DEVELOPMENT OF THULIUM FIBER LASERS OPERATING AT 1.9 MICRON REGION

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In memory of my father Md Zen bin Abu and to my mother Bayak binti Usop

ABSTRACT

This thesis describes a thorough study on a newly developed thulium bismuth co-doped fiber laser (TBDFL) in replace of a conventional thulium-doped fiber laser (TDFL). TDFL normally requires a high threshold pump power and thus cannot be pumped by a low power commercial laser diode. The fiber was fabricated using modified chemical vapour deposition (MCVD) in conjunction with the solution doping process. The experimental results revealed that the newly developed thulium bismuth co-doped fiber (TBDF) requires a comparatively shorter length for 1.9 micron lasing as compared to the conventional thulium-doped fiber (TDF). Both of the 802 nm and 1552 nm pumps can be used to generate lasing for the TBDF. The TBDFL performance is superior to the conventional TDFL with a threshold pump power of 80.1 mW and a slope efficiency of 42.23% at a fiber length of 0.4 m. The superior lasing performance exhibited by the TBDF is due to the selection of suitable fiber parameters, namely the dopants compositions, their relative proportions and the host glass composition. The Q-switched TBDFL is also demonstrated using a simple and low cost multi-walled carbon nanotubes (MWCNT) saturable absorber. It operates at the 1857.8 nm wavelength with a threshold pump power of 106 mW. It is observed that the repetition rate increases almost linearly from 12.84 kHz to 29.48 kHz with an increasing pump power of 106.6 mW to 160 mW. Meanwhile, the pulse width reduces from 9.6 μs to 6.1 μs with the increase in the pump power increases. At the maximum pump power of 160 mW, the maximum pulse energy is obtained at 61.7 nJ.

ABSTRAK

Tesis ini merangkumi kajian terperinci penghasilan laser menggunakan gentian Thulium didopkan bersama Bismuth (TBDFL) sebagai gentian kepada laser yang menggunakan gentian Thulium konvensional (TDFL). Kebiasaannya, TDFL memerlukan kuasa pam ambang yang tinggi dan tidak boleh dipam oleh diod laser komersial yang berkuasa rendah. Gentian tersebut telah dihasilkan menggunakan pengubahsuaian pemendapan wap kimia (MCVD) bersama dengan proses pengedopan cecair. Keputusan eksperimen menunjukkan bahawa TBDF yang dihasilkan memerlukan ukuran gentian yang lebih pendek berbanding gentian Thulium konvensional (TDF) bagi penghasilan laser pada 1.9 mikron. Kedua-dua pam pada panjang gelombang 802 nm dan 1552 nm boleh digunakan untuk menghasilkan laser bagi TBDF. Prestasi TBDFL adalah jauh lebih baik berbanding TDFL konvensional dengan kuasa pam ambang dan cerun kecekapan sebanyak 80.1 mW dan 42.23 %, masing-masing, bagi gentian sepanjang 0.4 m. Prestasi TBDF yang amat baik ini adalah disebabkan oleh pemilihan parameter gentian yang sesuai, iaitu bahan komposisi dopants, perkadaran relatif bahan dan komposisi kaca tuan rumah. Q-Switched TBDFL juga berjaya dihasilkan menggunakan penyerap saturable nanotube karbon perkepelbagaian sisi (MWCNT) yang ringkas dan berkos rendah. Ia beroperasi pada panjang gelombang 1857.8 nm dengan kuasa pam ambang sebanyak 106 mW. Melalui pemerhatian, kenaikan kadar pengulangan adalah hampir linear dari 12.84 kHz kepada 29.48 kHz dengan peningkatan kuasa pam dari 106.6 mW kepada 160 mW. Lebar denyut mengalami pengurangan daripada 9.6 μs kepada 6.1 μs seiring dengan kenaikan kuasa pam. Tenaga nadi maksimum yang diperolehi pada kuasa pam maksimum (160 mW) ialah 61.7 nJ.

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APPROVAL

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Electrical and Electronic Engineering)**. The members of the Supervisory Committee were as follows.

