DEVELOPMENT AND ANALYSIS OF SATURABLE ABSORBER FROM PLANT LEAF FOR Q-SWTICHED FIBRE LASER GENERATION

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honors

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DECLARATION

I declare that this report entitled "Development and Analysing of Saturable Absorber from Plant Leaf for Q-switched Fibre Laser Generation" is the result of my own work except for quotes as cited in the references.

Signature : ....

Author : AMAL MUAZ BIN MOHD NASIR

Date : 11 JANUARI 2022

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

Signature : ……………………………………

Supervisor Name : IR. DR. ANAS BIN ABDUL LATIFF

Date : 11 JANUARY 2022

DEDICATION

This study is wholeheartedly dedicated to my beloved parents, who have been the source of inspiration and gave me strength when I thought of giving up, who continuously provide their moral, spiritual, emotional, and financial support. To my brothers, sisters, relatives, mentor, friends, and classmates who shared their words of advice and encouragement to finish this technical research. And lastly, I, myself dedicated this technical research to the Almighty God, Allah s.w.t, thank you for the guidance, strength, power of mind, protection, and skills and for giving me, my family, my friends, and us all his servants a healthy life. All of these, are return and offer the Only Existence.

ABSTRACT

This project is about the development and analysis on organic material by generating a Q-switched pulse laser as a passive element in Saturable Absorber (SAs) for photonics technology. The saturable-absorption performance being analyze with the prepared SAs within the C-band region (1.55micron wavelength region). These Q-switched pulse lasers, being analyze with the usage of two SA's material which is from Spent Coffee Ground (SCG) film and plant leaf film (from eggplant leaf), with the slope efficiency of 0.95% and 2.35% respectively. For the SCG, the maximum repetition rate is 43.75 kHz, shortest pulse width of 8 µs and pulse energy up to 12.8 nJ. The maximum repetition rate of 38.61 kHz, shortest pulse width of 10.7 µs and pulse energy up to 31.34 nJ for the plant leaf film. The maximum power output generated was 0.56 mW and 1.21 mW respectively for SCG and plant leaf SA's.

ABSTRAK

Projek ini adalah mengenai penghasilan dan analisis bahan organik untuk menghasilkan laser Q-switched sebagai unsur pasif dalam penyerap tepu (SA) untuk teknologi fotonik. Prestasi penyerapan tepu sedang dianalisis dengan SA yang disediakan dalam kawasan C-band (rantau panjang gelombang 1.55mikron). Laser Q-switched ini, sedang dianalisis dengan penggunaan dua bahan SA iaitu daripada filem Spent Coffee Ground *(SCG) dan filem daun tumbuhan (daripada pokok daun terung), dengan kecekapan cerun masing-masing 0.95% dan 2.35%. Untuk SCG, kadar ulangan maksimum ialah 43.75 kHz, lebar nadi terpendek 8 µs dan tenaga nadi sehingga 12.8 nJ. Kadar pengulangan maksimum 38.61 kHz, lebar nadi terpendek 10.7 µs dan tenaga nadi sehingga 31.34 nJ untuk filem terung. Output kuasa maksimum yang dijana ialah 0.56 mW dan 1.21 mW masing-masing untuk SCG dan terung SA.*

ACKNOWLEDGEMENTS

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A large gratitude also goes out to all of my colleagues and those who have helped me on multiple events. Their perspectives and advice are quite beneficial. However, given this short area, it is not possible to mention all of them. I am grateful to every member of my family, to my mother who gives fully support and motivation, and my siblings as a great source of energy for me to continue and finish this research journey.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

PQS	:	Passive Q-Switched
PSM	:	Projek Sarjana Muda
TLS	:	Tunable Laser Source
GO	:	Graphene Oxide
SA	:	Saturable Absorber
Yb	:	Ytterbium
Er	:	Erbium
Tm	:	Thulium
ms	:	milliseconds
µs	:	microseconds
ns	:	nanoseconds
ps	:	picoseconds
fs	:	femtoseconds
OSA	:	Optical Spectrum Analyzer
SEM	:	Scanning Electron Microscope
EDS	:	Energy Dispersive Spectroscopy

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter explains about background of the study, research problem, research question, research objectives, scope of the research, limitation, and importance of the study. To complete a bachelor's degree Dissertation (Projek Sarjana Muda PSM) in Faculty of Electronic Engineering and Computer Engineering (Bachelor of Electronics Engineering with Honors), researcher chooses to develop and analyze saturable absorber from plant leaf for Q-switched fiber laser generations. In this report, it demonstrated a passive Q-switched (PQS) from plant leaf at central wavelength region of 1.55µm (C-band region). This report also will discuss on the SA repetition rate, pulse width, pulse period, and the optical spectra output of the film. This is one of the early research projects of plant leaf SA for the 1.55µm band region Q-switched fibre laser generation.

1.2 Background of the study

Q-switching is the method to produce high energy pulsed lasers. This process allows the laser to have population inversion in the saturable absorber respecting to wavelength of the gain medium, Erbium Dopped Fibre (EDF) to grow until it becomes fully saturated.

At this point the Q-switched will 'opened' and allowed all the stored energy to be emitted in one rapid pulse in C-band region (1.55µm). The main idea is to develop an organic passive Q-switched saturable absorber (SA) using plant leaf. This is basic research that comprises a proper experimental approach together with a proprietary method to produce and analyse a new result.

1.3 Problem Statement of the project

There are certain drawbacks recorded for several founded passive Q-switched (PQS) based on previous research hence promoting the research and development to analyze and develop new passive Q-switch using organic material:

1) SESAMs have the disadvantages of a complicated manufacturing process and a limited operational bandwidth. [1]
2) The graphene has weak absorption efficiency at 2 µm wavelength that limits its modulation ability for light.
3) The carbon nanotubes performance is poor when used in 2 µm wavelength solid-state lasers.
4) Black phosphorus is easily oxidized in the presence of oxygen and water, resulting in its poor stability.

1.4 Research Questions

1) What are the factors that influencing the rate of dispersion in the passive Q-switch Erbium Doped Fibre Laser?
2) What is the most critical factor that influencing the selection for passive Q-switch material?
3) What are the relationships between independent variables and dependent variables to build the Q-switch laser?

1.5 Research Objectives

1) To analyze the pulses range of plant leaf passive Q-switching for stable laser pulse in the mid-infrared waveband (1.55 μm). **[RO1]**
2) To develop a saturable absorber from plant leaf for varying passive Q-switching fiber laser generation. **[RO2]**

3) To study the saturable absorber material for passively Q-switched and diagnosing the Erbium Dopped Fiber Laser (EDFL) to utilize the system at its optimum performance. **[RO3]**

1.6 Scope of Work [Work Activity - WA]

1.6.1 Deliverables

- This saturable absorber from plant leaf was developed for the application of passive Q-switching for short pulses from the laser by modulating the intracavity losses. It can generate substantial pulse energies (mJ) in conjunction with microsecond pulse durations. A single mode 980 nm laser diode with maximum output power of 500mW is act as pump source, according to the required specifications of the EDFL.

1.6.2 Timeline

- It is expected to build this project in a journey of 28 weeks including Final Year Project 1 and 2. This period was shown in the Gantt chart.
- The barrier, obstacles and limitation of this project will be discussed throughout the weeks with the other co-researcher (postgraduates) and Supervisor.

1.6.3 Limitation

- Triggering – PQS have cannot be control over when the laser pulses were emitted as the pulse repetition rate will be solely dependent on the absorber saturates.
- Pulse Energy – some passive Q-switch are capable to produce high energies (mJ level) but the active Q-switch tends to lead higher pulse energies.

1.7 Significance of Study

This research was intended to find a new finding that can be comparable with the other passive Q-switch as mentioned in the problem statement. This factor is including the operating bandwidth, absorption rate of the SA, saturable intensity, Signal-to-Noise ratio, slope efficiency and repetition rate of the pulsed laser. This project aims to assist Malaysia's communication providers and medical sector in having more reasonably faster data rate transfer and good medical instruments in the future by incorporating pulse laser technology into telecommunication devices and medical appliances that can benefit the community and society.

- This research promotes of bio-based sustainable development of United Nation’s SDGs #9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
- The process of manufacturing design of the passive Q-switch in the lab have use minimal or no adverse environmental impact.
- By recycling and reuse of the feedstock for subsequent depositions is very recommended to improve the sustainability of the optic fiber research and development.
- With all that, Passive Q-switched promote advantages in terms of fabrication, design, cost, simplicity, and project integration.

1.8 Summary

Throughout this chapter, researcher had explained on some elements in this research which are background of the study, problem statements, research questions, and research objectives, scope of study, limitation, and significance of study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Due to their high peak power and pulse energy, fiber-based lasers with ultra-short pulses operating in the 1.0-2.0 m wavelength region have proved appealing. They have a high absorption rate in water and human tissues and are safe in the eye-safe range [2]. As a result, 1.55 m optic fibre lasers with ultra-short pulses will be notably useful for medical diagnostics, material processing, surgery, range, and nonlinear optical frequency conversion. Fiber lasers have piqued the interest of photonic researchers due to its unique properties such as high refractive index, high efficiency, high solubility, broad transmission, and low phonon energy.

Q-switching techniques are useful approaches for producing ultra-short pulses (in microsecond). Q-switch is a simple and convenient method for producing microsecond period (s) pulsed lasers. A solid-state laser's Q-switching operation, which may easily get a steady pulse train and adjustable pulse repetition frequency as needed. The energy of an active Q-switched laser pulse can approach millijoules or even hundreds of nanojoules [2]. Based on prior research, laser radiation has been shown in the 2-m waveband, for example, using a Tm,Ho:YLF crystal, a Tm,Ho:GdVO4Ho:GdVO4 crystal, a Ho:YAG crystal, a Ho:YAP crystal, and a Ho:YLF crystal. [3]

In contrast to active Q-switching, passive Q-switching using a saturable absorber (SA) is a low-cost and compact method of achieving microsecond (s) pulse Q-switching operation in the mid-infrared (1.55-m) waveband. Because of the SA's damage threshold limit, the energy per pulse of the PQS laser is in the nano or micro joule range, which is lower than active Q-switching. Many SAs have been used for PQS operations, including semiconductor saturable absorber mirrors (SESAMs), carbon nanotubes (CNT), graphene, black phosphorus, and topological insulators exhibiting broadband saturable absorption at 1–2 m. The goal is to collect carbon from plant leaves and utilise it as a passive Q-switched saturable absorber [2]. SA's broad saturable absorption, quick recovery time, and moderate saturation intensity have been cited as standards for being a good SA. Previously, SESAMs were utilised as saturation absorbers in the 2-m waveband. [3] [4].

While there are While there are many schemes for generating pulsed laser emission, passive mode-locking or Q-switching using a saturable absorber (SA) (a material that exhibits an intensity-dependent transmission) are frequently preferred because they allow access to a wide range of pulse parameters without the use of expensive and complex electrically-driven modulators that eventually impair [4]. Because of their unique features in comparison to bulky analogues, 2D materials such as graphene, topological insulators (TIs), black phosphorus (BP), and transition metal dichalcogenides (TMDs) have been intensively explored and published. [4]. But for this research, it will be purposedly focusing on only the passive Q-switched from organic material which is the plant leaf.

There are three main components in laser technology which is energy source, the gain medium and the resonator. Light is pumped into a gain medium by the energy source. It differs depending on the type of laser. A laser diode, an electrical discharge, a chemical reaction, a flash bulb, or even another laser might be involved. When activated by light, the gain medium emits light of a specified wavelength. It is thought to be a source of optical gain. The name of a laser is usually derived from its gain medium. The gain medium of a CO2 laser, for example, is CO2 gas. The optical gain or resonator is amplified by the resonator via mirrors that surround the gain media. Bulk mirrors in solid-state lasers, cleaved or coated facets in laser diodes, and Bragg reflectors in fibre lasers are examples.

2.2 Type of lasers

Lasers are distinguished by their gain medium and are frequently classified by the radiating species that produce stimulated emission. Atoms and molecules in a dilute gas, organic molecules dispersed at very low concentrations in aqueous systems, semiconductor materials, and dielectric materials such as crystalline solids or glasses doped with a high concentration of ions are examples of radiating species [5]. For this section, the focus will be on the most common commercially available lasers. The names of these systems (depending on their medium) are given in Table 1, along with their nominal features and parameters. This table will be useful during the upcoming talks of the distinct laser classes.

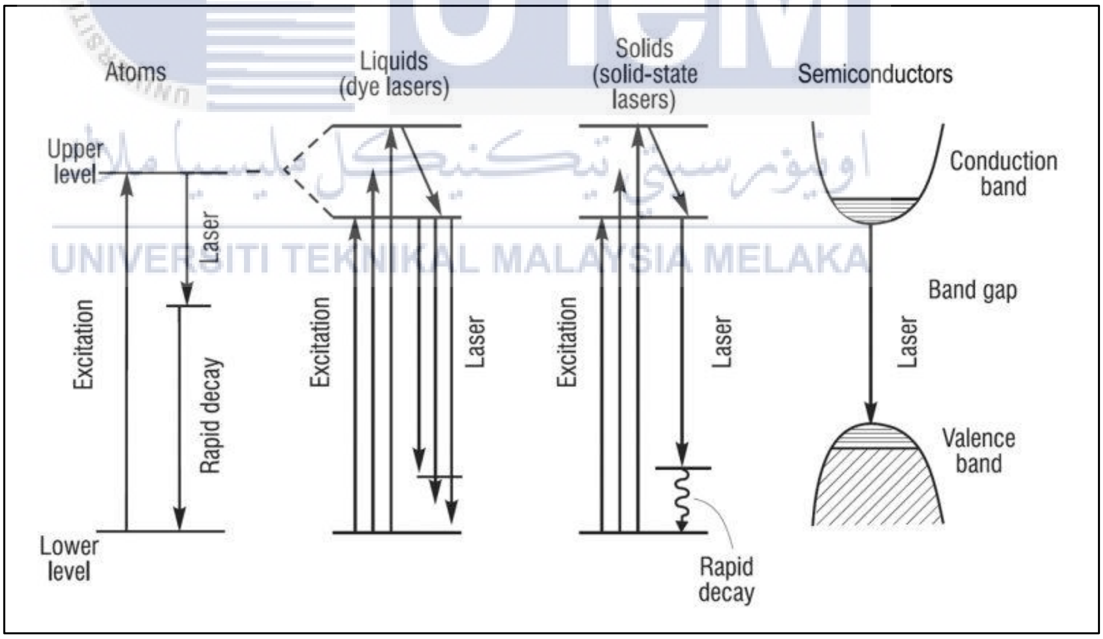


Figure 1: Typical inversion processes in gases, liquids, solids, and semiconductors [5]

Table 1: Characteristics and parameters for common lasers with their respective wavelength [5].

