ERBIUM DOPED FIBER LASERS UTILIZING GADOLINIUM OXIDE, NEODYMIUM OXIDE AND SAMARIUM OXIDE AS PASSIVE SATURABLE ABSORBERS

RABI'ATUL 'ADAWIYAH BINTI MAT YUSOFF

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

SEPTEMBER 2022

DEDICATION

I dedicate this project to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. He has been the source of my strength throughout this program and on His wings only have I soared. This thesis work is also dedicated to my husband, Muhammad Amin and my son, Nuh Iman, who has been a constant source of support and encouragement during the challenges of post-graduate school and life. I am truly thankful for having you in my life. To my father, Mat Yusoff and late mother, Rofiah who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

Thank you. My love for you all can never be quantified. May Allah bless you.

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my supervisor, Dr. Nabilah Kasim, for her continuous support of my PhD study and research, and for her patience, motivation, and enthusiasm. I am also thankful to my external supervisor, Prof. Ir. Dr. Sulaiman Wadi Harun for sharing his immense knowledge and guiding me thoroughly with the right methodology to carry out my research. Both supervisors were very supportive in every aspect that I could not imagined having better advisors and mentors for my PHD study, and for that I am forever thankful.

I also would like to express my appreciation to the Ministry of Higher Education and Universiti Teknologi Malaysia for the financial support under ZAMALAH UTM which allows me to complete my PHD studies. Special thanks to the Photonics Engineering Laboratory at the University of Malaya for providing suitable facilities and equipment throughout my research work.

I am extremely thankful to my husband, Muhammad Amin, and my son, Nuh Iman, for their unconditional love, sacrifices, patience, and continuous support throughout my study. I am forever grateful to my parents, Mat Yusoff and Rofiah, and also my parents-in-law, Saniman and Radiah, for their undying love, never-ending prayers, and consistent moral support in the completion my PHD study. Not to forget, bunch of thanks to my sisters, brothers, and in-law’s family for their enthusiastic support and valuable prayers.

Lastly, millions of thanks to my friends and research colleagues, Farhanah Zulkifli, Afiq Arif, Athiella, Farina Saffa, Haziq Aiman, Farid, Faiznur, Shairah Gafar, Norizan Ahmed, Suziana and many others. Without their support and constant encouragement, I may not have possibly completed my PHD studies. I am very grateful and thankful for every contribution from all of you.

ABSTRACT

Erbium doped fiber laser (EDFL) plays an important role in generating laser in the 1.5-micron region which contributes to many applications such as material processing, optical communication and biomedical. The main goal of this research is to improve the passive technique in generating mode-locked and Q-switched pulsed fiber laser. The passive technique uses a saturable absorber (SA) as a passive optical loss modulator for the creation of pulses inside the laser cavity. Three rare earth oxides (REO) are chosen to be utilised as the saturable absorbers that are Gadolinium Oxide (Gd_2O_3), Neodymium Oxide (Nd_2O_3) and Samarium Oxide (Sm_2O_3). The REO-based SA was fabricated in the form of thin film by mixing it into polyvinyl alcohol (PVA) aqueous solution to produce a free-standing polymer composite SA film. The characterisations of SA films include physical and optical properties. The physical properties were characterised using field emission electron microscopy (FESEM) and energy dispersive X-ray spectroscopy (EDX). The characterisations of optical properties include linear and nonlinear absorptions. The Q-switched pulses were generated by inserting the SA film into the laser cavity. The addition of 100 m single mode fiber (SMF) with group dispersion delay (GVD) of -21.7 ps^2/km into the laser cavity increased its nonlinearity to balance the total cavity dispersion, consequently, promoted the mode-locking action. The performance of pulsed lasers were analysed and discussed in term of the pulsed laser parameters. The mode-locked pulsed laser with Sm_2O_3 SA had successfully generated stable pulses with the minimum pulse width of 3.4 ps. Gd_2O_3 and Nd_2O_3 SA films generated the mode-locked laser pulses with pulse widths of 3.82 ps and 4.62 ps respectively. The Q-switched laser performances acquired using the three SA films also show desirable laser outputs. Based on the performances of Q-switched and mode-locked pulsed lasers, this research was successfully done with less tedious SA preparation and simple laser cavity setup, thus it have a good potential for photonics applications.

