UNIVERSITI PUTRA MALAYSIA

NEW PUMP DELIVERY SCHEME FOR REMOTELY PUMPED L-BAND ERBIUM-DOPED FIBER AMPLIFIER

MUHAMMAD HAFIZ BIN ABU BAKAR

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By

MUHAMMAD HAFIZ BIN ABU BAKAR

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Chair: Professor Mohd Adzir Bin Mahdi, PhD

Faculty: Faculty of Engineering

Several enhancements to the pump delivery scheme for remotely pumped L-band erbium-doped fiber amplifier (R-EDFA) were investigated in this research. The proposed pumping scheme utilized stimulated Raman scattering (SRS) generated during the pump light propagation and use it as a pump in order to improve the performance of the L-band amplifier. The pumping scheme took advantage of the SRS and utilizes it as a higher-order pump source to increase the amount of pump power available for amplification. Initially, the proposed pumping scheme was focused on the pump delivered to the R-EDFA itself. Two Raman laser wavelengths at 1455 and 1423 nm were tested as the primary pump. A total of 44.5 mW delivered pump power was derived from the 1455 nm laser and the 1555 nm SRS second-order pump. Amplification of the SRS saturated the R-EDFA and induced gain-clamping effect. The SRS also contributed to the generation of 1567 nm laser in the transmission line that dominated the Raman amplification and reduced the transmission gain and optical signal-to-noise ratio (OSNR) at the shorter L-band wavelengths. The utilization of SRS at 1512 nm eliminated the effect of gain

saturation and allowed maximum gain up to 27.3 dB. However, the SRS location far from the L-band region reduced the Raman amplification effect and subsequently lowered the transmission gain.

From the 1567 nm laser produced by the 1555 nm SRS, another enhancement to the pumping scheme was proposed. The idea was to utilize the 1567 nm laser, which was generated by the ultra-long Raman fiber laser (ULRFL) phenomenon, as a third-order pump for a section of passive EDF deployed prior to the end of the transmission span. The transmission gain was improved over the conventional R-EDFA for 0 dBm signal power but the gain for the lower signal levels was clamped due to the saturation of the passive EDF by the 1567 nm ULRFL. The integration of the conventional R-EDFA architecture with passive EDF section was then performed, with the ULRFL acting as the second-order pump for the passive EDF. A wavelength-selective reflector was incorporated for variation of ULRFL seed wavelength, from which an optimized ULRFL wavelength range was acquired from 1553 to 1557 nm. This amplifier architecture obtained the best gain performance at all signal levels with minimal OSNR penalty. This is attributed to the high ULRFL power and the location of the ULRFL at wavelength with high erbium absorption. The findings demonstrated the performance improvements accorded through the use of the proposed pumping scheme. There is immense potential for further enhancement by optimizing the Raman laser wavelength and striking a balance between efficient pump-to-signal conversion and Raman amplification.

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

SKIM PENGHANTARAN PAM BARU UNTUK PENGUAT GENTIAN TERDOP ERBIUM L-BAND YANG DIPAM SECARA JAUH

Oleh

MUHAMMAD HAFIZ BIN ABU BAKAR

Februari 2011

Pengerusi: Profesor Mohd Adzir Bin Mahdi, PhD

Fakulti: Fakulti Kejuruteraan

Beberapa peningkatan kepada skim penghantaran pam bagi penguat gentian terdop erbium L-band yang dipam secara jauh (R-EDFA) telah disiasat dalam kajian ini. Skim pam yang diusulkan ini menggunakan penyerakan Raman terangsang (SRS) yang dijana sewaktu pergerakan cahaya pam sebagai pam demi meningkatkan prestasi penguat L-band. Skim pam ini mengambil kesempatan daripada SRS dan meggunakannya sebagai sumber pam peringkat lebih tinggi untuk meningkatkan jumlah kuasa pam yang tersedia untuk penguatan. Pada mulanya, skim pam yang diusulkan ini ditumpukan kepada pam yang dihantar kepada R-EDFA itu sendiri. Dua jarak gelombang laser Raman pada 1455 dan 1423 nm telah diuji sebagai pam utama. Sejumlah 44.5 mW kuasa pam diperolehi dari laser 1455 nm dan pam peringkat kedua SRS 1555 nm. Penguatan SRS telah menepukan R-EDFA itu dan mendorong kesan gandaan yang diapit. SRS itu juga menyumbang kepada penjanaan laser 1567 nm di dalam talian penghantaran yang mendominasi penguatan Raman dan merendahkan gandaan penghantaran dan nisbah isyarat-kepada-hingar optik (OSNR), di jarak gelombang L-band yang lebih pendek. Penggunaan SRS pada 1512

