it offers higher capacity than unidirectional rings [3]. In this architecture, there are  $N$  independent SONET rings, one for each of the  $N$  available wavelengths [4]. At any particular office, one or more of these  $N$  wavelengths may be dropped from the optical transmission path and be connected to an electronic multiplexer, where the digital signals are processed and new signals are added back into the optical transmission path at the same wavelength. The remaining wavelengths pass through the office unaffected, without being added or dropped at the optical level. For this ring type, there are two working fibers that carry different transmission signals, and a corresponding two protection fibers to allow optical protection switching in the event of a failure on one of the working paths.

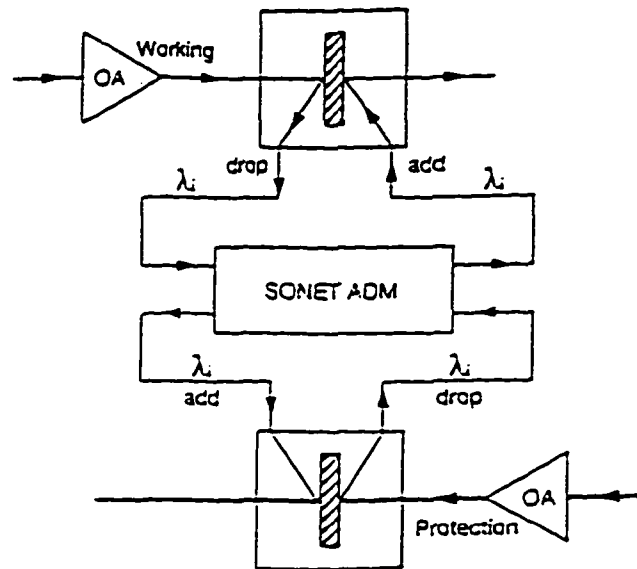
The capacity and the connectivity of four-fiber WDM ring can be described using the block diagram shown in Figure 2.3. The connectivity among offices depends on the wavelength dropping plan assigned to each office. With  $N$  offices on the WDM ring, it is

possible to achieve a full mesh connectivity if there are  $(N^2-1)/8$  wavelengths and if each office drops  $(N-1)/2$  wavelengths. These wavelengths are dropped from both working paths, with the clockwise path dropping traffic from the nearest  $(N-1)/2$  upstream offices, and the counter-clockwise path dropping traffic from the other  $(N-1)/2$  offices. In a full mesh connectivity, each office has a dedicated one-way transmission path to every other office, amounting to a total of  $N(N-1)/2$  two-way connections. Each with a capacity equal to the electronic ADM capacity. For example, a WDM four-fiber ring with 11 offices would require 15 available wavelengths to achieve a full mesh connectivity, would drop 5 wavelengths at each office, and would have a total aggregate capacity of 550 Gb/s if the individual electronic ADMs operate at 10 Gb/s. The total capacity is found from  $N.M.R$ , where  $N$  is the total number of offices on the ring,  $M$  the number of wavelengths added/dropped at each office, and  $R$  the bit rate.

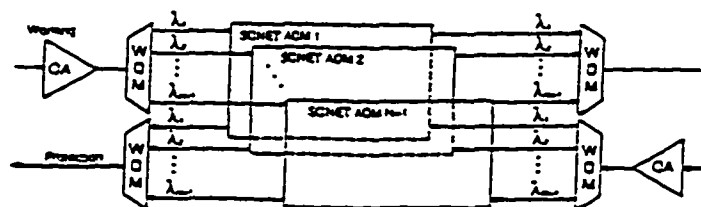
### 2.2.3) Upgrade from SONET four fiber ring to WDM:

It is possible to start with a standard four fiber-fiber bi-directional SONET ring and upgrade gracefully to a WDM ring, without taking the SONET ring out service. At one of the offices interrupt the transmitting side of one of the working path causing a protection switch to recover the interrupted traffic. However, this will disable the automatic protection switching needed to recover from legitimate faults that may occur. Then, install a selected-wavelength transmitter and a transmitting WDM multiplexer in the interrupted path at this office, then restore the interrupted traffic through the transmitting WDM multiplexer using the newly installed selected-wavelength transmitter. Move to next office on the ring and perform similar upgrade at the receiving side of that ADM, then at

the transmitting side of the ADM. Repeat the same procedure for the rest of the nodes on the ring, starting at the receiving end, and moving to their transmitting side, till returning to the original office. Follow that by upgrading the second working path. After this, the protection fibers can be moved to optical protection switches at each office, freeing the original ADM protection path electronics. The free ADM electronics can be used to increase the capacity at any office by using the newly installed WDM multiplexers to drop available new wavelengths.



a



b

Figure 2.2 Optical component a) at local office, b) at hub office.



## **Chapter 3**

### **Critical Technologies for WDM ring Network : Components characterization**

#### **3.1 ) Introduction:**

In this chapter, we investigate the critical enabling technologies, that are needed to build and operate WDM networks. For such a multiwavelength system, it is desirable to maintain a fixed reference optical power per level at the input to the switches in each office. This is assured by including multiwavelength optical amplifiers on the receiving fibers at each office. This permits a completely general wavelength dropping plan that allows wavelengths to pass through any office without being dropped, and allows the optical protection switching operation to occur without significant changes in the optical power at any receiver during a protection switch.

The architectures reviewed here serve as a basis for investigation of a variety of technical and economic issues related to WDM ring networks. The wavelength dependent characteristics of the cascaded amplifier gain and noise, and their impact on the performance of WDM ring networks, require further investigations. Several technical

problems related to the analysis of cascaded amplifiers with multiple wavelengths and the possibility of gain equalization needs to be addressed.

For directly modulated laser diodes, laser chirp generally increases linewidth substantially beyond the fundamental information bandwidth of the signal. The laser spectrum could limit the number of cascaded WDM components and possibly the number of offices in the ring. Passband spectral width requirements for the WDM components as a function of bit rate, and power penalties arising from non-ideal passband shape are important design parameters that need further quantification.

Fiber chromatic dispersion could also cause system penalties in rings with a large circumference unless dispersion shifted fiber or external modulators are used. Careful consideration of dispersion effects is necessary to set requirements for laser chirp in large rings.

### **3.2) Key enabling technologies**

Components reviewed will cover light sources (i.e. discrete laser sources, and array lasers), modulators, different multiplexing technologies, optical Erbium Doped Fiber Amplifier (EDFA), photonic switching and optical receivers.

#### **3.2.1) Light sources and modulators:**

Single channel lasers are a common sources for lightwave communication systems. They provide narrow linewidth, high power, and stable pulses. They provide the capability to

fine tune their wavelengths over small range through temperature control. For optical systems, these lasers are mainly semiconductor laser diodes[8,9]. Other light sources are the array lasers which are desirable for multiwavelength operation[10], however, they don't provide control over individual channels. Other attractive light sources for multiwavelengths operation, is the wavelength selectable laser[11].

### **Single Channel lasers:**

Semiconductor lasers are the main source for single frequency lasers, and they are divided into two types. Distributed-Bragg-Reflector (DBR), and Distributed-Feedback (DFB) lasers. Figure 3.1 shows the structure of both types of semiconductor lasers. In both cases, the grating is shown in a passive waveguide layer adjacent to the active gain region. The grating can be produced with either a periodic variation of either gain, phase, or both along the structure. The phase grating is a region of periodically varying refractive index that serves to couple two counter-propagating traveling waves [12]. The coupling is a maximum for wavelengths close to the Bragg wavelength,  $\lambda_B$ , which is related to the grating spatial period  $\Lambda$  by

$$\lambda_g = 2n_e \Lambda / l$$

Eq. 3.1

Where  $n_e$  is the effective refractive index of the mode and  $l$  is the integer order of the grating. First order gratings provide the strongest coupling, but second order gratings are sometimes used because they are easier to fabricate,, with their larger spatial period.

In a DFB laser without facet or other extraneous reflections, and with an ideal grating, longitudinal modes are spaced symmetrically around  $\lambda_B$  at wavelengths given by:

$$\lambda = \lambda_B \pm \left[ 2nL \frac{(m+1/2)\lambda_B^2}{2nL_e} \right]$$

Eq. 3.2

where  $m$  is the mode index and  $L_e$  is the effective grating length. These modes exist outside of the transmission stop-band centered on  $\lambda_B$ . There are two equivalent lowest order modes ( $m = 0$ ) and oscillation on at least two frequencies is expected. Because of grating imperfections and end-facet reflections, actual DFB lasers are not perfectly symmetric and single frequency operation on one of the modes is often the result. Comparing the performance of both types of lasers, the DFB laser has minor degradation.

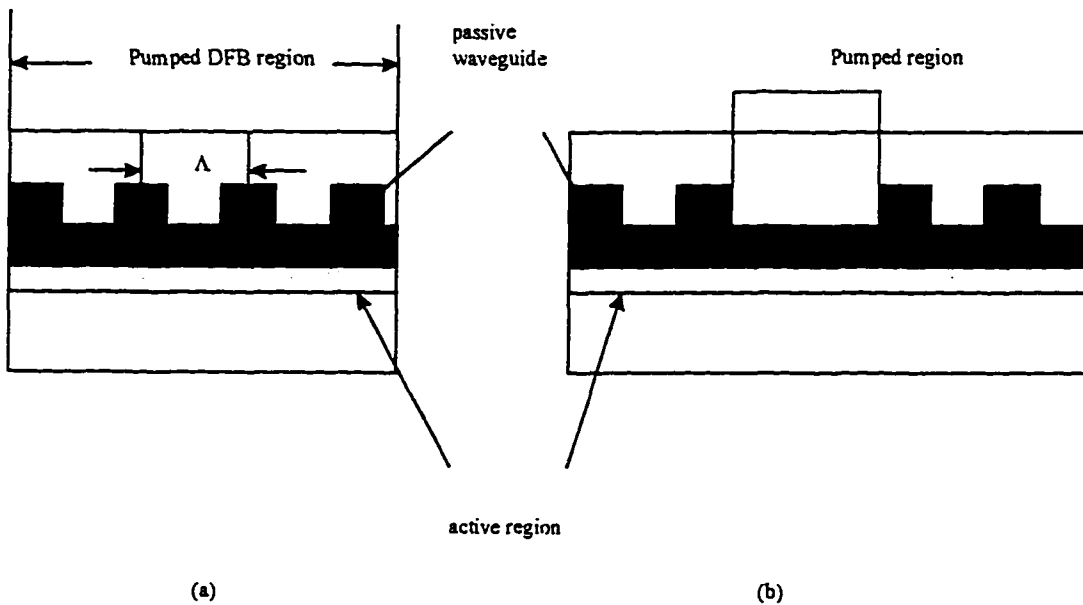


Figure 3.1 Schematic representation (a) DFB laser, (b) DBR laser.

Tunable and switchable lasers:

Many suppliers have developed single-frequency DFB and DBR lasers that can be selected to provide the required comb of optical carrier frequencies for WDM for FDM circuit

connections. They have also reported research on multi-electrode DFB and DBR lasers that will allow continuous and/or discrete covering a limited range ( $\sim 10$  nm or  $\sim 1$  THz). However, the tuning speed been slow (1ms) due to thermal and feedback circuit time constants, as illustrated by an experiment to lock a carrier comb to a set of modes of a fiber Fabry-Perot resonator [13]. A novel approach to fast frequency switching ( $< 10$ ns) for optical packet distribution that provides that access to equi-spaced frequencies reproducible from laser to laser over the full range (960 GHz) of a 2-electrode DBR has been reported by AT&T [14]. The laser consists of a long lasing section acting as a Fabry-Perot (FP) whose longitudinal dimension is selected to provide closely resonances (40 GHz). The lasing section is followed by a distributed-Bragg-reflector (DBR) section acting as a frequency selective mirror for choosing the desired resonance from the FP comb. The DBR reflection bandwidth is designed to select one and only FP frequency and is tuned by injecting current in the DBR section. The laser is tunable by a single variable current to 24 discrete frequencies equally spaced by the free-spectral range (FSR) of the FP lasing section. All of the frequencies can be accessed by tuning the current through 100ma. Frequency selection is robust against small relative tuning current variations since the channel spacing  $\Delta f$  (40 GHz) is much larger than the modulation bandwidth ( $< 5$  GHz), and the receiver bandwidth ( $\sim \Delta f/2$ ) is designed to be much greater than the error in a frequency step. Fast switching among the 24 frequencies is realized because locking to the FP resonances is obtained within the laser rather with an external feedback circuit. The switching time is limited only by the lifetime of the carriers injected into the DBR section, which is few nanoseconds.

The switching time two frequencies varies from 2 ns for adjacent frequencies to 8 ns for frequencies separated by 960 GHz. The switching time capability of the laser was also investigated using the 10-staircase waveform switching [14]. Further research on the switched DBR laser includes reducing  $\Delta f$  ( as narrow as 10 GHz), increasing the number of accessible frequencies (as many as 500), and incorporating an absorption modulator and switched branching output in a photonic integrated circuit. Other areas of research are focusing on Multiwavelength DFB laser arrays[10].

A six channel,  $\lambda$  selectable laser, has been designed for WDM applications[15 ] and is shown in Figure 3.2. Light from six DFB lasers travels through a passive combiner into a single output waveguide. This design allows for  $\lambda$ -selection without requiring the adjustment of an analog quantity for tuning (voltage, current) that is subject to aging, and also provides the known spectral stability of DFB lasers. An electroabsorption modulator is used rather than direct modulation, both to provide low the low chirp required for ultra-long distance transmission, and to allow for a single high-speed drive input to the module as desired for simple  $\lambda$ -selectable operation. Channel selection in this module is thus accomplished by the simple DDC activation of the appropriate laser lead, with no change to the high-speed drive connection.

As lasers provide the carrier for data information, modulators are the means by which this data is delivered to the channel. Modulation may be done direct or external. Figure 3.3 illustrates the difference between the two schemes. Aside from the architectural difference,

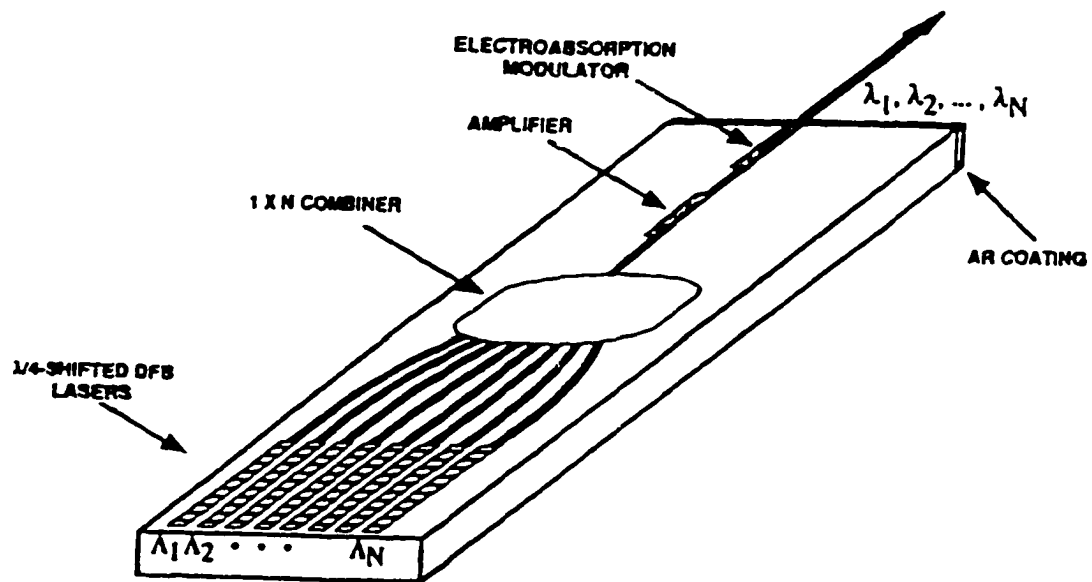


Figure 3.2 structure of six-channel selectable laser[15]

direct modulation is associated with high chirp, therefore limiting the speed and distance the signal can travel with. Though external modulation adds more cost and complexity, it also provides less chirping in the signal. However, research in direct modulation is still active, and recently a push-pull type DFB laser was reported to have low chirp at 2.5Gb/s[16]. This type uses a DFB laser with multiple metal contact layers. The job is to balance the carrier density for “1” and “0” levels, through compensating one of the contacts for the modulation current applied to the other contact.

Another type of modulator integrated with semiconductor laser, designed to have low controllable chirp, is the electro-absorption modulator [17,18,19]. To overcome the excessive dispersion in standard fiber and to meet the need for a large bit rate span product, it is desirable to use negatively pre-chirped modulation[20]. However, it still

doesn't provide the advantage of external modulation. Lithium Niobate ( $\text{LiNbO}_3$ ) external modulators provide a controllable low chirp operation[21].

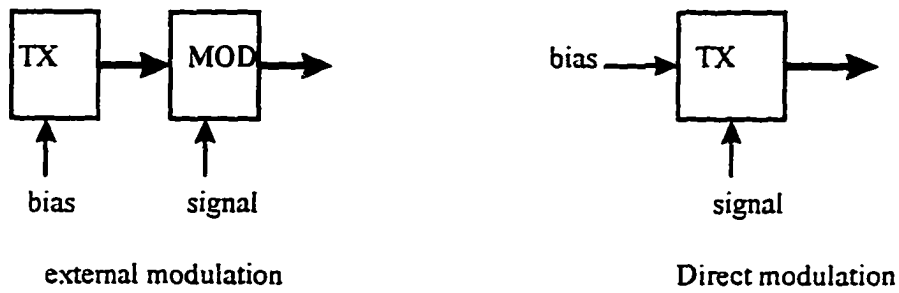


Figure 3.3 comparing external and direct modulation schemes.

Figure 3.4 shows the structure of a controllable  $\text{LiNbO}_3$  external modulator. For this type of modulator, the phase modulation is eliminated, by applying opposite bias to the two waveguide arms, therefore making the change in the propagation constant,  $\Delta\beta$ , the same for the two waveguides, but with opposite sign. Thus, the chirp parameter ( $\alpha$ ) is zero,

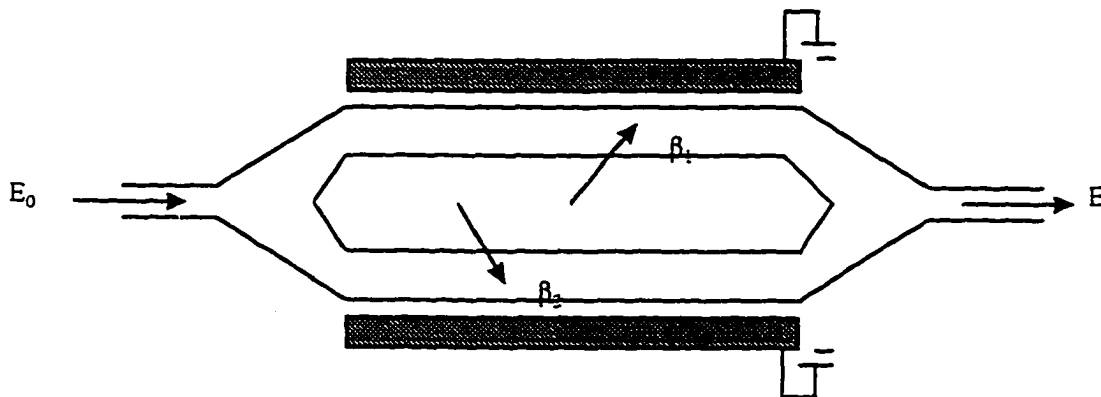


Figure 3.4 Schematic structure of Mach-Zehnder interferometer type modulator.

where  $\alpha$  is defined as  $\Delta n' / \Delta n''$ , and where  $\Delta n'$  and  $\Delta n''$  are the relative change of the real part and imaginary part of the refractive index, respectively. The relationship between the chirp parameter, the instantaneous intensity and the phase change  $\phi$  of the output light is [21]:

$$\frac{d\phi}{dt} = \frac{\alpha}{2S} \frac{dS}{dt} ; S=|E|^2 \quad \text{Eq. 3.3}$$

We used a simple approach to measure the chirp for a LiNbO<sub>3</sub> , external modulator to be used in our 10Gb/s ring network experiment. This technique is based on measuring the dispersion and the chirp parameter over transmission in a dispersive medium, [22] through the aid of an HP network analyzer (HP 8703). Figure 3.5 shows the frequency response obtained from the measurement. From the resonance peak frequencies  $\alpha$  and D the dispersion of a standard fiber were found. These parameters are calculated using small signal analysis. Assume the electric field of the light of the form  $E = \sqrt{I}e^{j\phi(I)}$ , where I is the intensity of the light, and  $\phi$  the phase of the electric field[22]. For V=2.19 and -0.69 volts,  $\alpha$  was 1.1 and -0.54 respectively.

