UNIVERSITI PUTRA MALAYSIA

ZINC OXIDE-BASED SATURABLE ABSORBER FOR GENERATION OF PASSIVELY Q-SWITCHED AND MODE-LOCKED ERBIUM- DOPED FIBER LASER

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Zinc Oxide-Based Saturable Absorber for Generation of Passively Q-Switched and Mode-Locked Erbium-Doped Fiber Laser

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By

SYARIFAH ALOYAH BINTI SYED HUSIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

August 2018

This work is dedicated to:

My parents: Syed Husin Bin Syed Hamid and Sarifah Radzah Binti syed Hussin

My Brothers: Sy Tahir and Sy Hamid

My sisters: Sy Nabila and Sy Asiah

and to all my beloved friends

~May Allah bless them~

Amin

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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SYARIFAH ALOYAH BINTI SYED HUSIN

August 2018

Chairman: Farah Diana Binti Muhammmad, PhD
Faculty: Science

There are two techniques that can be used to generate the mode-locked and Q-switched pulses namely active and passive technique. The passive technique is more preferable compared to the active technique due to its simplicity and easy operation. Passively pulsed fiber laser regimes can be generated by saturable absorber device. However, most of the SA used earlier have some limitation in terms of the optoelectronic properties, making them undesirable for certain optoelectronic applications. Zinc oxide (ZnO), a semiconductor of II-IV group, has a high potential as the saturable absorber (SA) which holds the advantage of easily available and inexpensive. In addition, the high third-nonlinear coefficient and ultrafast recovery time of ZnO also become its some plus points towards suitable and promising candidate as SAs, which could offer another alternative to the existing SA materials. This study introduces two techniques of fabrication of ZnO-based SA for the application in Q-switched and mode-locked fiber laser generation. The first technique is called as the evaporation technique whereby ethanol solution is used to adhere ZnO powder on the surface of a fiber ferrule through the evaporation process. The second technique is called as the ZnO-PDMS polymer composite-clad microfiber whereby the ZnO powder is mixed with the polydimethylsiloxane (PDMS) polymer to be coated around the microfiber. The structural properties of the fabricated ZnO-based SA by both techniques are characterized by Raman spectroscopy, field emission scanning electron microscopy (FESEM) and high power microscopy and their saturable absorption properties are characterized by dual measurement setup. The modulation depth and saturation intensity for the ZnO-based SA by evaporation technique are measured to be 1.7% and 0.0014 $MWcm^{-2}$. On the other hand, the modulation depth and saturation intensity for the ZnO-PDMS polymer composite-clad microfiber are measured to be 6.4% and 4.15 $MWcm^{-2}$ respectively. A Q-switched erbium-doped erbium-doped fiber laser (EDFL) is successfully demonstrated by inserting the ZnO-based SA deposited by the evaporation technique into the laser cavity. Self-started and stable Q-switching is achieved at a low power of 20.34 mW. At the maximum pump power of 48.58 mW, the Q-switched EDFL generates the central wavelength, pulse repetition rate, pulse width, average

output power and pulse energy of 1558.32 nm, 25.93 kHz, 3.65 μs, 0.46 mW and 19.34 nJ respectively. On the other hand, the integration of the ZnO-PDMS polymer composite-clad microfiber into the laser cavity results in mode-locked pulse generation. The mode-locked laser has a central wavelength, 3 dB spectral bandwidth, pulse duration, pulse repetition rate and time-bandwidth product of 1558 nm, 5.02 nm, 1.03 ps, 9.77 MHz and 0.6266 respectively. These results indicate that the proposed ZnO-PDMS polymer composite-clad microfiber could be useful as a simple, low-cost and ultrafast SA device.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENYERAP BOLEH TEPU BERASASKAN ZINK OKSIDA UNTUK PENJANAAN PASIF SUIS-Q DAN MOD BERKUNCI LASER FIBER BERDOP ERBIUM

