ENHANCEMENT OF THE OPTICAL TRANSMISSION SYSTEM UTILIZING A DUAL-FUNCTION REMOTELY PUMPED ERBIUM-DOPED FIBER AMPLIFIER

By

AHMED WATHIK NAJI AL-KAISSI

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

December 2006

In the Name of God, Most Gracious, Most Merciful

Dedication

To my parents, for their support and encouragement.

To my beloved wife and my sons,

My brother, sister and my friends for their

encouragement and love.

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

ENHANCEMENT OF THE OPTICAL TRANSMISSION SYSTEM UTILIZING A DUAL-FUNCTION REMOTELY PUMPED ERBIUM-DOPED FIBER AMPLIFIER

By

AHMED WATHIK NAJI AL-KAISSI

December 2006

Chairman: Associate Professor Mohd Adzir Mahdi, PhD

Faculty: Engineering

Optical fiber communication system is an active research area for its high demand especially in the long-haul communication system. A lot of work has been done to improve the optical transmission system (OTS) as a long-haul system using remotely-pumped Erbium-Doped Fiber Amplifier (R-EDFA) and Distributed Raman Amplification (DRA). Despite these achievements, there is still room for enhancements and developments to solve the existing system's problems.

This work presents a thorough research on OTS using hybrid R-EDFA and DRA approach. The research work includes gain enhancing technique under low pump power, enhanced dispersion compensating technique, new R-EDFA location-optimization technique, and a figure of merit is introduced to determine the optimal setting for R-EDFA with respect to its practical applications (Post- and Pre-amplifier).

Various designs for low pump R-EDFA are proposed and investigated in this research work. A dual-function R-EDFA configuration, in which a Chirped Fiber Bragg Grating (CFBG) is placed inside the R-EDFA configuration, is demonstrated in this research work. This configuration offers two functions at the same time, where it can achieve both double-pass amplification technique as well as dispersion compensating technique. A practical comparative analysis is conducted to compare the performance of the newly developed configuration with the conventional R-EDFA configurations, this configuration is found to give better performance compared to the conventional amplifier configurations, where a gain of 23 dB is achieved for input signal power of less than -35 dBm at only 10 mW pump power. Since the location of R-EDFA has a high impact on the total transmission distance, a new technique is proposed to find the optimum location of R-EDFA, where a location close to the receiver is found to give a longer distance.

In this research work, many configurations of OTS are developed and presented. A maximum transmission distance of 293 km is achieved using an optimized OTS which utilizes dual-function R-EDFA at 2.5 Gbps. A bit error rate (BER) is used as the main performance parameter with a threshold value of better than 10^{-10}. In addition to that, a mathematical modeling for this optimized configuration is carried out in this research work, which deals with the post- and pre-length of the system as well as the R-EDFA and DRA.

Finally, in order to evaluate further the performance of the optimized configuration with respect to the previous systems, a new performance parameter called Pump Power Consumption (PPC) is introduced. This optimized OTS configuration has a better PPC (0.682 mW/km) compared to the previous OTS.

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

PENAMBAHBAIKAN SISTEM PENGHANTARAN OPTIK MENGGUNAKAN PENGUAT GENTIAN TERDOP ERBIUM DWI-FUNGSI DENGAN PAM JARAK JAUH

Oleh

AHMED WATHIK NAJI AL-KAISSI

Disember 2006

Pengerusi: **Profesor Madya Mohd Adzir Mahdi, PhD**

Fakulti: **Kejuruteraan**

Sistem komunikasi gentian optik adalah satu bidang penyelidikan yang aktif kerana permintaan yang tinggi terutamanya bagi sistem komunikasi jarak jauh. Banyak usaha telah dilakukan untuk memperbaiki system penghantaran (OTS) menggunakan penguat gentian terdop erbium dengan pam jarak jauh (R-EDFA) dan penguat teragih Raman (DRA). Walaubagaimanapun, masih terdapat ruang untuk peningkatan dan pembangunan untuk menyelesaikan masalah di dalam sistem yang sedia ada.

Usaha ini mengandungi penyelidikan yang teliti ke atas OTS menggunakan pendekatan gabungan R-EDFA dan DRA. Kerja-kerja penyelidikan termasuklah teknik meningkatkan penggandaan pada kuasa pam yang rendah, teknik peningkatan mengurangkan serakan, teknik pengoptimum lokasi R-EDFA, dan bentuk merit yang

baru untuk menentukan pengesetan yang optimum untuk R-EDFA selari dengan aplikasi yang praktikal (Penguat Pasca dan Pra).

