UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION OF ULTRASHORT PULSE LASER IN RING-TYPE ERBIUM-DOPED FIBER LASER WITH SINGLE WALL CARBON NANOTUBE SATURABLE ABSORBER

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By

HAFIZAH BINTI MOHAMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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Research works based on pulsed mode-locked fiber laser (MLFL) were realized by employing numerous techniques such as nonlinear polarization rotation, saturable absorber (SA) and active modulator. The generation of MLFL encourages substantial research efforts due to its fascinating characteristics such as ultrashort pulse duration, broad spectral bandwidth and intense pulse energy, which are highly desirable in various industrial applications. The MLFL possesses several significant issues that need to be addressed such as dispersion management and operating wavelength region. Subsequently, this research work focuses on both issues, which are dispersion optimization and switchable wavelength laser operation

In this research, a ring-configuration erbium-doped fiber laser (EDFL) setup is employed to generate multiwavelength-based MLFL which is assisted by an inline single-walled carbon nanotube (SWCNT) SA. The ultrashort pulse signal initiated by this SA is accompanied with the typical soliton-based mode-locked laser characteristics such as the observation of multiple Kelly's sidebands, output pulse train with constant round-trip time, and pulse width within femtosecond range.

The initial work in this experiment is to investigate dispersion management within the mode-locked EDFL, leading to pulse width generation of 970 fs with the employment of 10 m HP980 erbium-doped fiber (EDF). This MLFL regime generates multiple pulses which resembles the harmonic mode-locking laser scheme. This pulsed laser scheme is unstable, due to the lengthy EDF used which contributes to high nonlinear effects at high pump power. Therefore, the EDF length is shortened to 5 m in order to reduce the possibility of unstable pulses generation as aforementioned. The pulse width generated by 5 m EDF-incorporated MLFL is 886 fs, with more stable pulses observed from spectral and temporal measurements. Dual-laser regime is observed with the lasers observed at around 1530 nm and 1560 nm. Therefore, a red/blue coupler is employed in order to provide a cleaner output at 1560 nm. After the laser cavity is optimized through length

variation of single mode fiber, the pulse width is found at 864 fs with total cavity length of 17m.

Based on the experimental findings during dispersion management process, the dual-laser regime is employed in order to generate switchable dual-lasing MLFL. The mode-locked laser output can be discretely varied from 1533 nm to 1560 nm or can be made to simultaneously oscillate at both regions, thus producing a dual-wavelength mode-locked operation. This is realized by spooling the fiber in the laser cavity into different radii of 1.60 cm, 1.07 cm and 0.80 cm respectively, resulting in the respective insertion loss of 0.11 dB, 1.21 dB and 4.20 dB. Subsequently, the pulse widths generated by each case are 734 fs, 800 fs and 1.06 ps, respectively. Therefore, by spooling the fiber into different radii, the switchable MLFL is generated at different wavelength region, where the pulse width can be tailored.

In conclusion, this research work has successfully overcome the issues in MLFL performance on dispersion management and operating wavelength bands. Both issues are significant in typical MLFL where further research investigation can be made in studying the different mode-locked regimes of dark pulse, stretch pulse and harmonic pulse.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

PENGOPTIMUMAN DENYUT ULTRA-PENDEK DALAM GENTIAN LASER TERDOP ERBIUM JENIS CINCIN DENGAN PENYERAP BOLEH TEPU KARBON TIUB NANO BERDINDING TUNGGAL

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Kerja-kerja penyelidikan berdasarkan denyutan laser selakan mod (MLFL) direalisasikan dengan menggunakan pelbagai teknik seperti putaran kutub tak linear, penyerap boleh tepu (SA) dan pemodulat aktif. Penjanaan MLFL menggalakkan usaha penyelidikan yang besar kerana ciri-cirinya yang mempersona seperti tempoh denyutan ultrapendek, lebar spectrum jalur lebar dan tenaga denyut beramatan, di mana dikehendaki tinggi dalam pebagai aplikasi perindustrian. MLFL mempunyai beberapa isu-isu penting yang perlu diberi perhatian seperti pengurusan penyerakan dan kawasan operasi jarak gelombang. Selepas itu, kerja-kerja penyelidikan ini memberi tumpuan kepada kedua-dua isu, pengoptimuman penyerakan dan operasi laser pembolehalih jarak gelombang.

