



UNIVERSITI PUTRA MALAYSIA

**CHARACTERIZATION OF DISCRETE GAIN CLAMPED RAMAN FIBER
AMPLIFIER**

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**CHARACTERIZATION OF DISCRETE GAIN CLAMPED RAMAN FIBER
AMPLIFIER**

By

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**CHARACTERIZATION OF DISCRETE GAIN CLAMPED RAMAN FIBER
AMPLIFIER**

By

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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, P_{in} 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 hybrid 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.



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CHARACTERIZATION OF DISCRETE GAIN CLAMPED RAMAN FIBER AMPLIFIER

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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 penyelidikan 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 konvensional. 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 gandaan 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:

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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.

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Date: 27 September 2007



TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	iv
ACKNOWLEDGEMENTS	vi
APPROVAL	vii
DECLARATION	ix
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS/NOTATION	xvii

CHAPTER

1	INTRODUCTION	
1.1	Background of Raman Amplifier	1
1.2	Statement of Problems	3
1.3	Objectives	5
1.4	Scope of Work	6
1.5	Thesis Organization	7
2	LITERATURE REVIEW	
2.1	Raman Amplification in Optical Fibers	8
2.2	Raman Noise Sources	10
2.3	Review on Discrete Raman Amplifier	12
2.3.1	Introduction of Discrete Raman Amplifier	12
2.3.2	Principle of Raman: Raman Gain and Bandwidth	14
2.3.3	Amplifier Characteristics	15
2.4	Raman Gain Fiber	17
2.4.1	Raman Properties of Germano-Silicate Fibers	17
2.4.2	Dispersion Compensating Fiber (DCF) as Raman Gain Medium	19
2.5	Discrete Raman Fiber Amplifier based on Dispersion Compensating Fiber (DCF)	22
2.6	Gain-Clamped Discrete Raman Fiber Amplifier (GC-DCRFA)	24
2.7	Erbium Doped Fiber Amplifier	28
2.7.1	EDFA Amplification Mechanism	30
2.7.2	Gain-Clamped Erbium Doped Fiber Amplifier (GC-EDFA)	33
2.8	Hybrid Gain-Clamped Discrete Raman Fiber Amplifier and Erbium Doped Fiber Amplifier	36
2.9	Conclusion	39



3	METHODOLOGY	
3.1	Introduction	40
3.2	Raman Amplifier Design Parameters	41
3.2.1	Input Signal	42
3.2.2	EDFA and Raman Pump Wavelength and Power	43
3.2.3	Lasing Wavelength and Intensity	43
3.3	Raman Amplifier Performance Parameter	44
3.3.1	Gain	44
3.3.2	Noise Figure	45
3.4	Raman Pump Module	47
3.5	Gain-Clamped Discrete Raman Fiber Amplifier Design	48
3.6	Erbium Doped Fiber Amplifier (EDFA) Design	50
3.7	Hybrid Discrete Raman Fiber Amplifier (DCRFA) and Erbium Doped Fiber Amplifier (EDFA)	51
3.8	Components and Device in the DCRFA and EDFA Configuration	53
3.8.1	Avanex Powerform Dispersion Compensating Module	53
3.8.2	JDSU 14xx Laser Diode	53
3.8.3	Handling High Pump Power	55
3.9	Polarization Maintaining Splicing Process	56
3.10	Analysis of Discrete Raman Fiber Amplifier (DCRFA) Characteristics	57
3.10.1	Gain and Noise Figure	58
3.11	Conclusion	59
4	RESULTS AND DISCUSSION	
4.1	Introduction	60
4.2	Unclamped Discrete Raman Fiber Amplifier (DCRFA) Characteristics	60
4.3	Comparison of Unclamped Discrete Raman Fiber Amplifier (DCRFA) and Gain-Clamped Discrete Raman Fiber Amplifier (GC-DCRFA)	64
4.4	Effects of Lasing Wavelengths in Gain-Clamped Raman Fiber Amplifier (GC-DCRFA)	68
4.5	Effect of Input Signal Wavelengths Selection	72
4.6	Erbium Doped Fiber Amplifier (EDFA) Characteristics	73
4.7	Comparison of Conventional Unclamped Hybrid DCRFA and EDFA	76
4.8	Comparison of Gain-Clamped Hybrid DCRFA and EDFA	77
4.9	Conclusion	82
5	CONCLUSION AND FUTURE WORKS	
5.1	Introduction	83
5.2	Counclusion	83
5.3	Future Works and Suggestion	85



REFERENCES	87
BIODATA OF THE AUTHOR	91
LIST OF PUBLICATIONS	92



LIST OF TABLES

Table		Page
2.1	Typical characteristics of DCF	20



LIST OF FIGURES

Figure		Page
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)	3
1.2	The scope of work of the thesis	6
2.1	Schematic of the quantum mechanical process taking place During Raman scattering	8
2.2	Fiber transmission windows and attenuation of AllWave Fiber and standard Single Mode Fiber (SSMF)	13
2.3	Analog Raman amplifier for 1310 nm band	14
2.4	Schematic of simple Raman amplifier	15
2.5	Raman gain efficiency spectra of three types of germano-Silicate fibers, for a pump wavelength of 1450 nm	19
2.6	Schematic diagram of DCF module incorporating Raman Amplifier to offset insertion loss	23
2.7	Schematic of bi-directionally pumped DCRFA in Raman characterization setup	24
2.8	Experimental setup for gain-control using PID control circuit	26
2.9	Experimental setup for S-band Gain-clamped DCRFA	27
2.10	Counterpropagating AOGC designed by Bologini et. al	27
2.11	Gain-clamped DCRFA designed by Karasek et. al	27
2.12	Three possible EDFA configurations (a) co-pumping (b) counter-pumping and (c) bi-directional pumping	30
2.13	Simplified energy level diagram and various transition processes of Er^{3+} ions in silica	32
2.14	Typical configuration of gain-clamped EDFA with ring lasing oscillation	34
2.15	The configuration of gain-clamped using chirped FBG	35



