MULTIWAVELENGTH FIBER LASER BASED ON DIFFERENT TYPES OF SEMICONDUCTOR OPTICAL AMPLIFIERS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia

FEBRUARY 2020

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGMENT

First and foremost, I am grateful for the opportunity given by the Almighty who made this research project a successful achievement. Next, I am indebted to my dedicated supervisor Dr. Nelidya Md. Yusoff from Faculty of Razak Faculty of Technology and Informatics of Universiti Teknologi Malaysia Kuala Lumpur. Useful and invaluable advice are provided by her so I can always produce consistent results in this research project. She is the leader for our Research University Grant Project and under Fundamental Research Grant Scheme which had supported me financially as a research student.

I also appreciate the advice from my co-supervisor Dr. Abdul Hadi Sulaiman from Institute of Power Engineering of Universiti Tenaga National who had helped in my progress and reviewed my conference paper. Also, I am pleased to acknowledge my lecturers, seniors and workstation-mates from UTM who has been my exemplary along this project. Thanks to my family members for their love and encouragement.

ABSTRACT

Communication system in optical fiber technology has emerged as a demanding field especially for the new dense wavelength-division multiplexed (DWDM) system wherein many functional applications and basic laser system are included. The generation of multiple laser lines in multiwavelength fiber laser (MWFL) is significant in semiconductor optical amplifier (SOA) device utilization as a medium of gain to achieve a flat laser spectrum. Apart from Erbium-doped fiber amplifier (EDFA) and Raman amplification that have high mode competition and high pumping power respectively, MWFL configuration has delegated SOA due to its special inhomogeneous characteristic as a device of stability compared to other devices of scattering and amplification effects. An investigation on the types of different wideband travelling wave (TW) SOA with parameters such as optical gain, output power, noise figure (NF) and amplified spontaneous emission (ASE) noise and bias current was carried out through OptiSystem and MATLAB software and then verified by benchtop experiments. Linear SOA had the most flat gain with low NF and ASE pattern at input power -30 dBm compared with nonlinear SOA. A practical Lyot-combed and fiber Bragg grating (FBG) were constructed using unidirectional single cavity in different types of SOA and linear SOA displayed the flattest peak powers. Multiwavelength spectrum from linear, nonlinear SOA and booster optical amplifier (BOA) were varied by intensity, polarization angle (PA), in-line polarizer and time stability by applying performance evaluator such as the number of laser lines, extinction ratio (ER), channel spacing and highest optical power. The laser experiment for linear SOA concluded with the flattest spectrum in time stability which was true to the characterization modelling result and it also acted differently as nonlinear SOA and BOA that vary greatly to nonlinearity with different PA.

ABSTRAK

Sistem komunikasi dalam teknologi gentian optik telah muncul sebagai bidang yang diperlukan terutamanya untuk sistem wavelength-division multiplexed (DWDM) yang baru, di mana terdapat pelbagai aplikasi fungsian dan sistem laser asas. Penjanaan pelbagai garisan laser dalam laser gentian saluran berbilang (MWFL) adalah penting dalam penggunaan peranti penguat optik semikonduktor (SOA) sebagai medium untuk mencapai spektrum laser datar. Selain dari penguatan penguat optik dopan Erbium (EDFA) dan penggandaan Raman yang masing-masing mempunyai persaingan mod yang tinggi dan kuasa pam yang tinggi, konfigurasi MWFL telah mewakilkan SOA disebabkan ciri khasnya yang tidak homogen sebagai alat yang stabil terhadap kesan penyerakan dan amplifikasi. Penyelidikan mengenai jenis SOA gelombang perjalanan jalur luas (TW) yang bervariasi dengan parameter seperti keuntungan optik, kuasa pengeluaran, angka bunyi (NF) dan pemancaran spontan terganda (ASE), dan arus bias telah dijalankan melalui perisian OptiSystem dan MATLAB dan kemudian disahkan dengan eksperimen. SOA jenis bergaris mempunyai penguatan paling datar disertai corak NF dan ASE pada kuasa kemasukan -30 dBm berbanding dengan SOA jenis bukan bergaris. Model praktikal penyisir Lyot dan jeriji Bragg gentian optik (FBG) telah dibina menggunakan rongga tunggal yang searah dalam pelbagai jenis SOA dan SOA bergaris telah memperlihatkan kuasa puncak paling rata. Prestasi spektrum bergelombang dari penguat optik (BOA) bergaris, bukan bergaris, dan semikonduktor penguat optik penggalak (BOA) telah diubah dengan menvariasikan intensiti, sudut polarisasi (PA), pengutub sebaris, dan kestabilan masa dengan menggunakan penilaian prestasi seperti jumlah garis laser, nisbah kepupusan (ER), saluaran jarak dan kekuasaan tertinggi. Eksperimen laser untuk SOA bergaris disimpulkan sebagai spektrum yang paling rata dalam kestabilan masa yang benar kepada keputusan pemodelan ciri dan ia juga bertindak secara berbeza dengan SOA bukan bergaris dan BOA yang mempunyai perbezaan yang ketara dengan PA yang pelbagai.