Dalam penyelidikan ini, persediaan laser gentian terdop erbium (EDFL) konfigurasi cincin bekerja untuk menjana dasar pelbagai jarak gelombang MLFL yang dibantu oleh nanotiub karbon berdinding tunggal sebaris (SWCNT) SA. Isyarat denyut ultrapendek terdorong oleh SA ini disertai dengan ciri-ciri selakan mod laser berdasarkan soliton seperti pemerhatian pelbagai jalursisi Kelly, keluaran denyut-pawai dengan pemalar masa pergi balik dan lebar denyut dalam julat femtosaat.

Kerja pemulaan dalam eksperimen ini adalah untuk menyelidik pengurusan penyerakan dalam selakan mod EDFL, menjurus kepada penjanaan lebar denyut 970 fs dengan menggunakan 10 m HP980 gentian terdop erbium (EDF). Rejim MLFL ini menjana berbilang denyut yang menyerupai skema laser selakan mod harmonik. Skema denyut laser ini tidak stabil, kerana panjang EDF yang digunakan menyumbang kepada kesan tak linear tinggi pada kuasa pam yang tinggi. Oleh itu, panjang EDF dipendekkan kepada 5 m untuk mengurangkan kemungkinan penjanaan denyut tak stabil seperti di atas. Lebar denyut dihasilkan oleh 5 m EDF dalam MLFL ialah 886 fs, dengan denyut yang lebih stabil diperhatikan dari spectrum dan ukuran-ukuran sementara. Rejim dwi-laser didapati dengan laser-laser yang terletak di sekitar 1530 nm dan 1560 nm. Oleh itu, pengganding

merah/biru bekerja untuk menghasilkan keluaran yang lebih jelas pada 1560 nm. Selepas rongga laser dioptimum mealui variasi panjang gentian mod tunggal, lebar denyut didapati 864 fs dengan jumlah panjang rongga 17 m.

Berdasarkan penemuan eksperimen sepanjang proses pengurusan penyerakan, regim dwi-laser digunakan dalam menjana pembolehalih dwi-laser MLFL. Keluaran laser selakan mod diubah diskret daripada 1533 nm kepada 1560 nm atau boleh dibuat untuk berayun serentak di kedua-dua regim, dengan itu menghasilkan operasi serakan mod dwi-jarak gelombang. Ini direalisasikan oleh menggulung gentian dalam rongga laser ke dalam jejari yang berbeza 1.60 cm, 1.07 cm dan 0.80 cm masing-masing, menyebabkan kehilangan sisipan masing-masing 0.11 dB, 1.21 dB and 4.20 dB. Selepas itu, lebar denyut yang di hasilkan oleh setiap kes adalah 734 fs, 800 fs dan 1.06 ps, masing-masing. Oleh itu, dengan menggulung gentian kepada jejari yang berbeza, pembolehalih MLFL terhasil di regim jarak gelombang yang berbeza di mana di mana lebar denyut boleh disesuaikan.

Kesimpuannya, kerja penyelidikan ini berjaya mengatasi isu-isu prestasi MLFL di dalam pengurusan penyerakan dan operasi jalur jarak gelombang. Kedua-dua isu bererti dalam jenis MLFL di mana penyelidikan lanjut boleh dibuat dalam mengkaji perbezaan rejim selakan mod denyut gelap, denyut regang dan denyut harmonik.