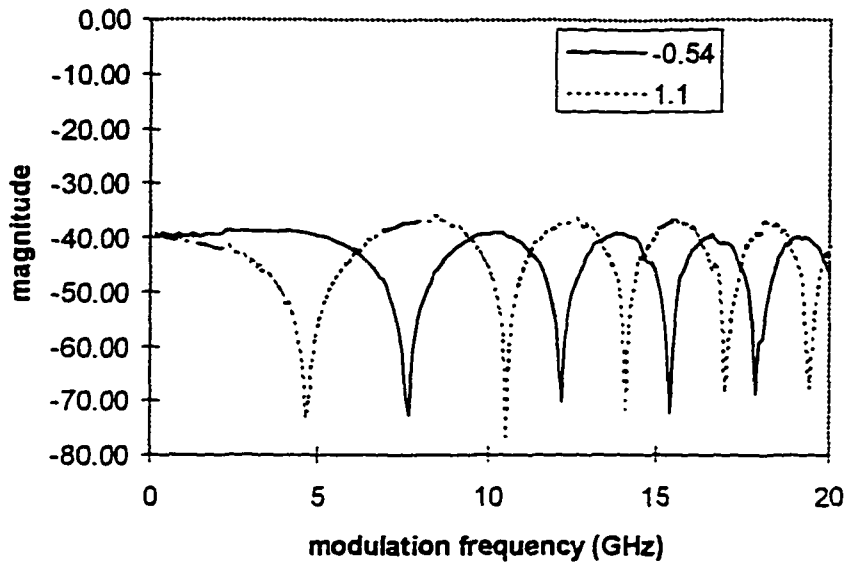


Figure 3.5 Frequency response of 83 km of standard fiber, using LN modulator.

When modulation applied the small signal analysis is then performed as in Eq. 3.4, where  $m$  is modulation depth, and  $f$  is the modulation frequency. Taking the fourier transform of the electric field (Eq. 3.5), the electric field can then be developed into a  $m$  power series, with the fourier coefficients of the form seen in Eq. 3.6.

$$I = I_0(1 + m \cos(2\pi ft))$$

Eq. 3.4

$$E = e^{j\omega_0 t} \sum_{-\infty < p < \infty} A_p e^{j2\pi p f t}$$

Eq. 3.5

$$A_{-1} = \sqrt{I_0} m \frac{(1 + j\alpha)}{4}; A_0 = \sqrt{I_0}; A_1 = \sqrt{I_0} m \frac{(1 + j\alpha)}{4}$$

Eq. 3.6

For a dispersive medium of length  $L$ , and dispersion parameter  $D$ , the propagation constant of the electric field is defined as :

$$\beta_{\pm p} = \beta_0 \pm \frac{2\pi p f}{v_g} - \frac{\pi \lambda^2 D p^2 f^2}{c}$$

Eq. 3.7

where  $v_g$  is the group velocity. The phase of the electric field in Eq. 3.4, becomes  $(2\pi p f t - \beta_p L)$ . From the intensity of light  $I = 0.5 \Re(E^* E)$ , and with substituting for the Fourier coefficients, the intensity of signal becomes  $I_f$ , of Eq. 3.8. From the argument of the cosine, we find the peak resonance frequencies, by setting the cosine to "0".

$$I_f = I_0 m \sqrt{1 + \alpha^2} \left| \cos \left( \frac{\pi \lambda^2 D L f^2}{c} + \arctan(\alpha) \right) \right|$$

Eq. 3.8

These resonance frequencies are defined by:

$$f_u^2 L = \frac{c}{2D\lambda^2} \left( 1 + 2u - \frac{2}{\pi} \arctan(\alpha) \right)$$

Eq. 3.9

Where  $\alpha$  is the chirp parameter.

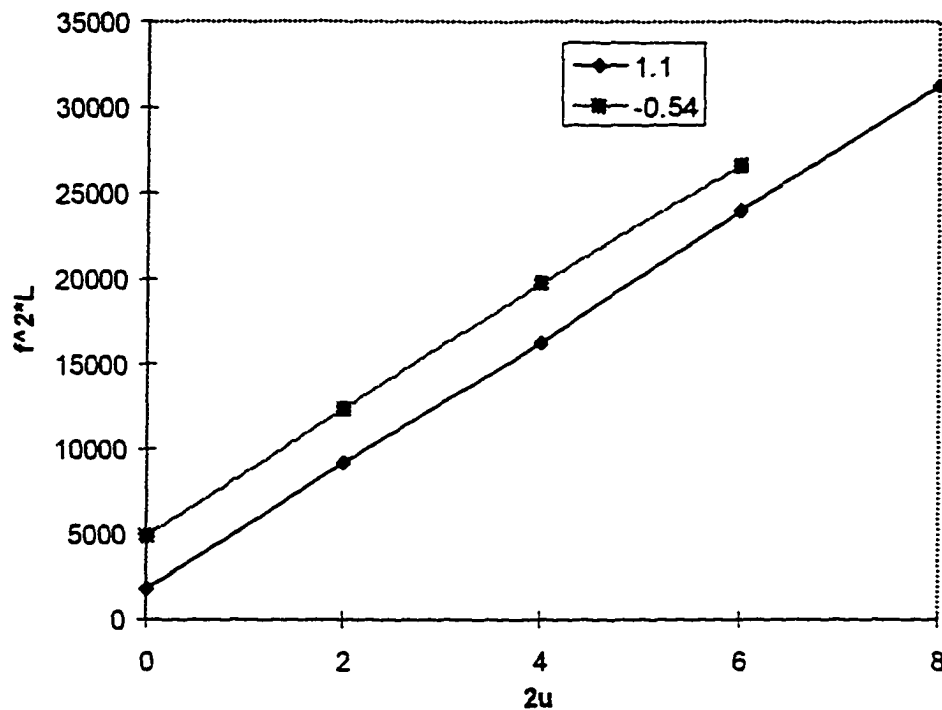


Figure 3.6 Resonant frequencies, to calculate the chirp parameter and dispersion factor

### 3.2.2) Wavelength Division Multiplexers (WDM):

Two forms of wavelength division multiplexing technologies are considered, for eight wavelengths spaced by 1.6 nm WDM system. The end-to-end bandwidth of a long link, with filters in cascade, is considerably less than that of a single node which is determined by the bandwidth of a long link which is determined by the bandwidth of a single filter. To transport the high-density multiplex requires an end-to-end bandwidth of at least 0.5nm. Thus, knowing the passband characteristics of the optical filter, one can calculate the required bandwidth for a single stage. However, if this bandwidth is too large, crosstalk

can occur between adjacent channels due to the poor wavelength discrimination of the filter. This problem gets worse as the wavelength spacing decreases.

Thus it has been necessary to study the various types of optical filter to decide which gave the best compromise between crosstalk, end-to-end bandwidth, insertion loss, and physical availability. These studies have also established that the degree of crosstalk is far more severe when a network is being considered rather than a point to point link.

The objective of the filter study was to evaluate which filter technology could give acceptable crosstalk with a passband of approximately 1 nm and a channel spacing of 1.6nm. Phase-Arrayed Waveguide (PAW) and multilayer interference filters (MI) were studied to determine their transmission characteristics. Detailed analysis of the effects of concatenation on bandwidth, and crosstalk were completed and this allowed decisions to be made on the filter types to be used in the our 8 node ring demonstration.

A key component in efficiently using the full bandwidth of the optical fiber, is the wavelength division multiplexer (WDM)[23,24]. This allows multiwavelength operation to meet the needs of today broadband services. Different technologies have been developed to achieve that goal ranging from grating[25,26], Mach-Zehnder interferometer, phase-array-waveguide (PAW)[27,28,29,30,31], and multi-layer thin film interference filters based multiplexers (MI) [71,32]. In this work, we have evaluated the PAW and MI types.

### Phase-Arrayed Waveguides(PAW):

The PAW is based on passing light through curved waveguide geometry, for which light at the output will arrive with different phases associated with each waveguide. The grating consists of single mode channel waveguides of different lengths. The waveguides designed such that the length difference ( $\Delta L$ ) between any two adjacent ones would result in a phase difference of  $2\pi n_c \Delta L / \lambda$ , where  $n_c$  is the refractive index inside the waveguide[33]. With  $d$  being the pitch between the waveguide channels at the exit, the coupling fibers at the receivers end could be placed to satisfy the relation in Eq. 3.10, where  $n_s$  corresponds to the refractive index in the converging space,  $\theta$  is the diffraction angle, and  $m$  the diffraction order. The position of these output fibers is found from the dispersion relation  $dy/d\lambda$ , where  $y$  is the position at focal image plane, and  $f$  is the focal length. Figure 3.7 shows an example of an Arrayed Waveguide (AWG) or Phase Arrayed Waveguide (PAW) type multiplexers, or Dragone coupler .

$$n_c \Delta L + n_s d \sin\theta = m\lambda$$

Eq. 3.10

$$\frac{dy}{d\lambda} = \frac{fm}{n_s d}$$

Eq. 3.11

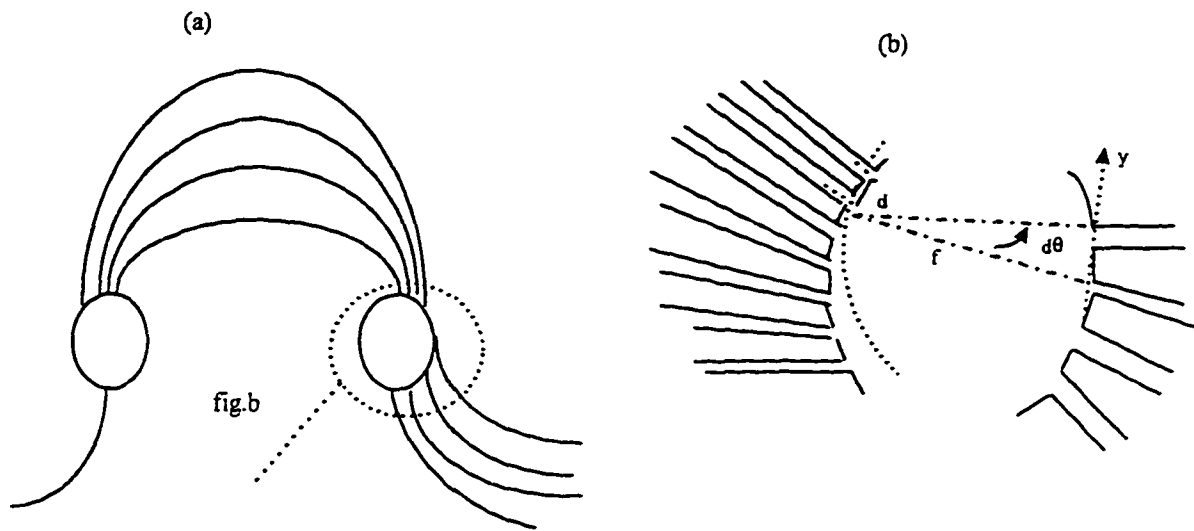


Figure 3.7 Schematic representation of a phased array demultiplexer[34] (a), and magnification of the output focusing coupler (b).

#### Multilayer Interference Filters:

The MI bases multiplexers are built from thin film structures by alternating layers of high and low refractive index. Each layer has a thickness equal to one half or quarter wavelength ( $1.5\mu\text{m}$ ). Figure 3.8 shows the structure of such thin film cavity, where the number of alternating layers could vary from 20 to 30 layers. Placing these thin film filters on a rectangular glass substrate, and employing multireflection, multiplexing can be achieved. As shown in Figure 3.9, one particular wavelength will pass through one filter and the remaining signals will be reflected. The reflected beam will go through the same cycle of transmission and reflection at the opposite filter in the rectangular structure.

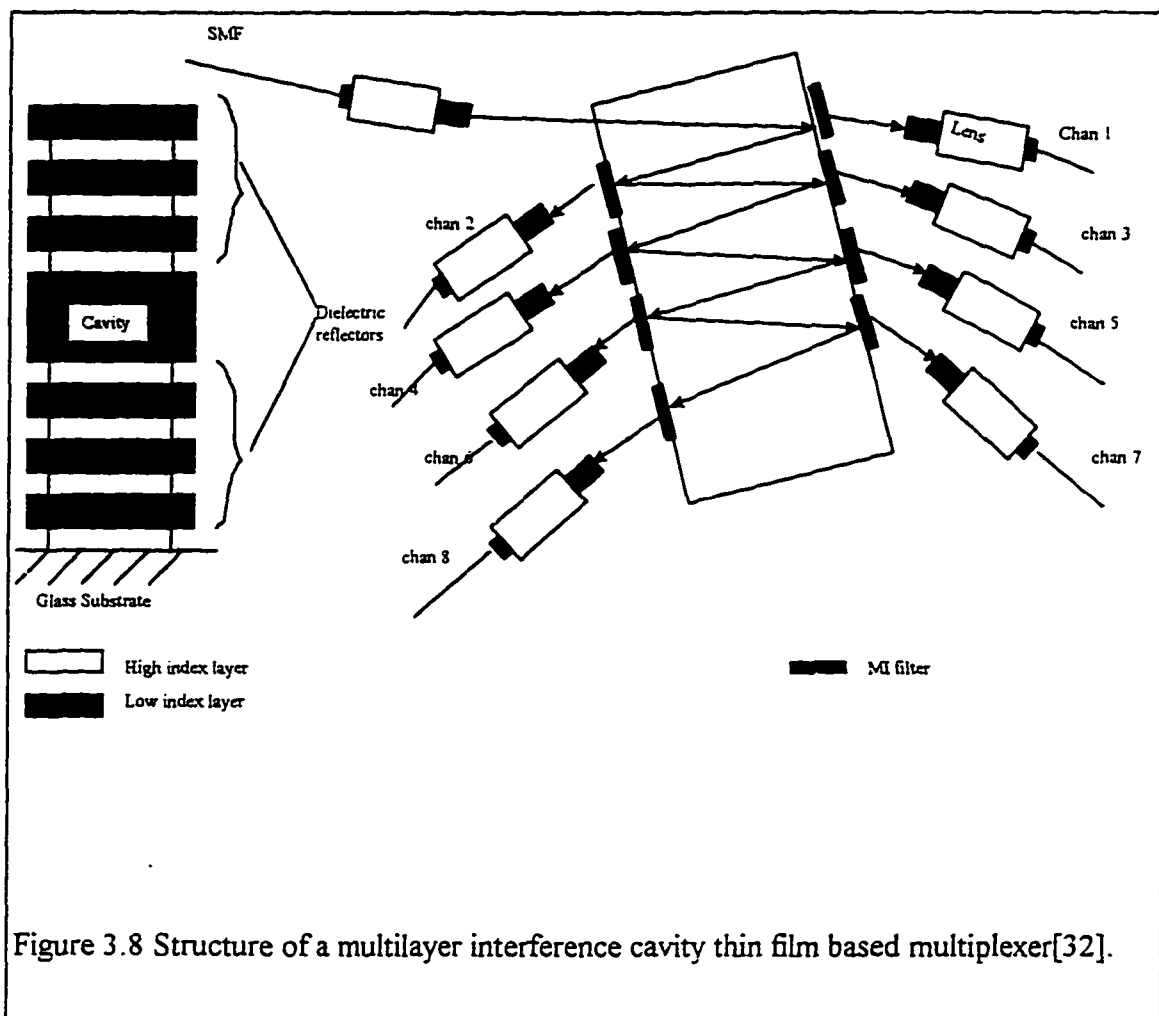


Figure 3.8 Structure of a multilayer interference cavity thin film based multiplexer[32].

The two WDM types are compared in Table 5-1. The advantage of MI over PAW type is that it doesn't require temperature control, which makes them simpler to use. Another advantage is the relatively lower insertion loss and the better crosstalk performance. In addition, a pair MUX/DEMUX can be designed and combined to give a flatter and lower insertion loss compared to the PAW. The PAW, on the other hand, has a periodical structure which makes it flexible to wavelength selection as long as the shift in wavelength falls within the WDM spectral range. They may be integrated with photodetectors for use

in array receivers[34], array transmitters, and have the ability to have large capacity multiplexers i.e. 16 and 32 wavelengths [35].

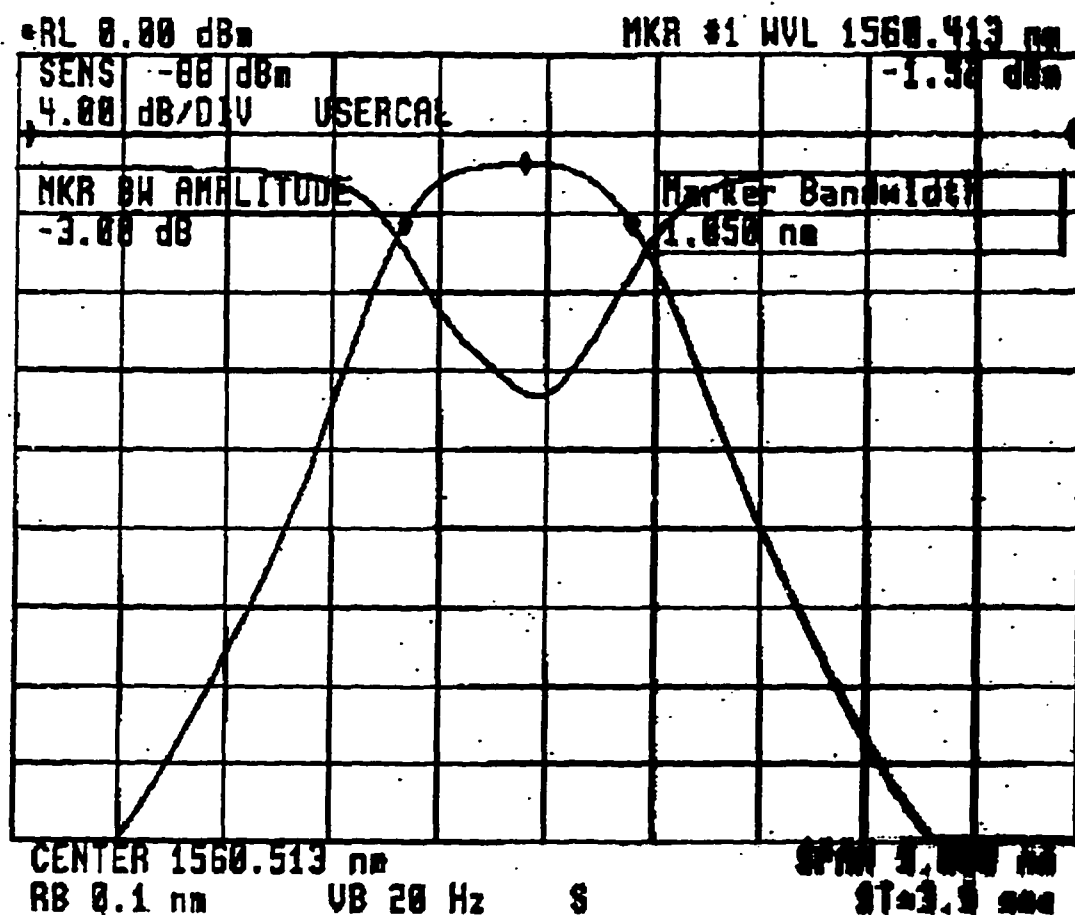


Figure 3.9 transmission and reflection of an MI filter.

### 3.2.3) Erbium Doped Fiber Amplifiers:

Optical amplifiers are used to overcome node to node losses arising from the splitters, filters, switches, and combiners. However, they also introduce amplified spontaneous emission noise which will ultimately limit network dimensions. Additionally, in a WDM

network it is important that the amplifier response is flat over the band of interest. Although an amplifier with aluminosilicate host glass can provide high optical gain in the wavelength range between 1.53 $\mu\text{m}$  and 1.56 $\mu\text{m}$ , its gain spectrum has a sharp peak at a wavelength of approximately 1.531 $\mu\text{m}$ , with a lower gain at longer wavelengths. When several such amplifiers are cascaded the overall gain difference is obviously unacceptable. An effective way to overcome this problem is to insert a bandstop filter within the length of the amplifier to suppress the peak at 1.531 $\mu\text{m}$ . Clearly the position of the filter is an important factor and an amplifier model was used to determine the optimum positioning of the filter from both a signal and noise point of view.

