GENERATION OF TUNABLE Q-SWITCHED ERBIUM-DOPED FIBER LASER BASED ON GRAPHITE FLAKES SATURABLE ABSORBER

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To my beloved family

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ABSTRACT

Pulsed fiber laser has tremendous application in laser processing and laser sensor. The key element to produce a passively Q-switched fiber laser is by using a saturable absorber (SA). Passively Q-switched fiber laser is the most desirable pulse in laser technology due to its ability to generate optical pulses in microsecond and nanosecond. The aim of this study is to construct a single ring erbium-doped fiber (EDF) laser based on graphite flakes SA to produce short pulse laser. Graphite flakes SA were prepared by mechanical exfoliation techniques and was transferred onto a fiber ferrule tip. The saturable absorption property of the graphite was measured using twin detector method which resulted in a modulation depth of 23.82% with a saturation intensity of 0.031 MW/cm^2. Surface morphology, elemental analysis and absorbance characteristics of the graphite flakes were analyzed by the field emission scanning electron microscope (FESEM), energy dispersive X-ray spectroscopy (EDX) and ultraviolet visible spectroscopy (UV-VIS). The result showed that the carbon element on the SA has a very strong peak intensity. The two different EDF coefficient of 6.43 dB/m and 18.93 dB/m (EDF M-5 and EDF I-12) showed a repetition rate of 41.62 kHz and 60.00 kHz with a pulse width of 6.45 µs and 3.38 µs, respectively at a pump power of 268.8 mW. The wavelength tunability of passively Q-switched fiber laser for EDF M-5 and EDF I-12 were optimized at fixed pump power where the tuning range of EDF M-5 occurred between 1544 nm to 1560 nm and 1552 nm to 1570 nm for EDF I-12. The passively Q-switched fiber laser with different EDF coefficients were successfully constructed in a single ring configuration with more selection of wavelength that is up to L band by using higher EDF coefficient.

ABSTRAK

Laser gentian denyutan mempunyai aplikasi yang luar biasa dalam pemprosesan laser dan pengesan laser. Elemen utama untuk menghasilkan laser gentian pensuisan-Q pasif menggunakan penyerap tepu (SA). Pensuisan-Q pasif merupakan teknologi denyutan laser yang bagus kerana keupayaannya menghasilkan denyutan optik dalam mikrosaat dan nanosaat. Tujuan pembelajaran ini adalah untuk membentuk satu bulatan laser gentian terdop-erbium (EDF) bersama dengan serpihan grafit SA untuk menghasilkan denyutan pendek. Serpihan grafit SA disediakan oleh teknik pengelupasan mekanikal dan dipindahkan ke permukaan gentian simpai logam. Sifat penyerapan grafit diukur menggunakan kaedah pengesan berkembar dimana kedalaman modulasi sebanyak 23.82% serta keamatan tepu 0.031 MW/cm^2. Ciri-ciri permukaan morfologi, analisa unsur dan ciri-ciri penyerapan serpihan grafit dianalisis oleh mikroskop elektron pengimbas pancaran medan (FESEM), spektroskopi tenaga serakan sinaran-X (EDX) dan spektroskopi ultralembayung-cahaya nampak (UV-VIS). Ini menunjukkan bahawa unsur karbon di dalam serpihan grafit mempunyai keamatan tepu yang sangat tinggi. Dua pekali EDF yang berbeza iaitu 6.43 dB/m dan 18.93 dB/m (EDF M-5 dan EDF I-12) menunjukkan kadar pengulangan 41.62 kHz dan 60.00 kHz dengan lebar denyut sebanyak 6.45 µs dan 3.38 µs pada tenaga pengepaman 268.8 mW. Peralihan panjang gelombang laser gentian pensuisan-Q pasif EDF M-5 dan EDF I-12 dioptimumkan pada tenaga pengepaman sama di mana penalaan EDF M-5 berlaku antara 1544 nm hingga 1560 nm dan 1552 nm hingga 1570 nm untuk EDF I-12. Laser gentian pensuisan-Q dengan pekali EDF yang berbeza telah berjaya dibentuk dalam satu konfigurasi bulatan tunggal dengan lebih banyak pilihan panjang gelombang sehingga jalur L dengan menggunakan pekali EDF yang lebih tinggi.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

D_{λ}	-	Dispersion parameter
L	-	length or distance
β_2	-	GVD parameter
ω	-	Angular wave velocity
v_g	-	Group velocity