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS AND SYMBOLS

SESAM	Semiconductor saturable absorber mirror
SA	Saturable absorber
SWCNT	Single wall carbon nanotubes
YDFL	Ytterbium-doped fiber laser
EDFL	Erbium-doped fiber laser
TDFL	Thulium-doped fiber laser
EDF	Erbium-doped fiber
C-band	Commercial wavelength-band
SMF	Single mode fiber
L-band	Long wavelength-band
S-band	Short wavelength-band
GVD	Group velocity dispersion
TBP	Time bandwidth product
SAM	Self-amplitude modulation
CNT	Carbon nanotubes
WDM	Wavelength division multiplexing
OSA	Optical spectrum analyzer
HML	Harmonic mode-locking
$Sech^2$	Secant hyperbolic
TBF	Tunable bandpass filter
FBG	Fiber Bragg grating
AWG	Arrayed waveguide grating
ASE	Amplified spontaneous emission
PC	Polarization controller

SNR	Signal-to-noise ratio
RF	Radio frequency
Q	Quality factor of resonator
Es	Stored energy in resonator
El	Loss energy per resonator cycle
f	Pulse repetition rate
c	Speed of light
n	Refractive index of laser cavity
L	Cavity length
Tr	Cavity round-trip time
I	Laser intensity
N	Total number of locked longitudinal modes
ω	Angular frequency
$\Delta\tau$	Pulse width
$\Delta\nu$	Spectral bandwidth
K	Limitation of TBP
ν	Velocity of wave in vacuum
τ	Propagation time
Vg	Group of Velocity
$\beta2$	GVD coefficient
λ	Operating wavelength
D_λ	Dispersion parameter
n2	Material-dependent coefficients
w	Propagating transverse beam profile of radius
φ	on-axis phase

γ_{SPM}	Product of non-linear coefficient
P	Pulse power
Pp	Peak power
τ_{FWHM}	Pulse duration of full-width at half-maximum
Ep	Pulse Energy
Ns	Soliton period
τ_{ac}	Pulse duration
$\Delta\lambda$	3-dB spectral bandwidth
Eout	Energy of optimum pulse
Pout	Output power

CHAPTER 1

INTRODUCTION

1.1 Overview

In 1960s, first Q-switched mode-locked laser was introduced using a Helium-Neon (HeNe) laser by Hargrove et al. [1]. This laser produces picosecond or femtosecond pulse duration which is modulated by a Q-switched pulse envelope, with pulse repetition rate typically ranging from several hundreds of kilohertz to sub-megahertz. The mode-locked laser plagued by instability-induced Q-switched envelope due to the emission of mode-locked bunches is termed as “Q-switched instabilities”. This continued to be an obstacle until the first demonstration of semiconductor saturable absorber mirror (SESAM) by Keller et al. in 1992 to overcome the Q-switched instabilities phenomenon [2].

A saturable absorber (SA) is used to initiate mode-locked lasers. Solid-state laser, dye laser, and conventional fiber laser are some examples of mode-locked lasers which are assisted by SA to generate ultrashort pulse. As aforementioned, SESAM is an intra-cavity SA which generates self-started stable passively mode-locking of diode-pumped solid-state lasers. SESAM shows excellent performance in terms of its possibility for defect engineering and micro-fabrication growth [3]. Nevertheless, SESAM possesses intrinsic drawbacks such as high fabrication cost, precise alignment technology requirement, complex molecular beam epitaxial growth technique for micro-fabrication and relatively small operation wavelength range of about 10 nm [4, 5]. At this point, frontiers of ultrafast mode-locked lasers are pushed to conventional fiber laser using carbon-based materials.

The advent of inline SA based on carbon-based materials such as graphene [6] and carbon nanotubes [7] has provided a viable alternative for high performance mode-locked fiber lasers. SA employing single wall carbon nanotubes (SWCNT) has fast response time, ultrafast recovery time (~500 fs), low saturable absorption threshold, polarization insensitive, ease of integration into optical system and wide tunable band gap [8-10]. SWCNT possesses direct bandgap depending on the diameter and chirality of nanotube [11]. By mixing SWCNT with different diameter distribution, mode-locked lasers can be initiated [12, 13]. Inline SWCNT-polymer composite films are commonly chosen for fiber lasers as they are compact, inexpensive, and can be easily fabricated. Conventional ultrashort pulse fiber laser integrated with SWCNT-SA is indispensable due to its array of applications in photonics devices, biomedical diagnostics, optical fiber communication and material processing [14-16]. Laser source possessing nanosecond to sub-picosecond pulse width plays significant role in the portfolio of leading laser manufacturers [17]. Rapid pulses allow the generation of high power required for multiple applications without the adverse heat effect typically associated with continuous wave lasers.

