



UNIVERSITI PUTRA MALAYSIA

**DESIGN AND ANALYSIS OF A HIGHLY SENSITIVE HYBRID
DISPERSION-COMPENSATED ERBIUM-DOPED FIBER AMPLIFIER**

MD ZAINI BIN JAMALUDIN

FK 2007 72



**DESIGN AND ANALYSIS OF A HIGHLY SENSITIVE HYBRID
DISPERSION-COMPENSATED ERBIUM-DOPED FIBER AMPLIFIER**

MD ZAINI BIN JAMALUDIN

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of
Philosophy**

June 2007



DEDICATION

To

My Loving Parents:
Saudah Binti Md Yatim
And
My Late Father:
Jamaludin Bin Ibrahim

My Wife:
Norashikin Binti Abdul Kadir

My Children:
Muhammad Hafiz, Hani Izzati, Ahmad Syafiq and Nurhanani Amni



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in
fulfilment of the requirement for the degree of Doctor of Philosophy

**DESIGN AND ANALYSIS OF A HIGHLY SENSITIVE HYBRID DISPERSION-
COMPENSATED ERBIUM-DOPED FIBER AMPLIFIER**

By

MD ZAINI BIN JAMALUDIN

June 2007

Chairman: Professor Mohamad Khazani bin Abdullah, PhD

Faculty: Engineering

Optical amplifiers have a great impact on optical communications due to their ability to amplify light along the optical path. Thus optical amplifiers have become indispensable components in high-performance optical communication links. However, while optical amplifiers are effective in mitigating link power loss problems, they are conventionally unusable and irrelevant for another major fiber optic transmission which is dispersion. Compensation of dispersion is a necessity in high speed and/or long distance links. This is separately achieved by use of a dispersion compensator which is either of fiber optics based or fiber Bragg grating based. Thus there is clear need for an integrated system which can achieve both important functions at the same time.



New designs have been envisaged and achieved in this thesis. It has shown a great enhancement in performing simultaneous function in amplifying the power as well as compensating the dispersion of the signal (Hybrid). The double-pass erbium-doped fiber amplifier (EDFA) with embedded chirped fiber Bragg grating and as well as other filtering technique (optical Bragg grating) have been demonstrated and investigated. It is shown through simulations and by the hardware implementation that the new design is significantly better than that of existing double pass amplifier and double pass amplifier with tunable filter.

There are two levels of tests carried out in this study; device level and system (transmission) level. At the device level, the performance parameters of the new configurations are thoroughly characterized showing improvement in gain, noise figure, and the output power, considering the effects of pump power, input signal level, and input signal wavelength. The device configuration is based on double-pass amplification with a Bragg grating employed as the reflector. The grating also serves as a filter suppressing the Amplified Spontaneous Noise from the signal. At the system level, the performance parameters investigated are power sensitivity, power penalty, signal-to-noise ratio (SNR), eye amplitude, eye opening and jitter which all see a level of improvements, based on Wavelength Division Multiplexing (WDM) system.

A gain as high as 53.4dB, a noise figure of as low as 5.36dB, and sensitivity of -40dBm have been achieved at the BER of 10^{-12} for the transmission speed of 2.5Gbps. The new hybrid amplifier provides power gain improvement of 12.5 dB and 8.4 dB for single and multi channel system. The power penalty incurred by the new hybrid amplifier for single and multi channel system are 3.5 dB and 3.2 dB respectively. Comparisons are made against the conventional double pass amplifiers and back-to-back connection.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**MEREKABENTUK DAN MENGANALISA SEBUAH PEMBESAR HYBRID
SENSITIF PAMPASAN SEBARAN FIBER TERDOPAN ERBIUM**