Laser	Type	Wavelength	Applications
Dye	Liquid	400-1000 nm	Spectroscopy, laser medicine
Yb:YAG	Solid-state	1030 nm	Materials processing, optical refrigeration, LIDAR
Yb-glass	Fiber	1030 nm	Materials processing, ultrashort pulse research, LIDAR
Nd:YAG	Solid-state	1060 nm	Material processing, range finding, surgery, tattoo/hair removal, pumping other solid-state lasers
Er-glass	Fiber	1530-1560 nm	Optical amplifiers for telecommunications
Tm:YAG, Ho:YAG	Solid-state	2000-2100 nm	Tissue ablation, kidney stone removal, dentistry, LIDAR
CO_2	Gas	10600 nm	Material processing, surgery, dental laser, military lasers

2.2.1 Gas Laser

A gas laser is a type of laser in which an electric current is sent through a gas to create light via a process known as population inversion. Gas lasers include carbon dioxide (CO2) lasers, helium–neon lasers, argon lasers, krypton lasers, and excimer lasers. Gas lasers are utilised in a wide range of applications, including holograms, spectrometry, barcode scanners, air pollution measures, material processing, and laser treatment. CO2 lasers are the most well-known gas lasers, and they are mostly used for laser marking, laser cutting, and laser welding [5]. CO2 and excimer lasers, which continue to play important roles in the laser processing and medical eye surgery businesses, are exceptions to this trend. [5]

2.2.2 Liquid Laser

Certain organic dye molecules can act as radiating species for lasing since they have sufficiently long lifetimes in their upper energy levels and can therefore radiate energy from that level instead of losing energy due to collisions. To ensure the proper concentration of radiating species are present, the dye molecules (typically in powder form) are dissolved in a solvent at a concentration of about one part in ten thousand. Due to this solution form, the system is known as a liquid dye laser. [5] A The gain medium of liquid lasers is an organic dye in liquid form. Dye lasers are also utilised in laser treatment, spectroscopy, birthmark removal, and isotope separation. Dye lasers have the benefit of being able to create a significantly larger variety of wavelengths, making them suitable candidates for tunable lasers, which means that the wavelength can be adjusted while the laser is operating [5].

2.2.3 Semiconductor Laser

A semiconductor laser is often referred to as a laser diode since it operates like a diode with current flowing in the forward direction of the junction. By injecting charge carriers into the region of space defined by the junction, recombination radiation can occur. Provided this current injection is strong enough, a population inversion can be achieved, and stimulated emission will occur. Laser diodes, also known as diode lasers and semiconductor lasers, feature a positively-negatively (PN) charged junction, similar to ordinary diodes. The distinction is that laser diodes feature an inherent layer at the PN junction composed of materials that produce spontaneous emission. The intrinsic layer is polished, which amplifies the produced photons, transforming the electric current into laser light.

Because their gain medium is solid, laser diodes are categorised as solid-state lasers. They are, however, in a class of their own due to their PN junction. Laser diodes are frequently utilised as energy sources for other lasers. These lasers are known as diode-pumped lasers. In these circumstances, laser diodes are generally stacked to pump additional energy, as seen in the graphic below [5]. Unsurprisingly, they are one of the most significant groups of lasers in use today, not only for their employment in applications such as optical data storage and optical fibre networking, but also as pumping sources for solid-state lasers. [5].

2.2.4 Solid-state Laser

A solid-state laser is one whose gain medium is made up of active ion species injected as impurities in an optically transparent host material (typically crystals or glasses). Materials with strong and spectrally narrow transition cross-sections, strong absorption bands for pumping, and a long-lived metastable state are ideal for laser operation. These properties are commonly observed in ions with optical transitions between states of inner, incomplete electron shells. However, in order to retain their desired properties, these ions must be protected or insulated from other ions. This is done by embedding the ions in a solid host material with a lattice that allows for ion doping levels adequate for a gain medium while also protecting the ions from one another. Solid-state lasers produce population inversion by optical pumping, which can be performed via a flashlamp or direct pumping from another laser source such as a laser diode or a DPSS system. [5].

Transition-metal and lanthanide-metal (or rare-earth) ions are the most often employed dopant ions in solid-state laser medium [5]. The most common transition-metals used are titanium (Ti) and chromium (Cr) while the lanthanides are neodymium (Nd), ytterbium (Yb), erbium (Er), thulium (Tm), and holmium (Ho) [5]. Depending on the dopant, host material, and application, the dopant ions are normally spread throughout the host at a concentration (often about one part in one hundred). These ions have electrons that are protected from interacting with surrounding dopant ions by a "screen" (of electrons from the host material). As a result, the ions may radiate their energy rather than degrade through collisions, as organic dye molecules do in a liquid solvent. When these ions absorb light, the energy is converted into an excited energy level, which functions as the higher laser level. This higher level has a very long lifespan (the metastable level) before radiatively decaying due to the screening provided by the host material. A population inversion can occur (see Figure 1) because the lower laser levels are being rapidly depopulated by collisions with the neighboring atoms as these levels are not protected the way the upper levels are.

Because of the wide diversity of host materials and dopant ions accessible, solid-state lasers come in a variety of shapes and sizes. Figure 2 shows some of the more commonly found lasers, along with their gain bandwidths. Solid-state media can clearly have huge gain bandwidths with broad wavelength tunability or narrow gain bandwidths with highly monochromatic linewidths. Aside from spectrum agility, modifications in gain media allow systems to display a wide range of features, such as very high output powers, lower powers with excellent spatial beam quality, CW output with exceptional power stability, or ultrashort pulses with ps or fs durations. Because of this versatility, solid-state lasers may be utilised for everything from multiphoton microscopy to light detection and ranging (LIDAR) to material processing/marking/cutting and even laser fusion.

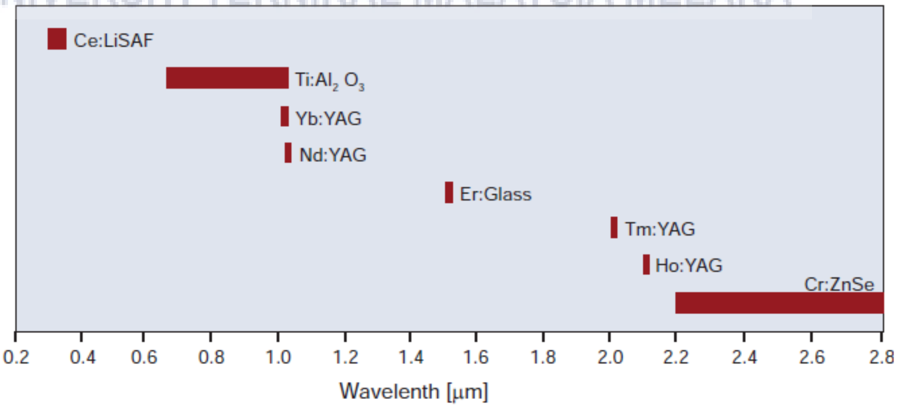


Figure 2: Bandwidths of laser gain for popular solid-state laser materials

2.2.5 Fibre laser

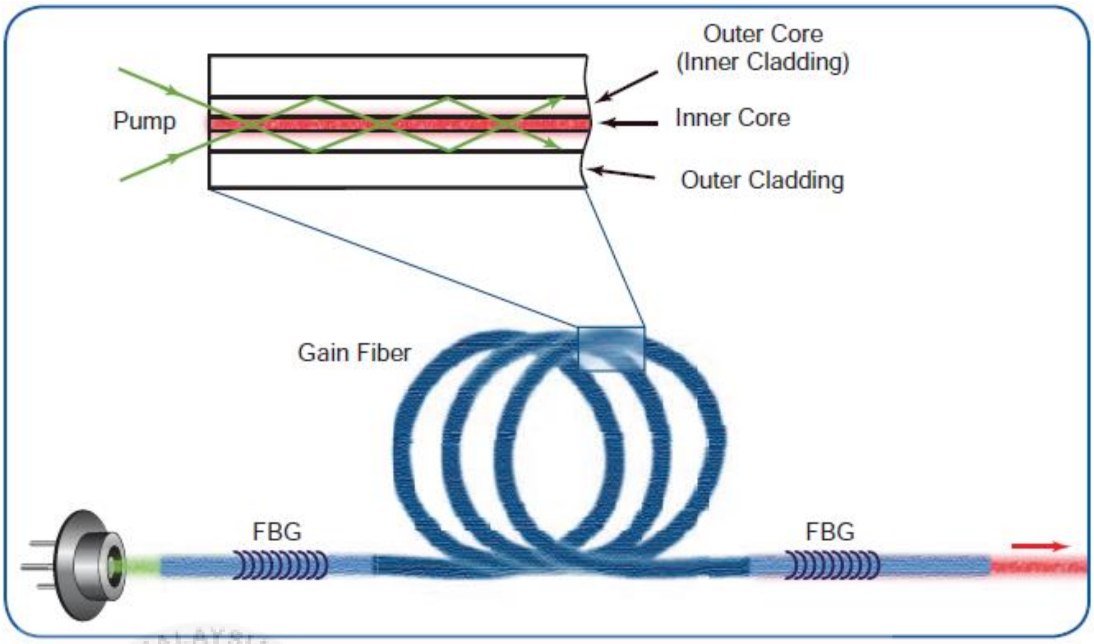


Figure 3: A simplified design of a laser diode-pumped fibre laser with reflectors made of fibre Bragg gratings (FBGs). [5]

A fibre laser is generated when a solid-state gain medium is built into an optical fibre and a resonator is incorporated [6]. Because of the unique light-guiding features of fibres, such as significant spatial confinement over extended distances, this class of lasers is normally handled independently from the "bulk" solid-state lasers mentioned above. A fibre laser is described as a laser in which the optical fibre serves as the gain medium, as opposed to another form of laser or gain medium that is merely linked to an optical fibre. Laser-active ions are often doped into the core of the optical fibre, which is made of glass. The rare-earth elements like Yb, Er, and Tm, whose laser gain bandwidths are shown in Figure 2, are the most often used dopant ions. [5] [6]. Laser diodes or other fibre lasers optically pump almost all fibre lasers. Double-clad fibres, as illustrated in Figure 3, are frequently used to efficiently couple laser diodes with lower-quality spatial modes into fibres.. There are several methods for incorporating a resonator into a fibre laser design, including simply coupling the light out of the fibre and reflecting it off a standard cavity mirror, producing a fibre loop mirror, or using fibre Bragg gratings (FBGs) (see Figure 3) which may be made immediately in a fibre laser that can create high output powers, operate in either pulsed or continuous-wave mode, generate high-quality output beams, and cover a large portion of the NIR and MIR spectral regions. This explains why they are used in a wide range of applications such as optical fibre communications, laser surgery, LIDAR and range-finding, and seeding of stronger lasers. Fiber lasers are also dominant in the high-power continuous-wave materials processing business. [5] [3].

A fibre laser is a form of solid-state laser that is distinct from others. The gain medium in fibre lasers is an optical fibre (silica glass) combined with a rare-earth element. The optical fiber's light guiding capabilities are what distinguishes this form of laser: the laser beam is straighter and narrower than with other types of lasers, making it more accurate. Fiber lasers are also well-known for their tiny size, high electrical efficiency, cheap maintenance, and low operating costs. Fiber lasers are utilised in a variety of applications such as material processing , medical, and directed energy weaponry. Ytterbium and erbium-doped fibre lasers are examples of fibre lasers utilised for these purposes [5].

2.3 Methods for Pulsed-Laser operation

A laser in continuous-wave mode has a constant output power as a function of time. This is the outcome of attaining a steady-state condition in which the balance between laser cavity gain (determined by the population inversion, which is proportional to the pumping rate) and loss is maintained (which includes the cavity losses and the stimulated emission rate) [7]. As previously stated, it is frequently advantageous to operate lasers in a pulsed mode since this may considerably boost peak output power. Pulsed-laser operation is accomplished by passing a continuous-wave laser output via an external modulator that functions as a switch, enabling light to transmit for only brief periods of time. (see Figure 4, left). This straightforward strategy has several drawbacks. The approach is inefficient since the modulator blocks the majority of the light. Furthermore, the peak power must never surpass the CW source's average power. The duration of the pulse is likewise restricted by the modulator's speed. An internal, intracavity modulation technique is a more efficient way. (see Figure 4, right) [5] [7]. The lasing process may be successfully turned on and off by regulating the gain or loss in the cavity. Energy can be of two types:

(i) The laser medium stores a huge population inversion that may be swiftly released to allow lasing or

(ii) It is kept in the resonator until it is released. These technologies enable pulsed-laser output with peak strengths much above those of continuous-wave lasers. The next section discusses the most prevalent ways for producing laser pulses via internal modulation.