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LIST OF SYMBOLS

I - bias current

G_0 - unsaturated gain

G - amplifier gain

P_{out} - optical output power

P_{in} - optical input power

P_{sat} - saturated power

$OSNR_i$ input of optical siganl-to-noise ratio

$OSNR_o$ output of optical siganl-to-noise ratio

τ_s - gain dynamics

n_c - core refractive index

V - common cross-sectional fiber parameter

r - core radius

k_0 - number of modes in fiber propagation

α_{dB} - fiber attenuation constant

P_T - transmitted power in attenuation

P_0 - initial power in attenuation

Ω - oscillation frequency

β_1 - propagating constant for groups of dispersion

β_2 - propagating constant for groups of dispersion

D - dispersion parameter

Lb - beat length

B - birefringence

λ_B - Bragg wavelength

y - Molar fraction of Arsenide in the active region

L_c - central active region length

L_t - tapered active region length
d - active region thickness
W - central active region width
K_g - bandgap shrinkage coefficient
n_{eff} - effectve index at zero carrier density
η_{in} - input coupling loss
η_{out} - output coupling loss
K_0 - carrier independent absorption loss coefficient
K_1 - carrier dependent absorption loss coefficient
A_{rad} - linear radiative recombination coefficient
B_{rad} - bimolecular radiative recombination coefficient
A_{nrad} - linear nonradiative recombination coefficient due to traps
B_{nrad} - bimolecular nonradiative recombination coefficient
C_{aug} - Auger recombination coefficient
D_{leak} - leakage recombination coefficient
a - bandgap energy quadratic coefficient
b - bandgap energy quadratic coefficient
c - bandgap energy quadratic coefficient
m_e - effective mass of electron in the covalence band
m_{hh} - effective mass of a heavy hole in the valence band
m_{lh} - effective mass of a light hole in the valence band
N_s - number of injected signals
v_k - optical frequency
$Es_k^{\pm}(z)$ - complex traveling wave in the positive and negative z direction
β_k - signal propagation coefficient
g_m - material gain coefficient
α - material loss coefficient

$N_j^{\pm}(z)$ - spontaneous emission photon rate traveling wave in the positive and negative z direction

R_{sp} - emission noise coupled into the spontaneous emission

LIST OF ABBREVIATIONS

AR	anti-reflected
APC	angled physical contact
ASE	amplified spontaneous emission
BERs	bit error rates
BOA	booster optical amplifier
C-	conventional
CW	continuous wave
EDFA	Erbium-doped fiber amplifier
EDFL	Erbium-doped fiber laser
ER	extinction ratio
FBG	fiber Bragg grating
FFP-TF	fiber Fabry-Perot tunable filter
FP	Fabry-Perot
FWHM	full-width-half-maximum
FWM	four-wave mixing
HWP	half wave plate
InGaAsP	indium gallium arsenide phosphide
Laser	light amplified by stimulated emission of radiation
LDC	laser diode controller
Maser	microwave amplified by stimulated emission of radiation
MWFL	multiwavelength fiber laser
MWFRL	multiwavelength fiber ring laser
MZI	Mach-Zehnder interferometer
NF	noise figure
NPR	nonlinear polarization rotation
OML	optical Moore's law
ONN	optical network node
OPM	optical power meter
OSA	optical spectrum analyser
OSNR	optical signal-to-noise ratio