ABSTRAK

Laser gentian terdop erbium memainkan peranan penting dalam menjana laser pada rantau 1.5 mikron yang menyumbang dalam banyak aplikasi seperti pemprosesan bahan, komunikasi optik dan bioperubatan. Matlamat utama penyelidikan ini adalah untuk menambah baik teknik pasif dalam menjana laser gentian denyut selakan-mod dan suis-Q. Teknik pasif menggunakan penyerap boleh tepu sebagai pemodulat kehilangan optik pasif untuk penciptaan denyutan di dalam kaviti laser. Tiga nadir bumi oksida telah dipilih untuk digunakan sebagai penyerap boleh tepu iaitu Gadolinium Oksida (Gd_2O_3), Neodinium Oksida (Nd_2O_3) dan Samarium Oksida (Sm_2O_3). Penyerap boleh tepu berasaskan nadir bumi oksida telah difabrikkan dalam bentuk saput nipis dengan mencampurkannya ke dalam larutan berakua alkohol polivinil untuk menghasilkan saput penyerap boleh tepu yang arca bebas komposit polimer. Pencirian saput penyerap boleh tepu merangkumi sifat fizikal dan optikal. Sifat fizikal dicirikan dengan menggunakan mikroskop imbasan elektron pancaran medan dan spektroskopi sinar-X penyebaran tenaga. Pencirian sifat optikal merangkumi penyerapan linear dan tidak linear. Denyutan suis-Q telah dijana dengan memasukkan saput penyerap boleh tepu ke dalam kaviti laser. Penambahan 100 m gentian mod tunggal dengan lengah penyerakan kumpulan sebanyak -21.7 ps^2/km ke dalam kaviti laser meningkatkan ketaklinearan untuk mengimbangi jumlah penyerakan kaviti seterusnya menggalakkan tindakan selakan-mod. Prestasi laser denyut dianalisis dan dibincangkan dari segi parameter-parameter laser denyut. Laser denyut selakan-mod dengan penyerap boleh tepu Sm_2O_3 berjaya menjana denyutan stabil pada lebar denyut minimum 3.4 ps. Gd_2O_3 dan Nd_2O_3 saput penyerap boleh tepu telah menjana laser selakan-mod dengan lebar denyut masing-masing 3.82 ps dan 4.62 ps. Prestasi laser suis-Q diperolehi dengan menggunakan tiga saput penyerap boleh tepu juga menunjukkan keluaran laser yang diinginkan. Berdasarkan prestasi daripada laser denyut suis-Q dan selakan-mod, penyelidikan ini berjaya dilakukan dengan penyediaan penyerap boleh tepu yang kurang rumit dan penyediaan laser kaviti yang ringkas, dengan demikian ia mempunyai potensi yang bagus dalam aplikasi fotonik.

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LIST OF ABBREVIATIONS

ASE	-	Amplified Stimulated Emission
CW	-	Continuous Wave
EDF	-	Erbium Doped Fiber
EDFA	-	Erbium Doped Fiber Amplifier
EDFL	-	Erbium Doped Fiber Laser
EDX	-	Energy Dispersive X-Ray
EM	-	Electromagnetic
FESEM	-	Field Emission Scanning Electron Microscopy
FWHM	-	Full Width at Half Maximum
Gd_2O_3	-	Gadolinium Oxide
GDD	-	Group Dispersion Delay
GVD	-	Group Velocity Dispersion
LASER	-	Light Amplification by Stimulated Emission Of Radiation
LD	-	Laser Diode
Nd_2O_3	-	Neodymium Oxide
NDLR	-	Non-Linear Dispersive Regime
NPR	-	Nonlinear Polarization Rotation
OPM	-	Optical Power Meter
OSA	-	Optical Spectrum Analyzer
PVA	-	Polyvinyl Alcohol
REO	-	Rare Earth Oxide
RF	-	Radio Frequency
SA	-	Saturable Absorber
SAM	-	Self-Amplitude Modulation
Sm_2O_3	-	Samarium Oxide
SMF	-	Single Mode Fiber
SNR	-	Signal To Noise Ratio
SPM	-	Self-Phase Modulation
TBP	-	Time-Band Product
TIR	-	Total Internal Reflection