Pelbagai rekabentuk untuk pam jarak jauh berkuasa rendah R-EDFA dicadangkan dalam usaha penyelidikan ini. Konfigurasi pam jarak jauh R-EDFA dwi fungsi yang baru dengan parutan pecahan gentian Bragg (CFBG) yang diletakkan di dalam konfigurasi R-EDFA di persembahkan di dalam usaha penyelidikan ini. Konfigurasi ini menawarkan dua fungsi serentak, di mana ia boleh mencapai penggandaan dwi-laluan dan juga teknik nyah serakan. Satu analisa pembandingan telah dijalankan untuk membandingkan prestasi konfigurasi dengan konfigurasi konvensional R-EDFA. Konfigurasi yang baru dibangunkan ini didapati memberikan prestasi yang lebih baik dibandingkan dengan konfigurasi konvensional dimana penggandaan sebanyak 23 dB telah dicapai semasa kuasa isyarat masukan sebanyak -35 dBm dengan hanya 10 mW kuasa pam. Memandangkan lokasi R-EDFA mempunyai impak yang tinggi terhadap jarak penghantaran, satu teknik pengoptimum lokasi R-EDFA telah dicadang. Lokasi R-EDFA yang dekat dengan penerima didapati memberikan jarak penghantaran yang lebih jauh.

Dalam usaha pnyelidikan ini, banyak rekabentuk OTS telah dibangunkan dan dipersembahkan. Jarak penghantaran maksimum sebanyak 293 km dicapai dengan menggunakan OTS optimum, termasuklah sebuah pam jarak jauh R-EDFA dwi-fungsi semasa kadar bit 2.5 Gbps. Kadar ralat bit (BER) digunakan sebagai parameter prestasi utama dengan kadar had yang lebih baik daripada 10^{-10}. Selain dari itu, satu model matematik untuk rekabentuk ini telah dilakukan dalam usaha penyelidikan ini,

berhubung dengan jarak pasca dan pra sistem dan juga R-EDFA dan DRA. Akhir sekali, untuk menilai prestasi seterusnya untuk rekabentuk ini dengan kaitan dengan sistem sebelumnya, parameter prestasi yang baru dipanggil penggunaan kuasa pam (PPC) diperkenalkan. Rekabentuk ini didapati memberikan PPC yang lebih baik (0.682 mW/km) berbanding dengan rekabentuk sebelum ini.

ACKNOWLEDGEMENTS

In the name of God, Most Gracious, Most Merciful

The author would like to express his utmost thanks and gratitude to Almighty Allah S.W.T for giving him the ability to finish this project successfully.

The author gratefully wishes to express his profound appreciation and gratitude to his supervisor Associate Professor Dr. Mohd Adzir Mahdi for his affectionate guidance, prompt decision and supervision throughout the duration of this project until it turned to real success.

The author is also indebted to the members of his supervisory committee, Associate Professor Dr. Mohd Khazani Abdullah and Dr. Syed Javaid Iqbal for their valuable assistance during this period.

Appreciation also to the assistance rendered by the respective lecturers, staff, and all friends in the Photonic and Fiber Optics System Laboratory of the Faculty of Engineering for providing the facilities required for undertaking this project.

The author would like to thank his family for the encouragement and support for making this project a success, and not forgetting his friends for their invaluable support.

I certify that an Examination Committee has met on 7th December 2006 to conduct the final examination of Ahmed Wathik Naji on his Doctor of Philosophy thesis entitled "Enhancement of the Optical Transmission System Utilizing a Dual-Function Remotely Pumped 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:

Abd. Rahman Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sudhansh Shekar Jamuar, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Borhanuddin Mohd Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Shabudin Shaari, PhD
Professor
Institute of Nanoelectric and Micro Engineering
Universiti Kebangsaan Malaysia
(External Examiner)

_____
HASANAH MOHD. GHAZALI, PhD
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 18 JANUARY 2007

This thesis 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 Supervisory Committee are as follows:

Mohd Adzir Mahdi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Khazani Abdullah, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Syed Javaid Iqbal, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 8 FEBRUARY 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.

_____

AHMED WATHIK NAJI AL-KAISSI

Date: 18 DECEMBER 2006

TABLE OF CONTENTS

		Page
ABSTRACT		ii
ABSTRAK		v
ACKNOWLEDGEMENTS		viii
APPROVAL		ix
DECLARATION		xi
LIST OF TABLES		xv
LIST OF FIGURES		xvi
LIST OF ABBREVIATIONS		xx
CHAPTER		
1	**INTRODUCTION**	
1.1	Background	2
1.2	Advantages of Optical Fiber Transmission	2
1.3	Principles of Optical Fibers Transmission Systems	4
1.3.1	Repeatered Optical Transmission System	5
1.3.2	Unepeated Optical Transmission System	6
1.4	The differences between remotely-pumped and locally-pumped EDFA	9
1.5	Problem Statement and Critical Review	10
1.6	Research Objectives	11
1.7	Scope of Work	12
1.7	Organization of the Thesis	13
2	**LITERATURE REVIEW**	
2.1	Introduction	14
2.2	Optical Fiber Transmission System	14
2.3	Important Factors in OFCS	15
2.3.1	Attenuation	15
2.3.2	Optical Signal Dispersion	21
2.4	Loss Compensating Techniques in OFCS	23
2.4.1	Doped Fiber Amplifiers	23
2.4.2	Raman Amplification	38
2.5	Dispersion Compensating Techniques in OFCS	43
2.5.1	Dispersion Compensating Fiber	44
2.5.2	Chirped Fiber Bragg Gratings	45
2.5.3	Higher Order Spatial Mode Compensators	46
2.5.4	Bulk Optic Phased Array	47
2.6	Optical Transmission System	47
2.7	Summary	58