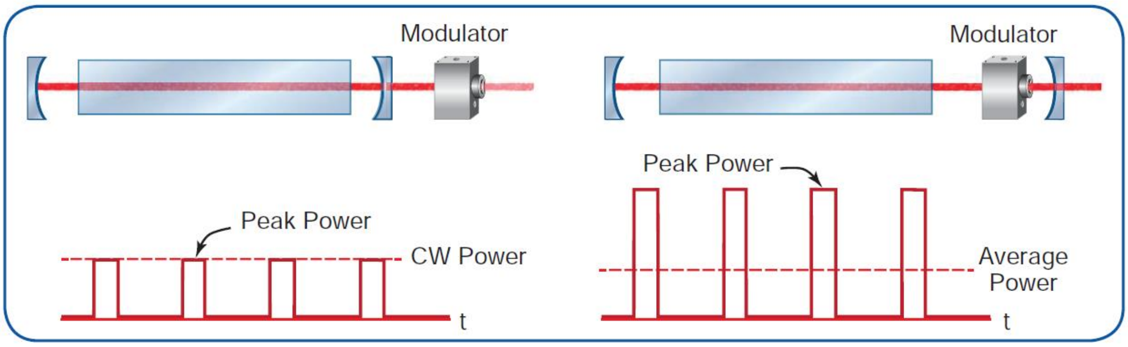


Figure 4: A comparison of pulsed laser outputs obtained using an external modulator (left) and an internal modulator (right) [5]

2.3.1 Gain Switching

For steady-state lasing, the gain remains constant because the stimulated emission depletes the population inversion as quickly as the pumping rate produces it. A temporary event known as gain switching can occur if the gain medium is pumped significantly quicker than the steady-state amount. The population inversion (and hence the gain coefficient) accumulates significantly quicker in this scenario than the rate of stimulated emission within the laser cavity. The photons in the cavity gain a tremendous amount of gain, resulting in a fast increase in laser intensity. As a result, considerable stimulated emission occurs, rapidly depleting the population inversion. The result is a short pulse of light (see Figure 5) [5]. Gain switching is a modulation technique in which the gain is changed by turning on and off the pumping source. This is possible through flashlamp pumping, which produces pulses in the µs to ms range. Gain switching, on the other hand, is most commonly utilised in semiconductor lasers since it is simple to vary the electric current needed for pumping. This can result in pulses with durations ranging from a few ns to tens of ps and repetition rates reaching several GHz. This approach is frequently used to create laser sources for optical telecommunications [7], where high repetition rates are desired to enhance the quantity of information transferred per unit time.

2.3.2 Q-Switching

Q-switching implies storing energy in the laser gain medium as well, but not via regulating the pump source. By ensuring that the cavity losses are significant, the laser pumping process is permitted to build up a population inversion considerably greater than the conventional threshold value, preventing lasing. The optical feedback is inhibited by inserting a loss into the laser cavity. The cavity feedback is turned back on when a substantial inversion has been established. The laser then experiences gain that much outweighs losses, and the accumulated energy is released in a brief and powerful light pulse. (see Figure 5) [5]. The quality factor (Q) is the ratio of a cavity's energy stored to its energy loss per cycle. This modulation method is known as Q-switching because it entails switching the cavity Q from a low to a high value. Devices used for Q-switching must be able to rapidly modulate the cavity Q in order to create brief pulses and are classified as active or passive. Active devices, such as acousto-optical switches, electro-optical shutters, and revolving mirrors, require an external action to cause modulation. Passive devices switch automatically based on the element's non-linear optical response, such as saturable absorption in organic dyes or semiconductors. Q-switching produces ns laser pulses with pulse energy of mJ or larger [8, 5].

2.3.3 Cavity Dumping

Unlike the other approaches, which store energy in the laser medium via population inversion, cavity dumping stores energy in the photons within the resonator. [7]. For a short period, the losses within the resonator are kept low by making the cavity mirror transmittances minimal, thereby trapping photons in the cavity and allowing a strong pulse to build up. After one round trip, an intra-cavity element is switched and the pulse is "dumped" out of the cavity. (see Figure 5). An acousto-optic modulator or electro-optic shutter is commonly used as an optical switch. One advantage of cavity dumping over Q-switching is that the latter necessitates an increase in pulse duration as the pulse repetition rate increases. Cavity dumping, on the other hand, enables very high pulse repetition rates, such as several MHz, while preserving pulse lengths of a few ns. Cavity dumping can be used in conjunction with other pulse production techniques to extract larger pulse energy than would otherwise be possible [5].

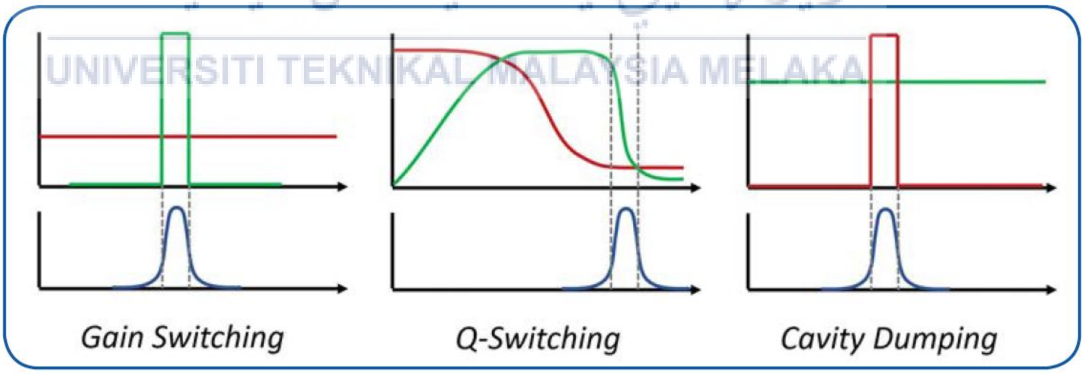


Figure 5: A schematic depicting several modulation methods for creating pulsed lasers, with loss (red), gain (green), and laser output (blue) represented as functions of time.

2.3.4 Mode-Locking

The pulse-generation techniques discussed above generate pulses that are just a few nanoseconds long. To create ultrafast pulses with durations as short as a few fs, a technique known as mode-locking is used, in which the cavity losses are modified on a regular basis during the laser pulse's round-trip time [5]. Mode-locking is a dynamic steady-state process, as opposed to the other techniques, which are based on transient phenomena within a laser cavity. If these laser modes are linked together and brought into phase at the mirror, constructive and destructive interference can occur, resulting in the formation of an ultrashort pulse (see Figure 6). The coupling of these modes is accomplished by the use of an extremely rapid intracavity shutter that runs at the intervals of the laser pulse's round trip and effectively coordinates the time of arrival of these modes, therefore locking their phases. Mode-locking devices, like Q-switching, can be active or passive. Various amplitude and phase modulators are examples of active devices that require external modulation. Passive devices rely on nonlinear optical phenomena in appropriate materials, such as slow and rapid saturable absorption and intensity-dependent changes in the refractive index [5].

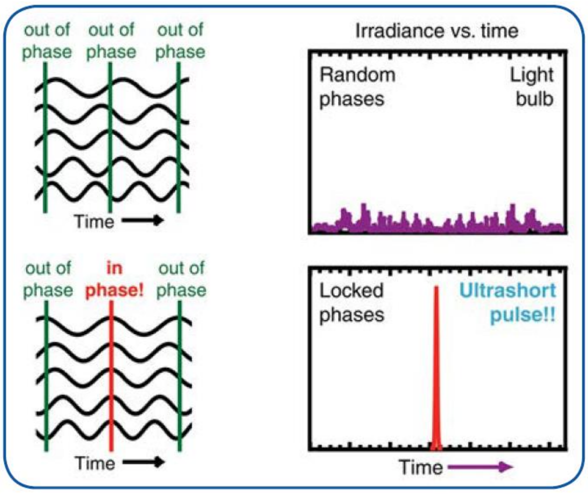


Figure 6: Locking the phases of the laser frequencies yields an ultrashort pulse.

2.4 Laser Operation Mode

All lasers may work in one of two ways: their laser beams can be pulsed or continuous. This is referred to as their way of operation. There is a continual flow of energy in continuous-wave lasers, which means that the laser constantly emits a single, unbroken laser beam. The most frequent example is a laser pointer's continuous beam. Continuous-wave lasers are frequently used for laser cutting and welding. The laser beam is interrupted at regular intervals in pulsed lasers, allowing energy to accumulate and achieve a higher peak power than in continuous-wave lasers. The laser beam is emitted in pulses with a fixed period known as the pulsed duration. Many applications, such as spot welding and etching, need high energy densities.

2.5 Types of Pulse Durations

Pulsed lasers are classified into numerous types based on the length of their pulses. A modulator is a device that regulates the number of pulses per second. As a result, each pulse has a certain duration, which is referred to as pulse duration, pulse length, or pulse width. The pulse duration is the amount of time that elapses between the start and finish of a pulse. To pulse laser beams, several modulation mechanisms are utilised, including q-switching, gain-switching, and mode-locking. The greater the energy peaks, the shorter the pulse. The most popular units for expressing pulse duration are milliseconds (ms), microseconds (µs) [2, 6, 9], nanoseconds (ns), picoseconds (ps) and femtoseconds (fs).

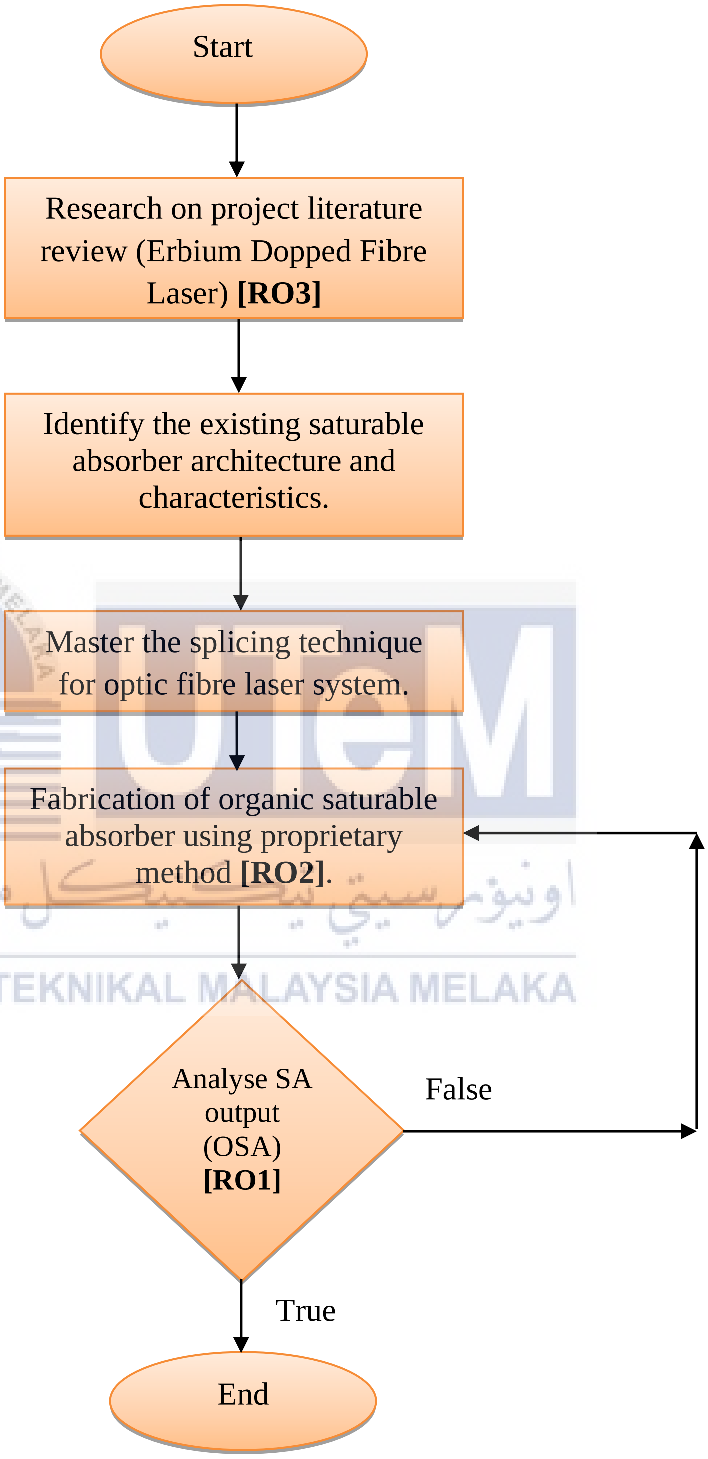
CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explained in detail about the research methodology used in the process to develop the PQS by using plant leaf. This chapter also outlined the research flow chart, research description, scope of work, limitation, and research process. The researcher describes the research design that was chosen for the purpose of this study and the reasons for this choice. The instrument that was used for data collection is also described and the procedures that were followed to carry out this study are included. The researcher also discusses the methods used to analyze the data. Lastly, the ethical issues that were followed in the process are also discussed.

