UNIVERSITI PUTRA MALAYSIA

ENHANCED STRUCTURE FOR DISCRETE AND REMOTE L-BAND ERBIUM-DOPED FIBER AMPLIFIERS

NELIDYA MD. YUSOFF

ENHANCED STRUCTURE FOR DISCRETE AND REMOTE L-BAND ERBIUM-DOPED FIBER AMPLIFIERS

By

NELIDYA MD. YUSOFF

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

August 2013

Special dedication to;

Mohd. Heemi Fazeree

Lya Umaira

Lya Rihanna

Rizq Dhani

Bapak

Mak

Papa

Mama

Adelina

Fezraal

Elaisya

Izziara

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

ENHANCED STRUCTURE FOR DISCRETE AND REMOTE L-BAND ERBIUM DOPED FIBER AMPLIFIERS

By

NELIDYA MD. YUSOFF

August 2013

Chairman: **Professor Mohd. Adzir Mahdi, Phd**

Faculty: **Engineering**

The growth of data traffic and Internet forces the telecommunication window to widen up in order to accommodate the increasing number of channels in wavelength division multiplexing network systems. This however requires wide bandwidth optical amplifiers with flat gain spectrum for multiwavelength signals to propagate simultaneously. Unfortunately, the accumulation of attenuation inside the fiber (0.2 dB/km) restricts the accessible distance of the transmitted signal and thus, causes the system performance to drop tremendously. Erbium-doped fiber amplifier (EDFA), which is able to boost the transmitted signal for longer communication distance at low pump power with significant wideband gain, is identified as an alternative to overcome the drawbacks caused by the electronic repeaters.

This research work focuses on designing and developing two different structures of L-band EDFA which are discrete and remote. A flat L-band gain response is the main target in both designs with high gain, low noise figure (NF) and high optical signal-to-noise ratio. For discrete L-band EDFA, the research concentrates on designing and developing a dual-stage EDFA where a new pumping scheme utilizing distributed pumping concept is introduced. This pumping scheme uses power coupler to distribute the pump power between two different amplifier stages with different lengths of erbium-doped fiber. Optimizations of the splitting ratios, erbium doped fiber lengths and pump power are required in order to achieve better performance over the L-band region. This dual-stage EDFA utilizing distributed pumping scheme offers gain and NF improvement of 1.2 dB and 5 dB respectively with better gain flatness of less than 0.4 dB when compared with the conventional single-stage EDFA. As conclusion, this dual-stage EDFA utilizing distributed pumping scheme is cost efficient as it only implements a single pump laser in the design and it does not require any gain equalizing filter to attain a reasonably flat gain response over the entire L-band region.

For the other amplifier structure, the work focuses on designing and developing a remotely pumped EDFA (R-EDFA) that works at low pump power and at the same time has the ability to compensate dispersion. Due to attenuation and scattering effects that occur in the transmission fiber, a reduced 1497 nm Raman pump power is delivered to pump the R-EDFA. The presence of Raman effects in the L-band wavelength range helps to boost up the propagated signal for higher transmission gain and optical signal-to-noise ratio at the output of the proposed R-EDFA. L-band multiwavelength dispersion compensation module is used as signal reflector to form a double-pass amplifier structure and also as dispersion compensator. The work successfully demonstrates that the gain and NF are improved by 5.55 dB and 4.03 dB respectively with 4.24 dB gain flatness in comparison to conventional R-EDFA. In addition, the proposed amplifier also has the ability to compensate overall dispersion in the transmission fiber.

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

STRUKTUR DIPERTINGKAT UNTUK PENGUAT-PENGUAT GENTIAN TERDOP ERBIUM JALUR L DISKRIT DAN JARAK JAUH

Oleh

NELIDYA MD. YUSOFF

Ogos 2013

Pengerusi: **Professor Mohd. Adzir Mahdi, Phd**

Fakulti: **Kejuruteraan**

Pembangunan trafik data dan Internet telah memaksa tetingkap telekomunikasi untuk diluaskan bagi menampung peningkatan jumlah saluran dalam sistem rangkaian pemultipleksan bahagian panjang gelombang. Bagaimanapun, ini memerlukan penguat-penguat optik dengan lebar jalur yang luas dan gandaan spektrum yang rata bagi memancarkan isyarat gelombang pelbagai secara serentak. Malangnya, pengecilan yang terkumpul di dalam gentian (0.2 dB/km) menghadkan jarak yang boleh dicapai oleh isyarat yang dihantar, lantas menyebabkan prestasi sistem merosot secara mendadak. Penguat gentian terdop Erbium (EDFA) yang berupaya untuk meningkatkan isyarat terpancar untuk komunikasi jarak yang lebih jauh pada kuasa pengepaman rendah beserta gandaan jalur luas yang ketara, dikenalpasti sebagai satu penyelesaian yang berpotensi untuk mengatasi kelemahan yang berpunca dari pengulang-pengulang elektronik.

Kajian ini memfokus kepada merekacipta dan menghasilkan dua struktur EDFA jalur L yang berbeza iaitu diskrit dan jarak jauh. Tindakbalas gandaan rata jalur L adalah sasaran utama dalam kedua-dua rekaan dengan gandaan tinggi, bacaan hingar (NF) rendah dan nisbah isyarat-kepada-hingar. Bagi EDFA jalur L diskrit, kajian ini tertumpu kepada merekacipta dan menghasilkan sebuah EDFA dwi-peringkat di mana skim pengepaman baru yang digelar konsep pengepaman teragih telah diperkenalkan. Skim pengepaman ini menggunakan pengganding kuasa untuk mengagihkan kuasa pam di antara dua peringkat penguat yang berbeza dengan panjang gentian terdop Erbium yang berbeza. Nisbah pengagihan, panjang EDF dan kuasa pam perlu dioptimumkan bagi mencapai prestasi yang lebih baik sepanjang rantau jalur L. EDFA dwi-peringkat ini yang menggunakan skim pengepaman teragih menawarkan penambahbaikan gandaan dan NF sebanyak 1.2 dB dan 5 dB masing-masing dengan gandaan rata yang lebih baik iatu kurang daripada 0.4 dB apabila dibandingkan dengan EDFA konvensional peringkat tunggal. Sebagai kesimpulan, EDFA dwi-peringkat yang menggunakan skim pengepaman teragih ini adalah kos efisyen kerana ia hanya menggunakan pam laser tunggal di dalam rekaan dan ia tidak memerlukan sebarang penapis gandaan sama rata bagi mendapatkan sebuah respon gandaan rata yang boleh diterima pada keseluruhan rantau jalur L.

Untuk struktur penguat seterusnya, kajian memfokus kepada merekacipta dan menghasilkan sebuah EDFA pengepaman jarak jauh (R-EDFA) yang beroperasi pada kuasa pam rendah dan pada masa yang sama mempunyai kebolehan untuk memampas penyebaran. Disebabkan oleh kesan-kesan pengecilan dan penyerakan yang berlaku di dalam gentian penghantaran, pam kuasa terkurang telah dihantar kepada pengepam EDFA tersebut pada 1497 nm. Kehadiran kesan-kesan Raman di dalam julat panjang gelombang jalur L membantu untuk meningkatkan isyarat terpancar bagi gandaan penghantaran yang lebih tinggi dan OSNR pada keluaran R-EDFA yang diusulkan. Gelombang pelbagai modul pampasan penyebaran jalur L telah digunakan sebagai pemantul isyarat untuk membentuk sebuah struktur penguat laluan berganda dan juga sebagai pemampas penyebaran. Kajian ini telah berjaya menunjukkan yang gandaan dan NF meningkat sebanyak 5.55 dB dan 4.03 dB masing-masing dengan 4.24 dB kerataan gandaan semasa perbandingan dibuat dengan R-EDFA konvensional. Sebagai tambahan, penguat yang dicadangkan juga mempunyai kebolehan untuk memampas keseluruhan penyebaran di dalam gentian penghantaran.

ACKNOWLEDGEMENTS

Alhamdulillah, all praise is due to Allah for the strengths and His blessings in completing this thesis successfully. My sincerest appreciation goes to my supervisor, Professor Dr. Mohd Adzir Mahdi, for his supervision and continuous support. His priceless guidance, useful ideas and constructive suggestions throughout the years have ultimately brought this amazing journey to its end. In addition, my gratitude goes to my co-supervisors, Associate Professor Dr-Ing. Ahmad Fauzi Abas and Associate Professor Dr. Salasiah Hitam for their encouragement and knowledge sharing.

My deepest gratitude goes to my beloved soulmate, Mohd Heemi Fazeree, my two beautiful princesses, Lya Umaira and Lya Rihanna and lastly, my newborn baby boy, Rizq Dhani. They are always there to cheer me up and stood by me through the good times and bad times. I would also like to thank my beloved parents, Mr. Md Yusoff Zakaria and Mrs. Norlia Murad, as well as my siblings and in-laws for their endless prayers, help, love and support.

Finally, earnest thanks goes to all my beloved friends especially Hafizah, Hafiz, Yeo Kwok Shien, Hadi, Mas Izyani, Shahnan, Baktiar, Aziz and others for their thoughtfulness, support and assistance during my study. Million thanks for the beautiful memories that we shared together during our study. To those who have indirectly contributed in this work, your kindness means a lot to me.

Without the encouragement and love from all the above-mentioned people, my dream to complete the doctoral degree would never have come true. Thank you very much.

I certify that a Thesis Examination Committee has met on **21st August 2013** to conduct the final examination of Nelidya Bt. Md. Yusoff on her thesis entitled **Enhanced Structure For Discrete And Remote L-Band Erbium-Doped Fiber Amplifiers** in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Doctor of Philosophy.