OTDR	-	optical time domain reflectometer
PA	-	polarization angle
panda	-	polarization-maintaining and absorption-reducing
PC	-	polarizer controller
PM-FBG	-	polarization-maintaining chirped fiber Bragg grating
PD	-	photodetector
PDG	-	polarization dependent gain
PER	-	polarization extinction ratio
PMF	-	polarization maintaining fiber
RPC	-	reduced pressure collapsing
Rx	-	receiver system
SLM	-	single-longitudinal-mode
SMF	-	single mode fiber
SMSR	-	side-mode suppression ratio
SNR	-	signal-to-noise ratio
SOA	-	semiconductor optical amplifier
TBF	-	tunable bandpass filter
TC-FBG	-	two-channel fiber Bragg grating
TDFA	-	Thulium-doped fiber amplifier
TDFL	-	Thulium-doped fiber laser
TE	-	transverse electric
TEC	-	thermoelectric cooler
TF	-	tunable filter
TFG	-	tilted fiber grating
TLS	-	tunable laser source
TM	-	transverse magnetic
TTD	-	true-time-delay
TW	-	travelling wave
Tx	-	transmitter system
UPC	-	ultra physical contact
VOA	-	variable optical attenuator
WDM	-	wavelength-division multiplexed
Yb	-	Ytterbium

CHAPTER 1

INTRODUCTION

1.1 Background

The task for communication for a human in society has meet various limitations not only in our own community but in a globally scale. It is therefore a demand that is necessary for consistency improvement, for example a wider and more massive transmission network system is built from years to years. The communication system is currently supporting largely on the Internet users. As mentioned by Stalling [1], in estimation over 20 billion of fixed and mobile electronic networking devices and also machine-to-machine networking will emerge in year 2016, with an increase from about 7 billion devices from year 2011. Larger traffic growth is always posing a challenge on the evolution of communication system.

As communication system is surging in capacity and demand, researches in communication is always evolving through many generations. Communication system in history has evolved from telegraph (1830), telephone (1876), electrical signal (1940), microwave (1948) into lightwave system [2]. Lightwave communication system is basically the latest technology until now and is chosen as the best one. The invention of optical fiber is a great turning point in the telecommunication system industry as the coaxial cable invented only had limited in transmission using electrical wave. The extremely low attenuation in optical fiber and other reasons win the competition of the best among various guiding media. Continuous development on optical communication technology is intended to cope with high information capacity demand, long distance, physically weight, cost and the like.

Thirty years of lightwave technology history had transformed into five generations [3]. The optical Moore's law (OML) had structured the first 10 years of light wave technology but it shall be overcome in the next coming 20 years. According to the OML prediction, the capacity for a single fiber cable should accommodate approximately 7 million Tb/s over worldwide distance. Thus it is suggested to improve the capacity performance by inventing powerful massive optical components as well as upgrading into wavelength division multiplexing (WDM) system.

1.2 Introduction

The researches on the multiwavelength fiber laser (MWFL) are basically focused on the generation of multiple lines of fiber laser where the lasers have been on many functions in optical WDM system. Generally, examples of functional applications in WDM systems are in the precise interferometers [4], [5] and optical sensing devices [6]. More specific applications that are co-field with optical processing can be found in fiber link monitoring system [4], all-optical clock recovery [6] and continuous true-time delay beamforming [5]. The published works in MWFL are also focused on numerical theories while various detailed discussion on the filtering combs are reviewed such as Lyot filter comb pattern effect suppression [7] and also fiber Fabry-Perot tunable filter (FFP-TF) pattern simulation [8].