3.2 Research Flow Chart



3.3 Research Description

Figure 7 depicts the proposed Q-switched EDFL. The employment of SAs material (eggplant leaf) within the Ring Cavity is critical to the creation of the pulse laser. A pump source with a fixed wavelength of 980nm from the Laser Diode (LD) pump was used to examine the performance of the Q-switch pulse laser. After that, the pump power going into 980/1550nm wavelength division multiplexer (WDM) interface. The erbium doped fibre (i-25) core with a length of 2.4 m was chosen as the model type of gain medium. To ensure only one-way operation and to prevent backscattering signal produced by self-pulsing instability within the q-switched laser cavity, the optical isolator was put after the gain medium.

The ring cavity uses a (90:10) coupler ratio to generate lasing effects in the 1.55-micron region while employing an EDF gain medium. Because the coupler deflected 90% of the light back into the ring cavity, only 10% of photons (light) are transmitted out for measurement. These measurements were obtained using an Optical Spectrum Analyzer (OSA), a Radio Frequency Analyzer (RFA), an Oscilloscope (OSC), and an Optical Power Meter, and they were recorded and analysed using a graph diagram technique (OPM).

3.3.1 Erbium Dopped Fiber Laser

3.3.1.1 Laser Diode Pump

a. Also known as Tunable Laser Source (TLS).

b. Provide high wavelength stability and narrow linewidth by selecting the wavelength.

c. Output match Erbium Dopped Fiber Amplifier EDFA at 1.48μm band wavelength (good efficiency).

3.3.1.2 Wavelength Division Multiplexing (0.98µm)

a. Fiber optic transmission technique that enables the use of multiple light wavelengths to send data over the same medium (optical fiber).

3.3.1.3 Erbium Dopped Fiber – Gain Medium

a. Material in the ring cavity that also called as gain medium (rare earth element – solid crystal).

b. Gain medium (Amplify optical signal in 1.55µm via optical excitation).

3.3.1.4 Isolator

a. Consists of passive magneto optic that only allows light to travel in only one direction.

b. Protect from back signal that can damage the laser source or modulate the amplitude.

3.3.1.5 Q-switch

a. Produce high energy pulse laser (mJ) with the 1.55 µm wavelength range in a short period of time (micro-to-nanoseconds).

b. Short pulses laser can be used for applications in medical diagnostics, material processing, surgery, ranging, and nonlinear optical frequency conversion.

c. The Q-switch was connected between the Erbium Dopped Fiber EDF and the Coupler.

3.3.1.6 90/10 Coupler

a. Take out 10% of the output laser from the Q-switch direct to the Optical Spectrum Analyzer (OSA) to analyze the frequency, time, and power output.

b. Whilst the 90% of the output laser will go back into the system.

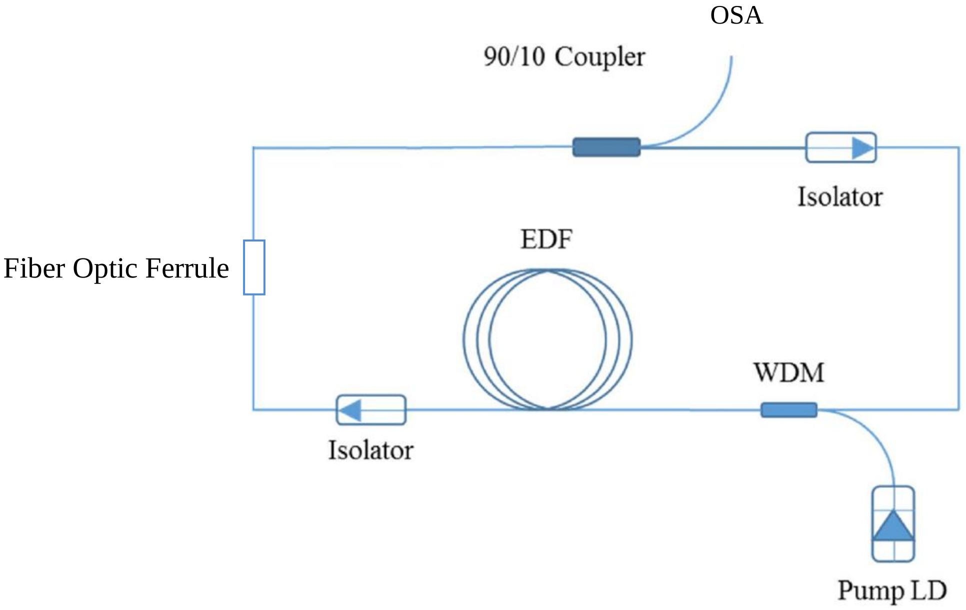


Figure 7: Erbium dopped Fiber Laser, EDFL

3.3.2 Identification of Existing SA architecture and characteristics

a. There are 2 types of Q-switches which is active and passive. In this technical research students are focusing more on the real passive Q-switch. [2]

b. Most of the real Saturable Absorber (SA) was experimented with fibre dopped rare earth material ions such as ytterbium ion (Yb3+), neodymium (Nd3+), erbium (Er3+), thulium (Tm3+) and holmium (Ho3+). These materials carry their own unique characteristics such as high refractive index, high efficiency, high solubility, low phonon energy, broad transmission region and some of it have unlimited power operation. [2] [5]

c. Instead of using the rare earth material which hard to find and cost consuming, the initiative of using organic material have been demonstrated to promote for future sustainable development goals.

3.3.3 Fiber optic splicing technique

Fiber splicing is the process of permanently joining two fibers together. Unlike fiber connectors, which are designed for easy reconfiguration on cross-connect or patch panels.

a. Put on the fusion splice protection sleeve.

b. Strip the fiber. Strip back all fiber coatings down to the 125um bare fiber. Clean the bare fiber with 99% isopropyl alcohol.

c. Cleave the fiber. The fiber needs to be cleaved with a high precision cleaver. Most splicing machines come with a recommended cleaver. Fiber cleaving is a very important step as the quality of the splice will depend on the quality of the cleave.

d. Put the fibers into the fiber holders in the fusion splicer. Press the start button to start the fusion splicing.
e. Heat shrinks the protection sleeve to protect the splicing joint.

3.3.4 Fabrication and synthesizing of organic saturable absorber using proprietary method.

The standard fabrication process for saturable absorber is by using some chemical reaction of isopropyl alcohol (IPA) and Polydimethylsiloxanes (PDMS) with the SA material such as Graphene Oxide (GO) [1]. For our case, this is one of the early-stage research and development of SA by using organic saturable absorber. For that, there will be another process before the general process below which is to burn the organic material under high degree until it can derive the presence of Carbon and then grind the organic material to be in a powder state. Below shows an illustration of the general process for preparing the Plant Leaf SA.

Because of its simplicity and inexpensive cost, a drop-casting approach was chosen to create the organic SA film in this study. As shown in Figure 8, this procedure includes preparing a base material solution (first stage), preparing a polymer solution (second stage), and mixing the two solutions together (third stage). The plant leaf powder was first dissolved in 50 cc of ethanol. The powder was entirely dissolved after 24 hours of stirring at room temperature.

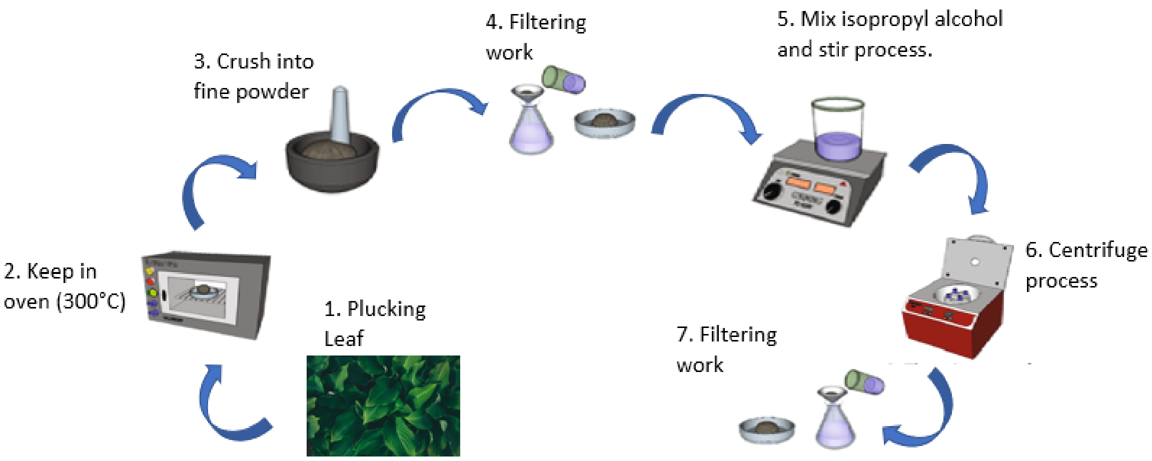


Figure 8: Synthesizing and liquid phase exfoliation process [2]

The solvent was then immersed in ultra-sonification for 45 minutes. Researchers utilized polyvinyl alcohol (PVA) as a polymer in the second stage because of its high melting point. To begin, heat 1 g of PVA with 100 ml distilled water to roughly 90 °C and stir until PVA is completely dissolved. Both solutions were combined for 2 hours in the third stage, resulting in the development of the composite pioneer solution. The pioneer solution was then placed into petri dishes and dried in the air humidifier for 24 hours at 55 °C to speed up the process of drying up the water/solution and then plant leaf SA film was obtained.

CHAPTER 4

RESULTS AND DISCUSSION

This study used SCG PVA SA film and plant leaf PVA SA film in an EDFL cavity (1.55-m). The following subtopics explain the precise laser cavity designs and laser performances. Figure 7 depicts the SA setup of EDFL with SCG and the eggplant leaf film. The cavity is made up of a 2.4 m long erbium-doped fibre (EDF) that serves as the gain medium and is pumped by a 980/1550 nm WDM (DKPhotonics-FWDM-95-L-1–25-10-FP). An isolator (OPLink-1550 nm) ensures that light propagates unidirectionally in the cavity. The 90/10 optical coupler in the EDFL cavity splits the laser output into two halves, with 90 percent remaining in the cavity and the remaining 10 percent routed out for measurements. A 1 mm × 1 mm (estimated) piece of SA film was sandwiched between the fiber ferrules connection in the cavity.

An OSA (Anritsu MS9710C: 600–1750 nm) was used to measure the optical spectrum of the Q-switched operation. The 350 MHz 5GS/s digital oscilloscope (GWINSTEK: GDS3352) was used to measure the Q-switched pulse train. A RFSA (Anritsu MS2683A 9 kHz- 7.8 GHz) monitored the radio frequency spectrum through a 1.2 GHz InGaAs photodetector (THORLABS: DET01CCG). An optical power metre was used to measure the optical power (PM100D THORLABS). The overall length of the cavity was estimated to be roughly 10 meters.

4.1 Spent Coffee Ground PVA SA Film (SCG) – Latest Organic SA

To understand the properties and relationship between the parameter of the pulsed lasers, the latest organic material SA, spent coffee ground (SCG) was examined. Figure 9 illustrate the connection between the repetition rate (kHz) and the pulse width (us) when the input pumping source power is increased. The repetition rate (kHz) of the proposed EDFL utilising spent coffee ground (SCG) as a saturable absorber were increase from 24.78 kHz to 43.75 kHz, with the corresponding input pump power varying from 74.12 mW to 121.1 mW before the SA's completely degrade (no pulse at oscilloscope trace). While varying the pump source (pump increase), the measured pulse width decreases from 18.6 us to 8 us. However, data analysis revealed that the most stable Q-switched pulsed laser was discovered between 71.26 mW and 99.21 mW of pumping source. These analyses were carried out using the pulse energy (nJ) produced. Based on Table 2, 0.12 mW to 0.56 mW of output power was created, with a pulse width of 18.6 us to 8 us.

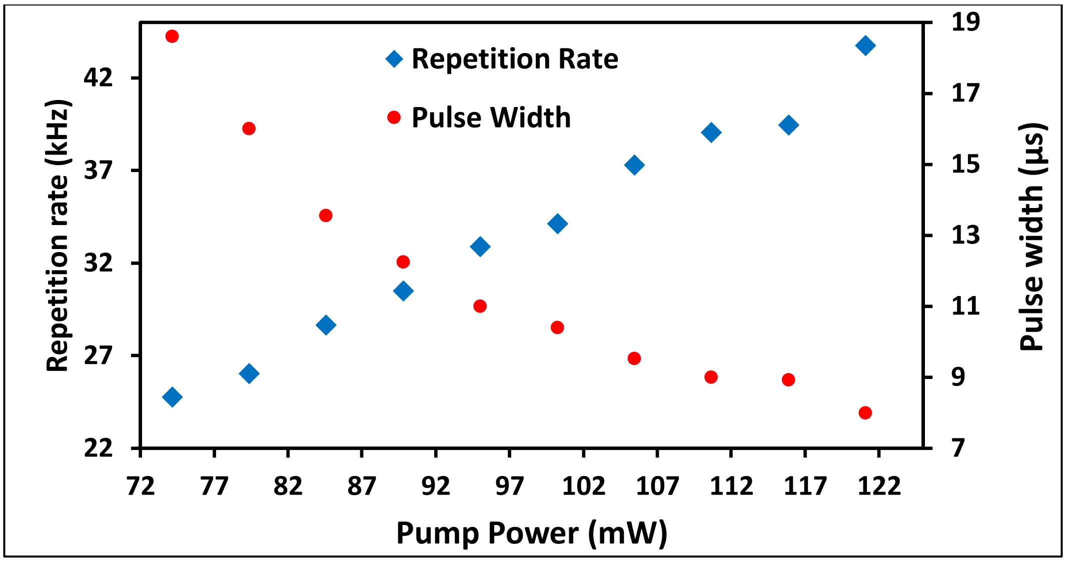


Figure 9: Repetition Rate and Pulse Width versus Input Pump Power of SCG SA Film

Table 2: Power Input (mW), Repetition Rate (kHz) and Pulse Width (µs) of SCG SA Film

Power Input (mW)	Repetition Rate (kHz)	Pulse Width (µs)
74.1397	24.78	18.6
79.3567	26.04	16
84.5737	28.65	13.55
89.7907	30.49	12.25
95.0077	32.89	11
100.2247	34.13	10.4
105.4417	37.31	9.525
110.6587	39.06	9
115.8757	39.47	8.925
121.0927	43.75	8

Whilst, Figure 10 represents the relationship between average output power (mW) and pulse energy (n.J) as a function of pump power. The data was collected, and it was discovered that when the pump source grew, both the average output power and the pulse energy rose synchronously. The greatest pulse energy obtained was 12.8 nJ with a pump power source of 121.1 mW. Due to cavity losses and material loss absorption, the slope efficiency for this suggested Q-switched EDFL cavity was 0.95 percent with the SA.

