



**UNIVERSITI PUTRA MALAYSIA**

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

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

**By**

**ASMAHANIM AHMAD**

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fulfilment of the requirement for the degree of Master of Science

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

By

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**AUGUST 2007**

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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**

Oleh

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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 **15<sup>th</sup> 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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**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 <sub>2</sub> | 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 <sub>2</sub> | 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   |
| $A_{\text{eff}}$ | 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                                       |
| $n_{\text{sp}}$  | inversion parameter   |
| $P_{\text{ASE}}$ | ASE power   |
| $P_{\text{in}}$  | input signal power  |
| $P_{\text{out}}$ | output signal power   |
| $RB_i$           | measurement resolution  |
| $\alpha$         | loss  |
| $\nu_p$          | pump photon   |
| $\nu_s$          | 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).

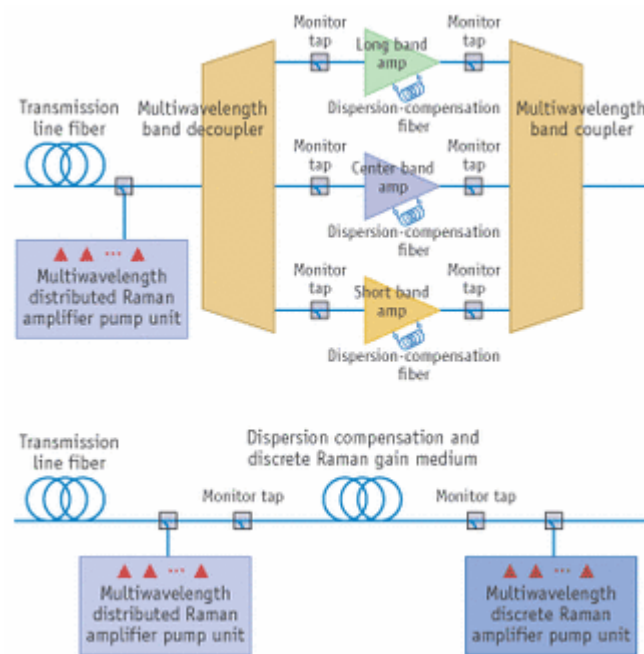


In its distributed form, Raman amplification prevents the signal from decaying as much as it otherwise would have if no amplification was provided in the span. Consequently, the optical signal-to-noise ratio (OSNR) does not drop as much as it would have in system based on transmission through a passive 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,  $A_{\text{eff}}$ . 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

