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LYOT-FILTER-BASED MULTIWAVELENGTH FIBER LASER USING A SEMICONDUCTOR OPTICAL AMPLIFIER ASSISTED BY NONLINEAR POLARIZATION ROTATION EFFECT

ALI MOHAMMED ALI AL-SAEGH

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By

ABDUL HADI BIN SULAIMAN

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Chair: Professor Mohd. Adzir Mahdi, PhD

Faculty: Engineering

Research works based on multiwavelength fiber laser (MWFL) were realized by utilizing several types of comb filter such as Lyot filter, Mach-Zehnder interferometer and Sagnac loop mirror interferometer. The generation of MWFL based on Lyot filter is highly interesting to be explored due to its advantage of narrow linewidth, low power loss and simple structure. The multiwavelength generation based on Lyot filter has several issues that need to be focused such as narrow wavelength range and hardly explored of bidirectional configuration. This doctoral research focuses on both issues, where they are closely related to the research objective that is wavelength range improvement and a new design of bidirectional configuration within the Lyot filter scope.

In this doctoral research, an ability of intensity equalizer is utilized to flatten the spectrum, and it is obtained from an effect of nonlinear polarization rotation (NPR) which is induced from a combination of semiconductor optical amplifier (SOA) and polarizer. This NPR effect induces two mechanisms of intensity dependent transmission (IDT) or intensity dependent loss (IDL), which depends on the adjustment of polarization controller (PC). To obtain a flat multiwavelength spectrum, the adjustment of the PC and the intensity is very important in order to achieve high cavity loss in the IDT and IDL mechanisms.

The first main finding in this study is about a wide wavelength range of 30.7 nm based on a unidirectional Lyot filter. The best performance has 307 number of lines within 5 dB bandwidth. The channel spacing for the most data is 0.1 nm due to the length of polarization maintaining fiber of 53.2 m. The highest extinction ratio and peak power is 12 dB and -43 dBm, respectively. The flatness deteriorates with intensity increment due to the IDT mechanism in the cavity. Without the use of polarizer in the experimental structure, no multiwavelength spectrum is generated because the polarizer is an important component in inducing the IDT mechanism.

The next main finding is a new design of bidirectional Lyot filter. This filter is unique because the incoming lights to the filter can propagate simultaneously in two different directions of clockwise and counter clockwise. This advanced filter can has two simultaneous constructive interferences, where it can give an advantage of light reshaping for a flat spectrum generation. The best multiwavelength performance based on this new filter produces 96 number of lines within 5 dB bandwidth, with high peak power of -34 dBm. This design can be simply changed to a unidirectional configuration, but the spectrum flatness is deteriorated because the occurrence of constructive interference is only once. The multiwavelength performance is also deteriorated when the laser structure is modified into different coupling ratio of optical coupler, different SOA type, configuration of bidirectional SOA and without polarizer in the laser structure.

In conclusion, this doctoral research has successfully solved the issues of multiwavelength performance based on Lyot filter. The wavelength range is wider as compared to the previous works, while a new structure of bidirectional Lyot filter is successfully designed.

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

LASER GENTIAN BERBILANG SALURAN BERDASARKAN PENAPIS LYOT MENGGUNAKAN SEBUAH PENGGANDA OPTIK SEMIKONDUKTOR DIBANTU OLEH EFEK PUTARAN POLARISASI TIDAK LURUS

Oleh

ABDUL HADI BIN SULAIMAN

Februari 2015

Pengerusi: Profesor Mohd. Adzir Mahdi, PhD

Fakulti: Kejuruteraan

Kerja-kerja penyelidikan berdasarkan laser gentian saluran berbilang (MWFL) telah banyak direalisasikan menggunakan pelbagai jenis penapis sisir seperti penapis Lyot, interferometer Mach-Zehnder dan interferometer cermin gelung Sagnac. Penghasilan MWFL berdasarkan penapis Lyot amat menarik untuk diterokai disebabkan oleh kelebihan penapis Lyot yang mempunyai kelebaran garisan yang sempit, kehilangan kuasa yang rendah dan struktur yang ringkas. Penghasilan saluran berbilang berdasarkan penapis Lyot mempunyai beberapa isu-isu yang perlu difokuskan seperti julat saluran yang sempit dan konfigurasi dwihala yang jarang diterokai. Penyelidikan doktoral ini memfokus pada kedua-dua isu tersebut, dimana ianya berkait rapat dengan objektif penyelidikan ini iaitu meningkatkan julat saluran dan mereka konfigurasi dwihala yang baharu dalam skop penapis Lyot.