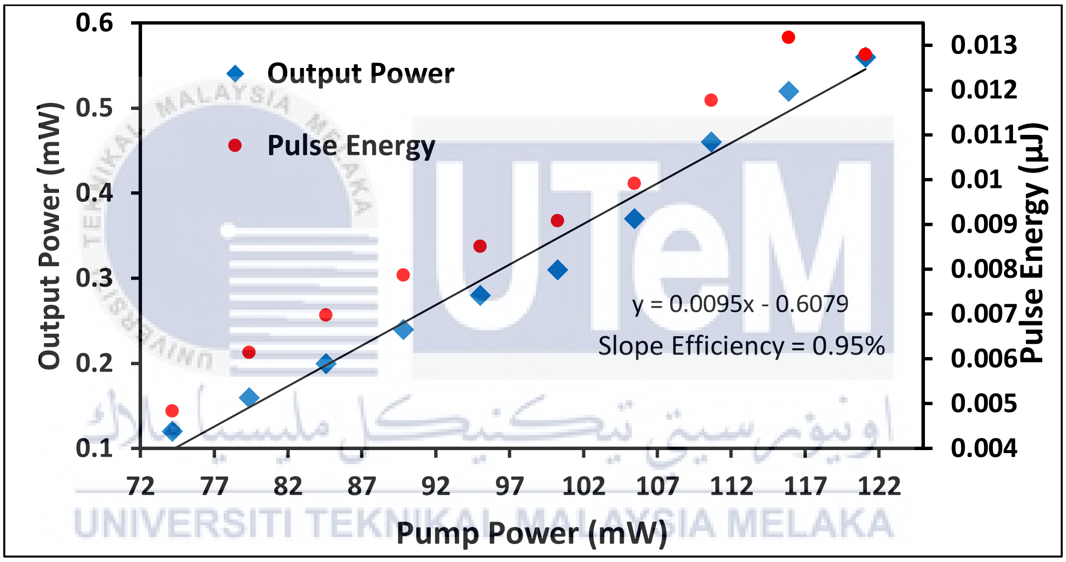


Figure 10: Output power and Pulse Energy versus Pump Power of SCG SA Film

Table 3: Output Power and Pulse Energy generated from the SCG Film with the Input Power and Current respectively

Input Current (mA)	Input Power (mW)	Output Power (mW)	Repition Rate (kHz)	Pulse Width (us)	Pulse Energy (uJ)
155	74.1397	0.12	24.78	18.6	0.00484
165	79.3567	0.16	26.04	16	0.00614
175	84.5737	0.2	28.65	13.55	0.00698

Input Current (mA)	Input Power (mW)	Output Power (mW)	Repition Rate (kHz)	Pulse Width (us)	Pulse Energy (uJ)
185	89.7907	0.24	30.49	12.25	0.00787
195	95.0077	0.28	32.89	11	0.00851
205	100.2247	0.31	34.13	10.4	0.00908
215	105.4417	0.37	37.31	9.525	0.00991
225	110.6587	0.46	39.06	9	0.01177
235	115.8757	0.52	39.47	8.925	0.01317
245	121.0927	0.56	43.75	8	0.0128

Based on the latest research using organic material from SCG film, the optical spectrum output after Q-switched can be analyzed thru the Optical Spectrum Analyzer (OSA). The Q-switched emission spectrum with a center wavelength of 1563 nm is shown in Figure 11 which happened when a substantial population inversion was attained, creating a single brief laser pulse. It is also induced by the fibre cavity's significant normal dispersion. This proven that the film operates in the C-band area.

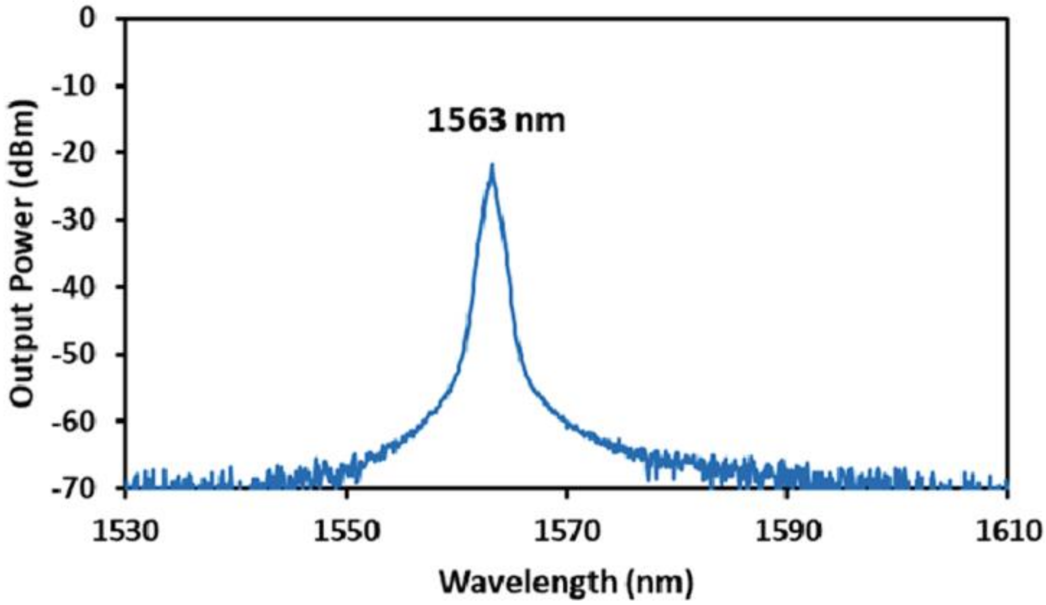


Figure 11: Output spectrum of SCG Film

4.2 Plant Leaf PVA SA Film

Figure 12 and Table 5 shows the steady pulse energy being detected and initiated at the pump source of 63.71 mW with a minimal output power threshold of 0.17 mW. According to the observations, when the pump power source (mW) increases, the repetition rate increases/varies from 16.67 kHz to 38.61 kHz with a steady pulse energy (nJ). Meanwhile, as the pump power is increased, the pulse width decreases. These relationships were inversely proportionate to one another. The shortest pulse width was 10.7 us, with the highest output power threshold at 1.21 mW, corresponding to a repetition rate of 38.61 kHz.

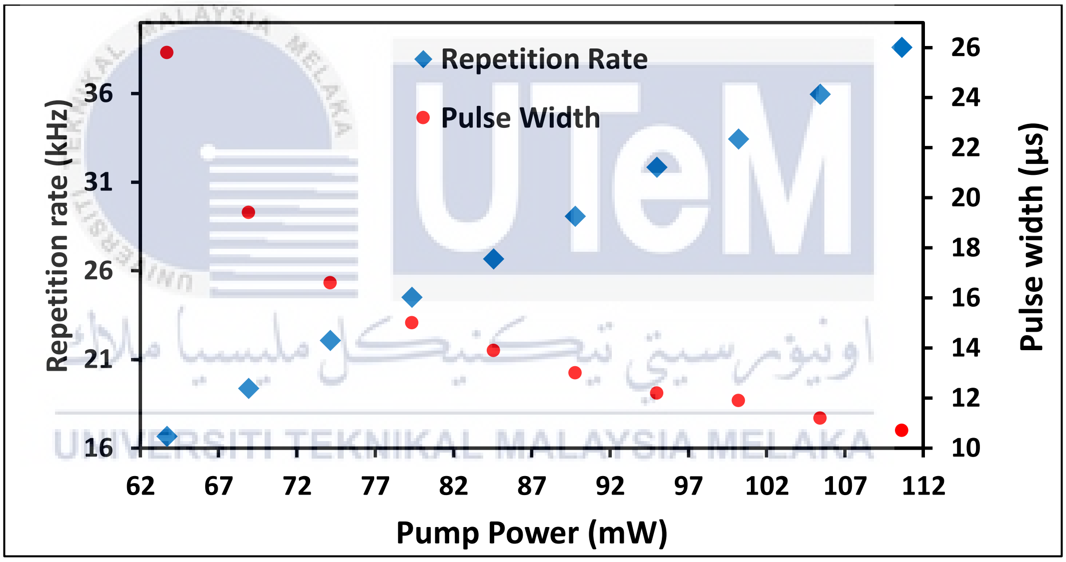


Figure 12: Repetition Rate and Pulse Width versus Input Pump Power of plant leaf SA Film

The mechanism of Q-switched pulse defined the relationship between the number of pulse width distance, repetition rate value, and pump power source. As the pump source was increased, more gain was given to saturate the SA, resulting in a reduction in pulse width and pulse period. Figure 13 depicts the observed output power and computed pulsed energy (nJ) ranging from 0.17 mW to 1.21 mW and 10.2 nJ to 31.34 nJ with a pump source varying from 63.71 mW to 110.66 mW. The output power and pulsed energy are monitored and computed using the 10/90 Optical Coupler's 10% fibre (OC). The slope efficiency for this Q-switched EDFL cavity was 2.35 percent with the SA. As in this research, the planned EDFL performance was recorded/detected utilising a digital oscilloscope (OSC) and an optical power metre at the same time (OPM).

Table 4: Power Input (mW), Repetition Rate (kHz) and Pulse Width (μs) of plant leaf SA Film

Power Input (mW)	Repitition Rate (kHz)	Pulse Width (μs)
63.7057	16.67	25.8
68.9227	19.38	19.4
74.1397	22.08	16.6
79.3567	24.51	15
84.5737	26.67	13.9
89.7907	29.07	13
95.0077	31.85	12.2
100.2247	33.44	11.9
105.4417	35.97	11.2
110.6587	38.61	10.7

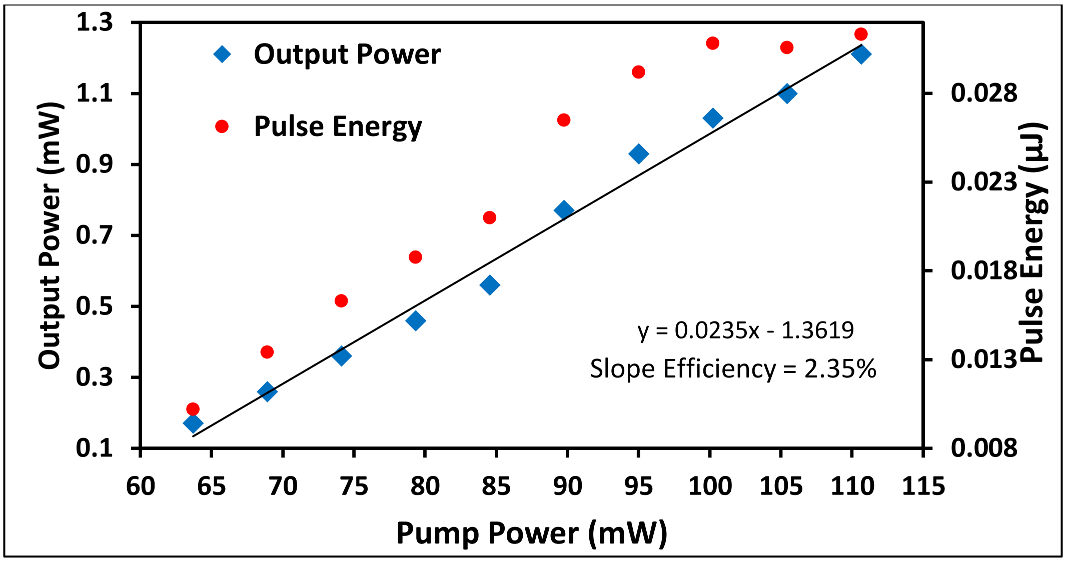


Figure 13: Output power and Pulse Energy versus Pump Power of plant leaf SA Film

Table 5: Output Power and Pulse Energy generated from the plant leaf SA Film with the Input Power and Current respectively

Input Current (mA)	Input Power (mW)	Output Power (mW)	Repition Rate (kHz)	Pulse Width (us)	Pulse Energy (uJ)
135	63.7057	0.17	16.67	25.8	0.01019
145	68.9227	0.26	19.38	19.4	0.01341
155	74.1397	0.36	22.08	16.6	0.01630
165	79.3567	0.46	24.51	15	0.0187
175	84.5737	0.56	26.67	13.9	0.02099
185	89.7907	0.77	29.07	13	0.02648
195	95.0077	0.93	31.85	12.2	0.02919
205	100.2247	1.03	33.44	11.9	0.03080
215	105.4417	1.1	35.97	11.2	0.03058
225	110.6587	1.21	38.61	10.7	0.03133