Oleh

SYARIFAH ALOYAH BINTI SYED HUSIN

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Terdapat dua jenis kaedah yang dapat digunakan untuk menjana denyutan bersuis-Q dan mod-terkunci, iaitu dikenali sebagai kaedah aktif dan pasif. Laser gentian denyut secara pasif adalah lebih baik berbanding dengan laser denyut aktif kerana sistemnya yang ringkas dan operasinya yang mudah. Rejim laser gentian denyut pasif boleh dihasilkan oleh peranti penyerap boleh tepu (SA). Walau bagaimanapun, kebanyakan SA yang digunakan sebelum ini mempunyai had tertentu dari segi sifat optoelektronik, menjadikan ia tidak diperlukan untuk beberapa aplikasi optoelektronik. Zink oksida (ZnO), kumpulan II-IV semikonduktor, mempunyai potensi tinggi sebagai calon penyerap boleh tepu kerana mempunyai kelebihan seperti mudah didapati dan murah. Tambahan pula, ZnO mempunyai pekali tak linear ketiga yang tinggi dan masa pemulihan yang sangat pantas menjadi beberapa mata tambahan ke arah calon yang sesuai dan menjanjikan sebagai SA, yang boleh menawarkan alternatif lain kepada bahan SA yang sedia ada. Kajian ini memperkenalkan dua teknik fabrikasi penyerap boleh tepu berasaskan ZnO untuk aplikasi dalam penjanaan gentian bersuis-Q dan bermod-terkunci. Teknik pertama dipanggil sebagai teknik penyejatan di mana cecair etanol digunakan untuk melekatkan serbuk ZnO pada permukaan hujung gentian optik melalui proses penyejatan. Teknik kedua dipanggil sebagai mikrofiber bersalut komposit polimer ZnO-PDMS di mana serbuk ZnO dicampurkan dengan polimer polydimethylsiloxane (PDMS) untuk disalutkan di keliling gentian optik tirus. Ciri-ciri struktur penyerap boleh tepu berasaskan ZnO yang difabrikasi oleh kedua-dua teknik ini dicirikan oleh spektroskopi Raman, mikroskopi elektron pengimbasan pelepasan medan (FESEM), mikroskop kuasa tinggi dan sifat penyerapan boleh tepu kedua-dua gentian ini dicirikan melalui dwi pengukuran konfigurasi. Kedalaman modulasi dan keamatan ketepuan untuk penyerapan boleh tepu berasaskan ZnO oleh teknik penyejatan diukur menjadi 1.7% and 0.0014 $MWcm^{-2}$ masing-masing. Sebaliknya, kedalaman modulasi dan keamatan ketepuan untuk penyerapan boleh tepu berasaskan selaput polimer ZnO-PDMS gentian mikrofiber diukur sebanyak 6.4% and 4.15 $MWcm^{-2}$ masing-masing. Laser fiber berdop erbium (EDFL) bersuis-Q berjaya didemonstrasikan dengan memasukkan SA berasaskan ZnO yang didepositkan melalui

proses penyejatan ke dalam kaviti laser. Peralihan sendiri dan suis-Q dicapai pada kuasa rendah iaitu 20.30 mW. Pada maksimum kuasa pam iaitu 48.58 mW, EDFL bersuis-Q menjana gelombang pusat, kadar pengulangan denyut, lebar denyutan, purata kuasa output dan tenaga denyutan sebanyak 1558.32 nm, 25.93 kHz, 3.65 µs, 0.46 mW dan 19.34 nJ masing-masing. Sebaliknya, gabungan mikrofiber bersalut komposit polimer ZnO-PDMS ke dalam kaviti laser menghasilkan penjanaan denyutan mod-terkunci. Laser mod-terkunci mempunyai pusat gelombang, jalur lebar 3dB spektrum, tempoh denyutan, kadar pengulangan denyutan, produk jalur lebar masa masing-masing sebanyak 1558 nm, 5.02 nm, 1.03 ps, 9.77 MHz dan 0.6266. Keputusan ini menunjukkan bahawa gentian optik tirus selaput komposit polimer ZnO-PDMS boleh digunakan sebagai gentian penyerapan boleh tepu yang mudah, murah dan sangat pantas.