Di dalam penyelidikan doktoral ini, suatu keupayaan iaitu penyama kerataan telah digunakan untuk meratakan spektrum, dan ianya diperolehi daripada kesan putaran polarisasi tidak lurus (NPR) yang dirangsang daripada kombinasi pengganda optik semikonduktor (SOA) dan pengutub. Kesan NPR ini merangsang dua mekanisma samada penghantaran bersandarkan keamatan (IDT) atau kehilangan bersandarkan keamatan (IDL), bergantung pada pengubahan terhadap pengubah polarisasi (PC). Untuk mendapatkan spektrum saluran berbilang yang rata, pengubahan pada PC dan keamatan amatlah penting supaya dapat memperoleh kehilangan kaviti yang tinggi dalam mekanisma IDT mahupun mekanisma IDL.

Penemuan utama yang pertama dalam pengajian ini ialah berkenaan julat saluran yang luas selebar 30.7 nm berdasarkan penapis Lyot sehala. Prestasi yang paling baik mempunyai jumlah saluran sebanyak 307 dalam lingkungan jalur lebar berkeluasan 5 dB. Selang saluran untuk kebanyakan data ialah 0.1 nm berdasarkan panjang fiber

pengekal polarisasi yang panjangnya 53.2 m. Nisbah pemadaman yang paling tinggi ialah 12 dB dan kuasa puncak tertinggi ialah -43 dBm. Kerataan menjadi semakin teruk dengan kenaikan pada keamatan disebabkan oleh mekanisma IDT di dalam kaviti. Tanpa menggunakan pengutub pada struktur eksperimen, tiada spektrum saluran berbilang dapat dihasilkan kerana pengutub merupakan komponen yang penting dalam merangsang mekanisma IDT.

Penemuan utama yang seterusnya ialah rekaan baharu penapis Lyot dwihala. Penapis ini unik kerana kemasukan cahaya-cahaya ke penapis tersebut boleh merambat secara serentak dalam dua haluan berbeza iaitu mengikut arah jam dan melawan arah jam. Penapis termaju ini boleh mempunyai dua interferens konstruktif yang berlaku secara serentak, dimana ianya dapat memberikan kelebihan dalam pembentukan cahaya untuk penghasilan spektrum yang rata. Prestasi saluran berbilang yang terbaik berdasarkan penapis baharu ini menghasilkan jumlah saluran sebanyak 96 dalam lingkungan jalur lebar 5 dB, dengan kuasa puncak setinggi -34 dBm. Rekaan ini boleh diubah kepada konfigurasi sehala dengan mudah, akan tetapi kerataan pada spektrum menjadi lebih teruk kerana interferens konstruktif hanya berlaku sekali. Prestasi saluran berbilang juga didapati semakin teruk apabila struktur laser ini dimodifikasikan kepada nisbah pencantuman yang berbeza pada pencantum optik, jenis SOA yang berlainan, konfigurasi SOA dwihala dan ketiadaan pengutub pada struktur laser.

Sebagai kesimpulan, penyelidikan doktoral ini telah berjaya menyelesaikan isu-isu berkenaan prestasi saluran berbilang berdasarkan penapis Lyot. Julat saluran didapati lebih lebar berbanding kerja-kerja sebelum ini, manakala sebuah struktur baharu berkenaan penapis Lyot dwihala telah berjaya direka.

