UNIVERSITI PUTRA MALAYSIA

CHARACTERIZATION OF DICRETE GAIN CLAMPED RAMAN FIBER AMPLIFIER

ASMAHANIM AHMAD

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By

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By

ASMAHANIM BINTI AHMAD

AUGUST 2007

Chairman: **Associate Professor Mohd. Adzir bin Mahdi, PhD**

Faculty: **Engineering**

Modern Dense Wavelength Division Multiplexing (DWDM) optical networks consist of add/drop elements to enhance the flexibility of the network. However it introduces transient phenomena which induce Optical signal-to-Noise Ratio (OSNR) degradation and non-linear impairments. Such effect can be alleviated by using Gain-clamped Discrete Raman Fiber Amplifier (GC-DCRFA) which will maintain the gain of the amplifier regardless the input power. The GC-DCRFA in this research work design is realized by utilizing a pair of circulators at the input and output of the amplifier. A portion of counter-propagating amplified spontaneous emission (ASE) is extracted and used to clamp the gain at desired values. The GC-DCRFA is pumped using a pair of 1465 nm Laser Diodes (LD) and input signal wavelength of 1560 nm is used throughout the research work. The GC-DCRFA is also tested using other lasing wavelengths of 1550 nm and 1565 nm. The proposed

GC-DCRFA configuration is believed to offer less component losses compared to other amplifier configurations discussed previously.

The amplifier characteristics such as the gain and noise figure (NF) are investigated in the research work. The GC-DCRFA is proven to be able to produce a wider dynamic range compared to the conventional DCRFA. For example, at gain of 15 dB, the GC-DCRFA is able to maintain constant gain for input signal, Pin ranges from -25 dBm up to -1.6 dBm with gain variation as of 0.3 dB. On the other hand, the NF is recorded between 5.1 to 6.0 dB. Meanwhile the conventional DCRFA gain starts at 17.8 dB and maintains the gain with the same variation for input signal up to -10 dBm.

The effect of adding an Erbium Doped Fiber Amplifier (EDFA) to form a hybrid gain-clamped amplifier configuration is also studied. The hybrid gain-clamped DCRFA/EDFA has wider dynamic range and the availability of maintaining small gain variation. At gain of 15.5 dB, the hybrid gain-clamped DCRFA/EDFA has a dynamic range of between -25 dBm to -1.61 dBm and gain variation of 1.2 dB. Meanwhile for the same dynamic range, the hybrid gain-clamped EDFA/DCRFA generates bigger gain variation of 3.5 dB. However the Noise Figure (NF) seems to be smaller in the hybrid gain-clamped EDFA/DCRFA compared to the other hybrd configuration. The existence of the EDFA seems to influence the dynamic range as it is operating in low pumping regime which causes weak population inversion.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

CHARACTERIZATION OF DISCRETE GAIN CLAMPED RAMAN FIBER AMPLIFIER

Oleh

ASMAHANIM BINTI AHMAD

OGOS 2007

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

Fakulti: **Kejuruteraan**

Rangkaian optik DWDM moden mempunyai elemen tambah/turun untuk meningkatkan fleksibiliti rangkaian. Namun demikian, ia menyebabkan fenomena fana yang mencetuskan penurunan OSNR dan kerosakan tidak linear. Kesan tersebut dapat dikurangkan dengan menggunakan Amplifier Diskret Gentian Raman Gandaan Terkawal (GC-DCRFA) yang dapat menetapkan gandaan pada nilai yang tertentu tanpa mengira kuasa isyarat masukan. Rekabentuk GC-DCRFA dalam peyelidikan ini dapat direalisasikan dengan penggunaan sepasang *circulator* pada input dan output amplifier itu. Sebahagian daripada ASE yang merambat secara bertentangan diekstrak dan digunakan untuk mengapit gandaan pada nilai yang dikehendaki. GC-DCRFA dipam menggunakan sepasang Laser Diod (LD) pada jarak gelombang 1465 nm dan isyarat masukan pada jarak gelombang 1560 nm digunakan sepanjang penyelidikan ini. GC-DCRFA diuji menggunakan jarak gelombang *lasing* yang lain iaitu pada 1550 nm dan 1565 nm. Konfigurasi GC-DCRFA ini dipercayai dapat

mengurangkan pelemahan kuasa di dalam komponen berbanding konfigurasi amplifier lain yang telah dibentangkan sebelum ini.

