TUNABLE CHANNEL SPACING MULTIWAVELENGTH FIBER LASER BASED ON SEMICONDUCTOR OPTICAL AMPLIFIER AND LYOT FILTERS

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

Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia

AUGUST 2021

DEDICATION

This work is dedicated to my dear husband, Mohd Nasir, who has been considerate and supportive throughout the duration of my study, to my beloved parents, Muridan Ali and Amrah Yusoff, who have always love me unconditionally and to my children; Aishna, Arasy, Luqman, Nuha, Ahmad and Khadeeja who are indeed a treasure from Allah Almighty.

ACKNOWLEDGEMENT

Foremost, I would like to impart my gratefulness to Allah Almighty for His guidance and blessing throughout the four years of study. I would like to express my sincere appreciation to my main supervisor, Dr. Nelidya Md. Yusoff for encouragement and critics throughout the process of completing this research. I am also very thankful to my co-supervisor Dr. Abdul Hadi Sulaiman who puts very much efforts in assisting me. Special thanks also dedicated to Dr. Azura for her kind advice and motivation. Finally, I humbly extend my thanks to one and all, who directly or indirectly, lent their hands in this regard.

ABSTRACT

Requirements of high speed and vast data transmission capacity in fiber optic communication have led to the tunability enhancement of multiwavelength fiber laser (MWFL). Comparisons of MWFL performance based on different types of semiconductor optical amplifiers (SOAs) as the gain medium are rarely investigated. The achievement of channel spacing tunability by using a multi-segment Lyot filter based on SOA is also limited. This research focused on the generation of tunable channel spacing MWFL incorporating an SOA and advanced multi-segment Lyot filter. SOA offers several advantages such as lower mode competition and a wider wavelength bandwidth as compared to erbium-doped fiber amplifier. The unpredictable behavior of MWFL at different SOA, nonlinearity, and gain in the ring cavity leads to the investigation of multiwavelength spectra's performance based on linear SOA (LSOA), nonlinear SOA and booster optical amplifier utilizing a single Lyot filter. LSOA exhibits a flat and stable spectrum with 14 lasing lines within 3 dB bandwidth, extinction ratio (ER) of 42 dB, and peak power at -14.1 dBm. Later, a polarization-dependent isolator is added into the laser cavity, and the result showed an improvement in the overall laser performance for all SOAs. This is due to the intensity-dependent loss mechanism induced by the combination of SOA and polarizer. The LSOA is used for multiwavelength generation at different Lyot filter configurations as it outperforms other SOAs in terms of the number of lasing lines, ER, and the highest peak power. To achieve channel spacing tunability, the single Lyot filter is replaced with a parallel Lyot filter. A stable and tunable multiwavelength spectrum of up to three channels spacings is demonstrated for all the sets within the 10 dB bandwidth. The main novelty of this study is an advancement of the Lyot filter by adding another Lyot filter serially to the parallel Lyot filter to improve channel spacing tunability. Through polarization controllers' adjustments, the channel spacing tunability has significantly improved and generated up to eight different channel spacings compared to only three used by previous researchers. The enhanced configuration of the Lyot filter with LSOA as the gain medium has a high potential in improving the performance of MWFL in channel spacing tunability for the wavelength division multiplexing system.

ABSTRAK

Keperluan kapasiti penghantaran data berkelajuan tinggi dan luas dalam komunikasi gentian optik telah mendorong peningkatan kemampuan laser gentian pelbagai gelombang (MWFL). Perbandingan prestasi MWFL berdasarkan jenis penguat optik semikonduktor (SOA) berbeza sebagai medium penguatan jarang dikaji. Pencapaian penalaan jarak saluran menggunakan penapis Lyot berbilang segmen berdasarkan SOA juga terhad. Penyelidikan ini memfokuskan pada penjanaan MWFL pada jarak saluran yang dapat ditala menggabungkan SOA dan penapis Lyot berbilang segmen termaju. SOA menawarkan kelebihan seperti persaingan mod lebih rendah dan lebar jalur panjang gelombang lebih luas berbanding penguat gentian terdop erbium. Kelakuan MWFL tidak dapat diramalkan pada SOA yang berbeza, tidak linear, dan perolehan dalam rongga cincin membawa kepada penyelidikan prestasi spektrum panjang gelombang berdasarkan SOA linear (LSOA), SOA tidak linear dan penguat optik penggalak menggunakan penapis Lyot tunggal. LSOA mempamerkan spektrum rata dan stabil dengan 14 garis lasing dalam lebar jalur 3 dB, nisbah kepupusan (ER) 42 dB, dan daya puncak pada -14.1 dBm. Kemudian, isolator yang bergantung pada polarisasi ditambahkan ke dalam rongga laser dan hasilnya menunjukkan peningkatan dalam prestasi laser keseluruhan untuk semua SOA. Ini disebabkan oleh mekanisme kehilangan bergantung kepada intensiti yang disebabkan oleh kombinasi SOA dan pengutub. LSOA digunakan untuk penjanaan pelbagai panjang gelombang pada konfigurasi penapis Lyot berbeza kerana ia mengatasi SOA lain dalam jumlah garis lasing, ER, dan daya puncak tertinggi. Untuk mencapai penalaan jarak saluran, penapis Lyot tunggal digantikan dengan penapis Lyot selari. Spektrum panjang gelombang yang stabil dan boleh ditala hingga tiga jarak saluran dihasilkan oleh semua set dalam lebar jalur 10 dB. Pembaharuan utama kajian ini adalah kemajuan penapis Lyot termaju dengan menambahkan penapis Lyot secara bersiri ke penapis Lyot selari untuk meningkatkan penalaan jarak saluran. Melalui penyesuaian pengawal kekutuban, penalaan jarak saluran telah ditingkatkan dengan ketara dan menjana hingga lapan jarak saluran berbeza berbanding hanya tiga yang dicapai oleh penyelidik sebelumnya. Konfigurasi dipertingkatkan penapis Lyot dengan LSOA sebagai medium penguatan berpotensi tinggi dalam meningkatkan prestasi MWFL dalam penalaan jarak saluran untuk sistem pemultiplek pembahagi panjang gelombang.