3 RESEARCH METHODOLOGY

3.1 Introduction 60
3.2 Remotely-pumped Erbium Doped Fiber Amplifier 62
3.2.1 Post R-EDFA 62
3.2.2 Pre R-EDFA 63
3.3 Distributed Raman Amplification 63
3.4 Optimization of R-EDFA Location 64
3.5 Optical Transmission System 65
3.6 Parameter Under Study 67
3.6.1 Design Parameters 67
3.6.2 Performance Parameters 69
3.8 Summary 71

4 OPTICAL AMPLIFIERS

4.1 Introduction 72
4.2 Erbium Doped Fiber Amplifier 72
4.2.1 Pump Power Effect on Gain and Noise Figure 74
4.2.2 Figure of Merit for Optical Amplifiers 79
4.3 Post Remotely Pumped Erbium Doped Amplifier 80
4.4 Pre Remotely Pumped Erbium Doped Amplifier 82
4.4.1 Comparison between CFBG and TBF 86
4.4.2 Comparison between Single-stage and Double-stage configuration 88
4.4.3 Finding The Optimum EDF length 90
4.4.4 Finding The Operating Pump Power 92
4.5 Raman Amplifier 94
4.6 Summary 97

5 OPTICAL TRANSMISSION SYSTEM

5.1 Introduction 98
5.2 R-EDFA Location 98
5.2.1 Development of BER Scanning Technique to Optimize R-EDFA location 99
5.2.2 Verification of The BER Scanning Technique For different R-EDFA configurations 104
5.3 Optical Transmission System configuration 106
5.3.1 Optical Transmission System using Pre R-EDFA 107
5.3.2 Impact of Distributed Raman Amplifier 108
5.3.3 Impact of Post R-EDFA 109

5.4 Optimized Design of Optical Transmission System 114
5.5 Summary 118

6 MATHEMATICAL MODELING
6.1 Introduction 119
6.2 System Description 119
6.3 Modeling of the Optical Transmission System 121
6.3.1 Modeling of the Post-length 121
6.3.2 Modeling of the Pre R-EDFA 122
6.3.3 Modeling of the pre-length 129
6.4 Summary 133

7 CONCLUSION AND FUTURE WORK
7.1 Conclusion 134
7.2 Future Work 136

REFERENCES 137
APPENDICES 148
BIODATA OF THE AUTHOR 164
LIST OF PUBLICATIONS 165

LIST OF TABLES

Table		Page
1.1	The differences between locally- and remotely-pumped EDFA	10
2.1	Optical transmission experiments over the past few years	57
4.1	Comparison between CFBG and TBF	86
4.2	The residual pump power with ON and OFF input signal	95
5.1	Experimental Details of optimizing the location of post R-EDFA	111
5.3	Pump Power Consumption for the previous optical systems	118
6.1	EDF parameters used to simulate the R-EDFA	123
6.2	The values of the SMF parameters which is used to simulate DRA	130

LIST OF FIGURES

Figure		Page
1.1	Long distance repeatered optical transmission system	5
1.2	Unrepeatered optical fiber transmission system	6
1.3	Local-pumped EDFAs optical transmission system	7
1.4	Remotely-pumped EDFAs optical transmission system	8
1.5	Scope of research work	12
2.1	Total attenuation of a silica glass fiber versus signal wavelength.	17
2.2	Rayleigh scattering, showing attenuation of an incident stream of photons owing to localized variations in refractive index	18
2.3	Macrobending	20
2.4	Microbending	20
2.5	Energy levels of Erbium ions with possible pump bands	26
2.6	Atom with respective energy level	28
2.7	Schematic representations of absorption and emission between energy level	30
2.8	Population in a two energy levels system	32
2.9	Energy level of two-levels system	33
2.10	Two possible configurations of a single-pass EDFA	37
2.11	Raman amplification energy level diagram	40
2.12	Dispersion compensation of a chirped bragg grating	45
2.13	A typical CFBG reflection and transmission light	46

