Q-SWITCH ERBIUM DOPED FIBER LASER USING ORGANIC SATURABLE ABSORBER

MOHAMAD AL-AMEEN BIN AZME

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
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Q-SWITCH ERBIUM DOPED FIBER LASER USING ORGANIC SATURABLE ABSORBER

MOHAMAD AL-AMEEN BIN AZME

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in partial fulfilment of the requirements for the degree of
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2024

DECLARATION

I declare that this thesis entitled "Q-SWITCH ERBIUM DOPED FIBER LASER USING ORGANIC SATURABLE ABSORBER is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : MOHAMAD AL-AMEEN BIN AZME

Date : 19 June 2024

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APPROVAL

I hereby declare that I have checked this report entitled " Q -SWITCH ERBIUM DOPED FIBER LASER USING ORGANIC SATURABLE ABSORBER ", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electricals Engineering with Honours.

Signature	:	
Supervisor Name	:	Ts.Dr MOHAMAD FAIZAL BIN BAHAROM
Date	:	19 June 2024

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DEDICATIONS

To my supervisor,

Ts.Dr. Mohamad Faizal Bin Baharom,

To my beloved mother and father,

To all my supportive members,

Thank you for all your endless support .

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ABSTRACT

Over the past decade, fiber laser technology has garnered significant technological focus and benefits. They improve the instability, affordability of maintenance, efficient heat dissipation, simplicity, and reliability of existing bulk lasers. Q-Switched fiber lasers have recently garnered significant attention. They possess the capacity to generate pulses with considerable energy levels, making them valuable for a range of applications such as micro-machining, biomedical imaging, communication, remote sensing, laser range finding, and medical surgery. Fiber lasers may generate ultra-short pulses at repetition rates of millions and thousands of cycles per second, respectively, by functioning Q-switched states. This thesis proposed and demonstrated novel SA devices based on organic material which is Clam shell ($CaCO_3$) and for developing Q-switched fiber lasers operating 1.5 µm regions. New passive SAs based on Calcium Carbonate ($CaCO_3$) have been successfully characterized in this work. $CaCO_3$ materials were embedded into polyvinyl alcohol (PVA) to compose a film absorber, which was then sandwiched between two fiber ferrule connectors with a fiber adapter to form a fiber compatible SA. The Q-switched fiber lasers have been successfully demonstrated in 1.5-micron regimes by using the newly developed SAs. For instance, a Q-switched EDFL operating at 1568.64 nm of wavelength was demonstrated using the $CaCO_3$ SA. The laser generates a stable pulses train with a pump power range from 140mW to 170 mW with the maximum repetition rate 34kHz, the shortest pulse width of 14.3 µs and the highest pulse energy of 0.88021 nJ.

ABSTRAK

Sepanjang dekad yang lalu, teknologi laser gentian telah memperoleh tumpuan dan faedah teknologi yang ketara. Mereka meningkatkan ketidakstabilan, kemampuan penyelenggaraan, pelesapan haba yang cekap, kesederhanaan, dan kebolehpercayaan laser pukal sedia ada. Laser gentian Q-Switched baru-baru ini mendapat perhatian yang ketara. Mereka mempunyai kapasiti untuk menjana nadi dengan tahap tenaga yang besar, menjadikannya berharga untuk pelbagai aplikasi seperti pemesinan mikro, pengimejan bioperubatan, komunikasi, penderiaan jauh, pencarian julat laser dan pembedahan perubatan. Laser gentian boleh menghasilkan denyutan ultra-pendek pada kadar pengulangan berjuta-juta dan beribu-ribu kitaran sesaat, masing-masing, dengan berfungsi dalam keadaan Q-switched. Tesis ini mencadangkan dan menunjukkan peranti SA novel berasaskan bahan organik iaitu Clam shell ($CaCO_3$) dan untuk membangunkan laser gentian suis Q yang beroperasi di kawasan 1.5 µm. SA pasif baharu berasaskan Kalsium Karbonat ($CaCO_3$) telah berjaya dicirikan dalam kerja ini. Bahan $CaCO_3$ dibenamkan ke dalam polivinil alkohol (PVA) untuk membentuk penyerap filem, yang kemudiannya diapit di antara dua penyambung ferrule gentian dengan penyesuai gentian untuk membentuk SA yang serasi dengan gentian. Laser gentian bertukar Q telah berjaya ditunjukkan dalam rejim 1.5 mikron dengan menggunakan SA yang baru dibangunkan. Sebagai contoh, EDFL Q-switched yang beroperasi pada 1568.64 nm panjang gelombang ditunjukkan menggunakan CaCO3 SA. Laser menjana kereta api denyut yang stabil dengan julat kuasa pam dari 140mW hingga 170 mW dengan kadar pengulangan maksimum 34kHz, lebar nadi terpendek 14.3 µs dan tenaga nadi tertinggi 0.88021 nJ.

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LIST OF SYMBOLS AND ABBREVIATIONS

NaCl	-	Sodium Chloride
Nd: YAG	-	Neodymium-doped yttrium aluminium garnet
Er:YAG	-	Erbium-doped yttrium aluminium garnet
Cr_4+:YAG	-	Chromium-doped Yttrium Aluminum Garnet
CO_2+:$MgAl_2O_4$	-	Cobalt-doped magnesium aluminate spinel
CO_2+:ZnSe	-	Cobalt-doped zinc selenide
V_3+:YAG	-	Vanadium-doped yttrium aluminum garnet
EDFLs	-	Erbium Doped Fiber Laser
SAs	-	Saturable Absorber
$CaCO_3$	-	Calcium Carbonate
SCG	-	Spent Ground Coffee
HeNe	-	Helium-Neon

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1.1 Background

Fiber laser technology is being pursued with the investigation of clam shells as possible saturable absorbers in Q-switched erbium-doped fiber lasers (EDFLs). Q-switching is a laser technique that creates high-energy pulses. Applications ranging from telecommunications to materials processing depend on it[1]. In the past, synthetic materials like carbon and graphene Nonetheless, the growing focus on sustainable technology and the search for environmentally suitable substitutes has sparked curiosity about natural, biocompatible material[2].

Clam shells ($CaCO_3$) offer a special chance for this kind of investigation because of their complex biological makeup. The use of clam shells as saturable absorbers seems promising due to their ecological friendliness, possible nonlinear optical responses, and modulation depth. To optimize laser settings for improved Q-switching performance, this study aims to investigate the basic interaction between clam shell materials and erbium-doped fiber. Otherwise, it might not only enhance Q-switched EDFL technology but also further the more general search for environmentally friendly and naturally inspired photonic solutions.

Intriguing possibilities for saturable absorption in Q-switched EDFLs, clam shells have a special combination of characteristics due to their complex biological structure. Because of their plentiful supply and potential for nonlinear optical responses like saturable absorption due to their organic makeup, clam shells are a desirable and environmentally beneficial substitute for manufactured materials. Optimizing Q-switched EDFL performance requires a thorough understanding of the relationship between clam shells and erbium-doped fiber. Clam shell research as saturable absorbers is in line with the expanding movement to use natural resources for cutting-edge technology applications, supporting sustainability and lessening the negative environmental effects of laser technologies.

Clam shells ($CaCO_3$) may serve as organic saturable absorbers in Q-switched erbium-doped fiber lasers. This is the primary objective of this work. Along with other nonlinear optical properties of clam shells, this requires a detailed examination of the modulation depth and its impact on pulse creation. In this study, the fundamental physics behind the clam shell materials' interaction with the erbium-doped gain

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medium are clarified. Optimizing laser parameters and conducting experimental analysis are intended to enhance the Q-switching dynamics of erbium-doped fiber lasers. For nonlinear optical systems, clam shells provide an environmentally friendly and naturally inspired option. Their effective employment as saturable absorbers in Q-switched EDFLs will not only enhance laser technology.

1.2 Motivation

The motivation for researching Q-switched erbium-doped fiber lasers (EDFLs) lies in their pivotal role in advancing optical technologies. Q-switching enables the production of high-energy, ultrashort pulses, a characteristic highly desirable in applications such as telecommunications, sensing, and material processing. EDFLs, with their erbium-doped gain medium, offer a platform for generating such pulses. However, there is a continuous drive to enhance the efficiency, versatility, and environmental sustainability of these lasers. This research seeks to contribute to these objectives by exploring an integrating clam shell as saturable absorbers into Q-switched EDFLs.

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The motivation extends to the exploration of sustainable and biocompatible materials for optical devices. Synthetic saturable absorbers have been conventionally used, but the ecological impact of such materials raises concerns. Clam shells, as organic and naturally occurring entities, present a promising alternative. Utilizing clam shells as saturable absorbers not only aligns with the global effort towards sustainable technologies but also introduces the prospect of eco-friendly components in photonics. This resonates with the broader scientific and industrial commitment to reducing the environmental footprint of advanced technologies.

The motivation further stems from the intriguing possibility that clam shells may possess unique nonlinear optical properties. Clam shells, with their complex organic structure, have not been extensively studied in the context of photonics. Investigating their nonlinear optical responses, such as modulation depth and their impact on pulse generation, could unveil new opportunities for tailored applications. Understanding these properties is essential for harnessing clam shells effectively as saturable absorbers and optimizing their integration into Q-switched EDFLs.

Finally, the motivation extends to the broader advancement of laser technology and its applications. If successful, this research could lead to the development of more efficient and environmentally friendly Q-switched EDFLs. The outcomes may not only contribute to the optimization of these lasers but also pave the way for exploring bio-inspired materials in other nonlinear optical devices. This interdisciplinary approach has the potential to impact various fields, making the research not just a technological advancement but a step towards holistic and sustainable innovation.

1.3 Problem Statement

In the area of fiber laser technology, the development of Q-switched lasers has attracted significant attention due to their applications in various fields like telecommunications, sensing, and material processing. It is crucial to investigate alternative and environmentally sustainable materials for use clam shell as saturable absorbers to improve the efficiency and adaptability of Q-switched erbium-doped fiber lasers (EDFLs).

The necessity for effective and adaptable pulse production in fiber lasers is the focus of the problem statement for research on a Q-switched erbium-doped fiber laser employing clamshell as a saturable absorber. Q-switching is a commonly used method in laser technology to generate short-duration, high-energy pulses. Fiber lasers doped with erbium are well-known for their use in material processing, medical, and telecommunications. But selecting the right saturable absorber is essential to getting the best Q-switching results.

Besides that, the application of clam shells as organic saturable absorbers in laser technology offers a viable path towards pollution control and environmental sustainability. A natural and renewable source of material, clam shells are a byproduct of the seafood industry and are rich in calcium carbonate and organic matrix. Clam shells can be recycled and used as saturable absorbers in Q-switched Erbium-Doped Fiber Lasers (EDFLs) to achieve several environmental advantages and pollution avoidance techniques.

Otherwise, optimizing the nonlinear optical properties of clam shell materials is crucial for their application as saturable absorbers in Q-switched Erbium-Doped

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Fiber Lasers (EDFLs). The material's reaction to strong light, specifically how its absorption behaviors alter with changing light intensities, is referred to as nonlinear optical characteristics. Investigating the nanoscale interactions between incident laser light and clam shell is necessary to comprehend these nonlinear optical features. Effective modulation, in which the saturable absorber regulates the accumulation and release of optical energy to produce laser pulses, depends on this interaction.