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LIST OF ABBREVIATIONS

ASE	-	amplified spontaneous emission
BOA	-	booster optical amplifier
C	-	conventional band
CW	-	continuous wave
EDFA	-	Erbium doped fiber amplifier
ER	-	extinction ratio
FBG	-	Fiber Bragg Grating
FP	-	Fabry Perot
FWM	-	four wave mixing
HWP	-	half wave Plate
IDL	-	intensity dependant loss
IDT	-	intensity dependant transmission
L	-	long band
LSOA	-	linear semiconductor optical amplifier
MWFL	-	multiwavelength fiber laser
MZI	-	Mach Zender Interferometer
NLSOA	-	non-linear semiconductor optical amplifier
NOLM	-	nonlinear optical loop mirror
NPR	-	nonlinear polarization rotation
OSA	-	optical spectrum analyzer
PC	-	polarization controller
PMF	-	polarization maintaining fiber
QWP	-	quarter wave plate
SOA	-	semiconductor optical amplifier
TDFA	-	Thulium doped fiber amplifier
TLS	-	tunable light source
VOA	-	variable optical attenuator
WDM	-	wavelength division multiplexer
WoS	-	Web of Science

LIST OF SYMBOLS

L_{eff}	-	effective length
$\Delta\lambda_e$	-	channel spacing from experimental work
$\Delta\lambda_c$	-	channel spacing from calculation
λ	-	wavelength
B	-	birefringence
L1	-	length of PMF1
L2	-	length of PMF2
L3	-	length of PMF3

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

This chapter serves as an introduction to this research work on generation of multiwavelength fiber laser (MWFL) based on semiconductor optical amplifier (SOA). The main novelty is an advanced Lyot filter with three segments of Lyot filter arranged in parallel and another segment put in serial in respect to the first group, along with nonlinear polarization rotation (NPR) effect which exist within the configuration. In Section 1.1, a brief discussion on introduction of MWFL is presented. Next is the problem statement relevant to the research scope prior to motivation behind the work. Subsequently is the elaboration of the objectives of the research followed by the scope of research. Then the description of research motivation follows. Before the summary at the end of the chapter, a detail of the thesis organization is presented. Overall, this chapter has covered the first step of the research as it is essential to understand the flow of the research starting from the problem statement, the motivation of research, the objective of research, the scope of research and the thesis organization before going further to the extensive theories and reviews as well as the experimental discussion later on in the following chapters.

Research on MWFL has been a major attraction to researchers in the photonics area due to its potential application in such fields as optical telecommunications [1]. With the higher requirements for Internet transmission speed, as well as capacity, the dense wavelength division multiplexing (DWDM) technology has been developed rapidly. MWFL is an ideal light source for multiple channels of DWDM, which greatly reduces the cost of building the system. This component is used to divide and combine different wavelength channels, each carrying an optical data signal. Channel of

MWFLs have the advantages of generating multiple lasing wavelengths simultaneously from a single fiber laser [2]. In addition, MWFLs are also widely used in optical fiber sensor and microwave photonics [3-6]. There have been a great number of articles on MWFL published contributing to the various significant discoveries in multiwavelength characteristics [2,7-9]. Those publications focus mostly on the performance and improvements on number of lasing lines, channel spacing tunability, wavelength tunability, peak power values, extinction ratio (ER), multiwavelength flatness and multiwavelength bandwidth.

Generation of MWFL involves two main components namely comb filters and gain medium in the laser system. A comb filter within laser structure plays a role in producing MWFL by slicing the amplified spontaneous emission (ASE) of the laser for wavelength selectivity. This can be achieved by several types of comb filter such as Fiber Bragg Grating (FBG) [10-12], Mach Zehnder Interferometer (MZI) [9,13] Fabry-Perot (FP) [14], Sagnac Loop Mirror (SLM) [15] and Lyot filter [16-19]. Lyot filter offers simple structure and output variability. This can be done simply by varying the parameter of polarization maintaining fiber (PMF) which is the main component of a Lyot filter [20]. There is also research done by combining two basic comb filters in a MWFL system. They demonstrated the combination of SLM with Lyot filter [21,22].

In recent years, based on the number of reported papers, one of the mechanisms to generate gain in MWFL is by scattering effects such as Raman [23,24], Brillouin [25] and random distributed feedback (RDF) [26] laser. They are particularly attractive due to low noise and ability to be generated at any wavelength without the need for a specialized gain medium. Another mechanism is the use of rare earth doped amplifiers such as erbium doped fiber amplifier (EDFA) [27,28], thulium doped fiber amplifier (TDFA) [14,29] and Ytterbium doped fiber amplifier (YbDFA) [30,31]. Prominent among these methods is the use of EDFA as a gain medium [32-35].This is mainly due to its advantages of low polarization sensitivity and high saturation power which will not affect the overall multiwavelength laser system [36]. SOA is another choice of gain medium which also attracts researchers for the advantages it offers [37-40].

NPR effect is an interesting method which should be highly considered in generating MWFL due to its advantages of having changeable operating regimes of multiwavelength lasing as well as passively mode locked at adjustment of polarization state [32,39,41,42]. Due to the NPR effect, intensity dependant loss (IDL) or intensity dependant transmission (IDT) is induced, that will suppress the mode competition in order to achieve stable multiwavelength output with narrow wavelength spacing [38,43,44]. The degree of IDL can be controlled by adjusting polarization controller (PC) in order to change the polarization state [45]. The combination of SOA and polarization devices in a ring cavity causes NPR effect [39,46].

1.2 Problem Statement

In recent years, the increasing demands for bandwidth have seen more attention being given to the development of fiber laser sources capable of producing a simultaneous multiwavelength output. Fiber laser system involves two main elements namely the comb filter and the gain medium. MWFL based on Lyot filter as the comb filter offer a variety of advantages such as simple and compact structure, cost effective and low optical loss in multiwavelength operation. Most of researches on Lyot based MWFL use EDFA as the gain medium for some advantages it offers [47,48]. However, EDFA produces high mode competition as it is a homogeneous broadening gain medium at room temperature, which leads to instability and limitation of the number of lasing lines produced by the system [43]. Other than that, the MWFL setup for EDFA is complex as it requires WDM coupler, optical pump and nonlinearity device as it does not have nonlinearity. EDFA also has limited bandwidth for the generation of MWFL. SOA is the best option to replace EDFA as it has its advantages [49] of having an inhomogeneous gain broadening to suppress the strong mode competition, allowing the generation of stable and flat lasing lines [37,38,46,50]. Besides that, SOA has a simpler setup than EDFA since it does not require optical pumping. SOA also offer selection of low or high nonlinearity. Hitherto, within author’s knowledge, only studies on single type of SOA were carried out by other researchers [38,39,44,46]. MWFL performance comparison based on different type of SOA has never been done before. A group of researchers used three different SOAs, however, all is under the same in line type [44]. The behaviour of multiwavelength laser performance at different SOA nonlinearity and gain is unpredictable in the ring cavity, thus an interesting aspect to be investigated. Making adjustments to PCs is crucial as the operation of a polarization maintaining device relies on the polarization state of the incoming light [40,51]. However, there are very limited studies investigated simultaneously the PCs adjustments, as they only adjusted one waveplate, either HWP or QWP at a time [17].