Abdul Rahman bin Ramli, PhD
Associate Professor
Faculty of Engineering
University Putra Malaysia
(Chairman)

Makhfudzah binti Mokhtar, PhD
Faculty of Engineering
University Putra Malaysia
(Internal Examiner)

Abu Sahmah bin Mohd Supa'at, PhD
Professor
Faculty of Electrical Engineering
University Teknologi Malaysia
(External Examiner)

BUJANG KIM HUAT, 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. Adzir Mahdi, PhD
Professor
Faculty of Engineering
University Putra Malaysia
(Chairman)

Ahmad Fauzi bin Abas @ Ismail, PhD
Associate Professor
Faculty of Engineering
University Putra Malaysia
(Member)

Salasiah Hitam, PhD
Associate Professor
Faculty of Engineering
University Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

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

NELIDYA BT. MD. YUSOFF

Date : 21 August 2013

TABLE OF CONTENTS

Page

DEDICATION ii
ABSTRACT iii
ABSTRAK v
ACKNOWLEDGEMENTS viii
APPROVAL ix
DECLARATION x
LIST OF TABLES xv
LIST OF FIGURES xvi
LIST OF ABBREVIATIONS / SYMBOL xxii

CHAPTER

1 INTRODUCTION 1
- 1.1 Overview 1
- 1.2 Problem Statement 3
- 1.3 Motivation 4
- 1.4 Objectives 4
- 1.5 Scope of Work 5
- 1.6 Thesis Outline 6

2 THEORETICAL BACKGROUND AND LITERATURE REVIEW ON EDFA 7
- 2.1 Introduction 8
- 2.2 Theoretical Background on EDFA 10
  - 2.2.1 Energy Levels of Erbium Ions in Silica Glass Host 10
  - 2.2.2 Two-level Laser System 14
    - 2.2.2.1 Population Inversion 14
  - 2.2.3 Amplified Spontaneous Emission (ASE) 19
    - 2.2.3.1 Noise Figure Characteristics 22
  - 2.2.4 Stimulated Emission 24
    - 2.2.4.1 Gain Saturation 26
      - 2.2.4.1.1 Factors for Gain Saturation 28
    - 2.2.4.2 Pumping Configuration 29
  - 2.2.5 Principles of L-band Amplification 32
    - 2.2.5.1 Gain and Noise Figure Measurement 35
- 2.3 Raman Amplification in Optical Fibers 37
  - 2.3.1 Advantages in Raman Amplification 39
  - 2.3.2 Challenges in Raman Amplification 41
- 2.4 SBS Effect in the Optical Fiber 43
  - 2.4.1 SBS Effect Suppression 44
    - 2.4.1.1 Phase Modulation 45
- 2.5 EDFA Structures 47
  - 2.5.1 Discrete EDFA 47
    - 2.5.1.1 Gain Enhancement Technique in Discrete EDFA 48

2.5.1.2 Previous Work on Gain Enhancement with Gain Flattened Technique for Discrete L-band EDFA 50
2.5.2 Remote EDFA 55
2.5.2.1 Previous Work on Gain Enhancement Remotely Pumped L-band EDFA 58
2.5.2.2 Previous Work on Gain Enhancement Technique with Dispersion Management for L-band R-EDFA 61
2.6 Summary 63

3 DISCRETE L-BAND ERBIUM-DOPED FIBER AMPLIFIER 66
3.1 Basic Characterization of Single-stage EDFA 70
3.1.1 Pump Power Optimization 70
3.1.1.1 Experimental Setup 70
3.1.1.2 Results and Discussions 71
3.2 Basic Characterization of Dual-stage EDFA 77
3.2.1 EDF Length Optimization 77
3.2.1.1 Results and Discussions 79
3.3 Forward Pumped Dual-stage L-band EDFA 80
3.3.1 Experimental Setup 80
3.3.2 Results and Discussions 81
3.3.3 Comparison Between Forward Pumped Single-stage and Dual-stage EDFA 91
3.4 Bidirectional Pumped Dual-stage L-band EDFA 97
3.4.1 Experimental Setup 98
3.4.2 Results and Discussions 98
3.4.2.1 Comparison between Forward Pumped and Bidirectional Pumped Dual-stage EDFA. 99
3. 5 Enhanced Design of Dual-stage EDFA 106
3.5.1 Experimental Setup 106
3.5.2 Results and Discussions 107
3.5.3 Comparison with Bidirectional Pumped Single-stage EDFA. 111
3.5.3.1 Results and Discussions 112
3.6 Comparison between the Enhanced Design and the Single-stage EDFA 114
3.7 Summary 120

4 REMOTELY PUMPED L-BAND ERBIUM DOPED FIBER AMPLIFIER 123
4.1 Basic Characterization of Single Wavelength R-EDFA 127
4.1.1 Pump Power Optimization 127
4.1.1.1 Experimental Setup 127
4.1.1.2 Results and Discussions 129
4.1.2 EDF Length Optimization 132
4.1.2.1 Results and Discussions 133
4.1.3 Performance Measurement for Single Wavelength R-EDFA 136
4.1.4 Phase Modulation Technique 140

4.1.4.1 Characterization of SBS Threshold 142
4.1.4.1.1 Experimental Setup 142
4.1.4.1.2 Results and Discussions 143
4.1.5 Single Wavelength R-EDFA with PM 145
4.1.5.1 Experimental Setup 145
4.1.5.2 Results and Discussions 146
4.1.5.2.1 Transmission Gain and OSNR 146
4.1.5.2.2 R-EDFA Gain and NF 149
4.1.5.3 Raman Distributed Gain 150
4.2 Multiwavelength R-EDFA 153
4.2.1 Experimental Setup 153
4.2.2 Results and Discussions 154
4.2.2.1 EDF Length Optimization 154
4.2.2.2 R-EDFA Gain and NF 155
4.2.2.3 Transmission Gain and OSNR 157
4.2.2.4 Raman Distributed Gain 161
4.2.3 Comparison with Conventional R-EDFA 162
4.2.3.1 Experimental Setup 162
4.2.3.2 Results and Discussions 163
4.2.4 R-EDFA Performance with Multiwavelength Input 166
4.2.4.1 Single Saturating Tone Technique 167
4.2.4.1.1 Experimental Setup 167
4.2.4.1.2 Results and Discussions 168
4.2.5 Dual Saturating Tones Technique 170
4.2.5.1 Experimental Setup 170
4.2.5.2 Results and Discussions 171
4.3 Repeaterless Transmission Measurement 174
4.3.1 Measurement for 10 Gbps Data Rate 175
4.3.1.1 Experimental Setup for Post-compensation 175
4.3.1.2 Results and Discussions 177
4.3.1.3 Transmission Measurement for Single Channel R-EDFA 180
4.3.1.3.1 Experimental Setup 180
4.3.1.3.2 Results and Discussions 181
4.3.2 Measurement for 40 Gbps Data Rate 184
4.3.2.1 Results and Discussions 184
4.4 Summary 188

5 CONCLUSIONS, RESEARCH CONTRIBUTIONS AND FUTURE RECOMMENDATIONS 191
5.1 Conclusions 191
5.2 Research Contributions 195
5.3 Future Recommendations 199

REFERENCES 200
BIODATA OF STUDENT 214
LIST OF PUBLICATIONS 215

LIST OF TABLES

Table		**Page**
2.1	Gain enhancement with gain flattened technique for discrete L-band EDFA.	64
2.2	Gain enhancement with dispersion management for L-band R-EDFA.	65
3.1	The average gain, NF and OSNR at different splitting ratios when 0 dBm input signal is varied from 1570 nm to 1605 nm.	84
3.2	Summary of performance for forward pumped dual-stage EDFA.	90
3.3	FOM for bidirectionally pumped dual-stage EDFA.	105
3.4	FOM for enhanced dual-stage EDFA design.	111
3.5	The summary of different configurations of discrete L-band EDFA.	122
4.1	SBS threshold power at different RF tones selection.	145
5.1	Enhanced performance of dual-stage discrete L-band EDFA over conventional single-stage EDFA.	194
5.2	Enhanced performance of multiwavelength remotely pump L-band EDFA over conventional R-EDFA.	194
5.3	The main contribution for discrete L-band EDFA.	197
5.4	The main contribution for remote L-band EDFA.	198

LIST OF FIGURES

Figure **Page**

1.1 Scope of work. 6

2.1 Erbium ion energy level with possible pump bands. 11

2.2 (a) The dominant transition in Er^{3+} ions energy level diagram. (b)Stark splitting in energy level due to glass or crystal electric field. 12

2.3 Absorption spectrum of silica-based EDF. 13

2.4 Energy level for two-levels system. 16

2.5 (a) Absorption (b) Spontaneous emission (random photons) (c) ASE. 20

2.6 (a) The absorption process and (b) the process of stimulated emission. 24

2.7 The input saturation power when the amplifier is operated in the saturation regime. 27

2.8 The output saturation power when the amplifier is operated in the saturation regime. 27

2.9 Three different pumping configurations for EDFA. a) forward pumping b) backward pumping c) bidirectional pumping. 31

2.10 Erbium gain coefficient at different inversion levels. 33

2.11 Schematic diagram of L-band amplification. 34

2.12 Screenshot of gain and NF measurement captured from OSA. 36

2.13 Energy level illustration of the Raman scattering process. 38

2.14 Raman gain profile for dispersion compensating fiber (DCF), nonzero dispersion fiber (NZDF), and superlarge area(SLA) when it is pumped at 1450 nm. 38