### Fundamentals of Fiber Amplifiers:

Erbium Doped Fiber Amplifiers(EDFA) are attractive for optical transmission systems because of their large usable bandwidth and high gain. However, they are characterized by a wavelength dependent, non-uniform gain[36]. EDFA can be modeled as two or three level system. Figure 3.10 shows a three level system energy diagram, where level 1 is ground state, 2 is the metastable level characterized by long lifetime  $\tau$ , and level 3 is the pump level.  $R_{13}$  is the pumping rate from 1 to 3, and  $R_{31}$  is the pump emission rate. Once ions are excited to the third level, there are two possibilities for decay: radiative

( $A_3^R = A_{32}^R + A_{31}^R$ ), and non-radiative decay ( $A_{32}^{NR}$ ), with  $A_{32}^{NR} \gg A_3^R$ .  $W_{12}$  and  $W_{21}$  are the stimulated absorption and emission rates respectively.  $A_2 = A_{21}^R + A_{21}^{NR}$  is the spontaneous radiative and non-radiative decay between level 1 and 2, with a predominant

radiative decay rate. With  $N_1$ ,  $N_2$ , and  $N_3$  being the fractional atomic densities at level 1, 2 and 3, the laser ions density is then :  $\rho$ , where  $\rho = N_1 + N_2 + N_3$ . The rate equations defining the 3 level system are:

$$\frac{dN_1}{dt} = -R_{13}N_1 + R_{31}N_3 - W_{12}N_1 + W_{21}N_2 + A_{21}N_2$$

Eq. 3.12

$$\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - A_{21}N_2 + A_{32}N_3$$

Eq. 3.13

$$\frac{dN_3}{dt} = R_{13}N_1 - R_{31}N_3 - A_{32}N_3$$

Eq. 3.14

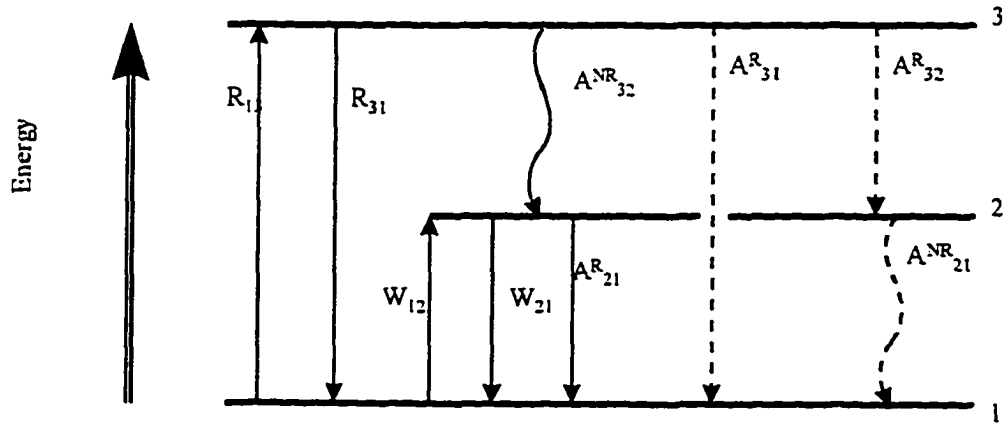


Figure 3.10 Energy level diagram corresponding to three-level system.

When a signal of intensity  $I_s$ , and at wavelength  $\lambda_s$  is launched into a lasing medium of thickness  $dz$ , it will undergo an intensity change  $dI_s$ , defined in Eq. 3.15, where  $\sigma_{12}$ ,  $\sigma_{21}$  are absorption and emission cross-section areas for the laser, and  $N_1$ , and  $N_2$  are the ground and upper level atomic populations. The gain coefficient is then defined by Eq. 3.16, where  $\sigma_{e,a}(\lambda_s)$  is the emission and absorption cross-section for the laser.

$$dI_s = \{\sigma_{21}(\lambda_s)N_2 - \sigma_{12}(\lambda_s)\}$$

Eq. 3.15

$$g = \sigma_e(\lambda_s)\{\eta(\lambda_s)N_2 - N_1\}; \quad \eta(\lambda_s) = \frac{\sigma_e(\lambda_s)}{\sigma_a(\lambda_s)}$$

Eq. 3.16

EDFAs modeling have been the subject of intensive study since the late 1980s, different modeling schemes have been analyzed [37,38,39]. Operating conditions under different pump wavelengths[40,41,42], pumping direction (i.e. forward, backward, or even bi-directional)[43], various fiber length[44], single stage and multistage[45].

A basic EDFA model consists of an Erbium doped single mode fiber, and a pump laser, either at 980 or 1480nm, to excite the erbium ions to high energy level for population inversion. Different architectures have been demonstrated for the single stage amplifier, as shown in Figure 3.11. The length of the fiber and the pump power required to operate the amplifier are parameters depending on the application requirements. A multiwavelength

mode of operation with large flattened bandwidth will require longer length comprising some signal gain. Multistage amplifiers are designed for large gain ( $G > 40\text{dB}$ ). Other systems requirements may impose restriction on the EDFA design, such as noise figure, for a cascaded chain of EDFAs[46].

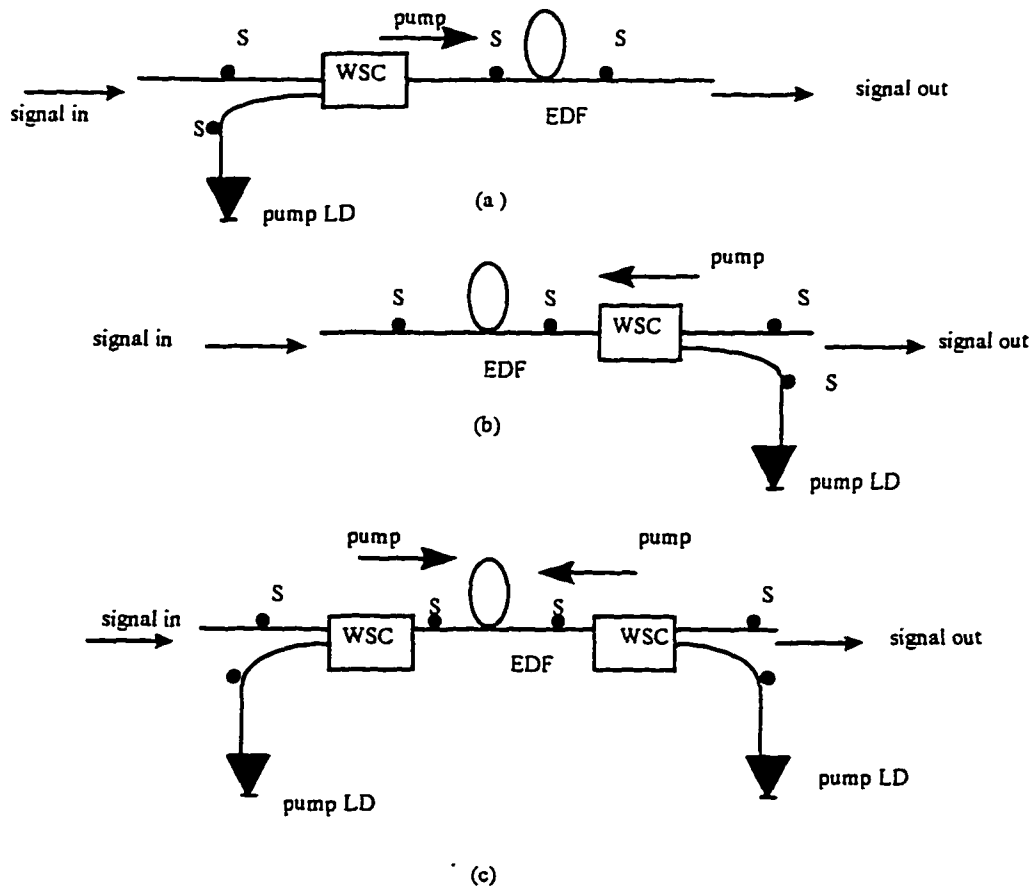


Figure 3.11 Basic EDFA device architectures: (a) forward pumping, (b) backward pumping, (c) bi-directional pumping. S: fiber splice, WSC :wavelength selective coupler, and EDF: erbium-doped fiber[36].

#### 3.2.4) Optical Switches:

Wavelength Division Multiplexed (WDM) optical network architectures require optical cross-connect switches to switch and route optical signals. Optical switches have several applications in fiber-optic communication systems. There the ON/OFF type used for passing or blocking light, the  $1 \times N$  switch used for output ports selection, and the  $N \times N$  or  $N \times M$  used for different combinations of input/output ports routing. These switching fabrics are used for protection switching against fiber cuts or components failure in WDM network, for traffic routing and for measurements in performance monitoring, and for Add/Drop application in WDM network element.

Mechanical switches are used to perform these operations. These switches are classified into two types: fiber moving type and optical component moving type. Connector moving type belongs to the first category, and is characterized by low insertion loss, since there are no other optical components inserted between the fibers. The second class of mechanical switches have prisms, mirrors or lenses as their moving parts. Advantages of mechanical switches are their wavelength independence, their low insertion loss ( $\sim 3\text{dB}$ ), their transparency to bit rate, and their, and their polarization independence. However, their large size makes them impractical for large system integration, and their slow switching speed (50 - 100ms) limits their applications.

In this work we will examine the fiber moving type mechanical switch fabric. It is a  $16 \times 16$  switch based on collimated beam alignment [47]. This switching fabric consists of two

piezoelectric bender elements connected in series to produce bidimensional movement. An optical fiber tip is attached to the benders free end and is movable in the focal plane of a lens. The emerging beam is collimated by the lens and is directable by determining the position of the fiber end.

Figure 3.12 shows the structure of this switch where several tens of transmitters, arranged in 2-D arrays, facing a similar array of receivers. This will be used to construct an optical cross-connect prototype. A detailed performance analysis will be made in chapter 5.

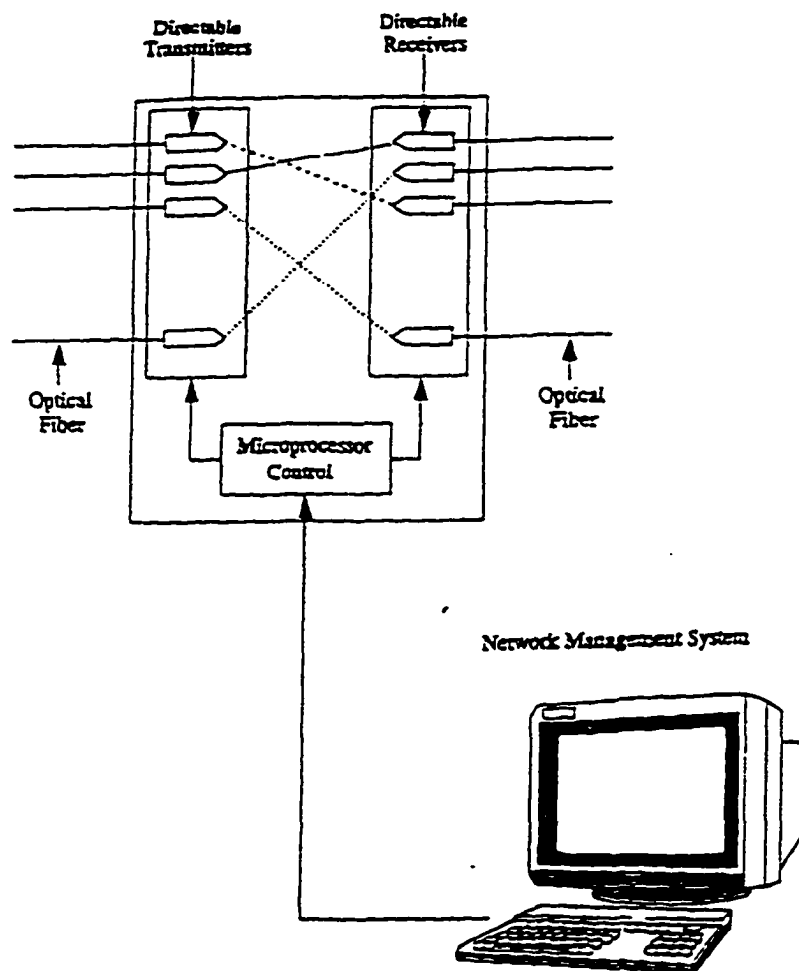


Figure 3.12 optical switch construction.

## **Chapter 4**

### **Performance analysis of individual components and their impact on overall system performance**

#### **4.1) Introduction**

In this chapter, we examine the performance of individual components of a WDM network element. Aspects investigated included the optical amplifier performance in multiwavelength system, the chirp induced by external modulators, and the narrowing of cascaded filter bandwidth.

#### **4.2) Design Approach for an optical network layer:**

The network design approach to be undertaken in this work, is based mainly on the study of system transmission in a ring architecture. Preliminary analysis of the end-to-end transmission path through a network comprising a number of interconnected nodes. Each node consists of a number of critical components in the path namely, the optical filter, the amplifier, the switch fabric and the combiners and splitters. All of these components affect the transmission performance and each required an individual study of their characteristics before incorporation into an end-to-end transmission model. Currently the switch matrix

under consideration is a passive one and hence is modeled only by its insertion loss; Future the model will be upgraded to include InP active switches to cater for the possibility of a lossless optical switch.

#### **4.3) Performance analysis/assessment of EDFA cascade with multiwavelength handling capabilities:**

A WDM ring circulating multiwavelength signals involves the cascade of several EDFAs. The amplifier performance is affected by the total input signal power; therefore, a change in that power due to loss of one or more signals, will alter the power of the remaining channels, in a way that could exceed the receiver's dynamic range. In addition, for a WDM network, it is desired that the amplifier response is as flat as possible over the signals band of interest. The next section will cover the major issues to be examined for multiwavelength operation.

##### **4.3.1) Introduction:**

We will develop an understanding of the various technological difficulties facing EDFA cascades with multiwavelength handling capabilities. Three related fundamental problems will be addressed:

- i) Gain control and WDM output stabilization: The amplifier response is dependent on total signal input power, thus, a loss of signals will result in an increase in

output power for the remaining signals that might exceed the receiver's dynamic range.

- ii) spectral gain non-uniformity or "gain equalization". This is one of the major remaining problems facing multiwavelength lightwave networks with fiber-amplifier cascades. When wavelength-multiplexed signals traverse a single amplifier, the individual channels experience various gains determined by the spectroscopy of the gain medium, the fiber length, and the signal and pump power levels. In a single amplifier, these spectral gain variations are generally modest, but they accumulate from stage to stage in a cascade, rapidly growing too large to allow adequate noise performance at the less-favored signal wavelengths .

- iii) noise accumulation in high data rate WDM repeater chain:

The main objective is to ensure sufficient gain flatness to permit amplifiers to be cascaded while maintaining acceptable inter channel power variations and signal-to-noise ratios at all wavelengths.

#### 4.3.2) EDFA's Gain Equalization:

WDM optical add-drop (W-ADM) multiplexers are of interest to construct high capacity self-healing WDM ring networks[3] in future optical transport network layers[48]. A key technical problem is compensating for the wavelength dependent gain of erbium-doped fiber amplifiers (EDFA) which will be needed within the W-ADM, to overcome the losses of the WDM components and the fiber attenuation between nodes on the ring. Several

solutions have been proposed to compensate for the non- flat EDFA gain, including the use of strongly inverted EDFAs[49], variable attenuators[50,[51], and gain compensating optical filters consisting of Mach-Zehnder interferometers[52]-[53]. The goal of our work was to demonstrate a gain-equalized, eight-wavelength W-ADM, and to measure the stability of the output signal levels against variations of input signal power, pump power, and input signal polarization.

### Experimental Results:

Figure 4.1 shows the W-ADM and the measurement set-up. The optical signals from eight DFB lasers spanning 1538-1558 nm were launched with equal powers into a single-mode fiber using 8x8 star coupler. The W-ADM consisted of a 1480 nm pumped EDFA, a grating-based WDM demultiplexer with 2.0 nm channel spacing, variable optical attenuators that were set to give equal output levels, and a multiplexer that combined the equalized output signals in the output fiber. The total signal power at the W-ADM input was adjusted using a variable attenuator at the output of the star coupler. For this experiment, the W-ADM was configured to pass through all eight signals in order to measure their outputs under various operating conditions. This is not a typical configuration in a network, since normally one or more wavelengths would be dropped and added by the W-ADM.

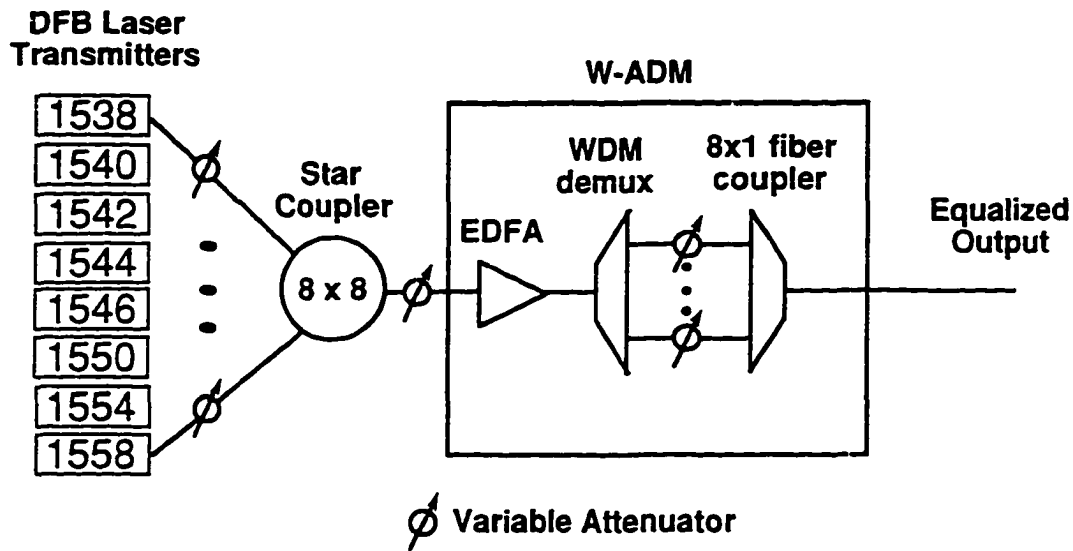


Figure 4.1 Experimental setup for gain equalization measurements

Figure 4.2 shows the equalized internal gain for each wavelength as a function of the total input power, with the maximum launched pump power of 27.5 mW(14.4 dBm). Each measured gain curve was offset by a fixed attenuation factor in the range 0 to 6.5 dB, such that the gain curves for all eight wavelengths had the same gain of 15 dB, which occurred at an input power level of -8.5 dBm.

Figure 4.3 shows the 6.5 dB range of signal powers in the unequalized EDFA output. For an input power level of -8.5dBm, the EDFA was saturated by 9 dB in the wavelength range of 1538-1560 nm, as indicated by the 9 dB reduction in the ASE relative to the ASE power spectrum obtained with no input signals.

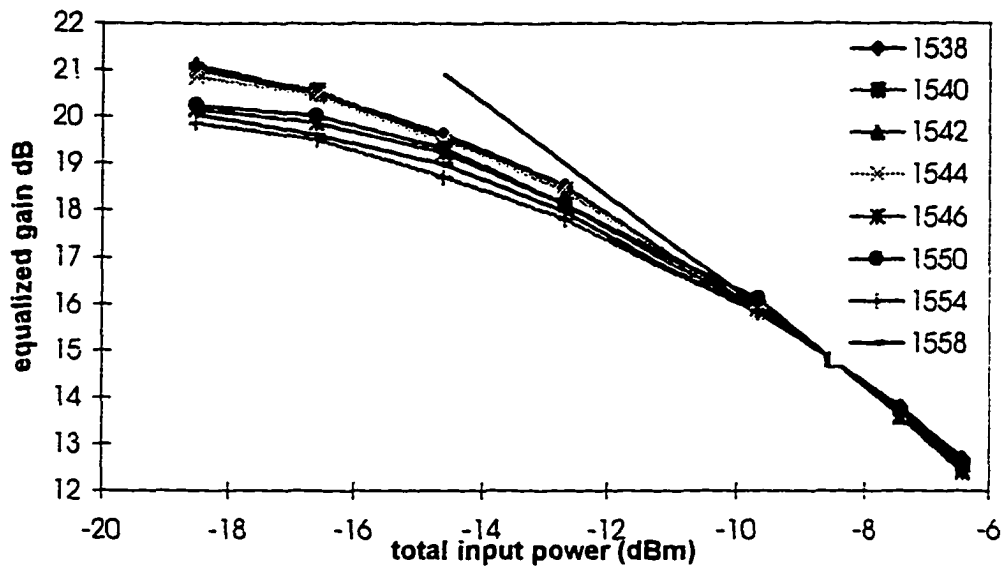


Figure 4.2 Equalized internal gain of eight wavelengths versus signal input power, for a pump of 27.5 mW.

Figure 4.4 shows the output signals which were equalized to within  $\pm 0.1$  dB, by adjusting the attenuators.

With the attenuators fixed, the gains at all eight wavelengths remained equalized to within 1.2 dB, even though the total input power was varied by 12 dB, as shown in Figure 4.2.