The performance of MWFL is evaluated based on flatness, number of lasing lines, extinction ratio, highest peak power, wavelength range and stability. In addition to the abovementioned criteria of the multiwavelength output, it is also necessary for lasers to have flexible channel spacing tunability that will have great potential application in many fields mainly in telecommunication and photonic sensing. Single Lyot filter consists of a length of PMF between two polarizers which will determine the channel spacing between lasing lines. In order to have tunable channel spacing, it is inconvenient to replace the fiber each time [17]. This problem can be resolved by adding more segment of Lyot filter into the fiber laser system which would enable convenient control of the channel spacing through adjustment of polarization state in the filter [52-54].

Up to present, the limited number of studies reported on channel spacing tunability are solely based on the use of multi segment Lyot filter, thus presenting an opportunity to explore the potential of Lyot filter in advanced configuration within MWFL system. Furthermore, they reported a limited channel spacing tunability for the use of PMF lower than two segments, where the highest tunability achieved was only three [55]. Another conundrum that has yet to be resolved is tunability of the wavelength range and number of lasing lines simultaneously, which is a very crucial aspect in MWFL for many applications.

1.3 Motivation of Research

Lyot filter based MWFL is an attractive choice for multiple laser generation due to its many useful qualities such as low optical loss and simple structure [38,45,56]. An approach of using SOA as the gain medium in MWFL based on Lyot filter setup is an interesting option as SOA possesses a characteristic of inhomogeneous line broadening which allows for stable multiwavelength lasing operation and high number of lines at room temperature due to its low mode competition. Another advantage of SOA is that it does not require an external optical pump, hence no additional device is necessary, resulting in a simpler setup when compared to EDFA as the gain medium [55,57]. Different SOA exhibits different nonlinearity and gain in the laser system which will affect the MWFL performance. Thus, it is crucial to choose SOA with the best performance in the generation of multiwavelength.

Even though there is a small number of studies reported for MWFL based on Lyot Filter, however, there exists a potential for research to investigate utilization of more than one segment of Lyot filter in different configurations. It is based on the characteristic of the generated multiwavelength that can be controlled by manipulating the Lyot filter properties. The spacing between the generated lines can be manipulated by adjusting the length of the PMF in the filter. Based on the principle operation of the Lyot filter, the spacing of the individual line can be controlled by employing more Lyot filters in a system. This is a significant advantage over existing fiber lasers, where there is minimal control over the spacing between wavelength lines [39,58]. Lyot based systems can be potentially used to control multiwavelength properties thus allowing room for flexibility of wavelength and interval spacing tuning.

The proposed configuration in this study is to arrange two segments of Lyot filter in parallel within the ring cavity. With such configuration, the generation of multiple laser lines can be achieved through the use of the parallel arrangement of Lyot filter as a comb filter and NPR as nonlinear effect. The NPR effect induces a mechanism of IDL or IDT which will help in flattening the multiwavelength generation [41,44,45,55]. Operating the filter in such configuration could provide better filter performance and utilize the device to its maximum potential. With the proven achievements of generating multiwavelength SOA fiber laser based on parallel Lyot Filter, it raises the opportunity and motivation to explore more the potential of Lyot filter based MWFL [38]. Other advantages of Lyot filter for obtaining multiwavelength lasing lies in the simplicity of configuration and their stable operation. The findings of the research have developed more interest in Lyot filters. Other researchers investigate experimentally the multi-stage Lyot filters by using EDFA as the gain medium. However, EDFA suffers homogeneous gain broadening which will prevent the generation of flat spectrum.

1.4 Aim and Objective of Research

The aim of this research is to generate the best performance of MWFL experimentally in terms of channel spacing tunability by using an advanced multi-segment Lyot filter as the comb filter with SOA as the gain medium for prospective practical applications such as in telecommunications and optical sensing. To achieve this, a few objectives have been outlined to guide the research route:

Objectives:

1. To investigate the best multiwavelength spectrum performance based on three different SOAs utilizing a Lyot filter.
2. To demonstrate channel spacing tunability of MWFL based on SOA by using a parallel Lyot filter.
3. To improve the channel spacing tunability based on advanced parallel and cascaded multi segment Lyot filters.

1.5 Scope of Research

MWFL can be generated using linear or ring cavity configuration. For both configurations, many articles have been published using several types of multiwavelength selective filtering methods with different gain medium and nonlinear effects in the generation of MWFL. The methods that have been studied by many researchers in the generation of multiwavelength are FP, FBG, SLM, MZI and Lyot filter. This study focuses on Lyot filter as it offers advantages such as low complexity and good tunability in terms of number of lasing lines and channel spacing based on its configuration. On the other hand, the gain media that can be utilized in the generation of MWFL can be grouped into two. They are the rare earth doped fibers and SOA. The most popular choice for rare earth doped gain medium is EDFA, besides TDFA and YbDFA. SOA can be grouped into three which are linear, nonlinear and booster. Meanwhile, nonlinear effects such as four wave mixing (FWM), stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and NPR effect play an important role in generating MWFL. The NPR effect induces IDL which influences the flatness and stability of the spectrum. In this work, at the first step, single segment Lyot filter is experimentally investigated using three types of SOA (Linear C band SOA1013S, nonlinear inline SOA1117S and nonlinear booster BOA1014S, all manufactured by Thorlabs). The generated MWFL are analyzed based on the number of lasing lines, multiwavelength bandwidth and ER to investigate the performance of MWFL for all the SOAs. Then another PC and a polarization dependent isolator (PDI) are added to the configuration to study their effects. The combination of SOA and polarizer in the laser system induced NPR effect that generates flat and stable multiwavelength spectra. The best SOA among the three is then selected based on the performance of the generated multiwavelength spectra. Later, the selected SOA is used as the gain medium in the generation of MWFL for a setup consisting of two of Lyot filters that arranged in parallel to obtain channel spacing tunability. Then, three Lyot filters from the combination of parallel and cascaded configurations are further explored to achieve higher tunability of the channel spacing. Figure 1.1 illustrates the scope of research that will be studied which is narrowed down from three major fields of wavelength selective filtering method, gain medium and nonlinear effect in the ring cavity. The specific topics are related to each other and are preferred due to various advantages and several gaps that will be filled and explored.