The Q-switched EDFL system must incorporate the saturable absorbers developed from clam shells after they have been optimized. Making ensuring the Erbium-doped fiber gain medium is compatible and aligned correctly is necessary. Ensuring that clam shell materials are suitable for Q-switching applications will require systematic performance testing that evaluates pulse duration, repetition rate, and stability. The potential of the clam shell material as a sustainable and affordable substitute for conventional saturable absorbers in Q-switched EDFLs is maximized by an iterative method that incorporates testing feedback for ongoing fabrication process optimization.

As a result, using clam shells as organic saturable absorbers in Q-switched Erbium-Doped Fiber Lasers not only improves the laser system's performance but also offers a creative and sustainable alternative. This strategy lessens pollution, lessens the environmental effect of using conventional materials, and aids in the shift to more environmentally friendly and sustainable technology by recycling trash from the seafood sector.

1.4 Hypothesis

Organic materials generator from clam shells are proposed as exceptionally effective saturable absorbers in the laser system for research Q-switched Erbium-Doped Fiber Lasers (EDFLs). Clam shells, with their unique organic matrix and calcium carbonate mixture, offer a promising solution for controlling pulse dynamics in laser cavities with their inherent nonlinear optical characteristics. When saturable absorbers constructed on clam shells are included into the EDFL design, improved laser performance and hitherto unheard-of advantages including shorter pulse durations and increased pulse modulation are expected. The objective of this study is to investigate the potential of organic materials obtained from clam shells, offering a unique approach to improve the efficiency of Q-switched EDFLs by the utilization of sustainable, naturally occurring saturable.

1.5 Objective

The project for a study of Q-switched erbium-doped fiber laser using organic saturable absorber is aimed to fulfill the following three objectives:

1. To study a new organic material which Clams Shell ($CaCO_3$) as a saturable absorber by using Q-Switched erbium doped fiber laser(EDFL) setup.
2. To characterize the organic materials Clams Shell ($CaCO_3$) in terms of pulse energy,pulse width , wavelength, and repetition rate.
3. To compare the performance of clam shell($CaCO_3$) with others organic and inorganic materials in terms of pulse energy,pulse width , wavelength and repetition rate.

1.6 Scope

Organic saturable absorbers generated from clam shells in Q-switched Erbium-Doped Fiber Lasers (EDFLs) cover several important areas, with the main emphasis being on the production of Q-switched pulse lasers. First and foremost, the study intends to explore the inherent nonlinear optical characteristics of materials made of clam shells. This comprises a through examination of the organic components' recovery durations, nonlinear response, and saturable absorption properties inside clam shells. Comprehending these characteristics is essential for customizing the clam shell saturable absorber to efficiently adjust the pulses inside the EDFL system. The optimization of the absorber formed from clam shells for improved Q-switching performance will be guided by this fundamental exploration.

The scope of the project includes the careful design and optimization of the laser cavity, considering both ring cavity configurations of 1.55μm wavelength Erbium-Doped Fiber Laser (EDFL) ring cavity. The effective Q-switching with saturable absorbers produced from clam shells requires careful laser cavity design. To improve the performance of the Q-switched EDFL in the context of ring cavity configurations, the work will involve optimizing the shape and parameters of the ring resonator.

Finally, the project aims to assess the practical application of the clam shell-based Q-switched EDFL, going beyond the confines of the laboratory. This entails evaluating its performance parameters and contrasting them with conventional Q-switching methods. These criteria include pulse energy, pulse width, repetition rate and wavelenght. Furthermore, the environmental sustainability component will be highlighted, with an emphasis on clam shells' eco-friendliness and their capacity to lessen the environmental damage caused by traditional saturable absorber materials. The final goal is to investigate how saturable absorbers made from clam shells can be integrated into current laser technologies and to pinpoint possible uses. This study will be positioned within the larger framework of effective and sustainable laser systems.

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1.7 K-Chart

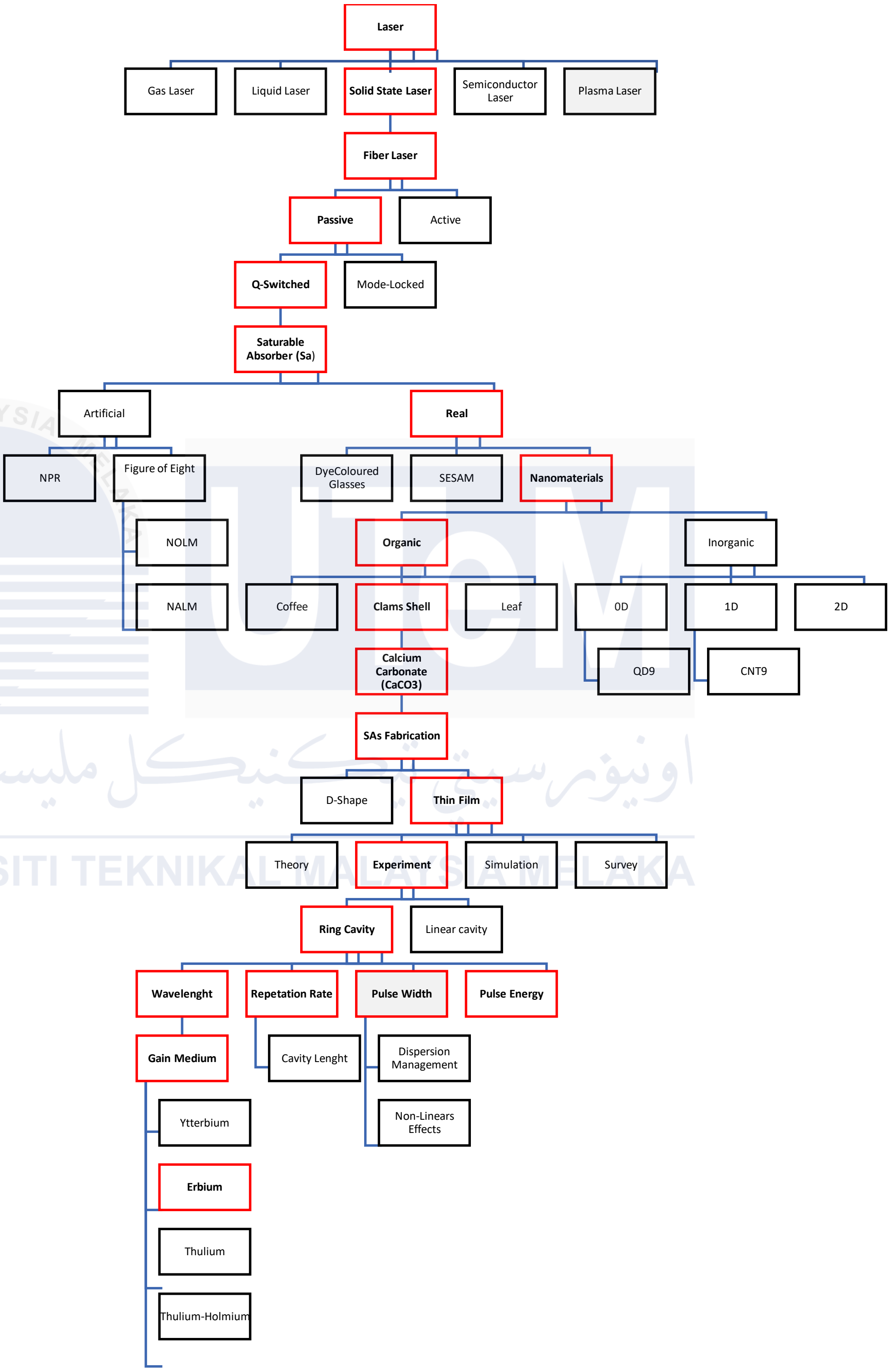

Figure 1: K-Chart.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Fiber laser technology gives a thorough introduction of lasers, their types, and an overview of erbium doped fiber lasers that use Q-Switch technology. This research on a Q-switched erbium-doped fiber laser uses clam shell as a saturable absorber to look at novel ways to increase the versatility and efficiency of fiber lasers. Q-switching is an essential technology used to create short-duration, high-energy pulses, and erbium-doped fiber lasers are helpful for many different applications. A suitable saturable absorber must be chosen to optimize the Q-switching process.

The unique optical characteristics, clamshell-based saturable absorbers offer an interesting possibility in this regard. In the context of Q-switched erbium-doped fiber lasers, the study will investigate the viability and efficiency of clamshell as a saturable absorber, analyzing its effects on pulse generation dynamics, nonlinear absorption behavior, and overall laser system performance. The study's expected results could contribute to our understanding of laser technology and have real-world consequences for material processing, medical treatments, and telecommunications.

2.2 Defination of Laser

The abbreviation for "light amplification by stimulated emission of radiation" is "laser." The visible, ultraviolet, and infrared portions of the electromagnetic spectrum are where laser's function. On July 7, 1960, Theodore H. Maiman produced the first laser by using ruby as the lasing medium to produce strong, high-energy flashes. The 1960s will always be remembered as the decade that created over ten distinct types of lasers using semi-conductor, liquid, gaseous, and solid lasing media [4]. Even now, technology is always evolving, and when more advanced lasers are developed, this tendency will continue. A solid understanding of lasers and light sources is required for optimal outcomes. Furthermore, to provide laser therapy that works, a basic grasp of.

Laser emission is shaped by the constraints of quantum physics, which limit atoms and molecules to having finite quantities of stored energy that change based on the kind of atom or molecule. An atom has its lowest possible energy when all its electrons are in the closest orbits to its nucleus (see electronic configuration). This phase is known as the ground state. When one or more electrons in an atom absorb energy and can reach outer orbits, the atom is said to be “excited”. Because light is generated as electrons move from higher to lower energy levels, excited states are often unstable.

It dawned on Einstein that there were two methods to generate this emission. Discrete light packets, or photons, are emitted on their own and without the aid of an outside source [4]. On the other hand, an atom or molecule may release light if the energy of the passing photon exactly matched the energy that an electron would release spontaneously upon falling to a lower-energy configuration. Whether a process is dominant is determined by the ratio of lower-energy to higher-energy combinations. Setups with less energy are usually more prevalent. Accordingly, it is more likely for a photon that spontaneously emits to be absorbed and raise an electron from a lower-energy configuration to a higher-energy configuration than it is for a second photon to be released to cause a higher-energy configuration to descend to a lower-energy configuration. Stimulated emission will cease if lower-energy states are more prevalent.

A population inversion cannot be produced by heat alone; an additional technique is needed to specifically excite the atoms or molecules [5]. Nonetheless, spontaneously released photons are more likely to trigger more emissions, creating a cascade of photons, if higher-energy configurations predominate (a situation referred to as population inversion)[6]. This is usually accomplished by either shining a strong light on the laser material or by running an electric current through it.