LIST OF ABBREVIATIONS

Ag	-	Silver
AOM	-	Acousto-optic modulator
ASE	-	Amplified Spontaneous Emission
AWG	-	Arrayed wavelength grating
Bi_2Te_3	-	Bismuth diselenide
CNT	-	Carbon nanotube
CVD	-	Chemical vapor deposition
CW	-	Continous wave
Co_3O_4	-	Cobalt oxide nanocube
dB/m	-	decibel per meter
DC-EDF	-	Depressed-cladding erbium-doped fiber
EDF	-	Erbium-doped fiber
EDFA	-	Erbium-doped fiber amplifier
EDFL	-	Erbium-doped fiber laser
EDX	-	Energy Dispersive X-ray spectroscopy
EOM	-	Electro-optic modulator
Er3+	-	Erbium ion
FBG	-	Fiber Bragg Grating
FESEM	-	Field emission Scanning Electron Microscope
FWM	-	Four wave mixing
Fe_3O_4	-	Ferroferric-oxide
Fe_3O_4-PVA	-	Ferroferric-oxide- Polyvinyl alcohol
Fe_3O_4-PI	-	Ferroferric-oxide-Polyimide
GO	-	Graphene oxide
GVD	-	Group velocity dispersion
kHz	-	kilohertz

LD	-	Laser diode
MCVD	-	Modified chemical vapor deposition
MWCNTs	-	Multi-walled carbon nanotubes
MoS_2	-	Molybdenum disulfide
Nd	-	Neodymium
NIR	-	Near infrared
NIO	-	Nickel oxide
NLSE	-	Nonlinear Schrodinger equation
OPM	-	Optical power meter
OSA	-	Optical spectrum analyzer
OC	-	Oscilloscope
OC	-	Optical coupler
OVD	-	Outside vapor depostion
PLD	-	Pulsed laser deposition
RF	-	Radio Frequency
SA	-	Saturable absorber
SBS	-	Stimulated Brillouin scattering
Sb_2Te_3	-	Antimony Telluride
SESAM	-	Semiconductor saturable absorber mirror
SRS	-	Stimulated Raman scattering
SPM	-	Self-phase modulation
SWNTs	-	Single-walled nanotubes
TBF	-	Tunable bandpass filter
TiO_2	-	Titanium dioxide
TIs	-	Topological insulators
TMDs	-	Transition metal dichalcogenides
Tm	-	Thulium
UV-VIS	-	Ultraviolet-visible
VAD	-	Vapor axial deposition
WDM	-	Wavelength division multiplexing
XPM	-	Cross phase modulation
Yb	-	Ytterbium
ZnO	-	Zinc Oxide

LIST OF PUBLICATIONS

List of Publications:

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LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.0 Background of study

In recent years, pulsed fiber laser operation is being industrialized due to abrupt growth in many applications such as industrial fiber sensor, micromachining, and telecommunications. In 1964, Koester is the first person who invented glass fiber and fiber amplifiers which give an advantage in the development of fiber optic technology [1]. In order to produce fiber laser, there are three important parts that need to be consider which are pump source, resonator and gain medium. The laser source uses a single mode diode that can emit power of few tens of milliwatts (mW) due to the large gain and single mode continuous-wave lasing. The fiber laser resonator could be aligned in a linear or single ring fiber laser to produce a pulse. These fiber lasers continue to grow since 1990 especially after the fabrication of rare-earth-doped ions such as neodymium (Nd), erbium (Er), ytterbium (Yb) and thulium (Tm) that were employed in the fiber laser which act as a gain medium [2]. The material of the gain medium of the fiber laser is a rare-earth doped ion that are able to produce a broad wavelength range of laser [3].

In 1961 Snitzer, proposed that first laser action in barium crown glass doped with Nd^{3+} but now the fiber laser mostly uses Yb^{3+} in silica fiber. This Yb^{3+} doped ion has its advantages in terms of operating wavelength, high quantum efficiency, absence of ground-state absorption and excited-state absorption [4]. Later on, Er glasses are under investigation until they found the advantages of Er^{3+} ions due to the small absorption cross section and narrow pumping spectral band. Erbium doped fiber (EDF) within C-band region from 1.53 μm to 1.56 μm frequency range which is important in optical communication application [5]. Furthermore, Nd^{3+} and Yb^{3+} doped ion silica fiber lasers can operate at 1 μm while Er^{3+} doped ion is at 1.5 μm. In this study, an EDF laser was chosen because the lasing is near to the C-band region at 1.55 μm, which is located in the optical fiber low loss window and useful in sensing application [6]. The erbium doped fiber laser is utilized as an active material in the fiber laser cavity to create high Q-switched pulse with very narrow linewidth output [7-8].