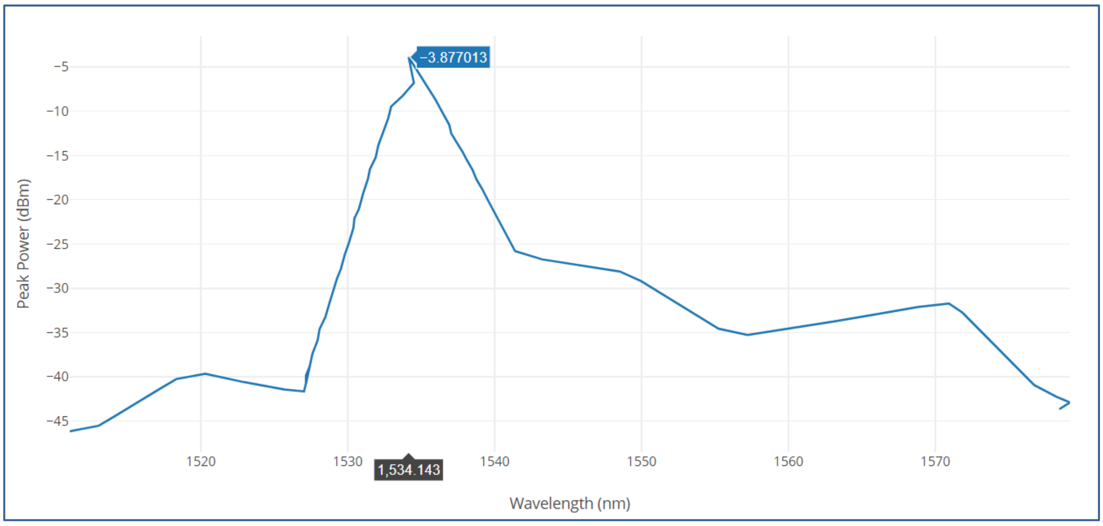


Figure 14: Output optical spectra at 110.66mW (Q-switched-SA)

The Q-switched emission spectrum with a center wavelength of 1534.143 nm is shown in Figure 14. The Q-switched spectrum has a narrow bandwidth than the continuous wave spectrum (without SA) in Figure 15, which happened as a substantial population inversion was attained, creating a single brief laser pulse. It is also induced by the fibre cavity's significant normal dispersion. This demonstrates that the film operates in the C-band area. The change of the peak when the SA is inserted into the cavity is due to the insertion or intracavity losses of the SA film.

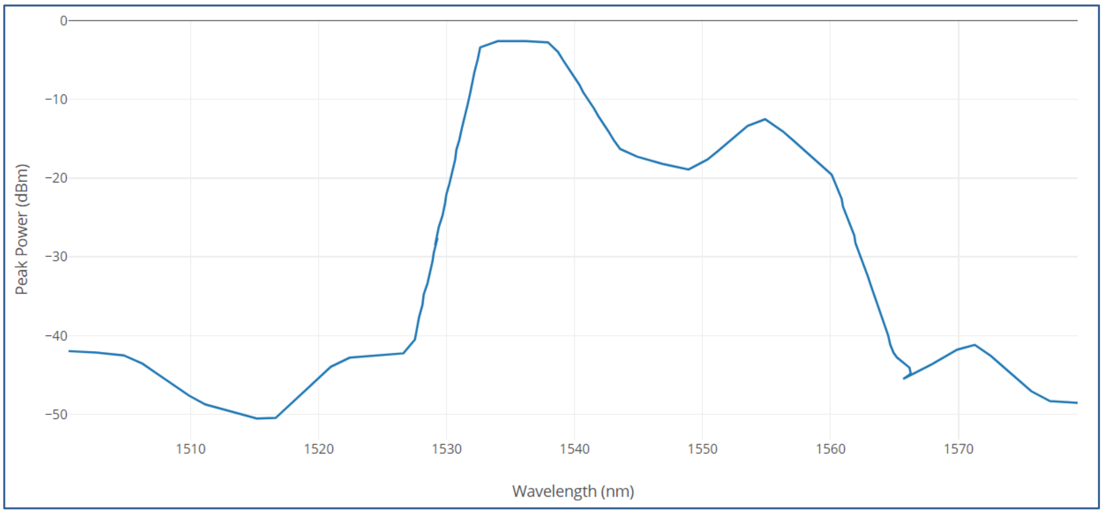


Figure 15: Output optical spectra at 110.66 mW (without SA film)

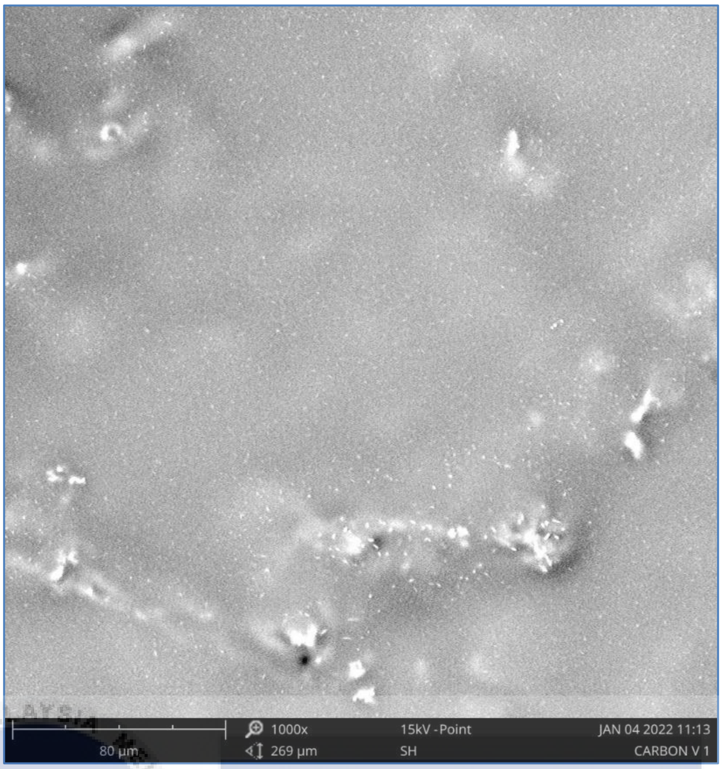


Figure 16: SEM image of plant leaf SA.

As to show the plant leaf is fully soluble into the PVA film through the fabrication process, the Scanning Electron Microscope (SEM) was conducted. To detect the microstructure of materials, a scanning electron microscope is always utilized. Based on Figure 16, the base material (plant leaf) were fully dispersed into the PVA film.

Table 6: EDS element percentage

Element Symbol	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. wt Conc.
C	64.48	57.68	C	100.00
O	35.52	42.32		

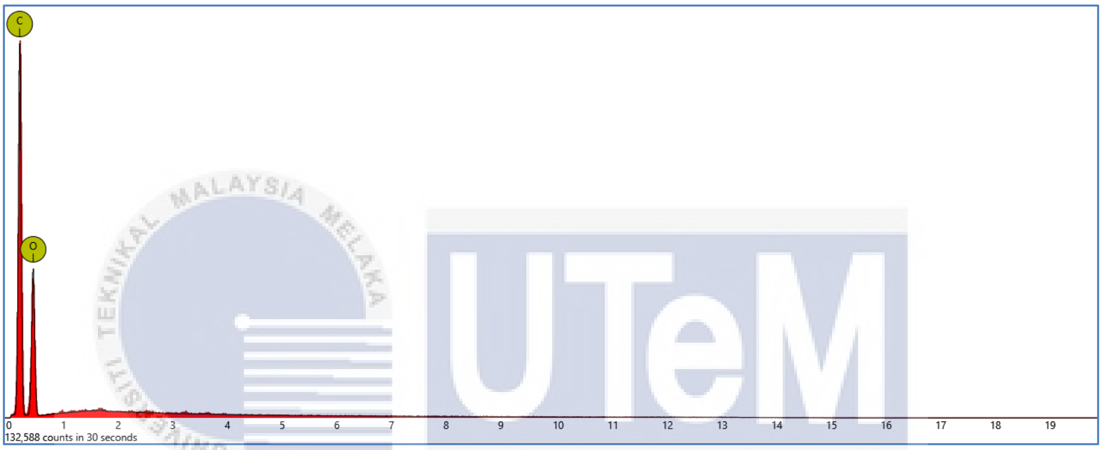


Figure 17: EDS analysis on plant leaf SA

The EDS spectrum of the plant leaf SA microstructure is seen in Figure 17. The SEM and Energy Dispersive Spectroscopy (EDS) are used to examine the morphology and elemental analyses of the plant leaf SA. Figure 17 depicts the picture of a plant leaf after it has been inspected by the EDS. As shown, the EDS analysis clearly demonstrates a significant intensity peak of carbon (C). The silicon oxygen (O) elements are present due to the fiber compound element identified by the EDS. This meant that the plant leaf can be used as a pioneer feedstock film for saturable absorber like other previous SA like SCG and graphene in pulse laser technology.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

The use of a saturable absorber (plant leaf) in the cavity allowed for the effective fabrication of Q-switched EDFL. Both ways for SA preparation that use the drop casting process are capable of producing a steady Q-switching pulse train. The conventional techniques were chosen primarily because they were cost effective, widely available materials, simple, and used little chemical operations in the SA production process. According to the study, employing plant leaf film directly onto the surface of a fibre ferrule in this research may produce the higher pulse energy of 31.34 nJ with a maximum power output of 1.21 mW, compared to SCG SA, which has a maximum pulse energy of 12.8 nJ and a maximum power output of 0.56 mW.

Eggplant plant leaf SA had a maximum pulse width and repetition rate of 10.7 us and 38.61 kHz, respectively. These studies are reported with maximum input pump power of 110.66 mW and 121.1 mW before the SA performance began to deteriorate or burned for those SA.

Based on the findings of this study, more work and development will be undertaken. Improvements in pulsed laser performance in large mode area fibres (due to lower device lengths, nonlinearity, and sensitivity to damage) are anticipated to lead to additional increases in the pulse energy and peak powers that can be produced from fibre systems. By leveraging developing nonlinearity and dispersion control approaches, 100 mJ Q-switched and multi-millijoule femtosecond systems are within reach. The ability to use spatial mode shaping on either diffraction-limited or strongly multimode (MM) beams opens up new and interesting possibilities. Using both bulk and fiber-based mode shaping methods, preliminary findings in this direction are beginning to emerge.

Combining such sophisticated lasers with appropriate feedback and adaptive algorithms should result in lasers that self-optimize their outputs to suit specific end applications, significantly improving process efficiency and control. Clearly, many problems lay ahead in attempting to put such ideas into effect; yet, possibilities to make considerable inroads in this area exist and will undoubtedly be seized on in the future decade. There are several technical options available, such as coherent or incoherent, active or passive, multi-core fibres or multiple single-core fibres. Major effort in these areas is expected in the future decade, with significant improvement expected in both the cw and pulsed regimes.

With new glass types providing increased wavelength coverage and breakthroughs in external frequency conversion from the soft X-ray to terahertz domains, the future prospects for fibre laser research and commercialization look highly promising.

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APPENDICES

This part is where all the process of this research will be compiled. All the cost projection with the timeline of the project will fully displayed in the appendices. On the other hand, the apparatus, material and the machine also will be provided based on its respective model as it can be reference for future research and development in the laser technology.

Table 7: Research Timestone

A. PERANCANGAN PROJEK
PROJECT PLANNING (GANTT CHART)

Senaraikan aktiviti-aktiviti yang berkaitan bagi projek yang dicadangkan dan nyatakan jangka masa yang diperlukan bagi setiap aktiviti.
List all the relevant activities of the proposed project and mark the period of time that is needed for each of the activities.

Aktiviti Projek Project Activities	SEM I																			SEM BREAK					SEM II															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Project Title Determination		X																																						
Proposal Defense Presentation			X	X																																				
Research on project literature review			X	X	X	X	X	X	X	X		X	X	X	X																									
Identify the existing saturable absorber architecture and characteristics.				X	X	X																																		
Master the splicing technique for optic fibre laser system.				X	X																																			
Construct the EDFL system						X	X	X	X		SEMINAR PSM I																											SEMINAR PSM II		
Fabrication of organic saturable absorber using proprietary method					X	X	X																																	
Analyse SA output (OSA)										X		X	X	X		X	X	X	X						X	X	X	X	X	X										
Data Documentation																													X	X	X	X	X	X						
Final Year Project Presentation																																					X			
Report Submission																																							X	X

Table 8: Cost Allocation for completion of the research

Unit	Components	Cost Allocation (RM)
	Provided and sponsored by PERG-UTeM Lab:	
1	1. Isopropyl Alcohol	-
1	1. SA film for fabrication	-
1	1. Fiber Optic	-
1	1. 90/10 Coupler	-
1	1. EDF	-
1	1. WDM	-
1	1. Isolator	-
	Purchase by students:	
1	1. Beaker	70.00
1	1. Tweezer	68.00
1	1. Grinder	40.00
	Total (RM)	178.00