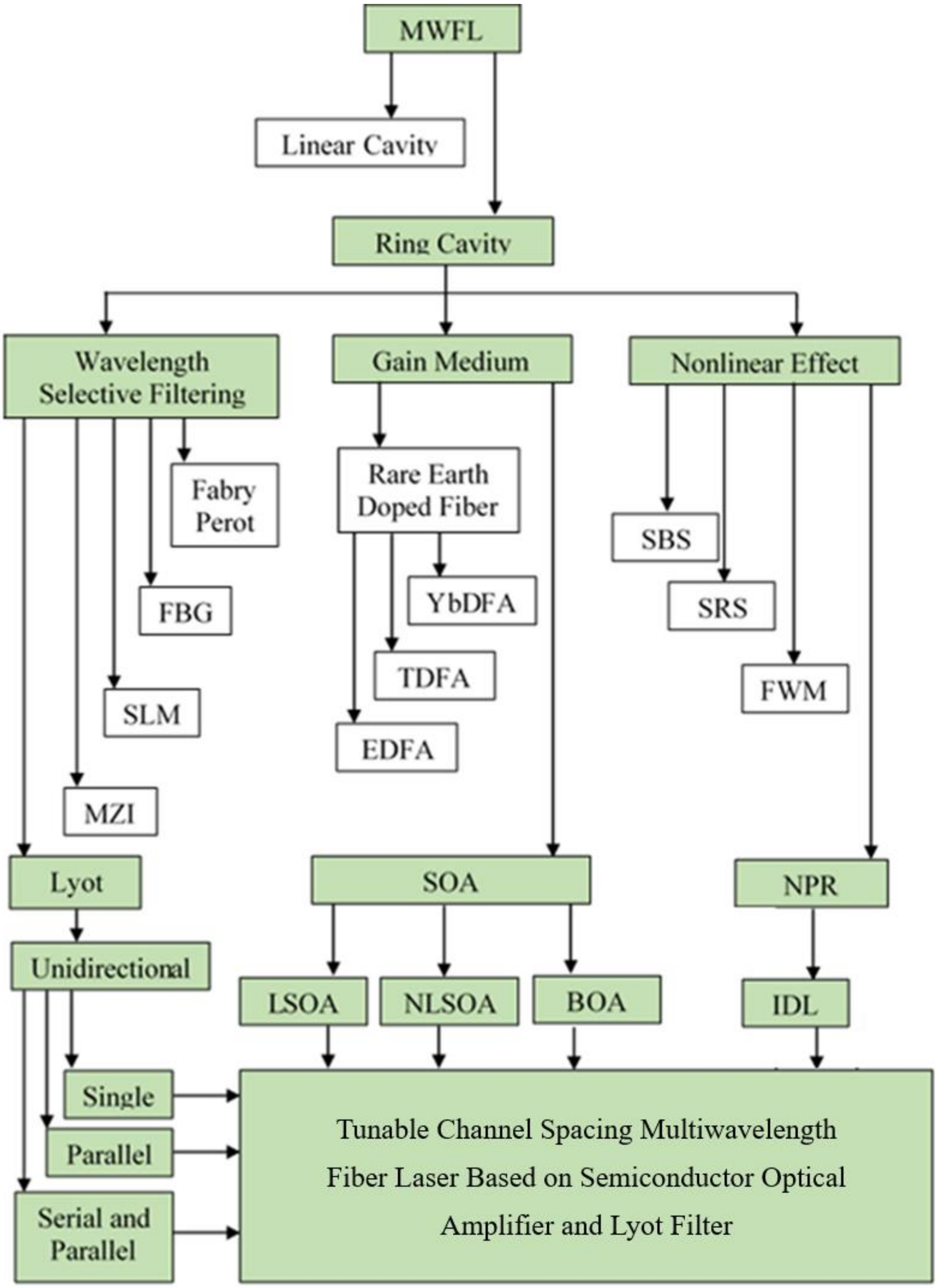

Figure 1.1 The scope of the research

1.6 Significance of Research

This research contributes to the development of dense wavelength division multiplexing (DWDM) technology that have been extremely important for modern wireless communications as there are great demands for Internet transmission speed and capacity. The investigation aims to achieve the best performance of MWFL as it is the ideal light source for multiple channels of DWDM. Other than in communications, MWFLs also have promising potential in optical sensing and detection technology. SOA which possesses unique attributes such as wide bandwidth, low power consumption and compactness is used as the gain medium in the generation of MWFL. Another interesting advantage of SOA is the ability for integration with any system. All the advantages offered by SOA contributes to the requirement of cost-effectiveness. The tunability of wavelength spacing is of prime significance in this study which meets the requirement of multifunctional devices as well as the operational flexibility and capabilities that are necessary for the ever-changing requirements. Overall, the proposed SOA based MWFL with flexible wavelength interval tunability mechanisms and simple structure potentially meet the application requirements of various occasions.

1.7 Thesis Organization

This thesis is categorized into seven chapters including this chapter, which serves as an introduction to the thesis. In each chapter, there will be a brief enclosed summary that states the accomplishments and findings according to the respective chapter. This current chapter describes an overview of the research background and identifies the problems involved. The objectives and scopes of the research are also presented accordingly. The research methodology that indicates the matters considered in accomplishing the work is briefly provided.

Chapter 2 widens the discussion on the theoretical background and the description of the involved devices and mechanisms in the proposed experimental setup that will be carried out. Different types of gain medium involved in the MWFL system are mentioned and discussed. SOA is explained in detail regarding its structure, principle of operation, parameters and type of configuration. Then, previous findings from literature on different types of wavelength filtering methods are presented. Brief introduction is provided for FBG, MZI, FP, SLM and LF in order to have some knowledge on different types of filter mechanisms that have been used in the MWFL research. Here, the possible areas of improvement for the multiwavelength generation are identified. Following is a detailed discussion as well as several reviews on LF as the chosen filter for this research work. Subsequently, the PMF as a birefringence device is explained. This chapter also explores the NPR effect, which introduces the IDT and the IDL mechanisms. The theory of polarization device namely the PC and polarizer is also included. Next, measurement parameters that will be used in analyzing MWFL spectrum are described. Last but not least is the critical reviews on MWFL based on SOA as the gain medium, multi segment Lyot filter as well as reviews on channel spacing.

Chapter 3 mainly demonstrates in detail the methodology of this research. A flowchart of the works to be carried out experimentally is presented. Three types of SOAs that will be used in the experiment are fully detailed. Four Lyot filter configurations are presented based on schematic diagrams and principle of operations.