Q-switched fiber laser is a technique to produce microsecond or nanosecond pulses in a highly compact fiber laser. Generally, the Q-switched pulse can be generated by two techniques, which are active and passive. The active technique uses a modulator to control the Q-factor of the resonator inside the cavity. However, this technique is complicated and bulky. In contrast, the passive technique uses a saturable absorber (SA) as a modulator which acts as an absorbing medium. This method is easy, simple and low cost to fabricate and operate. Passively Q-switched SA is a technique to produce short pulses with a high peak and modulation depth provided that the SA has high heat dissipation and high damage threshold [9].

The single wavelength fiber laser emits narrow linewidth output due to low phase noise and high spectral purity. A narrow linewidth laser is important to produce high coherent output that can be used in longer wavelength applications. There are few devices to generate single wavelength fiber laser such as fiber Bragg grating (FBG), tunable bandpass filter (TBF) and arrayed waveguide grating (AWG) as the wavelength selective element. However, FBG and AWG are limited operating wavelength. Thus, TBF is used to validate the selection of wavelength in single ring configuration can cover broad wavelength.

Initially semiconductor material such as semiconductor saturable absorber mirror (SESAM) is the first method used to generate pulse Q-switched [10]. Nonetheless, this technique remains questionable since it is unreliable and complicated to fabricate [11]. Another type of SA material is carbon allotrope and topological insulator (TIs). The carbon allotrope includes graphene [12-14], graphite [15] and single-walled carbon nanotube (SWNTs) [14,16] whereas TIs is bismuth diselenide (Bi_2Te_3) SA [17-18]. However, TIs conducts a higher modulation depth about 98% which may indicate less performance of the pulse Q-switched.

Among the previously researcher mentioned graphene SA represents broadband bandwidth due to zero bandgap characteristic [19-20]. In addition, graphene allows light to absorb at low intensity and hence transmits it at high intensity due to the electronic configuration of the material. Graphene also presents fast relaxation time and wideband operation. Furthermore, previous research reported on graphite SA as an alternative material since this material is facile and low-cost [21]. Therefore, it will use as a base material for practical and cost-effective SA [22].

1.1 Problem statement

In general, Q-switched fiber laser usually generates pulse width in micro-second (μs) to nanosecond (ns). The most common technique used in the generation of Q-switched is semiconductor saturable absorber modulator (SESAM). However, this technique has several limitations such as suffer from high intensity losses, limited operating wavelength and the difficulties in preparing the optical alignment. In the last few years, many researchers have used materials such as graphene, graphite, bismuth diselenide (Bi2Te3), black phosphorus and single-walled carbon nanotube (SWCNT) as SA to produce Q-switched fiber laser since they are broadband and cost-effective. Graphite is commonly used as SA based on exfoliation technique in passively Q-switched fiber laser generation due to its simple preparation and low-cost method. Previous researchers were mainly focusing on varying the material of SA to generate high repetition rate. Other parameters such as gain medium and cavity length are among other factors that can be considered in generating high repetition rate. In general, the repetition rate can be achieved up to several kilo hertz (kHz) with certain condition such as EDF absorption coefficient and applied pump power. Theoretically, higher EDF absorption coefficient could offer higher repetition rate due to the population inversion which accumulates at high energy level. In this study, the EDF absorption coefficients are used in order to generate high repetition rate with narrow pulse width.

1.2 Aim

The aim of this research is to produce passively Q-switched fiber laser based on graphite flakes SA with high and low EDF coefficients.

1.3 Objectives

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

1. To develop a single ring fiber laser based on graphite flakes saturable absorber.
2. To analyze passively Q-switched fiber laser characteristic of low and high erbium doped fiber absorption coefficients.
3. To validate passively Q-switched fiber laser for wide band operation by using tunable bandpass filter.

1.4 Significant of study

In industrial technologies, passively Q-switched fiber laser operation is much compact and inexpensive in fabrication. The passively Q-switched fiber laser is constructed in a single ring configuration which literally resistant to high input power. This research covers the effect of two different EDF absorption coefficients on the pulsed fiber laser. Higher EDF absorption produces higher output power which aids the saturable absorption by the SA. Consequently, the laser produces higher pulse repetition rates, higher pulse energy and lower pulse width indicating a good Q-switching performance. Besides that, a wide band wavelength is produced based on EDF absorption coefficient properties. Therefore, greater EDF absorption has the capability to produce a wideband tunable wavelength of the passively Q-switched fiber in the C-band which extends to the L-band region.