VOA	-	Variable Optical Attenuator
WDM	-	Wavelength-Division Multiplexer
WLS	-	White Light Source

LIST OF SYMBOLS

Er^{3+}	-	Erbium Ion
n_1	-	Refractive Index
θ_a	-	Acceptance Angle
Q	-	Q-Factor
v_o	-	Central Frequency
W	-	Energy Stored
L	-	Resonator Length
C	-	Speed Of Light
λ_o	-	Central Wavelength
Δt	-	Pulse Duration
P_E	-	Pulse Energy
R_r	-	Repetition Rate
P_p	-	Pulse Width
η	-	Laser Efficiency

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

A fiber laser was firstly demonstrated by Elias Snitzer in 1963 using a Neodymium doped fiber as the gain medium [1]. It took almost another two decades of development before fiber lasers are ready for commercial production. The first fiber laser device was introduced to the market in the late 1980s and this laser was pumped by a single mode laser diode to produce output power at a few tens of milliwatts [2]. Since then, fiber lasers have garnered more interests whereas many developments have been carried out to further improve the laser performance. They have several physical attributes that differentiate them from other class of lasers in term of functionality, performance and practically [3].

Presently, lasers are widely used in many applications for our daily lives. The advances in fiber-optics have revolutionized the laser technology especially in communication and medical fields. Optical fiber technology was conceived as a superior alternative to conventional copper cables in telecommunications applications. The operation and configuration of the laser is much more stable by utilizing a fiber laser. The revolution of fiber laser continued with the deployment of new rare earth elements such as erbium, ytterbium and thulium [6]. The rare earth elements in laser cavity act as an active ion to provide the energy level in the laser system. Erbium ion (Er^{3+}) is one of the important rare earth elements that have attracted many interests from researchers to construct fiber laser operating at 1.5-micron region. Other famous rare earth elements that also attracted researchers are ytterbium and thulium ions which can be used to generate lasers operating at 1-micron and 2-micron region, respectively.

In general, pulse generation can be realized by two approaches: Q-switching and mode locking. Q-switched lasers are based on the modulation of the intracavity loss or Q-factor [7]. During pumping, the Q-factor is lowered to prevent the feedback of the light into the gain medium and thus can induce a population inversion build up. The Q-factor is then rapidly returned to its initial high value to trigger a very fast oscillation build up, which causes the emission of short pulse of light output from the laser. This process can generate high energy pulses. However due to limited photon lifetime within the laser cavity, the repetition rate of the generated pulses is limited to only tens of kHz. Mode-locking, on the other hand, locks the relative phases of the multiple lasing modes within the cavity to generate pulses with a shorter pulse width and higher repetition rate [8]. It is achieved by modulating the loss or gain of the cavity at an integer multiple of the fundamental intermodal frequency spacing to the force of longitudinal modes into a phase coherence. The coherent multiple lasing modes then manifest themselves into a well-defined temporal pulse form.

Q-switched and mode-locked fiber lasers can be accomplished by two basic techniques which are active and passive. The most common used modulators for active technique are electro-optic modulator or rotating mirror by inserting them into a laser cavity. Particularly, the output pulse width from active technique is limited by the speed of the modulator. The pulse shortening in active technique is limited by the speed of externally driving force and become ineffective for very short pulses. This drawback can be overcome by using the passive technique. Passive technique utilized the wave inside the cavity itself instead of using the external driven force to cause a change in some factors through an element which in turn changes the pulse inside. The fundamental principle of passive is originally obtained by modulating the quality factor of laser cavity which can be realized by inserting a saturable absorber (SA).