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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 Mahdi, Phd
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Datuk Harith Ahmad, PhD
Distinguished Professor
Faculty of Science
Universiti Malaya
(Member)

Salasiah Hitam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Muhammad Zamzuri Abdul Kadir, PhD
Senior Manager
Telekom Research and Development Sendirian Berhad
TM Innovation Centre
(Member)

Muhammad Hafiz Abu Bakar, 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: 25th June 2015

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Name of Member of Supervisory Committee: ____________________

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

Signature: ____________________
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Signature: ____________________
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ASE	Amplified spontaneous emission
AWG	Array waveguide grating
C-band	Commercial-band
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
FC/APC	Ferule connector/ angled physical contact
FC/PC	Ferule connector/ physical contact
FP-SOA	Fabry-Perot SOA
FWM	Four-wave mixing
HWP	Half wave plate
IDL	Intensity dependent loss
IDT	Intensity dependent transmission
InGaAsP	Indium Gallium Arsenide Phosphide
L1	The first PMF
L2	The second PMF
L-band	Long wavelength-band
MWFL	Multiwavelength fiber laser
MZI	Mach-Zehnder interferometer
NPR	Nonlinear polarization rotation
NOLM	Nonlinear optical loop mirror
OSA	Optical spectrum analyzer
PBS	Polarization beam splitter
PC	Polarization controller
PC1	The free-space PC

PC2	The PC based on looped fiber
PDI	Polarization dependent isolator
PDM	Professional digital multimeter
PMF	Polarization maintaining fiber
PMF1	The first PMF
PMF2	The second PMF
PMEDF	Polarization maintaining erbium-doped fiber
PTC	Polarization and temperature controller
QWP	Quarter wave plate
S-band	Short wavelength-band
SBS	Stimulated Brillouin scattering
SLM	Sagnac loop mirror
SMF	Single mode fiber
SOA	Semiconductor optical amplifier
SOA1	SOA manufactured from QPhotonics
SOA2	SOA manufactured from Alphion
SOA3	SOA manufactured from Thorlabs
SRS	Stimulated Raman scattering
STPT	Spacing tunability per temperature
TW-SOA	Travelling wave SOA
WDM	Wavelength division multiplexing
YDFA	Ytterbium-doped fiber amplifier
$\overline{n_c(t)}$	Average excess carrier density
$\bar{n}$	Effective refractive index of SOA
ΔT	Temperature difference

ΔB	Birefringence difference
a	Gain constant
B	Birefringence value
C	Auger recombination constant
d	Thickness of SOA
dI	Change of SOA current
$\mathrm{d}n_{\mathrm{r}}/\mathrm{d}n_{\mathrm{c}}$	Nonlinear change in refractive index
dP	Change of power output
e	Charge of electron
E	Electric field
E1	Energy level 1
E1	Energy level 1
f	Fraction of spontaneous emission
G	Signal gain
G_0	Unsaturated gain
G_S	Single pass gain
$h\upsilon$	Photon energy
I	Output intensity
I_C	Injection current
$\mathrm{I_O}$	Original intensity
k_0	Wave number in vacuum
L	PMF length
L_{eff}	Efficient length
L_{SOA}	Length of SOA
M_C	Jones matrix for the incoming light

M_{PC}	Jones matrix of PC1
M_{PC2}	Jones matrix of PC2
M_{PMF}	Jones matrix of PMF
n	Injection current density
n_0	Injected carrier density
n_c^0	Equilibrium of excess carrier density
P	Optical power of ASE
P/I	Power over intensity
P_{ASE}	Power of ASE
P_S	Saturation power
R	Radiative recombination constant
R_1	Residual reflectivity of first facet of SOA
R_2	Residual reflectivity of second facet of SOA
T	Transmission
W	Width of SOA
α	Linewidth enhancement factor
Γ	Confinement factor
$\Delta\lambda$	Channel spacing
$\Delta\lambda_1$	First channel spacing
$\Delta\lambda_2$	Second channel spacing
$\Delta\lambda_3$	Third channel spacing
$\Delta\phi$	Phase shift
ϑ	Angle between polarizer and analyzer
θ	Splicing shift
θ_1	Angle between output polarization direction of PC and PMF vertical axis

θ_2	Angle between axes of polarizer and vertical axis of output PDI
θ_i	Angle of the incident light polarization orientation with x-axis
θ_{j}	Angular orientations of the three waveplates
λ	Operating wavelength
σ	Optical absorption
ϕ	Phase shift through SOA
ϕ_0	Nominal phases shift
ϕ_{L}	Linear phase shift
ϕ_{NL}	Nonlinear phase shift