In Chapter 4, experimental works for a single Lyot filter in fiber laser configuration are carried out. Two different configurations are utilized in order to study the effect of PDI in the setup. All the three SOAs are used as the gain medium for both setups. All the collected spectra are analyzed. The findings in this chapter are used to determine SOA with the best performance.

Chapter 5 reports the experimental results for parallel Lyot filter. There are two PMFs in this configuration addressed as PMF1 and PMF2 with L1 and L2 as the lengths respectively. Experimental investigation is divided into 3 groups based on PMF length. In the first group, both PMFs have short lengths. While in the second group, both have long PMF lengths. For the third group, it is a mix of long and short PMF lengths.

Chapter 6 contains the novelty of this research work. The laser system discussed in the previous chapter is improved as another segment of Lyot filter is inserted into the ring cavity. The new design now consists of two segments of Lyot filter arranged in parallel and another segment of Lyot filter positioned in series with the two. Overview of the different set of PMF lengths is provided.

Finally, the overall conclusions of the thesis are highlighted in Chapter 7. In the first sub chapter, detailed explanations on the achievements of all the objectives are presented. Then, the main contributions of this study are discussed in terms of SOA, advanced Lyot filter configuration and channel spacing tunability. The recommendations on the future works for further advancements to this research are fundamentally identified before the end of this chapter.

REFERENCES

[1] Kumar, A. B., et al., 'Tunable wavelength demultiplexer for DWDM application using 1-D photonic crystal', *Prog. Electromagn. Res. Lett.*, 2012. 33.

[2] Zhang, X., et al., 'Tunable multiwavelength SOA fiber laser with ultra-narrow wavelength spacing based on nonlinear polarization rotation', *Opt. Express,* 2009. 17(19), pp. 17200-17205.

[3] Wang, H. Y., Chi, Y. C. and Lin, G. R. 'Remote beating of parallel or orthogonally polarized dual-wavelength optical carriers for 5G millimeter-wave radio-over-fiber link', *Opt. Express*, 2016. 24(16), pp. 17654.

[4] Budka, K. C., et al., ' Communication network architecture and design principles for smart grids ', *Bell Labs Technical Journal*, 2010. 15(2), pp. 205-227.

[5] Melián, B., Laguna, M. and Moreno-Pérez, J. A. 'Capacity expansion of fiber optic networks with WDM systems: Problem formulation and comparative analysis', *Comput. Oper. Res.*, 2004. 31(3), pp. 461-472.

[6] Diaz, S., Laendro, D. and Lopez-Amo, M. 'Stable Multiwavelength Erbium Fiber Ring Laser With Optical Feedback for Remote Sensing', *J. Light. Technol.*, 2015. 33(12), pp. 2439-2444.

[7] Li, Y., et al., 'Tunable multiwavelength erbium-doped fiber laser based on nonlinear optical loop mirror and birefringence fiber filter', *Appl. Phys. B,* 2015. 19, pp. 363-370.

[8] Liang, X., et al., 'A switchable and tunable ytterbium-doped fiber ring laser with a Sagnac loop mirror', *Optoelectron. Lett.*, 2016. 12(4), pp. 261-263.

[9] Jasim, A. A. and Ahmad, H. 'A highly stable and switchable dual-wavelength laser using coupled microfiber Mach-Zehnder interferometer as an optical filter', *Opt. Laser Technol*., 2017. 97, pp. 12-19.

[10] Shen, F., et al., 'Switchable dual-wavelength erbium-doped fibre laser utilizing two-channel fibre Bragg grating fabricated by femtosecond laser', *Laser Phys.*, 2016. 26(10).

[11] Zhang, L., et al., 'Wavelength-tunable thulium-doped fiber laser with sampled fiber Bragg gratings', *Opt. Laser Technol.*, 2019. 120, pp. 105707.

[12] Chen, X., et al., 'Phase-shift induced in a high-channel-count fiber bragg grating and its application to multiwavelength fiber ring laser', *IEEE Photonics Technol. Lett.*, 2011. 23(8), pp. 498-500.

[13] Ovvyan, A. P., et al., 'Cascaded Mach–Zehnder interferometer tunable filters', *J. Opt.*, 2016. 18(6), pp. 1-7.

[14] Camarillo-Aviles, A., et al., 'Stable multi-wavelength thulium-doped all-fiber laser incorporating a multi-cavity fabry-perot filter', *IEEE Photonics J.*, 2019. 11(6), pp. 2-7.

[15] Xiong, H., et al., 'Tunable multiwavelength SLM fiber laser based on Rayleigh and Brillouin scattering effects', *Opt. Eng.*, 2017. 56(5), pp. 056113.

[16] Jo, S., Kim, Y. and Lee, Y. W., 'Study on Transmission and Output Polarization Characteristics of a First-Order Lyot-Type Fiber Comb Filter Using Polarization-Diversity Loop', *IEEE Photonics J.*, 2015. 7(4).

[17] Liu, S., et al., 'Multi-Wavelength Thulium-Doped Fiber Laser Using a Fiber Based Lyot Filter', *IEEE Photonics Technol. Lett.*, 2016. 28(8), pp. 864-867.

[18] Yan, Z., et al., 'All-fiber polarization interference filters based on 45°-tilted fiber gratings', *Opt. Lett.*, 2012. 37(3), pp. 353.

[19] Saleh, S., et al., 'Lyot-based multi-wavelength fiber laser', *Int. J. Electr. Comput. Eng. 7*, 2017. pp. 981-985.

[20] Zhao, Q., et al., 'Wide tuning range and high OSNR self-seeded multiwavelength Brillouin-erbium fiber laser based on a Lyot filter', *Appl. Opt.*, 2018. 57(36), pp. 10474-10479.

[21] Wang, S., et al., 'Wavelength-spacing-controllable multi-wavelength fiber laser based on a Lyot–Sagnac filter', *Appl. Opt.*, 2018. 57(30), pp. 8845-8850.

[22] Zou, H., et al., 'Stable multi-wavelength fiber laser based on a compounded nonlinear polarization rotation effect', *Laser Phys.*, 2014. 24(11).

[23] Ye, J., et al., 'Power scalability of linearly polarized random fiber laser through polarization-rotation-based Raman gain manipulation', *Opt. Express*, 2018. 26(18), pp. 22894.

[24] Xiao, Q., et al., 'Bidirectional pumped high power Raman fiber laser', *Opt. Express*, 2016. 24(6), pp. 6758.