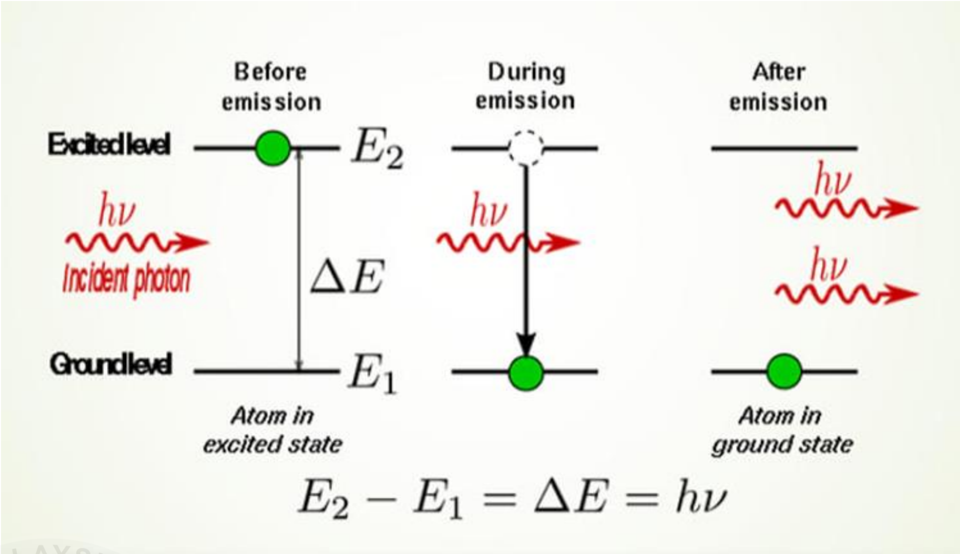

Figure 2: Behavior of atoms and molecules.

From figure 2, the behavior of atoms and molecules as well as the concepts of quantum mechanics serve as the foundation for the phenomena of radiation emission. Fundamentally, emission happens when a molecule or atom changes from a higher energy state to a lower energy state. Electromagnetic radiation, a release of energy, coincides with this shift. Nevertheless, these high-energy states are usually unstable, as electrons tend to relax down to lower energy levels.

The extra energy is released during this relaxation as discrete electromagnetic radiation packets called photons. The energy difference between the end lower energy state and the initial higher energy state is represented by the energy of these photons. This energy differential determines the frequency, and thus the wavelength, of the radiation that is emitted. This fundamental principle contributes to our understanding of the numerous mechanisms driving radiation emission across the electromagnetic spectrum. It underpins several natural and manmade processes, including fluorescence, atomic and molecular transitions, and laser operation.

2.3 Type of Laser

There are several varieties of lasers, or Light Amplification by Stimulated Emission of Radiation, each intended for a particular use. Semiconductor lasers use semiconductor materials to emit light; they are frequently found in commonplace technology such as laser pointers and DVD players. Neodymium-doped lasers, which are employed in industrial and medical settings, are an example of a solid-state laser that uses solid gain media such as crystals or glasses. Gas lasers, such helium-neon lasers, are used in barcode scanners and spectroscopy.

They use gas as the gain medium. Fiber lasers, which are frequently used in material processing and telecommunications, use optical fiber as the gain medium to produce highly efficient and high-quality beams. Finally, organic dye solutions are used as the gain medium in dye lasers, which provide tunability over a wide variety of wavelengths and is used in medical research. Every kind of laser has special qualities that make it ideal for applications in a variety of scientific and technological domains.

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Gas lasers amplify light by using a gaseous medium as the active gain medium. The helium-neon (HeNe) laser, which emits observable red light, is the most well-known gas laser. Another important kind of gas laser is the carbon dioxide (CO_2) laser, which emits infrared light. Gas lasers work by employing electrical discharge to excite gas molecules to higher energy levels, which causes them to produce photons when they return to lower energy states. Specifically, CO_2 lasers are extensively utilized in industrial settings for tasks like cutting, welding, and engraving because of their exceptional infrared power and efficiency.

A solid crystal or glass is used as the gain medium in solid-state lasers. Rare-earth elements like neodymium or ytterbium are usually the active ions in solid-state medium. Neodymium-doped yttrium aluminum garnet, or Nd: YAG, the lasers are common examples of solid-state lasers that are used in a variety of industries and fields, such as research, material processing, medical, and industry. Solid-state lasers are appropriate for a wide range of applications due to their high power, efficiency, and longevity.

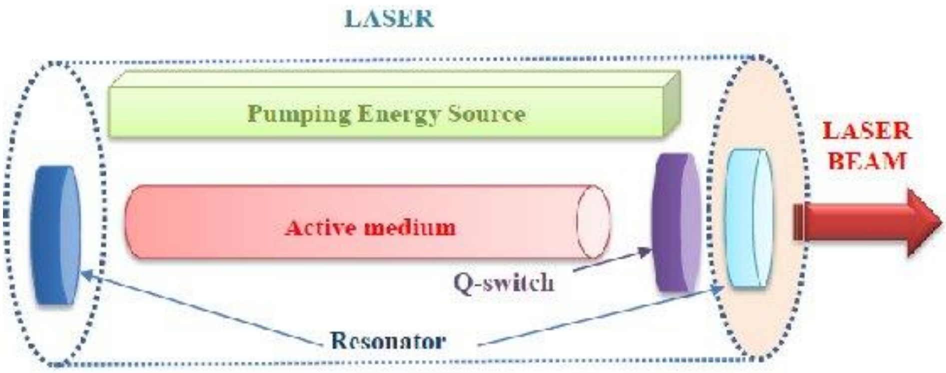

Figure 3: Solid State Laser Structure[6].

Table 1:Show the Advantages and Disadvantages for every types of Laser.

Types of Laser	Advantages	Disadvantages
Semiconductor Diode	-Compact size and low cost -Efficient electrical to optical conversion -Wavelength tunability	-Limited power scalability -Temperature sensitivity -Limited beam quality
Nd:YAG	-High power and energy	-Relatively large size and cost
Solid-State	-Continuous and pulsed operation -Good beam quality	-Cooling requirements -Fixed wavelength (in some cases)
Gas	-Excellent beam quality -Continuous and pulsed operation	-Requires special cooling methods -Fixed wavelength
Fiber	-Compact and lightweight design	-Limited power compared to some solid-state lasers
Fiber Optic	-Excellent beam quality -High efficiency in fiber delivery -Ideal for telecommunications applications	-Limited wavelength flexibility -Susceptible to damage from high-power pulses

2.3.1 Solid State Laser

A solid-state laser is a kind of laser that uses a solid gain medium instead of a gaseous or liquid one. This solid gain media is usually crystalline or glass. Rare-earth element ions, such as neodymium, ytterbium, or erbium, are present in the active gain medium of this laser setup. The active medium that can intensify light through stimulated emission is formed by these ions imbedded in a solid host material. Optical pumping is commonly used to excite the gain medium. This process involves supplying external energy to raise the energy levels of the electrons in the solid-state material. The process known as spontaneous emission occurs when these electrons go back to their lower energy states and emit photons. The laser's output is produced when the photons that are released excite the nearby excited ions, causing them to create coherent, monochromatic light[6].

Solid-state lasers have several benefits, including as steady output characteristics, small design, and high efficiency. These lasers are more robust and dependable due to their solid-state gain medium, which makes them appropriate for a variety of uses. Nd: YAG (neodymium-doped yttrium aluminum garnet) lasers, which emit light in the near-infrared spectrum, and Er: YAG (erbium-doped yttrium aluminum garnet) lasers, which function in the mid-infrared region, are typical examples of solid-state lasers.Solid-state lasers are widely used in many different domains, including research, industry, healthcare, and telecommunications, demonstrating their adaptability and usefulness in a range of technical applications[7].

2.3.2 Fiber Laser

A fiber laser is a kind of laser in which the gain medium is an optical fiber, and light amplification takes place inside the fiber. In contrast to conventional lasers that include larger gain media, fiber lasers have a more efficient and compact architecture. To improve the performance of the laser, rare-earth elements like erbium or ytterbium are usually doped into the gain medium. The excellent power efficiency of fiber lasers is one of their main benefits. Because of the optical fiber's unique design, light can travel long distances efficiently and concentrate into a small core, producing concentrated power. This architecture guarantees superior beam quality in addition to enabling the production of high-power laser beams.

Furthermore, because of the fiber's capacity to reduce the effect of external conditions on the laser's stability, fiber lasers are renowned for their dependability and longevity. Fiber lasers are extremely versatile and can be used in a wide range of fields, such as scientific research, healthcare, materials processing, and telecommunications. They have been widely adopted and have played a significant role in expanding laser technology because of their small size and ease of integration into various systems due to their compatibility with fiber optics.

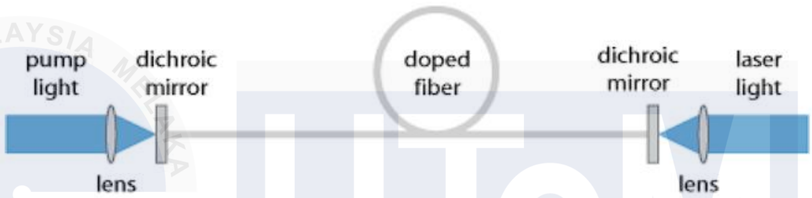

Figure 4 : Fiber laser sandwich compartment.

2.4 Passive and Active Fiber Laser

2.4.1 Passive Fiber Laser

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Passive Q-switching, or self Q-switching, automatically regulates the losses using a saturable absorber. Here, the pulse starts to develop as soon as gains (and hence, the energy stored in the gain medium) hits a sufficient threshold. Pump power changes usually only impact the pace at which pulses repeat; the energy and length of the pulses are usually constant (assuming complete absorber recovery in between).

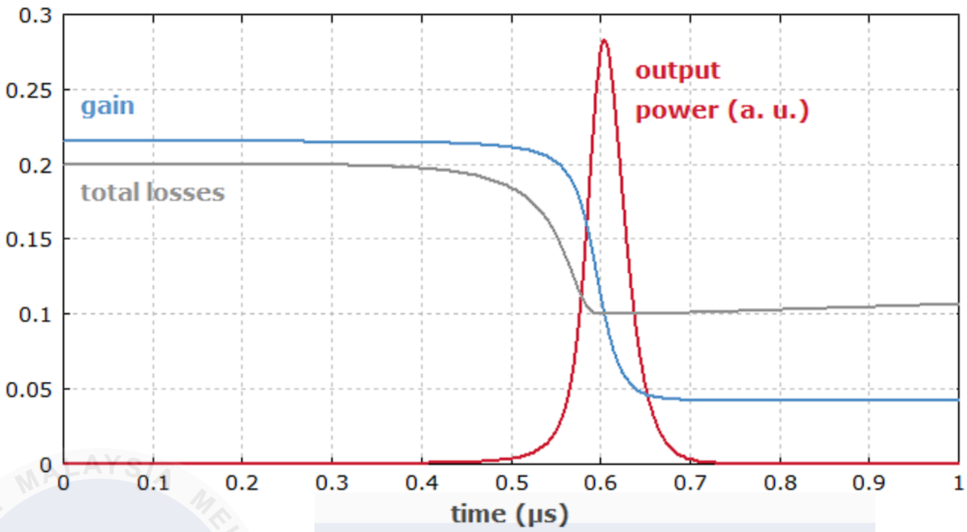

Figure 5: Temporale evolution of gain losses in passively Q-Switch laser .

A brief pulse is released shortly after the laser gain surpasses the resonator losses. When the absorber begins to become saturated, the power increases quickly until the gain reaches the 10% resonator losses threshold[8].