The SA is a nonlinear material, which is sandwiched in between two fiber ferrules inside an all-fiberized laser configuration. The ideal SA should exhibit wide bandwidth tunability, high optical damage threshold, strong optical properties, and excellent long-term stability. Most of the available materials utilized as SA matches those criteria. However, they may require a complicated synthesizing method to produce a functional SA device. In 2004, Yamashita et al. proposed carbon nanotubes

(CNTs) as SA to generate an ultrafast laser in hybrid erbium-doped fiber laser (EDFL) cavity [9]. The use of CNT as a passive SA revealed the advantages include versatile operational modes (transmission, reflection and bidirectional), ultrafast relaxation time, polarization-independent, and robust SA device. The main drawback of CNT is that is has a low operational bandwidth and thus less favourable for tuneable pulsed laser. Its geometry-dependent wavelength operation contributed to a complicated synthesizing procedure, which leads to the development of other carbon precursors as a SA. Besides CNTs, graphene [10][11], graphene oxide (GO) and reduced graphene oxide (r-GO) [12] were also widely investigated due to their saturable absorption ability and optical nonlinearity. Furthermore, graphene owns outstanding physical properties with ballistic electron mobility, which prevents lattice dislocation to the atom at high temperatures. As opposed to the CNT, graphene possesses faster relaxation time (~100 fs) and wider operational bandwidth, which was attributed to the zero bandgap nature of this semi-metal [12].

On the other hand, few other 2-dimensional (2D) materials were also used as a SA such as black phosphorus (BPs) [13][14], transition-metal dichalcogenides (TMDs) [15], topological insulators (TIs) [16], bismuthene [17], and MXene [18]. Those 2Ds' mimic graphene in terms of physical and optical properties with ultrafast carrier dynamics, wideband saturable absorption, and high electron mobility. Due to the excellent second-order susceptibility, TMDs such as molybdenum disulfide [19] and tungsten disulfide [20], are widely used as a SA in a broad near-infrared region. They beat graphene, which possesses a very weak second-order nonlinearity that eventually limits the pulse performance in the laser cavity [21]. In 2015, Chen et al. [22] demonstrated mechanically exfoliated BPs as a functional SA device to generate Q-switched and mode-locked pulses in erbium-doped fiber laser (EDFL). BPs own a layer-dependent direct bandgap, which was from 0.3 eV (bulk) to 2 eV (monolayer), in contrast to the TMDs with an indirect bandgap, thus require bandgap alteration for the implementation as SA in the near-infrared laser generation. However, BPs are very sensitive to the environment causing the saturable absorption property to diminish after the exposure of BPs to air for a few hours.

Recently, bismuthene [23] and MXene [24] were introduced as a functional SA for pulses generation in 1.55 micron region. Bismuthene is believed to own a promising electronic-transport and enhanced long term-stability, huge improvement to BPs. The nontrivial bandgap (~0.55 eV) of this allotrope makes it efficient for photonic and optoelectronic applications in a broad electromagnetic spectrum from ultraviolet to near-infrared [25]. In the meantime, few works utilized MXene as a SA in a broad near-infrared region ranging from 1 micron meter to 2 micron meter region [26]. The 2D-metal carbides/nitrides are attractive since they own a broad optical response, high electron mobility, and high optical transparency [27]. In addition, their optical properties were amazing, including high optical damage tolerance, strong switching capability, and effective absorption coefficient for ultrafast laser [28]. Despite their excellent optical and physical properties, those 2D-materials needed complex preparation methods to be implemented as a SA device in a near-infrared laser cavity. Therefore, newly prepared SA material with excellent optical properties and ease of preparation must be invented.

In this research work, there are three new SAs were selected based on rare earth oxide materials which are Gadolinium Oxide (Gd_2O_3), Neodymium Oxide (Nd_2O_3) and Samarium Oxide (Sm_2O_3) to generate Q-switched and mode-locked pulses in erbium doped fiber laser (EDFL) cavities. All these materials are capable of operating in 1.55 μm wavelength regions based on their characterization. These materials have been embedded into polyvinyl alcohol (PVA) polymer so that they can easily integrated into a laser cavity to act as SA. Based on the research had been carried out, these three new materials have a good potential to work in the 1.55-micron region.