The optical signal to noise ratios in a 0.1 nm bandwidth were greater than 20 dB, over the 12 dB range of total input power. Assuming a minimum gain of 15 dB, the spectral gains were equalized to within 1 dB over 8 dB range of the total input power, although output

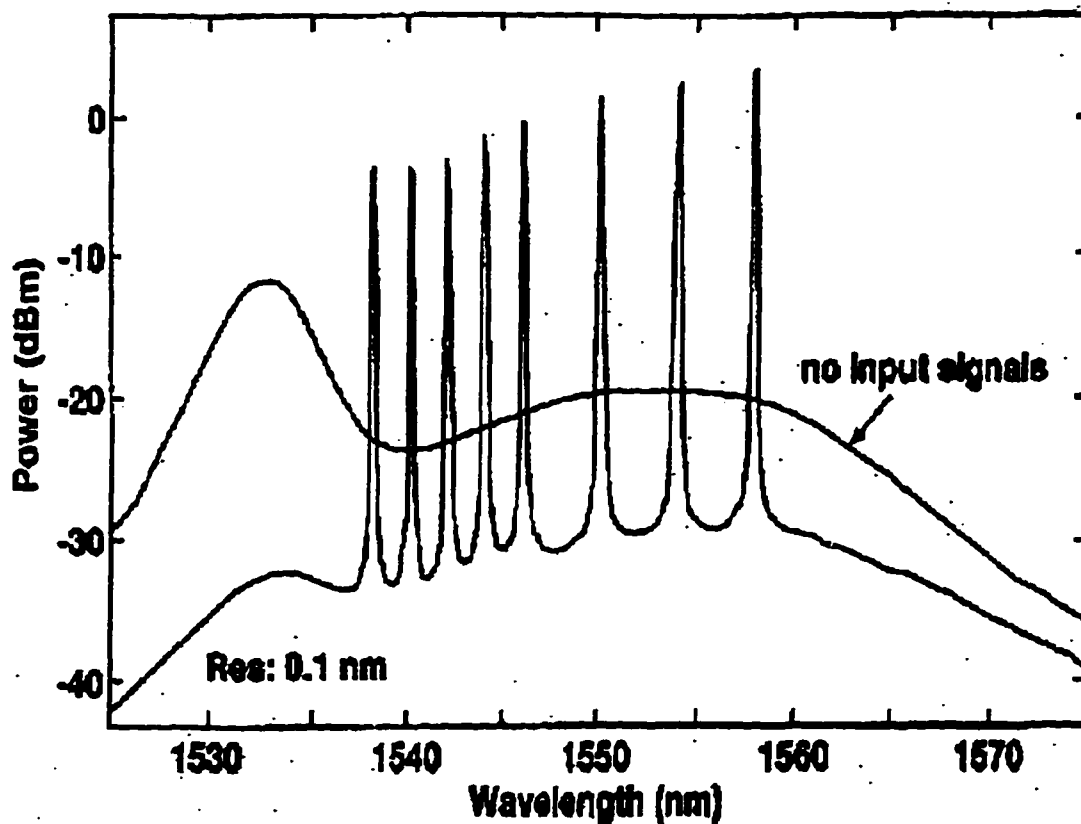


Figure 4.3 EDFA output with and without input signals,  $P_p = 27.5\text{mW}$ ,  $P_{\text{tot}} = -8.5\text{ dBm}$ .

power levels drop at lower input power levels. By operating the amplifier in saturation with total input power greater than  $-12.6\text{ dBm}$ , the individual output powers of all 8 wavelengths were constant to within  $1\text{ dB}$  over a  $6\text{ dB}$  range of input power. We also examined experimentally the case of inter-channel power variations. For example, removing any one channel entirely had the same effect as reducing by one eighth the total

input power in all eight channels. Thus the saturation of the EDFA depends on the total input power, but not the wavelengths of the saturating signals.

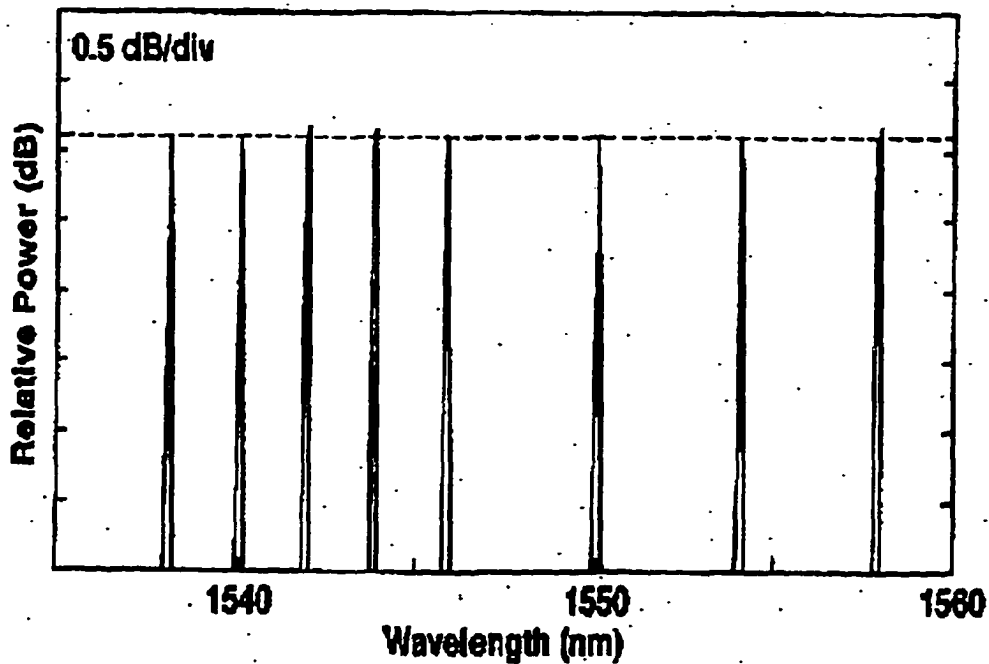
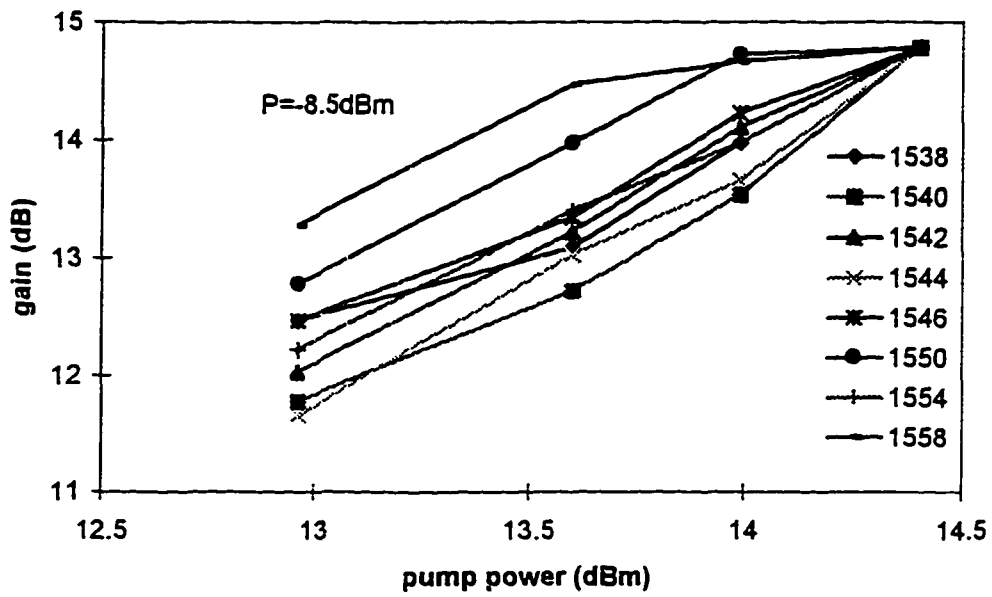


Figure 4.4 Optical spectrum measured at the output of the W-ADM showing the eight equalized output signals.

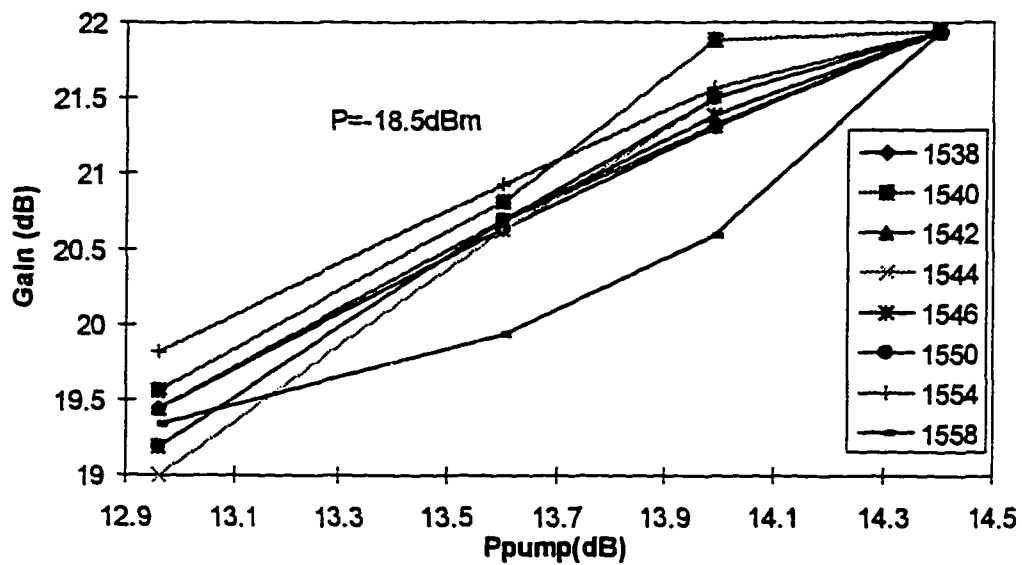
Figure 4.5 (a) shows the gain variation of each wavelength as function of pump power degradation. The eight wavelengths were equalized with a total input power of -8.5 dBm and pump power of 14.4 dBm. A 1.4 dB reduction in pump power produced a 1.8 dB in gain variation. At a lower input signal power of -18.5 dBm, we observed less than 1 dB in

gain variation for 1.4 dB of pump reduction, as shown in Figure 4.5 (b). However, at this low input power level, the output signal powers were reduced by 4 dB, and the lowest optical SNR values of 20 dB were obtained for each channel.

Polarization dependent losses (PDL) of the optical components in the W-ADM converted input signal polarization fluctuations into output power variations. To examine the effect of polarization on the equalization of the output signals, we introduced a polarization controller at the input of the W-ADM. The output power of each channel varied independently by 1.6 dB as the polarization controller was adjusted. We chose the weakest output signal, and determined its range of output power due to polarization fluctuations, as shown by the dashed lines in Figure 4.6. Then for each channel the input polarization state was adjusted for maximum throughput and its power was attenuated to the level of the upper edge of the 1.6 dB band. With this procedure, we ensured that the output powers for all eight wavelengths varied over the same 1.6 dB range. However, if the attenuators had been set to equalize the output power levels without regard to input polarization, then a larger spread of 3.2 dB in output powers could have occurred. As a worst case, consider two input signals  $S_1$  and  $S_2$  whose input polarization states correspond to minimum and maximum PDL, respectively. Assume the two output signals are equalized to the same value  $P_1 = P_2 = P_{out}$ . As the input polarization fluctuates with time,  $P_1$  would vary between  $P_{out}$  and  $P_{out} - 1.6$  dB, whereas  $P_2$  would vary between  $P_{out}$  and  $P_{out} + 1.6$  dB. In the worst case the difference between  $P_1$  and  $P_2$  would be 3.2 dB. The observed polarization-induced power fluctuations of 1.6 dB can be largely accounted for



(a)



(b)

Figure 4.5 Equalized internal gains at eight wavelengths vs. Pump power, for total input signal of power (a)-8.5 dBm, (b) -18.5dBm.

from the measured PDL's of the various optical components: WDM demux: 0.7 dB; optical isolator: 0.4 dB; optical spectrum analyzer: 0.3 dB; EDFA WDM coupler: 0.2 dB.

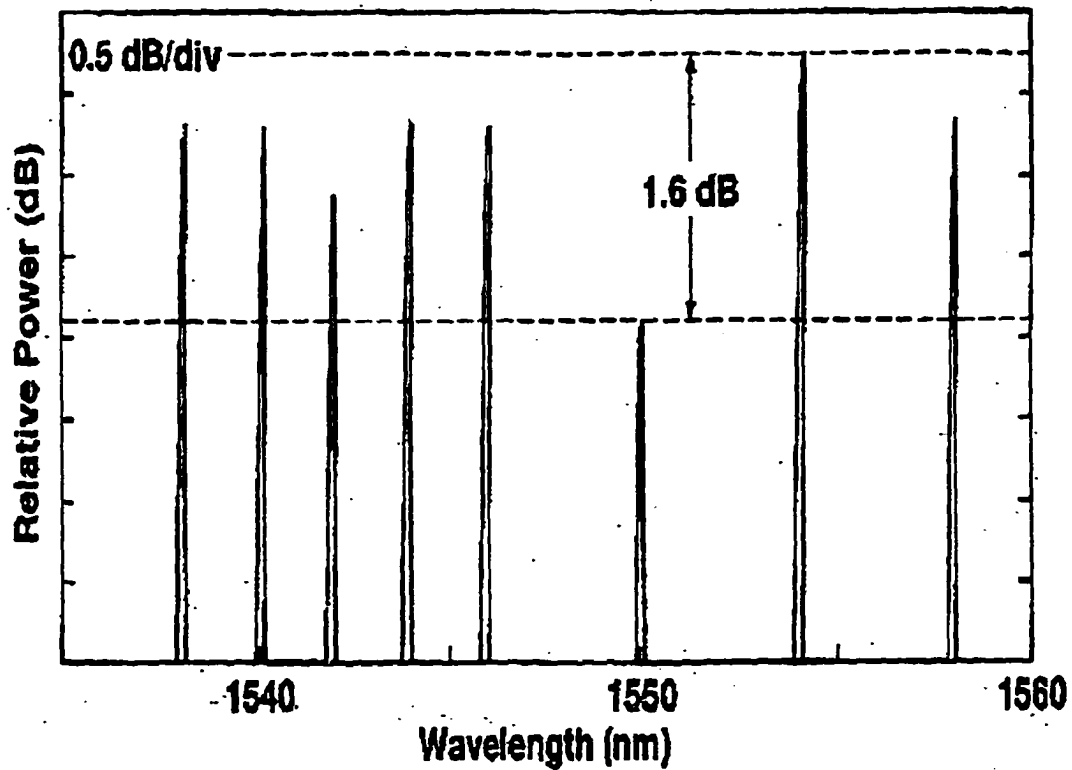


Figure 4.6 Optical spectrum measured at the output of the W-ADM, showing 1.6 dB power variation due to random polarization states among the 8 signals.

The performance of a gain equalized, eight wavelength W-ADM has been measured. By operating the EDFA in 9 dB saturation, the gain variations and output power levels were relatively insensitive to the input signal power. However, the output power levels were more strongly affected by pump power degradation and by the PDLs of the optical

components in the W-ADM. The polarization effect cannot be equalized by fixed attenuators since it is a time dependent effect, indicating the need to use optical components designed for minimum PDL. Otherwise the cumulative PDL through a WDM network with many optical components would result in unacceptably large power fluctuations which occur randomly with time. As signals gain and power levels are equalized, another problem rises: the stability of these signals as individual channels are lost due to system failure.

#### 4.3.3) Gain control and WDM output stabilization of EDFA:

A serious problem for WDM networks is the wavelength-dependent gain saturation of the EDFAs. Because of this effect, the loss or removal of one or more channels at the input of an EDFA can cause large changes in the output powers of the remaining channels. Gain clamping [54] and channel equalization [53,55] have been shown to be effective methods to stabilize the WDM output of the EDFAs. As an alternative solution, we have investigated EDFA gain control under multiwavelength operation, comparing three different methods: 1) pump power control [56], 2) adding a co-propagating control signal [57], and 3) adding a counter-propagating control signal. Previously refs. [56,57] demonstrated the effectiveness of these gain control techniques for single channel operation. We will also introduce a new technique to achieve stabilized EDFA performance, based on deeply saturating the amplifier, and not requiring feedback circuitry.

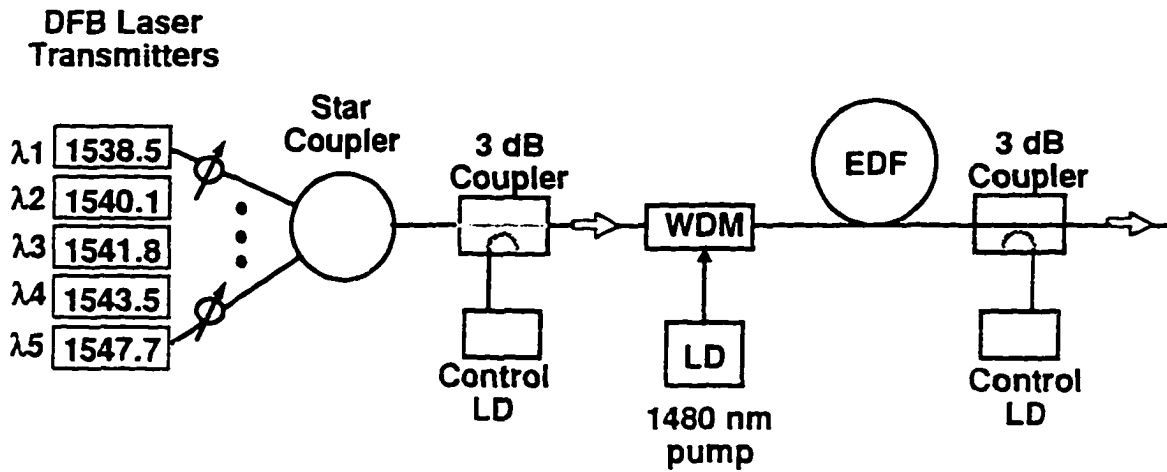


Figure 4.7 Experimental setup for gain stabilization employing control signals.

#### Comparison of three stabilization techniques:

Figure 4.7 shows the experimental setup for the pump power control method. Five signals equalized to -22dBm per channel, at wavelengths ranging from 1538.5nm to 1547.7nm, were launched into the EDFA. The maximum pump power coupled into the EDFA was 15.3 dBm. The saturated gain of the amplifier was 18.6dB at 1538.5nm and 20.5dB at 1547.7nm. The small signal gains were about 5 dB higher.

Table 4-1 shows the change in the WDM output power levels when one or more channels was removed from the input. The first row of the table shows the desired output levels at the maximum pump power of 15.3 dBm. The lower rows list the resultant power levels, when one or more input signals were removed, with constant pump power of 15.3 dBm. The last column gives the adjusted pump power needed to restore output signals to their original levels listed in the first row.

Table 4-1 EDFA WDM outputs with and without pump control.

| $\lambda_{\text{lost}}$                      | $P(\lambda_1)$ dBm | $P(\lambda_2)$ dBm | $P(\lambda_3)$ dBm | $P(\lambda_4)$ dBm | $P(\lambda_5)$ dBm | $P_{\text{pump}}$ (dBm) |
|----------------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-------------------------|
| —                                            | -3.44              | -2.89              | -3.42              | -2.72              | -1.5               | 15.3                    |
| $\lambda_1$                                  | —                  | -2.59              | -3.36              | -2.69              | -1.42              | 14.9                    |
| $\lambda_1, \lambda_2$                       | —                  | —                  | -2.58              | -1.92              | -0.89              | 14.5                    |
| $\lambda_1, \lambda_2, \lambda_3$            | —                  | —                  | —                  | -1.5               | -0.39              | 13.9                    |
| $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ | —                  | —                  | —                  | —                  | +0.44              | 13.6                    |

In the second gain control method, we added a co-propagating control channel ( $\lambda_6$ ) whose power was adjusted to offset any change in input power due to the loss of one or more of the 5 signal channels. For simplicity, a 3dB coupler at the EDFA input was used to combine the control signal at 1559.4nm with the 5 multiplexed output signals. With this arrangement, the input signal power was reduced to by the 3 dB coupler to -25 dBm per channel. The control signal power was adjusted to keep total input power into the amplifier fixed independent of the loss of any channels. This constant total signal power will ensure stability of the remaining WDM signals. Without the control signal, output power variations as large as 2 dB results from the loss of one or more channels, as shown in Table 4-2. The last column in the table gives the control signal power needed to stabilize the outputs of the remaining channels to within  $\pm 0.1$  dB.