Saturable absorber materials such as Cr_4+: YAG are widely employed for passive Q switching of 1-µm YAG lasers. Co_4+: $MgAl_2O_4$, Co_4+: ZnS, and other cobalt-doped crystals, as well as glasses doped with PBSs quantum dots, are options for 1.5-µm erbium lasers. Crystals of V_3+: YAG are appropriate for the 1.3-µm range. Semiconductor saturable absorber mirrors are primarily utilized for lower pulse energy and can be utilized at different wavelengths [9].

Using a saturable absorber inside the laser cavity to produce regulated and quick pulses is the basis of a passively Q-switched fiber laser. The saturable absorber, a substance with a nonlinear optical response that modifies its absorption properties in response to the intensity of incident light, is the essential element in this arrangement. The saturable absorber effectively captures photons at lower light intensities; but, as the intensity rises, the material saturates, turning transparent and permitting light to pass through. This occurrence opens a "gate" within the laser cavity by allowing the saturable absorber to function as a passive modulator[10].

Changes in the intracavity light intensity cause the saturable absorber to alternate between high and low absorption states while the fiber laser is operating. In the low-absorption state, the absorber allows optical gain to build up inside the laser cavity[11],[12]. The absorber then quickly lowers the gain as it transitions to its high-absorption state, causing the stored energy to be released as a brief yet powerful pulse. The laser pulse duration is determined by the time it takes the saturable absorber to change states.

2.4.2 Active Fiber Laser

The active control element (active Q-switched) in active Q-switching is often an acousto-optic or electro-optic modulator, which is used to regulate the losses. Here, the generation of the light pulse is followed quickly by the receipt of an electrical trigger signal. One other kind of mechanical Q-Switched is the spinning mirror, which is employed as the end mirror in laser resonators. Depending on the pump power, pulse repetition rate, or energy stored in the gain medium, the generated pulse energy and length will vary.

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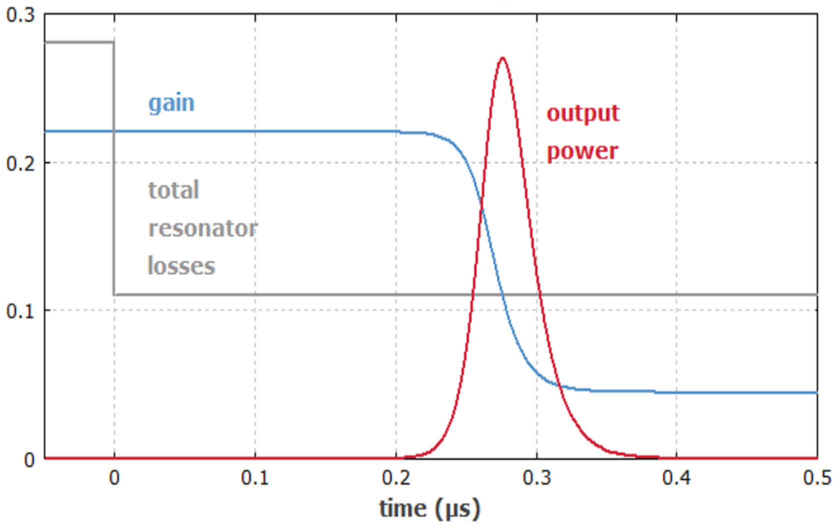

Figure 6 : Temporal evolution of gain and losses in an actively Q-switched laser.

At the zero second mark, the Q switch is turned on. At this point, the power begins to increase exponentially, reaching a peak only after approximately 0.2 us. In real-world scenarios, the delay time is frequently much longer than the pulse length[13]. It is interesting to note that since it takes multiple resonators round trips for a strong pulse to generate, the modulator switching time need not be equal to the pulse duration. In fact, it can be much longer. On the other hand, multiple pulses or other instabilities could result from a too long switching period[14].

2.5 Q-Switched Erbium-Doped Fiber Laser

Using active modulation of the laser cavity's quality factor (Q-factor) to regulate laser pulse emission is the basic working concept of a Q-Switched Erbium-Doped Fiber Laser (EDFL). The Q-switch is the essential part of this laser setup since it modulates the laser cavity's environment to allow optical energy to accumulate and abruptly release. In an Erbium-Doped Fiber Laser, the gain medium consists of erbium ions that are implanted within the fib[15], [16], [17]. Actively modifying the Q factor of the laser cavity is the Q-switched, which is often an acousto-optic or electro-optic device.

By keeping the cavity's losses high during the Q-switching operation, the Q-switch first stops a continuous laser oscillation from forming. The Q-switched is quickly shifted to a low-loss state as the gain medium is pumped and energy builds up, enabling the abrupt release of the stored energy in the form of a brief yet powerful pulse [18]. Short-duration pulses with high peak power are produced by this Q-switching process. Applications for Q-switched Erbium-Doped Fiber Lasers include materials processing, sensing, and telecommunications, where the capacity to generate precisely controlled pulses is essential for a few technological developments.

2.6 Saturable Absorber (SAs)

An optical component known as a saturable absorber has a specific light absorption loss that decreases at increasing optical intensity[21]. For example, in a material containing absorbing dopant ions, such nonlinear absorption can happen when a significant optical intensity causes the ground state of these ions to be depleted. In semiconductors, excitation of electrons from the valence band into the conduction band lowers the absorption for photon energies slightly above the band gap energy. Similar effects can be seen in these materials. Artificial saturable absorbers are also available (see below), in which the optical loss reduces with increasing optical power instead of actual absorption.

In laser technology, saturated absorbers are commonly utilized, especially for mode-locking and Q-switching. Using a saturable absorber to regulate the accumulation of optical gain inside the laser cavity, Q-switching allows for the active modulation of a laser's output. When the accumulated gain is released by this modulation, brief, powerful pulses are generated[21]. Saturable absorbers are employed in mode-locking to produce ultrashort pulses at a set repetition rate.

Graphene, carbon nanotubes, semiconductor materials, and some chemical compounds are frequently employed as saturable absorbers. The material selection is based on the application's unique requirements, including the intended wavelength range and pulse duration. The creation of high-performance lasers that can produce ultrafast, high-intensity pulses for a range of scientific, industrial, and medical applications requires the use of saturated absorbers as essential components.

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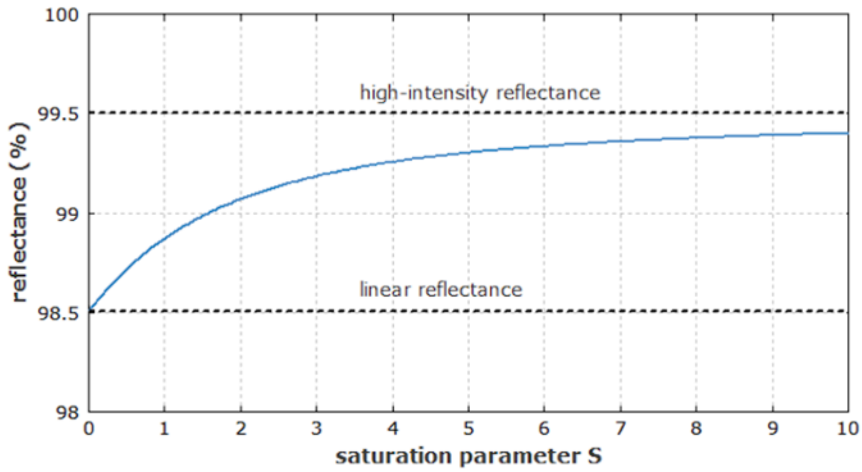

Figure 7: Reflectance of a slow saturable.

2.6.1 Real Saturable Absorber (SAs)

Real saturable absorbers are incorporated into laser cavities in practical applications in order to actively adjust the laser output. A real saturable absorber, for instance, can be employed in a Q-switched laser to selectively block or let light flow, regulating the accumulation of optical gain and causing the emission of brief pulses upon release of the collected gain.

Real saturable absorbers are incorporated into laser cavities in practical applications in order to actively adjust the laser output[22]. A real saturable absorber, for instance, can be employed in a Q-switched laser to selectively block or let light flow, regulating the accumulation of optical gain and causing the emission of brief pulses upon release of the collected gain.Comprehending the properties, constraints, and efficacy of actual saturable absorbers is imperative in the development and enhancement of laser systems for distinct uses, including everything from scientific investigations to commercial operations and healthcare protocols.

2.6.1.1 Nanomaterials

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Real saturable absorbers, or nanomaterials, are essential for developing ultrafast optics and laser technologies . These materials, which are usually designed at the nanoscale, have special optical and electrical characteristics that enable them to modulate light in laser systems very well. Carbon nanotubes, graphene, and certain semiconductor nanoparticles are frequently used as saturable absorbers.

A single sheet of carbon atoms organized in a hexagonal lattice, graphene is the perfect saturable absorber due to its remarkable electrical characteristics[23]. Its quick recovery times and wide bandwidth absorption allow for fine control over pulse production in lasers. Carbon nanotubes are spherical structures constructed of rolled graphene sheets that are well-known for their high absorption coefficients and broad-spectrum absorption capabilities.

They can be used in a variety of laser applications due to their adaptability in accommodating different wavelengths. Quantum dots and other semiconductor nanoparticles have electronic characteristics that vary with their size [24]. These nanoparticles may be made to match particular laser wavelengths by adjusting their size, providing a customizable method of creating saturable absorbers.

a) Organic Materials

In laser technology, true saturable absorbers are made of an intriguing class of nanomaterials called organic materials. These materials, which are primarily carbon-based compounds, have special optical and electrical characteristics that enable them to be used for light manipulation in ultrafast laser systems. The properties of organic saturable absorbers can be tailored to specific laser applications using molecules, polymers, or other carbon-containing structures.

Organic dyes or molecules are a well-known example of materials that are organic and can be employed as saturable absorbers. By altering their chemical structure, these dyes can be made to have particular absorption and emission properties. These organic molecules can be integrated into a saturable absorber arrangement to effectively absorb and release photons, which helps to modulate laser pulses in a controlled manner. Furthermore, because of their adaptable optical characteristics and compatibility with laser systems, some organic polymers, such as polymeric films or nanoparticles, can function as efficient saturable absorbers.

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Using organic materials in nanomaterial-based saturable absorbers has several benefits, including their potential for biocompatibility, cost-effectiveness, and design flexibility. Organic molecules are very adaptable candidates for a wide range of laser applications due to their tunability, which enables exact engineering of their absorption and emission propertiesClick or tap here to enter text.. Organic saturable absorbers help create small, effective, and customized ultrafast laser systems for a variety of applications, including biomedical imaging and telecommunication, as nanomaterials research advances.

2.7 Clam Shell ($CaCO_3$) as Organic Saturable Absorber (SAs)

In the field of ultrafast optics and laser technology, using clam shells as organic materials in nanomaterial-based real saturable absorbers offers a fresh and sustainable solution. Clam shells ($CaCO_3$) are a naturally occurring and sustainable resource that can be used for cutting-edge photonic applications because they are made of calcium carbonate and organic matrix. When treated at the nanoscale, the organic materials found in clam shells have special optical qualities that make them attractive options for use as saturable absorbers in lasers.

The organic components of clam shells must be extracted and refined to convert them into nanomaterial-based saturable absorbers. Through meticulous nanoengineering of these organic components, scientists can effectively modulate laser pulses by utilizing their nonlinear optical properties. When incorporated into laser cavities, the nanomaterials generated from clam shells aid in the regulated absorption and release of photons, allowing for accurate mode-locking or Q-switching in Erbium-Doped Fiber Lasers (EDFLs) or other laser systems.