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LIST OF ABBREVIATIONS

SYMBOLS

ASE	Amplified Spontaneous Emission
Bi	Bismuth
CW	Continuous Wave
CNT	Carbon Nanotube
Er	Erbium
FBG	Fiber Bragg Grating
FWHM	Full Width Half Maximum
GaAlAs	Gallium Aluminium Arsenide
GSA	Graphene Saturable Absorber
Ho	Holmium
LD	Laser Diode
MCVD	Modified Chemical Vapor Deposition
MWCNT	Multi-walled Carbon Nanotube
Nd	Neodyium
OPM	Optical Power Meter (OPM)
OSA	Optical Spectrum Analyzer
PC	Polarisation Controller
PD	Photo-detector
Pr	Praseodymium
PVA	Polyvinyl Alcohol
SA	Saturable Absorber
SMF	Single Mode Fiber

SPM	Self-Phase Modulation
SWCNT	Single-walled Carbon Nanotubes
TBDF	Thulium Bismuth co-doped Fiber
TBDFL	Thulium Bismuth co-doped Fiber Laser
TDF	Thulium Doped Fiber
TDFL	Thulium Doped Fiber Laser
Tm	Thulium
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation
Yb	Ytterbium

CHAPTER 1

INTRODUCTION

1.1 Background

Light Amplification by the Stimulated Emission of Radiation (LASER) has been used in many popular culture science fictions and other futuristic weapon in the movies. In the reality, lasers have produced powerful sources of photons that have been used in many industrial applications. The laser is one of the most significant technologies of the late twentieth century. It was first invented in 1958 and since then many new technologies based on lasers were established for various applications (Schawlow & Townes, 1958). The idea of laser originated from Albert Einstein's theory on 'Stimulated Emission' in which, when it encounters a photon, matter may lose energy by emitting the exact same photon. As a result, the amplification of light is achievable under condition of population inversion. In addition to the gain media, another essential device is the optical cavity (resonator) in which the light can circulate and get amplified. As long as the gain is larger than the loss, the power of the light in the laser cavity quickly rises. Significant power output is thus only achievable above the so-called laser threshold, the power of which the small-signal gain is just sufficient to compensate the cavity loss.

The first laser action was demonstrated by Theodore H. Maiman in 1960 at Hughes Research Laboratories in Malibu, California using 2 cm long ruby (chromium in corundum) cylinder as the active gain medium (Maiman, 1960). A flash lamp was used to pump the ruby rod in generating laser at 694 nm. However, Gordon Gould was the first person to use the word 'laser'. Interestingly, in 1962 the first diode laser was developed by Robert N. Hall at the General Electric (Hall, Fenner, Kingsley, Soltys, & Carlson, 1962) (Feng et al., 2006). It was a gallium-arsenide p-n junction emitting at the wavelength of 842 nm. The development of a powerful and efficient diode laser has been essential for fiber laser development due to their employment as pump sources. Meanwhile, the first visible wavelength laser diode was demonstrated by Nick Holonyak Jr later in 1962 (Held, 2008). Since then laser physics has always been driven by a genuinely scientific quest to extend existing limits such as higher power, shorter pulse, narrower linewidth and new wavelength. Over the last fifty years, developments in the laser field have occurred at a rapid pace. Many new lasers have been discovered, each with its own special properties and applications, showing dramatic improvement in their cost, performance or practicality.

Recently a great deal of researches on 2 μm 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, military applications and molecular spectroscopy (Wu, Yao, Zong, & Jiang, 2007) (Harun et al., 2012) (Geng, Wu, Jiang, & Yu, 2007). 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 lasers 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.

The 2 µm laser can be realized using a Thulium doped fiber (TDF) 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. Meanwhile, the first 2 µm Q-switched TDFL was carried out in 1993 by an acousto-optic modulator (Myslinski et al., 1993). The pulsed laser has many potential applications such as in 2 - 4 µm pumping (Creeden et al., 2008) (Godard, 2007) and medical applications (Esterowitz & Pinto, 1993). 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 thesis, Q-switched 2 micron fiber lasers are proposed using a passive saturable absorber (SA) using TDF or Thulium Bismuth co-doped fiber (TBDF) as the gain medium.