nm menghapuskan kesan penepuan gandaan dan membenarkan gandaan maksimum setinggi 27.3 dB. Walau bagaimana pun, lokasi SRS yang terletak jauh dari rantau L-band mengurangkan kesan penguatan Raman dan seterusnya merendahkan gandaan penghantaran.

Daripada laser 1567 nm yang dihasilkan oleh SRS 1555 nm, satu peningkatan kepada skim pam ini telah diusulkan. Ideanya adalah untuk menggunakan laser 1567 nm itu, yang dijana oleh fenomena laser gentian Raman ultra-panjang (ULRFL), sebagai pam peringkat ketiga bagi satu seksyen gentian terdop erbium (EDF) pasif yang diletakkan sebelum penghujung jengkal penghantaran. Gandaan penghantaran telah ditingkatkan bagi kuasa isyarat 0 dBm berbanding R-EDFA konvensional akan tetapi gandaan telah diapit bagi kuasa isyarat yang lebih rendah kerana ULRFL 1567 nm telah menepukan EDF pasif. Integrasi rekabentuk R-EDFA konvensional dan seksyen EDF pasif kemudian dilakukan, dengan ULRFL berperanan sebagai pam peringkat kedua bagi EDF pasif. Satu pemantul jarak gelombang terpilih digabungkan untuk memvariasikan jarak gelombang benih ULRFL dan melaluinya satu julat jarak gelombang optimum telah diperolehi dari 1553 ke 1557 nm. Rekabentuk penguat ini menghasilkan prestasi gandaan terbaik pada semua tahap isyarat dengan penalti OSNR yang rendah. Ini disebabkan oleh kuasa ULRFL yang tinggi dan lokasinya pada jarak gelombang dengan penyerapan erbium yang tinggi. Penemuan ini mendemonstrasikan peningkatan prestasi yang diberikan melalui penggunaan skim pam yang diusulkan. Terdapat potensi besar bagi peningkatan seterusnya dengan mengoptimumkan jarak gelombang laser Raman dan menemukan keseimbangan antara penukaran pam-ke-isyarat yang efisyen dan penguatan Raman.

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UPM School of Graduate Studies

Department of Computer & Communication Systems Engineering

This anxiety-filled yet exciting journey would not have come to its end if not for the invaluable assistance from all the parties involved. Again, thank you.

I certify that a Thesis Examination Committee has met on 24 February 2012 to conduct the final examination of Muhammad Hafiz Bin Abu Bakar on his thesis entitled **"New Pump Delivery Scheme for Remotely Pumped L-band Erbium-doped Fiber Amplifier"** 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 Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Abdul Rahman Bin Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ahmad Shukri Bin Muhammad Noor, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Salasiah Binti Hitam, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Lawrence R. Chen, PhD
Professor
Department of Electrical and Computer Engineering
McGill University
Canada
(External Examiner)

SEOW HENG FONG, 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 fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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

Ahmad Fauzi Bin Abas, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Makhfudzah Binti Mokhtar, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

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

Date:

DECLARATION

I 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 at any other institution.

MUHAMMAD HAFIZ BIN ABU BAKAR

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LIST OF ABBREVIATIONS

ASE	Amplified Spontaneous Emission
CFBG	Chirped Fiber Bragg Grating
DCF	Dispersion Compensating Fiber
DRA	Distributed Raman Amplifier
DSF	Dispersion-shifted Fiber
DWDM	Dense Wavelength-division Multiplexing
EDF	Erbium-doped Fiber
EDFA	Erbium-doped Fiber Amplifier
ESA	Excited State Absorption
FOM	Figure of Merit
FWM	Four-wave Mixing
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
PCE	Power Conversion Efficiency
R-EDFA	Remotely Pumped Erbium-doped Fiber Amplifier
SBS	Stimulated Brillouin Scattering
SMF	Single-mode Fiber
SNR	Signal to Noise Ratio
SRS	Stimulated Raman Scattering
SSE	Source Spontaneous Emission
TBF	Tunable Bandpass Filter
WDM	Wavelength-division Multiplexing