Oleh

MD ZAINI BIN JAMALUDIN

Jun 2007

Pengerusi: Profesor Mohamad Khazani Abdullah, PhD

Fakulti: Kejuruteraan

Pembesar optik mempunyai satu kesan besar di dalam komunikasi optik disebabkan oleh keupayaannya untuk membesarkan cahaya sepanjang lintasan optic. Oleh itu pembesar optik telah menjadi sebahagian daripada komponen-komponen penting di dalam talian komunikasi optik berprestasi tinggi. Walaupun optik amplifier dapat memberi kesan yang efektif dalam menangani kehilangan kuasa dalam gentian optik, tetapi secara konvensional tidak berkesan untuk mengatasi masalah utama dalam fibre transmisi optik iaitu kesan sebaran. Pampasan sebaran adalah satu keperluan dalam talian yang berkelajuan tinggi dan/atau rangkaian jarak jauh. Ini selalu nya diperolehi secara berasingan dengan menggunakan penyebaran pemampas yang berdasarkan optik fibre atau berdasarkan fibre Bragg parutan. Oleh itu terdapat



satu keperluan yang jelas dan penting untuk mengujudkan satu sistem bersepadu yang boleh menghasilkan kedua-dua fungsi pada masa yang sama.

Rekaan terbaru telah berjaya menepati jangkaan dan pencapaian dalam tesis ini. Ia telah berjaya membuktikan satu peningkatan dalam menjalankan secara serentak fungsi memperbaiki serakan (compensation) dan juga mengandakan isyarat secara kacukan (hybrid). Pembesar kacukan terdopan Erbium laluan berganda (DP-EDFA) bersama-sama dengan tertaman parutan chirped Bragg berserta dengan teknik penapisan yang lain (pemboleh ubah parutan optik Bragg) telah didemonstrasikan dan disiasat. Siasat telah di jalankan secara simulasi dan juga secara ujilari komponen di dalam makmal.

Terdapat dua jenis ujian yang telah dijalankan dalam kajian ini; tahap alatan dan tahap sistem (transmisi). Di tahap ujian alat, parameter prestasi tatarajah baru adalah dengan sempurna menggambarkan sifat menunjukkan pembaikan dalam keuntungan, angka hingar, dan kuasa keluaran, dengan mengambil kira kesan-kesan kuasa pam , aras isyarat masukan, dan isyarat jarak gelombang masukan. Konfigurasi alat berdasarkan kepada pembesar dua kali-laluan dengan satu Bragg parutan yang bertindak sebagai pemantul isyarat. Parutan juga berkhidmat sebagai satu penuras mengurangkan ataupun menghalang kesan Dikuatkan Bunyi Spontan (ASE) daripada isyarat. Di peringkat sistem, parameter prestasi disiasat adalah kuasa kepekaan, mendayai penalti, nisbah

isyarat dengan hingar (SNR), amplitud mata, keterbukaan mata dan ketaran dimana terdapat suatu peningkatan yang ketara, ujian berdasarkan sistem Bahagian Jarak Gelombang Multipleksan (WDM). Satu keuntungan setinggi 53.4dB telah didapati, satu bunyi bising angka serendah 5.36dB, dan kepekaan -40dBm telah tercapai di BER 10^{-12} untuk kelajuan penghantaran 2.5Gbps. Rekaan terbaru kacukan (hybrid) pembesar ini telah berjaya menambahbaikkan gandaan kuasa se banyak 12.5 dB dan 8.4 dB masing-maing bagi system satu saluran dan pelbagai saluran. Ia juga dikenakan kuasa penalti sebanyak 3.5 dB and 3.2 dB masing-masing bagi system satu dan pelbagai saluran. Perbandingan-perbandingan ini dibuat terhadap gandan pembesar konvensional dan sambungan tanpa gentian fiber.



ACKNOWLEDGEMENTS

All praise is to ALLAH SWT the greatest and the most merciful.

I would like to express my deepest gratitude to Professor Dr Mohammad Khazani Abdullah, I feel fortunate to have him as my supervisor and adviser. His way of thinking is full of brilliant ideas, dedications and patient in providing me with the guidance in completing my studies. I feel honored to have been a part of his research group for the past four years and I am sure that his thought and ideas would inspire his future students.