Clam shells ($CaCO_3$) are an environmentally waste product from the fishing industry, therefore using them as organic nanomaterials is in line with sustainable and green chemistry principles. In addition to having the potential to advance laser technology, the use of materials derived from clam shells in genuine saturable absorbers also encourages a resource- and environmentally conscious approach to materials science in the field of photonics[25].

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2.8 Performance of Organic Materials as Saturable Absorber (SAs)

Organic materials have special qualities that make them attractive options for saturable absorber applications. These materials can include different dyes, polymers, and carbon-based compounds [26].

The tunability of organic saturable absorbers is a crucial feature. By altering the chemical structure of organic materials, researchers may adjust their emission and absorption characteristics, enabling them to create absorbers that correspond to laser wavelengths. To maximize a saturable absorber's performance in a particular laser system, this tunability is necessary.

Another important consideration is the organic saturable absorbers' response time. Rapid alterations in the material's absorption state are necessary for the effective modulation of laser pulses. Ultrafast response times can be exhibited by organic materials, especially those that are nanoengineered, which allows for fine control over pulse creation in ultrafast lasers.

Organic materials are very appealing in saturable absorber applications because of their affordability and adaptability. The performance of organic materials as saturable absorbers keeps becoming better as research into nanomaterials and organic compounds progresses. This creates new opportunities for creating small, effective, and adaptable ultrafast laser systems for a range of academic and commercial.

2.9 Summary

The research of Q-switched Erbium-Doped Fiber Lasers (EDFLs) utilizing organic materials derived from clam shells ($CaCO_3$) as saturable absorbers is a new and sustainable technology. Clam shell materials exhibit potential as nonlinear optical materials for laser pulse modulation once reduced to nanomaterial form. The objective of the research is to examine the characteristics of saturable absorbers made from clam shells and assess their effectiveness in Q-switching EDFLs. Besides that, the objective of the study is to ascertain if adding organic saturable absorbers composed of clam shell materials to the ring cavity design of fiber lasers operating at 1.55-micron wavelengths for Q-switched applications is both possible and practical to determine the pulse width, wavelength, pulse energy and maximum repetition rate.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter is about the methodology of this study. The detailed explanation for the methodology is presented based on the flowchart below to show the progress of the project for Final Year Project 2.

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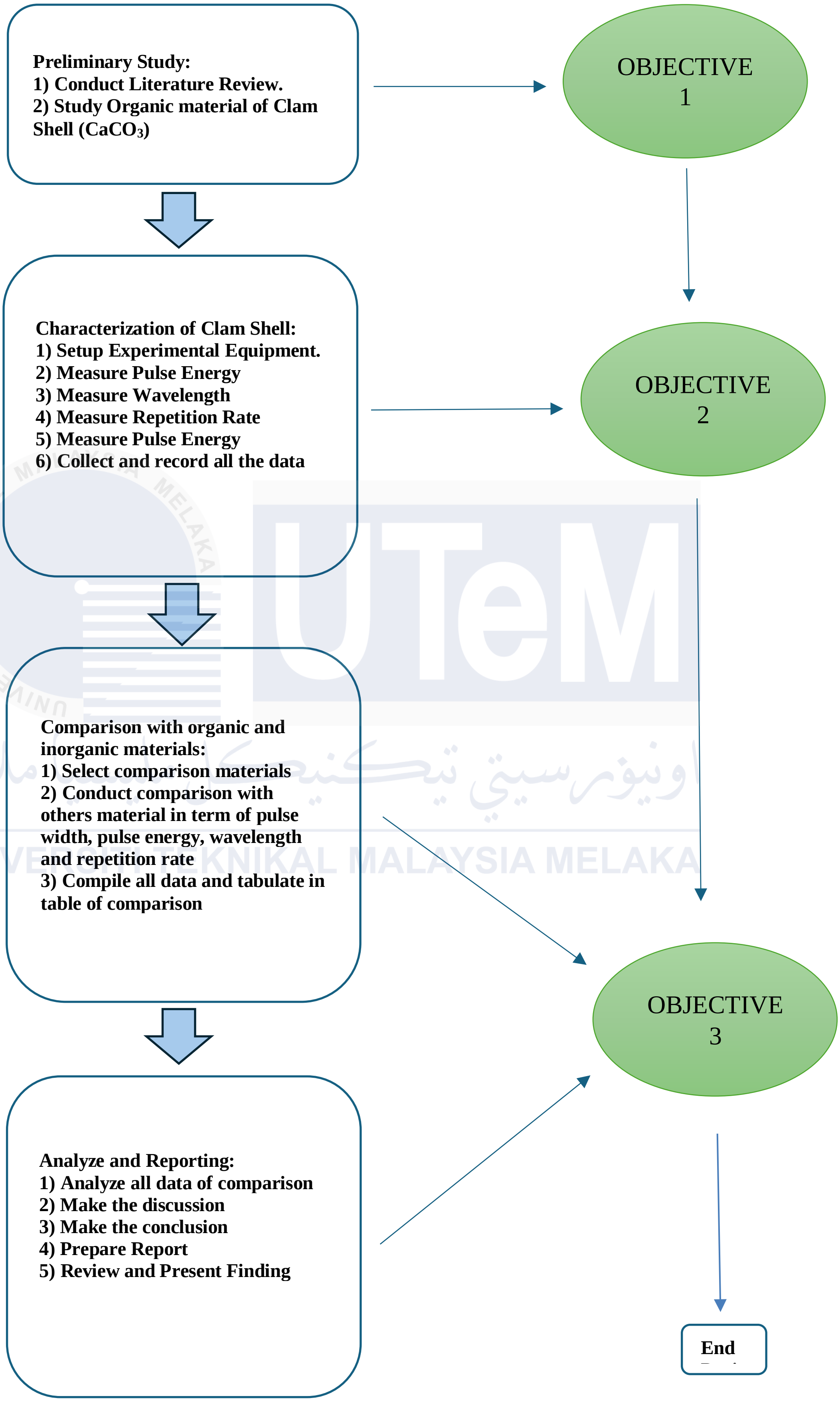
3.2 Project Flowchart

Flow chart shows the overall progress for final year project 2. The 1.55-micron Q-Switch fiber laser experimental project stage procedure ;



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3.2.1 Experimental setup(1.55µm Q-Switch Erbium Doped Fiber Laser)

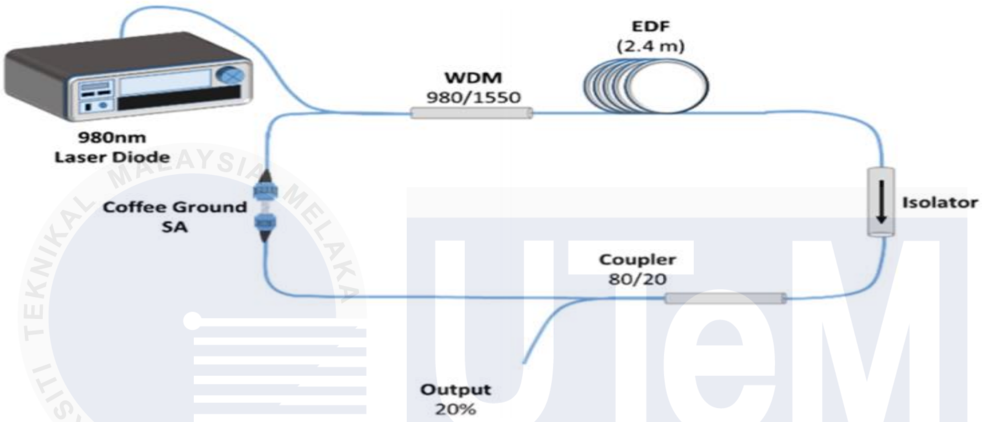

Figure 8: Q- Switch Ebium Doped Fiber Laser setup cofiguration with $CaCO_3$ thin film.

The 1.55µm Q-Switch EDFLs system is seen in Figure 8 above. It includes a 980nm laser diode pump power, 980/1550 m wavelength division multiplexing (WDM), 2.4 m erbium doped fibre (EDF), an isolator, a 90/10 coupler with 10% output, and a saturable absorber device unit (SAs).

Figure 9 : Configuration setup at laboratory.

Figure 9 above illustrates the arrangement of the 1.55µm Q-Switch EDFLs setup in the laboratory.To get the best possible performance, this system underwent an optimisation procedure for every component.In order to verify whether every component is functioning properly, those have been unplugged in order to restart the plug-in procedure. As a result, this arrangement will provide an accurate result using this technique.

3.2.1.1 Equipment and Function of 1.55µm Q-Switch EDFLs

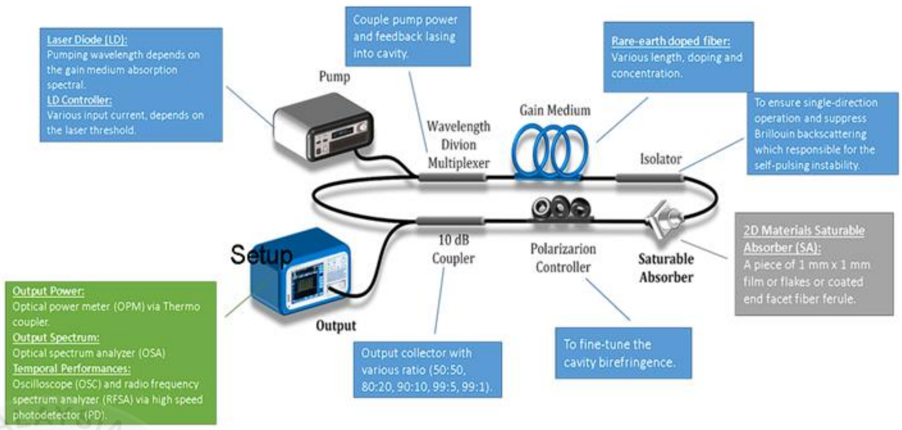

Figure 10 : Shows the function for each component from the setup configuration.

The 1.55µm Q-Switch EDFLs setup's component functions are displayed in Figure 10 above.A laser diode is used to pump a wavelength that is dependent on the spectrum absorption of the gain medium.Pump power and feedback laser are coupled into the cavity via wavelength division multiplexing.Furthermore, the target medium in this project is 2.4 m Erbium Doped Fibre (EDF), which comes in different lengths, concentrations, and levels of doping that affect the setup depending on the project's goal.Moreover, an isolator is employed to guarantee unidirectional functioning and inhibit Brillouin backscattering, which is accountable for the self-pushing instability.Next, a Saturable Absorber (SA) device that consists of a coated end facet fibre ferule or a piece of 1 mm x 1 mm film or flakes is used.Additionally, couplers with output collectors in different ratios 90/10 with 10% of the output were employed in this project.Last but not least, this project also employed temporal performance, output power, and output spectrum, such as an optical spectrum analyzer (OSA), to capture and show all of the output data.

