UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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THULIUM-DOPED FIBER AS GAIN MEDIUM AND SATURABLE ABSORBER FOR PULSED FIBER LASERS

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DECLARATION

I declare that this thesis entitled “Thulium-doped Fiber as Gain Medium and Saturable Absorber for Pulsed Fiber Lasers” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………………

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electronic Engineering.

Signature : …………………………
Name : ………………………...
Date : …………………………

DEDICATION

To the great mentor, Sulaiman Wadi Harun from University of Malaya

ABSTRACT

The study focuses on developing and demonstrating fiber laser applications using newly developed thulium-doped fiber (TDF). TDF functions as two different devices in this study. Firstly, TDF is use as gain medium to increase gain significantly at 2 μm wavelength. It specifically functions at that region due to pumped thulium ions reaction force an emission at 2 μm region. The energy transition of ${}^3F_4 \rightarrow {}^3H_6$ can be obtained by pumping TDF with 802 nm and 1552 nm source. Secondly, TDF is use as passive saturable absorber. Passive saturable absorber works to generate self-starting pulse. This happen when TDF absorb lights that going through it until accumulated energy reached saturation level. At saturation level, accumulated energy will discharge and forcing pulse to occur. Instead of TDF, carbon nanotubes (CNT) are also used as saturable absorber in generating pulse. Pulse, or commonly known as ultra-fast pulse are divided into two; Q-switched pulse and mode-locked pulse. Q-switched pulse is a short, high energy pulse from a laser modulating through the intracavity losses and the quality (Q) factor of the ring laser. The microsecond pulse usually occurs in kHz frequency. High pulse energy will force the frequency of the pulse to increase, while the pulses become thinner. Mode-locked pulse is an ultra-short pulses from laser cavity with duration of nanosecond to femtosecond. Due to some circumstances, mode-locked pulse can only appears in a very low power laser cavity. As a result, no stimulated emission will occur since loss is higher than the power. In most cases, mode-locked pulse has a fixed frequency and pulse width depending on the cavity, even the power is changed.

ABSTRAK

Kajian ini tertumpu untuk membangunkan dan mendemonstrasikan aplikasi laser gentian menggunakan gentian berdopkan thulium (TDF) baharu. TDF berfungsi sebagai dua peranti berbeza di dalam kajian ini. Pertamanya, TDF digunakan sebagai medium gandaan bagi meningkatkan gandaan secara mendadak di jarak gelombang 2 µm. Ia berfungsi pada panjang gelombang itu disebabkan oleh ion thulium yang dipam bertindak balas dan menghasilkan sinaran dalam lingkungan 2 µm. Peralihan tenaga $^3F_4 \rightarrow {}^3H_6$ *boleh berlaku apabila TDF dipam oleh sumber 802 nm dan 1552 nm. Keduanya, TDF digunakan sebagai penyerap boleh tepu pasif. Penyerap boleh tepu pasif berfungsi bagi menghasilkan denyut mula kendiri. Ini berlaku apabila TDF menyerap cahaya yang melaluinya sehingga tenaga itu berkumpul dan mencapai takat tepu. Pada takat tepu, tenaga yang terkumpul itu akan dinyahcas, memaksa denyut untuk terjadi. Selain TDF, tiub nano karbon (CNT) juga digunakan sebagai penyerap boleh tepu dalam penghasilan denyut. Denyut, atau biasa dikenali sebagai denyut teramat laju terbahagi kepada dua; denyut Q-suis dan denyut mod kekunci. Denyut Q-suis ialah denyut pendek, bertenaga tinggi daripada laser yang bergerak melalui kehilangan dalam kaviti dan kesan faktor kualiti (Q) pada gegelung laser. Denyut mikro saat biasanya berlaku dalam frekuensi kHz. Denyut berkuasa tinggi memaksa frekuensi denyut itu meningkat, dalam masa yang sama denyut akan menjadi semakin nipis. Denyut mod kekunci ialah denyut teramat pendek daripada kaviti laser dengan durasi nano saat hingga femto saat. Dalam beberapa keadaan, denyut mod kekunci hanya akan berlaku pada kadar kuasa yang amat rendah pada kaviti laser. Ini menyebabkan tiada sinaran terangsang akibat daripada kehilangan yang tinggi berbanding kuasa. Kebanyakkannya, denyut mod kekunci mempunyai frekuensi dan lebar denyut yang tetap bergantung pada kaviti, walaupun kuasanya diubah.*