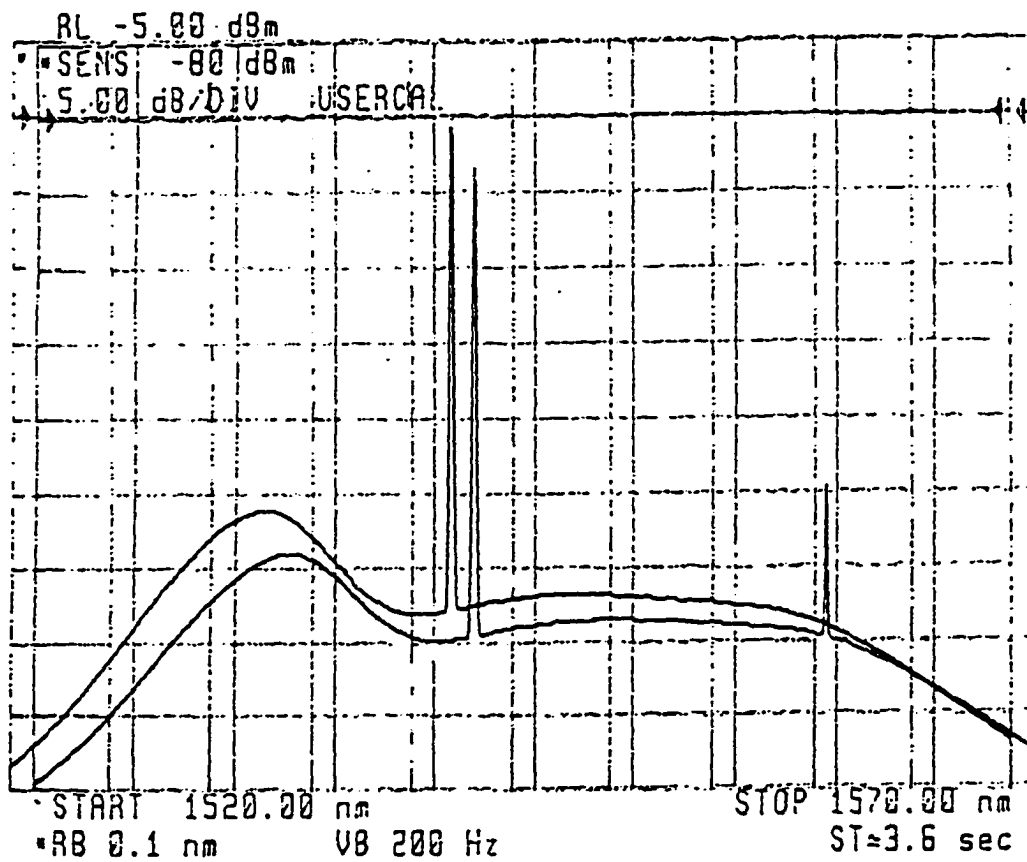


Figure 4.8 Spectrum of one surviving channel, when four out of 5 are dropped, employing Counter-propagating control signal technique for gain stabilization

Table 4-2 EDFA WDM outputs with and without co-propagating control signal.

| $\lambda_{\text{lost}}$                      | P( $\lambda_1$ ) dBm | P( $\lambda_2$ ) dBm | P( $\lambda_3$ ) dBm | P( $\lambda_4$ ) dBm | P( $\lambda_5$ ) dBm | P( $\lambda_6$ ) dBm |
|----------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| —                                            | -4.7                 | -5.3                 | -6.79                | -4.69                | -3.67                | —                    |
| $\lambda_1$                                  | —                    | -4.83                | -6.03                | -4.23                | -3.57                | -24.84               |
| $\lambda_2, \lambda_3$                       | -4.13                | —                    | —                    | -4.0                 | -3.37                | -22.06               |
| $\lambda_1, \lambda_2, \lambda_3$            | —                    | —                    | —                    | -3.63                | -2.27                | -19.84               |
| $\lambda_1, \lambda_2, \lambda_3, \lambda_5$ | —                    | —                    | —                    | -2.67                | —                    | -18.63               |

In the third method, the control channel was launched in a counter propagating direction, using a 3dB coupler at the EDFA output. Table 4-3 shows the variation in output levels when one or more input channels are removed and the power needed by the control channel to restore the remaining signals to their original status. Figure 4.8 demonstrates the effectiveness of this technique, as it clearly shows that the surviving channel recovers to within  $\pm 0.2$  dB in the presence of the control signal.

Table 4-3 EDFA WDM outputs with and without counter-propagating signal.

| $\lambda_{\text{lost}}$                      | P( $\lambda_1$ ) dBm | P( $\lambda_2$ ) dBm | P( $\lambda_3$ ) dBm | P( $\lambda_4$ ) dBm | P( $\lambda_5$ ) dBm | P( $\lambda_6$ ) dBm |
|----------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| —                                            | -3.97                | -4.4                 | -3.69                | -2.86                | -1.86                | —                    |
| $\lambda_1$                                  | —                    | -4.03                | -3.22                | -2.72                | -1.33                | -18.02               |
| $\lambda_1, \lambda_4$                       | —                    | -3.31                | -2.68                | —                    | -0.78                | -16.53               |
|                                              | —                    | -2.31                | -1.91                | —                    | —                    | -15.08               |
| $\lambda_1, \lambda_2, \lambda_4, \lambda_5$ | —                    | —                    | -1.08                | —                    | —                    | -14.17               |

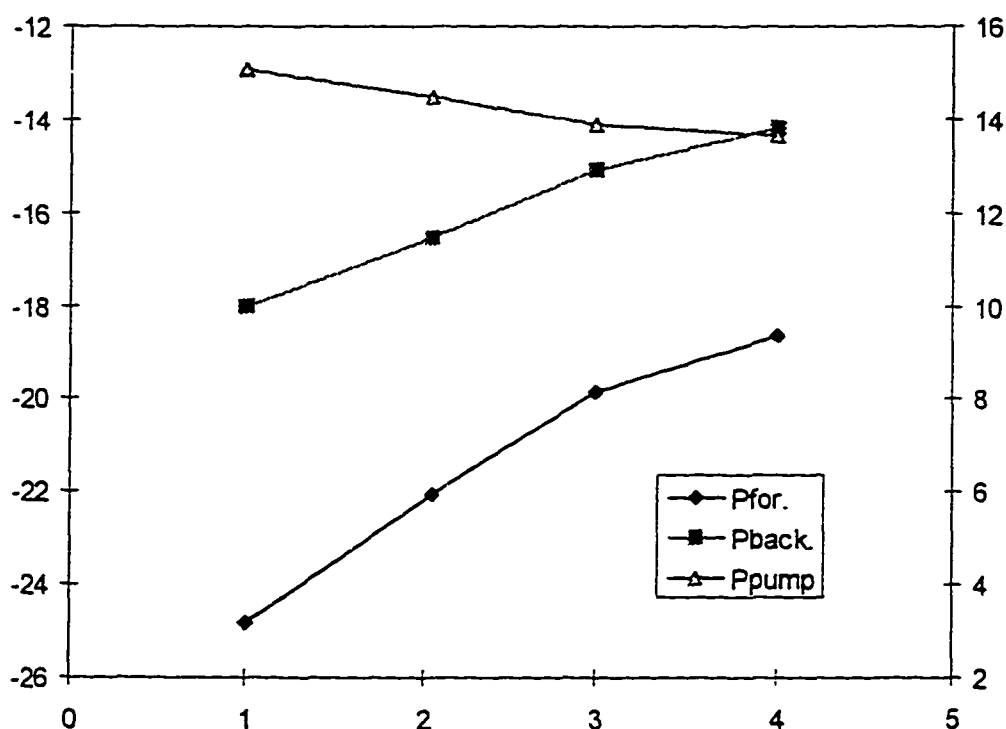


Figure 4.9 Power needed for control signal in co- and counter-propagating directions, and for 1480nm pump to stabilize WDM output levels.

Figure 4.9 summarizes the results of these three gain control methods. Very precise control of the pump power over a small range of 1.7 dB was needed to keep the gain constant with the loss of one to four channels. This result reflects the sensitive dependence of the EDFA's gain on the pump power. The EDFA gain was less sensitive to the control signal power, for both co- and counter-propagating configurations. In addition, the low absolute power levels for the control signal, in the range of -15 to -10 dBm, suggests that

one laser could be used to provide control signals for several EDFAs within a WDM network element.

### **Novel Stabilization Technique**

When studying the stability of the EDFA, as channels are lost, not only the static increase in power of the surviving channel(s) is of importance, but the transient response of the amplifiers as well. Recent studies [58] have shown that the dynamic response of cascaded chains amplifiers is much faster than single EDFAs. Therefore fast detecting and recovery time on the feedback circuit, is required to be about 4 $\mu$ s. As a simple solution, we are in the process of showing that operating the EDFA in deep saturation, sacrificing some gain, would alleviate that requirement by eliminating the need for feedback control.

A saturating channel was employed for that purpose. Transient response for this scheme was measured by modulating a strong signal by a square pulse, and examining the change of power in a second weak signal [59]. The experiment was done using two signals, one weak representing one channel of -13dBm, and another signal with level of -4.5dBm, equal to the seven remaining signals for an 8 wavelength transmission system. A CW saturating signal was applied, resulting in 6 dB reduction in gain for the data channels, as illustrated in Figure 4.10. This figure represents a comparison of the penalty paid in output power when saturation is employed versus normal operation. The dotted spectrum shows the output of the two signals, strong and weak, with total power corresponding to 8

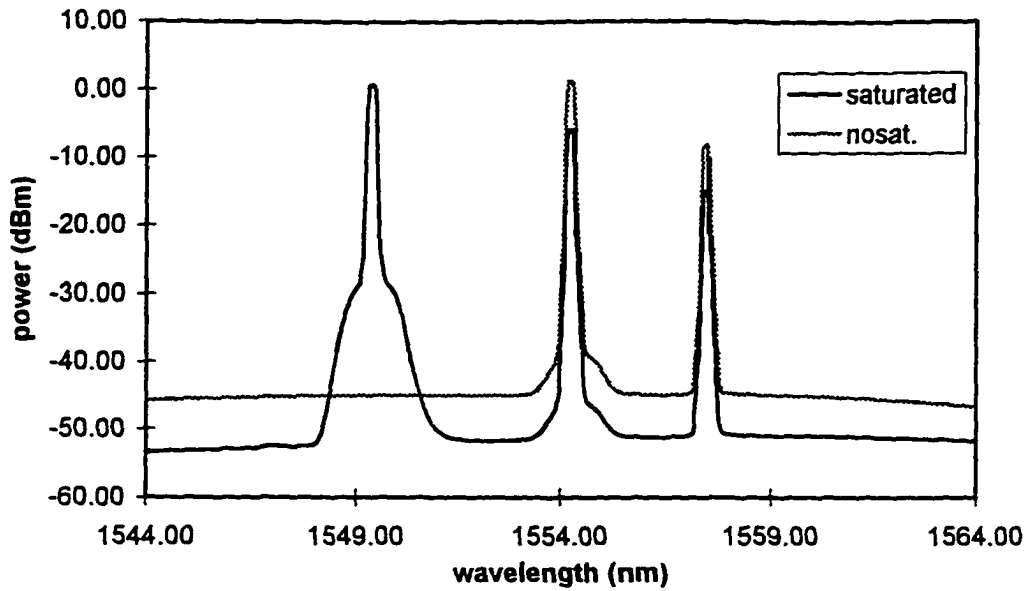


Figure 4.10 the spectrum of transmission simulating 8 channels, when no saturation applied and the case when saturation is used. 6dB in output power is lost.

signals of -13dBm each. The straight line spectrum illustrates the reduction in signals output power to about 6dB, when a strong saturating signal of 1dBm is applied at the input of the first amplifier. However, in this way when seven channel were lost, only 1dB in gain increase was observed for the surviving weak signal.

Loss of signals in a WDM system could occur due to reconfiguration at the routers, laser failure or to drop and add operation for a very short time. This loss is translated into reduction in total input power to the amplifier, which would result in an increase in surviving signal output levels, keeping the amplifier total power constant. Figure 4.11 summarizes what happens when seven signals are removed and one survives for two cases. One case involving a saturating signal to achieve gain stabilization, and another without

resort to any control scheme. For the uncontrolled case, the remaining channel increases by 13dB, whereas the stabilized regime signal increases only by one dB.

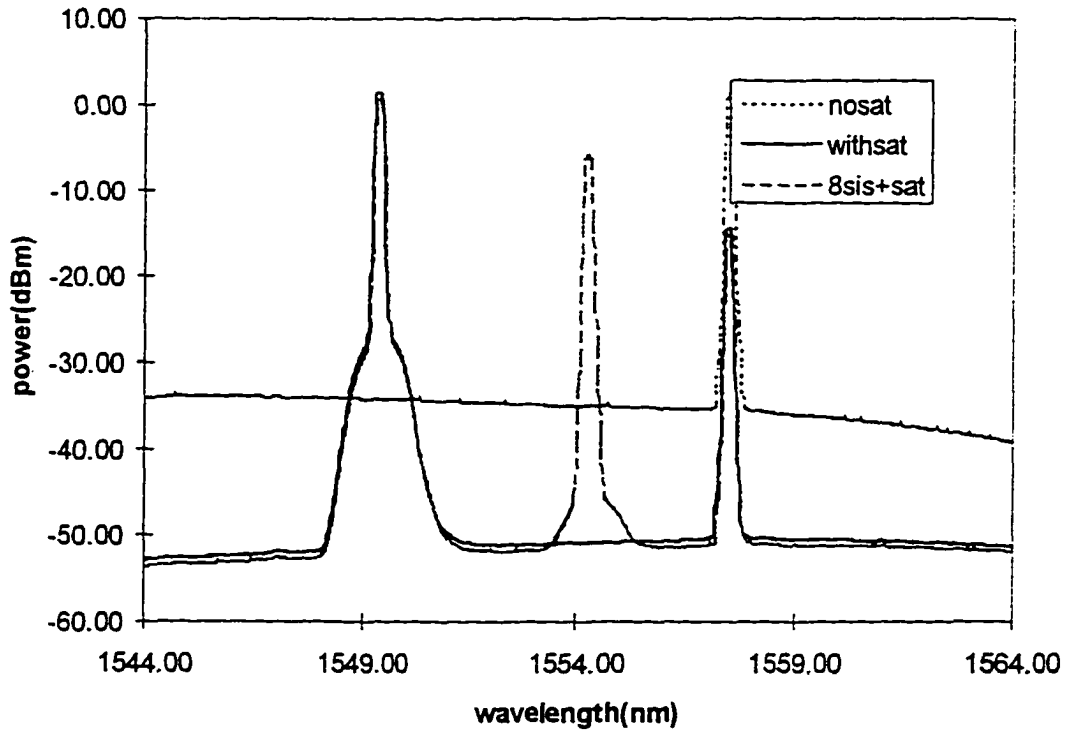


Figure 4.11 applying a saturating signal and observing the impact of dropping 7 channels on the system.

The setup in Figure 4.13 was used to measure the transient response for 2 Network elements (NE) involving 3 EDFAs. Channel 4 (from the MONET set of wavelength, 1554.13nm) was modulated was modulated by a square pulse with  $T=200\text{ms}$ . The transient response was then measured for the 2 cases analyzed in the previous section. The stabilizing CW signal is multiplexed into the transmission system, hence one laser source is needed to supply it. The signal levels are

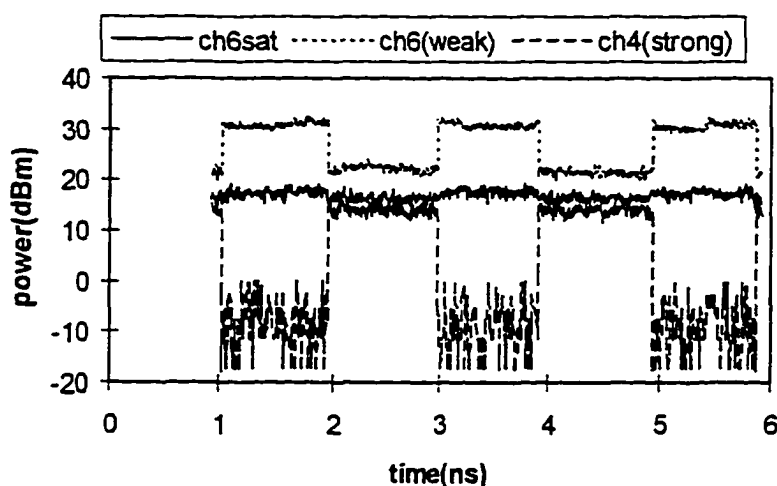


Figure 4.12 transient response for pulse width of 100ms.

equalized using variable attenuators, which would remain intact once set, if stabilization schemes are employed. The signal response in Figure 4.12 shows a 1dB increase in the surviving signal when 7 are lost, if the amplifier is stabilized, compared to 10dB otherwise. Recent publications showed interest in link stabilization versus individual amplifier control[60,61 ]. A link would consist of a

chain of EDFAs cascaded in a point-to-point transmission, or between switching fabrics. For this scheme, a single channel is used to maintain a constant total input power to the first amplifier in the link.

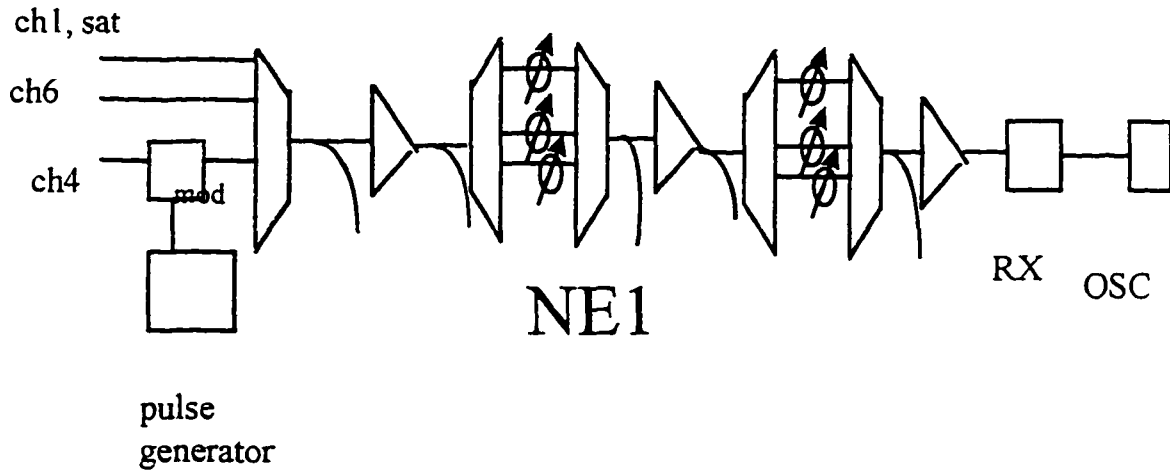


Figure 4.13 setup used to measure transient response for 3 EDFAs in a WDM system.

#### 4.4) External modulation chirp and laser frequency misalignment and their impact on the overall WDM ring network performance.

Chirp poses limitations on WDM signals at high bit rate, and can ultimately limit achievable system performance. The combination of the chirp and the chromatic dispersion of standard single mode fiber can cause a performance penalty for high-speed systems operating at  $1.55\mu\text{m}$  wavelength region, as the leading and trailing edges of a pulse spread away from the pulse center [62]. This problem is more

severe when using direct modulation. For our system, we are using external modulation to alleviate the effect of chirping. However, external modulation doesn't eliminate the chirp completely. This problem will be studied in a ring configuration in chapter 5, where two bit rates, 2.5 and 10 Gb/s, were used to evaluate the system performance and penalty induced by wavelength misalignment, for different chirp conditions .

#### **4.5) WDM Cross-connects and its impact on the WDM ring network transmission performance**

##### **Importance of cross-connects**

Wavelength selective cross-connect (WSXC) switches are attractive to provide reconfigurable wavelength routing of signals in broadband optical networks [63]. Several WSXC architectures have been evaluated [64], which combine WDM de/multiplexers with optical space division switch fabrics. The choice of the optical space switch fabric is determined by optical characteristics such as attenuation, crosstalk, polarization dependent loss, polarization dispersion, and switching speed. In addition, strictly non-blocking space switching capability is often required. Coherent crosstalk has been identified [65,66] as one of the key characteristics in performance specifications of WSXC network elements and WDM network design.

## Configuration of a prototype WSXC

Figure 4.14 shows the architecture of the prototype 8-wavelegnth, 8x8 WSXC evaluated in this work. Each multiwavelength fiber input and output included an EDFA and an 8 channel WDM de/multiplexer. Variable optical attenuators were used for WDM channel equalization. DFB lasers with a frequency spacing of 200GHz, with channel 3 at 193.1 THz (1552.524nm), were used to provide 8 WDM test signals at all inputs of the WSXC. The optical space switch fabric consisted of arrays of steerable collimated optical beams [67]. This type of space switch fabric technology has several attractive performance characteristics, including strictly non-blocking switching, insertion loss <3.5dB, polarization dependent loss <0.1dB, and optical crosstalk  $\alpha$ <-75 dB. For comparison, the optical crosstalk levels for integrated 8x8 space switch fabrics are much higher, typically  $\alpha$ >-35dB. In this work, the space switch fabric was partially populated with a 16x16 space switch which was partitioned as two 8x8 space switches to provide cross-connections for channels 1 and 2 only. However, this configuration was sufficient to evaluate the coherent crosstalk levels due to the 8x8 space switch fabric, which would be the same for each wavelength . A complete WSXC, as shown in Figure 4.14, would use a total of eight 8x8 space switch fabrics, one for each of the 8 wavelengths. Eight DFB lasers with a frequency spacing of 200 GHz, with channel 3 at 193.100 THz (1552.524), were used to provide identical WDM test signals at all eight multiwavelength fiber inputs of the WSXC. This insured that all inputs to a particular 8x8 space switch had the same wavelength, in order to maximize coherent crosstalk effects.