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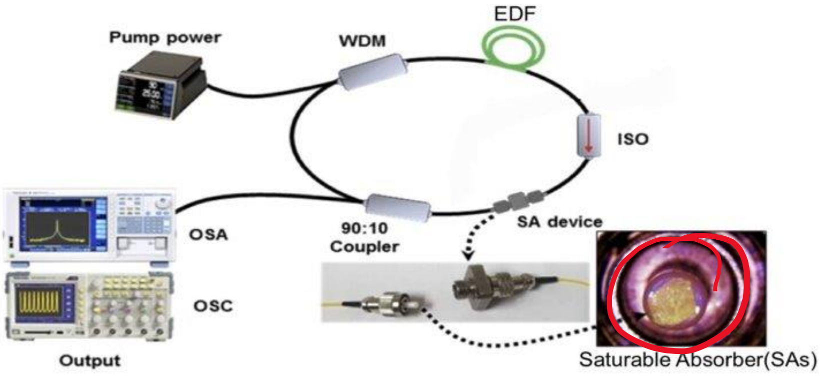

Figure 11: The 1.55μm Q-Switch setup with Saturable Absorber (SAs) device.

Figure 11 above shows the arrangement of 1.55μm Q-Switch EDFLs and the Saturable Absorber (SAs) device.PVA thin-film saturable absorbers (SAs) were introduced into the SA device to allow photons from the pump laser to pass through the sample and display 10% output at the Optical Analyzer Spectrum (OSA).

3.3 Saturable Absorber (SAs) Fabrication

Throughout the manufacturing process, a few critical steps must be taken to utilize the nonlinear optical characteristics of clam shell-derived saturable absorbers for Q-switched Erbium-Doped Fiber Lasers (EDFLs). Clam shells are first harvested and prepared to extract the organic components necessary for their saturable absorption properties. During this extraction process, it could be essential to clean, grind, and purify to create a refined substance that is prepared for further processing. After the raw material is prepared, organic compounds derived from clam shells are processed using nanomaterial production processes to produce thin films or nanoparticles. To create the appropriate nanostructured morphology that improves the material's nonlinear response, a variety of procedures can be applied, including chemical vapors deposition, sol-gel processes, and other nanofabrication methods [26].

The clam shell ($CaCO_3$) material undergoes Nano structuring optimization to enhance its saturable absorption properties[27]. To get the necessary optical response within the targeted wavelength range of the Erbium-Doped Fiber Laser, this may necessitate altering the nanomaterial's size, shape, and surface characteristics. The goal is to create a saturable absorber with quick reaction times, suitable nonlinear optical properties, and the ability to modify laser pulses during Q-switching.

Finally, the artificially produced saturable absorbers made from clam shells ($CaCO_3$) are included into the laser cavity of the Q-switched EDFL. During this integration procedure, the material made from clam shells is precisely aligned and inserted into the laser setup to ensure the optimal interaction with the Erbium-doped fiber gain medium. The performance of the Q-switched laser is then evaluated, accounting for pulse duration, repetition rate, and stability. To fully realize the potential of saturable absorbers made from clam shells in Q-switched EDFL systems, the whole process aims to offer insights into their production, optimizations, and integration.

3.4 Table of Performance Comparison from the past research .

Table 2:Comparative study of laser output with various SAs.

SA Materials	*Central Wavelength*	*Threshold pump power (mW)*	*Maximum Repetition Rate (kHz)*	*Pulse Width (µs)*	*Pulse Energy (nJ)*	*Refs.*
SCG	1559.4	16	42.23	6.40	89	[13]
Ti2ALC	1559.4	30	27.45	4.88	68.2	[31]
Mo2Ti2AlC2	1559.4	20	40.4	8.90	27.2	[32]
Ti2AlC	1557	86.8	29.20	2.85	92.8	[33]
Fe3O4	1560	62	13.91	10.52	93.60	[34]

3.5 Limitation of Proposed Project Methodology

Generation of Q-switched pulse lasers is the primary focus, there are other significant applications for organic saturable absorbers made from clam shells in Q-switched Erbium-Doped Fiber Lasers (EDFLs). The study aims to investigate the intrinsic nonlinear optical properties of materials composed of clam shells first and foremost. The recovery times, nonlinear response, and saturable absorption characteristics of the organic components inside clam shells ($CaCO_3$) will all be carefully examined. The clam shell saturable absorber must be customized to effectively modify the pulses inside the EDFL system. This requires an understanding of these features. This basic investigation will direct the optimization of the clam shell absorber for enhanced Q-switching performance.

Futhermore ,by utilizing organic materials from clam shells as saturable absorbers, Q-switched Erbium-Doped Fiber Lasers (EDFLs) represent a novel and sustainable technological advancement. Clam shell ($CaCO_3$) materials indicate potential as nonlinear optical materials for laser pulse modulation once reduced to nanomaterial form. The study aims to investigate the inherent properties of clam shell saturable absorbers, optimize the production process, and evaluate their performance in Q-switching EDFLs. The purpose of the study is to discover if adding organic saturable absorbers comprised of clam shell materials to the ring cavity design of fiber lasers operating at 1.55µm wavelengths for Q-switched applications is both possible and practicable.

This project's goal is to evaluate the Q-switched EDFL's practicality outside of lab conditions by using parts produced from clam shells. This entails examining its operational metrics in detail and contrasting them with accepted Q-switching techniques. Important factors that are considered include pulse energy, length, and repetition rate. Additionally, this study will underline the eco-friendly side of clam shells, emphasizing their ability to decrease environmental effect compared to typical saturable absorber materials. The goal is to investigate possible uses and integration of saturable absorbers produced from clam shells into current laser technology. This inquiry will be set within the wider framework of constructing efficient and sustainable laser systems.

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3.6 Summary

The methodology for Q-switching Erbium-Doped Fiber Lasers (EDFLs) employing clam shells as organic saturable absorbers incorporates a systematic approach to evaluate and optimize the performance of the laser system. The initial step involves a comprehensive investigation of the inherent nonlinear optical characteristics of materials made of clam shells. This involves a thorough analysis of the saturable absorption properties, nonlinear response, and recovery durations that are present in the organic materials that make up clam shells ($CaCO_3$).

The clam shell ($CaCO_3$) saturable absorber must be customized to successfully alter pulses inside the EDFL system. A thorough comprehension of the discovered nonlinear optical characteristics is necessary for this. The purpose of customization is to improve the clam shell absorber's suitability for Q-switching applications.

After the customization, the research explores the possibility of using clam shell materials as nonlinear optical substances for laser pulse modulation by reducing them to nanomaterial form. A critical component in guaranteeing the effective incorporation of clam shell saturable absorbers into the Q-switched EDFL system is production process optimization.

Furthermore, to determine if it is feasible to use clam shell-derived organic saturable absorbers in the ring cavity design of 1.55μm wavelength fiber lasers for Q-switched applications, the study thoroughly evaluates the performance metrics. The complete analysis of operational parameters considers important elements such as pulse energy, pulse width , repetition rate and wavelenght .

Finally, this study underscores the environmentally beneficial feature of clam shells, emphasizing its capacity to mitigate environmental effect in comparison to traditional saturable absorber materials. Building effective and sustainable laser systems is the overarching objective that this environmentally conscious strategy supports.

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CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Early Result (FYP 1)

For semester 1 ,this project undergo only for 1.55µm Q-Switch Erbium-doped fiber laser setup configuration by testing MO_2TiAlC_3 Pva thin film (Molybdenum(MO),Titanium(Ti),Aluminium(Al)annd Carbon(C) saturable absorber (SAs) into the ring cavity .The results are displayed and recorded in terms of wavelength, pulse energy, and repetition rate.

Figure 12 : 1.55µm Q-Switch Configuration setup at laboratory.

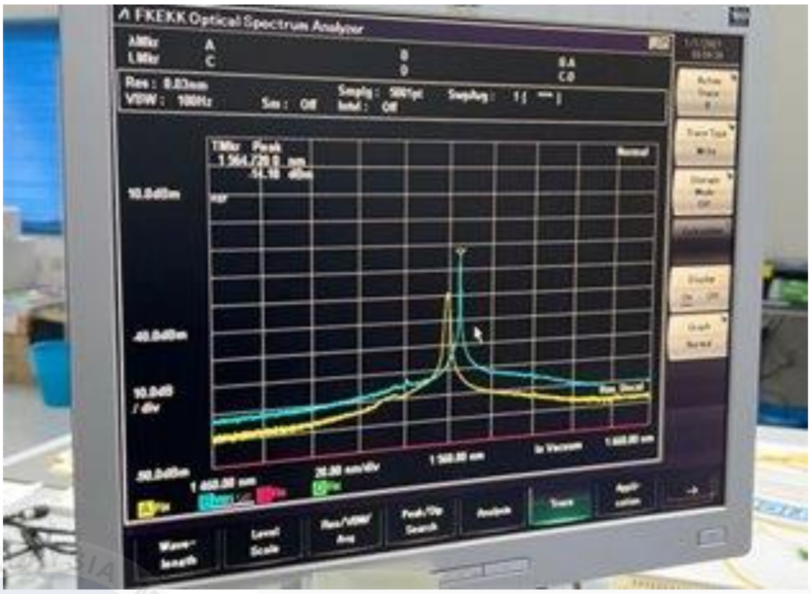

Figure 13: MO_2TiAlC_3 saturable absorber (SAs) wavelenght .

We can observe from Figure 13 , above that the MO_2TiAlC_3 saturable absorber (SAs) tested into the ring cavity produced the 1.55µm wavelength.

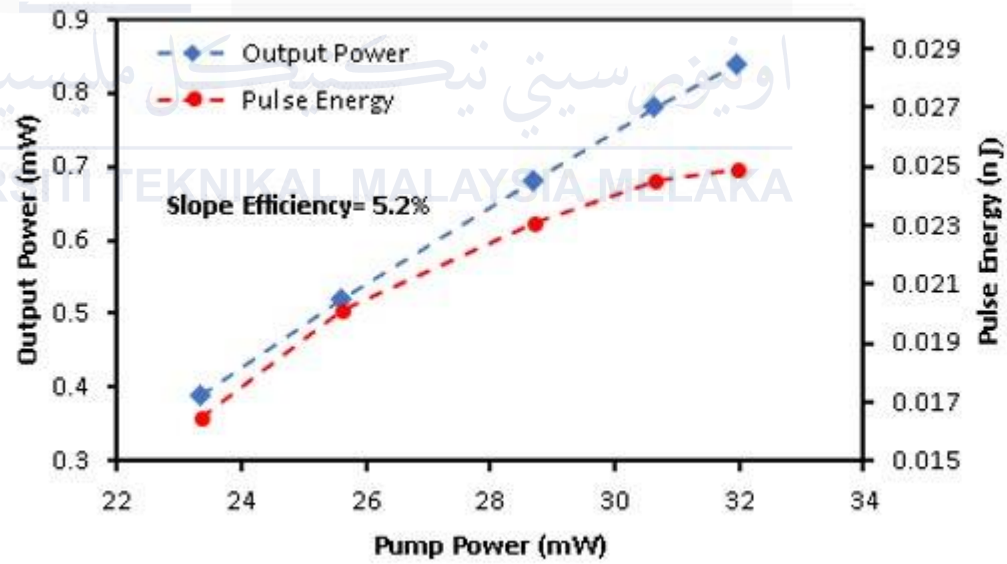

Figure 14 : MoTiAlC3 saturable absorber (SAs) Slope Efficiency.

