HARMONIC FEMTOSECOND FIBER LASER BASED ON SUPERCONTINUUM GENERATION WITH CARBON NANOTUBES SATURABLE ABSORBER

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"*Allah (Providers) light (to) heaven and earth. The parable of His Light is like a hole that niches wherein a lamp is. The lamp is in a glass (and) the glass is as if the stars (glowing) like pearls, which kindled from a tree blessing, (namely) the olive tree, neither of the east (a) nor in the west (her), whose oil (only) almost luminous, though fire scarce touched. Light upon light (layered), Allah guides to His light whom He pleases, and Allah sets forth parables for man-kind, and Allah knows all things.* "

(An-Nur : 35)

Dedicated to

My beloved abah and mama and also my family that help me through this journey

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ABSTRACT

An ultrashort pulse fiber laser has been proposed due to the problem of bulky size and high cost of the Titanium Sapphire laser and other commercial ultrashort pulse fiber lasers. Thus, this study focused on the development of a robust, compact and stable femtosecond mode-locked fiber laser via optical telecommunication components. This laser was designed to have a high repetition rate (80 - 100 MHz) and average output power (30 - 50 mW), and also a narrow pulse width (< 100 fs) which are crucial for a laser source used in all-fiber terahertz time domain spectroscopy system. A short cavity was needed in order to get a high repetition rate while the effect of optical dispersion in the cavity was included in order to produce a narrow pulse width. This design employed a passive mode-locked technique with a carbon nanotube thin film as the saturable absorber. Initially, a diode laser of 980 nm wavelength was used as a pumping source and a 0.4 m long of highly erbium-doped fiber with 110 dB/m peak absorption at wavelength of 1530 nm was utilised as a gain medium. Then, in order to achieve the desired parameters, the pump power was increased to raise the repetition rate of the pulse laser and a supercontinuum generation technique was adopted to compress the pulse width. The preliminary results of the designed laser show a fundamental repetition rate of 67.8 MHz at mode-locking threshold pump power of 63.5 mW. The average output power and pulse width obtained are 0.77 mW and 410 fs respectively. The increment of pump power to 104.2 mW significantly increased the fundamental repetition rate to 193.5 MHz which corresponds to the 3rd order harmonic and compressed the pulse width to 70 fs. The average output power after compressing the pulse width is 4.27 mW. As the conclusion, two of the targeted parameters of the laser have been successfully attained. This design however has not been able to produce the targeted average output power and to operate with the desired parameters simultaneously.

ABSTRAK

Satu laser gentian denyut ultra-pendek telah dicadangkan kerana masalah berhubung dengan saiz yang besar dan kos yang tinggi bagi laser Titanium Sapphire dan laser gentian denyut ultra-pendek komersial yang lain. Oleh itu, kajian ini menjurus kepada pembangunan laser gentian mod terkunci femto-saat yang tahan lasak, lebih kecil dan stabil menggunakan komponen telekomunikasi optik. Laser ini direka bentuk untuk mempunyai kadar pengulangan (80 - 100 MHz) dan kuasa output purata (30 - 50 mW) yang tinggi, dan juga lebar denyut yang sempit (< 100 fs) kesemuanya penting bagi satu sumber laser yang digunakan dalam sistem spektroskopi domain masa terahertz semua gentian. Satu rongga pendek diperlukan untuk menghasilkan kadar pengulangan yang tinggi manakala kesan penyebaran optik dalam rongga diambil kira untuk menghasilkan lebar denyut sempit. Reka bentuk ini menggunakan teknik mod terkunci pasif dengan filem nipis karbon bertiub nano sebagai penyerap boleh tepu. Pada mulanya, laser diod dengan panjang gelombang 980 nm digunakan sebagai sumber pam dan gentian berdop erbium sepanjang 0.4 m dengan penyerapan puncak 110 dB/m pada panjang gelombang 1530 nm digunakan sebagai medium gandaan. Kemudian, untuk mencapai parameter yang dikehendaki, kuasa pam dinaikkan untuk meningkatkan kadar pengulangan denyut laser dan teknik penjanaan ultra-selanjar telah digunakan untuk memampatkan lebar denyut. Hasil awal laser yang direka bentuk menunjukkan kadar pengulangan asas ialah 67.8 MHz pada kuasa ambang pam mod terkunci 63.5 mW. Kuasa output purata dan lebar denyut yang diperoleh masing-masing ialah 0.77 mW dan 410 fs. Peningkatan kuasa pam kepada 104.2 mW telah meningkatkan kadar pengulangan asas dengan ketara kepada 193.5 MHz yang dipadankan dengan harmonik tertib ketiga dan memampatkan lebar denyut kepada 70 fs. Sebagai kesimpulannya dua parameter laser yang disasarkan telah berjaya diperolehi. Reka bentuk ini bagaimanapun tidak dapat menghasilkan kuasa output purata yang disasarkan dan beroperasi dengan parameter yang diinginkan secara serentak.