The integration of inline SWCNT-based SA with rare-earth-doped fiber gain medium in optical fiber cavity is the simplest method of generating mode-locked laser [4]. The choice of rare earth determines the operating wavelength of fiber laser. For instance, simultaneous pulsed fiber lasers are generated [12], whereby ytterbium-doped fiber laser (YDFL), erbium-doped fiber laser (EDFL) and thulium-doped fiber laser (TDFL) are generated at the operating wavelength of 1 μm, 1.5 μm and 2 μm respectively. Erbium is identified as being an excellent laser platform, which coincides with the low loss window of modern optical fibers thus allowing higher energy generation with lower power consumption.

1.2 Problem Statement

The performance of a conventional mode-locked fiber laser is highly influenced by dispersion. For instance, net anomalous dispersion produces soliton-based mode-locked laser. Contrarily, dissipative soliton-based mode-locked laser is generated due to net normal dispersion. Soliton-based mode-locked laser produces shorter pulse duration, whereas dissipative soliton-based mode-locked laser is more stable with higher signal-to-noise ratio measurement [18]. Before net dispersion is computed, the dispersion effects of fiber connector, optical fiber, SA and contribution from active gain medium employed in laser cavity are taken into consideration. Although the dispersion value from standard optical fiber is widely available, similar situation is not observed for specialty fibers such as Erbium-doped fiber (EDF). Manufacturer-bundled specifications usually exclude the dispersion values thus complicating the task of optimizing dispersion within laser cavity. Combined with the intense focus on novel SA, dispersion effect on mode-locked fiber laser has received little attention from researchers in this area.

In addition, laser tunability is a specific feature of a conventional mode-locked laser. This issue contributes to high interest of research investigations due to its multiple practical applications, particularly in signal processing and optical communication. In conjunction to the development of laser tunability technology, variable optical attenuator [19], and variation of fiber length and fiber type [20, 21] have been proposed to achieve pulse width tunability of a mode-locked laser. However, the first technique is too bulky and costly, whereas the latter technique requires interchanging of different optical fibers with different fiber length within the laser cavity, which complicates the operational procedures of pulsed laser generation.

1.3 Motivation and Objectives

Optimization of dispersion value within laser capability boosts the substantial research efforts to give readers an efficient point of views to seize the knowledge on ultrafast optics. This work would be highly beneficial to provide an understanding on the impact of mode-locking operation under different dispersion characteristics. Besides, the manipulation of cavity loss with simpler design shows the novelty which fulfils the research gap of achieving wavelength switchable mode-locked lasers. In overall, the main objective of this work is to generate a SWCNT-SA based mode-locked fiber laser with optimized length of gain medium, whereby this laser can be shifted flexibly at different operating regions across C-band transmission window by monitoring the cavity loss. Four specific research objectives along the pathway to achieve the main objective include:

1) To design and develop a ring-structured mode-locked EDFL assisted by SWCNT-SA
2) To analyse the impact of different cavity dispersion values on the laser performance
3) To find the optimum cavity length for the proposed mode-locked EDFL
4) To achieve wavelength switchable mode-locked EDFL by managing the cavity loss with fiber spooling method.