2.15 NF for (a) actual system (b) effective system for Raman backward pumping. 40

2.16 SBS effect in optical fibers. 43

2.17 Optical spectrum (a)without phase modulation (b)with phase modulation. 46

2.18 Spectrum after implementing PM to suppress the SBS effect. 46

2.19 Discrete EDFA in optical communication systems. 48

2.20 Remote pumped EDFA in optical communication system. 55

2.21 Optical transmission system with different configurations. 57

3.1 The work flow for discrete L-band EDFA. 69

3.2 Design for single-stage L-band EDFA. 71

3.3(a) Optimization of pump power, the signal power is fixed at 0 dBm. 72

3.3(b) The gain flatness of the L-band amplified signal at 600 mW pump power. 73

3.4 Variation of gain obtained at different signal powers. 74

3.5 Variation of NF obtained at different signal powers. 75

3.6 OSNR variation at different signal power throughout the L-band region. 76

3.8 The output spectrum of the 1587 nm amplified signal at different signal powers. 77

3.8 The design layout for EDF optimization using Optisys. 78

3.9 Signal gain obtained from simulation. 79

3.10 Dual-stage EDFA using forward pumping. 81

3.11 Variation of gain obtained at different splitting ratios when 0 dBm input signal wavelength is varied from 1570 nm to 1605 nm. 83

3.12 Gain of the first stage EDFA at different splitting ratios. 85

3.13 Gain of the second-stage EDFA at different splitting ratios. 86

3.14 NF at different splitting ratios in a function of signal wavelength when the signal power is at 0 dBm. 87

3.15 NF of the first stage EDFA at different splitting ratios. 88

3.16 NF of the second-stage EDFA at different splitting ratios. 89

3.17 OSNR variation at 0 dBm signal power within the L-band region. 90

3.18 Gain obtained at two different configurations for signa power of 0 dBm. 92

3.19 The improvement of NF when comparison is made between forward pumped single-stage and dual-stage EDFA for signal power of 0 dBm. 93

3.20	Gain difference with the increment of signal power.	94
3.21	NF performance at different signal power for both single-stage and dual-stage amplifier.	96
3.22	Output power and PCE in a function of signal power.	97
3.23	Dual-stage EDFA utilizing bidirectional pumping.	98
3.24	Gain discrepancies between forward and bidirectional pumped.	99
3.25	NF variation at two different pumping directions.	100
3.26	OSNR discrepancy between forward and bidirectional pumped dual-stage EDFA.	101
3.27	The output spectrum of 1587 nm amplified signal at two different pumping configurations.	102
3.28	(a) Gain and (b) NF in a function of input signal power for different pumping directions.	103
3.29	Output power and PCE at different signal power for two different configurations.	105
3.30	Enhanced design of dual-stage EDFA.	107
3.31	Variation of gain at different splitting ratios against input signal wavelengths.	108
3.32	NF in a function of signal wavelengths when 0 dBm signal power is applied.	109
3.33	The variation of OSNR at different splitting ratios.	110
3.34	Bidirectional pumped single-stage pumping scheme.	111
3.35	Comparison of gain and NF at different configurations when the signal power is at 0 dBm.	112
3.36	OSNR obtained at different signal wavelengths when 0 dBm signal power is used.	113
3.37	Gain characteristics when the signal power is varied from -30 dBm to 0 dBm.	115
3.38	NF characteristics with respect to the variation of signal power for two different configurations.	116

3.39 Output power obtained when the signal power is varied from -30 dBm to 0 dBm. 117

3.40 PCE in a function of signal power for both configurations. 118

3.41 Output spectrum for three different configurations. 119

3.42 Output spectrum for enhanced dual-stage L-band EDFA. 119

4.1 Flow chart for remotely-pumped L-band EDFA. 126

4.2 Experimental setup for single channel R-EDFA. 128

4.3 The received pump power after propagating through a 41 km SMF. 130

4.4 Raman gain spectrum observed at different pump powers (Point B). 131

4.5 The unwanted laser at 1604.9 nm due to Rayleigh scattering that acts as a virtual mirror in the transmission fiber. 132

4.6 Gain at different EDF lengths with different signal power using DCG. 134

4.7 Output spectrum of the amplified signal after went through a DCG. 134

4.8 Optimized EDF length in a function of signal power. 135

4.9 Transmission gain at different signal power with SBS occurrence. 136

4.10 Output spectrum with SBS effect (a) at different signal power (b) at 0 dBm signal power. 138

4.11 The overall NF when the signal power is varied from -30 dBm to 0 dBm with SBS occurrence. 139

4.12 OSNR with the existence of SBS at different signal power. 140

4.13 Phase modulation technique. 141

4.14 Electrical spectrum observed from RF tone mixer. 141

4.15 Optical signal linewidth broadening using RF Toner at different number of tones. 142

4.16 Experimental setup for the SBS threshold characterization. 143

4.17 SBS threshold at different RF tones. 144

4.18 Enhanced experimental setup that incorporates PM to increase the SBS threshold effect in the transmission fiber. 145

4.19 Transmission gain obtained at different input signals after suppressing SBS. 147

4.20 OSNR with its improvement at different signal powers after utilizing PM. 148

4.21 (a) The increment of OSNR and (b) the output spectrum at different input signals when PM is utilized into the setup. 149

4.22 The R-EDFA gain and NF in a function of signal power. 150

4.23 Raman distributed gain at 1590.05 nm signal in a function of signal power. 152

4.24 The Raman distributed gain observed at the output spectrum. 152

4.25 Experimental setup for multiwavelength measurements. 153

4.26 Average gain of L-band signal at different EDF length when 0 dBm signal power is applied to the setup. 155

4.27 Signal gain for R-EDFA when signal power is varied from -30 dBm to 0 dBm. 156

4.28 NF for R-EDFA at different signal powers ranging from -30 dBm to 0 dBm. 157

4.29 Transmission gain in a function of signal wavelengths. 158

4.30 The transmission OSNR when the signal power is varied from -30 dBm to 0 dBm. 160

4.31 Output spectrum observed at just after the R-EDFA and the transmission output. 160

4.32 Raman distributed gain for multiwavelength R-EDFA. 162

4.33 Design for conventional R-EDFA with dispersion compensator. 162

4.34 (a) Transmission gain and (b) the output spectrum of conventional R-EDFA at different signal powers. 164

4.35 Transmission gain penalty over conventional R-EDFA. 165

4.36 OSNR penalty between conventional and proposed R-EDFA at different signal powers. 166

4.37 Saturating tone technique using single saturating tone. 167

4.38 Transmission gain and obtained at three different saturating signal when the probe signal is varied from 1570.45 nm to 1604.92 nm. 169

4.39 Overall NF obtained at three different saturating signals when the probe signal is varied from 1570.45 nm to 1604.92 nm. 169

4.40 Design for dual saturating tones technique. 170

4.41 Transmission gain. 171

4.42 The overall NF and OSNR obtained at the output of the setup in a function of signal wavelength. 172

4.43 The R-EDFA gain and NF when dual saturating signals is applied to the setup. 173

4.44 Raman distributed gain. 174

4.45 (a) Experimental setup for DCG's post-compensation and (b) detailed setup for transmitter and receiver. 176

4.46 The eye diagram for back-to-back. 178

4.47 The dispersed signal after propagating through 75 km SMF. 178

4.48 Eye diagram for the recompressed signal after propagating through DCG. 179

4.49 Spectra of NRZ-modulated optical signals. 179

4.50 BER in a function of received power for post-compensation. 180

4.51 Experimental setup with single channel R-EDFA. 181

4.52 Eye diagram when R-EDFA is applied to the transmission at 15 dBm launching power. 182

4.53 BER in a function of received power at different configurations. 183

4.54 Eye diagram when conventional R-EDFA is applied to the transmission. 184

4.55 Eye diagram for back-to-back measurement using 40 Gbps data rate. 185

4.56 The eye diagram when REDFA is applied to the transmission system at 15 dBm launching power. 186

4.57 BER versus received power for different setup at 40 Gbps. 187

4.58 The eye diagram when conventional REDFA is applied to the transmission system at 15 dBm launching power. 188

LIST OF ABBREVIATIONS / SYMBOLS

EDFA	Erbium-doped fiber amplifier
EDF	Erbium-doped fiber
NF	Noise figure
OSNR	Optical signal-to-noise ratio
SR	Splitting ratios
FOM	Figure of Merit
PCE	Power Conversion Efficiency
RPU	Raman pump unit
TLS	Tunable laser source
OPM	Optical power meter
OSA	Optical spectrum analyzer
WDM	Wavelength division multiplexing
DWDM	Dense wavelength division multiplexing
ASE	Amplified Spontaneous Emission
G	Gain
GSA	Ground-state absorption
ESA	Excited-state absorption
BER	Bit error rate
DCG	Dispersion Compensation Grating
DCM	Dispersion Compensating Module
SMF	single mode fiber
SRS	Stimulated Raman Scattering
RBS	Rayleigh backscattering

FBG	Fiber Bragg grating
SBS	Stimulated Brillouin Scattering
PM	Phase modulation
RF	Radio frequency
ESA	Electrical spectrum analyzer
SHB	Spectral hole burning
MZM	Mach-Zehnder external modulator
NZDF	Nonzero Dispersion Fiber
SLA	Superlarge area
PRBS	Pseudo random bit sequence
PPG	Pulse pattern generator
NRZ	Nonreturn zero
OGF	Optical grating filter
DCA	Digital Communication Analyzer
CFBG	Chirped Fiber Bragg Grating
DSF	Dispersion shifted fiber
FWM	Four-wave mixing
GEF	Gain equalizing filter
LD	Laser diode
SOA	Semiconductor optical amplifier
ULRFL	Ultralong Raman Fiber laser
TBF	Tunable bandpass filter
OTDR	Optical time domain reflectometry
BPF	Bandpass filter
GEQ	Gain equalizer