Thus, we can conclude that the 1.55µm Q-Switch Erbium Doped Fibre laser setup is fully optimised and suitable for usage. Based on the MoTiAlC3's slope

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efficiency of 5.2%, which is acceptable in terms of performance, as shown in Figure 14 above .

4.2 Project Discussion for (FYP 1)

Performance evaluation, challenges with integration, and sustainability concerns are all covered in detail in this research of a Q-switched Erbium-Doped Fiber Laser (EDFL) using clams as a saturable absorber.

Furthermore, clam shell has potential unique nonlinear optical characteristics, clams present an intriguing choice in terms of performance as saturable absorbers. Only with efficient Q-switching implementation which necessitates an understanding of, and optimization of these properties can short, high-energy laser pulses be generated. Performance evaluations will analyze parameters such as repetition frequency, stability, and pulse duration to provide insight into how well clams work in comparison to conventional saturable absorbers.

Q-switch fiber laser system integration presents challenges. Because of the delicate construction of the laser cavity, especially in ring cavity designs, careful alignment and compatibility with the saturable absorber made of clam shells are necessary. The clam shell material's thickness, composition, and production techniques must all bez to get beyond these challenges and provide a seamless integration. The long-term viability of clams as a saturable absorber also hinges on research into sustainable and ecologically friendly manufacturing methods.

An important component of this research is sustainability considerations. Clam shells present a possible environmentally beneficial substitute for conventional saturable absorbers. Clams are a naturally occurring material that has the benefits of being plentiful and biodegradable, which is in line with the increasing demand for environmentally friendly laser technology processes. Assessing the recyclability, scalability, and environmental impact of saturable absorbers made from clam shells will advance the conversation on sustainable materials in laser technologies.

Finally, the study of q-switched Erbium-Doped Fiber Lasers using clams ($CaCO_3$) as saturable absorbers delves into a wide range of topics, including sustainability implications, integration issues, and performance assessments. By using a comprehensive approach to increase our knowledge of the feasibility and possible benefits of using clam shells in Q-switched fiber laser systems.

4.3 Final Year Project 2 (FYP 2) result

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Figure 15 : Q- Switch Ebium Doped Fiber Laser setup cofiguration with $CaCO_3$ thin film.

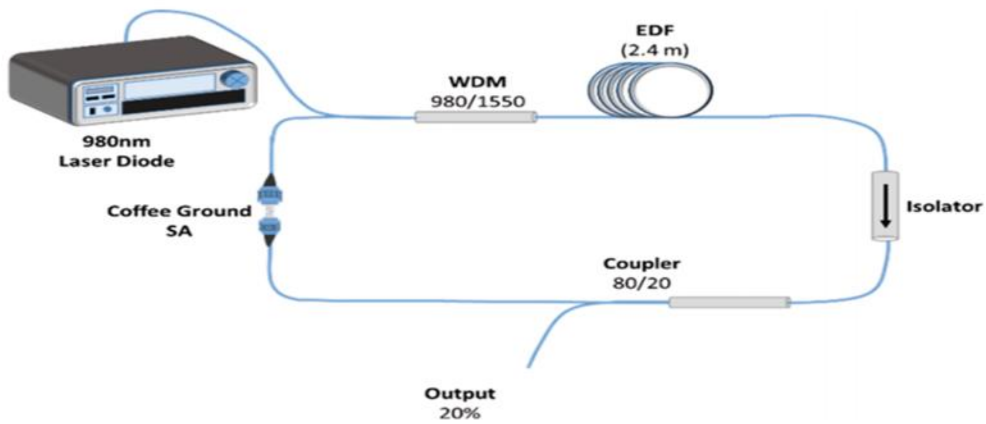

Figure 16 : Schematic diagram for Q-Switch EDFL operating at 1.55 µm region with $CaCO_3$.

In this section, passively Q-switched pulses are generated in an EDFL cavity using the $CaCO_3$ SA as a Q-switcher. The 1.55µm Q-Switch EDFLs system is seen in figure 16 above. It includes a 980nm laser diode pump power, 980/1550 m wavelength division multiplexing (WDM), 2.4 m erbium doped fibre (EDF), an isolator, a 90/10 coupler with 10% output, and a saturable absorber device unit (SAs).

4.3.1 Central Wavelenght for (140mA) and (160mA)

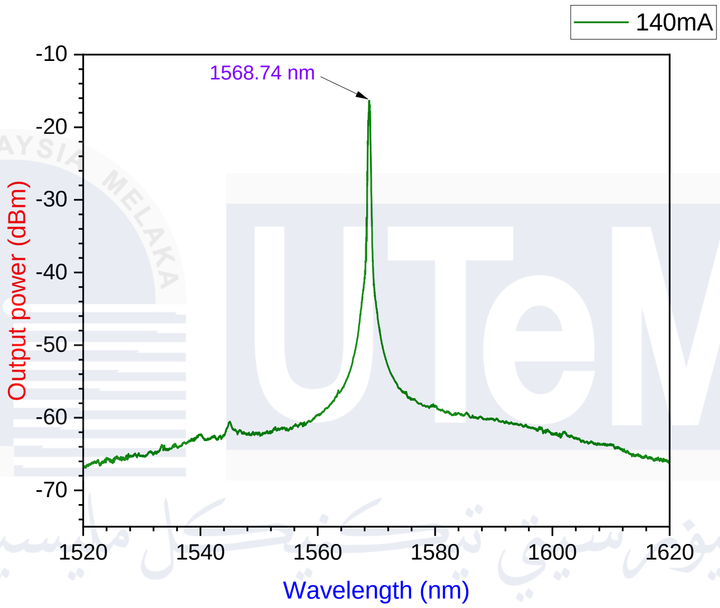

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Figure 17 : Central wavelenght for 140mA is 1568.74 nm.

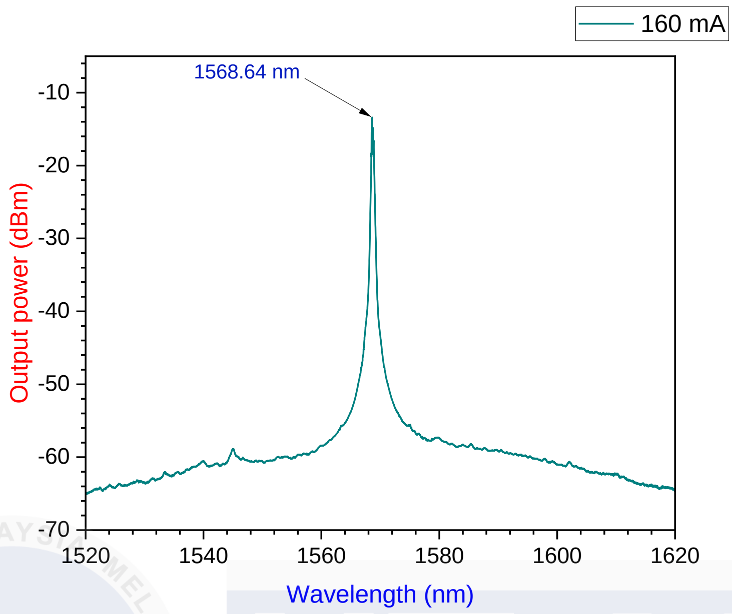

Figure 18 : Central wavelenght for 140mA is 1568.64 nm.

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4.3.2 Result Performance of Clams Shell ($CaCO_3$) .

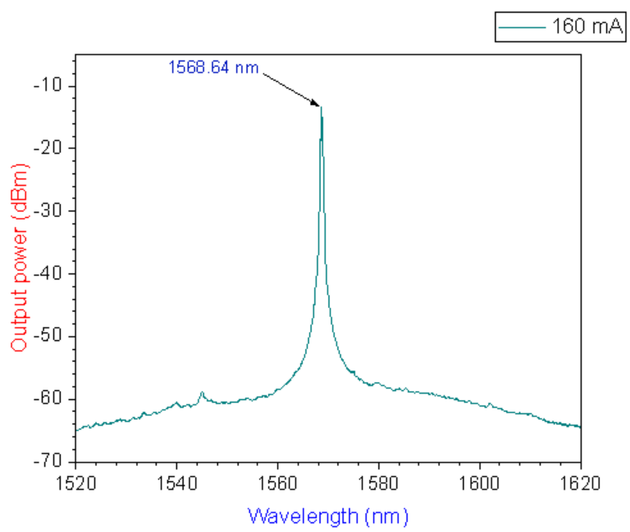

Figure 19 : Central wavelenght .

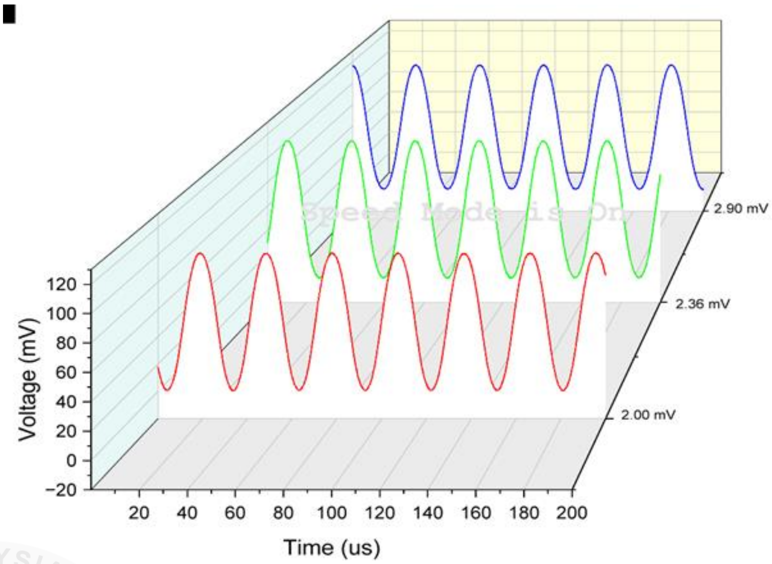

Figure 20 : Pulse train.

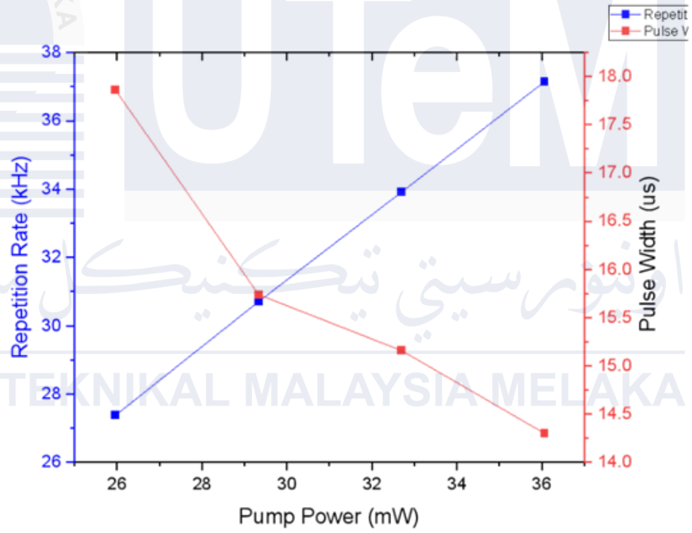

Figure 21 : Repetetion rate and pulse width .