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LIST OF SYMBOLS

ω - Angular frequency

τ - Pulse width

σ - Absorption cross-section

ν - Phase velocity

$\alpha(i)$ - Nonlinear absorption coefficient

$\alpha\ (I)$ - Intensity dependent

$q(t)$ - Fast saturable absorber

f - Pulse repetition rate

$T(I)$, - Optical transmittance

$R(t)$ - Reflection

E_P - Pulse energy

τ_P - Pulse duration

λ_o - Central wavelength

λ - Wavelength

$\Delta\lambda$ - Spectral bandwidth at full width half maximum

Yb^{3+} - Ytterbium ions

Tm^{3+} - Thulium ions

T - Cavity period

Sa^{3+} - Samarium ions

Pr^{3+} - Praseodymium ions

Nd^{3+} - Neodymium ions

N - Concentration of carbon nanotubes saturable absorber

n - Refractive index of the medium

n - Harmonic order

l - Gain medium length

L - Total cavity length

k - Constant factor

Ho^{3+} - Holmium ions

$\hbar$ - Photon

Er^{3+} - Erbium ions

E - Energy

D - Dispersion parameter

c - Speed of light

$A(t)$ - Effective area

$\Delta\tau$ - Temporal pulse width at full width half maximum

$\Delta\nu$ - Spectral pulse width at full width half maximum

ΔE - Change of output pulse energy

ΔP - Power ratio

Δf_{Res} - Resolution bandwidth of the spectrum analyser in Hz

Δf - Frequency width

τ_{rex} - Energy relaxation time

τ_{SA} - Recovery time

τ_{AC} - Pulse width autocorrelation

λ_D - Zero dispersion wavelength

$\gamma_0(\nu)$ - Signal gain coefficient

β_2 - Group velocity dispersion coefficient

α_{ns} - Non-saturation absorption

α_0 - Linear absorption

q_0 - Non-saturated saturable loss

l_0 - Linear non-saturable loss

V_g - Group velocity

P_{SA} - Saturation power

P_P - Peak power

I_{sat} - Saturation intensity

$G_0(\nu)$ - Signal gain

E_{SA} - Saturation energy

D_{AC} - Deconvolution factor

ω_l - Laser frequency

LIST OF ABBREVIATIONS

AFM	-	Atomic force microscopy
ASE	-	Amplified spontaneous emission
BFA	-	Brillouin fiber amplifier
BNC	-	Bayonet Neill–Concelman
CNT	-	Carbon nanotubes
CW	-	Continuous wave
dBm	-	Decibel per milliwatts
dB/m	-	Decibel per meter
DCF	-	Dispersion compensating fiber
DSO	-	Digital storage oscilloscope
EDF	-	Erbium-doped fiber
EDFL	-	Erbium-doped fiber laser
EMI	-	Electromagnetic interference
FC/PC	-	Flat physical contact
FELs	-	Free electron laser
FWHM	-	Full width at half maximum
FWM	-	Four wave mixing
GVD	-	Group velocity dispersion
HNLF	-	Highly nonlinear fiber
LD	-	Laser diode
L-I	-	Light– Current
mA	-	Milliampere
MHz	-	Megahertz
MI	-	Modulation instability
MLFL	-	Mode-locked fiber laser

mW	-	Milliwatts
NA	-	Numerical aperture
NIR	-	Near-infrared
NPR	-	Nonlinear polarization rotation
OPM	-	Optical power meter
OSA	-	Optical spectrum analyser
PC	-	Personal computer
PD	-	Photo diode
PDL	-	Polarization dependent loss
POP	-	Plane of polarization
QHML	-	Quasi-harmonic mode-locked
RBM	-	Radial breathing mode
RFA	-	Raman fiber amplifier
RFSA	-	Radio frequency spectrum analyser
SA-CNT	-	Carbon nanotubes saturable absorber
SBR	-	Saturable Bragg reflector
SC	-	Supercontinuum
SCG	-	Supercontinuum generation
SESAM	-	Semiconductor saturable absorber mirror
SMA	-	Sub-miniature version A
SNR	-	Signal-to-noise ratio
SOA	-	Semiconductor optical amplifier
SPM	-	Self-phase modulation
SPM	-	Scanning probe microscopes
SRS	-	Stimulated Raman scattering
SSFS	-	Soliton self-frequency shift
SWCNT	-	Single-walled carbon nanotubes
TDS	-	Time-domain spectroscopy
TEC	-	Thermoelectric cooler
THz	-	Terahertz
THz-TDS	-	Terahertz time-domain spectroscopy
TLS	-	Tunable laser source