[25] Zhang, L., et al., 'Multi-Wavelength Brillouin Random Fiber Laser via Distributed Feedback from a Random Fiber Grating', *J. Light. Technol.*, 2018. 36(11), pp. 2122-2128.

[26] Sugavanam, S., Zulkifli, M. Z. and Churkin D. V., 'Multi-wavelength erbium/Raman gain based random distributed feedback fiber laser', *Laser Phys.*, 2016. 26(1), pp. 15101.

[27] Bing, F., et al., 'Experimental research on an L-band multi-wavelength erbium-doped fiber laser based on a cascaded Sagnac loop and M–Z filters', *Laser Phys*., 2019. 29(6), pp. 065102.

[28] Li, Y., et al., 'Tunable multiwavelength Er-doped fiber laser with a two-stage Lyot filter', *IEEE Photonics Technol. Lett. 29*, 2017. pp. 287-290.

[29] Qin, Q., et al., 'Investigation of a multiwavelength thulium-doped fiber laser incorporating a two-mode fiber filter', *Infrared Phys. Technol*., 2020. 108, pp. 103360.

[30] Drobyshev, R. V., et al., 'Multi-wavelength gain-switched Yb-doped fiber laser', *Laser Phys. Lett.*, 2020. 17(6), pp. 172020.

[31] Zhang, Z., Zhang, L. and Xu, Z., 'Tunable multiwavelength ytterbium-doped fiber laser based on nonlinear polarization rotation', *J. Nonlinear Opt. Phys. Mater*., 2012. 21(3), pp. 1-7.

[32] Feng, X., Tam, H. and Wai, P. K. A., 'Stable and uniform multiwavelength erbium-doped fiber laser using nonlinear polarization rotation', *Opt. Express*, 2006. 14(18), pp. 8205.

[33] Cholan, N. A., et al., 'Switchable single- and dual-wavelength erbium-doped fiber laser assisted by four-wave mixing with wide and continuous tunability', *Appl. Phys. B Lasers Opt.*, 2014. 115, pp. 251-256.

[34] Zhao, Z., et al., 'Highly Polarized Multiwavelength Er-doped Fibre Laser Using All Fibre Lyot Filter', *16th International Conference on Optical Communications and Networks*, 2017. 1, pp. 16-18.

[35] Yusoff, N. M., et al., 'Stable dual-wavelength laser incorporating polarization maintaining erbium-doped fiber', *Opt. Laser Technol.*, 2021. 135, pp. 106707.

[36] He, W., et al., 'Tunable and stable multi-wavelength erbium-doped fiber laser based on a double Sagnac comb filter with polarization-maintaining fibers', *Optik (Stuttg).*, 2017. 137, pp 254-261.

[37] Sulaiman, A. H., et al., 'Tunable multiwavelength fiber laser based on bidirectional SOA in conjunction with Sagnac loop mirror interferometer', *Results Phys.*, 2020. 18.

[38] Sulaiman, A. H., et al., 'Investigation on factors influencing flatness of a

bidirectional SOA-based multiwavelength fiber laser', *Infrared Phys. Technol.*, 2020. 112, pp. 103593.

[39] Zhou, X., et al., 'Multi-wavelength SOA fiber laser with ultra-narrow wavelength spacing based on NPR effect', *IEEE Photonics J.*, 2020.

[40] Wei, L., et al., 'Continuously Tunable Comb Filter Based on a High-Birefringence Fiber Loop Mirror with a Polarization Controller', *Journal of Lightwave Technology*, 2021. 8724.

[41] Wang, F., Zhang, X. and Cui, J., 'Tm-doped fiber laser with multiwavelength output and switchable wavelength difference based on nonlinear polarization rotation effect,' *Opt. Laser Technol.*, 2020. 130, pp. 30-33.

[42] Lian Y., et al., 'Switchable multiwavelength fiber laser using erbium-doped twin-core fiber and nonlinear polarization rotation', *Laser Phys. Lett.*, 2017. 14(5), pp. 0-7.

[43] Feng X., et al., 'Mechanism for stable, ultra-flat multiwavelength operation in erbium-doped fiber lasers employing intensity-dependent loss', *Opt. Laser Technol.*, 2012. 44(1), pp. 74-77.

[44] Sulaiman, A. H., et al., 'Multiwavelength fiber laser based on bidirectional lyot filter in conjunction with intensity dependent loss mechanism', *Indones. J. Electr. Eng. Comput. Sci.*, 2018. 10, pp. 840-846.

[45] Sulaiman, A. H., et al., 'Broad bandwidth SOA-based multiwavelength laser incorporating a bidirectional Lyot filter', *Chinese Opt. Lett.*, 2018. 16, pp. 090603.

[46] Hao, H. T., et al., 'Wavelength-number-tunable multi-wavelength SOA fiber laser based on NPR effect', *Opt. Fiber Technol.*, 2020. 58.

[47] El-Mashade, M. and Mohamed, A., 'Characteristics Evaluation of Multi-Stage Optical Amplifier EDFA', *Br. J. Appl. Sci. Technol.*, 2017. 19(4), pp. 1-20.

[48] Zhao, X., et al., 'Switchable multi-wavelength and tunable wavelength spacing erbium-doped fiber laser based on a phase-shifted fiber Bragg grating combined with a Mach-Zehnder interferometer', *Opt. Laser Technol.*, 2019. 112, pp. 500-507.

[49] Sulaiman,A. H., et al., 'Flatness investigation of multiwavelength SOA fiber laser based on intensity-dependent transmission mechanism', *Opt. Commun.*, 2013. 291, pp. 264-268.

[50] Sulaiman, A. H., et al., 'Investigation of multiwavelength performance utilizing

an advanced mechanism of bidirectional lyot filter', *IEEE Photonics J.*, 2013. 5(6).

[51] Ge, J., et al., 'High-speed tunable microwave photonic notch filter based on phase modulator incorporated loop mirror filter', *Opt. Fiber Commun. Conf. OFC 2015*, 2015. 40(1), pp. 48-51.

[52] Zhao, Q., et al., 'Switchable Multi-Wavelength Erbium-Doped fiber laser with adjustable wavelength interval', *J. Light. Technol.*, 2019. 37, pp. 3784-3790.

[53] Ge, J. and Fok, M. P., 'Passband switchable microwave photonic multiband filter', *Sci. Rep.*, 2015. 5.

[54] Jung, J. and Lee, Y. W., 'Continuous wavelength tuning of the first-order general comb spectrum', *Opt. Express*, 2019. 27(5), pp. 6549.