My special thanks go to all other members of the photonics group who have helped me make my PhD worked an enjoyable and rewarding. My special appreciation is extended to my supervisory committee members: Associate Professor Dr Mohd Adzir Mahdi and Associate Professor Dr Faidz Abdul Rahman. Also would like to thank my fellow students and friends: Sham, Mansori, Latif, Suhairi, Samsuri, Ashrif, Fairuz, Bard and Shahnan for their encouragement. Finally, I would like to thank my parents and family for their support through out my studies.



I certify that an Examination Committee has met on 26 June 2007 to conduct the final examination of Md Zaini Jamaludin on his Doctor of Philosophy thesis entitled “Design and Analysis of a Highly Sensitive Hybrid Dispersion-Compensated Erbium Doped Fiber Amplifier” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Wan Mahmood Mat Yunus, PhD

Professor
Faculty of Sains
Universiti Putra Malaysia
(Chairman)

Syed Javaid Iqba, PhD

Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Sabira Khatun, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Sahbudin Shaari, PhD

Professor
Faculty of Engineering
Universiti Kebangsaan Malaysia
(Independent Examiner)

HASANAH MOHD. GHAZALI, PhD.

Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:



This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Khazani Abdullah, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Adzir Mahdi, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Faidz Abdul Rahman, PhD

Associate Professor
Faculty of Engineering
Multimedia University
(Member)

AINI IDERIS, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 15 November 2007



DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

MD ZAINI BIN JAMALUDIN

Date:

TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	vi
ACKNOWLEDGEMENTS	ix
APPROVAL	x
DECLARATION	xii
LIST OF TABLES	xvi
LIST OF FIGURES	xvii
LIST OF ABBREVIATIONS	xxiv
CHAPTER	
1 INTRODUCTION	
1.1 Background	1.1
1.2 Problem Statement and Motivation	1.5
1.3 Scope of work	1.9
1.4 Objectives	1.11
1.5 Overview of The Thesis	1.12
2 THEORETICAL BACKGROUND AND CRITICAL REVIEW	
2.1 Introduction	2.1
2.2 Optical Amplification Fundamentals	2.2
2.2.1 Atomic Physics of Rare Earths	2.2
2.2.2 Characteristics of Erbium Doped Fiber Amplifier (EDFA)	2.15
2.2.3 Amplified Spontaneous Emission	2.21
2.2.4 Bit Error Rate (BER) and Receiver Sensitivity	2.22
2.3 Fundamental of Dispersion	2.23
2.3.1 Chromatic Dispersion	2.24
2.3.2 Compensation Techniques	2.26
2.4 Critical Review	2.32
2.4.1 Critical Review of Erbium Doped Fiber Amplifier Designs	2.32
2.4.2 Critical Review on Dispersion Compensation Technologies	2.37
2.4.3 Simulation Software	2.43
2.4.4 Variable Optical Bragg Grating	2.43
2.5 Summary	2.45



3	METHODOLOGY	
3.1	Introduction	3.1
3.2	General Approach	3.1
3.3	Equipment	3.4
3.3.1	Transmitter and Receiver	3.4
3.3.2	Optical Spectrum Analyzer (OSA)	3.5
3.3.3	Bit Error Rate Tester (BERT)	3.5
3.3.4	Pump Sources	3.6
3.3.5	Variable Optical Attenuator (VOA)	3.8
3.4	Components	3.9
3.4.1	Wavelength Selective Coupler	3.9
3.4.2	Circulators	3.10
3.4.3	Tunable Band-pass Filter	3.10
3.4.4	Erbium Doped Fiber	3.11
3.5	Parameters Under Study	3.13
3.5.1	Design Parameter	3.13
3.5.2	Performance Parameter	3.15
3.6	Summary	3.18
4	HYBRID DOUBLE- PASS COMPENSTION EDFA: DEVICE LEVEL ANALYSIS AND DISCUSSION	
4.1	Introduction	4.1
4.2	Double-pass EDFA With Internal Reflection Mechanism	4.3
4.2.1	DP-EDFA and DPF-EDFA _I : Simulation Result and Analysis	4.7
4.2.2	Experimental Results and Analysis	4.10
4.2.3	Amplifier Sensitivity	4.24
4.3	Double-pass EDFA with External Reflection Mechanism	4.26
4.3.1	Experimental Results and Analysis	4.28
4.4	Comparative Analysis Between Internal and External Configuration	4.36
4.5	Summary	4.37
5	HYBRID DOUBLE-PASS COMPENSTION EDFA: SYSTEM LEVEL ANALYSIS AND DISCUSSION	
5.1	Introduction	5.1
5.2	Single Channel Hybrid Double-pass EDFA: Internal Reflection Mechanism DPC-EDFA _I and DPF-EDFA _I	5.4
5.2.1	DP-EDFA and DPF-EDFA _I : Simulation Result and Analysis	5.7
5.2.2	Experimental Results and Analysis	5.9