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I certify that a Thesis Examination Committee has met on 6 August 2018 to conduct the final examination of Syarifah Aloyah binti Syed Husin on her thesis entitled "Zinc Oxide-Based Saturable Absorber for Generation of Passively Q-Switched and Mode-Locked Erbium-Doped Fiber Laser" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

SA	Saturable Absorber
EDFL	Erbium Doped Fiber Laser
ZnO	Zinc Oxide
TBP	Time bandwidth product
CNT	Carbon nanotube
PDMS	Polydimethylsiloxane
FESEM	Field Emission Scanning Electron Microscope
SMF	Single mode fiber
IMG	index matching gel
WDM	Wavelength division multiplexer
SMFF	Single mode fiber ferrule
GVD	Group Velocity Dispersion
TIR	Total Internal Reflection
SNR	Signal-Noise-Ratio
EDF	Erbium doped fiber
LD	Laser diode
PC	Polarizer controller
WDM	Wavelength division multiplexer
EFDA	Erbium doped fiber amplifier
ASE	Amplified spontaneous emission
OPM	Optical Power Meter
Osc	Oscilloscope
RFSA	RF spectrum analyzer
OSA	Optical spectrum analyzer
NDT	nondestructive testing
LASER	Light Amplification by the Stimulated Emission of Radiation
LIDAR	Light detection and ranging
EOM	electro-optic modulator
AOM	acousto-optic
FWHM	Full width at half maximum
NPR	nonlinear polarization rotation
NALM	nonlinear amplifying loop mirror
NPE	nonlinear polarization
NLMS	nonlinear optical loop mirror
2D	Two-Dimensional
SPR	surface plasmon resonance
CVD	Chemical vapor deposition
HOPG	Highly order pyrolytic graphite
DMF	Dimethylformamide
PLD	Pulse Laser Deposition
ITMA	Institute of Advanced Technology
CW	continuous wave

CHAPTER 1

INTRODUCTION

Fiber lasers are lasers which is produced from the gain medium of the optical fiber doped with rare earth ion by pumping source. Erbium ion is one of the rare earth ions apart from the Thulium ion (Tm^{3+}), Ytterbium ion (Yb^{3+}) and neodymium ion (Nd^{3+}), which are commonly used as dopants for rare earth doped fiber. Unlike the other dopant fiber laser, Erbium-doped fiber amplifies the signal in the intracavity as erbium-doped fiber laser (EDFL) within the range of C and L band which is in the wavelength range approximately between 1500 to 1600 nm. The fiber laser can be designed to operate in either continuous wave or pulse mode (Harun et al., 2012).

Most of the researchers are interested in the EDFL for the pulse laser application because it can be operated in the mid-infrared region. Pulsed lasers operating in the C-band (1550 nm) region have attracted great technical attention in recent years because they can be used in many practical applications including laser surgery (Fried et al., 2005), LIDAR (light detection and ranging) (Henderson et al., 1993), free-space communication (Ebrahim-Zadeh et al., 2008), medical diagnostics (Bouma et al., 1993) and gas sensing (McAleavey et al., 1997). Recently, pulsed lasers are essential devices for a variety of applications, such as high speed optical communications, biomedical imaging and material processing (Lee et al., 2013). In general, there are three different modes of laser operation such as continuous wave, mode-locking and Q-switching.

High energy pulse lasing can be generated by the Q-switching operation. Generally, Q-switching is one of the techniques that can be performed to generate the pulse laser by suddenly switching the cavity losses (Loesel et al., 1998). Recently, many researcher are interested in the Q-switched fiber lasers because of their advantages, including high efficiency, flexibility, compactness, and high spatial beam quality (Ahmad et al., 2016c and Tsai et al., 2009). On the other hand, mode-locking is another technique to generate the pulse laser (Lee et al., 2017 and Fernmann et al., 2003). Mode-locking is one of the techniques that can change the continuous wave into ultrashort optical pulse due to the nonlinearity of the optical element (Kuo et al., 2014; Arthurs et al., 1973; Haus et al., 2000 and Haus et al., 1976). In wide application, mode-locked fiber laser can generate high peak power, high repetition rate and ultrashort pulse duration (Rusdi et al., 2017). Mode-locked fiber lasers are powerful sources of ultra-short pulses (Li et al., 2015; Quarterman, 2009 and Oktem et al., 2010).