1.4 Scope of Research

Figure 1.1 lists the research scope studied in this work which includes:

i. Fiber laser.
   Continuous wave laser is the pre-requisite before a mode-locked laser is generated. The continuous wave laser is generated using an all-fiberized ring-configuration laser setup, which is constructed with several components. An important component for laser generation is gain medium. Among the feasible gain media, a rare-earth medium, EDF is employed in the experiment.
ii. Erbium-doped fiber.
   EDF pumped by a laser source forms an amplifier, which is efficient for laser generation based on amplified stimulated emission. In brief, a signal exceeds lasing threshold power releases more photons when an incoming photon is received by the EDF. These tremendous photons released at the gain medium output forms an intense and coherent laser signal.
iii. Pulsed fiber laser.
   A continuous wave laser is converted into pulsed laser by an SA. An SA absorbs low light intensity due to faster recombination rate than absorption rate, thus transmitting high light intensity. The saturated absorption state is formed by continuous pumping of photons which are then accumulated at the metastable state. In other words, SA strongly absorbs low intensity pulse wings, and weakly absorbs high intensity pulse peak, thus shorten the pulse. After several repetitive round-trip through the SA, the pulse is further shortened until it is limited by the bandwidth (due to time bandwidth product) and dispersion.
iv. Dispersion effect.
   Dispersion limits the pulse width whereby shorter pulse width can be achieved in a net anomalous dispersion mode-locked laser regime. Besides, stable soliton-based mode-locked lasers can only be achieved when net group velocity dispersion approaches zero or anomalous.
v. Cavity loss.
   The cavity loss is contributed by the insertion loss of all optical components within the laser cavity. The intra-cavity loss is manipulated by spooling the fiber into smaller radius in order to induce higher macro-bending loss. The variation in macro-bending loss shifts the operating wavelength of the mode-locked laser across the C-band transmission laser region flexibly without the use of either bulky attenuator or excessive optical fibers. This exploits the research novelty of achieving laser tunability with simpler and cost effective technique.

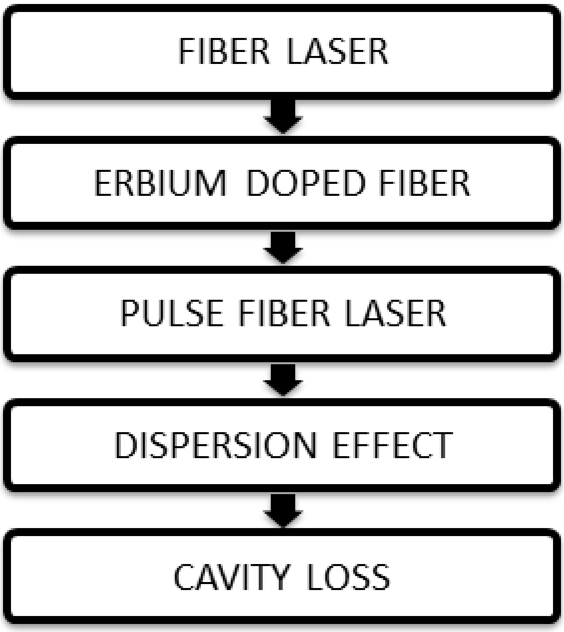

Figure 1.1: **Scope of the research.**

1.5 Thesis Organization

This chapter presents the overview of this thesis. First and foremost, development of ultrafast optics is investigated from technology of early 1960s to the employment of saturable absorber in these recent years. An ultrafast laser is commonly generated by mode-locking regime. The dominant obstacles in designing a mode-locked laser are related to dispersion and laser tunability issues. For instance, the manufacturers usually exclude the dispersion information of optical fibers which obscuring the optimization task. An optimized mode-locked laser is further investigated with its capability of tuning the laser into different operating wavelengths whereby the previous reported techniques are either too bulky or procedural complicated. These problems motivate the research effort on optimization of different dispersion characteristic within a mode-locked laser cavity and a simpler technique is proposed to achieve laser tunability. Therefore, a mode-locked laser is designed with different cavity dispersion characteristics, which are subsequently analyzed in order to optimize the cavity length of the proposed mode-locked EDFL. The mode-locked laser is then examined with fiber spooling process to manipulate the cavity loss in order to achieve laser tunablity. In short, this work covers five research scopes including fiber laser, EDF, pulsed fiber laser, dispersion effect and cavity loss.

