

YTTERBIUM DOPED AND CO-DOPED Q-SWITCHED FIBER LASERS
UTILIZING PASSIVE SATURABLE ABSORBERS

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To my beloved parents,

Kasim bin Abbas and Munirah binti Ahmad,

and my family!

Thank you for all your supports, pray and blessing.

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ABSTRACT

Q-switched 2 micron fiber laser is a new area of research. Q-switching using passive technique by means of saturable absorber is quite rare in the research work. A stable passive Q-switched lasers operating at 1 micron, 1.5 micron and 2 micron wavelength regions were demonstrated using Ytterbium doped, Erbium-Ytterbium co-doped and Thulium-Ytterbium co-doped fibers, respectively as the gain medium. Carbon nanotubes and graphene based saturable absorbers (SA) were explored as the passive Q-switcher in the proposed lasers. The Q-switched Ytterbium doped fiber laser (YDFL) operating at 1060.2 nm was realized using a multi-walled carbon nanotubes / PEO saturable absorber. The repetition rate of the laser were varied from 7.92 kHz to 24.27 kHz by varying the pump power from 53.42 mW to 65.72 mW. At the 59.55 mW pump power, the lowest pulse width and the highest pulse energy were obtained at 12.18 μ s and 143.5 nJ, respectively. The YDFL was then used to demonstrate an all-fiber based MOPA system where the maximum pulse energy of 354.2 nJ was obtained at the maximum cladding pump power of 800 mW. The Q-switching of Erbium-Ytterbium fiber laser (EYFL) was demonstrated using a multi-layer graphene film based saturable absorber. The proposed laser was operated at 1532.5 nm and self-started at pump threshold of 44 mW to produce Q-switching pulse with repetition rate of 12.33 kHz and pulse width of 9.36 μ s. At the maximum pump power of 78 mW, the maximum pulse energy of 5.8 nJ and the shortest pulse duration of 2.68 μ s were achieved. Multi-wavelength and Q-switched fiber lasers were also demonstrated based on the newly developed octagonal shape double-clad Thulium-Ytterbium fiber (TYF) operating at 2 micron wavelength region. By incorporating the home-made multi-wall carbon nanotubes saturable absorber (MWCNTs SA) in the ring cavity, a Q-switching pulse train operating at 1983.4 nm was successfully demonstrated. By varying the 905 nm multimode pump power from 1570 to 1606 mW, the pulse repetition rate increased from 27.4 to 37.8 kHz and the pulse width fluctuated from 3.8 μ s to 4.9 μ s. The maximum pulse energy of 10.6 nJ was obtained at pump power of 1570 mW. Besides showing good Q-switching performance, the proposed saturable absorbers are easy to fabricate and inexpensive.

ABSTRAK

Pengsuisan-Q 2 mikron laser gentian adalah satu bidang penyelidikan yang baharu. Pengsuisan-Q menggunakan teknik pasif dengan kaedah penyerap tepu masih lagi jarang dilakukan dalam kerja penyelidikan. Sebuah laser pasif pengsuisan-Q yang stabil beroperasi di dalam kawasan panjang gelombang 1 mikron, 1.5 mikron dan 2 mikron ditunjukkan dengan menggunakan gentian terdop Ytterbium, ko-dop Erbium-Ytterbium dan ko-dop Thulium-Ytterbium, masing-masing sebagai ruang penggandaan. Penyerap tepu (SA) berasaskan karbon tiub nanodan graphene diterokai sebagai pengsuis-Q pasif dalam laser yang dicadangkan. Pengsuisan-Q laser gentian terdop Ytterbium (YDFL) yang beroperasi pada 1060.2 nm telah dilaksanakan dengan menggunakan karbon tiub nanodinding berlapis / penyerap tepu PEO. Kadar ulangan laser boleh berubah daripada 7.92 kHz hingga 24.27 kHz dengan mengubah kuasa pam daripada 53.42 mW hingga 65.72 mW. Pada kuasa pam 59.55 mW, lebar denyut paling rendah dan tenaga denyut tertinggi masing-masing diperoleh pada 12.18 μ s dan 143.5 nJ. YDFL kemudiannya digunakan dalam menunjukkan sistem MOPA berasaskan semua gentian di mana tenaga denyut maksimum 354.2 nJ diperoleh bila kuasa maksimum pam pelapisan pada 800 mW. Pengsuisan-Q dalam laser gentian Erbium-Ytterbium (EYFL) telah ditunjukkan dengan menggunakan SA berasaskan filem graphene pelbagai lapisan. Laser yang dicadangkan beroperasi pada 1532.5 nm dan mulai pada ambang pam 44 mW untuk menghasilkan denyut pengsuisan-Q dengan kadar ulangan 12.33 kHz dan lebar denyut 9.36 μ s. Pada kuasa pam maksimum 78 mW, tenaga denyut maksimum 5.8 nJ dan tempoh denyut terpendek 2.68 μ s dicapai. Pelbagai panjang gelombang dan pengsuisan-Q laser gentian juga telah ditunjukkan berdasarkan dua dinding gentian Thulium-Ytterbium (TYF) berbentuk segi lapan yang baharu dibangunkan yang beroperasi pada kawasan panjang gelombang 2 mikron. Dengan menggabungkan penyerap tepu karbon tiub nano dinding berlapis (MWCNTs SA) buatan sendiri dalam rongga cincin, siri denyut pengsuisan-Q beroperasi pada 1983.4 nm telah berjaya dipamerkan. Dengan mengubah kuasa pam pelbagai mod 905 nm daripada 1570 sehingga 1606 mW, kadar ulangan denyut bertambah daripada 27.4 sehingga 37.8 kHz dan turun naik lebar denyut sekitar 4.9 μ s kepada 3.8 μ s. Tenaga denyut maksimum pada 10.6 nJ diperoleh pada kuasa pam 1570 mW. Selain menunjukkan prestasi pengsuisan-Q yang baik, penyerap tepu yang dicadangkan adalah mudah untuk dicipta dan murah.