[55] Zhao, Q., et al., 'Tunable and interval-adjustable multi-wavelength erbiumdoped fiber laser based on cascaded filters with the assistance of NPR', *Opt. Laser Technol.*, 2020. 131.

[56] Drobyshev, R. V., Lobach, I. A. and Kablukov, S. I., 'Narrow-linewidth self sweeping fiber laser with scanning range control by a tunable Lyot filter', *Laser Phys.*, 2019. 29(10).

[57] Chang, Y., et al., 'Switchable and tunable multi-wavelength fiber ring laser employing a cascaded fiber filter', *Opt. Fiber Technol.*, 2020. 58, pp. 102240.

[58] Guzman-Chavez, A. D., Vargas-Rodriguez, E. and Cano-Contreras, M., 'Switchable, tunable and highly stable multi-wavelength fiber laser based on a spectral filter', *Laser Phys*., 2019. 29(4).

[59] Liu, X., 'Evolution of Fiber-Optic Transmission and Networking toward the 5G Era', *iScience*, 2019. 22, pp. 489-506.

[60] Agrell, E,. et al., 'Roadmap of optical communications', *J. Opt. (United Kingdom)*, 2016. 18(6).

[61] Hah, D., 'C-band optical filters with micromechanical tuning', *Microsyst. Technol.*, 2018. 24(1), pp. 551-560.

[62] Ivaniga, T. and Ivaniga, P., 'Comparison of the optical amplifiers EDFA and SOA based on the BER and Q-factor in C-band', *Adv. Opt. Technol.*, 2017. pp. 1-10.

[63] Lai, C. H., et al., 'Multi-Wavelength Laser Based on SOA and Polarization Maintaining Fiber for WDM System', *2017 IEEE Int. Conf. Consum. Electron. - Taiwan*, 2017. pp. 219-220.

[64] Liaw, S. K., et al., 'Multiwavelength linear-cavity SOA-based laser array design for multiparameter and long-haul sensing', *IEEE Sens. J.*, 2015. 15(6), pp. 3353-3358.

[65] Andrekson, P. A. and Karlsson, M., 'Fiber-based phase-sensitive optical amplifiers and their applications', *Adv. Opt. Photonics*, 2020. 12(2), pp. 367.

[66] Carvalho, D. O., et al., 'A review on pedestal waveguides for low loss optical guiding, optical amplifiers and nonlinear optics applications', *J. Lumin.*, 2018. 203, pp. 135-144.

[67] Bai, H., et al., 'A widely tunable single-longitudinal-mode ytterbium-doped fiber laser based on fiber Lyot filter', *Laser Phys.*, 2018. 28(9).

[68] Ong, Y. S., et al., 'Performance Investigation of Dual Wavelength Fiber Laser using different SOAs', *Int. J. Integr. Eng.*, 2020. 12(6), pp. 273-281.

[69] Sulaiman, A. H., et al., 'Stable and Broad Multiwavelength Generation with the Assistance of Intensity Dependent Loss Mechanism based on Bidirectional SOA', *J. Phys. Conf. Ser.*, 2020. 1593(1).

[70] Ma, L., et al., 'Multiwavelength generation by using a novel Brillouin-erbium fiber laser with double linear-cavity based on a double-pass Brillouin Pump (BP) amplification technique', *Opt. Laser Technol.*, 2019. 117, pp. 169-174.

[71] Jauregui-Vazquez, D., et al., 'A multi-wavelength erbium-doped fiber ring laser using an intrinsic Fabry-Perot interferometer', *Laser Phys.* 2016. 26(10).

[72] Wang, F., 'Tunable 12 × 10 GHz mode-locked semiconductor fiber laser incorporating a Mach-Zehnder interferometer filter', *Opt. Laser Technol.*, 2011. 43(4), pp. 848-851.

[73] Yang, X., et al., 'A stable narrow line-width dual-wavelength fiber laser based on nonlinear polarization rotation with a high finesse ring filter', *Appl. Mech. Mater.*, 2012. 130-134, pp. 1876-1879.

[74] Shahabuddin, N. S., et al., 'Multi-wavelength fiber laser based on nonlinear polarization rotation in semiconductor optical amplifier and photonic crystal fiber', *Laser Phys.*, 2012. 22(7), pp. 1257-1259.

[75] Yao, J., et al., 'Multiwavelength erbium-doped fiber ring laser incorporating an SOA-based phase modulator', *IEEE Photonics Technol. Lett.*, 2005. 17(4), pp. 756-758.

[76] Malik, D., Kaushik, G. and Wason, A., 'Performance evaluation of hybrid optical amplifiers in WDM system', *J. Opt.*, 2018. 47(3), pp. 396-404.

[77] Kharraz, O. M., et al., 'Performance enhancement of multi-wavelength generations based on SOAs with a microfiber Mach-Zehnder interferometer', *Laser Phys.*, 2017. 27(7).

[78] Zoiros, K. E., O'Riordan, C. and Connelly, M. J., 'Semiconductor optical amplifier pattern effect suppression using Lyot filter', *Electron. Lett.*, 2009. 20545(23), pp. 1187-1189.

[79] Singh, S. and Lovkesh, 'Ultrahigh speed optical signal processing logic based on an SOA-MZI', *IEEE J. Sel. Top. Quantum Electron.*, 2012. 18(2), pp. 970-977.

[80] Vedala, G., Hameed, M. A. and Hui, R., 'Digital compensation of SSBI in direct detection multicarrier system with SOA nonlinearities', *IEEE Photonics Technol. Lett.*, 2017. 29(4), pp. 369-372.

[81] Chen, Y., et al., 'Improving the SNR of the phase-OTDR by controlling the carrier in the SOA', *J. Mod. Opt.*, 2020. 67(14), pp. 1241-1246.

[82] Connely, M. J., *Semiconductor Optical Amplifiers*. Kluwer Academic Publishers, 2002.

[83] Mao, X., et al., 'Continuously tunable wideband semiconductor fiber-ring laser', *Laser Phys.*, 2017. 27(8), pp. 7-10.

[84] Shen, Z., et al., 'Tunable dual-wavelength single-longitudinal-mode fiber laser based on spectral narrowing effect in a nonlinear semiconductor optical amplifier', *Opt. Laser Technol.*, 2017. 94(26), pp. 72-76.

[85] Malek, A. Z., et al., 'Fiber bragg grating assisted cavity loss reduction in the generation of multiwavelength brillouin fiber laser', *Optik (Stuttg).*, 2018. 157, pp. 684-692.

[86] Huo, L., et al., '100-GHz wavelength-tunable all-optical clock recovery with Fabry-Perot filter and semiconductor optical amplifier', *Opt. Commun.*, 2016. 359, pp. 285-289.