CHAPTER I

INTRODUCTION

This chapter serves as an introduction to this doctoral work on multiwavelength fiber laser (MWFL) based on semiconductor optical amplifier (SOA), revolving around nonlinear polarization rotation (NPR) effect and Lyot filter. In Section 1.1, a brief introduction of MWFL will be discussed. Next discussion looks into the problem statement relevant to the research scope and followed by motivation behind the work. Subsequently, the objective of research will be elaborated. The scope of research as well as the thesis organization will then be detailed prior to the summary of the whole chapter.

Overall, this chapter has covered the first step of the doctoral research before going further to the extensive theories and reviews as well as the experimental discussion. It is important to understand the flow of the research starting from the introduction, the problem statement, the motivation of research, the objective of research, the scope of research and the thesis organization.

1.1 Introduction of MWFL

Research on MWFL has been a major attraction to researchers due to its potential application in optical communications, dense wavelength division multiplexing (WDM) system, WDM passive optical network, precise spectroscopy and optical sensing [1]. Many articles on MWFL have been published leading to the contribution of various significant discoveries in multiwavelength characteristics such as number of lines, channel spacing, extinction ratio, wavelength tunability and full band coverage [2].

In recent years, most of MWFL researches are based on the use of erbium-doped fiber amplifier (EDFA) due to its many advantages such as low polarization sensitivity and high saturation power. Owing to the EDFA lesser sensitivity to polarization, good stability can be achieved because temperature and environmental perturbation will not affect the overall multiwavelength laser system. Another popular gain mechanism for MWFL is Raman amplification [3], [4], which is particularly attractive due to low noise and its ability to be generated at any wavelength (dependent on pump wavelength) without the need for a specialized gain medium but high pump power is required to operate this laser [5].

A common method of generating multiple lasers is through the use nonlinear effects such as stimulated Brillouin scattering (SBS) [6], four-wave mixing (FWM) [7] and NPR [8]. NPR has emerged as an interesting choice due to its advantages of performing changeable operating regimes of multiwavelength lasing [9] as well as passively mode locked at adjustment of polarization state [10]. A simpler technique of producing MWFL is by deploying a comb filter within the laser structure. Several types of comb filter have been investigated for this purpose such as Fabry-Perot [11], Mach-Zehnder interferometer (MZI) [12], [13] and Lyot filter [14]. Lyot filter is coveted due to its simple structure and output variability, which is done simply by varying the chosen polarization maintaining fiber (PMF) parameter [15].

1.2 Problem Statement

Lyot filter-based MWFL is an attractive choice for multiple laser generation due to its many qualities such as low optical loss and simple structure. Most of MWFL based on the Lyot filter use EDFA as gain medium [9], [16]. However, the existence of mode competition in EDFA-based MWFL limits the number of laser lines produced by the system. Since the erbium-doped fiber (EDF) gain medium characteristic is naturally homogeneous, this leads to high mode competition and unstable lasing lines. This condition should be evaded in MWFL system that targets high number of lines, unless an additional device is inserted into the configuration setup to reduce the mode competition. The device is either piezo-electric transducer [17], highly nonlinear fiber [16] or polarization dependent isolator (PDI) [18], [19], which inadvertently increases the complexity and loss of the system. Although the inhomogeneous broadening of Raman amplification is a viable alternative, the high pump power required to induce the effect is a stumbling block in producing an efficient MWFL system. Additionally, previous researches on Lyot filter-based MWFL operated solely in unidirectional configuration, thus raising the opportunity to explore the potential of Lyot filter in bidirectional operation. Another conundrum that has yet to be solved is the limited wavelength range in a simple comb filter such as Lyot filter, which is a very crucial aspect in MWFL for WDM application.