DSCF	Dispersion slope compensation fiber
VDC	Variable dispersion compensator
DRA	Distributed Raman Amplifier
HNLF	Highly Nonlinear Fiber
GFF	Gain flattening filter
LPFG	Long Period Fiber Grating
DCF	Dispersion compensating fiber
RFA	Raman fiber amplifier
RFL	Raman fiber laser
VOA	Variable Optical Attenuator
DRS	Double Rayleigh scattering
MPI	Multipath interference
RIN	Relative intensity noise
G_{RAMAN}	Raman gain
P_{TRANS}	Transmission output power
P_{EDFA}	Output power at the output of EDFA
Att_{FIBER}	Fiber loss due to the attenuation
Tb/s	Terabit per second
ps/nm.km	Picosecond per nanometer per kilometer
µm	micrometer
dB/m	decibel per meter
nm	nanometer
m	meter
ps/nm	picosecond per nanometer
Gbps	Gigabit per second

GHz	Gigahertz
THz	Terahertz
mW	milliwatt
dB	decibel
dBm	Decibel meter
MHz	Megahertz
Tx	Transmitter
Rx	Receiver
Al	Aluminium
N_1	Atom density at energy Level 1 (E_1)
N_2	Atom density at energy Level 2 (E_2)
E_1	Energy Level 1
E_2	Energy Level 2
E_3	Virtual state
G_1	Gain for first stage
W_{12}	Stimulated absorption rate
W_{21}	Stimulated emission rate
H	Planck's constant
T	Temperature
K	Boltzmann constant
T	Radiative lifetime
R_{12}	Pumping rate between Level 1 and Level 2
A_{21}	Spontaneous decay rate between Level 2 to Level 1
A_{21}^{R}	Radiative decay rate
A_{21}^{NR}	Non-radiative decay rate

ρ	Total atom density
σ	Fiber’s cross-section
Γ	Inversion factor
v	Frequency
P	Power
A_{eff}	Effective area of fiber
P_P	Pump power
P_S	Signal power
P_{ase}	ASE power
P_{ASE}^{+}	ASE power traveling in forward direction
P_{ASE}^{-}	ASE power traveling in backward direction
LASEi	Level of ASE
Louti	Level of output power
Lini	Level of input power
$N(z)$	Amplified noise or ASE
η_{sp}	Amplifier spontaneous factor
N_{shot}	Shot noise
N_{s-sp}	Signal-spontaneous noise
N_{sp-sp}	Spontaneous-spontaneous noise
N_{th}	Thermal noise
Δv	Bandwidth
NF_1	Noise figure of first stage
NF_2	Noise figure of second stage
P_{out}	Output power
P_{in}	Input power

λi	Signal wavelength
RBi	Resolution at OSA
g_R	Raman gain coefficient
L_{eff}	Effective length
$G_{on\text{-}off}$	Raman on-off gain
NF_{span}	Overall NF for DRA
L	Passive span
α	Fiber attenuation coefficient
αL	Fiber loss
NF_{eff}	NF for effective amplifier
k	Polarization factor
g_0	Brillouin gain coefficient
Δv_B	Brillouin linewidth
Δv_P	Pump spectral width

CHAPTER 1

INTRODUCTION

1.1 Overview

Owing to the rapid growth of information technology in wavelength division multiplexing (WDM) network systems, it is essential to have longer distance of communication systems with wide bandwidth and at the same time able to transport multiwavelength signal simultaneously with less gain ripple spectrum. Unfortunately, the accumulation of attenuation inside the fiber confines the transmission distance for the light to propagate. In order to overcome this problem, it is essential to install electronic repeaters in between the fiber span to boost up the signal by converting the signal into the electrical form. Other than its drawbacks in terms of installation due to the large number of electronic repeaters, each repeater can only regenerate one signal which restricts its capability in transmitting more than one signal along a single fiber. This means that the more the signal is transmitted through the fiber, the more electronic repeaters are required, thus causing the system to be more expensive and not commercially viable. This problem becomes more complicated when the operating wavelength of the transmitted light is shifted from 1310 nm to 1550 nm. Due to the limitations of electronic repeaters in terms of high loss, signal distortion and high noise, optical amplifiers especially erbium-doped fiber amplifier (EDFA) have been implemented to overcome the issues.

EDFA, which uses rare earth component named erbium as the amplifying medium, has been established to generate considerable gain in C-band [1], L-band [2] and S-band [3] region. The work on EDFA was started in C-band but since the WDM transmission has reached its minimum channel spacing, this amplification window is exhausted resulting in the introduction of L-band window. Furthermore, since the L-band window is beyond 1550 nm, the impairment by nonlinear crosstalk caused by four-wave mixing (FWM) can be avoided [4]. In addition of this advantage, acceptable flat gain response can be easily obtained in L-band without using any gain equalizing filter (GEF) making it more preferable than the C-band. The use of GEF in C-band EDFA is not cost efficient since it requires higher level of fabrication complexity due to its higher gain ripple which leads to higher gain error across the intended bandwidth.

EDFA is proven to be able to offer up to 80 nm bandwidth when combination of these two regions, C-band and L-band are made [5]. However, due to its location which is far from the peak emission of erbium ions, the amplification in L-band EDFA offers low gain coefficient as compared to the C-band. As a result, gain enhancement techniques such as secondary pumping [6], multi stages design [7], and multi pass amplification [8] are required in L-band EDFA in order to overcome this limitation. For instance, the utilization of double pass technique allows the gain to increase by 11 dB with only 2 dB noise penalty for 1570 nm signal amplification at low pumping power [9]. Besides having some gain improvement, these techniques also improve the power conversion efficiency of an EDFA. On the other hand, these techniques may lead to the use of multiple pump laser diode (LD) or even higher pump power. These may cause complexity in design and thus, incurring higher cost.

The EDFA can be divided into two structures which are discrete [10] and remote [11]. Since the discrete EDFA requires pump laser to be close to the amplifier, it has no limitation in terms of pump power delivery. In fact, more pump power can be supplied to the amplifier as the pump light is free from any attenuation effects. As a result, this discrete EDFA can produce high gain with low NF due to the high pump power. However, for long distance applications such as submarine link for continent-island or island-island, there are some restrictions in the placement of the pump laser due to the absence of nearby power source. Since the pump lasers are placed near the transmitter (Tx) or the receiver (Rx), the remote EDFA needs to be implemented in the WDM system. However, the remote EDFA suffers from low pump power due to the unavoidable attenuation and scattering effects in the fiber.

1.2 Problem Statement

Since low average inversion is one of the limitations in L-band EDFA, more research works focus on the gain enhancement technique to improve its performance especially the gain, NF and output power. Besides, the absorption and emission coefficient in L-band are smaller as compared to C-band. These two limitations result in low gain coefficient to the L-band when compared with the C-band. In order to attain comparable gain with the C-band, longer length of EDF is needed which is six times longer for L-band amplifier [12]. However, longer length of EDF requires more pump power to excite the erbium ions for higher population inversion. Since longer transmission distance is the main target in WDM systems, high gain amplifiers are extremely needed so that the signal is amplified significantly in between the span. The main concerns in transmission system are the attenuation and scattering effects in the longer transmission distance that reduce the power of the propagating signal. Furthermore, the dispersion effects also cause the signal to be distorted that ultimately limits the bandwidth as well as the transmission distance. In contrast, for remote EDFA, the pump light is affected by those effects as it requires dedicated pump line to the amplifier. This limits the reachable amount of pump power at the amplifier that finally contributes to lower gain and lower output power. As a result, this lower output power limits the transmission distance of the propagated signal and at the same time, more noise is added to the amplifier that results in higher noise figure. Besides, dispersion effect due to the longer length of fiber needs to be managed as it affects the overall OSNR as well. All these limitations finally bring to more errors to the propagated signal when it reaches the transmission end.

1.3 Motivation

From the previous studies, the limitations in L-band EDFA such as pump power, output power, as well as signal gain and NF become important issues in designing a good amplifier for long distance transmission. Therefore, this study is carried out to find better solutions to the above-mentioned problems.

1.4 Objectives

There are many research works that focus on gain enhancement technique for both discrete and remote L-band EDFA in the past few years. This research work provides better findings in gain enhancement technique for both designs, which correspond to its objectives as listed below:-

i) To design and develop a dual-stage discrete L-band EDFA that utilizes efficient distributed pumping scheme to increase the overall performance.

ii) To design and develop a Raman-assisted remotely pumped L-band EDFA using a 1497 nm pump laser with dispersion compensation capability.

iii) To design and develop a highly efficient multiwavelength remotely pumped L-band EDFA that works at low pump power with the ability to compensate dispersion effects.

1.5 Scope of Work

Figure 1.1 describes the scope of work involved in this study on L-band EDFA. Both discrete and remote EDFA structures are investigated in this research. For discrete EDFA, the work is focused on the pumping scheme where a dual-stage EDFA with distributed pumping scheme is proposed. This distributed pumping scheme distributes the pump power between two different EDFA stages by using just a single pump laser. For remote EDFA, this work focuses on designing and developing a highly efficient optical amplifier that integrates Raman amplification in the transmission line. At the same time, this design is able to compensate the total dispersion that occurs in the transmission fiber by utilizing L-band multiwavelength dispersion compensator in the setup.