5.3	Single Channel Double-pass EDFA: External Reflection Mechanism DPC-EDFA _E and DPF-EDFA _E	5.16
5.3.1	BER Analysis in relation to Power Gain and Power Penalty	5.17
5.3.2	Effect of Variation in Fiber Length on Eye Diagram	5.18
5.4	Multi-Channel (WDM) Hybrid Double-pass EDFA: Internal Reflection Mechanism DPC-EDFA _I and DPF-EDFA _I	5.24
5.4.1	Effect of Channel Spacing on Hybrid EDFA Systems	5.26
5.4.2	Effect of Transmission distance on Hybrid EDFA Systems	5.33
5.5	Multi-Channel (WDM) Double-pass EDFA: External Reflection Mechanism DPC-EDFA _E and DPF-EDFA _E	5.39
5.5.1	Analysis of Channel Spacing Effect on the Multi-Channel (WDM) Double-pass EDFA: External Reflection Mechanism DPC-EDFA _E and DPF-EDFA _E	5.41
5.5.2	Analysis of Effective transmission distance on the Multi-Channel (WDM) Double-pass EDFA : External Reflection Mechanism DPC-EDFA _E and DPF-EDFA _E	5.47
5.6	Performance Analysis between Internal and External Reflection Mechanism	5.54
5.7	Conclusion	5.55
6	CONCLUSION	
6.1	Conclusion and Achievement of Objectives	6.1
6.2	Contribution	6.4
6.3	Future Work	6.5
	REFERENCES	R.1
	APPENDICES	A.1
	BIODATA OF THE AUTHOR	B.1
	LIST OF PUBLICATIONS	P.1



LIST OF TABLES

Table		Page
2.1	Different transmission fiber types	2.39
3.1	Required minimum run time for BER measurement at different transmission speed	3.6
3.2	Specifications of the EDF used in the study	3.12
4.1	ASE and noise figure when pump power is at 100 mW and input signal power is at -40 dBm for the three configurations	4.17
4.2	Comparative analysis between the internally and externally reflected EDFA when input signal power is -40dBm at pump power 100 mW	4.36
5.1	The performance parameters of single channel double-pass EDFA at 80 km	5.19
5.2	The quality of the eye-pattern with variance in channel spacing for DPC-EDFA _I and DPF-EDFA _I at fiber length of 80 km	5.30
5.3	The quality of the eye-pattern of the hybrid EDFA after 80 km of fiber length	5.39
5.4	The quality of the eye-pattern with variance in channel spacing for DPC-EDFA _E and DPF-EDFA _E at fiber length of 80 km	5.45
5.5	The quality of the eye-pattern of the double-pass EDFA after 90 km (80 km for DP-EDFA) fiber	5.52
5.6	The system level performance of the new double-pass EDFA when compared with that of conventional DP-EDFA at BER of 10^{-9}	5.54