CHAPTER 1

INTRODUCTION

1.1 Overview

Optical system has been at the forefront of the communication technology due to its exceptionally wide bandwidth which enables large data transmission. This feature is in-line with the increasing demand for higher data transmission brought upon by the rise of the Internet. Its status as the premier communication method is further solidified with its ability to transmit data at longer distance, thanks to the low attenuation coefficient of optical fiber. While the present fiber technology allows for fiber attenuation of about 0.2 dB/km, the accumulated loss inside the fiber will still limit the distance achievable by optical transmission. This limitation can be overcome through the use of optical amplifiers in between fiber spans. Previously, optical amplifiers came in the form of repeaters, which were basically electrical amplifiers equipped with optical-electro converters [1]. The drawback of this method was the complexity of the process, where light signals have to be converted into electrical signals, amplified in electrical domain and then converted back into optical signal for retransmission. This process became more complicated in wavelength-division multiplexing (WDM) networks since a repeater is needed for each wavelength. There is also less flexibility with repeaters as the components are transmission rate dependent. These added complexities increased the cost of repeaters and eventually the whole system. The situation calls for an alternative solution, namely amplifiers that can amplify in optical domain.

One of the frontrunner in the optical amplifier field is the erbium-doped fiber amplifier or EDFA. EDFA utilizes a length of fiber doped with a type of rare earth element called erbium as its gain medium. Erbium distinguishing characteristic is its emission spectrum in the 1.5 μm wavelength range, which coincides with the minimum loss region for modern communication fibers. EDFA has been the preferred choice of amplifier in recent times due to its ability to produce high gain with low pumping power. The amplification bandwidth can also go as wide as 80 nm [2] and the gain flatness can be easily achieved with the use of gain-flattening filters [3]. The drawback of EDFA is the additional cost due to the need for a specialized gain medium and the noise figure is also subjected to a theoretical quantum limit of 3 dB.

The wide amplification bandwidth of erbium allows the utilizations of EDFA in L-band transmission window (1570 to 1605 nm) that was introduced to support the growing need for bandwidth. The supplementary transmission window is crucial since the C-band wavelength range from 1530 to 1565 nm is already exhausted as the WDM transmission has already reached its minimum channel spacing. Additionally, WDM transmission in C-band is subjected to a glaring problem of four-wave mixing (FWM). FWM is a nonlinear effect associated with long distance transmission of multiple signals at small channel spacing [4]. Older optical lines employing dispersion-shifted fiber (DSF) was optimized for transmission in the 1.3 μm region, which was the previous wavelength range for optical transmission. DSF of that type has its zero-dispersion wavelength around 1550 nm, which is located in the current transmission window. The lack of dispersion in that area increases the susceptibility of phase-matching condition between WDM signals in C-band. Phase-matched signals mix to produce signals at other wavelengths thus adding noise in the transmission and reduce the power of the original signals. There is no non-zero dispersion wavelength in L-band operating range for either older or modern optical lines, thus reducing the effect of FWM in L-band WDM systems [5].

Earlier work on EDFA was confined to discrete-pumped amplifiers which encounter no problems in terms of pump power delivery. This approach however, would require the presence of the pump laser in the vicinity of the amplifier, which could be troublesome due to geographical obstruction and the need for large power supply in unreachable areas. The incorporation of remote pumping scheme in EDFA removed the obstacles involved with discrete pump method [6]. In remote pumping, the pump laser is delivered to the amplifier from another location using a dedicated pump line or through the transmission line itself.