Pencirian amplifier seperti pengukuran gandaan dan hingar (NF) telah dilakukan dalam peyelidikan ini. GC-DCRFA terbukti dapat menghasilkan julat dinamik yang lebih besar berbanding DCRFA konvesional. Contohnya ketika gandaan berada pada nilai 15 dB, GC-DCRFA itu dapat mengekalkan gandaan itu untuk isyarat masukan, Pin dari -25 dBm hingga -1.6 dBm dengan variasi gandaan sekecil 0.3 dB. Di samping itu NF yang direkodkan adalah antara 5.1 hingga 6.0 dB. Manakala gandaan DCRFA konvensional bermula pada 17.8 dB hanya dapat bertahan dengan variasi yang sama untuk input masukan setinggi -10 dBm sahaja.

Kesan dari penambahan amplifier gentian berdopan Erbium (EDFA) untuk membentuk konfigurasi amplifier gandaan terkawal hibrid juga telah dibentangkan. DCRFA/EDFA gandaan terkawal hibrid mempunyai julat dinamik yang lebih besar dan berkebolehan mengekalkan variasi gandaan yang kecil. Pada gandaaan 15.5 dB, DCRFA/EDFA gandaan terkawal hibrid dengan julat dinamik antara -25 dBm ke -1.61 dBm mempunyai variasi gandaan sebanyak 1.2 dB. Manakala untuk julat yang sama EDFA/DCRFA gandaan terkawal hibrid menghasilkan variasi yang lebih besar iaitu 3.5 dB. Walaubagaimanapun, NF bagi EDFA/DCRFA gandaan terkawal hibrid didapati lebih baik dengan nilai yang lebih kecil berbanding DCRFA/EDFA gandaan terkawal hibrid. Kemunculan EDFA telah menyebabkan julat dinamik berkurangan kerana ia beroperasi di bahagian berpam rendah yang mengakibatkan pembalikan populasi yang lemah.

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I certify that an Examination Committee has met on **15th August 2007** to conduct the final examination of **Asmahanim binti Ahmad** on her Master of Science thesis entitled "**Characterization of Discrete Gain-Clamped Raman 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:

Sudhansu Shekhar Jamuar, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ahmad Fauzi Abas, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

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

Faidz Abd. Rahman, PhD
Associate Professor
Faculty of Engineering
Universiti Multimedia
(External Examiner)

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

Date: 24 October 2007

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

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

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

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

Date: 15 November 2007

DECLARATION

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

ASMAHANIM BINTI AHMAD

Date: 27 September 2007

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LIST OF ABBREVIATIONS

AGC	Automatic gain control
AOGC	All-optical gain-clamping
ASE	Amplified spontaneous emission
CD	Chromatic Dispersion
DC	Directional coupler
DCF	Dispersion compensating fiber
DCM	Dispersion compensating module
DCRFA	Discrete Raman Fiber Amplifier
DOP	Degree of polarization
DRA	Distributed Raman Amplifier
DRS	Double Rayleigh scattering
DWDM	Dense Wavelength Division Multiplexing
EDF	Erbium doped fiber
EDFA	Erbium Doped Fiber Amplifier
Er	Erbium
FBG	Fiber Bragg grating
FOM	Figure of merit
GC-DCRFA	Gain-clamped Discrete Raman Fiber Amplifier
GC-EDFA	Gain-clamped Erbium Doped Fiber Amplifier
GeO_2	Germania
GVD	Group velocity delay
LD	Laser diode