Figure 18: Laser Diode Newport Model 6100

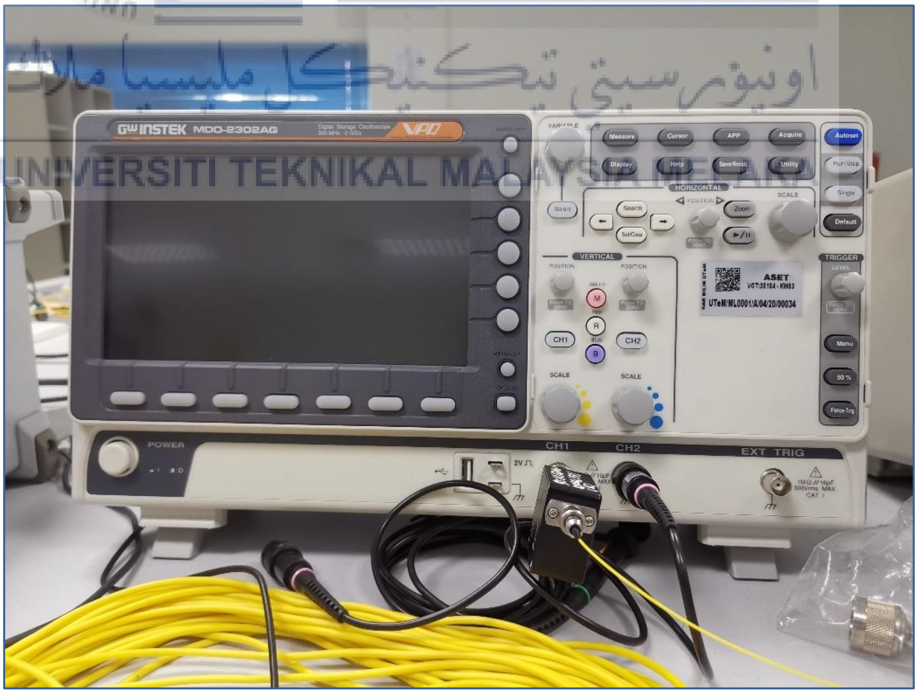

Figure 19: Digital Storage Oscilloscope GWINSTEK MOD-2302AG

Figure 20: Spectrum Analyzer 9kHz - 3 Ghz (PSA-3000)

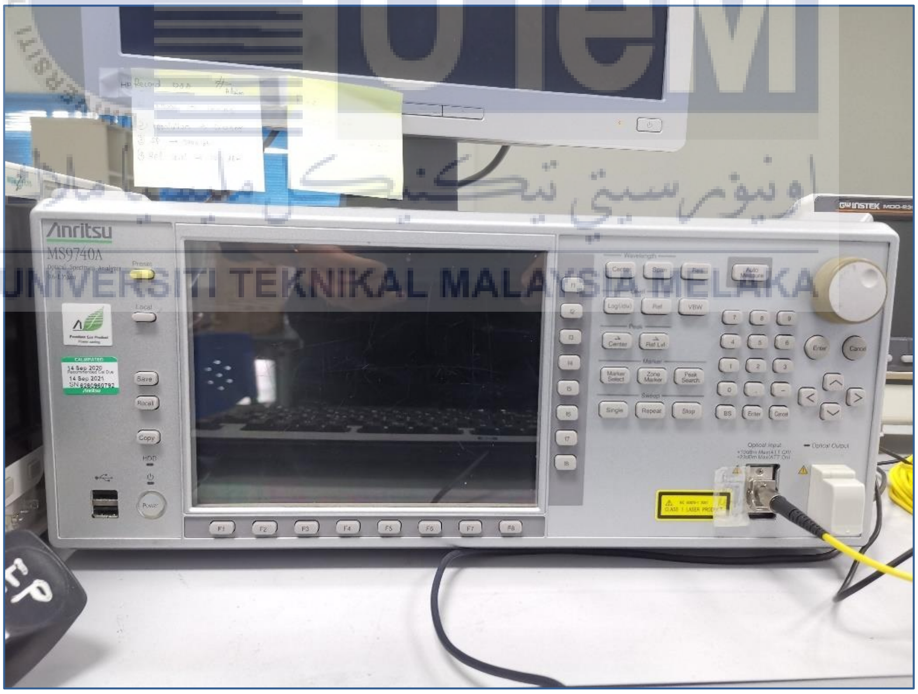

Figure 21: Optical Spectrum Analyzer Anritsu MS9740A

Figure 22: Ecocell Oven

Figure 23: Arc Fusion Splicer (Fujikura)

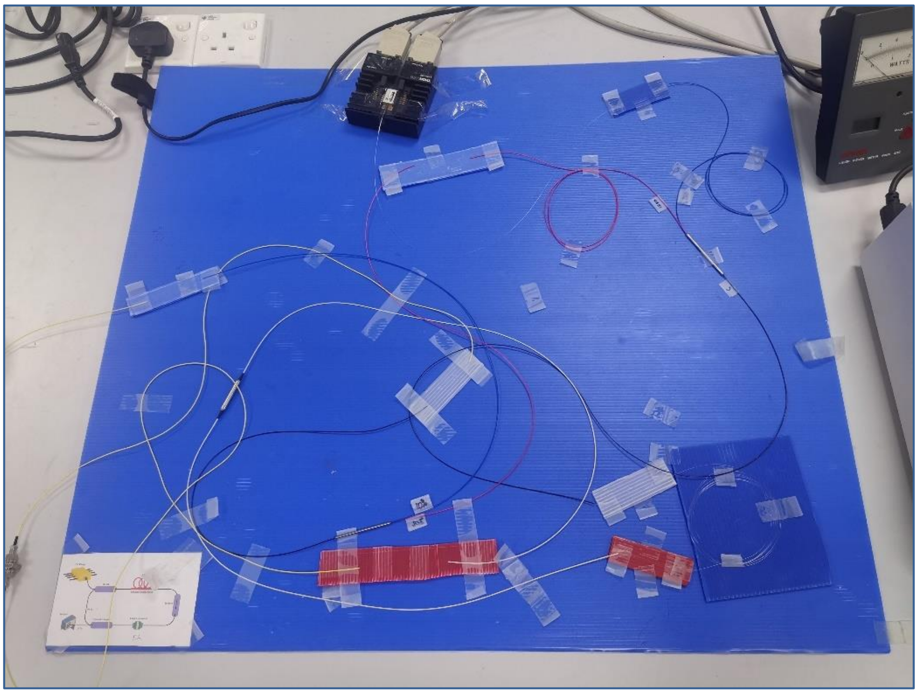

Figure 24: Erbium Dopped Fiber Laser cavity

Figure 25: Isolator

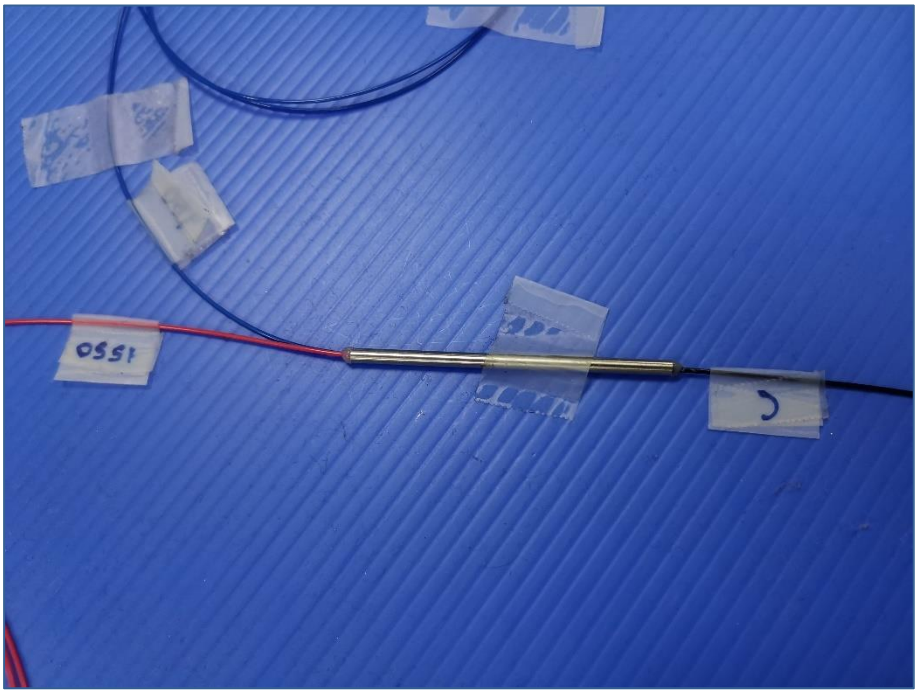

Figure 26: Wavelength Division Multiplexing (WDM)

Figure 27: 90/10 Coupler

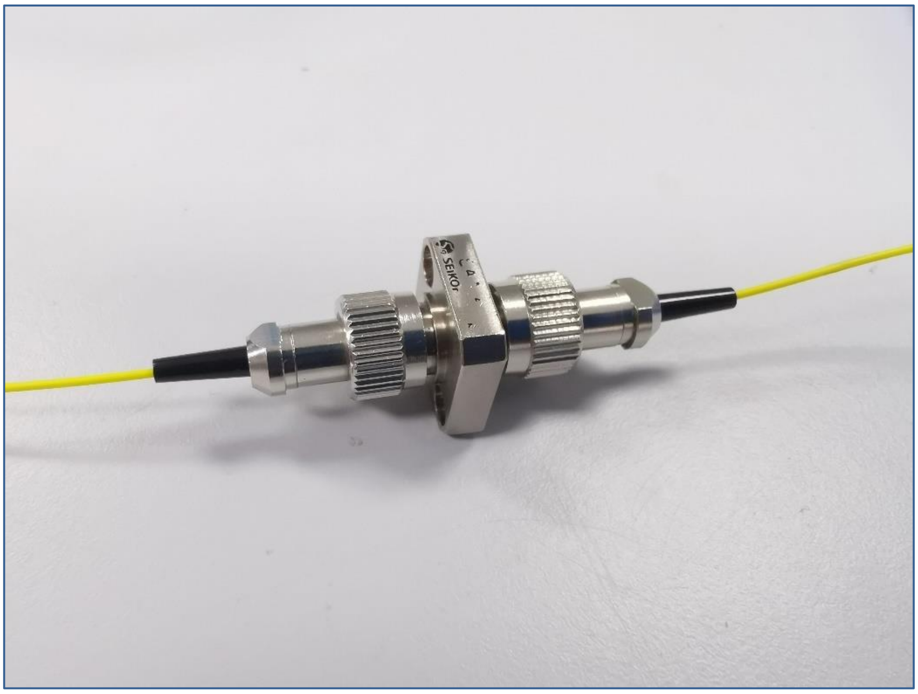

Figure 28: SA fiber ferrule connector (Q-switched)