2.16	Schematic diagram of hybrid gain controlled EDFA	36
2.17	Experimental setup and configuration of hybrid-type automatic gain controlled EDFA	36
2.18	Counterpumped Raman amplifier with possible pump reflectors	38
2.19	Hybrid Gain-clamped DCRFA/EDFA with residual pump design by Lee et. al	38
3.1	Flowchart of the processes involved in the study of Gain-Clamped DCRFA and Hybrid Gain-Clamped DCRFA-EDFA	40
3.2	Tunable Laser Source spectrum at specified wavelength	42
3.3	Spectral measurement used to determine amplifier gain	45
3.4	Spectral information for determining the NF of the optical Amplifier using interpolation	46
3.5	Raman Pump Unit	48
3.6	The configuration of the Gain-Clamped Discrete Raman Fiber Amplifier (GC-DCRFA)	50
3.7	Configuration of EDFA with EDF of 8 m and pumped with excess source from DCRFA	51
3.8	The configuration of Hybrid Gain-Clamped DCRFA/EDFA	52
3.9	The configuration of Hybrid Gain-Clamped EDFA/DCRFA	52
3.10	Test setup to characterize laser diodes	54
3.11	Laser Diode Current characteristics	55
3.12	PMF splicer machine	57
4.1	The chromatic dispersion of 11 km DCF measured using CD400L	61
4.2	Combined laser diodes Current-Power characteristics	62
4.3	Gain against Pump Power for different input signal power, P_{in}	63
4.4	Input and Output signal spectrum of unclamped DCRFA	65
4.5	Input and Output spectrum of gain-clamped DCRFA using	



	lasing wavelength of 1550 nm	65
4.6	Gain against input signal, P_{in} at wavelength 1560 nm using lasing wavelength of 1550 nm	67
4.7	Noise figure, NF against input signal, P_{in} at wavelength 1560 nm using lasing wavelength of 1550 nm	68
4.8	Gain and NF against P_{in} with different lasing wavelength (1550 nm and 1565 nm) at VOA attenuation set at 8 dB	69
4.9	Optical spectrum of the signal with lasing wavelength at 1550 nm	70
4.10	Optical spectrum of the signal with lasing wavelength at 1565 nm	70
4.11	Gain against noise figure, NF using different lasing wavelength at attenuation of 8 dB	71
4.12	The optical spectrum of 1560 nm input (yellow) and output (pink) signal. The peak at 1565 nm is operating lasing wavelength	72
4.13	The optical spectrum of 1530 nm input (yellow) and output (pink) signal. The peak at 1565 nm is the operating lasing wavelength	73
4.14	Gain and Noise Figure (NF) for EDFA with EDF length of 8 m for various P_{in}	74
4.15	Gain characteristic for unclamped hybrid configurations	76
4.16	Noise Figure (NF) performance for unclamped hybrid configurations	77
4.17	Gain and NF characteristics of various hybrid configurations for gain of 15 dB	78
4.18	Gain and NF characteristics of various hybrid configurations for gain of 13 dB	79
4.19	Gain and NF characteristics of various configuration for gain of 11 dB	80



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 ($2.99792458 \times 10^8 \text{ ms}^{-1}$)
C_R	Raman gain efficiency
G	Gain
h	Planck's constant ($6.6260755 \times 10^{-34} \text{ J}$)
N_1	population density at ground level
N_2	population density at excited level
n_{sp}	inversion parameter
P_{ASE}	ASE power
P_{in}	input signal power
P_{out}	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).

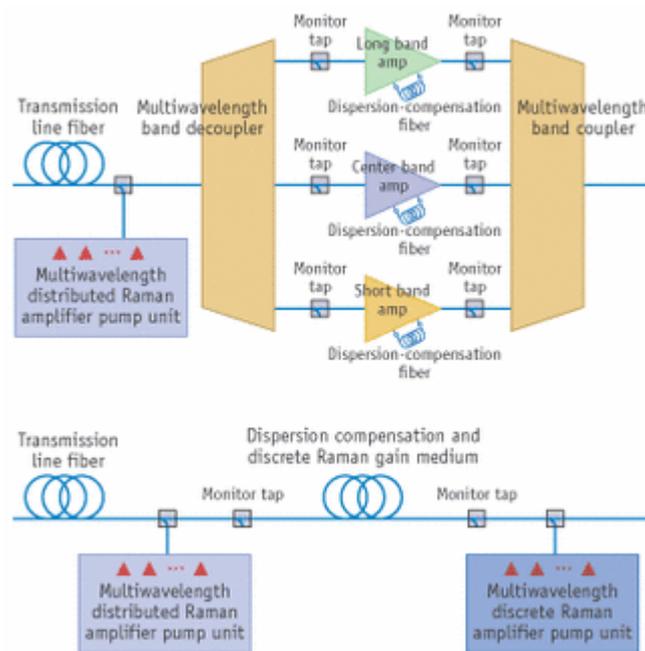


Figure 1.1: A multiband amplification system employing banded amplifiers and separate distributed Raman amplifier (top) System employing a wide-band all- Raman amplification system (bottom) (Islam and Nietubyc, 2002).

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