There are two type of the techniques to generate the Q-switched and mode-locked pulse laser which are active and passive Q-switching and mode-locking. The passive technique based on saturable absorbers (SAs) has significant advantages in compactness, simplicity and flexibility of implementation (Nady et al., 2012 and Pan et al., 2007), simple and cost-effective (Ahmad et al., 2016c)without requiring any additional switching electronics device (Ahmad et al., 2016c and Svelto et al., 2010) to generate the pulse laser. Typically passively Q-switched and mode-locked need the optical device such as saturable absorber (SA) within the cavity to produce the pulse laser.

The SA can act as an ultrafast mode-locker or a Q-switch (Lee et.al., 2015) depending on the intracavity optical conditions as well as the characteristics of the laser. It is the optical component in the laser cavity that absorbs the light and at same time introduces the loss for optical pulse formation SAs are significant mechanism to form the optical pulse in the laser cavity. There are two categories of SAs that can be used in the laser system which are the real saturable absorber and the artificial saturable absorber (Wang, 2017). Real saturable absorber includes the materials such as a dye, graphene, carbon nanotube, semiconductor and any type of nanomaterials that can be used as SA. On the other hand, the artificial SA is includes techniques such as nonlinear polarization (NPE) and nonlinear optical loop mirror (NLMS).

In order to generate those modes of fiber laser operation by passive method, appropriate SA required to be interested into the fiber laser cavity. Commonly most of the application in mode-locked lasers can be successfully used in many optoelectronic application. However, most of the SA used earlier are lack of properties for some application such as in electronic application and. For example, according to Jaroslow et al., 2016, graphene is a most attractive for electronic and optoelectronic. However, highly application potential allows to think on integrated electronic devices. The lack of band gap in graphene is particularly unwanted in some electronic applications. Thus, this is required to open the new material that is suitable for the electronic devices application

It has been of great interest lately to explore new materials to act as saturable absorbers (SAs) for passively Q-switched and mode-locked fiber laser. Of these attemps, Zinc-Oxide (ZnO) is one of the new finding for saturable absorber material. ZnO, which is originated from Zn, a semiconductor of the II-IV group has recently garnered great interest in scientific research as a viable material for saturable absorption (Ahmad et al., 2016b; Ahmad et al., 2016e; Wang, 2004 and Aziz et al., 2017) which could offer another alternative to the existing SA materials. ZnO-based SA had firstly demonstrated by Ahmad et al., 2016 for the generation of passively Q-switching EDFL.

In general, there are several methods that have been used to prepare the SA thin film on the facet of the optical fiber ferrules and such as chemical vapor deposition (CVD) (Chang et al., 2010 and Bao et al., 2009) and optically deposition((Martinez et al., 2012; Liu et al., 2014; Luo et al., 2013c and Zhang et al., 2014). All of those methods have their own benefit and advantage to make the thin film. For instance, the optical deposition is deposited by the combination of the optical trapping and heat conventional effects (Martinez et al., 2010). This method is simple and has an effective approached to deposit the thin film of material directly to the core of facet ferrules. However, this method requires the complex and random process to generate the heat and optical trapping during the deposition process the facet ferrules. Other than that, CVD technique is high power energy and a very efficient nanotechnology instrument to obtain the quality and uniformity of the thin film. However, this process is more expensive and requires demand precision for the parameter.

In addition, there are several drawbacks of the sandwiched type SA which are undesirable for specific applications. Since this technique involves physically touching scheme between the core area of the SA material inserted within the path of light propagation, this technique involves a small surface area interaction between the propagating light in the fiber core and the attached ZnO thin film. Thus, the SA will suffer from distortion and optical damage and would also inherently have short nonlinear interaction length (Ahmad et al., 2016e). This would also give a limitation to the thermal damage threshold of the SA due to its direct interaction towards the heat produced by the propagating light over the small surface area of the fiber core, thus reducing the lifetime of the SA and eventually degrades the pulse laser operation.