1.2 Problem Statement

Generation of Q-switched and mode-locked pulses have been widely explored and reported for the past few decades. Currently, fiber lasers are the most preferable alternative way to solid state lasers as they offer simpler and reliable. As stated in background of the study, there are two main approaches: active and passive method to achieve Q-switching and mode-locking. The latter is normally preferable as it utilized an all-fiberized and compact laser cavity [29]. In contrast to active method, which uses an electrical signal to trigger the pulse, the passive approach is simpler with relatively compact, stable, and cheap setup. Therefore, it has been widely explored in Q-switched and mode-locked fiber lasers. Various type of nano material such as single-walled carbon nanotubes (SWCNTs) [30][31] and graphene [32] have been largely explored for passively generating pulses. SWCNTs material is easier to be prepared but its absorption depends on its tube sizes thus limits its performance since the absorption determines the operation bandwidth. Graphene was widely used for pulse generation since it has wider absorption range. However, it has zero bandgap structure, which limits its optoelectronic applications. Other 2D materials such as black phosphorus [33], transition metal dichalcoganides [34][35] and topology insulator [36] have also engrossed many interest in recent years for pulse generation in infra-red region. More recently, lead sulphite (PbS) nano particles [37] and Antimonene [38] have also been employed as Q-switcher in mid infrared region. Nickel oxide (NiO) and titanium oxide (TiO_2) which belongs to the transition metal oxide (TMO) family also were proposed as functional SA [39] [40].

Despite many efforts in exploring new materials, rare earth oxide (REO) materials-based SA for the generation of Q-switching and mode-locking pulses are rarely being investigated. Recently, lutetium oxide (Lu_2O_3) [41][42], Europium Oxide (Eu_2O3) [43] and Scandium Oxide (Sc_2O_3) [44] which belongs to REO family were only proposed as functional SAs. Due to the rarely explored REO materials as SA, three new materials which are gadolinium oxide (Gd_2O_3), neodymium oxide (Nd_2O_3), and samarium oxide (Sm_2O_3) from REO family had been chosen to demonstrate as SA for generating Q-switched and mode-locked pulses. The research was carried out based on objectives discussed in the next topic due to this problem statement.

1.3 Objective of Study

The main goal for this research work is to fabricate new SAs and demonstrate Q-switched and mode-locked fiber lasers operating in 1.55-micron region using the newly proposed SAs, which were prepared using rare earth oxide (REO) materials.

Three new materials are being investigated in this research work which are gadolinium oxide (Gd_2O_3), neodymium oxide (Nd_2O_3), and samarium oxide (Sm_2O_3). The following objectives have been established to guide this research work towards achieving the main goal;

1. To fabricate the passive SA based on Gd_2O_3, Nd_2O_3 and Sm_2O_3 by mixing with polyvinyl alcohol (PVA) polymer to produce as thin film.
2. To characterize the physical and optical properties of the REO based SAs.
3. To demonstrate the Q-switched and mode-locked erbium-doped fiber lasers (EDFL) utilizing the passive REO based SAs.
4. To determine the performances of repetition rate, pulse width, output power, pulse energy, peak power, and slope efficiency of EDFL using REO based SAs.

1.4 Scope of Study

The research work aims to demonstrate Q-switched and mode-locked erbium doped fiber lasers utilizing the newly developed passive SAs. The research work begins with the characterization of pump laser, which was then used to excite Erbium ions to generate laser at 1550 nm wavelength region. This laser is based on InGaAs active material and operating in 980 nm wavelength. It is injected into an erbium doped fiber (EDF) to excite the active ions and create the condition of population inversion for generating laser in 1550 nm region via stimulated emission process. In this work, three passive SAs were fabricated based on rare earth oxide materials of neodymium oxide (Nd_2O_3), samarium oxide (Sm_2O_3), and gadolinium oxide (Gd_2O_3). The SAs were fabricated by dispersing the REO powder particles into polyvinyl alcohol (PVA) solution and the film forming was realized based on dry-casting technique. Then, several characterizations were made to examine the physical and optical properties of the fabricated SAs. First, Field Emission Scanning Electron Microscopy (FESEM) is used to characterize the surface morphology. The elemental analysis of SAs were observed by Energy-Dispersive X-ray spectroscopy (EDX) to confirm its elemental composition. Next, the linear absorption profile was measured by using white light source (WLS) ranging from wavelength 700 to 1700 nm. Then, we designed a balanced twin-detector measurement system to investigate the non-linear absorption profile. Afterward, the demonstration of Q-switched and mode-locked EDFL were carried out by sandwiching the SA in between two fiber ferrules and integrated this device inside an all-fiberized laser cavity. Lastly, the performances of EDFL using REO based SAs were characterized in terms of repetition rate, pulse width, output power, pulse energy, peak power, and slope efficiency.