1.3 Motivation of Research

Other popular gain medium in MWFL setup is SOA, instead of EDFA. The SOA is extremely beneficial in providing better multiwavelength generation due to its low mode competition and simpler setup. The low mode competition from SOA is attributed to its inhomogeneous gain broadening characteristic [20], [21], which allows the generation of stable MWFL with high number of lines at room temperature. SOA also requires no external optical pump and since no additional device to reduce mode competition is necessary, the laser has a simpler setup compared to its EDFA-based counterpart. With the SOA as gain medium, the generation of multiple laser lines can be performed through the use of a nonlinear effect and a comb filter such as NPR and Lyot filter, respectively. The combination of those three elements is never realized before, and became one of the motivations in completing this doctoral work.

The NPR effect induces mechanism of intensity dependent loss (IDL) or intensity dependent transmission (IDT). In this work, the mechanisms are utilized as assistance in flattening the multiwavelength generation. The discussion of both mechanisms based on SOA is hardly reported, and essential to be discovered. Meanwhile, from the previous study, the Lyot filter is usually in unidirectional configuration and the wavelength range is limited. Operating the filter bidirectionally could provide better filter performance and utilize the device to its maximum potential.

1.4 Objective of Research

1.) To improve the wavelength range in an MWFL based on Lyot filter.
2.) To investigate a new phenomenon in an MWFL based on NPR effect.
3.) To design a new bidirectional of Lyot filter that can be applied to other comb filter.

1.5 Scope of Research

Many articles have been published using several types of gain medium, nonlinear effect and comb filter in the generation of MWFL. The gain media that have been utilized in the MWFL setup are SOA [22], EDFA [23], ytterbium-doped fiber amplifier (YDFA) [10] and Raman amplifier [4]. On the other hand, the type of comb filters that have been used for multiwavelength generation are Sagnac loop mirror (SLM) [24], Fabry-perot [25], MZI [12], Lyot filter [26] and array waveguide grating (AWG) [21]. Meanwhile, the nonlinear effect is also the main element in generating the MWFL. Several published articles are based on the nonlinear effect of NPR [27], FWM [7], SBS [28] and stimulated Raman scattering (SRS) [29]. In this work, the SOA, the Lyot filter and the NPR effect are preferred as the gain medium, the comb filter and the nonlinear effect, respectively. Figure 1.1 illustrates the scope of research that will be studied in this doctoral work which is narrowed down from three major fields of gain media, nonlinear effect and comb filter. The specific topics are related to each other and are preferred due to various advantages and several gaps that were filled and explored.