[87] Gorman, A., Fletcher-Holmes, D. W. and Harvey, A. R., 'Generalization of the Lyot filter and its application to snapshot spectral imaging', *Opt. Express*, 2010. 18(6), pp. 5602.

[88] Huang, B., Wang, Y. and Mao, C., 'Lyot Filter with Femtosecond Laser-Induced High Birefringence Single-Mode Fiber for Torsion, Transverse Load and Temperature Sensing', *IEEE Access*, 2020. 8, pp. 25764-25769.

[89] Huang, B. and Shu, X., 'Highly sensitive twist sensor based on temperature-

and strain-independent fiber lyot filter', *J. Light. Technol.*, 2017. 35(10), pp. 2026-2031.

[90] Zeng, Y., et al., 'The effects of Lyot filter on the SNR of mode-locked fiber laser', *Opt. Laser Technol.*, 2020. 128, pp. 106148.

[91] Jo, S., Park, K. and Lee, Y. W., 'Lyot-type flat-top fibre multiwavelength filter based on polarisation-diversity loop structure', *Micro Nano Lett*., 2014. 9(12), pp. 858-861.

[92] Luo, A. P., Luo Z. C. and Xu, W. C., 'Channel-spacing switchable multiwavelength fiber ring laser with one segment of polarization maintain fiber', *Laser Phys. Lett.*, 2009. 6(8), pp. 598-601.

[93] Zhang, Z., et al., 'Wavelength-spacing switchable multiwavelength fiber lasers based on nonlinear polarization rotation with cascaded birefringence fibers', *J. Mod. Opt.*, 2011. 58(1), pp. 82-86.

[94] Liu, X. S., et al., 'Multiwavelength erbium-doped fiber laser based on nonlinear polarization rotation assisted by four-wave-mixing', *Opt. Commun.*, 2009. 282(14), pp. 2913-2916.

[95] Quan, M., et al., 'Multifunctional tunable multiwavelength erbium-doped fiber laser based on tunable comb filter and intensity-dependent loss modulation', *Opt. Commun.*, 2015. 340, pp. 63-68.

[96] Sun, J., Zhang, Y. and Zhang, X., 'Multiwavelength lasers based on semiconductor optical amplifiers', *IEEE Photonics Technol. Lett.*, 2002. 14(6), pp. 750-752.

[97] Sun, G., et al., 'Polarization controlled tunable multiwavelength SOA-fiber laser based on few-mode polarization maintaining fiber loop mirror', *Opt. Fiber Technol.*, 2010. 17(1), pp. 79-83.

[98] Liu, S., et al., 'A pump power controlled 1,060 nm multiwavelength fiber ring laser using nonlinear polarization rotation of SOA', *Appl. Phys. B Lasers Opt.*, 2013. 110(4), pp. 445-449.

[99] Sulaiman, A. H., et al., 'Investigation of multiwavelength laser performance based on temperature variation of PMF and different SOAs', *Int. J. Integr. Eng.*, 2018. 10, pp. 244-252.

[100] Ong, Y. S., et al., 'Effect of Semiconductor Optical Amplifiers Types on Multiwavelength Fiber Laser Performance', I*EEE 8th International Conference on Photonics*, 2020.

[101] Wang, M., et al., 'A tunable Lyot birefringent filter with variable channel spacing and wavelength using nonlinear polarization rotation in an SOA', *IEEE Photonics Technol. Lett.*, 2008. 20, pp. 1527-1529.

[102] Sugavanam, S., et al., 'Multiwavelength generation in a random distributed feedback fiber laser using an all fiber Lyot filter', *Opt. Express*, 2014. 22(3), pp. 2839.

[103] Fok, M. P., Shu, C. and Tang, W. W., 'A cascadable approach to produce widely selectable spectral spacing in birefringent comb filters', *IEEE Photonics Technol. Lett*., 2006. 18(18), pp. 1937-1939.

[104] Sova, R. M., Kim, C.S. and Kang, J. U., 'Tunable dual-wavelength all-PM fiber ring laser', *IEEE Photonics Technol. Lett.*, 2002. 14(3), pp. 287-289.

[105] Wang, W., et al., ‘Three Channel-Spacing Switchable Multiwavelength Fiber Laser with Two Segments of Polarization-Maintaining Fiber', I*EEE Photonics Technology Letters*, 2012. 24(6), pp. 470-472.

[106] Chen, J., et al., 'Research on tunable multiwavelength fiber lasers with two section birefringence fibers and a nonlinear optical loop', *Laser Phys.*, 2018. 28(5).

[107] Han, Y. G., et al., 'Lasing wavelength and spacing switchable multiwavelength fiber laser from 1510 to 1620 nm', *IEEE Photonics Technol. Lett.*, 2005. 17(5), pp. 989-991.

[108] Qureshi, K. K. and Tam, H. Y., 'Multiwavelength fiber ring laser using a gain clamped semiconductor optical amplifier', *Opt. Laser Technol.*, 2012. 44(6), pp. 1646-1648.

[109] Liu L. Y., et al., 'Stable L-band multiwavelength SOA fiber laser based on polarization rotation', *Appl Opt.*, 2017. 56(10), pp. 2787-2791.

[110] Han, M., et al., 'Tunable and channel spacing precisely controlled comb filters based on the fused taper technology', *Opt. Express*, 2018. 26(1), pp. 265.

[111] Han, Y. G., et al., 'Wavelength spacing tunable multiwavelength fiber laser with lasing wavelength selectivity', *Opt. Commun.*, 2005. 256(1-3), pp. 98-102.

[112] Sikta, J. N., et al., 'Wavelength spacing tenable capability of optical comb filter using Polarization Maintaining Fiber', *OSR Journal of Applied Physics*, 2014. 6(3), pp. 57-62.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Muridan, N.**, Sulaiman, A. H., Md. Yusoff, N. and Abdullah, F. (2021). Effect of Polarization Adjustment towards the Performance of SOA-based Multiwavelength Fiber Laser. *International Journal for Light and Electron Optics (OPTIK*), 242, 167007. **(Q2, IF:2.187), (Indexed in WoS and SCOPUS)**

Indexed Journal

1. **Muridan, N.**, Awang Lah, A. A., Sulaiman, A. H., Md. Yusoff, N., Abdullah, F. and Hamzah, A. (2021). Investigation of Multiwavelength Performance Based on Different SOAs.
    - Accepted to be published in International Journal of Integrated Engineering (IJIE) **(Indexed in WoS and SCOPUS)**.