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μ	-	micro
ASE	-	amplified spontaneous emission
c	-	centi
CO_2	-	carbon dioxide
CNT	-	carbon nanotubes
CPA	-	chirped pulse amplification
CW	-	continuous wave
dB	-	decibel
DIAL	-	differential absorption LIDAR
EDF	-	erbium-doped fiber
EDFL	-	EDF laser
EM	-	electromagenetic
Er	-	erbium
Er^{3+}	-	high concentration Er
EYDF	-	erbium ytterbium co-doped fiber
EYDFL	-	EYDF laser
FWHM	-	full-width at half maximum
G	-	giga
GVD	-	group velocity dispersion
g	-	gram
Hz	-	hertz

J - joule

k - kilo

l - liter

LIDAR - light detection and ranging

M - mega

m - meter

- mili

mol - mole

MWCNT - multi-walled CNT

n - nano

Nd:YAG - neodymium-doped yttrium aluminium garnet

Nd:YVO$_4$ - neodymium-doped yttrium orthovanadate

NOLM - nonlinear optical loop mirrors

NPR - nonlinear polarization rotation

OSA - optical spectrum analyser

OSNR - optical SNR

PC - polarization controller

PVA - polyvinyl alcholol

Q - quality

RBM - radial breathing mode

RF - radio frequency

rpm - rotation per minute

s - second

SA - saturable absorber

SDS - sodium dodecyl sulphate

SNR	-	signal to noise ratio
SPM	-	self-phase modulation
SWCNT	-	single-walled CNT
SESAM	-	semiconductor saturable absorber
TDF	-	thulium-doped fiber
TDFL	-	TDF laser
Tm	-	thulium
Tm^{3+}	-	high concentration Tm
V	-	volt
W	-	watt
WDM	-	wavelength division multiplexer

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CHAPTER 1

INTRODUCTION

1.1 The Evolution of Fiber Laser

A promising alternative to the conventional solid-state laser systems is the fiber laser due to several advantages such as compact size, high electrical efficiency, superior beam quality and reliability, great output power, lower maintenance, ownership cost, mobility and ruggedness. It was firstly invented by Elias Snitzer in 1963 and the first commercial fiber laser devices appeared on the market in the late 1980s (Snitzer, 1963). These lasers used single-mode diode pumping, emitted a few tens of mW, and attracted users because of their large gains and the feasibility of single-mode continuous-wave (CW) lasing for many transitions of rare-earth ions which is not achievable in the more-usual crystal-laser version. Fiber lasers use a specialized optical fiber doped with rare earth elements such as ytterbium, erbium and thulium as the gain medium. These rare earth elements have many advantages such as simple energy levels, long life time at high level, highly quantum efficiency, and a wide absorption spectrum which finally yield to develop high power fiber laser (Koechner, 2006) for many applications such as industry, communication, military, and etc. The most well-known application of fiber-laser technology is in 1550 nm erbium-doped fiber amplifiers (EDFAs).

Fiber laser evolution continued with the discovery of one of the rare earth material known as ytterbium. When this element is doped with fiber laser, in the 1 µm band it serve as a highly efficient gain medium that can offer high power conversion efficiencies and larger power levels than erbium-doped fiber lasers (EDFLs). Therefore, ytterbium-doped fiber amplifier can provide high power fiber laser that is now used extensively in industrial, medical, military and high quality imaging applications (Limpert et al., 2002, Jeong et al., 2004, Paschotta et al., 1997, Limpert et al., 2004). Recently a great deal of researches on 2-micron laser have been conducted in both solid-state laser and fiber laser field because of its wide applications in medicine, remote sensing, light detection and ranging (LIDAR), range finder, and molecular spectroscopy (Pang et al., 2014, Petros et al., 2014, Westermeier et al., 2014). The 2 micron fiber laser can be achieved using a thulium-doped fiber as the gain medium. The strong absorption by water and the weak absorption by human tissues at 2 μm also nominate it as an ideal wavelength for biological and medical applications including laser angioplasty in the coronary arteries, ophthalmic procedures, arthroscopy, laparoscopic cholecystectomy and refractive surgeries.