1.2 Motivation

The growing interest in various laser applications with emissions within the two micron spectral region motivated this research work. The 2 micron fiber lasers can be achieved using a TDF as the gain medium. The TDFL operates within the 1800 nm to 2100 nm wavelength region, which falls into the eye-safer category of lasers. This gives it potential advantages over 1 μm lasers especially for industrial and military applications. For instance, these lasers can be deployed in military laser weapon systems to replace 1 micron laser systems, which can cause serious eye hazard since their beams are invisible and the power can be imaged onto the retina. To date, pulsed laser systems may be used either for direct applications such LIDAR and range finding, or for conversion into the mid-IR for countermeasures, remote sensing, and spectroscopy applications.

In order to optimise the lifetime of $^3F_4$ and $^3H_5$ levels in TDF, co-doping with other elements such as Erbium, Ytterbium, Terbium and Bismuth has been attempted (Librantz, Gomes, Pairier, Ribeiro, & Messaddeq, 2008) (Braud et al., 2000). For instance, co-doping with Ytterbium is reported by Braud in which energy transfer from Ytterbium to Thulium reduces the effective lifetime of $^3F_4$ level (Braud et al., 2000). In this work, lasing at 1900 nm region is experimentally demonstrated using a TBDF as the gain medium for the first time. In addition to the cross relaxation process between thulium ions, this fiber provides effective energy transfer channels from bismuth to thulium, resulting in higher amplification efficiency in this region. The performance of the proposed TBDFL is then compared with a TDFL, which was obtained by using a commercial TDF.

1.3 Problem Statements

Compared to their 1 μm and 1.55 μm counterparts, 2 μm laser sources are more favourable pump sources for mid-IR generation for several reasons. First, quantum defects are lower at 2 μm, yielding higher quantum efficiency for generating mid-IR wavelengths. Second, many nonlinear crystals used for mid-IR generation are not transparent or have a much higher absorption at pump wavelengths shorter than 2 pm. Third, dispersion is too high at shorter wavelengths in some nonlinear crystals to achieve phase-matching for nonlinear parametric processes. And finally, 2 μm fibers can have larger core sizes and higher nonlinear thresholds, enabling higher-power 2 μm lasers and consequently, higher-power mid-IR output.

To date, many different glass host materials have been used to fabricate TDF for 2 μm laser operation, including silica and non-silica glass fibers such as germanate- and tellurite-based types. It is well known that the doping concentration of rare-earth ions in silica fiber is limited due to the intrinsic glass network structure. So that, various approaches have been developed to increase the doping concentration including co-doping with B_2O_3. The highest doping level in silica glass is limited to approximately 2 wt%. Due to the limited Thulium doping concentration, quantum efficiency of Thulium doped silica fiber lasers is also limited. The doped fiber has improved mechanical strength and better compatibility with silica fiber than other multicomponent glass fibers for more robust fusion splicing. Here, a new fiber so-called Thulium Bismuth co-doped fiber (TBDF) is developed to overcome the limitation of the conventional TDF. The conventional TDFL normally requires a high threshold pump power and thus cannot be pumped by a low power commercial laser diode.

In passive Q-switching using saturable absorption, CNTs are known to provide distinct advantages in their ultra-fast recovery time and wide absorption bandwidth compared to their semiconductor-based counterparts. Recently, many works have been reported on the use of CNT-based saturable absorbers for the implementation of Q-switched lasers. Most of these works focus on 1550 nm and 1060 nm applications using an erbium or ytterbium doped fiber gain media, respectively (Harun et al., 2012). There is still a lack of research work in 2 micron region.

Recently, a new member of carbon nanotubes family called multi-walled carbon nanotubes (MWCNTs) have also attracted much attention for nonlinear optics applications due to their lower production cost, which is 50% - 80% cheaper than the SWCNT material introduced in this thesis. Compared with SWCNTs, the MWCNTs have higher mechanical strength, photon absorption per nanotube and better thermal stability due to its higher mass density. In this thesis, the use of MWCNTs for SA in fiber laser is demonstrated for the first time.