The most common researches in MWFL are focused based on simulation and experiment [9] but the latest works had discovered on the number of lines, wavelength tuneability, channel spacing and others [10], [11]. The most popular gain media used is the rare-earth-doped fiber amplifier and it includes erbium-doped fiber amplifier (EDFA) as the most frequent used media. For different bandwidth amplification, Thulium-doped fiber amplifier (TDFA) [10] is another popularly rare-earth-doped amplifier while Ytterbium [11] is a codopant with Erbium, along with other mixed co-doped amplifiers [12]. Interferometers using scattering effects in fiber laser have been practiced such as Raman amplification [12], Brillouin amplification [13], [14], Rayleigh amplification [15] and other mixed random types of random amplifications [16]. Furthermore, small and compact optical device which is the semiconductor optical amplifier (SOA) will be another attractive gain medium option [17], [18].

The comb filtering configurations are further employed to produce nonlinear polarization rotation (NPR) effect. Common, simple type of comb filters are Fabry-

Perot (FP) filter [19], [20], Mach-Zehnder interferometer (MZI) [21], [22], fiber Bragg grating (FBG) filter [23], [24], Sagnac filter [25] and Lyot filter [18]. The normal fiber laser are either functioned in sensor direct detection or spectrum observation using interferometer mechanism, in which they are based on different combs in directions.

1.3 Problem Statement

Recent investigation in MWFL has focused numerous researches on EDFA since it has been an interesting subject due to high saturation power and low polarization sensitivity of EDFA. The relatively low polarization sensitivity is a credit to a stable laser line generated under room temperature [26] but EDFA has high mode competition and produced limited number of laser lines due to its homogeneous property. The SOA has inhomogeneous property [17], [18] which can be an advantage over the EDFA to establish as a stabilizing device in MWFL system.

Furthermore, Raman amplification is another potential gain mechanism in MWFL researches. It has the characteristics of low noise and able to produce dependent wavelength according to pump directly [12], albeit a high powered-pump is required to generate the lasers, thus SOA is able to operate without high pump power in this aspect [18]. This thesis includes the gain medium SOA in generating MWFL in different types of SOA in comparison which is not done by the previous works.

Apart from that, the types of comb configuration in laser filter include Lyot [18], FP [19], MZI [27], Sagnac [28] and others which are researched on extensively especially uni- and bi-directional [18] advanced Lyot filter mechanism. However it has narrow wavelength range and limited number of lines as the configuration disadvantages. The FBG filter has simpler configuration and reliably stable, besides it is preferred as the ideal optimum filter mechanism in this research work due to its wavelength selectivity option [29], [30].

1.4 Aim and Objectives

Overall, this work aims to compare the performance for different types of SOAs to generate MWFL with unidirectional FBG and Lyot filter. The objectives are as below:

1. To investigate SOA operating parameters through simulation and experiment;
2. To model and compare different types of SOAs in MWFL using FBG and Lyot filter.

1.5 Scope of Work

The scope of work is narrowed down from the literature of MWFL on the gain medium. In the wide MWFL field, the researches to generate multiple laser lines can be categorized based on different gain media used. The most popular gain medium is Erbium-doped fiber laser (EDFL) [20-24], [26], [28], [30-47] where the most popular rare-earth-doped fiber laser is Thulium-doped fiber laser (TDFL) [10], [25], [48-61] besides the other types of mixed rare-earth-doped fiber [11-12], [62-67]. Apart from the doped fiber lasers, another mechanism to generate gain in MWFL is by scattering effect. Several types of scattering effects in the previous researches on fiber lasers are Raman [16, 68], Brillouin [13-15, 68, 70-75] and random distributed feedback lasers [76-78].