1.5 Scope and limitation of the research

The study is focused on a construction of single ring fiber laser based on graphite flakes SA. The passively Q-switched fiber laser will be developed using high and low EDF absorption coefficients based on graphite flakes SA. The SA material will be exfoliated on the fiber ferrule tip by mechanical exfoliation process due to its simplicity and ease of fabrication. The two setups of passively Q-switched fiber laser are fixed except for the EDF absorption coefficients that were 6.43 dB/m and 18.93 dB/m. Finally, the passively Q-switched fiber laser is tuned by tunable bandpass filter to analyze the wavelength regions.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter describes the theoretical aspect of erbium doped fiber including McCumber theory, energy level, mode competition, homogeneous and inhomogeneous gain broadening. It is followed by the fiber laser itself where nonlinear and self-phase modulation are reviewed. Q-switched fiber laser is also discussed especially on the principle, parameter and material of saturable absorber.

2.1 Erbium doped fiber

In early 1960s, rare earth doped fiber started to be recognized as a light amplifier when researchers investigated glass fiber with trivalent neodymium (Nd) as the dopant where Nd^{3+} ion has a long lifetime of the metastable state. The dopant has the capability for guiding wave in term of power density when the light is confined in the small region making the rare-earth-doped is important. Other researchers found out another rare earth doped such as trivalent erbium (Er^{3+}) which becomes more preferable [23]. The Er^{3+} ion is suited as an amplifying medium for optical fiber communication system at 1550 nm [24].

The basic structure for erbium doped fiber amplifier (EDFA) consist of a pump laser, wavelength-division multiplexing (WDM), and a length of EDF as shown in Figure 2.1. The EDF is a small diameter crystal fiber which made up of erbium dopant together with silica-based as co-dopants into fiber core. The more dopant of erbium in silica-based generates higher concentration which in return produces more solubility of erbium ion. There are several techniques to fabricate rare-earth doped fiber such as modified chemical vapor deposition (MCVD) [25], vapor axial deposition (VAD), [26] outside vapor deposition (OVD) [27] and solution doping [28]. Other than that, the principle of the EDF based on the emission and absorption coefficient is related to the McCumber theory and this theory will be discussed in the next section.

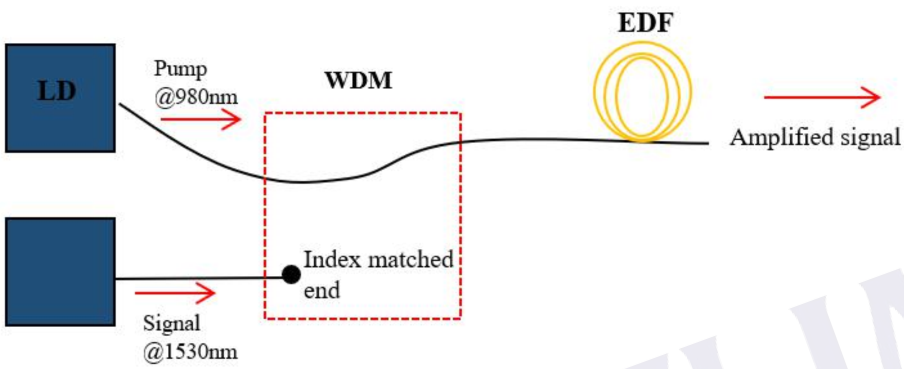

Figure 2.1: Basic structure of erbium doped fiber

2.1.1 McCumber theory

McCumber theory has been demonstrate for the study of $^4I_{15/2}$ and $^4I_{13/2}$ levels of erbium in glass host. This equation is a relationship between the effective cross-sections of emission and absorption of light in the laser gain media. The general equation based on McCumber theory relates the fluorescence to the absorption coefficient for the $^4I_{13/2}$ and $^4I_{15/2}$. Since, the erbium and fluorescence absorption coefficient can be measure with good accuracy which less than 2% error. Therefore, using this theory the transition of $^4I_{13/2}$ to $^4I_{15/2}$ in silica-based erbium doped fiber has been derived based on the following condition:

1. The $P_{pump} >> 1$, $P_{signal} << 1$;
2. $P_{pump} = 0$, $P_{signal} << 1$
3. $P_{pump} >> 1$, $P_{signal} = 0$

Thus, the operation condition, equation (2.1) is simplified to equation (2.2);

$$\frac{dP_t\,(\lambda,z)}{dz} = \frac{2}{\omega_s^2(\lambda)} \int_0^\infty \rho(r) \left\{ \sigma_e(\lambda) \frac{\beth_1+\beth_2}{1+\beth_1+\beth_3} [P_s(\lambda,\mathrm{z}) + 2P_0(\lambda)] - \sigma_a(\lambda) \frac{1+\beth_4}{1+\beth_1+\beth_4} P_s(\lambda,\mathrm{z}) \right\} \Psi_s\,(\lambda,\mathrm{r}) dr \quad (2.1)$$

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