To maximize the performance of the SA and as an improved scheme, the interaction between the evanescent field of the propagating wave and the SA material coated on microfiber surface has been exploited (Luo et al., 2012). This scheme is made possible by allowing the SA to interact with the leaking interface wave that propagates in the microfiber which holds the advantage of high power tolerance towards the optical power-induced thermal damage (Luo et al., 2012) and substantially increases the optical damage threshold, in contrast to direct interaction of light with material that is not suitable for operation in the high-power regime. In addition, this scheme provides a maximum efficiency of the nonlinear effect of the SA due to the large interaction area and long lateral interaction length between the evanescent field of the propagating wave with the surrounding SA material along the microfiber (Choi et al., 2014). In this regards, the SA integrated by this scheme has large functionalized area and is more disinclined to thermal damage, making it possible to overcome the aforementioned drawback of the sandwiched-based SAs.

Furthermore, there are several technique that can be applied as saturable absorber for generation of Q-switched and mode-locked EDFL. However, there are still lack of study toward the deposition technique and there is still no demonstration on mode-locked laser generation by employing the ZnO as the SA. Thus, this study demonstrates two techniques of ZnO-SA deposition on the fiber optic devices. The first technique is to form the fiber-ferrule type SA whereby the ZnO-SA is deposited on the tip of fiber ferrule by evaporation method. The second technique is to form the microfiber-type SA whereby the ZnO-PDMS polymer composite is coated around the tapered fiber by drop casting method.

1.1 Problem statement

There are two techniques that can be used to generate the mode-locked and Q-switched pulses namely active and passive technique. Actively pulsed laser normally uses the active modulation technologies as external signal to induce the modulation of intracavity light such as electro-optic modulator (EOM) (Ahmad et al., 2016; Chaboyer, 2012 and Lees et al., 1996b) or acousto-optic(AOMs) (Ahmad et al., 2016; Chaboyer, 2012; Bouyge et al., 2008; Myslinski et al., 1993; Kir’yanov et al., 2013 and Villegas et al., 2012). On the other hand, the passively pulse laser relies on the passive component that is placed into the laser cavity to generate the pulse laser. Unfortunately, the active approach is unsuitable for most real-world application due to the complexity and bulkiness of the device used. Thus, it is of interest to explore and investigate the passively pulse fiber laser due to its advantages of simplicity and cost-effective without requiring any additional switching electronics device (Ahmad et al. 2016c and Svelto et al., 2010).

Typically passively pulse fiber laser needs the optical device such as saturable absorber (SA). Recently, there has been growing interest among the researchers in exploring new materials to act as the SA for the generation of Q-switched and mode-locked fiber laser. Example of the materials examined as the SA are 2D materials, topological insulator, transition metal dichalcogenide, transition metal oxide and metal nanoparticle which show a great success as high performing material as SAs. While the performance characteristics of the materials have been proven to have tremendous potential for application as SAs, it must be noted that, consideration must also be given to other aspects of the SA, such as ease of fabrication and cost. In this regard, significant research has been expanded into the development of a cheaper material as saturable absorber with less complex fabrication for passive Q-switching and mode-locking.

In addition, most of the SA used earlier have some limitation in terms of the optoelectronic properties, making them undesirable for certain optoelectronic applications. Thus, it is of interest to explore new materials as the SA with good optoelectronics properties. Of these attempts, zinc-oxide (ZnO), which is originated from Zn, a semiconductor of the II-VI group, holds the advantage, as it is easily available and inexpensive. ZnO also has recently garnered great interest in scientific research as a viable material for saturable absorption (Ahmad et al., 2016b; Ahmad et al., 2016e; Wang, 2004 and Aziz et al., 2017). In addition, the high third-nonlinear coefficient (Ahmad et al., 2016b; Wang, 2004; Lin et al., 2005 and Petrov et al.,2003) and ultrafast recovery time of ZnO (Ahmad et al., 2016b and Johnson et al, 2004) also become its some points towards suitable and promising candidate as SAs, which could offer another alternative to the existing SA materials.