1.5 Significance of Study

Development of pulsed fiber laser utilizing passive saturable absorbers have given many contributions in occupying the demands of low-cost compact fiber laser with simple design of laser cavity, high repetition rate and narrow pulse width. This study would be beneficial to other researcher in understanding the construction of passively Q-switched and mode-locked fiber lasers based rare earth oxide SAs. Step by step with detailed explanations were briefly discussed in this whole thesis structured. Researcher may vary the type of material used in their research work by improvising the use of our techniques. The Q-switched and mode-locked laser sources have attracted considerable attention due to the versatile applications in widespread industry and scientific research areas, such as laser materials processing, remote sensing, range finding, medicine, telecommunications, and nonlinear optics.

1.6 Thesis Structure and Organization

This thesis is organized into five chapters which comprehensively demonstrate the development of passively Q-switched and mode-locked fiber lasers utilizing rare earth oxide based SAs. Chapter 1 briefs an overall introduction of this research work. The problem statement and objectives of this research is highlighted as a guide to the research work. The scope of the study is written in details and the contributions of this study are identified in the subtopic of significance of study.

Chapter 2 briefs the theoretical and the literature review related to this study including the theoretical background of pulse propagation in fiber laser. Also, possible techniques of pulse generation including Q-switching and mode-locking technique. The literature review focuses more on passive Q-switched and mode-locked fiber laser generation since the objective of this research is the generation of pulse laser using this technique. This chapter will also briefly introduce the essential parameters of Q-switched output characterization.

Chapter 3 introduces the methodology used in this research work including the optical component and optical instruments. The research frameworks are also graphically explained in this chapter for comprehensive development of pulse laser generation. The fabrication of saturable absorbers has been discussed in details to utilize in the laser cavity. Three type of saturable absorbers is chosen from rare earth oxide materials which are neodymium oxide (Nd_2O_3), samarium oxide (Sm_2O_3), and gadolinium oxide (Gd_2O_3) to have the optimization in output power. Subsequently, the Q-switched and mode-locked fiber lasers are demonstrated using passive saturable absorbers.

Chapter 4 covers all the analysis data for the whole work. This chapter begins with characterization of pump power for gain medium operating at 1.55-micron region. Then, the step by step of fabrication SAs were visualized and briefly explained in chapter. Afterward, the characterization of saturable absorbers is determined with several parameters such are surface morphology, elemental analysis, linear absorption profile and non-linear absorption profile. Then the output characterization and optimization of Q-switched and mode-locked fiber lasers utilizing using passive saturable absorbers will be discussed in detail in this chapter,

Chapter 5 will summarize all the results and discussions on the passive Q-switched and mode-locked fiber lasers utilizing passive saturable absorbers. The problems and limitation occurred during this research work also are discussed as well as future work needed to overcome the suggested problem.

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LIST OF PUBLICATIONS

Journal with Impact Journal

1. **Yusoff, R. A. M.**, Jafry, A. A. A., Kasim, N., Zulkipli, N. F., Samsamnun, F. S. M., Yasin, M., & Harun, S. W. (2020). Q-switched and mode-locked erbium-doped fiber laser using gadolinium oxide as saturable absorber. *Optical Fiber Technology,* 57. **(Q2, IF:2.53)**

2. Ramlan, N. A. A., **Yusoff, R. A. M**., Kasim, N., Jafry, A. A. A., Aziz, M. S., & Johari, A. R. (2021). A 1.0-µm pulsed generation in ytterbium-doped fiber laser with Gadolinium oxide as a saturable absorber. *Optics and Laser Technology,* 141. **(Q1, IF:3.867)**

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