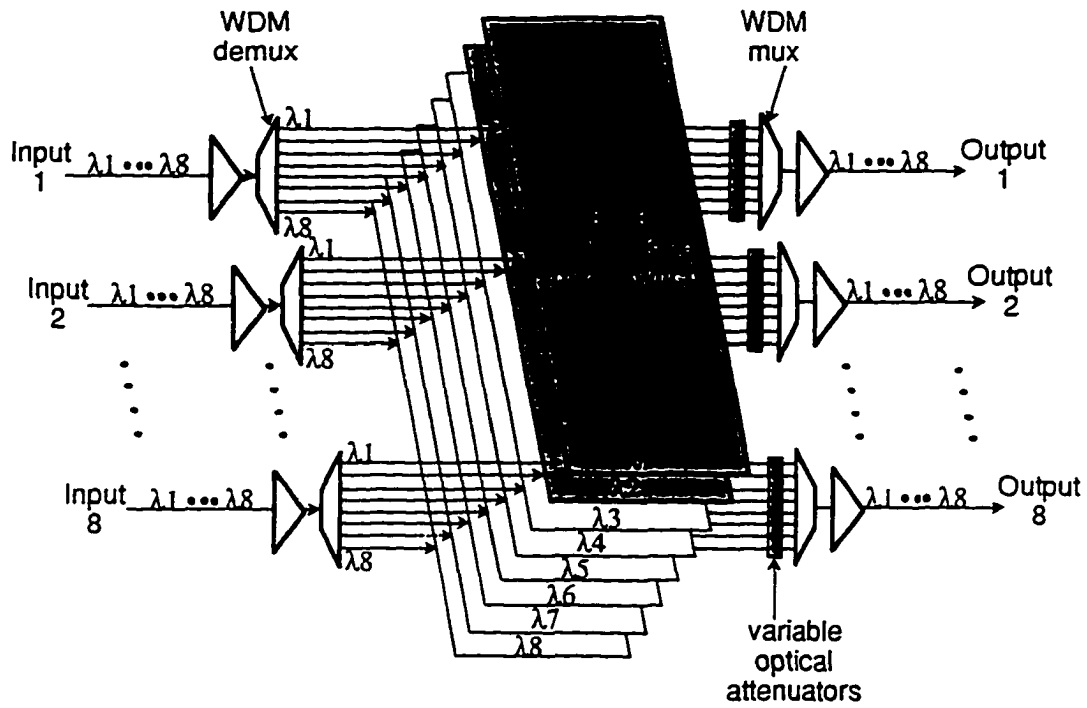


Figure 4.14 Architecture of an 8-wavelength, 8x8 wavelength selective cross-connect.

#### Determination of Coherent Crosstalk Power level for the 8-λ, 8x8 WSXC

Coherent crosstalk is generated in the WSXC by crosstalk in the 8x8 space switch fabric and by the crosstalk of the optical filters. At each output of an 8x8 space switch fabric, there are 7 possible coherent crosstalk signals with crosstalk level denoted by  $\alpha$ . For an 8 channel WDM demux/mux pair there are also 7 possible coherent crosstalk signals with crosstalk level  $\epsilon^2$ , where  $\epsilon$  is the crosstalk of a single filter. The maximum coherent

crosstalk of an 8 wavelength 8x8 WSXC is approximated by:  $7\alpha + 7\epsilon^2$  . Based on the experimentally measured values of  $\alpha < -75\text{dB}$  and  $\epsilon < -30\text{ dB}$ , the maximum coherent crosstalk power level of this experimental 8 wavelength 8x8 WSXC is estimated to be  $< -50\text{ dB}$ .

### Experimental Results

Transmission through a network of eight 8x8 WDM cross-connects was evaluated by

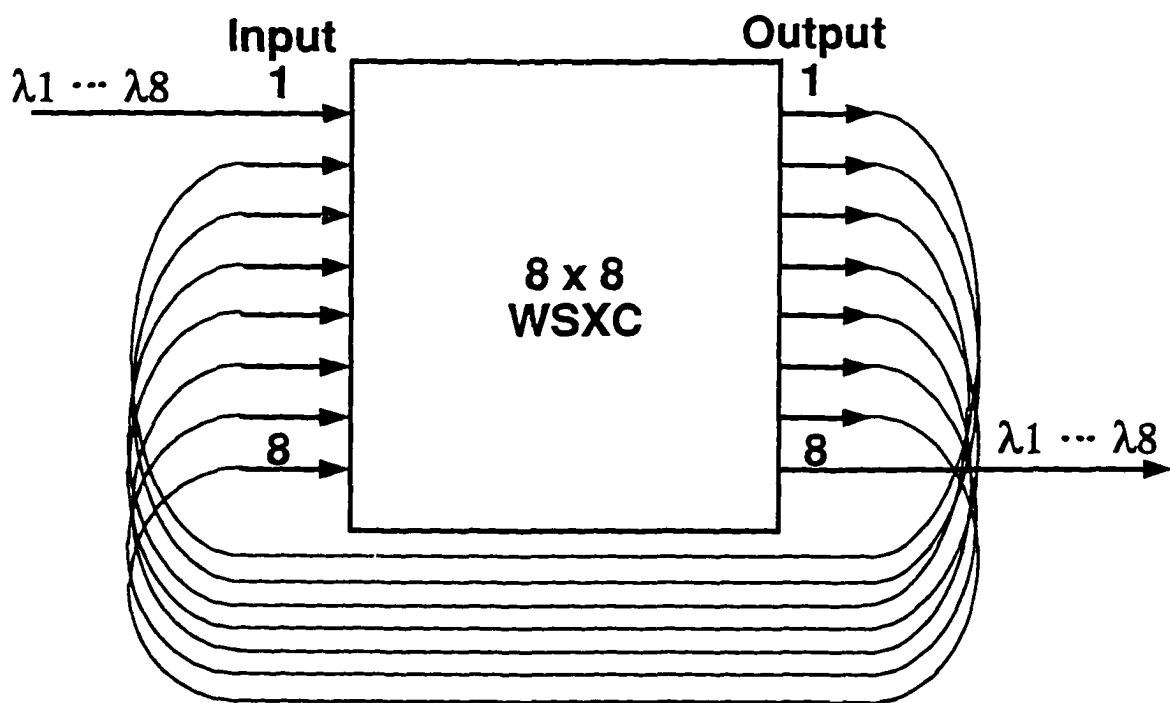


Figure 4.15 Transmission through a network of 8x8 WDM cross-connects(WSXC) was evaluated by routing a 2.5Gb/s signal at  $\lambda_1$  eight times through the WSXC.

routing a 2.5Gb/s signal at  $\lambda_1$  eight times through the same WSXC as shown in Figure 4.15.

The receiver included an EDFA optical preamplifier and a WDM demultiplexer to select the signal at  $\lambda_1$ . The BER penalty was less than 0.5dB after 8 passes through the experimental WSXC, as shown by the Bit-Error-Rate (BER) data in Figure 4.16. BER measurements were also made at  $\lambda_1$  after one pass through the WSXC with reconfiguration of the remaining space switch connections every 2 seconds. There was no

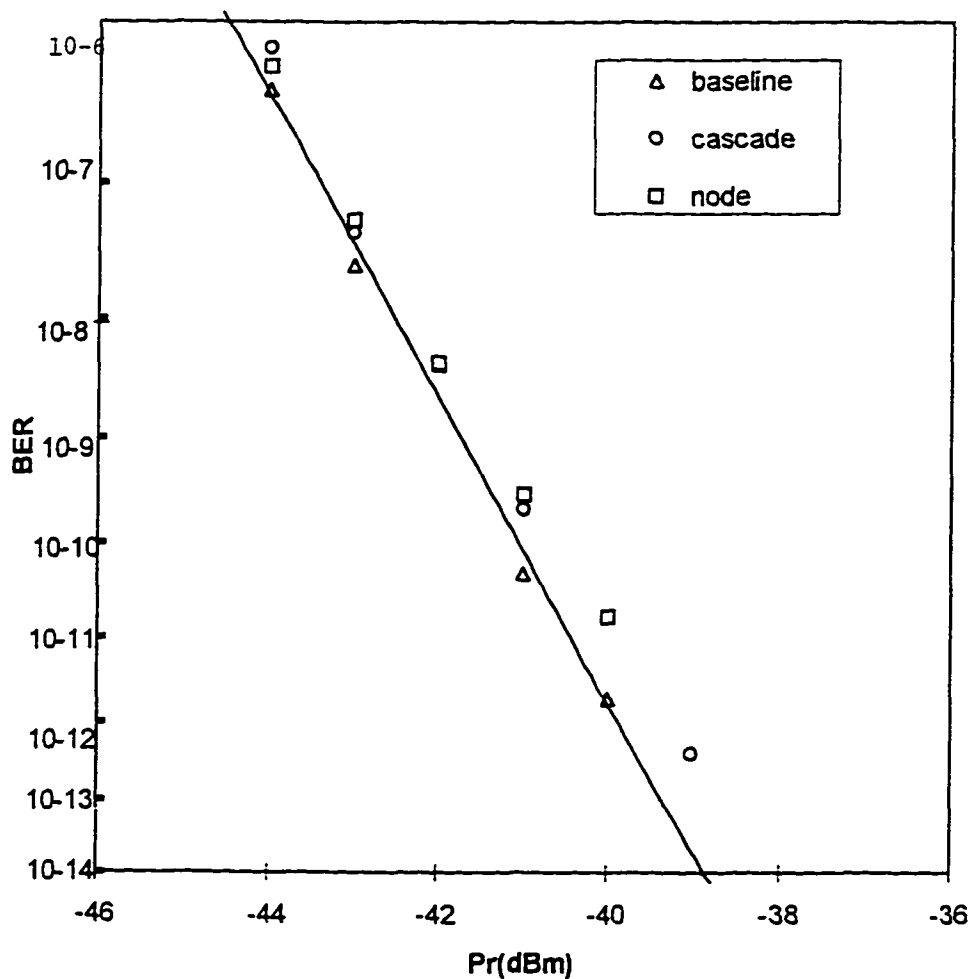


Figure 4.16 Bit Error Results, ○ baseline, □ transmission through 16 EDFAs and 16 de/mux filters, optical switch fabric removed, Δ transmission 8 times through the WSXC.

BER penalty over a period of 12 hours, confirming the strictly non-blocking capability of the space switch fabric.

## Chapter 5

### **WDM Ring Network Implementation: end-to-end system performance**

#### **5.1 ) Introduction**

In this chapter, we will build an 8 wavelengths, 8 node ring and study its end-to-end transmission performance. In a WDM network, an optical signal may pass through many nodes en route to the final destination. Signal degradation can occur at each node due to finite filter passbands and filter misalignment [68], added signals crosstalk, added EDFA ASE noise, and wavelength dependent gain. Driven by the emergence of optical systems, and intense research in the field of WDM transmission [63,69,70], we implemented this ring experiment, with the intent to investigate the accumulation of the optical degradations mentioned above, in an 8-node 8-wavelength WDM ring network with data rates of 2.5 and 10 Gb/s per channel .

#### **5.2) WDM Ring Network Experiment:**

Figure 5.1 shows the experimental configuration which included a ring of 8 prototype wavelength add/drop multiplexers (WADMs) network elements. As shown in by the insets in Figure 5.1, each WADM included an 8-channel demultiplexer/multiplexer pair with add/drop capability, and an EDFA with gain equalizing optical attenuators [3]. Two types of 8-channel WDM (de)multiplexers

were used: Phased Array Waveguide (PAW) [27,28] and Multilayer Interference (MI) filters [71]. In Node 1, eight signal lasers with a channel spacing of 200GHz were WDM multiplexed and modulated with  $2^{23} - 1$  pseudo-random data at either 2.488Gb/s or 9.952Gb/s, using for simplicity a single LiNbO<sub>3</sub> modulator [72]. The bits in the various channels were decorrelated by passing through a length of conventional fiber. A 7.5km fiber length was chosen such that the fiber chromatic dispersion generated two bits delay between adjacent channels. To measure the longest transmission path, the 8 signals were transmitted all the way around the ring, back to Node 1, where they were demultiplexed before detection. For

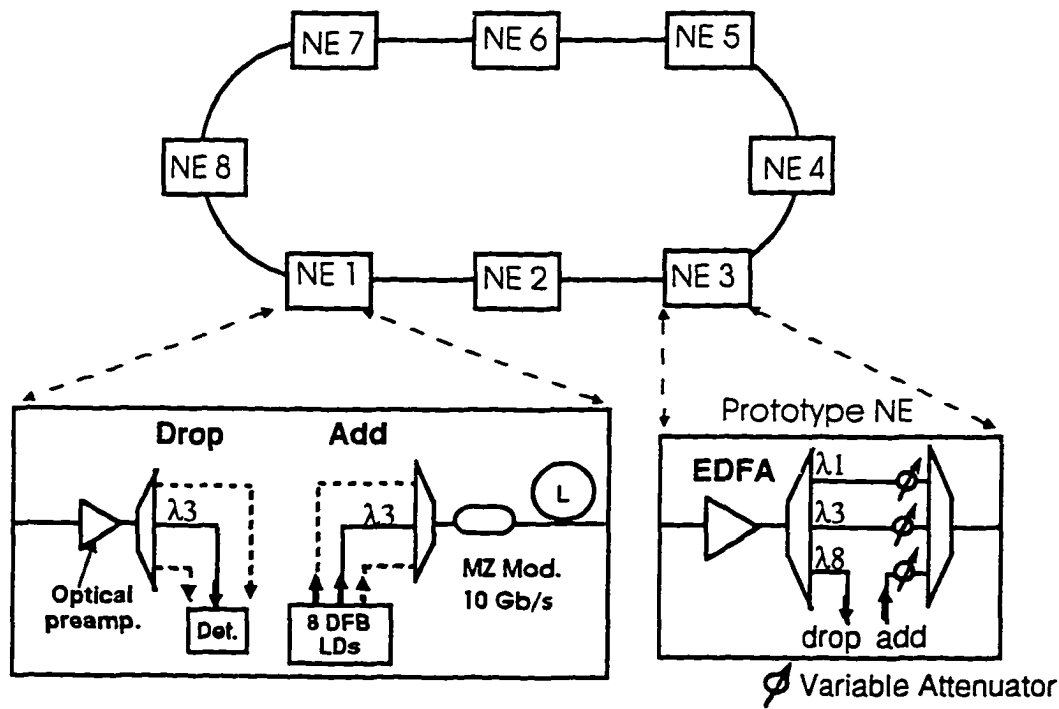


Figure 5.1 experimental setup for the ring measurements

10Gb/s detection, an optical preamplifier was inserted at the input to the eighth node. All eight signals passed through 16 cascaded optical filters and 8 stages of equalized gain. Signals could also be dropped and added at any of the nodes in the ring. Since the goal of this work is to study the effects of cascaded filters and amplifiers, the fiber losses between nodes were simulated using optical attenuators, so that the fiber dispersion was ignored.

Table 5-1 summarizes the characteristics of 12 PAW and 8 MI (de)multiplexers which were evaluated for this work. The best filter alignment results were obtained with the PAW components, where all filters fall within  $\pm 12.5$  GHz of the specified frequencies. The MI filter alignment is not as good in all cases. The worst filter misalignment of 37 GHz (0.3 nm) was obtained for one of the MI filters. However, the MI mux/demux components had significantly lower insertion losses and crosstalk, compared with the PAW mux/demux. The polarization dependent losses (PDL) of the MI type filters were all less than 0.2 dB, whereas the PAW type filters had PDL as high as 0.69 dB for one filter. The measured 3-dB bandwidth after 16 cascaded filters was  $50 \pm 4$  GHz for all 8 channels, as compared to 125 GHz for a single filter.

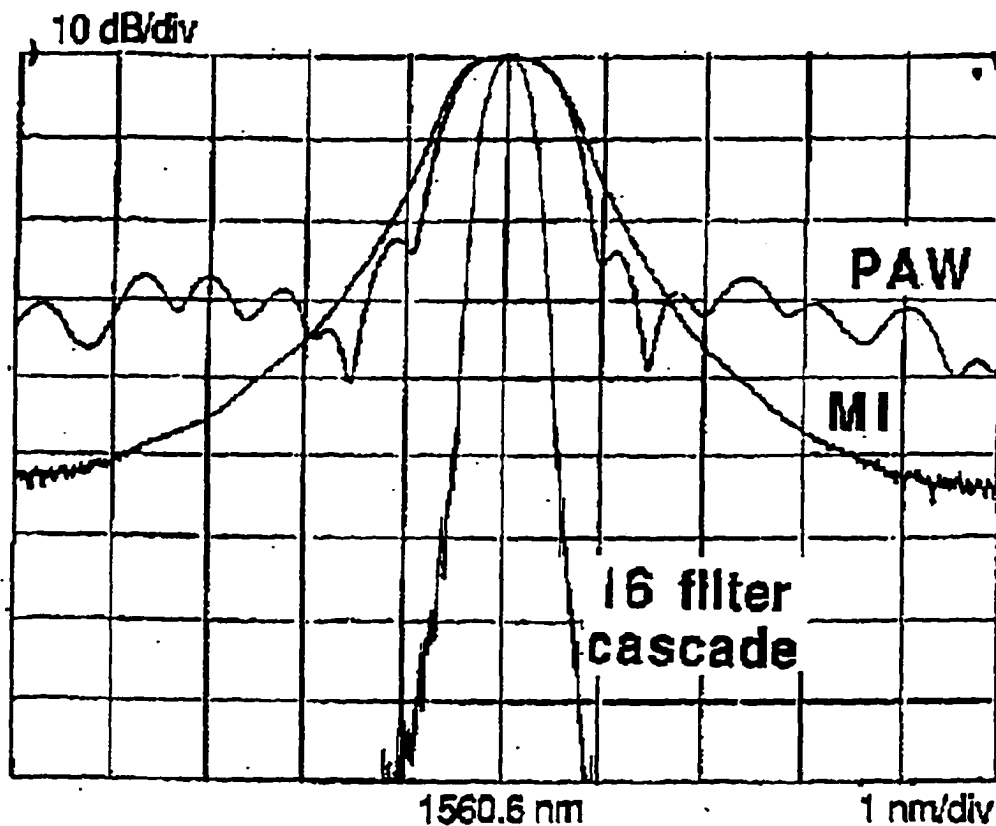


Figure 5.2 Passband evolution of the PAW and MI filters as they are cascaded

Figure 5.2 shows the passband of the two types of filters, and the corresponding cumulative transmission spectrum through the 8th node, for channel 8. Figure 5.3 shows the optical spectrum at the output of the 8th node. Using gain equalization attenuators, the signal powers were equalized to within 0.5 dB at the output of each node. For comparison, in a cascade of 6 EDFAs without gain equalization, the output signal powers varied by about 12 dB.

