

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

NORASMAHAN BINTI MURIDAN

UNIVERSITI TEKNOLOGI MALAYSIA

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NORASMAHAN BINTI MURIDAN

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## **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.

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## 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
TDFFA	-	Thulium doped fiber amplifier
TLS	-	tunable light source
VOA	-	variable optical attenuator
WDM	-	wavelength division multiplexer
WoS	-	Web of Science



## LIST OF SYMBOLS

$L_{\text{eff}}$	-	effective length
$\Delta\lambda_e$	-	channel spacing from experimental work
$\Delta\lambda_c$	-	channel spacing from calculation
$\lambda$	-	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.

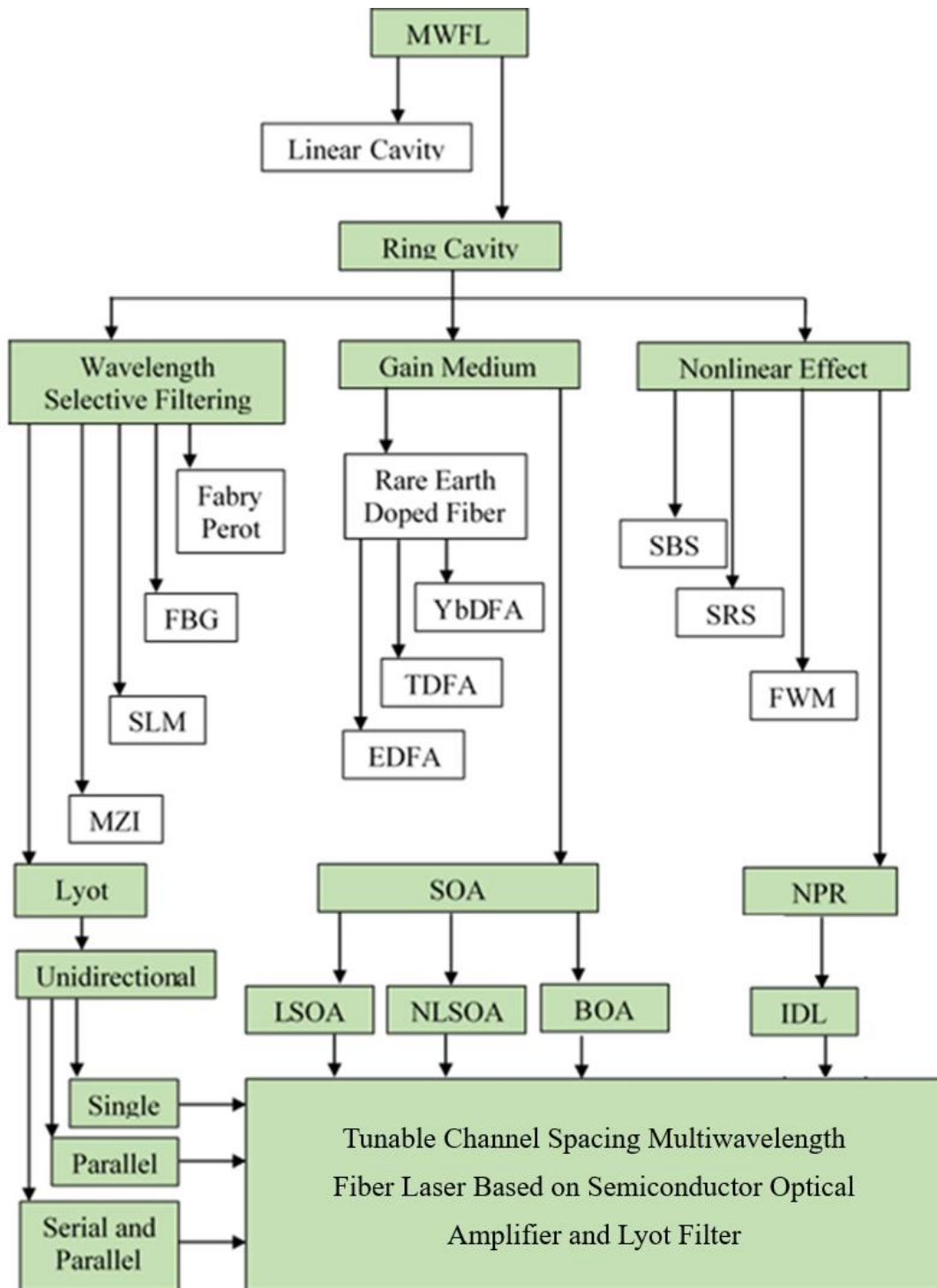


Figure 1.1 The scope of the research

## **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.

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## 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.
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