LIST OF FIGURES

Figure		Page
1.1	The K-chart shows the study model for the scope of work that was undertaken in this study	1.10
2.1	Absorption cross-section versus wavelength of Er^{3+} ion	2.3
2.2	The energy level diagram of the erbium ions showing absorption and radiative transitions. The transitions wavelengths in nanometers and possible pump bands	2.4
2.3	Schematic representation of the splitting of the $4f^N$ ground configuration under the effect of progressively weaker perturbations, the atomic and crystal field Hamiltonians	2.5
2.4	Atom with respective energy level (A) light absorption and (B) light emission.	2.8
2.5	Simplified energy-level and various transition processes of Er^{3+} ions in silica	2.9
2.6	Energy level system corresponding to three-level system	2.13
2.7	Dispersion in a standard single-mode optical fiber as a function of wavelength	2.26
2.8	Pre-compensated dispersion maps using a DCF in a fiber span	2.27
2.9	Post- compensation dispersion maps and power maps using DCF in the fiber span	2.28
2.10	Chirped fiber Bragg grating used as dispersion compensator	2.30
2.11	Chromatic dispersion compensation can be accomplished (A) placing the CFBG in the post-compensation (B) pre compensation position in the fiber span.	2.31
2.12	CFBG for compensating multiple wavelengths in a Wavelength Division Multiplexing (WDM) system	2.31

2.13	The reflection spectrum of CFBG used in the study	2.32
2.14	The reflection spectrum of VOBG taken from OSA shows the -3dB bandwidth is 0.2nm.	2.44
3.1	Experimental setup associating with transmitter, receiver and BERT	3.5
3.2	Experimental set-up for launched pump power measurement	3.7
3.3	Output/pump power response for current applied to 980 nm pump source	3.8
3.4	Characteristics of the WSC used in the experiment	3.9
3.5	The circulator used in the experiment	3.10
3.6	The wavelength spectrum of the TBF used in the experiment	3.11
3.7	The input signal of the single channel transmission system of -5 dBm	3.14
3.8	The input signal of -5 dBm with (A) channel spacing of 0.4 nm and (B) channel spacing of 0.2 nm respectively	3.15
3.9	The back-to-back eye-pattern of the input signal used in the experiment. The scales were sets at 60 ps/division on the x-axis and 10 μ W/division on the y-axis	3.17
4.1	The study plan of the experimental works	4.1
4.2	Experimental configuration of the Double-pass EDFA (A) with circulator C2 creating the double-pass effect, (B) with VOBG creating the double-pass effect only by reflecting the selected wavelength and (C) with CFBG creating the double-pass and compensation effect by reflecting the selected wavelength	4.4
4.3	The reflection spectrum of CFBG with center wavelength of 1550.3 nm	4.6



4.4	Output trace of DPC-EDFA _I system when input signal is fixed to -45 dBm.	4.7
4.5	Gain and noise figure against pump power for DP-EDFA and DPF-EDFA _I when input power is at -40 mW	4.8
4.6	The plot of gain (shaded symbols) and noise figure (clear symbols) vs. input power at pump power of 100 mW	4.9
4.7	OSNR verses input power when pump power is at 100 mW	4.9
4.8	The gain vs. pump power for input power of -10 dBm and -40 dBm obtained from DPC-EDFA _I , DPF-EDFA _I and DP-EDFA. The shaded symbols are gain when input signal is -40 dBm while clear symbols are gain when input signal is -10 dBm	4.10
4.9	The noise figure vs. pump power for input power of -10 dBm and -40 dBm obtained from DPC-EDFA _I , DPF-EDFA _I and DP-EDFA. The shaded symbols are noise figure when input signal is -40 dBm while clear symbols are noise figure when input signal is -10 dBm	4.13
4.10	Output power against pump power for input signal of -40 dBm (shaded symbol) and -10 dBm (clear symbol) for DPC-EDFA _I , DPF-EDFA _I and DP-EDFA	4.14
4.11	ASE level verses pump power for the three double-pass EDFA configurations at input signal power of -10 dBm (clear symbols) and -40 dBm (shaded symbols)	4.16
4.12	Gain conversion efficiency of the three double-pass EDFA configurations over consumed pump power for input signal of -40 dBm (shaded symbols) and -10 dBm (clear symbols)	4.18
4.13	The plot of gain (shaded symbols) and noise figure (clear symbols) vs. input signal at pump power of 100 mW	4.20
4.14	Output power and ASE against input signal power when the pump power is at 100 mW	4.22
4.15	OSNR against input power for all three configurations	4.24