MPI	Multi-path interference
Nd	Neodymium
NF	Noise Figure
NZDF	Nonzero dispersion fiber
OSA	Optical spectrum analyzer
OSNR	Optical signal-to-Noise ratio
PBC	Polarization Beam Combiner
PDG	Polarization dependant gain
PID	Proportional-integral-derivative
PMD	Polarization Mode Dispersion
PMF	Polarization maintaining fiber
Pr	Praseodymium
RDS	Relative dispersion slope
RIN	Relative intensity noise
RPU	Raman pump unit
SBS	Stimulated Brillouin scattering
SiO_2	Silicon dioxide
SLA	Superlarge effective area fiber
SOP	State of polarization
SRS	Stimulated Raman scattering
SSE	Spontaneous source emission
SMF	Singlemode Fiber
TBPF	Tunable bandpass filter
TLS	Tunable laser source
VOA	Variable optical attenuator

WDM	Wavelength division multiplexer
Yb	Ytterbium

List of Notations

$\Delta\nu$	bandwidth
A_{eff}	effective area
c	speed of light in the vacuum (2.99792458×10^{8} ms^{-1})
C_R	Raman gain efficiency
G	Gain
h	Planck's constant (6.6260755×10^{34} J)
N_1	population density at ground level
N_2	population density at excited level
n_{sp}	inversion parameter
P_{ASE}	ASE power
Pin	input signal power
Pout	output signal power
RB_i	measurement resolution
α	loss
ν_p	pump photon
ν_s	signal photon

CHAPTER 1

INTRODUCTION

1.1 Background of Raman Amplifier

Raman amplification demonstration on optical fibers has started as early as 1970s by Stolen and Ippen (Stolen and Ippen, 1973). However throughout the 1970s and the early 1980s, it just regarded primarily as laboratory curiosities. In the mid 1980s, though many research papers had explained the promises of Raman amplifiers, but Erbium Doped Fiber Amplifier (EDFA) had stolen its limelight by the late 1980s. Only at the end of 1990s there was a resurged of interest in Raman amplification which encouraged the deployment of Raman amplifiers into today's optical networks (Islam, 2002).

Conventional Raman deployment occurs in hybrid configurations with Erbium Doped Fiber Amplifier (EDFA), yet wide-band all-Raman amplification is achieved with increased understanding of Raman effects and high-power pump lasers. Lack of efficient power conversion has limited the role of Raman amplification to enhance the reach of EDFA in long-haul DWDM systems. With the increased understanding of Raman efficiency, Raman gain media and fiber-optics, and the arrival of more efficient, high-power optical pumping lasers, Raman amplifiers can be stand alone without the existence of EDFA as the sole means of amplifying long-haul and ultralong-haul DWDM transport (Islam and Nietubyc, 2002).

In its distributed form, Raman amplification prevents the signal from decaying as much as it otherwise would have if no amplification was provided in the span. Consequently, the optical signal-to-noise ratio (OSNR) does not drop as much as it would have in system based on transmission through a passive fiber followed by a discrete amplifier (Headley and Agrawal, 2005). Through the careful selection of the number, wavelength, and power of signal pumps, an all-Raman amplified system can operate over a wide band of wavelengths in a simple and cost-effective system (Islam and Nietubyc, 2002).

An all-Raman system consists of a discrete, or lumped, Raman amplification portion amplifying a wide continuous band of wavelengths in a single stage. To extend the reach of such a system, a distributed Raman amplification section is tightly coupled with the discrete portion offering the ability to transmit these signals over greater distances. A system which employs multiple bands of wavelengths requires the segregation of the bands through band couplers or Wavelength Division Multiplexer (WDM) (Islam, 2002). Distributed Raman amplification is then added separately to enhance span OSNR for ultralong link distances. Figure 1.1 shows the multiband amplification system which may need a lot of components compared to a system which is deploying wideband all-Raman amplification which only needs fewer components.