TOD	-	Third order dispersion
TPA	-	Two photon absorption
VOA	-	Variable optical attenuator
WDM	-	Wavelength division multiplexer
XPM	-	Cross-phase modulation
ZDW	-	Zero dispersion wavelength

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The laser invention in 1960 had sparked the interest in optical physics, and among the arising research field is ultrafast optics fields where generations of nanosecond (10^{-9}) pulses by the first mode-locked laser is initiated. Yet, the generation of ultrafast pulses are remained as the active research subject thus led to the variety of designs including assembly of time scale pulses of femtosecond (10^{-15}). The short pulse laser system had explored through a wide range of areas including scientific research field, medical and industrial applications. This system with ultrashort pulses had been studied in time resolves studies in chemistry, two photon and CARS spectroscopy and microscopy, optical coherence tomography and terahertz generation. In the medical field, the applications that related to short laser pulses are including eye laser surgery and dentist drill. For industry applications, ultrafast lasers are implied in micro-machining and marking [1].

Generally, for terahertz generation, multi-wavelengths lasers such as dual-wavelength lasers with closely spaced lines are required, either as a high-power continuous wave (CW) or pulse laser sources. One of the developments of the femtosecond laser that mostly been constructed for terahertz generation is Titanium Sapphire femtosecond lasers [2–5]. A solid state laser known as Titanium Sapphire

(Ti: sapphire) have operating wavelength at spectral range of 0.75 µm to 1.0 µm. This laser is most extensively utilised as an ultrafast optical source due to the large bandwidth and superior thermal properties of the laser. However, this laser came with bulky, complicated system, and very expensive. Therefore, due to this problem, a compact and cost-effective laser source should be considered, and the idea of femtosecond laser generation using fiber had been carried out. Fiber based sources commonly used for telecommunications in the wavelength region of 1.5 µm. Erbium doped fiber (EDF) is desirable as a gain medium in this region due to the development of wavelength division multiplexed systems (WDMs). Femtosecond fiber lasers offer several advantages over bulk solid-state lasers, including greater stability, reduced alignment sensitivity, and compact design [6–8]. Furthermore, fiber lasers are efficient and these qualities make short pulse fiber lasers more attractive.

Femtosecond fiber laser can also be achieved using electro-optics components integrate with the laser cavity which is known as the active approach. However, this approach introduces high loss and increased complexity to the setup. As an alternative, passive mode-locking is preferable compared to the active counterpart due to the compactness, simplicity, and reliability of a saturable absorber (SA) in the laser cavity design. Recently, single wall carbon nanotubes (CNTs) have emerged as a promising SA due to their low saturation intensity, sub-picosecond recovery time, and environmental robustness [9]. By contrast, the predominant SAs, for example, semiconductor saturable mirrors, are limited by their narrow tuning range for only a few nanometers (nm), high cost in the fabrication process and packaging [10]. Fabrication of these materials can be challenging in the 1.3–1.5 µm region for optical communication purposes [11,12].

Therefore, this work focused on the development of ultrashort femtosecond fiber laser pulses used as a laser source for terahertz wave generations. Research on the development of a robust, compact and stable of the laser is performed.

1.2 Problem Statement

Currently, fiber lasers are the alternative way to solid state lasers as they offer ultrashort pulse duration with good consistency, compactness, alignment free and excellent beam quality. Common techniques for prompting the mode-locked operation of a fiber laser is nonlinear polarization evolution (NPE) and semiconductor saturable absorber mirror (SESAM). Both techniques had limitations as they suffer from high-intensity losses, limited operation bandwidth and a complex and expensive fabrication process. Therefore, to overcome the issues, unconventional and new saturable absorbers such as carbon nanotubes, graphene and few-layer molybdenum disulfide (MoS_2) had been employed since they are broadband and cost-effective. Then, high repetition rate pulses in mode locked fiber lasers could be achieved either by shortening the cavity in centimeter scale or employed harmonic mode locking (HML). Synthesized carbon nanotubes microfiber saturable absorber in the laser cavity had generated pulse width of a passively mode-locked fiber laser. However, by compressing the designed passively mode-locked fiber laser using nonlinear dispersive media, it can narrow the pulse width and gives a superbly broadens spectrum known as supercontinuum generation. Thus, this believes can gives high repetition rate pulses in mode locked fiber lasers with narrow pulse width.