when pump power is at 100mW

4.16	BER against the modulated input signal power for all three configurations	4.25
4.17	Experimental configuration of the Double-pass EDFA (A) with VOBG to filter (DPF-EDFA _E) the selected wavelength, (B) with CFBG providing compensation (DPC-EDFA _E) effect by filtering the selected wavelength	4.27
4.18	Gain (shaded symbols) and noise figure (clear symbols) performance verses pump power when input signal is at -40 dBm for DPC-EDFA _E , DPF-EDFA _E and DP-EDFA	4.28
4.19	Output power verses the pumping configurations for input signal of -40 dBm	4.29
4.20	Gain conversion efficiency verses pump power when input power is at -40 dBm	4.30
4.21	Signal-to-noise ratio (SNR) (shaded symbols) and ASE (clear symbols) verses pump power when input signal is at -40 dBm	4.32
4.22	Gain and noise figure versus input signal power when pump power is 100 mW	4.33
4.23	Output power and ASE performance of the three double pass EDFA configurations at different input signal powers when the pump power is 100 mW	4.35
5.1	The K-chart study plan of transmission system level testing and analysis	5.2
5.2	The single channel system set-up (A) DP-EDFA (B) DPF-EDFA _I and (C) DPC-EDFA _I	5.5
5.3	The schematic diagram of (A) DP-EDFA and (B) DPF-EDFA _I	5.8
5.4	The plot of BER verses power received for both DP-EDFA and DPF-EDFA _I from simulation	5.9
5.5	The BER versus power received for input power of -10 dBm over the distance of 80 km	5.10

5.6	The eye-pattern of (A) 80 km (without amplifier), (B) DP-EDFA, (C) DPC-EDFA _I and (D) DPF-EDFA _I . The scales were set at 60 ps/division on x-axis and 10 μ W/division on y-axis	5.12
5.7	The plot of eye-amplitude versus fiber length for DPC-EDFA _I , DPF-EDFA _I and DP-EDFA	5.12
5.8	(A) The eye-width versus fiber length and (B) Optical signal-to-noise ratio (SNR) versus fiber length for DPC-EDFA _I , DPF-EDFA _I and DP-EDFA	5.14
5.9	The graph of Jitter versus fiber length for DPC-EDFA _I , DPF-EDFA _I and DP-EDFA for single channel transmission system	5.16
5.10	The graph of BER versus power received for DPC-EDFA _E , DPF-EDFA _E , DP-EDFA and SMF80km (without amplifier)	5.18
5.11	The eye-patterns taken after the fiber span of 80 km for (A) 80 km, (B) DP-EDFA, (C) DPF-EDFA _E and (D) DPC-EDFA _E . The scales were sets at 60 ps/division on x-axis and 10 μ W/division on y-axis	5.19
5.12	The eye-amplitude versus fiber length of DP-EDFA, DPF-EDFA _E and DPC-EDFA _E	5.20
5.13	The eye-pattern of DP-EDFA over 90 km of fiber. The scales were sets at 60 ps/division on x-axis and 10 μ W/division on y-axis	5.21
5.14	The eye-width versus fiber length for DP-EDFA, DPF-EDFA _E and DPC-EDFA _E	5.22
5.15	The OSNR versus fiber length for DP-EDFA, DPF-EDFA _E and DPC-EDFA _E	5.22
5.16	The jitter versus fiber length of DP-EDFA, DPF-EDFA _E and DPC-EDFA _E	5.23
5.17	The multi-channel (WDM) transmission system of hybrid double-pass EDFA (A) DPF-EDFA _I (B) DPC-EDFA _I	5.25