Besides, ZnO also possesses a wide direct band gap of 3.4 eV (Ahmad et al., 2016a; Jagadish et al., 2011 and Mang et al., 1995) and high binding energy of 60 meV at room temperature (Ahmad et al., 2016a; Jagadish et al., 2011; Mang et al., 1995; Reynolds et al., 1996 and Bagnall, 1997), large carrier density excitation (Ahmad et al., 2016b and Johnson et al., 2004) and low power threshold for optical pumping (Ahmad et al., 2016e and Janotti et al., 2009) making it highly attractive properties for optical and electronic applications as a saturable absorber in order to generate the pulse fiber laser.

In previous works, most of the ZnO-based SAs are integrated into the fiber laser cavity by sandwiching the ZnO thin film between fiber ferrules for the generation of Q-switched EDFL. For instance, Ahmad et al, 2016e used the ZnO powder combined with the mixture of silane and ethanol to form the ZnO polymer thin film. This ZnO polymer thin film was tested as the SA by embedding it in between two fiber ferrules. Similar method also had also been reported by Aziz et al, 2016, by using the ZnO – PVA thin film. However, there is still lack of research on ZnO-SA thin film deposited on the tip of fiber ferrule by evaporation method for the generation of Q-switched EDFL. Apart from that, there is still no demonstration on mode-locked laser generation by employing ZnO as the SA. To date, the deposition of ZnO on the microfiber to form the microfiber-type ZnO SA that works based on the evanescent field interaction has not been demonstrated in previous works.

In general, the performance of the output pulse laser depends on the saturable absorption properties of the SA such as modulation depth, saturation intensity and non-saturable loss. The modulation depth of an SA has a large influence in determining the performance of the output pulse, especially the pulse duration. A higher modulation depth of an SA is more desirable for producing shorter pulse duration. Thus, the higher the modulation depth of the SA has a higher tendency to generate mode-locked while the lower modulation depth has higher tendency to generate Q-switched. Other than that, non-saturable loss is the undesirable portion of the losses. Thus, for both passive mode-locking and Q-switching, it is necessary to have low non-saturable losses of the saturable absorber, in order to reduce the power losses as well as to maximize the output power and efficiency of the laser.

In addition, in terms of interaction area, a large interaction area between the propagating signal and the ZnO-SA through the evanescent field interaction provides higher efficiency of the nonlinearity effect, thus resulting in higher tendency for mode-locked generation. On the other hand, a small interaction area between the propagating signal and the ZnO-SA within the core region of the fiber ferrule provides lower efficiency of nonlinearity effect, thus resulting in higher tendency for Q-switched generation.

Hence, this study demonstrates two discrete techniques of ZnO-SA deposition on the fiber optic to form two types of ZnO SA devices, which are the fiber ferrule-type and the microfiber-type ZnO SA respectively. For the fabrication of the fiber-ferrule-type SA, the ZnO nanopowder which is dissolved in ethanol is deposited on the tip of the fiber ferrule by evaporation method. This fiber ferrule-type ZnO SA involves a small surface area interaction between the light and the attached ZnO thin film within the core of the fiber-ferrule. On the other hand, for the fabrication of the microfiber-type SA, a polymer composite solution of ZnO-PDMS is prepared to be coated around the tapered fiber by drop casting method. This microfiber-type SA involves a large surface area interaction between the evanescent field of the propagating wave and the coated ZnO on the microfiber surface. The nonlinear saturable absorption properties of each fabricated ZnO-based SA device are investigated before being integrated into the erbium-doped fiber laser (EDFL) cavity to study the respective performance of the output pulse generated.

1.2 Research objectives

There are three main objectives of this work, which are given as follows :

1. To fabricate the fiber-ferrule-type ZnO-based SA and ZnO-PDMS polymer composite-clad microfiber by using evaporation and drop-casting method respectively.