The literature review of this work is described in Chapter 2. There are three main parts being reviewed, including fiber laser, mode-locking techniques and ultrafast pulse laser. Q-switching and mode-locking are techniques to generate pulsed fiber laser. In comparison to Q-switched laser, mode-locked laser has higher pulse repetition rate, narrower pulse width and broader spectral bandwidth at the cost of lower pulse energy. Mode-locking laser is generated either by active or passive approaches. In active mode-locking, an external driven modulator synchronizes the acoustic wave to produce short pulse. On the other hand, short pulse is produced in passive mode-locking using a nonlinear medium, such as a saturable absorber. A saturable absorber is characterized with negligible loss when high light intensities or energies are applied. Self-amplitude modulation is induced when saturable absorber interacts with a modulated self-started short pulse to convert continuous wave laser to pulsed laser. This pulsed laser is commonly ultrafast ranging from picoseconds to femtoseconds. In ultrafast optics, the primary concern is the pulse width, which is transform-limited to its spectral bandwidth by time bandwidth product. Group velocity dispersion determines the dispersion regime of the mode-locked laser, whereby net anomalous dispersion is required to achieve stable soliton pulse. Soliton is stable against a variety of distortions by balancing mutual effect of group velocity dispersion and Kerr nonlinearity. Based on the critical review of former works, conventional soliton-based mode-locked EDFL is mostly generated by sandwich-structured SWCNT-SA. This promotes the research opportunity of exploring mode-locked laser with different SA structure such as microfiber-SA.

Chapter 3 demonstrates the dispersion managed ultrashort pulse mode-locked EDFL. A ring-configuration mode-locked EDFL resonator is designed and developed. A section of 5 m and 10 m Lucent HP980 EDF is employed respectively as the gain medium for laser generation. Dispersion variation within the laser cavity is realized by cutback method in order to study the impact of dispersion towards the performance of mode-locked fiber laser. A section of SMF-28 is stripped away with 1 m interval along the cutback method to optimize the laser cavity with two different EDF lengths, which is then observed thoroughly in order to obtain the shortest pulse duration. As a result, the dispersion within the laser cavity is optimized by balancing the sum of SMF-28 with anomalous dispersion coefficient of -17 ps/(nm.km) at 1550 nm and the normal-dispersed Lucent HP980 EDF.

Chapter 4 proposes a new technique to tune the operating wavelength of mode-locked laser across low loss C-band window. The wavelength shifting is controlled by gradual adjustment of fiber spooling into numerous radii. The small fiber spooling radius corresponds to higher macro-bending loss. The mode-locked laser is shifted towards shorter wavelength by possessing smaller net gain cross section of EDF with higher total cavity loss. In this proposal, three wavelength regions are targeted: discrete lasing at 1533 nm and 1560 nm, and simultaneous lasing at both operating regions. The shifting in the wavelength regions is predictably resulting in different pulse durations since the 3-dB spectral bandwidth is varied due to variable output spectrum profile, as these two parameters are inversely-proportional related. This design serves as an alternative way to replace the bulky attenuator and abundant employment of different optical fiber with numerous lengths. Therefore, a simpler technique to generate a high beam quality and reliable wavelength switchable mode-locked laser is developed which is of high interest in numerous research applications involving wavelength tunability and pulse width tunability.

Chapter 5 concludes the research work of this thesis in overall. Four research objectives are fulfilled with the demonstration of experimental approaches. This study brainstorms the research area into four future developments. The optimization of dispersion within the proposed mode-locked EDFL employing Lucent HP980 EDF as the gain medium can be extended to different rare-earth doped EDF, such as Ga-EDF and Zr-EDF, in which the dispersion of these gain media is usually excluded by fiber manufacturers. Subsequently, a new configuration of laser cavity is developed in order to generate two distinct ultrafast mode-locked laser outputs using only a saturable absorber, which significantly reduces the operational cost. The mode-locked lasers are designed at different wavelength, such as S-band and L-band regions by incorporating specific gain media. Last but not least, the mode-locked laser is applied for supercontinuum generation, whereby the investigation of nonlinearity effect of optical fiber with large birefringence remains an interesting topic, which is yet to be explored.

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LIST OF PUBLICATIONS

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