1.4 Objectives

The principal objective of this thesis and its chapter are to develop efficient 2 micron fiber lasers operating in both continuous wave (CW) and Q-switched pulse schemes. A Thulium-Bismuth co-doped fiber laser (TBDFL) is proposed and developed to generate an efficient laser within the 1.8 ~ 2 μm region. In addition to the cross relaxation process between thulium ions, TBDF provides effective energy transfer channels from bismuth to thulium, resulting in higher amplification efficiency at this region. To achieve the main objective, few secondary objectives have been proposed to guide the research direction, i.e.:

- To analyze a 2 µm laser emission using a commercial TDF as the gain medium.
- To investigate and compare the performance of TBDFL with the TDFL in terms of slope efficiency and threshold pump power.
- To generate a room temperature all-fiber dual-wavelength Thulium Bismuth co-doped fiber laser (TBDFL) operating in the 1900 nm region using a single fiber Bragg Grating (FBG) in a ring configuration.
- To develop Q-switched 2 micron fiber lasers using both commercial TDF and TBDF as the gain medium in conjunction with a passive saturable absorber.
- To evaluate both graphene and multi-walled carbon nanotubes saturable absorbers in producing energetic Q-switched pulses in the 2 micron wavelength region.

1.5 Research Methodology

These researches are carried out based on a standard research methodology. Before commencing any experiments, a literature review and understanding of operating principles of the TDFL and TBDFL are undertaken. After the review is completed, the development of Thulium Bismuth doped fiber (TBDF) was done with the assistance from our collaborator from Central Glass and Ceramic Research Institute (CGCRI), India. The lasing experiments were then carried out to compare the performance characteristic between the newly developed TBDF and the commercial TDF. The main characteristics such as ASE, slope efficiency and threshold are investigated.

Pulsed operation in Q-switching is achieved by using a homemade saturable absorption. A saturable is an optical component in which absorption decline when the incoming light intensity is raised. Two types of saturable absorbers (SAs); graphene and MWCNT were developed and used in this study. In fabricating a graphene based SA, the first step is to produce graphene flakes using electrochemical exfoliation process**.** The graphene flakes are processed and mixed with various polymer solutions to fabricate a graphene film. In the case of MWCNT, the carbon nanotubes powder is added with functionalizer solution so that it can be dissolved in water. The carbon nanotubes composite is also mixed with the polymer solution to fabricate the film. The SA is fabricated by cutting a small part of the prepared film by approximately 2×2 mm^2 and sandwiching it between two FC/PC fiber connectors. Apart from that, the performance evolution of the SA such as Raman spectroscopy is investigated. The Q-switched fiber lasers were then constructed by using either a commercial TDF or the TBDF as the gain medium. The lasing and Q-switching performances are investigated and then compared. Fig. 1.1 shows the flow chart of our research methodology.