5.18	The OSNR of (A) 0.8 nm (B) 0.4 nm and (C) 0.2 nm channel spacing of the multi-channel for hybrid EDFA system(DPC-EDFA _I)	5.27
5.19	The OSNR versus Channel Spacing for multi-channel hybrid EDFA transmission system for DPC-EDFA _I	5.28
5.20	The eye-pattern of the DPF-EDFA _I transmission system with variation in channel spacing (A) 0.2 nm, (B) 0.4 nm and (C) 0.8 nm respectively. The scales were sets at 60 ps/division on x-axis and 10 μ W/division on y-axis	5.29
5.21	The eye-pattern of the DPC-EDFA _I transmission system when the channel spacing has been varied from (A) 0.2nm, (B) 0.4 nm and (C) 0.8 nm respectively. The scales were sets at 60 ps/division on x-axis and 10 μ W/division on y-axis	5.30
5.22	The BER versus power received for DPC-EDFA _I and DPF-EDFA _I for 0.8 and 0.4 nm channels spacing with 80 km fiber	5.31
5.23	The BER versus fiber length of DPC-EDFA _I , DPF-EDFA _I and DP-EDFA for channel spacing of 0.8 nm (clear symbol) and 0.4 nm (shaded symbol) channels spacing at -29 dBm received power	5.34
5.24	Jitter versus fiber length of hybrid EDFA at 0.8 (clear symbol) and 0.4 nm (shaded symbol) channel spacings	5.35
5.25	The graph of eye-amplitude versus fiber length for hybrid EDFA with channel spacing of 0.8 (clear symbol) and 0.4 nm (shaded symbol)	5.37
5.26	The plot of Eye-opening versus fiber length for hybrid EDFA with channel spacing of 0.8 (clear symbol) and 0.4 nm (shaded symbol)	5.38
5.27	The plot of Signal-to-noise ratio versus fiber length for hybrid EDFA with channel spacing of 0.8 (clear symbol) and 0.4 nm (shaded symbol)	5.38
5.28	The multi-channel testing of double-pass EDFA (A) DPC-EDFA _E and (B) DPF-EDFA _E	5.41
5.29	The effect of OSNR with channel spacing of (A) 0.8 nm (B)	5.43



	0.4 nm and (C) 0.2 nm for DPC-EDFA _E	
5.30	Plot of OSNR versus channel spacing for multi-channel DPC-EDFA _E	5.43
5.31	The eye-pattern of DPF-EDFA _E with variation in the channel spacing from 0.2 to 0.8 nm respectively	5.44
5.32	The eye-pattern of DPC-EDFA _E with variation in the channel spacing from 0.2 nm to 0.8 nm respectively	5.45
5.33	BER versus power received of DPC-EDFA _E , DPF-EDFA _E and DP-EDFA for 0.8 and 0.4 nm channel spacings after 80km of SMF	5.46
5.34	The plot of jitter versus fiber length of multi channel double-pass EDFA at different channel spacing	5.48
5.35	The plot of eye-amplitude versus fiber length of multi channel double-pass EDFA at different channel spacing	5.49
5.36	The plot of eye-amplitude versus fiber length of multi channel double-pass EDFA at different channel spacings	5.50
5.37	The plot of OSNR versus fiber length of multi channel double-pass EDFA at different channel spacings	5.51
5.38	The BER versus fiber length of DPC-EDFA _E , DPF-EDFA _E and DP-EDFA for channel spacing of 0.8 nm (clear symbol) and 0.4 nm (shaded symbol) at -29 dBm received power	5.53

LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BER	Bit-error rate
BERT	Bit-error rate tester
BPF	Band-pass filter
CD	Chromatic dispersion
CFBG	Chirp Fiber Bragg grating
DCA	Digital communication analyzer
DCF	Dispersion compensation fiber
DFB	Distributed feedback laser
DP-EDFA	Double-pass - Erbium-doped fiber amplifier
DPC-EDFA _I	Double-pass CFBG- Erbium-doped fiber amplifier internal
DPC-EDFA _E	Double-pass CFBG- Erbium-doped fiber amplifier external
DPF-EDFA _I	Double-pass VOBG- Erbium-doped fiber amplifier internal
DPF-EDFA _E	Double-pass VOBG- Erbium-doped fiber amplifier external
DSF	Dispersion shifted fiber
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
EMI	Electromagnetic interference