2. To characterize the nonlinear saturable absorption and structural properties of the fabricated ZnO-based SA
3. To investigate the use of the fabricated ZnO-based SA for pulse laser generation in EDFL

1.3 Scope of Study

The overall presentation of this thesis consists of the experimental work on deposition of ZnO nanoparticle onto the fiber ferrules and ZnO-PDMS polymer-composite on the tapered fiber to form the ZnO SA, further experimental work on ZnO as saturable absorber for Q-switching and mode-locking as well as respective experimental results and analysis by applying the ZnO deposited in this work. The first chapter details the background of the work, beginning with a brief on fiber lasers, followed by an overview of the pulse laser such as Q-switching and mode-locking fiber laser and also the saturable absorber. In this chapter also brief the objective and the problem statement of this study. Chapter 2 of this thesis describes the theoretical aspects of this work, including the brief overview of fiber optics, optical tapered fiber, and fiber laser. The overview of fiber laser will cover the Erbium doped Fiber Laser (EDFL) as the type of laser used in this work and the pulse laser which consist of Q-switching and mode-locking. This chapter also discusses about saturable absorber, the parameters of a saturable absorber, literature review on ZnO-based saturable absorber and the fabrication process of the SA from the earlier works. Chapter 3 outlines a summary of experimental setup and procedure of the fabrication of ZnO-based SA by using two different techniques for the generation of the passively Q-switched and mode-locked EDFL respectively. The fabrication of ZnO- based SA include the fabrication of fiber ferrule-type ZnO-based SA and ZnO-PDMS-clad microfiber –based SA. The deposited ZnO is characterized by Raman spectroscopy, FESEM or high power microscope. The measurement of the saturable absorption properties of the deposited ZnO such as modulation depth, saturation intensity and non saturable absorption for each different method are carried out experimentally as decribed in this chapter.Taking advantage of the unique properties of the ZnO-based SA, the ZnO deposited in this work are demonstrated as the saturable absorber for Q-switching and mode-locking operation in the setup configurations; from basic setup of a simple ring cavity of Erbium doped fiber laser (EDFL). Chapter 4 outlines the experimental results taken and data analysed of the nonlinear-saturable absorption and structural properties of the ZnO-based SA. On the other hand, experimental results and data analysed that related to the Q-switching and mode-locking based on ZnO SA are also presented in in this chapter. Chapter 5 outline the summary of each previous chapter is presented in this chapter, followed by the conclusion of this research. The suggestion for the possible future works are also presented in this chapter.

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LIST OF PUBLICATIONS

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This study introduces two techniques of fabrication of ZnO-based SA for the application in Q-switched and mode-locked fiber laser generation. The first technique is called as the evaporation technique whereby ethanol solution is used to adhere ZnO powder on the surface of a fiber ferrule through the evaporation process. The second technique is called as the ZnO-PDMS polymer composite-clad microfiber whereby the ZnO powder is mixed with the polydimethylsiloxane (PDMS) polymer to be coated around the microfiber. The structural properties of the fabricated ZnO-based SA by both techniques are characterized by Raman spectroscopy, field emission scanning electron microscopy (FESEM) and high power microscopy and their saturable absorption properties are characterized by dual measurement setup. The modulation depth and saturation intensity for the ZnO-based SA by evaporation technique are measured to be 1.7% and 0.0014 $MWcm^{-2}$. On the other hand, the modulation depth and saturation intensity for the ZnO-PDMS polymer composite-clad microfiber are measured to be 6.4% and 4.15 $MWcm^{-2}$ respectively. A Q-switched erbium-doped erbium-doped fiber laser (EDFL) is successfully demonstrated by inserting the ZnO-based SA deposited by the evaporation technique into the laser cavity. Self-started and stable Q-switching is achieved at a low power of 20.34 mW. At the maximum pump power of 48.58 mW, the Q-switched EDFL generates the central wavelength, pulse repetition rate, pulse width, average output power and pulse energy of 1558.32 nm, 25.93 kHz, 3.65 µs, 0.46 mW and 19.34 nJ respectively. On the other hand, the integration of the ZnO-PDMS polymer composite-clad microfiber into the laser cavity results in mode-locked pulse generation. The mode-locked laser has a central wavelength, 3 dB spectral bandwidth, pulse duration, pulse repetition rate and time-bandwidth product of 1558 nm, 5.02 nm, 1.03 ps, 9.77 MHz and 0.6266 respectively. These results indicate that the proposed ZnO-PDMS polymer composite-clad microfiber could be useful as a simple, low-cost and ultrafast SA device.