1.2 Challenges of EDFA in L-band

The EDFA is capable of amplifying signal in L-band since its emission spectrum extends beyond 1610 nm. The emission at that particular wavelength range is also more uniform, simplifying the process of gain flattening. It is interesting to note that due to the attenuation curve of modern fiber, it is preferable for remotely pumped EDFA (R-EDFA) to utilize pump wavelength around 1480 nm to reduce the loss suffered by the pump laser. This works to the advantage of L-band EDFA that is remotely pumped through the transmission line as the Raman scattering effect in the transmission fiber will contribute to Raman amplification in the L-band region. Nonetheless, the performance of the whole system still hinges on the EDFA itself and it is very critical to consider the impact of accumulated fiber loss to the delivered pump power. This is because erbium emission in the L-band is substantially low in contrast to the earlier region of the emission cross-section. The difference translates to roughly 50% less gain per meter in L-band compared to in C-band. The low gain coefficient of EDFA in L-band forces the use of longer EDF lengths to produce gain comparable to C-band EDFA. Inadvertently, longer EDF lengths will require higher pumping power in order to produce the intended gain value. However, pump power is considered a luxury in R-EDFA since the pump laser is already subjected to attenuation and scatterings during its long distance delivery. The remaining pump power reaching the amplifier might not be sufficient to excite the longer gain medium required by L-band R-EDFA. Ultimately, this situation will lead to lower gain output and subsequently limit the length of transmission spans that can be deployed. In addition, since the noise figure is dependent on the gain value, the lower gain output will give out worse noise figure and increase the error in the transmission.

1.3 Objectives of This Research

A lot of studies have been done on gain enhancement techniques in discrete EDFA, either in C-band or L-band. On the contrary, the number of research done on remotely pumped EDFA has been sorely lacking, with the bulk of it focused on the C-band. This research intends to address this dearth by investigating pump delivery scheme designed to improve the performance of remotely pumped L-band EDFA.

The objectives of this study in detail are:

1. To design and develop a new pumping scheme for L-band R-EDFA utilizing stimulated Raman scattering (SRS) that can boost the amount of pump power available for amplification.
2. To implement L-band R-EDFA and span architectures that can utilize the proposed pumping schemes.
3. To obtain performance enhancements over conventional L-band R-EDFA through the use of the proposed pumping schemes and amplifier architectures.

1.4 Scope of Work

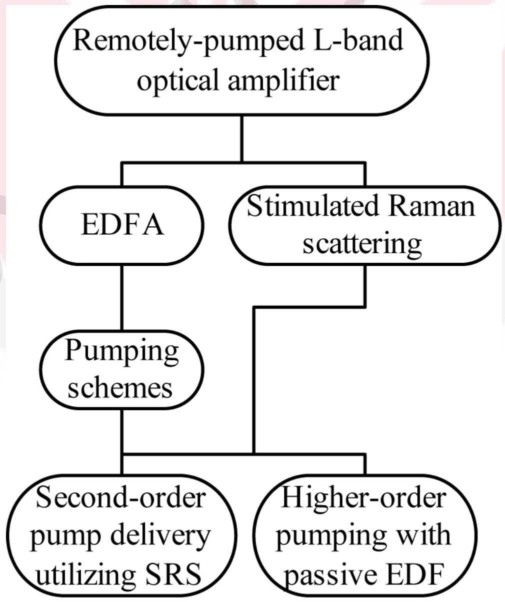

Figure 1.1: Scope of work.

This study is focused on enhancing the remotely pumped L-band EDFA. New pumping schemes were proposed to improve the performance of the remote amplifier. Two secondary pumping schemes that utilized SRS were investigated. The first pumping scheme introduced a second-order pump source derived from SRS generated during pump delivery in order to augment the pump power received by the R-EDFA. The performance was analyzed and subsequent revisions to the pumping scheme were detailed. The second proposed pumping scheme initiated the secondary pumping effect by employing a section of passive EDF that was pumped by a laser generated in the optical fiber. Optimization was performed accordingly in order to obtain the best performance improvements over conventional pumping scheme.

1.5 Outline of The Thesis

The contents are divided into 5 chapters including this chapter. Chapter 1 acts as the introduction chapter, where an overview of the remotely pumped L-band EDFA is presented, along with its challenges that became the basis of this research work. The objectives and the scope of work are also explained in the first chapter. In Chapter 2, the theory behind this research work will be elaborated along with a review of supporting literatures. Chapter 3 talks about the outcome of the study on the first enhanced pumping scheme for R-EDFA, where second-order pumping method utilizing stimulated Raman scattering is detailed along with the optimizations and variations performed during the study. Discussions in Chapter 4 are centered on the generation of secondary amplification effect through utilization of passive EDF. The principle behind the generation of pump power for the passive EDF and the steps taken to optimize the architecture are described as well. The methodologies involved with the architectures in Chapter 3 and 4 are included in each respective chapter. The thesis is wrapped up with Chapter 5, which consists of conclusions, research contributions and future recommendations.

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