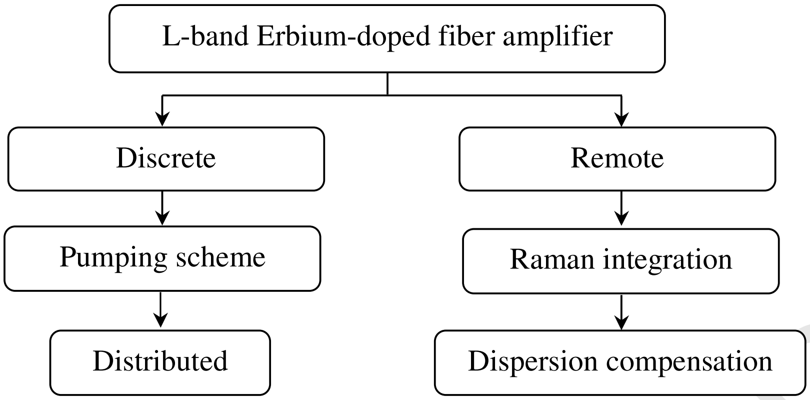

Figure 1.1: Scope of work.

1.6 Thesis Outline

This thesis comprises of 5 different chapters including this chapter. Chapter 1 includes the introduction, problem statement, motivation, objectives and scope of work involved in this research. Chapter 2 presents the theoretical background of EDFA and review on the previous reported research findings. It is then followed by Chapter 3 which discusses the methodology, results and analysis involved in the proposed discrete L-band EDFA. All the findings for remote L-band EDFA are discussed thoroughly in Chapter 4. The methodologies involved in both chapters are presented in a form of flow chart for better understanding. Finally, Chapter 5 summarizes the conclusions, research contributions and future recommendations for this research.

REFERENCES

[1] S.W. Harun, F. Abd Rahman, K. Dimyati, and H. Ahmad, "An efficient gain-flattened C-band Erbium-doped fiber amplifier", *Laser Physics Letters*, vol. 3, p. 536-538, 2006.

[2] F.A. Flood and C.C. Wang, "980-nm pump-band wavelengths for long-wavelength-band erbium-doped fiber amplifiers", *IEEE Photonics Technology Letters*, vol. 11, p. 1232-1234, 1999.

[3] J.B. Rosolem, A.A. Juriollo, R. Arradi, A.D. Coral, J.C.R.F. Oliveira, and M.A. Romero, "All silica S-band double-pass erbium-doped fiber amplifier", *IEEE Photonics Technology Letters*, vol. 17, p. 1399-1401, 2005.

[4] M. Jinno, T. Sakamoto, K. Jun-Ich, S. Aisawa, K. Oda, M. Fukui, H. Ono, M. Yamada, and K. Oguchi, "1580-nm band, equally spaced 8 x 10 Gb/s WDM channel transmission over 360 km (3 x 120 km) of dispersion-shifted fiber avoiding FWM impairment", *IEEE Photonics Technology Letters*, vol. 10, p. 454-456, 1998.

[5] Y. Sun, J.W. Sulhoff, A.K. Srivastava, J.L. Zyskind, T.A. Strasser, J.R. Pedrazzani, C. Wolf, J. Zhou, J.B. Judkins, R.P. Espindola, and A.M. Vengsarkar, "80 nm ultra-wideband erbium-doped silica fibre amplifier", *Electronics Letters*, vol. 33, p. 1965-1967, 1997.

[6] M.A. Mahdi and H. Ahmad, "Gain enhanced L-band Er^{3+}-doped fiber amplifier utilizing unwanted backward ASE", *IEEE Photonics Technology Letters*, vol. 13, p. 1067-1069, 2001.

[7] I.-B. Sohn and J.-W. Song, "Gain flattened and improved double-pass two-stage EDFA using microbending long-period fiber gratings", *Optics Communications*, vol. 236, p. 141-144, 2004.

[8] T. Szu-Chi, T. Tseng-Chien, L. Pi-Cheng, and C. Yung-Kuang, "High pumping-efficiency L-band erbium-doped fiber ASE source using double-pass bidirectional-pumping configuration", *IEEE Photonics Technology Letters*, vol. 15, p. 197-199, 2003.

[9] S.W. Harun, P. Poopalan, and H. Ahmad, "Gain enhancement in L-band EDFA through a double-pass technique", *IEEE Photonics Technology Letters*, vol. 14, p. 296-297, 2002.

[10] C.L. Chang, L. Wang, and Y.J. Chiang, "A dual pumped double-pass L-band EDFA with high gain and low noise", *Optics Communications*, vol. 267, p. 108-112, 2006.

[11] M.H.A. Bakar, M.A. Mahdi, M. Mokhtar, A.F. Abas, and N.M. Yusoff, "Investigation on the effect of stimulated Raman scattering in remotely-pumped L-band erbium-doped fiber amplifier", *Laser Physics Letters*, vol. 6, p. 602-606, 2009.

[12] P.C. Becker, N.A. Olsson, and J.R. Simpson, *Erbium-Doped Fiber Amplifiers*. San Diego: Academic Press. (1999.

[13] M.H. Al-Mansoori, A.W. Naji, S.J. Iqbal, M.K. Abdullah, and M.A. Mahdi, "L-band Brillouin-Erbium fiber laser pumped with 1480 nm pumping scheme in a linear cavity", *Laser Physics Letters*, vol. 4, p. 371-375, 2007.

[14] R. Olshansky, "Noise figure for erbium-doped optical fibre amplifiers", *Electronics Letters*, vol. 24, p. 1363-1365, 1988.

[15] E. Desurvire, C.R. Giles, J.R. Simpson, and J.L. Zyskind, "Efficient erbium-doped fiber amplifier at a 1.53-μm wavelength with a high output saturation power", *Opt. Lett.*, vol. 14, p. 1266-1268, 1989.

[16] E. Desurvire, J.R. Simpson, and P.C. Becker, "High-gain erbium-doped traveling-wave fiber amplifier", *Opt. Lett.*, vol. 12, p. 888-890, 1987.

[17] S.W. Harun, K. Dimyati, K.K. Jayapalan, and H. Ahmad, "An overview on S-band erbium-doped fiber amplifiers", *Laser Physics Letters*, vol. 4, p. 10-15, 2007.

[18] R.J. Mears, L. Reekie, I.M. Jauncey, and D.N. Payne, "Low-noise erbium-doped fibre amplifier operating at 1.54 m", *Electronics Letters*, vol. 23, p. 1026-1028, 1987.

[19] S. Yamashita and M. Nishihara, "L-band erbium-doped fiber amplifier incorporating an inline fiber grating laser", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 7, p. 44-48, 2001.

[20] C. Bo-Hun, P. Hyo-Hoon, C. Moojung, and K. Seung Kwan, "High-gain coefficient long-wavelength-band erbium-doped fiber amplifier using 1530-nm band pump", *IEEE Photonics Technology Letters*, vol. 13, p. 109-111, 2001.

[21] C.R. Giles, E. Desurvire, J.R. Talman, J.R. Simpson, and P.C. Becker, "2-Gbit/s signal amplification at λ=1530 nm in an erbium-doped single-mode fiber amplifier", *Journal of Lightwave Technology*, vol. 7, p. 651-656, 1989.

[22] H. Seongtaek and C. Kyuman, "Gain tilt control of L-band erbium-doped fiber amplifier by using a 1550-nm band light injection", *IEEE Photonics Technology Letters*, vol. 13, p. 1070-1072, 2001.

[23] L.F. Mollenauer, R.H. Stolen, and M.N. Islam, "Experimental demonstration of soliton propagation in long fibers: loss compensated by Raman gain", *Opt. Lett.*, vol. 10, p. 229-231, 1985.

[24] J.P. Blondel, "Achievable budget improvement with Raman amplification and remotely pumped postamplification at transmit side of 622 Mbit/s and 2.5 Gbit/s repeaterless systems", *IEEE Photonics Technology Letters*, vol. 7, p. 108-110, 1995.

[25] Y. Jin, Q. Dou, Y. Liu, J. Liu, L. Xu, S. Yuan, and X. Dong, "Gain-clamped dual-stage L-band EDFA by using backward C-band ASE", *Optics Communications*, vol. 266, p. 390-392, 2006.

[26] S.W. Harun, N. Md Samsuri, and H. Ahmad, "Gain enhancement in partial double-pass L-band EDFA system using a band-pass filter", *Laser Physics Letters*, vol. 2, p. 36-38, 2005.

[27] R.I. Laming, M.C. Farries, P.R. Morkel, L. Reekie, D.N. Payne, P.L. Scrivener, F. Fontana, and A. Righetti, "Efficient pump wavelengths of erbium-doped fibre optical amplifier", *Electronics Letters*, vol. 25, p. 12-14, 1989.

[28] T.J. Whitley, "Laser diode pumped operation of Er3+-doped fibre amplifier", *Electronics Letters*, vol. 24, p. 1537-1539, 1988.

[29] C. Bo-Hun, P. Hyo-Hoon, and C. Moo-Jung, "New pump wavelength of 1540-nm band for long-wavelength-band erbium-doped fiber amplifier (L-band EDFA)", *IEEE Journal of Quantum Electronics*, vol. 39, p. 1272-1280, 2003.

[30] L.A. Riseberg, M.J. Weber, and E. Wolf, *III Relaxation Phenomena in Rare-Earth Luminescence*, in *Progress in Optics*. 1977, Elsevier. p. 89-159.

[31] E. Desurvire, *Erbium-doped Fiber Amplifiers : Principles and Applications*. New York: John Wiley & Sons. (2002.