In this work, another type of gain medium in MWFL focused on is the SOA [79-83]. It can be further classified into pre, in-line and booster amplifier for both the linear and nonlinear SOAs. In this work, the first SOA is under in-line family and linear (linear SOA), while the second SOA is under in-line with high nonlinearity (nonlinear SOA). The third SOA is under booster family with high nonlinearity (booster SOA). Types of SOAs is used in this research work: Linear and nonlinear for modelling whereas linear, nonlinear and booster amplifier for experiment. Besides, the modelling of SOAs is carried out by using two simulation tools: OptiSystem Version 13 manufactured by Optiwave System Inc. and MATLAB computer software. The experiment is carried out using the same linear and nonlinear SOA and also booster optical amplifier (BOA) in determining the combed multiwavelength spectrum of FBG and Lyot filters.

1.6 Significance of Work

The utilization of SOA in the industry is expanding rapidly in a few hundreds of million during the 2000s decade. The application covers various manufacturing line where basically it is used mainly as a basic amplifier for WDM system. It also has been used in digital communication linkage, all-optical switches and others. Basic SOA in system applications include the simple booster, in-line and preamplifiers. Functional applications include wavelength converter, logic gate, intensity and phase modulator, add or drop multiplexer, pulse generator, dispersion compensator, clock recovery, tuneable filter and others.

All these technologies are evolving and maturing with the future for SOA technology is becoming more challenging. In the meantime, the manufacturing costs are becoming cheaper. This work can explore the future possibilities for the SOA performance as it is used widely in MWFL system. It is expected that SOA can be a stabilizing device for multi-wavelength fiber laser due to its inhomogeneous property.

1.7 Chapter Outline

This project consists of five chapters and starts with the project short introduction. Firstly, a brief background on lightwave communication system and MWFL are introduced. Then, problems on the research are identified alongside with aim and objectives are set. The scope of work is focused and then the significance of work is discussed. Lastly, Chapter 1 includes with the project outlined for all chapters.

Chapter 2 focuses on the study of SOA fundamentals in an introduction of point-to-point optical communication system. Physical SOA device is explored in more details such as chip module, carrier confinement and its theoretical stimulated emission of lasing mechanism. Then, the properties of SOA are explained with formulae, for example, the gain, polarization, output optical power, noise figure and last but not least fiber nonlinearity in brief. Short reviews on SOA and FBG are included.

Next, Chapter 3 explains the research methodology in which consists of project flowcharts. In this chapter, the research methodology has covered two objectives. The first objective has the characterisation in two methods of numerical steady-state model using MATLAB and the simulation of wideband TW-SOA using OptiSystem in Chapter 4 of modelling work. The following experiment is carried out in the quest of verifying two methods of modelling, where SOA characterisation is compiled under Chapter 5 under the first objective. Then, preliminary result for both FBG and Lyot filters in MWFL is realized under the second objective with different types of SOA in comparison. Lastly, Chapter 6 draws the conclusion for current and future work.

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LIST OF PUBLICATION

Indexed Journal

1. **Y. S. Ong,** O. M. Kharraz, A. H. Sulaiman, F. Abdullah, N. Md. Yusoff, "Characterization of Wideband Semiconductor Optical Amplifiers based on OptiSystem and MATLAB", (2018) International Journal of Integrated Engineering, Vol. 10, No. 7, pp. 263-272 **(Indexed by SCOPUS)**

Indexed Conference Proceedings

2. **Y. S. Ong,** O. M. Kharraz, A. H. Sulaiman, F. Abdullah, N. Md. Yusoff, "Modelling of Different Types of Semiconductor Optical Amplifier Characteristics", 2nd International Conference on Telematics and Future Generation Networks 2018 **(Indexed by SCOPUS)**

3. **Y. S. Ong,** O. M. Kharraz, A. H. Sulaiman, F. Abdullah, N. Md. Yusoff, "Effect of Semiconductor Optical Amplifiers Types on Multiwavelength Fiber Laser Performance", IEEE 8th International Conference on Photonics 2020 **(Indexed by SCOPUS)**