2.14	Configuration of optical transmission system	49
2.15	Signal power evolution experienced by forward DRA and post R-EDFA	50
2.16	Signal power evolution experienced by backward DRA and pre R-EDFA	51
2.17	Various configurations of optical transmission systems	52
3.1	Flowchart of the research methodology.	61
4.1	Experimental setups of EDFAs	73
4.2	Gain and noise figure against pump power at -22 dBm input signal power	76
4.3	Gain and noise figure against input signal power at 40 mW pump power, the input signal wavelength is 1550.3 nm	78
4.4	Figure of merit against input power at 40 mW pump power	80
4.5	Gain and noise figure against pump power at -10 dBm input power	81
4.6	Configuration of single-stage and double-pass pre R-EDFA with CFBG	82
4.7	The procedure of setting the two points (plus and minus) of the noise figure mask of OSA	85
4.8	Gain and noise figure against pump power at -30 dBm input power and 13.5 m EDF for single-stage and double-pass pre R-EDFA with TBF and CFBG configurations	87
4.9	Configuration of double-stage pre R-EDFA with CFBG	89
4.10	Gain and noise figure against pump power at -30 dBm input power and 13.5 m EDF for single- and double-stage pre R-EDFA configurations	89
4.11	Gain and noise figure against pump power at -30 dBm input power	90

4.12	Gain and noise figure against input signal power at 10 mw pump power	90
4.13	Characterization of the DP R-EDFA with CFBG	93
4.14	Experimental setup of Raman amplification	94
4.15	Raman gain of 64 and 51 km transmission fiber	96
4.16	Output signal power with and without Raman against signal wavelength	97
5.1	Experimental configuration for optimizing R-EDFA location in optical transmission link	100
5.2	BER against total transmission loss	102
5.3	Total transmission loss against SP R-EDFA location, the inset shows the eye-diagram of the received signal for BER better than 10^{-10}	103
5.4	Achievable total transmission loss at BER better than 10^{-10} over R-EDFA locations for three R-EDFA's configurations at 30 mW pump power	105
5.5	Configuration of optical transmission system using pre R-EDFA only	107
5.6	Configuration of optical transmission system using hybrid pre R-EDFA and backward DRA	108
5.7	Configuration of optical transmission system using post and pre R-EDFA with backward DRA	109
5.8	Configuration of optical transmission system which is used to optimize the post R-EDFA location	110
5.9	Output signal power against transmitted signal power	111
5.10	The experimental setup which is used to investigate the effect of SPM	112
5.11	BER against received power	113

5.12	The power penalty due to SPM effect against transmitted signal power at BER of 10^{-10}	113
5.13	Configuration of optimized optical transmission system utilizing booster and hybrid pre R-EDFA with backward DRA	114
5.14	The evolution of the signal power level along the 293 km transmission line	115
5.15	The spectrum of the received signal at the receiver	116
5.16	BER against received signal power for 293 km OTS	117
6.1	Optimized optical transmission system utilizing pre R-EDFA with backward DRA	120
6.2	Signal power along the post-length from analytical modeling. From function post of MatLab program	121
6.3	Upper state population and ground state population	124
6.4	Forward and backward signal power in dBm as a function of position in a 13.5 m Erbium doped fiber. From analytical modeling using function edfa of MatLab program	127
6.5	Forward and backward ASE power in mW as a function of position in a 13.5 m erbium doped fiber. From analytical modeling using function edfa of MatLab program	128
6.6	Signal power with and without Raman in dB as a function of position along the 51.91 km of pre-length. From analytical modeling using function raman of MatLab program	131
6.7	The overall practical and theory signal power propagation in dBm as a function of position along the whole optical transmission system	132

LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
BERT	Bit Error Rate Tester
CFBG	Chirped Fiber Bragg Grating
DCF	Dispersion Compensating Fiber
DRA	Distributed Raman Amplification
DUT	Device Under Test
DP R-EDFA	Double-pass Remotely-pumped EDFA
Er^{3+}	Erbium
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
FEC	Forward Error Correction
FOM	Figure of Merit
G	Gain
GCE	Gain Coefficient Efficiency
G_R	Raman Gain
LD	Laser Diode
L-EDFA	Locally-pumped EDFA

NA	Numerical Aperture
NF	Noise Figure
OFCS	Optical Fiber Communication System
OTS	Optical Transmission System
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
PRBS	Pseudo-Random Bit Sequence
PCE	Power Conversion Efficiency
PD	Photo-diode
Pp	Pump power
PPC	Pump Power Consumption
R-EDFA	Remotely-pumped EDFA
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SP R-EDFA	Single-pass Remotely-pumped EDFA
SMF	Single Mode Fiber
TLS	Tunable Laser Source
TBF	Tunable Band-pass Filter

VOA	Variable Optical Attenuator
WDM	Wavelength Division Multiplexing
WSC	Wavelength Selective Coupler