[32] R.I. Laming and D.N. Payne, "Noise characteristics of erbium-doped fiber amplifier pumped at 980 nm", *IEEE Photonics Technology Letters*, vol. 2, p. 418-421, 1990.

[33] Y. Barmenkov, "Resonant and thermal changes of refractive index in a heavily doped erbium fiber pumped at wavelength 980 nm", *Appl. Phys. Lett.*, vol. 85, p. 2466, 2004.

[34] Y.J. Song, L. Zhan, S. Hu, Q.H. Ye, and Y.X. Xia, "Tunable multiwavelength Brillouin-erbium fiber laser with a polarization-maintaining fiber Sagnac loop filter", *IEEE Photonics Technology Letters*, vol. 16, p. 2015-2017, 2004.

[35] W.J. Miniscalco, "Erbium-doped glasses for fiber amplifiers at 1500 nm", *Journal of Lightwave Technology*, vol. 9, p. 234-250, 1991.

[36] S.-C. Tsai, C.-M. Lee, S. Hsu, and Y.-K. Chen, "Characteristic comparison of single-pumped L-band erbium-doped fiber amplified spontaneous emission sources", *Optical and Quantum Electronics*, vol. 34, p. 1111-1117, 2002.

[37] M.A. Mahdi, A.A.A. Bakar, M.H. Al-Mansoori, S. Shaari, and A.K. Zamzuri, "Single-stage gain-clamped L-band EDFA with C-band ASE self-oscillation in ring cavity", *Laser Physics Letters*, vol. 5, p. 126-129, 2008.

[38] E. Desurvire, *Erbium-doped fiber amplifier: Principles and Applications*. New York: John Wiley and Sons Inc. (1994.

[39] S.W. Harun, H.A. Abdul-Rashid, S.Z. Muhd-Yassin, M.K. Abd-Rahman, M.R. Tamjis, and H. Ahmad, "Dual-stage Er/Yb doped fiber amplifier for gain and noise figure enhancements", *IEICE Electronics Express*, vol. 3, p. 517-521, 2006.

[40] M. Adzir Mahdi and S.-J. Sheih, "Low-noise 1480-nm pumped L-band erbium-doped fibre amplifiers incorporating a bypass isolator", *Optics Communications*, vol. 237, p. 295-299, 2004.

[41] K. Tajima, "Er3+-doped single-polarisation optical fibres", *Electronics Letters*, vol. 26, p. 1498-1499, 1990.

[42] M.A. Mahdi, S. Thirumeni, P. Poopalan, S. Selvakennedy, F.R. Mahamd Adikan, W.Y. Chan, and H. Ahmad, "Effects of Self-Saturation in an Erbium-Doped Fiber Amplifier", *Optical Fiber Technology*, vol. 6, p. 265-274, 2000.

[43] K. Smith, E.J. Greer, N.J. Doran, D.M. Bird, and K.H. Cameron, "Pulse amplification and shaping using a nonlinear loop mirror that incorporates a saturable gain", *Opt. Lett.*, vol. 17, p. 408-410, 1992.

[44] L. Juhan, R. Uh-Chan, A. Seong Joon, and P. Namkyoo, "Enhancement of power conversion efficiency for an L-band EDFA with a secondary pumping effect in the unpumped EDF section", *IEEE Photonics Technology Letters*, vol. 11, p. 42-44, 1999.

[45] F. Khaleghi, J. Li, M. Kavehrad, and K. Hyung, "Increasing repeater span in high-speed bidirectional WDM transmission systems using a new bidirectional EDFA configuration", *IEEE Photonics Technology Letters*, vol. 8, p. 1252-1254, 1996.

[46] M. Karasek and M. Menif, "Serial topology of wide-band erbium-doped fiber amplifier for WDM applications", *IEEE Photonics Technology Letters*, vol. 13, p. 939-941, 2001.

[47] B.O. Guan, H.Y. Tam, S.Y. Liu, P.K.A. Wai, and N. Sugimoto, "Ultrawide-band La-codoped Bi^2/O^3-based EDFA for L-band DWDM systems", *IEEE Photonics Technology Letters*, vol. 15, p. 1525-1527, 2003.

[48] S.W. Harun and H. Ahmad, "L-band erbium-doped fibre amplifier with clamped- and flattened-gain using FBG", *Electronics Letters*, vol. 39, p. 1238-1240, 2003.

[49] C. Headley and G. Agrawal, *Raman Amplification in Fiber Optical Communication Systems*. UK: Elsevier Academic Press. (2005.

[50] C. Fukai, K. Nakajima, J. Zhou, K. Tajima, K. Kurokawa, and I. Sankawa, "Effective Raman gain characteristics in germanium- and fluorine-dopedoptical fibers", *Opt. Lett.*, vol. 29, p. 545-547, 2004.

[51] F. Koch, S.A.E. Lewis, S.V. Chernikov, and J.R. Taylor, "Broadband Raman gain characterisation in various optical fibres", *Electronics Letters*, vol. 37, p. 1437-1439, 2001.

[52] J. Bromage, "Raman Amplification for Fiber Communications Systems", *J. Lightwave Technol.*, vol. 22, p. 79, 2004.

[53] Y. Emori and S. Namiki. "100nm bandwidth flat gain Raman amplifiers pumped and gain-equalized by 12-wavelength-channel WDM high power laser diodes", *Wavelength Division Multiplexing Components*. Optical Society of America, 1999.

[54] H. Kidorf, K. Rottwitt, M. Nissov, M. Ma, and E. Rabarijaona, "Pump interactions in a 100-nm bandwidth Raman amplifier", *IEEE Photonics Technology Letters*, vol. 11, p. 530-532, 1999.

[55] H. Masuda, S. Kawai, and K. Aida, "Ultra-wideband hybrid amplifier comprising distributed Raman amplifier and erbium-doped fibre amplifier", *Electronics Letters*, vol. 34, p. 1342-1344, 1998.

[56] M.N. Islam, "Raman amplifiers for telecommunications", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 8, p. 548-559, 2002.

[57] A.B. Puc, M.W. Chbat, J.D. Henrie, N.A. Weaver, H. Kim, A. Kaminski, A. Rahman, and H. FÈvrier. "Long-haul WDM NRZ transmission at 10.7Gb/s in S-band using cascade of lumped Raman amplifiers", *Optical Fiber Communication Conference*. Optical Society of America, 2001.

[58] V. Dominic, E. Mao, J. Zhang, B. Fidric, S. Sanders, and D. Mehuys. "Distributed Raman amplification with co-propagating pump light", *Optical Amplifiers and Their Applications*. Optical Society of America, 2001.

[59] S.A.E. Lewis, S.V. Chernikov, and J.R. Taylor, "Temperature-dependent gain and noise in fiber Raman amplifiers*", Opt. Lett.*, vol. 24, p. 1823-1825, 1999.

[60] E.P. Ippen and R.H. Stolen, "Stimulated Brillouin scattering in optical fibers*", Applied Physics Letters*, vol. 21, p. 539-541, 1972.

[61] F.S. Ferreira, *Nonlinear Effects in Optical Fiber*. America: John Wiley&Sons, Inc. (2010.

[62] J.M.C. Boggio, J.D. Marconi, and H.L. Fragnito, "Experimental and Numerical Investigation of the SBS-Threshold Increase in an Optical Fiber by Applying Strain Distributions*", Journal of Lightwave Technology*, vol. 23, p. 3808, 2005.

[63] Y. Takushima and T. Okoshi. "Suppression of stimulated Brillouin scattering using isolators", *Digest of Conference on Optical Fiber Communication*. Optical Society of America, 1992.

[64] H. Lee and G. Agrawal, "Suppression of stimulated Brillouin scattering in optical fibers using fiber Bragg gratings*", Opt. Express*, vol. 11, p. 3467-3472, 2003.

[65] Y. Liu, Z. Lv, Y. Dong, and Q. Li, "Research on stimulated Brillouin scattering suppression based on multi-frequency phase modulation*", Chin. Opt. Lett.*, vol. 7, p. 29-31, 2009.

[66] J.B. Coles, B.P.P. Kuo, N. Alic, S. Moro, C.S. Bres, J.M.C. Boggio, P.A. Andrekson, M. Karlsson, and S. Radic, "Bandwidth-efficient phase modulation techniques for Stimulated Brillouin Scattering suppression in fiber optic parametric amplifiers*", Opt. Express*, vol. 18, p. 18138-18150, 2010.

[67] M. Gao, C. Jiang, W. Hu, J. Wang, and H. Ren, "The effects of pump phase modulation on noise characteristics of fiber optical parametric amplifiers*", The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics*, vol. 40, p. 431-436, 2006.

[68] K. Shiraki, M. Ohashi, and M. Tateda, "Suppression of stimulated Brillouin scattering in a fibre by changing the core radius", *Electronics Letters*, vol. 31, p. 668-669, 1995.

[69] K. Shiraki, M. Ohashi, and M. Tateda, "SBS threshold of a fiber with a Brillouin frequency shift distribution", *Journal of Lightwave Technology*, vol. 14, p. 50-57, 1996.

[70] N. Yoshizawa and T. Imai, "Stimulated Brillouin scattering suppression by means of applying strain distribution to fiber with cabling", *Journal of Lightwave Technology*, vol. 11, p. 1518-1522, 1993.

[71] A. Liu, "Suppressing stimulated Brillouin scattering infiber amplifiers using nonuniform fiber andtemperature gradient", *Opt. Express*, vol. 15, p. 977-984, 2007.

[72] S. Korotky, P. Hansen, L. Eskildsen, and J. Veselka. "Efficient phase modulation scheme for suppressing stimulated Brillouin scattering", *Tech. Dig. Int. Conf. Integrated Optics and Optical Fiber Communications*. 1995.