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LIST OF SYMBOLS

n	–	refractive index
r	–	radial coordinate
θ	–	angle of incidence
NA	–	numerical aperture
L	–	cavity length
β	–	amplification coefficient
k	–	Boltzmann constant
ΔN	–	population inversion
P	–	power
$R1$	–	mirror 1
$R2$	–	mirror 2
δo	–	round trip loss
η	–	slope efficiency
λ	–	wavelength
NF	–	noise figure
h	–	Plank constant
ν	–	frequency
G	–	gain

CHAPTER 1

INTRODUCTION

1.1 Background

A promising alternative to the conventional solid-state laser systems is the fiber laser with some advantages like compact size, high electrical efficiency, superior beam quality and reliability, great output power, lower maintenance, low ownership cost, mobility and ruggedness. It was firstly invented by Elias Snitzer in 1963 [1,2] and in late 1980s, fiber laser devices appeared in the market. These lasers emitted a few tens of milliwatts because they used single-mode diode pump. In addition, these lasers have large gain and it is possible to realise single-mode continuous-wave (CW) lasing operation using many transitions of lanthanide ions not realisable in the more-usual semiconductor material laser version. The active medium are specialized optical fibers doped with rare earth elements such as Ytterbium, Erbium and Thulium [3–5]. These rare earth elements have many advantages such as simple energy levels, long life time at high level, high quantum efficiency, and wide absorption spectrum which is good to develop high power fiber lasers for many applications such as industry, communication, military, and etc [6–9]. The most famous application of fiber-laser technology is in 1550 nm erbium-doped fiber amplifiers (EDFAs) [10].

In the late 1980s, double clad fiber was developed for high power fiber laser applications [11]. This fiber has a core, which is doped with active dopant material

that functions to guide and amplify the signal light. The pump light guided by the inner cladding is used to provide the energy needed to allow amplification in the core of the fiber. In order to confine the light into the core, the outer cladding must have lowest refractive index compared to the core. Double clad fiber [12–15] is better rather than standard single clad fiber because it has low dispersion over a much wider wavelength range.

Fiber laser progress continued with the discovery of one of the rare earth material named Ytterbium. When this element is doped with fiber laser, in the 1 μm band it work as a highly efficient gain medium that can compromise 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 broadly in industrial, medical, military and high quality imaging applications. In addition, Ytterbium has acquired a prominent role in the form of the trivalent ion Yb^{3+} , which is used as a laser-active dopant in a variety of host materials. Particularly, wide attentions have been attracted by Yb^{3+} doped double clad fiber lasers. They have been extensively studied for some causes [16]. First, the wide bandwidth of Yb^{3+} doped fiber lasers which is larger than 1550 nm, make it well adapted for tunable laser application. Second, Yb ion has a quasi-three-level energy system that manage high efficiency because it can avoid any pump or signal excited-state absorption (ESA). Third, they allow for a low cost commercially existing laser diode as the pump source because Yb ion gifts a large absorption cross-section around 980 nm.

However, other than emission at 1 μm band, ytterbium also can be used as the sensitized element for erbium and thulium for the emission band at 1.5 μm and 2.0 μm . These bands would also give several industry applications such as in area of communication, remote sensing and biomedical applications. Yb^{3+} has the benefit to present only two multiplets which is the ground-state level $^2\text{F}_{7/2}$ and the excited-state level $^2\text{F}_{5/2}$, corresponding the highly efficiency absorption in the range of 900 nm-1000 nm. For efficient absorption emitting around 980 nm of commercially available laser diodes, this certain energy level structure is highly required and they avoid any

unwanted excited-state absorption under intense optical pumping. Based on the above consideration, ytterbium co-doping in erbium and thulium doped fiber is investigated and become an interest area of research. In this work, various fiber lasers operating in both continuous wave and Q-switching mode are proposed and demonstrated using a ytterbium doped and co-doped fibers as the gain medium.