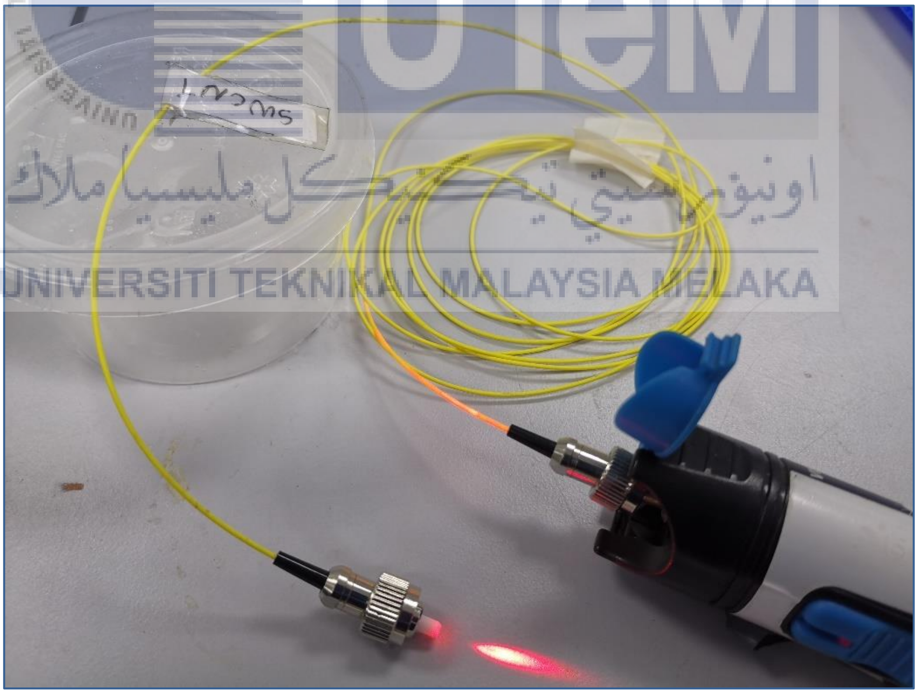

Figure 29: Visual fault locator

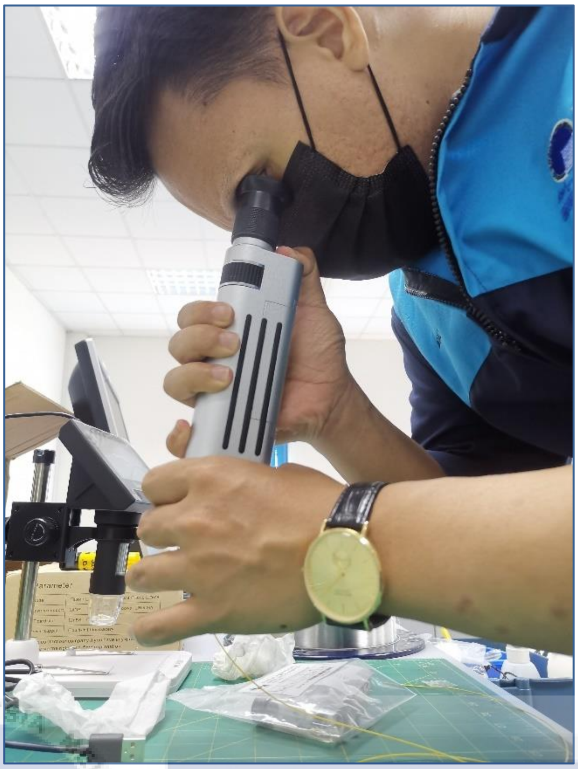

Figure 30: Precision rated fiber optic telescope

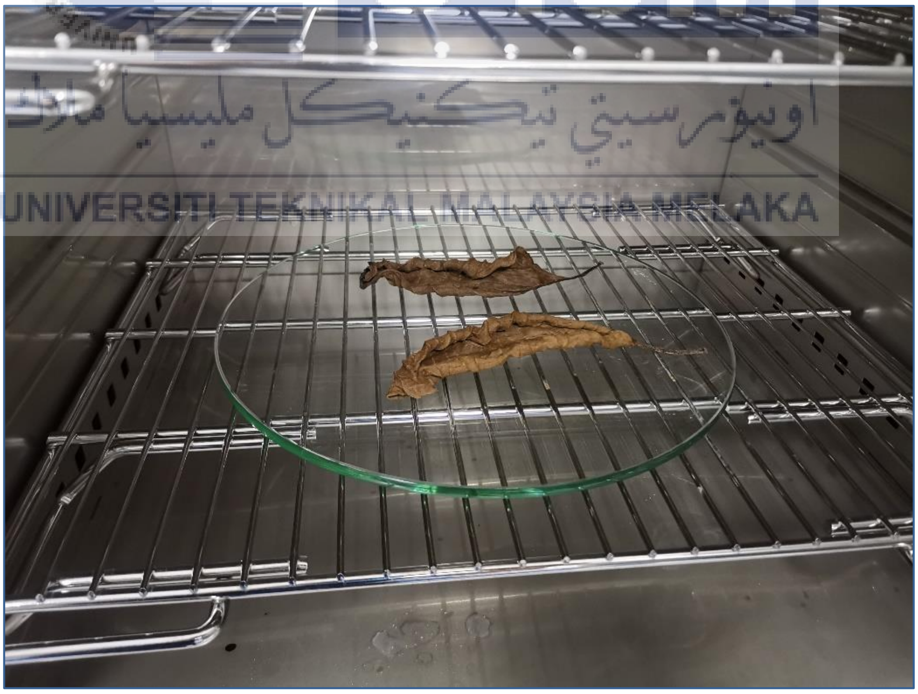

Figure 31: Dried up leaves in the lab Ecocell microwave

Figure 32: Grinding process for the making of SA base powder

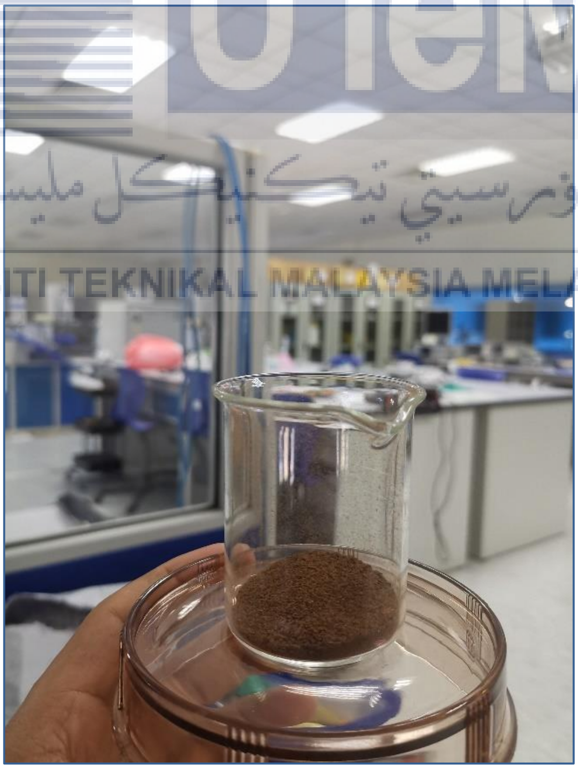

Figure 33: Plant Leaf SA based powder

Figure 34: Plant leaf SA based powder - cont

Figure 35: Weighted the based powder to make SA solution

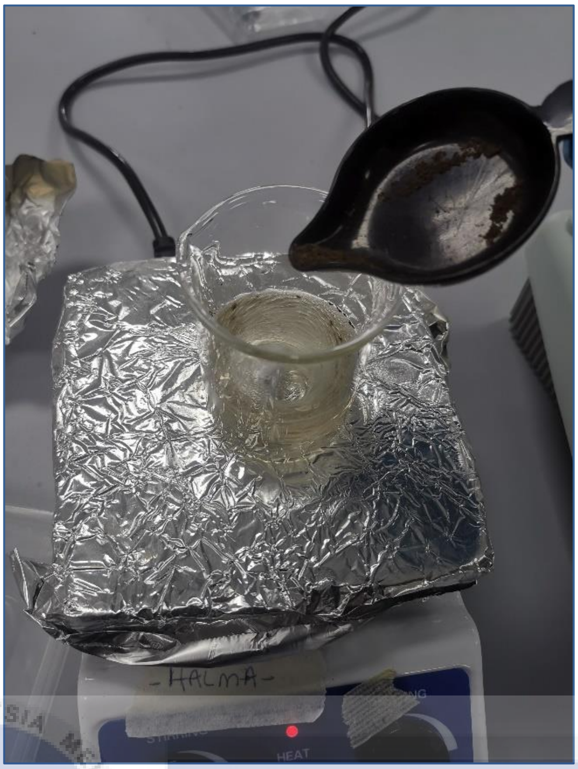

Figure 36: Stirring process after mixed up the SA based powder with alcohol

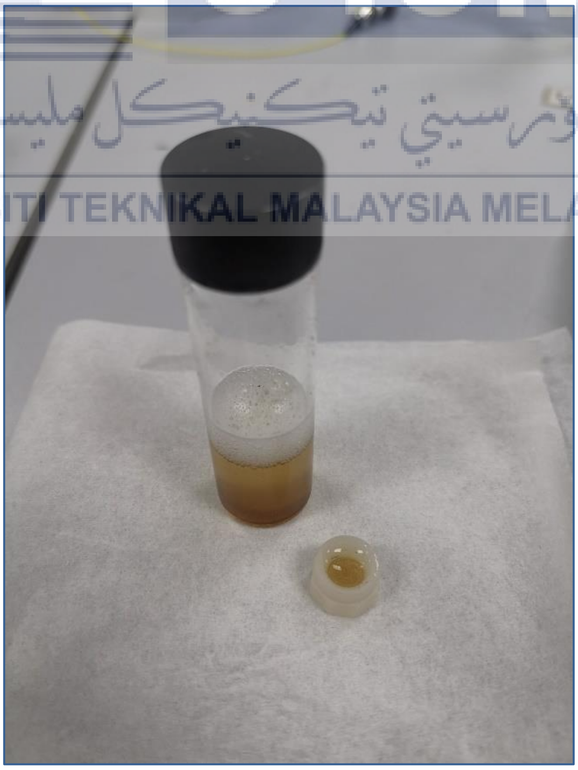

Figure 37: Plant Leaf SA solution

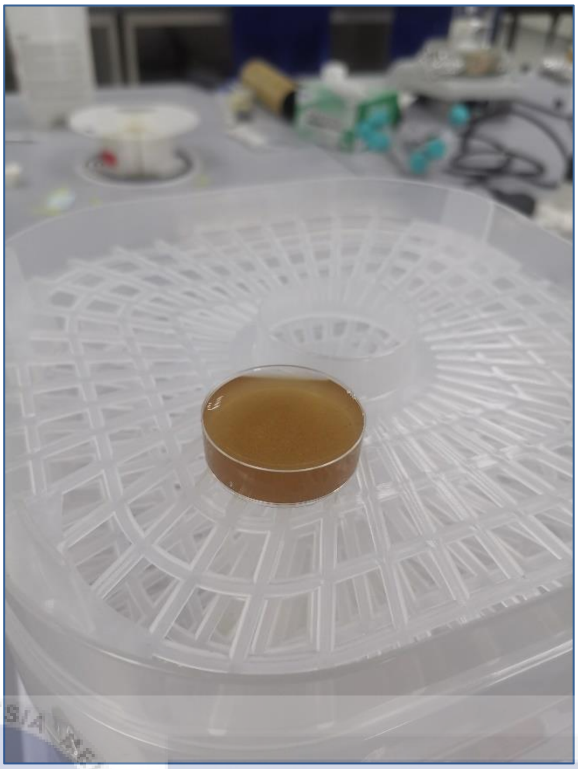

Figure 38: SA drying up process using air humidifier

Figure 39: SA plant leaf final product

Figure 40: SA plant leaf final product - Cont

Figure 41: Oscilloscope output showing that the stable pulse laser was achieved before tuning the signal to be readable

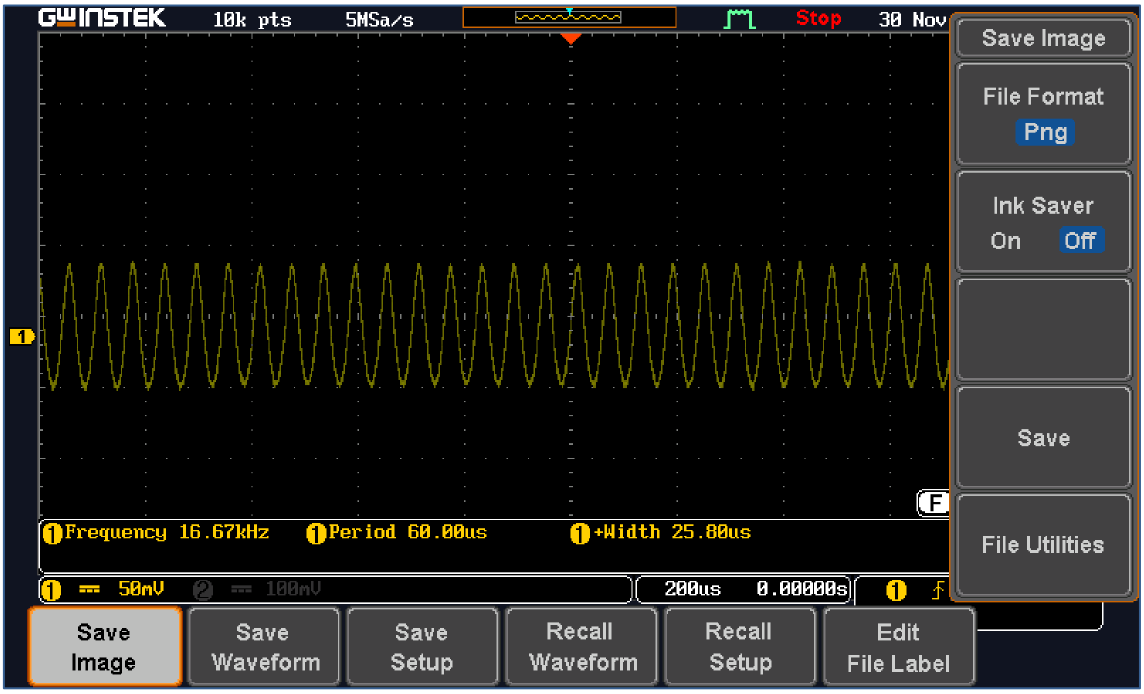

Figure 42: 1st data output (from minimum threshold value)

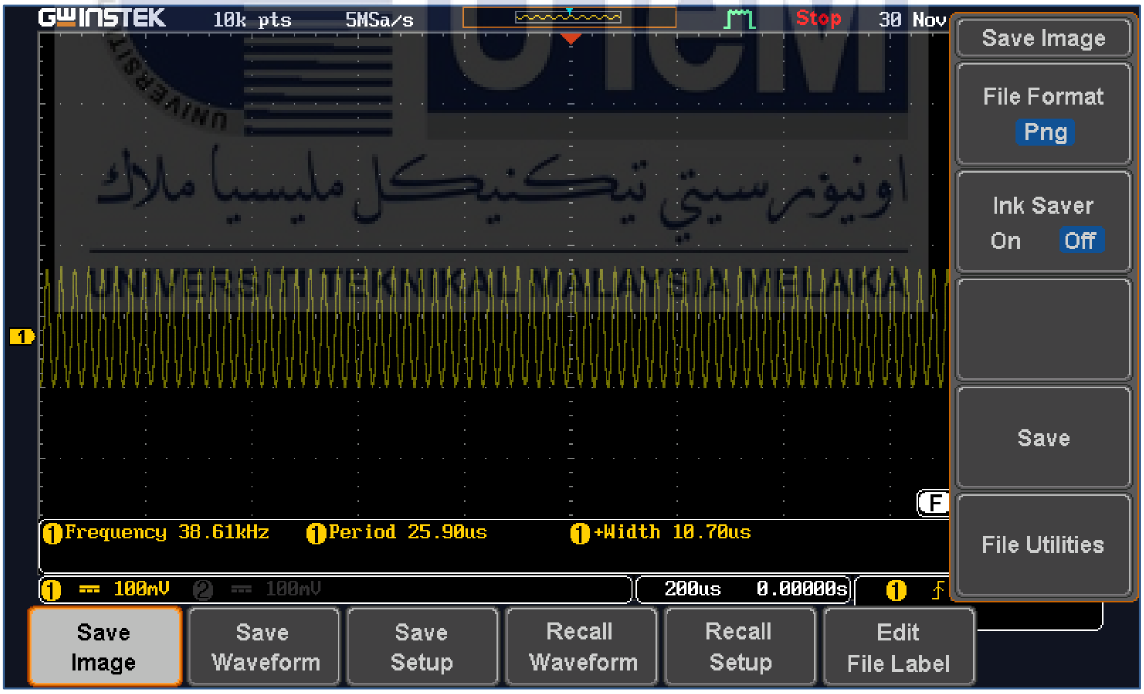

Figure 43: 10th data output (maximum threshold value)