Figure 5.4 shows the Bit Error Rate (BER) results which were measured after transmission through all 8 nodes at 2.5 Gb/s using Channel 2 and at 10 Gb/s using

**Table 5-1 Summary of PAW and MI WDM components**

| Parameter                  | PAW filter           | MI filter              |
|----------------------------|----------------------|------------------------|
| Number of units tested     | 12                   | 8                      |
| Bandwidth 1 dB             | 90GHz                | 105GHz                 |
| 3 dB                       | 125 Hz               | 145GHz                 |
| Insertion Loss, typical    | 6.5 to 8.0 dB        | 1.5 to 4.0 dB          |
| Frequency offset (GHz)     |                      |                        |
| typical                    | $< \pm 7\text{GHz}$  | $< \pm 12.5\text{GHz}$ |
| worst                      | $< \pm 13\text{GHz}$ | $< \pm 37\text{GHz}$   |
| Crosstalk Adj. Chan        | $< -25\text{ dB}$    | $< -25\text{ dB}$      |
| Non Adj.                   | -27 to -32 dB        | $< -45\text{ dB.}$     |
| Pol. shift of Center freq. | $< 3\text{GHz}$      | $< 7\text{GHz}$        |
| Pol. Depend. Loss, worst   | 0.69 dB              | 0.25 dB                |

Channel 6. With optical pre-amplification, the 10 Gb/s receiver sensitivity was

better than the sensitivity for 2.5 Gb/s without optical preamplification. At both data rates, there was a small penalty of 0.5 dB relative to the baseline measurement. For crosstalk measurements, Channel 6 was dropped at Node 2, amplified, and split 8 ways with a 1x8 fiber power splitter. These replica signals were then used as the added signals at each of the intermediate nodes in the WDM

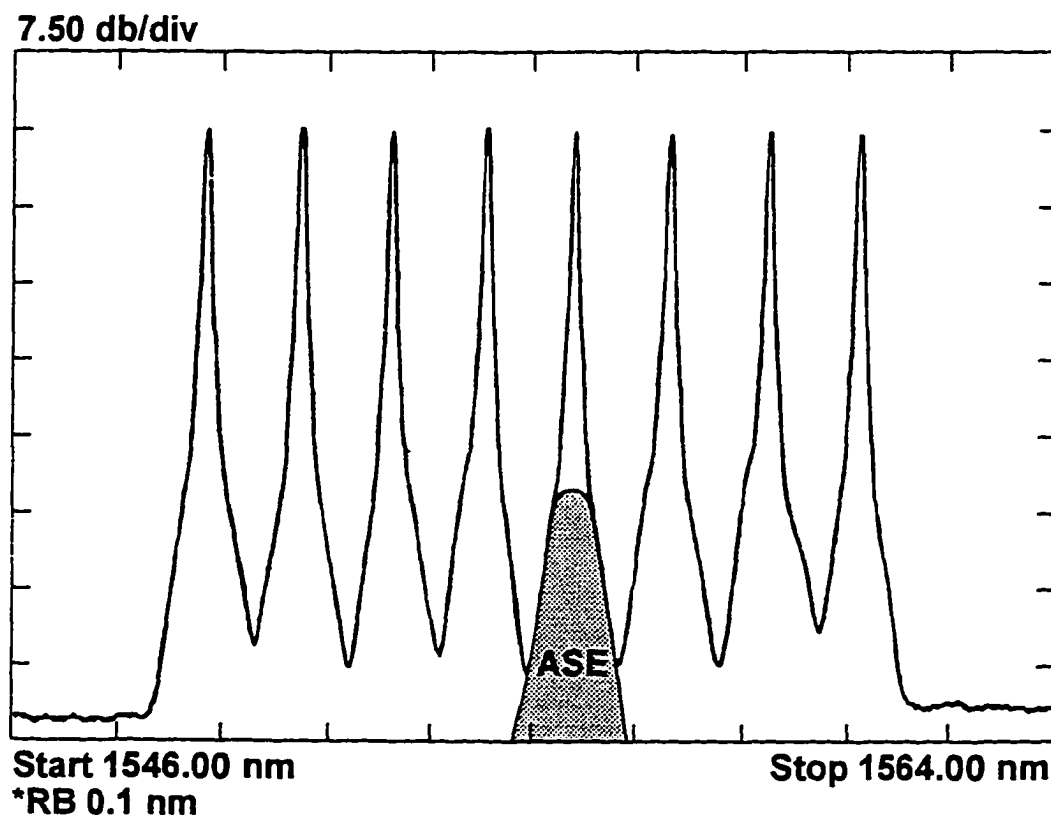


Figure 5.3 The spectrum of 8 channels at the output of the eighth node.

ring. This setup corresponds to the worst case for crosstalk, where all the crosstalk signals interfere coherently with the desired signal. At 10 Gb/s, there

was no measurable coherent crosstalk penalty for Channel 6 due to dropping and adding the same signal at all of the intermediate nodes. For this experiment Drop and Add was manually, with a preset wavelength, for that purpose. This way doesn't provide reconfigurability. However, other methods have been and still are under study to provide a cost effective mean for a fully reconfigurable W-ADM system [73,74,75].

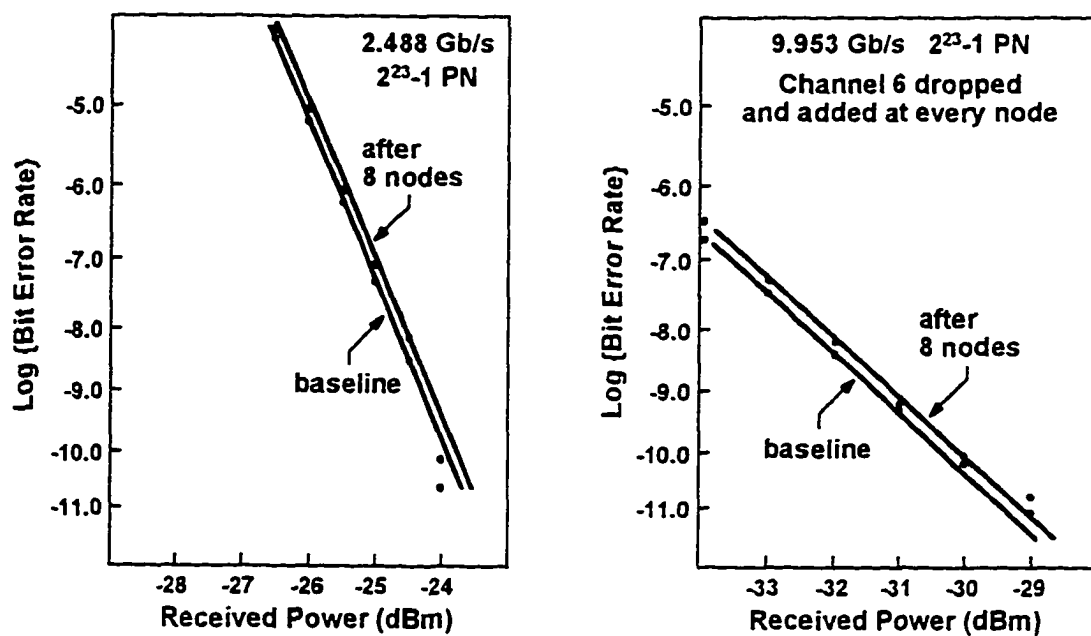


Figure 5.4 The Bit-Error-Rate performance at 2.5 and 10Gb/s rates for 8node, 8 channels ring experiment.

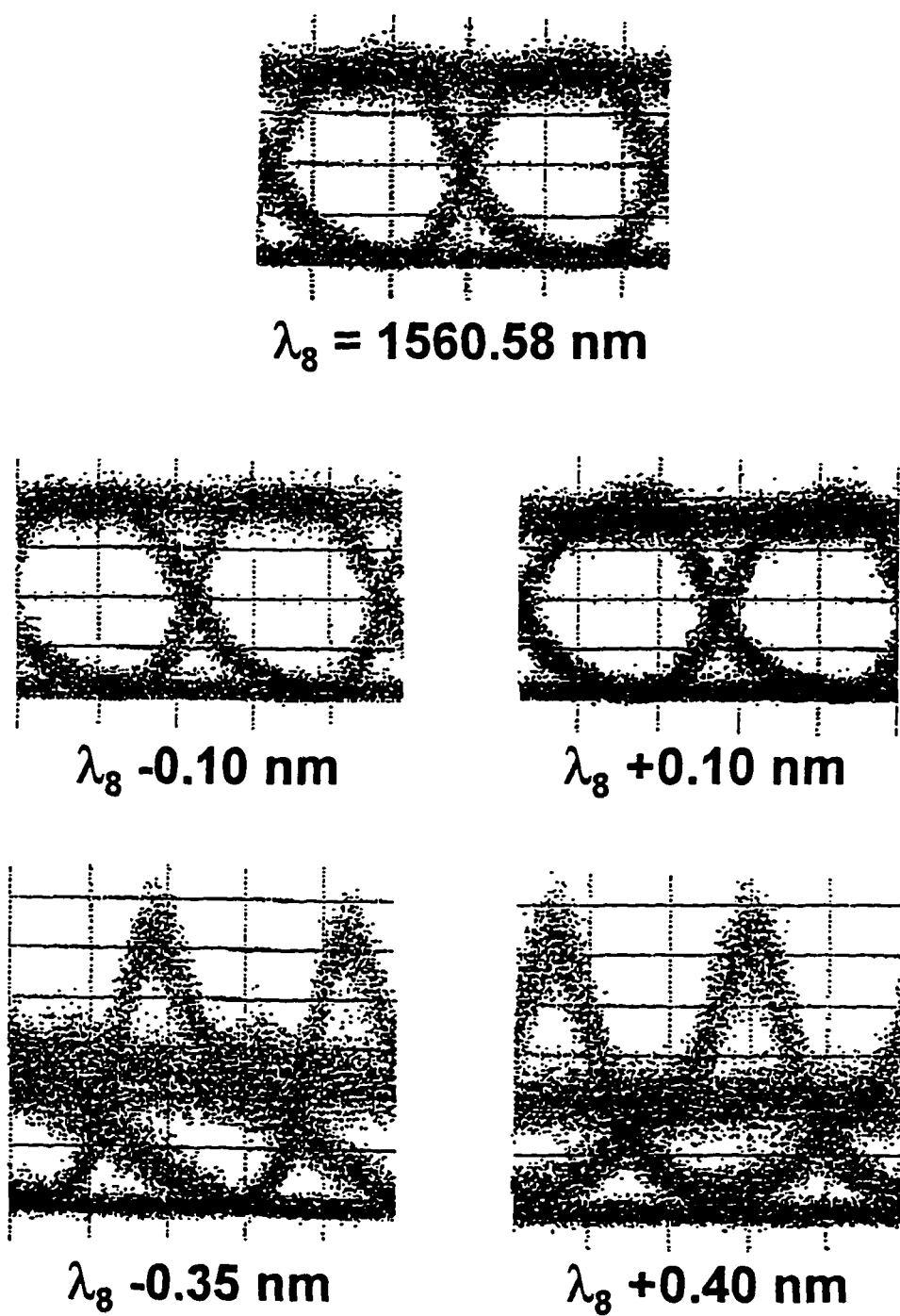


Figure 5.5 Eye diagram for channel eight as function of wavelength misalignment for 10Gb/s.

### 5.3 System Impairment due to laser misalignment and chirp:

Factors that can affect the system performance, aside from ASE noise accumulation, are the wavelength instability of the lasers, for which the wavelength fluctuates or degrades by aging, and the finite bandwidth of the filters. Therefore, the laser misalignment tolerance was measured at 10 Gb/s after transmission through all 16 filters. For this experiment, the filters were aligned to within  $\pm 1.25\text{GHz}$  with the exception of one PAW filter, which was  $\sim 25\text{GHz}$  off the required center frequency. For the case of the PAW (de)multiplexers, center frequencies of the filters can be tuned through temperature control, allowing for filter misalignment study as well. From Figure 5.5 one can see the distortion induced in the 10 GHz eye patterns, as the signal's optical frequency is moved away from the center of the filter. Figure 5.6 shows the BER penalty which was measured for Channel 8 as the laser frequency was detuned from the specified frequency by changing the laser's temperature. Misaligning the laser frequency by about  $\pm 30\text{GHz}$  resulted in a 1-dB BER penalty.

Since the filters have non-flat passband, their losses increase away from the center. In a system employing EDFAs, that additional power loss, will translate into a signal SNR degradation. Hence, Further study on laser misalignment was done, taking into account the degradation in optical SNR along the path of the eight node ring, as the signal's wavelength was tuned away from the filter's center. Since each network element is composed of one or more EDFAs, the accumulation of noise will reduce the SNR along the chain.

Figure 5.7 shows the evolution of SNR for the 8 node ring, where 5 dB degradation in SNR occurs at the center of the filters, and up to 14 dB when signal is away by  $\pm 3$  nm from the center.

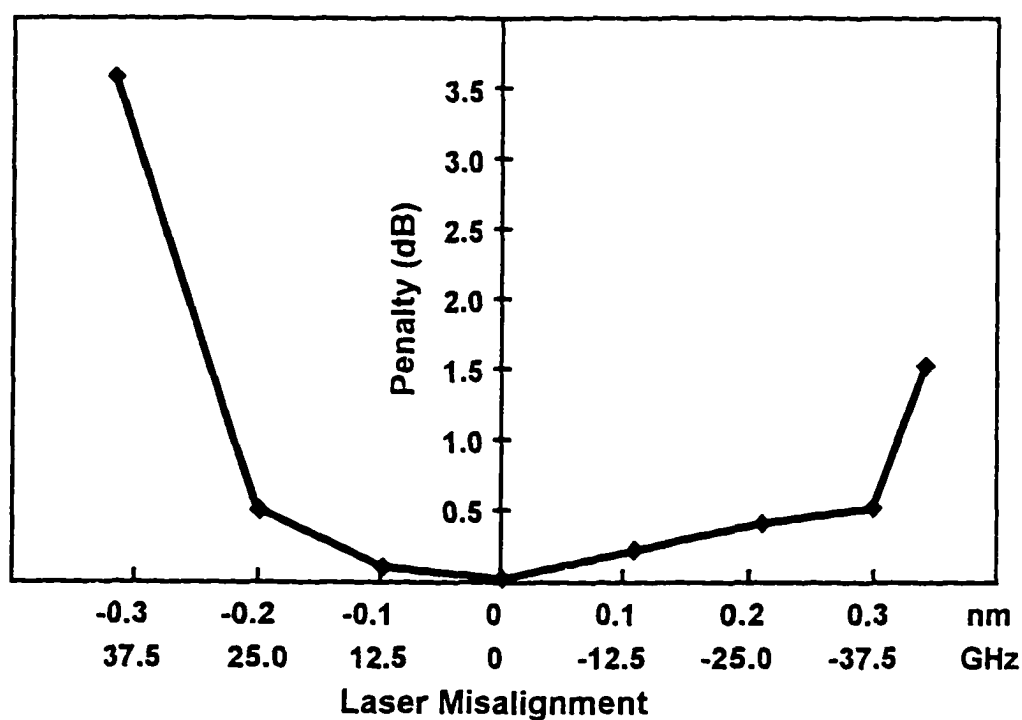


Figure 5.6 Laser misalignment penalty for 10Gb/s

For this measurements, one signal was launched into the ring with power equal to -10dBm, to eliminate the effect of crosstalk from adjacent channels. The same power level was

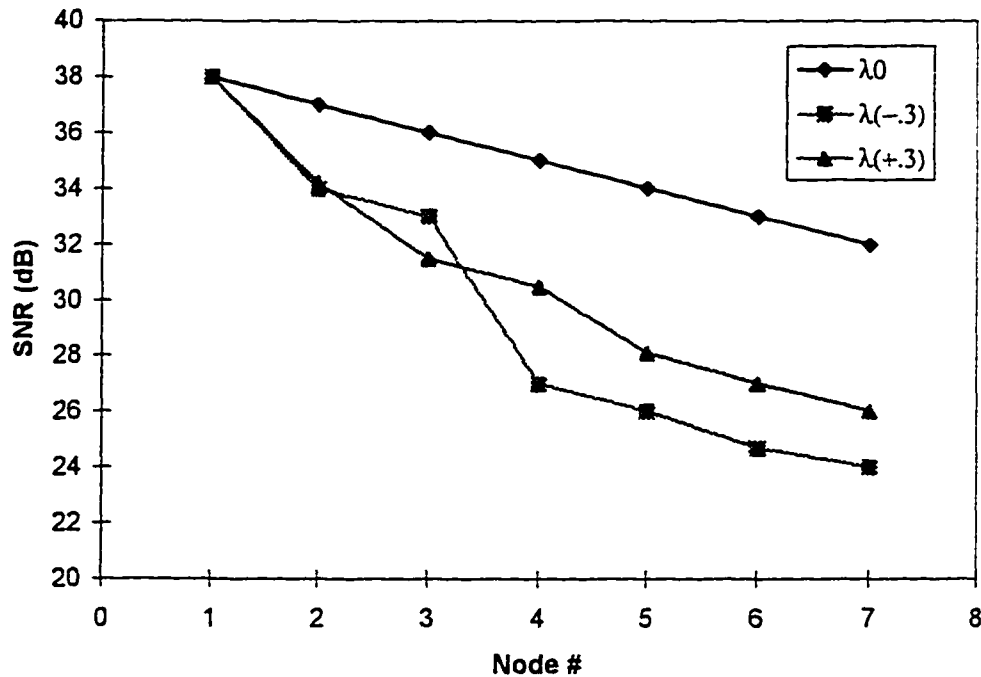


Figure 5.7 SNR degradation for eight node ring network as  $\lambda$  drifts from the filters' center.

used at each node. As we tuned the laser's wavelength, we didn't readjust the power levels. We measured in the BER degradation as well as the eye diagram distortion.

Previously, it was believed that dispersion in the filters [68] caused the system power penalty. However, measurements on filters' dispersion characteristics showed that 16 cascaded filters have dispersion equal to 1.3km of standard fiber. Dispersion measurement was done using an HP8703 lightwave network analyzer[22]. To double check the accuracy of this technique, we measured the dispersion of standard single mode fiber, and

the results were as expected. We took two approaches to understand the system penalty observed. First approach was to look at SNR requirements for  $10^{-12}$  BER at both 2.5 and 10Gb/s rates. For that goal, measurements were done for BER vs. Optical SNR, where the photodetector received power was maintained constant, but its SNR varied. Figure 5.8

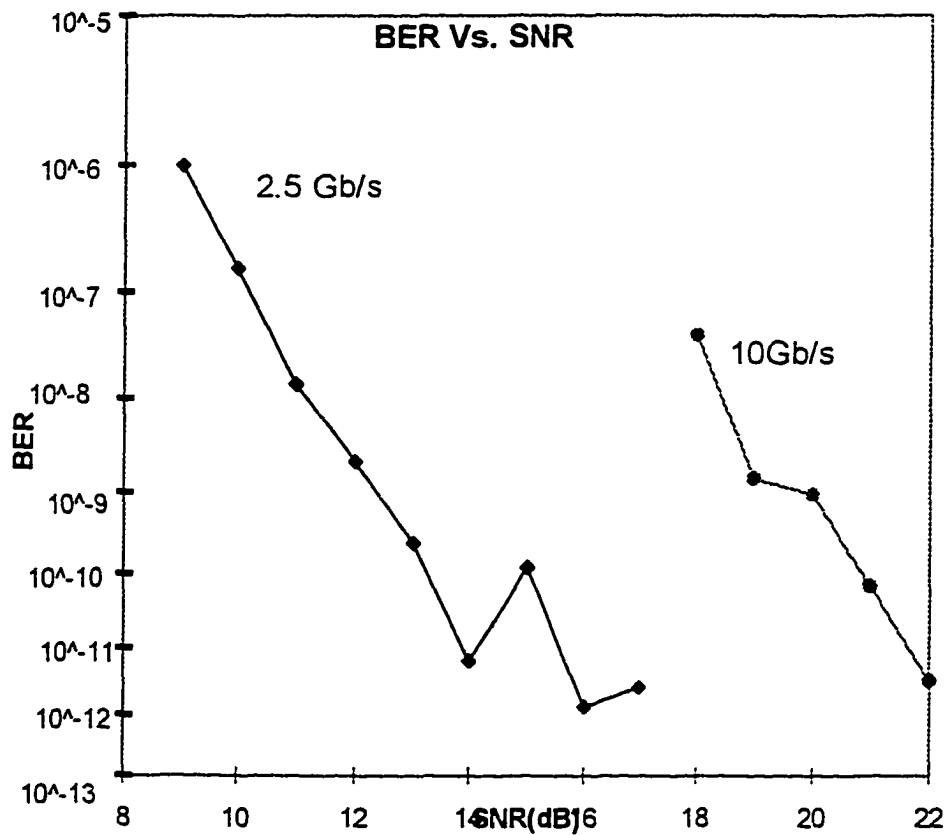


Figure 5.8 BER vs. Optical SNR for 2.5 and 10GHz signals.

shows the dependence of system performance on the quality of the received signal determined by the SNR. As mentioned above, the SNR degrades along the path. When signal's power was increased from -14 to -10dBm per channel, better SNR performance was observed, and the system penalty was reduced by 2dB for  $\pm 3$ nm, as shown in Figure

Figure 5.9 , in contrast to the 1.8 and 3.5 dB seen in Figure 5.6. However, waveform distortion was still observed in Figure 5.10 regardless of the value of SNR, so the second approach was to examine the effect of chirp parameter of the external modulator. We employed in this experiment a bias controlled chirp external modulator.

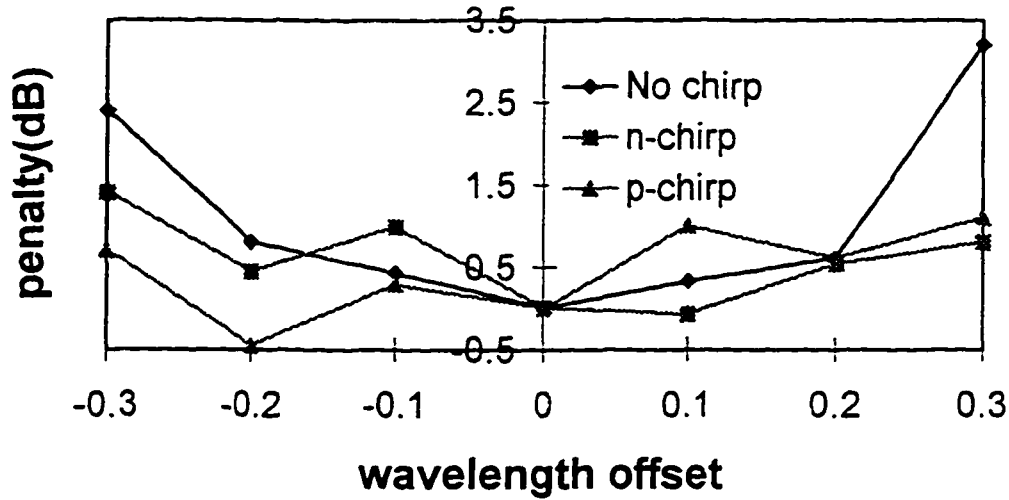


Figure 5.9 System penalty function of chirp parameter  $\alpha$

Figure 5.10 clearly shows that eye diagram distortion is due to chirp induced by the external modulator. A conflicting result appears in the Figure 5.9, and Figure 5.10, such that a chirp free signal suffers more penalty while its waveform suffers less distortion than the chirp case. This discrepancy could be due to bandwidth limitation or smaller extinction ratio in the chirp free modulator. A careful study should be done employing a fully adjustable chirp modulator. In our case, two different light sources as well as two different modulators packages, supplied by various vendors were used.