1.2 Problem Statement

Lasers operating in CW or quasi-CW mode have limited optical output power, depending on the maximum available pump power. The laser peak output power can be improved by concentrating the available energy in a single, short optical pulse, or in a periodic sequence of optical pulses as in a Q-switched fiber laser. Q-switching is a method that allows the generation of an optical pulse at repetition rate in kHz region and pulse width in a range of microseconds to nanoseconds by sudden switching of the cavity loss. Compared to CW fiber lasers, various applications, such as remote sensing, medicine, range finding and industrial processing are practically useful in high peak power Q-switched fiber lasers [17–20]. Although Q-switching does not produce the ultra-short pulses as in mode-locked lasers, it has several advantages such as inexpensive, easy to implement and efficient in extracting energy stored in upper laser level.

The Q-switched fiber laser can be achieved using either active or passive techniques. Active Q-switching is realised by introducing an electro-optic or an acoustic-optic modulator into the cavity. On the other hand, to simplify the cavity design and exclude the requirement for external Q-switching electronics, there is a convenient technique which is passive Q-switching by means of saturable absorbers (SAs). Different kinds of saturable absorbers (SAs), such as the transition metal-doped crystals [21–23] and semiconductor materials [24], have been applied to realize Q-switched fiber lasers especially for operation in 1550 nm region. However, extra alignment devices, such as mirrors, lens or U-bench units have to be applied when they

are used in the laser cavity. This may increase the insertion loss and the complexity of the laser cavity.

Recently carbon nanotubes and graphene are normally used as the SA for the Q-switched fiber lasers [25–27]. These SAs are a comparatively simple and cost-effective alternative compared to semiconductor SA (SESAM). This is because of their inherent advantages, as well as wide operating bandwidth, good compatibility with optical fibers, fast recovery time and low saturation intensity. On the other hand, due to their relatively big volume, SAs based on semiconductor and crystal cannot be used for an all fiber laser structure. However, most of the current works are focusing on Erbium-doped fiber lasers (EDFLs). There are still a lack of research works on Q-switching in both 1 micron and 2 micron regions. In this work, various types of low cost CNT and graphene based SAs are developed for Q-switching applications in Yb doped and co-doped fiber lasers.

1.3 Research Objectives

The main objective of this research is to design and construct an efficient and low cost Q-switched Ytterbium doped and co-doped fiber lasers operating in 1.0, 1.5 and 2.0 μm regions. This can be achieved by performing the following tasks;

1. To characterize CW and Q-switched fiber laser operating at 1 micron region using Ytterbium doped fiber as the gain medium. Both core and cladding pumping approaches are used in this study.
2. To characterize various types of passive saturable absorber based on multi-walled carbon nanotubes and graphene.
3. To demonstrate a Q-switched Erbium Ytterbium co-doped fiber laser using a multi-layer graphene film based SA.
4. To design a lasing characteristic on the newly developed Thulium Ytterbium co-doped fiber.

5. To demonstrate a Q-switched fiber laser operating at 2 micron region using the TYDF as the gain medium.

1.4 Organization of the Thesis

This thesis is organized into five chapters which comprehensively demonstrate the development of Q-switched fiber lasers operating in 1.0, 1.5 and 2.0 μm region using Ytterbium doped and co-doped fibers as the gain medium. Chapter 1 gives a brief description on the recent development of fiber lasers. The motivation and objective of this study are also highlighted. Chapter 2 furnishes a detailed literature on the basic theory of optical fibers, fiber lasers, Ytterbium fibers and Q-switching are described.

Chapter 3 presents the methodology used in the experimental works. All the components and measuring equipment that used in this work are discussed in details through this section. Chapter 4 presents thorough study on Yb^{3+} doped fiber laser (YDFLs) for both CW and pulse operations. Due to their compactness, low cost, and flexibility, this lasers become very attractive. An enormous range of applications of Yb^{3+} doped fiber laser have been found in in recent years including optical imaging, material processing and fiber communications. A passively Q-switched YDFL is then demonstrated by using multi-walled carbon nanotubes, which is embedded in PEO polymer as saturable absorber. The SA film was prepared by mixing the MWCNTs homogeneous solution into a dilute PEO polymer solution. It is sandwiched between two FC/PC fiber connectors and integrated into the laser cavity to generate a stable Q-switching pulse operating at 1 μm region.

Q-switched Erbium Ytterbium fiber laser (EYFL) operating at 1.5 μm region is demonstrated in Chapter 5 using a multi-layer graphene film based SA. The SA was fabricated by sandwiching a thin graphene film produced via electrochemical

exfoliation technique between two FC fiber connectors. In addition, the amplification characteristic of a double-clad Erbium Ytterbium co-doped fiber (EYDF) under 927 nm multimode pumping are investigated. The EYDF amplifier (EYDFA) combines the multimode pump into the star shape inner cladding EYDF using a multimode combiner.

Chapter 6 aims to develop 2 micron fiber laser using a Thulium Ytterbium co-doped fiber (TYDF) as the gain medium. A 2 micron laser is demonstrated using two types of double-clad TYDF. Both TYDFs are fabricated using a MCVD process in conjunction with solution doping. Chapter 6 also demonstrates multi-wavelength and Q-switched fiber lasers based on the newly developed octagonal shape double-clad TYDF operating at 2 micron region. A homemade MWCNTs SA is used in this experiment. Finally, Chapter 7 summarizes the findings for this PhD work.

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