Besides the advantage of obtaining gain across a single band without the use of lossy couplers, Raman combines the amplification process with chromatic-dispersion compensation. Higher Raman gain efficiency is best attained using a gain fiber with the smallest effective area, A_{eff}. Based on the various fiber types commercially available, dispersion-compensating fiber (DCF), exhibits the smallest A_{eff}, resulting in the highest Raman gain efficiency. Thus, the discrete Raman amplifier portion of an all-Raman system compensates for chromatic dispersion simultaneously with amplification (Islam and Nietubyc, 2002).

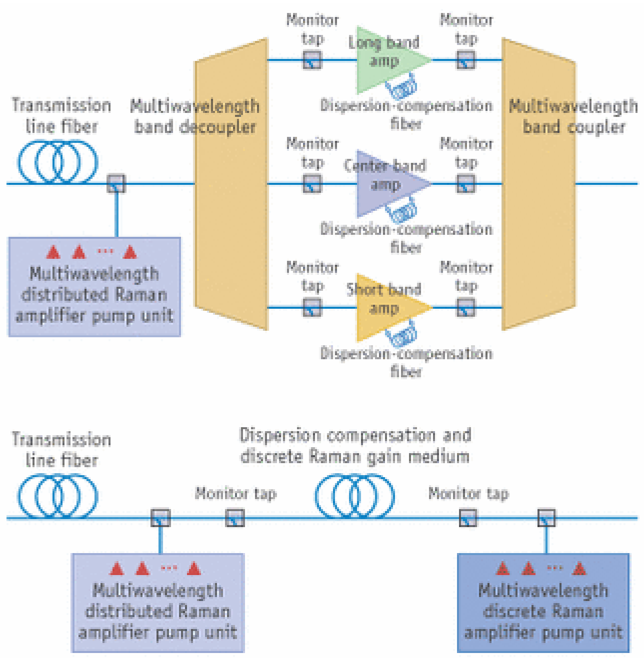

Figure 1.1: A multiband amplification system employing banded amplifiers and separate distributed Raman amplifier (top) System employing a wide-band all- Raman amplification system (bottom) (Islam and Nietubyc, 2002).

1.2 Statement of Problems

In the early days of fiber-based telecommunications, transmission distance was limited by the attenuation in the transmission fibers carrying the information. With the introduction of the EDFA, this limitation was overcome. With the recent advances in pump technology, large scale Raman amplification has become feasible. Discrete as well as distributed Raman amplification is now utilized. Moreover, Raman amplifiers are able to provide gain at any wavelength in any band, not suffering from the need of 'banding' in C- or L-band, known from the EDFA. With transmission distances largely increased by the general availability of suitable amplifiers, another obstacle arises. It is known as the chromatic dispersion of the optically transmitted signals. By carefully designing specialty fibers, the effect of chromatic dispersion may be reversed by inserting modules based on dispersion compensating fibers at discrete points in the transmission line. Dispersion Compensating Modules (DCM) may introduce additional loss. This loss will degrade the noise figure of the EDFA, and the loss of the highest loss module (typically compensating for the longest links of SSMF), will limit the EDFA design. Since dispersion compensating fiber (DCF) is an excellent Raman gain-medium, the insertion loss can be compensated by Raman amplification. Reducing or eliminating the insertion loss can also be used to incorporate other components in the EDFA, such as Optical Add/Drop Multiplexers (OADM), and thereby increasing the flexibility of the system. By increasing the pump power, the DCM can be converted into a Dispersion Compensating Raman Amplifier (DCRA), with positive net gain. Simultaneous compensation for dispersion, dispersion slope and Raman amplification is then achieved in just one component. Such a component can be used to replace an EDFA, or the pre-amplifier part of an EDFA.

In modern optical networks, optical add/drop becomes an important element to enable such networks to be more flexible. The transient phenomena that may occur in add/drop networks or networks with burst-mode traffic due to gain saturation of