1.3 Research Objectives

The main aim of this study is to develop a femtosecond fiber laser system with simple cavity design. This work is measured based on the performance of the designed fiber laser, where it is divided into four sequence objectives given as follows;

1. To characterise the erbium-doped fiber (EDF) as the gain medium and modes of the laser operation.
2. To attain ultra-short pulse fiber laser via the passively mode-locked technique using carbon nanotubes saturable absorber.
3. To determine the high pulse repetition rate ~80 to 100 MHz with harmonic mode-locked methods.
4. To narrow the pulse width from picosecond into femtosecond by using supercontinuum generation technique.

1.4 Scope of Study

This work is conducted to develop a femtosecond fiber laser and the scope is focused on using a passively mode-locking technique. It is preferable to the active counterpart owing to the compactness, simplicity, and reliability of a saturable absorber (SA) in the laser cavity design. A carbon nanotubes thin film is employed as a promising saturable absorber due to the low saturation intensity, sub-picosecond recovery time, and environmental robustness. A laser diode of InGaAs at the wavelength of 980 nm is efficiently pumping for compact and reliable of laser source at wavelength 1.5 -1.6 µm. Erbium doped fiber (EDF) gain medium operating in the telecommunication wavelength region of 1.55 µm is utilised because it has the simplest approach to designing fiber laser system, and potential to deliver high-quality mode-locked pulses. The gain medium has two different absorption peak power of 16 dB/m with length fixed at 300 cm and 110 dB/m with length varied from 30 cm, 40 cm, to 50 cm. These gain medium lengths are depending on the total cavity length for laser generation. A hundred meters of highly nonlinear fiber is employed as dispersive media for pulse narrowing thru supercontinuum generation due to its zero dispersion wavelengths at 1568 nm, which corresponds to the region of injected mode-locked erbium doped fiber laser (ML-EDFL).

1.5 Significances of Study

Generation of the femtosecond fiber laser had facilitated in improving the laser technology and move away from Titanium; Sapphire solid state laser into compact pulse fiber laser. The primary contributions of this study are occupying the demands of low-cost compact fiber laser as a source of all fiber system terahertz time domain spectroscopy. Through this study, it will benefit to the other researchers in understanding and construct the femtosecond fiber laser step by step. Researchers may vary the technique used for femtosecond fiber laser generation and also improvise using novel theory and method.

1.6 Thesis Structure and Organization

The thesis outline has begun with the introduction to the work in Chapter 1. Divide into several subtopics, the study frameworks are discussed through the problem statements, followed by objectives of the research. Then, scopes of study applied are stated in detail and contributions of this study are identified in the subtopic of significance of the study.

In Chapter 2, the theoretical aspects of this work are highlighted, including the theoretical background of pulse propagation in optical fibers, rate equation of erbium doped fiber (EDF) as the gain medium, mode operation of the laser; continuous wave and pulse wave. Also, possible techniques of pulse generations include; Q-switching, mode-locking and Q-switched mode locking. Most focus is on passively mode locking since the objective is the mode locked generation using this technique. This chapter also concisely introduced with theoretical equations and the essential parameters of the mode locked output characterization.

Chapter 3 introduces the optical instrument or components utilised in this work. Optical properties, including pump laser diode, Erbium doped fiber absorption properties, carbon nanotubes saturable absorber characterization method based on a literature review, and setup for a series of the experiment are graphically explained and presented in this chapter.

The experimental results taken based on the presented setup in chapter 3 and data analyses are covered in Chapter 4. This chapter starts with a basic characterization of pump laser diode, then different length of Erbium doped fiber which acts as a gain medium with different absorption are analysed. The output performance of the constructed simple ring cavity of Erbium doped fiber laser (EDFL) with different length and Erbium-doped concentration is analysed and discussed. Afterward, the characterization of the pulse wave laser generated by inserting the carbon nanotubes saturable absorber known as a passively mode-locking generation is obtained and discussed. To generate a high repetition rate of the mode-locked laser, harmonic mode locking at a particular pump power is observed. Further development of the femtosecond fiber laser, the EDFL based carbon nanotubes saturable absorber is demonstrated as a pulse source for supercontinuum (SC) generation, and 100 m of highly nonlinear fiber (HNLF) is being required as the nonlinear medium.

Chapter 5 summarized all the results and discussions on the generation of the ultrashort pulse fiber laser. The outlook and aim of this work are again highlighted. The problems and limitation occurred during the research work are discussed as well as the future work needed to overcome the problems are suggested.

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