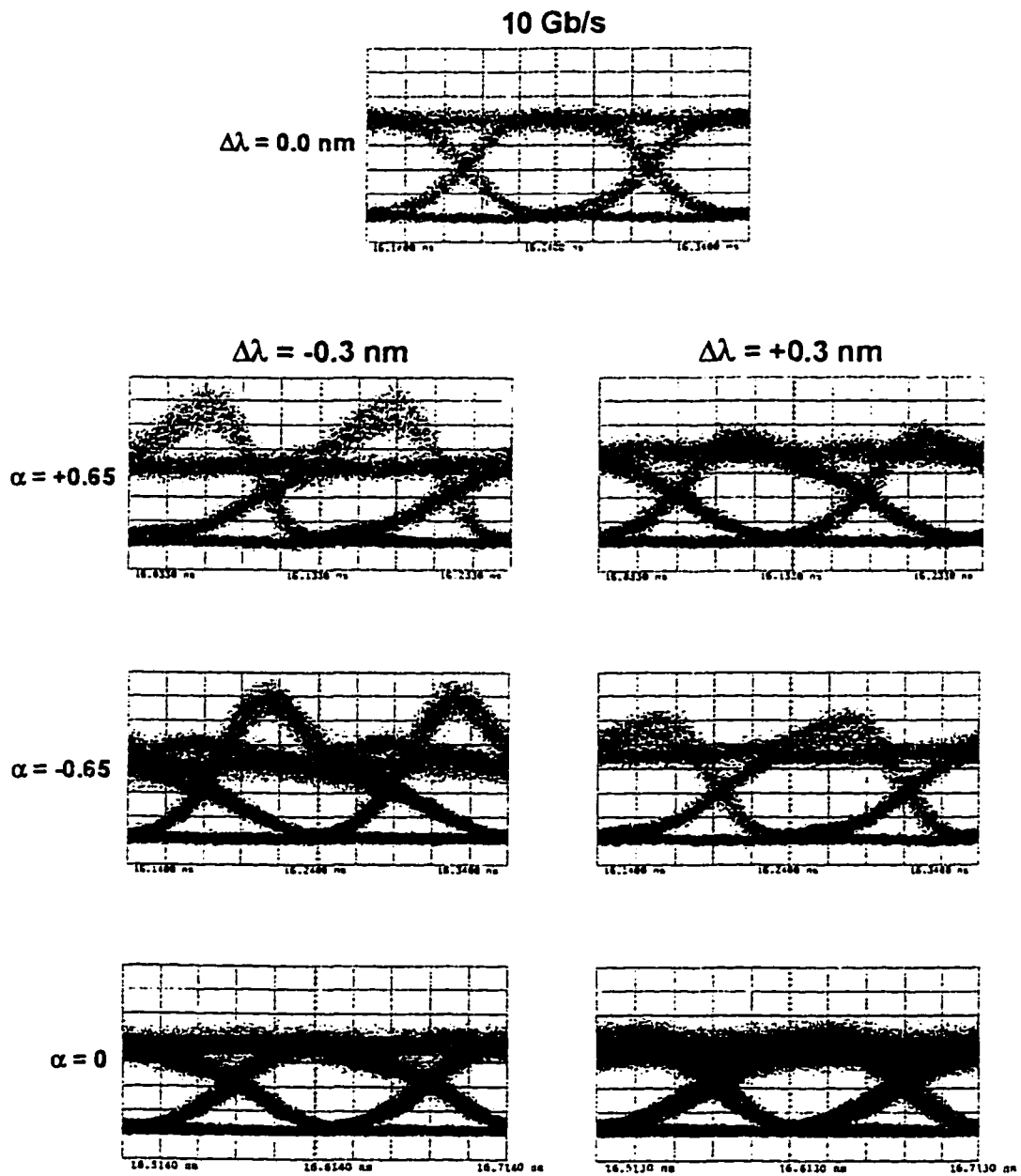


Figure 5.10 Eye diagram distortion function of  $\alpha$  parameter at 10 Gb/s

## Chapter 6

### Conclusion

#### 6.1) Conclusion

In this thesis, we investigated the technological requirements necessary to build self-healing interoffice ring networks. We used all commercially available components to implement an 8-node WDM ring. Technology used in this work, covered Wavelength Division Multiplexers (WDM), Erbium-Doped Fiber Amplifier (EDFA), and cross-connect switch fabrics.

Erbium Doped Fiber Amplifiers (EDFAs) make it possible to realize this new generation of high speed and large bandwidth transmission media. EDFAs, characterized by large flat gain region, are the engine behind the multiwavelength system, as they can amplify signals over a range of 35nm, contrary to the optical semiconductor amplifiers (OSA), which are single signal amplifiers. For this work we studied the performance of these wide band amplifiers under different operating conditions. We examined the EDFA gain dependence on pump power and total signal power fluctuations. An EDFA with 9dB in saturation was employed for this study, the tolerance for total input signal variation was found to be 12dB, producing gain change in signal of less than 1dB. Similar measurements were done to examine the pump tolerance, it was found that the EDFA is strongly affected by pump power variations. For 1.4dB in pump power reduction, a 1dB in output signal power variation occurred.

We did also investigate the EDFA stability under multiwavelength operation. This is important, since the amplifier output power depends on the total input signal levels. As reconfiguration of the system occurs (i.e routing, drop/add) the amplifier dynamic response will be affected by these changes in signal levels. Thus, a control mechanism is required to reduce or eliminate the impact of input power variation on the amplifier response. Three stabilization techniques were demonstrated. Two of these techniques employed an auxiliary signal for output power control, either in co-or counter-propagation regime. The third technique relied on adjusting the pump power to maintain stable signal output power. However, all these techniques required feedback circuitry, which would mean power monitoring and fast feedback response. Another technique was introduced, which won't require any feedback. This method consisted of adding a strong saturating signal to stabilize the amplifier performance, where no monitoring or feedback mechanisms were required.

EDFAs in conjunction with WDM were used in a ring configuration, consisting of 8 node. Each node was formed by a pair Mux/demux, variable attenuators for signal equalization, and an EDFA for power restoration. signals were launched into the ring at both 2.5 and 10Gb/s rates. A system penalty of less than 0.5 dB was measures for both cases, indicating for through transmission (no add/drop); thus, ASE noise accumulation didn't degrade the system performance. A single channel add/drop was performed, the system penalty was measured (<1dB), with no crosstalk impact from the WDM filters. Analysis on the importance of laser frequency stability on concatenated filters was done. We did detune the laser frequencies from the central of the filters, and found that the main

limitations came from the chirp induced by the external modulators. An approximately 2dB penalty was observed when laser wavelength drifted by  $\pm 0.3\text{nm}$  from the filter's center.

## References:

- 
- 1 S. Wagner, and T. E. Chapuran, "Multiwavelength ring networks for switch consolidation and interconnection," Proceedings of the IEEE International conference on Communication ICC'92, p. 340.5.1.
  - 2 M-C. Chow, "understanding SONET/SDH standards and applications," Andan publisher, 1995.
  - 3 A. F. Elrefaie, "Multiwavelength survivable ring network architectures," IEEE international conference on communication ICC'93, Geneva, p. 1245, 1993.
  - 4 R. E. wagner, et al., "Survivable WDM Rings for interoffice networks," Fifth Optoelectronics Conference OEC'94, paper 14C3-1, Japan, July 1994.
  - 5 Bellcore, GR-2918-CORE, Generic criteria for SONET point-to-point WDM systems in the 1550nm region," issue 1, July 1996.
  - 6 Bellcore, GR-1400-CORE ILR, "SONET dualfed unidirectional path switched ring (UPSR) equipment generic criteria, Nov., 1994.
  - 7 Bellcore GR-1230-CORE, " SONET bidirectional line switched ring equipment criteria, issue 2, Nov., 1995.
  - 8 G. Keiser, "Optical fiber communications," Mc-Graw-Hill, New York, 1991.
  - 9 J. E. Bowers, and M. A. Pollak, "Semiconductor lasers for telecommunications," in Optical Fiber Telecommunications, S. Miller, and I. Kaminow, eds., Academic Press, 1988.

- 
- 10 T. p. Lee, et al., "Multiwavelength DFB laser array transmitters for ONTC reconfigurable optical network testbed," IEEE journal of Lightwave Technol., vol. 14, no.6, p.967, June 1996.
  - 11 M. G. Young, et al., "Six channel WDM transmitter module with ultra-low chirp and stable  $\lambda$  selection," Proceedings of ECOC'95, paper Th.B.3.4,
  - 12 H. Kogelink, and C. V. Ahank, "Coupled-wave theory of distributed feedback lasers," J. Appl. Phys. , vol. 43, p. 2327-2335, 1972.
  - 13 B. Glance et al., "Optical frequency synthesizer," Electron. Lett., vol. 25, no. 17, p. 1193-1195, Aug. 1989.
  - 14 B. Glance, et al, "Discretely-tuned N-frequency laser for packet switching applications based on WDM," Electron. Lett., vol. 27, no. 15, July 1991.
  - 15 M. G. Young, et al., "Six-channel WDM transmitter module with ultra-low chirp and stable  $\lambda$  selection," Proceedings of ECOC'95, paper Th.B.3.3, Brussels, 1995.
  - 16 M.C. Nowell et al., "Low-chirp enhanced frequency direct push-pull modulation of DFB lasers", IEEE journal of selected topics in quantum electronics, vol. 1, no., 2, p. 433, june, 1995.
  - 17 J.A.J. Fells et al., "controlling the chirp in electroabsorption modulators under digital modulation," Elect. Lett., vol. 30, no. 24, pp.2066, 1994.

- 
- 18 H.Q. Hou et al., "Nearly free chirp electro-absorption modulation using InGaAs-InGaAlAs-InAlAs coupled quantum wells," *IEEE photon. Technol. Lett.*, vol. 7, no.2, pp. 167, 1995.
  - 19 K. Wakita et al., "High speed, high efficiency modulator module with polarization insensitivity and very low chirp," *Electron. Lett.*, vol. 31, no. 23, pp. 2041, 1995.
  - 20 K. Yamada et al., "Negative-chirp electroabsorption modulator using low-wavelength detuning," *IEEE Photon. Technol. Lett.* Vol. 7, no. 10, pp. 1157, 1995.
  - 21 F. Koyama, K. Iga, "Frequency chirping in external modulators," *IEEE journal of Lightwave Technology*, vol.6, no.1, pp.87, Jan. 1988.
  - 22 F. Devaux et al., "Simple measurement of fiber dispersion and of chirp parameter of intensity modulated light emitter," *IEEE journal of Lightwave Technology*, vol. 11, no. 12, pp. 1937, 1993.
  - 23 N. Kashima, "Passive optical components for optical fiber transmission," Artech House, Boston, 1995.
  - 24 J.C. Midwinter and Y.L. Guo, " Optoelectronics and lightwave technology," J. Wiley, New York, 1994.
  - 25 R. Watanabe et al., "Optical grating multiplexer in the 1.1-1.5 $\mu$ m wavelength region," *Electron. Lett.*, vol.16, pp.108-109, 1980.

- 
- 26 H.Ishio et al., "Review and status of wavelength -division multiplexing technology and its applications," IEEE Journal of Lightwave Technol. Vol.2, no.8, pp.448-463, 1984.
  - 27 M.K. Smit, "New focusing and dispersive planar component based on an optical phased array," Electron. Lett., vol. 24, no.7, pp.385, 1988.
  - 28 C. Dragon, "An NxN optical multiplexer using a planar arrangement of two star couplers," IEEE photon. Techn. Lett, vol. 3, no. 9, pp.812, 1991.
  - 29 M. Zirginbil et al., "Demonstration of a 15x15 arrayed waveguide multiplexer on InP," IEEE Photon. Technol. Lett., vol.4, no.11, pp.1250, 1992.
  - 30 T. Suhara and H. Nishihara, "Integrated optics components and devices using periodic structures," IEEE Journal of Quant. Electr., vol. 22, no.6, pp.846, 1986.
  - 31 M. Zirngibl et al., "Polarization independent 8x8 wavelength grating multiplexer on InP," Electr. Lett., vol. 29, no. 2, pp. 201, 1993.
  - 32 M. A. Scobey and D. E. Spock, "Passive DWDM components using Microplasma optical interference filters," OFC'96, paper ThK1, San Jose, Feb. 1996.
  - 33 H. Takahashi et al., "Arrayed waveguide grating for wavelength division multi/demultiplexer with nanometer resolution," Electron. Lett. Vol. 26, no. 2, P.87, 1990.
  - 34 M.R. Amersfoort, "Phased-array wavelength demultiplexers and their integration with photodetectors," Ph.D. thesis, Delft university, The Netherlands, 1994.

- 
- 35 K. Oda, et al., "10 channel x 10Gb/s over 500 km optical FDM-Add/Drop multiplexing experiment employing a 16-channel arrayed-waveguide-grating ADM filter," Proceedings of ECOC'95, paper Mo.A.4.1, 1995.
- 36 E. Desurvire, "Erbium Doped Fiber Amplifiers," J. Wiley, New York, 1993.
- 37 P. R. Morkel and R. I. Laming, "Theoretical modeling of erbium-doped fiber amplifiers with excited state absorption," Opt. Lett., vol. 14, p. 1062-1064, 1989.
- 38 C. R. Giles, and E. Desurvire, "Modeling Erbium-Doped -Fiber Amplifiers," IEEE Journal of Lightwave Technol., vol. 9, no. 2, p. 271, Feb. 1991.
- 39 A. A. M. Saleh, et al., "Modeling of gain in erbium-doped fiber amplifiers," IEEE Photon. Technol. Lett., vol. 2, no. 10, p.714, 1990.
- 40 A. J. Lucero, et al., "Comparison of 980- and 1480nm pumped amplifiers in multiwavelength systems," in OFC'95, Techn. Digest., paper TuC2, pp. 3-4, 1995.
- 41 M. Ali, et al., "A detailed comparison of the overall performance of 980 and 1480nm pumped EDFA cascades in WDM multiple-access lightwave networks,," IEEE Journal of Lightwave of Technol. Vol. 14, no. 6,p. 1436, June, 1996.
- 42 E. Desurvire, "Analysis of noise figure spectral distribution in erbium doped fiber amplifiers pumped near 980 and 1480nm," Applied Optics, vol. 29, no. 21, pp. 3118, 1990.
- 43 T. Kakinuma, et al., "Gain and Noise Characterisitcs of Er-doped fiber amplifiers with different-pumping directions," Proceedings of the Optical Amplifiers and their Applications topical meeting, paper TuB1, Monterey CA, 1990.

- 
- 44 J. L. zyskind, et al., "Length dependence of saturation power in erbium-doped fiber amplifiers," SPIE, Fiber Laser Sources and Amplifiers III, vol. 1581, pp. 257-265, 1991.
- 45 J.-M. P Delavaux and J. Nagel, "Multi-stage Erbium-Doped Fiber Amplifier Designs," IEEE Journal of Lightwave Technol. Vol. 13, no. 5, pp.703, 1995.
- 46 C. R. Giles, E. Desurvire, "Propagation of signal and noise in concatenated Erbium-Doped Fiber Optical Amplifiers," IEEE Journal of Lightwave Technol., vol. 9, no. 2, p. 147, Feb. 1991.
- 47 H. Laor, "Optical switching using piezoelectric driven beams for fiber to fiber coupling," OFC'83, paper TUG8.
- 48 G.R. Hill, et al., "A transport network layer based on optical network elements," J. Lightwave Technol., vol.11, no.5, pp 667-687, 1993.
- 49 E.L. Goldstein, et al., "Multiwavelength propagation in lightwave systems with strongly inverted fiber amplifiers," IEEE Photon. Technol. Lett., vol.6, pp266-269. 1994.
- 50 A.R. Charplyvy, et al., "Equalization in amplified WDM lighthwave transmission systems," IEEE Photon. Technol. Lett. vol. 4, pp.920-922, 1992.
- 51 A.F. Elrefaie, et al., "Fiber amplifier cascades with gain equalization in multiwavelength unidirectional inter-office ring networks," IEEE Photon. Techol. Lett., vol.5, pp. 1026-1028, 1993.

- 
- 52 K. Inoue, et al., "Tunable gain equalization using a Mach-Zehnder optical filter in multistage fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol.3, pp. 718-720, 1991.
- 53 J.Y. Pan, et al., "Fiber amplifier cascades with equalization employing Mach-Zehnder optical filters in multiwavelength systems," in *Dig. Top. Meet. Opt. Amplifiers (Lake Tahoe, NV)* Opt. Soc. Amer., Washington, DC, Aug. 1994, paper FA3.
- 54 M. Fake, et al., "Optically stabilized EDFA for in-band WDM systems," in *proc. OFC'95*, San Diego, paper TuP3.
- 55 F. Shehadeh et al., "Gain equalized eight-wavelength WDM optical add-drop multiplexer with 8 dB dynamic range," in *Proc. OFC'95*, paper TuH2.
- 56 C.R. Giles et al., "Transient gain and crosstalk in erbium doped fiber amplifier," *Opt. Lett.* vol14, no. 16, pp. 880, 1989.
- 57 E. Desurvire et al., "Dynamic gain compensation in saturated erbium-doped fiber amplifiers," *IEEE Photon. Technol. Lett.* Vol.3, no. 5, pp. 453, 1991.
- 58 J.L Zyskind et al., "Fast power transients in optically amplified multiwavelength optical networks," *OFC'96*, paper PD31, San Jose, Feb. 96.
- 59 E Desurvire, et al., "Gain Saturation Effects in high-speed, multichannel Erbium-Doped Fiber Amplifiers at  $\lambda=1.53\mu\text{m}$ ," *IEEE journal of Lightwave Technol* vol. 7, no.12, pp. 2095, 1989.

- 
- 60 B. Clesca, et al., "Upper limit and control scheme for power channel in optically-amplified WDM systems," paper WeP.31, ECOC'96, SLO.
- 61 J. L. Zyskind, et al., "Fast link control protection for surviving channels in multiwavelength optical networks," paper ThC.3.6, ECOC'96, OSLO.
- 62 J. C. Cartledge, and G. S. Burley, "Chirping-induced waveform distortion in 2.4-Gb/s lightwave transmission systems," *IEEE journal of Lightwave of Technol.*, vol. 8, no. 5, 1990.
- 63 *IEEE Journ. Of Lightwave Technol.*, special issue, Vol.11, no.5/6, 1993.
- 64 *IEEE J. on Selected Areas in Communications*, special issue on Optical Networks, vol. 14, no. 5, June, 1996.
- 65 E.L. Goldstein et al., " Performance implications of component crosstalk in transparent lightwave networks," *Photon. Tech. Lett.* , vol. 6, no. 5, pp. 657, May, 1994.
- 66 P.J. Legg et al., "Inter-channel crosstalk phenomena in optical time division multiplexed switching networks," *Photon. Tech. Lett.*, vol. 6, no. 5, p. 661, May, 1994.
- 67 H. Laor, "Optical switching using piezoelectric-driven beams for fiber to fiber coupling," in *Tech. Digest, OFC'83*, paper TuG8, pp. 52, Feb., 1983.
- 68 N.N. Khrais et al., "Effect of cascaded misaligned optical (de)multiplexers on multiwavelength optical network performance," *Conf. on Optical Commun., OFC'96*, paper ThD4, Feb. 1996.

- 
- 69 A. H. Gnauk et al., "One terabit/s transmission experiment," Conf. On Optical Commun., OFC'96, paper PD20, San Jose, 1996.
- 70 H. Onaka, et al., "1.1 Tb/s WDM transmission over a 150km 1.3 $\mu$ m zero-dispersion single-mode fiber," Conf. On Optical Commun., OFC'96, paper PD19, San Jose, 1996.
- 71 H. A. Macleod, "Thin film optical filters," Adam Hilger Ltd., Bristol, 1986.
- 72 A.H. Gnauk, et al., "Transmission of 8 20Gb/s channels over 232km of conventional fiber," Conf. on Optical Commun., OFC'95, postdeadline paper PD23, 1995.
- 73 A. Mariconda, and S. Merli, " An optical add/drop multiplexer (OADM) node architecture in a fully transparent self healing ring network," Proceedings of ECOC'96, paper ThD.1.10, Oslo, 1996.
- 74 J. M. Rijnders, et al., " Experimental demonstration of a simple, optically transparent, add/drop multiplexer at 2.5 Gb/s without local optical source," Proceedings of ECOC'96, paper TuP.24, Oslo, 1996.
- 75 M. Erman, "What technology is required for the Pan-European network, what is available and what is not," Proceedings of ECOC'96, paper TuB.2.2, Oslo, 1996.