[73] F.W. Willems, W. Muys, and J.S. Leong, "Simultaneous suppression of stimulated Brillouin scattering and interferometric noise in externally modulated lightwave AM-SCM systems", *IEEE Photonics Technology Letters*, vol. 6, p. 1476-1478, 1994.

[74] E. Lichtman, R.G. Waarts, and A.A. Friesem, "Stimulated Brillouin scattering excited by a modulated pump wave in single-mode fibers", *Journal of Lightwave Technology*, vol. 7, p. 171-174, 1989.

[75] T.C. Liang, N.J. Cheng, and S.C. Hung, "Gain enhancement in L-band gain-flattened EDFA using a reflective-type structure", *Microwave and Optical Technology Letters*, vol. 37, p. 393-395, 2003.

[76] C.R. Giles and E. Desurvire, "Modeling erbium-doped fiber amplifiers", *Journal of Lightwave Technology*, vol. 9, p. 271-283, 1991.

[77] S. Yan, J.W. Sulhoff, A.K. Srivastava, J.L. Zyskind, C. Wolf, T.A. Strasser, J.R. Pedrazzani, J.B. Judkins, R.P. Espindola, A.M. Vengsardar, and Z. Jianhui. "An 80 nm ultra wide band EDFA with low noise figure and high output power", *Integrated Optics and Optical Fibre Communications, 11th International Conference on, and 23rd European Conference on Optical Communications (Conf. Publ. No.: 448)*. 1997.

[78] R.J. Mears, L. Reekie, I.M. Jauncey, and D.N. Payne, "Low-noise erbium-doped fibre amplifier at 1.54pm", *Electronics Letters*, vol. 23, p. 1026-1028, 1987.

[79] M. Yamada, H. Ono, and Y. Ohishi, "Low-noise, broadband Er3+-doped silica fibre amplifiers", *Electronics Letters*, vol. 34, p. 1490-1491, 1998.

[80] M. Harumoto, M. Shigehara, and H. Suganuma, "Gain-Flattening Filter Using Long-PeriodFiber Gratings", *J. Lightwave Technol.*, vol. 20, p. 1027, 2002.

[81] S. Ik-Bu, B. Jang-Gi, L. Nam-Kwon, K. Hyung-Woo, and S. Jae-Won, "Gain flattened and improved EDFA using microbending long-period fibre gratings", *Electronics Letters*, vol. 38, p. 1324-1325, 2002.

[82] M. Yamada, H. Ono, T. Kanamori, T. Sakamoto, Y. Ohishi, and S. Sudo, "A low-noise and gain-flattened amplifier composed of a silica-based and a fluoride-based Er3+-doped fiber amplifier in a cascade configuration", *IEEE Photonics Technology Letters*, vol. 8, p. 620-622, 1996.

[83] H. Masuda and Y. Miyamoto, "Low-noise extended L-band phosphorus co-doped silicate EDFA consisting of novel two-stage gain-flattened gain blocks", *Electronics Letters*, vol. 44, p. 1082-1083, 2008.

[84] M. Kakui, T. Kashiwada, M. Onishi, M. Shigematsu, and M. Nishimura. "Optical Amplification Characteristics around 1.58 μm of Silica-Based Erbium-Doped Fibers Containing Phosphorous / Alumina as Codopants", *Optical Amplifiers and Their Applications*. Optical Society of America, 2006.

[85] Z. Yanbin, L. Xiaoming, P. Jiangde, F. Xue, and Z. Wei, "Wavelength and power dependence of injected C-band laser on pump conversion efficiency of L-band EDFA", *IEEE Photonics Technology Letters*, vol. 14, p. 290-292, 2002.

[86] M. Bumki, Y. Hosung, L. Won Jae, and P. Namkyoo, "Coupled structure for wide-band EDFA with gain and noise figure improvements from C to L-band ASE injection", *IEEE Photonics Technology Letters*, vol. 12, p. 480-482, 2000.

[87] M.A. Mahdi, F.R. Mahamd Adikan, P. Poopalan, S. Selvakennedy, and H. Ahmad, "Effects of signal seeding on long-wavelength-band Er3+-doped fiber amplifiers", *Optical Engineering*, vol. 40, p. 186-192, 2001.

[88] M.A. Mahdi and H. Ahmad, "Long-wavelength-band Er3+-doped fiber amplifier incorporating a ring-laser as a seed signal generator", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 7, p. 59-63, 2001.

[89] J. Nilsson, S.Y. Yun, S.T. Hwang, J.M. Kim, and S.J. Kim, "Long-wavelength erbium-doped fiber amplifier gain enhanced by ASE end-reflectors*", IEEE Photonics Technology Letters*, vol. 10, p. 1551-1553, 1998.

[90] S. Qin, J. He, Y. Zou, and Z. Qiang. "An Improved 3-stage L-band Erbium Doped Fiber Amplifier", *Optical Transmission Systems, Switching, and Subsystems VIII*. Optical Society of America, 2010.

[91] Q. Mao and J.W.Y. Lit, "Amplification enhancement of L-band erbium-doped fiber amplifiers by reflection scheme*", Optics Communications*, vol. 201, p. 61-69, 2002.

[92] M.R. Haleem, M.H. Al-Mansoori, M.Z. Jamaludin, F. Abdullah, and N.M. Din, "High gain double-pass L-band EDFA with dispersion compensation as feedback loop*", Laser Physics*, vol. 21, p. 419-422, 2011.

[93] L.L. Yi, L. Zhan, J.H. Ji, Q.H. Ye, and Y.X. Xia, "Improvement of gain and noise figure in double-pass L-band EDFA by incorporating a fiber Bragg grating*", IEEE Photonics Technology Letters*, vol. 16, p. 1005-1007, 2004.

[94] S.K. Liaw and Y.S. Huang, "C + L-band hybrid amplifier using FBGs for dispersion compensation and power equalisation*", Electronics Letters*, vol. 44, p. 844-845, 2008.

[95] S.-K. Liaw, L. Dou, A. Xu, and Y.-S. Huang, "Optimally gain-flattened and dispersion-managed C+L-band hybrid amplifier using a single-wavelength pump laser*", Optics Communications*, vol. 282, p. 4087-4090, 2009.

[96] L. Shien-Kuei, H. Yu-Sheng, H. Hsin-Kai, C. Nan-Kuang, H. Kuei-Chu, Y. Yi-Lin, W. Ting, A. Manshina, and Y. Tver'yanovic. "Dispersion management and gain flattened for a bridge-type hybrid amplifiers in a pumping recycling mechanism", *International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*. 2010.

[97] M.-N. Guo, S.-K. Liaw, P.-P. Shum, N.-K. Chen, H.-K. Hung, and C. Lin, "Single wavelength-pump-based bi-directional hybrid fiber amplifier for bi-directional local area network application.*", Optics Communications*, vol. 284, p. 573–578, 2011.

[98] Z. Li, C.-L. Zhao, Y.J. Wen, C. Lu, Y. Wang, and J. Chen, "Optimization of a Raman/EDFA hybrid amplifier based on dual-order stimulated Raman scattering using a single-pump*", Optics Communications*, vol. 265, p. 655-658, 2006.

[99] Q. Mao and J.W.Y. Lit, "Amplification enhancement of L-band erbium-doped fiber amplifiers by reflection scheme", *Optics Communications*, vol. 201, p. 61-69, 2002.

[100] H.S. Chung, M.S. Lee, D. Lee, N. Park, and D.J. DiGiovanni, "Low noise, high efficiency L-band EDFA with 980 nm pumping", *Electronics Letters*, vol. 35, p. 1099-1100, 1999.

[101] M.A. Mahdi and H. Ahmad, "Low-noise and high-gain L-band EDFA utilising a novel self-generated signal-seeding technique", *Optics Communications*, vol. 195, p. 241-248, 2001.

[102] K. Hagimoto, K. Iwatsuki, A. Takada, M. Nakazawa, M. Saruwatari, K. Aida, K. Nakagawa, and M. Horiguchi, "250 km nonrepeated transmission experiment at 1.8 Gb/s using LD pumped Er3+-doped fibre amplifiers in IM/direct detection system", *Electronics Letters*, vol. 25, p. 662-664, 1989.

[103] P.B. Hansen, V.L. da Silva, G. Nykolak, J.R. Simpson, D.L. Wilson, J.E.J. Alphonsus, and D.J. DiGiovanni, "374-km transmission in a 2.5-Gb/s repeaterless system employing a remotely pumped erbium-doped fiber amplifier", *Photonics Technology Letters, IEEE*, vol. 7, p. 588-590, 1995.

[104] P.M. Gabla, J.L. Pamart, R. Uhel, E. Leclerc, J.O. Frorud, F.X. Ollivier, and S. Borderieux, "401 km, 622 Mb/s and 357 km, 2.488 Gb/s IM/DD repeaterless transmission experiments using erbium-doped fiber amplifiers and error correcting code", *IEEE Photonics Technology Letters*, vol. 4, p. 1148-1151, 1992.

[105] D. Mahgerefteh, C. Liao, X. Zheng, Y. Matsui, B. Johnson, D. Walker, Z.F. Fan, K. McCallion, and P. Tayebati, "Error-free 250 km transmission in standard fibre using compact 10 Gbit/s chirp-managed directly modulated lasers (CML) at 1550 nm", *Electronics Letters*, vol. 41, p. 543-544, 2005.