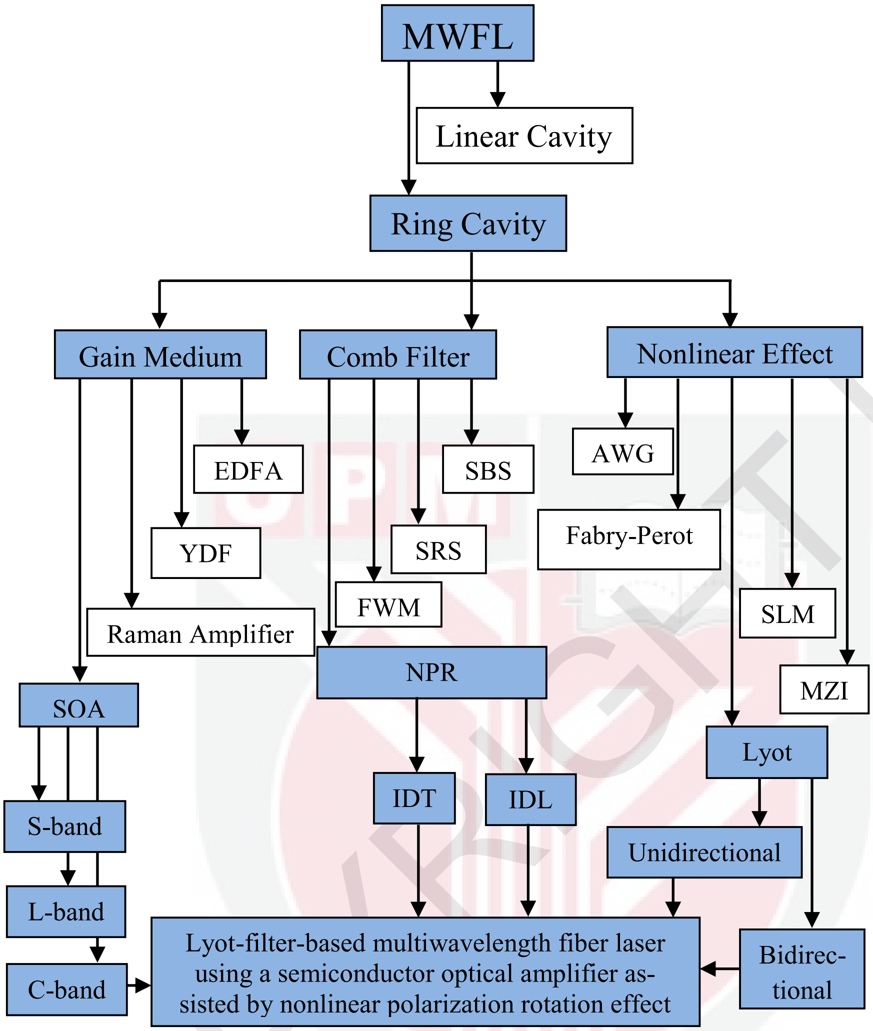

Figure 1.1: The scope of the research.

1.6 Thesis Organization

Overall, the research work that reported in this thesis contains five chapters. The first chapter discusses the introduction of MWFL for the application of optical telecommunications and WDM systems. This chapter also elaborates the problem statement, the motivation, the objective and the scope of research, as well as thesis organization. Chapter 2 will cover the theoretical background and the description of the involved devices in the experimental setup. In the SOA section, the discussion is about the introduction, the principle of operation, the material and structure as well as the research contribution in the SOA area. Subsequently, the background and the theory of PMF and birefringence will be explained. PMF is a device that responsible for the phenomenon of constructive interference, whilst the birefringent device is the PMF and it is an important component in Lyot filter. Next discussion is about the NPR effect, which introduces the IDT and the IDL mechanisms. Further on, the description and the theory of polarization device in polarization controller (PC) and polarizer will also be elaborated. The important topic in Lyot filter will also be covered. Also in this section, several reviews are made on MWFL based on the Lyot filter as well as its theoretical background. Then, the discussion continues with the review on MWFL based on the SOA, which covers from the earliest research to the current work. Chapter 2 finally discusses the critical review on the NPR effect and the Lyot filter. In this section, the gaps and the weakness of the previous work will also be discussed.

Chapter 3 will cover the experimental results of the doctoral work. In this chapter, the main contribution is the flatness investigation at intensity dependence. The flat and high lasing line of multiwavelength spectrum is obtained at low intensity. Then, other parameter changes will also be investigated and discussed. The relationship of the IDT mechanism to the flatness variations will be explained extensively. The flatness performance of MWFL will also be discussed at variation of intensity, throughput port ratio and polarization state. Chapter 3 will also investigate an adjustable extinction ratio value when half wave plate (HWP) rotation or PMF length is changed. Other discussion is regarding to the performance of multiwavelength spectrum with the removal of PDI and the laser stability.

Chapter 4 will discuss the experimental results on bidirectional Lyot filter. The entire results will be investigated, analyzed and then compared with the best multiwavelength spectrum. In the first part of this chapter, the lasing threshold, the transmission spectra and the stability regarding the best multiwavelength spectrum will be discussed. Next, the experimental results are discussed regarding the variation of SOA current, HWP position and temperature. The decrement of SOA current reduces the number of lines, while the rotation of HWP position can deteriorate the flatness of multiwavelength spectrum. The experimental work on different temperature is also done to investigate the channel spacing tunability. The second part of Chapter 4 discusses the multiwavelength performance on the modification of experimental setup. The modification investigates the laser output based on different coupling ratio, polarizer removal, unidirectional configuration, different SOAs, two segments of PMF and bidirectional SOA. With the modifications, different phenomena of multiwavelength spectrum were observed.

The final chapter, Chapter 5 will conclude the works of this doctoral research. The other discussion is recommendation of future work which obtained from the experimental work based on the performance investigation of the SOA-based MWFL.

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