1.2 The Demand for Applications

Recently a great deal of researches on 2 micron laser have been conducted in both solid-state laser and fiber laser field because of its wide applications in medicine, remote sensing, LIDAR, range finder, and molecular spectroscopy (Damanhuri et al., 2013, Tao et al., 2013). The strong absorption by water and the weak absorption by human tissues at 2 μm also nominate it as an ideal wavelength for biological and medical applications including laser angioplasty in the coronary arteries, ophthalmic procedures, arthroscopy, laparoscopic cholecystectomy and refractive surgeries. In addition, other features of 2 μm laser such as the lower atmospheric absorption, smaller scattering and "eye-safe" property make the wavelength desirable for material processing, ranging, low altitude wind shear and remote sensing, which includes Doppler LIDAR wind sensing and water vapor profiling by differential absorption LIDAR (DIAL). Such wavelength is also an ideal pump source for mid-infrared optical material.

Likewise, the interest on pulsed fiber lasers is also increasing in recent years for various applications. The pulsed fiber lasers are normally realized based on two approaches; Q-switching and mode locking. Both lasers can be constructed by using various techniques such as passive saturable absorber (SA). SA is an important component in fiber laser especially for generating ultra-short pulse train. It operates by generating a certain optical loss for low intensity light and reduce the loss significantly for high intensity to pass through (Wang et al., 2008).

Q-switching and mode locking ultrafast lasers can be realized using either active or passive techniques. Passive fiber lasers are usually achieved using nonlinear polarization rotation (NPR) (Anyi et al., 2013), semiconductor saturable absorbers (SESAMs) (Luo et al., 2011) and single-walled carbon nanotubes (SWCNTs) (Ismail et al., 2012). Although these approaches are well established, NPR induced lasers tend to be environmentally unstable and do not provide self-starting pulsed operation while SESAMs based lasers have limited operating band. Lasers produced with the use of SWCNTs saturable absorber are known to have ultra-fast recovery time and wide absorption bandwidth. A new member of carbon nanotubes family called multi-walled carbon nanotubes (MWCNTs) (Jusoh et al., 2014, Ahmad et al., 2014) have also captured much attention for nonlinear optics applications as an alternative to SWCNTs. They possess similar characteristics to the SWCNTs but have lower production cost, which is 50% - 80% cheaper than the SWCNT material (Ahmad et al., 2014). Compared to SWCNTs, the MWCNTs have higher mechanical strength, photon absorption per nanotube and better thermal stability due to its higher mass density (Tiu et al., 2014, Ahmed et al., 2015).

The 2 μm laser can be realized using a thulium-doped fiber as the gain medium. The TDF laser (TDFL) was firstly discovered by Hanna et al. in 1988 with a 797 nm dye laser as the pump source (Hanna et al., 1988). Meanwhile, the first 2 μm Q-switched TDFL was carried out in 1990 by acousto-optic modulator (Esterowitz and Stoneman, 1990). The pulsed laser has many potential applications such as in pumping 2-4 μm and medical applications (Scholle et al., 2010). The Q-switched TDFL can be realized by either active or passive techniques. The active Q-switching is based on an active loss modulation with a Q-switcher and thus its pulse repetition rate can be externally controlled. Normally, active Q-switches are mechanical Q-switches, electro-optical Q-switches and acousto-optic Q-switches. Besides that, as an alternative to the active Q-switched laser, the passively Q-switched laser gives low cost, reliable operation without high voltages. In this dissertation, Q-switched 2 micron fiber laser is proposed using low cost MWCNTs based passive saturable absorber. The TDF is also used as a SA for generating nanosecond mode-locked pulse train in erbium-doped fiber laser (EDFL) cavity. Finally, the TDF is once again use as a gain medium in order to design tunable TDFL operating at 2 μm region using stretched fiber Bragg gratings (FBGs).

1.3 Objectives

This work aims to explore the usage of TDF as gain medium and saturable absorber for pulsed fiber lasers. This study embarks on the following objectives:

i. To propose and demonstrate a Q-switched TDFL operating in 2 μm region using a homemade MWCNTs based passive SA as a Q-switcher.
ii. To demonstrate a mode locked EDFLs using TDF as saturable absorber.
iii. To demonstrate a tunable TDFL based on Fiber Bragg grating stretching