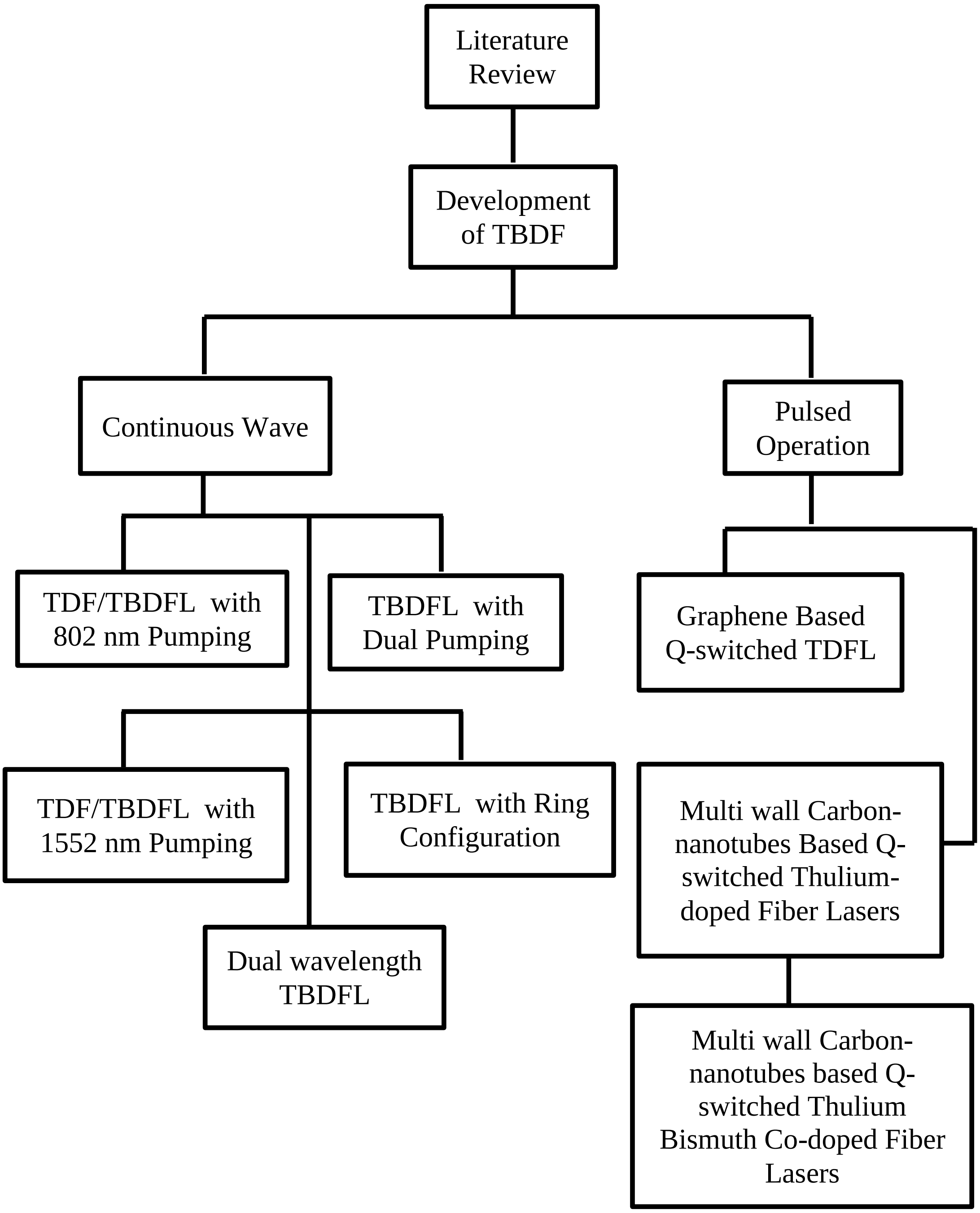

Fig 1.1: Research methodologies for the thesis

1.6 Thesis Overview

In this thesis, we focus on developing a 2 micron fiber laser operating in both CW and Q-switching modes using two different gain media; commercial TDF and the newly developed TBDF. This thesis is arranged into five chapters, where the background on fiber laser, introduction on the TDFL, motivation and objective of the proposed work are described in this chapter.

Chapter 2 is devoted to some fundamental and literature review of Thulium fiber laser, the discussion on pulse generation based on Q-switching as well as the potential of graphene and carbon nanotubes as a saturable absorber.

Chapter 3 presents an experimental investigation of the Thulium Bismuth co-doped fiber laser (TBDFL) characteristics and all fiber dual-wavelength TBDFL generation at room temperature. The performance comparison between TBDFL and TDFL is also demonstrated and discussed in this chapter.

Chapter 4 focuses on demonstrating stable passive Q-switched 2 micron fiber lasers using both the commercial TDF and TBDF as the gain medium. In this work, both multi-walled carbon nanotubes (MWCNT) and multi-layer graphene film based saturable absorber were used to realize a stable Q-switched fiber laser operating at 1900 nm region. The performance of these lasers is also compared for two different pumping schemes; 802 nm and 1552 nm.