[106] P.B. Hansen, L. Eskilden, S.G. Grubb, A.M. Vengsarkar, S.K. Korotky, T.A. Strasser, J.E.J. Alphonsus, J.J. Veselka, D.J. DiGiovanni, D.W. Peckham, E.C. Beck, D. Truxal, W.Y. Cheung, S.G. Kosinski, D. Gasper, P.F. Wysocki, V.L. da Silva, and J.R. Simpson, "529 km unrepeatered transmission at 2.488 GBit/s using dispersion compensation, forward error correction, and remote post- and pre-amplifiers pumped by diode-pumped Raman lasers", *Electronics Letters*, vol. 31, p. 1460-1461, 1995.

[107] O. Gautheron, S.S. Sian, C. Grandpierre, M.S. Chaudhry, J.L. Pamart, T. Barbier, E. Bertin, P. Bonno, E. Brandon, M. Genot, P. Marmier, M. Mesic, P.M. Gabla, and P. Bousselet, "481 km, 2.5 Gbit/s and 501 km, 622 Mbit/s unrepeatered transmission using forward error correction and remotely pumped postamplifiers and preamplifiers", *Electronics Letters*, vol. 31, p. 378-380, 1995.

[108] P.B. Hansen, L. Eskilden, S.G. Grubb, A.M. Vengsarkar, S.K. Korotky, T.A. Strasser, J.E.J. Alphonsus, J.J. Veselka, D.J. DiGiovanni, D.W. Peckham, E.C. Beck, D. Truxal, W.Y. Cheung, S.G. Kosinski, D. Gasper, P.F. Wysocki, V.L. da Silva, and J.R. Simpson. "2.488-Gb/s Unrepeatered Transmission over 529 km using Remotely Pumped Post- and Pre-Amplifiers, Forward Error Correction, and Dispersion Compensation", *Optical Fiber Communications Conference*. Optical Society of America, 1995.

[109] P.B. Hansen, V.L. da Silva, G. Nykolak, J.R. Simpson, D.L. Wilson, J.E.J. Alphonsus, and D.J. DiGiovanni, "374-km transmission in a 2.5-Gb/s repeaterless system employing a remotely pumped erbium-doped fiber amplifier", *IEEE Photonics Technology Letters*, vol. 7, p. 588-590, 1995.

[110] H. Masuda, H. Kawakami, S. Kuwahara, A. Hirano, K. Sato, and Y. Miyamoto, "1.28 Tbit/s (32 x 43 Gbit/s) field trial over 528 km (6 x 88 km) DSF using L-band remotely-pumped EDF/distributed Raman hybrid inline amplifiers", *Electronics Letters*, vol. 39, p. 1668-70, 2003.

[111] M. Tsukitani, M. MATSUI, E. SASAOKA, and M. NISHIMURA. "Ultra Low Nonlinearity Fiber with Improved Microbending Performance", *Opto-Electronic Communication Conference, OECC2002, 11D1-3*. 2002.

[112] J.-P. Blondel, E. Brandon, L. Labrunie, P.L. Poux, D. Toullier, and G. Zamies, "Error-free 32 x 10 Gbit/s unrepeatered transmission over 450 km", *Proc. ECOC'99*, p. Paper PD2-6, 1999.

[113] L. Labrunie, F. Boubal, P. Le Roux, and E. Brandon, "500 km WDM 12 x 10 Gbit/s CRZ repeaterless transmission using second order remote amplification", *Electronics Letters*, vol. 39, p. 1394-1395, 2003.

[114] T. Miyakawa, I. Morita, and N. Edagawa, "40 Gbit/s x 25 WDM unrepeatered transmission over 362 km", *Electronics Letters*, vol. 38, p. 726-727, 2002.

[115] M.H. Abu Bakar, A.F. Abas, M. Mokhtar, H. Mohamad, and M.A. Mahdi, "Utilization of stimulated Raman Scattering as secondary pump on hybrid remotely-pump L-band Raman/erbium-doped fiber amplifier", *Laser Physics*, vol. 21, p. 722-728, 2011.

[116] M.H. Abu Bakar, F.R. Mahamd Adikan, and M.A. Mahdi, "Rayleigh-Based Raman Fiber Laser With Passive Erbium-Doped Fiber for Secondary Pumping Effect in Remote L-Band Erbium-Doped Fiber Amplifier", *IEEE Photonics Journal*, vol. 4, p. 1042-1050, 2012.

[117] A.W. Naji, M.S.Z. Abidin, M.H. Al-Mansoori, S.J. Iqbal, M.K. Abdullah, and M.A. Mahdi, "Enhancement of Unrepeatered Transmission Efficiency Incorporating Double-pass Remotely-pumped Optical Amplifier", *Journal of Optical Communications*, vol. 27, p. 201, 2006.

[118] H. Maeda, G. Funatsu, and A. Naka, "Ultra-long-span 500 km 16 x 10 Gbit/s WDM unrepeatered transmission using RZ-DPSK format", *Electronics Letters*, vol. 41, p. 34-35, 2005.

[119] H. Kawakami, H. Masuda, and Y. Miyamoto, "Directional bypass configuration in remotely-pumped EDF/distributed Raman hybrid amplifier scheme for online OTDR monitoring", *Electronics Letters*, vol. 40, p. 259-260, 2004.

[120] T.-C. Liang and S. Hsu, "The L-band EDFA of high clamped gain and low noise figure implemented using fiber Bragg grating and double-pass method", *Optics Communications*, vol. 281, p. 1134-1139, 2008.

[121] M. Mahdi, B. Bouzid, and M. Abdullah, "Enhanced structure of a double-pass erbium-doped fiber amplifier for multiple wavelength amplifications", *Laser Physics*, vol. 18, p. 1200-1203, 2008.

[122] N. Yusoff, M. Abu Bakar, S. Sheih, F. Mahamd Adikan, and M. Mahdi, "Gain-flattened erbium-doped fiber amplifier with flexible selective band for optical networks", *Laser Physics*, vol. 20, p. 1747-1751.

[123] H. Ono, M. Yamada, and Y. Ohishi, "Gain-flattened Er^{3+}-doped fiber amplifier for a WDM signal in the 1.57-1.60-um wavelength region", *IEEE Photonics Technology Letters*, vol. 9, p. 596-598, 1997.

[124] H. Ono, M. Yamada, T. Kanamori, S. Sudo, and Y. Ohishi, "1.58-um Band Gain-Flattened Erbium-Doped Fiber Amplifiers for WDM Transmission Systems", *Journal of Lightwave Technology*, vol. 17, p. 490, 1999.

[125] M. Adzir Mahdi and S.-J. Sheih, "Low-noise 1480-nm pumped L-band erbium-doped fibre amplifiers incorporating a bypass isolator", *Optics Communications*, vol. 237, p. 295-299, 2004.

[126] Q. Mao, J. Wang, X. Sun, and M. Zhang, "A theoretical analysis of amplification characteristics of bi-directional erbium-doped fiber amplifiers with single erbium-doped fiber", *Optics Communications*, vol. 159, p. 149-157, 1999.

[127] E. Desurvire, "Analysis of gain difference between forward- and backward-pumped erbium-doped fiber amplifiers in the saturation regime", *IEEE Photonics Technology Letters*, vol. 4, p. 711-714, 1992.

[128] C.-F. Su and L. Wang, "Gain enhancement of L-band EDFA by using residual pump power in a three-stage configuration", *Optics Communications*, vol. 280, p. 412-416, 2007.

[129] P.F. Wysocki, J.B. Judkins, R.P. Espindola, M. Andrejco, and A.M. Vengsarkar, "Broad-band erbium-doped fiber amplifier flattened beyond 40 nm using long-period grating filter", *IEEE Photonics Technology Letters*, vol. 9, p. 1343-1345, 1997.

[130] S.A. Babin, A.E. El-Taher, P. Harper, D.V. Churkin, S.I. Kablukov, E.V. Podivilov, and S.K. Turitsyn. "Ultra-long raman laser with a feedback based on the Rayleigh scattering", *European Conference on Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference. CLEO Europe - EQEC 2009*. 2009.

[131] J.D. Marconi, J.M.C. Boggio, and H.L. Fragnito, "Narrow linewidth fibre-optical wavelength converter with strain suppression of SBS", *Electronics Letters*, vol. 40, p. 1213-1214, 2004.

[132] S.W. Harun, N. Tamchek, P. Poopalan, and H. Ahmad, "Double-pass L-band EDFA with enhanced noise figure characteristics", *IEEE Photonics Technology Letters*, vol. 15, p. 1055-1057, 2003.

[133]. D.M. Baney and J. Stimple, "WDM EDFA gain characterization with a reduced set of saturating channels", *IEEE Photonics Technology Letters*, vol. 8, p. 1615-1617, 1996.

[134] F.A. Flood, "Gain saturation behavior in L-band EDFAs", *IEEE Photonics Technology Letters*, vol. 12, p. 1156-1158, 2000.

[135] A. Bakar, M. Mahdi, M. Al-Mansoori, S. Shaari, and A. Zamzuri, "Single-stage gain-clamped L-band EDFA with C-band ASE saturating tone", *Laser Physics*, vol. 19, p. 1026-1029, 2009.

[136] M.A. Mahdi, F.R.M. Adikan, P. Poopalan, S. Selvakennedy, and H. Ahmad, "High-gain bidirectional Er^{3+}-doped fiber amplifier for conventional- and long-wavelength bands", *IEEE Photonics Technology Letters*, vol. 12, p. 1468-1470, 2000.

[137] M. Haleem, M. Al-Mansoori, M. Jamaludin, F. Abdullah, and N. Din, "High gain double-pass L-band EDFA with dispersion compensation as feedback loop", *Laser Physics*, vol. 21, p. 419-422, 2011.