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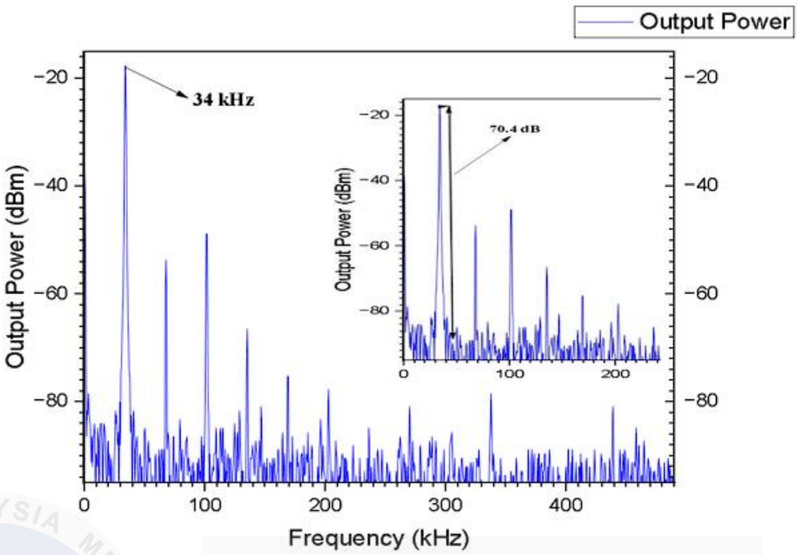

Figure 22 : RF spectrum .

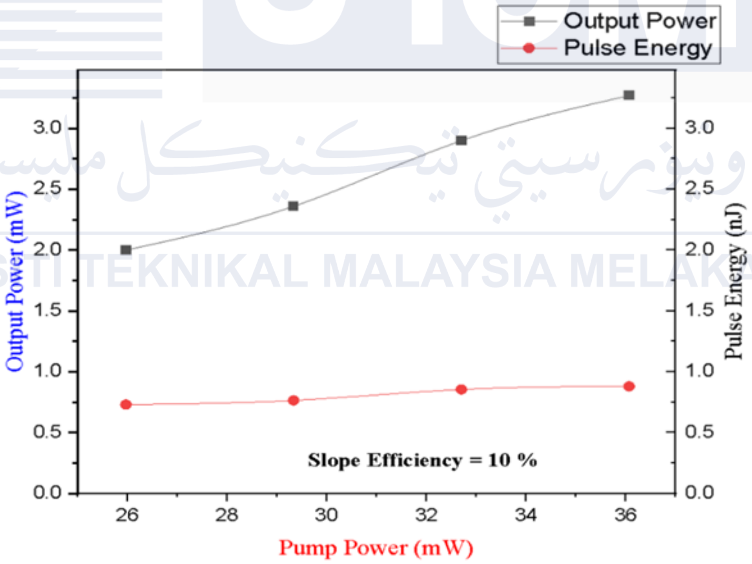

Figure 23 : Output power and pulse energy .

4.3.2.1 Result Discussion

First and foremost, a free running continuous wave laser with a pump power of 25.968 mW is first produced in the EDFL following the insertion of the $CaCO_3$ SA into the ring cavity. With an additional 30.069 mW of pump power, the EDFL produces a series of Q-switched microsecond laser pulses. The output spectrum (wavelength) of the laser at 36.069 mW of pump power is seen in Figure 19. The wavelength of the laser is centred at 1568.64 nm. The accompanying RF spectrum is shown in Figure 22, and it shows that the pulses have a maximum repetition rate of 34 kHz at 30.069 mW pump power. It is noticed that the fundamental frequency's signal-to-noise ratio is more than 45 dB, confirming the stability of such Q-switched functioning.

The typical oscilloscope traces at pump powers of 2.00 mW, 2.36 mW, and 2.98 mW are plotted in figure 20, which shows the pulse train. It is evident that every pulse train has the same strength and contour. The pulse rates are 27.38, 30.71, and 33.92 kHz, corresponding to the pulse durations of 36.52, 32.56, and 29.48 μs, respectively. It demonstrates the feature of the passive Q-switching condition, which is a progressive rise in repetition rate accompanied by a reduction in pulse width with an increase in pump power. Furthermore, the pulse train exhibits no change in peak intensity and the pulse amplitude remains constant across the repetition rate's adjustable range, demonstrating the exceptional stability of the Q-switching state.

Besides that, the performance parameters of a Q-switched fibre laser are depicted in the accompanying graph on figure 23, which focuses on the relationship between pump power and output power as well as pulse energy. The output power (shown by black squares and measured on the left Y-axis) clearly increases linearly as the pump power goes from 26 mW to 36 mW, indicating a 10% slope efficiency. This steady increase in output power suggests that the laser maintains stable efficiency across the testing range by effectively converting the pump power into output power.

Red circles on the right Y-axis represent the pulse energy, which is steady and increases slightly from 0.7 nJ at 26 mW to over 1.0 nJ at 36 mW. This stability shows that the laser produces homogeneous pulse characteristics, which are necessary for applications like material processing and scientific research that require consistent pulse energy. Overall, the graph highlights the efficiency and consistency of the Q-switched fibre laser for demanding applications by showing its consistent and dependable growth in output power with stable pulse energy.

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4.3.3 Performance Comparison of Organic Materials

Table 3 :Result Performance comparison of SCG and Clam Shell ($CaCO_3$).

SAs	Central Wavelenght (nm)	Threshold (mW)	Maximum Repetation Rate (kHz)	Pulse Width (µs)	Pulse Energy (nJ)	Ref.
SCG	1559.40	16	42.23	6.4	89	[10]
$CaCO_3$	**1568.74**	**25.968**	**34**	**14.3**	**0.80760**	This Study

4.3.3.1 Discussion

In this study, the performance of Clams Shell ($CaCO_3$) as a saturable absorber (SA) in a Q-switched erbium-doped fiber laser (EDFL) was compared to the previously studied SA, SCG, based on several key laser parameters. The central wavelength of is observed at 1568.74 nm, which is slightly longer than SCG's central wavelength of 1559.40 nm. This indicates a shift in the emission wavelength when using $CaCO_3$, which might be due to its unique optical properties. However, $CaCO_3$ demonstrates a significantly higher threshold power of 140 mW compared to SCG's 16 mW, suggesting that $CaCO_3$ requires more input power to initiate the Q-switching process. This higher threshold might be attributed to less efficient energy absorption or different nonlinear absorption characteristics of $CaCO_3$.

When examining the performance metrics, SCG shows superior performance across multiple parameters. SCG achieves a maximum repetition rate of 42.23 kHz, which is substantially higher than $CaCO_3$'s 34 kHz. This indicates that SCG can generate pulses at a much faster rate. Additionally, the pulse width produced by SCG is significantly shorter at 6.4 μs compared to $CaCO_3$'s 14.3 μs, which means SCG can produce much shorter and more frequent pulses. Consequently, SCG also achieves a much higher pulse energy of 89 nJ, far exceeding $CaCO_3$'s 0.80760 nJ. These comparisons highlight that while $CaCO_3$ can function as a saturable absorber, SCG exhibits much better performance in terms of threshold power, repetition rate, pulse width, and pulse energy. Future research could focus on optimizing $CaCO_3$'s properties to potentially enhance its performance and reduce the disparity between these metrics.

4.3.4 Performance Comparison of Organic and Inorganic Materials

Table 4 :Result Performance of Clam shell($CaCO_3$) with Organic and Inorganic Saturable absorber (SAs).

SAs	Central Wavelenght (nm)	Threshold Pump Power (mW)	Maximum Repetition Rate (kHz)	Pulse Width (μs)	Pulse Energy (nJ)	Ref.
SCG	1559.40	16	42.23	6.4	89	[10]
$CaCO_3$	**1568.74**	**25.968**	**34**	**14.3**	**0.80760**	This Study
Ti_2AlC	1559.44	30	27.45	4.88	68.2	[28]
Ho_2O_3	115.8	45	115.8	0.64	0.524	[29]
$Mo_2Ti_2AlC_2$	1559.4	20	40.4	8.9	27.2	[30]
Ti_2AlC	1557	86.8	29.20	2.85	92.8	[31]
Fe_3O_4	1560	62	13.91	10.52	93.60	[32]
8-$HQCDCL_2H_2O$	1530	50	136	2.076	172	[33]
Tm_2O_3	1559.4	81.13	62.70	9.50	6.22	[34]
Ti_4AlN_3	1559.4	29.9	59.2	5.75	39.5	[35]

4.3.4.1 Discussion

In the provided table, calcium carbonate ($CaCO_3$) stands out with distinct performance metrics compared to other materials listed. Specifically, $CaCO_3$ exhibits a central wavelength of 1568.74 nm and requires a relatively high threshold pump power of 25.968 mW. This high threshold indicates that CaCO3requires significant energy input to initiate and sustain its laser properties. In contrast, other materials like titanium aluminum carbide (Ti_2AlC) at 1559.44 nm and $Mo_2Ti_2AlC_2$ at 1559.4 nm have lower threshold pump powers of 30 mW and 20 mW, respectively, suggesting they are more efficient in converting pump energy into laser emission.

Moreover, when considering maximum repetition rates and pulse energies, $CaCO_3$ performs moderately with a maximum repetition rate of 34 kHz and a pulse energy of 0.80760 nJ. This places it in a range where it can deliver laser pulses at a relatively frequent rate but with lower pulse energy compared to many other materials listed. For instance, Ti_2AlC (1557 nm) and Fe_3O_4 (1560 nm) exhibit higher pulse energies of 92.8 nJ and 93.60 nJ, respectively, indicating they can deliver more powerful laser pulses per emission cycle.

In conclusion, while calcium carbonate ($CaCO_3$) shows a specific wavelength and moderate performance in terms of repetition rate and pulse energy, its higher threshold pump power suggests it requires more energy input for laser generation compared to materials like Ti_2AlC and $Mo_2Ti_2AlC_2$. The choice of material for laser applications depends not only on wavelength compatibility but also on factors such as efficiency in energy conversion and desired pulse characteristics. $CaCO_3$'s performance characteristics highlight its unique properties in the context of laser applications, albeit with specific energy requirements that may influence its suitability for different laser systems and applications.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In overall, the findings of this project highlight the significance of using Clams Shell ($CaCO_3$) as new saturable absorber (SA) devices were investigated in this study to create Q-switched Erbium-doped fibre lasers (EDFL) operating in the 1.55 μm range.The primary accomplishments and discoveries of this study may be summed up as follows:

1. Successful study new passive SAs based on Clams Shell (CaCO3).
2. Successful characterize of Q-switched fiber lasers based on the newly developed $CaCO_3$ SAs in the 1.55-micron region in term of wavelenght, pulse width, pulse energy and repetition rate.
3. Successful demonstration of Q-Switch fiber lasers based on the newly developed $CaCO_3$ SAs in term of wavelenght, pulse width, pulse energy and repetition rate.
4. Successfully compare $CaCO_3$ optical performance with organic and inorganic material SAs in term of wavelenght, pulse width, pulse energy and repetition rate.

The $CaCO_3$ (clam shell) was investigated as an alternative SA due to its promising nonlinear optical absorption characteristics. In this study, Q-switched were demonstrated using the newly developed $CaCO_3$ SA. The SA was prepared by embedding $CaCO_3$ material Polyvinyl Alcohol (PVA) to compose a film absorber, which was then inserted between two fiber ferrules to form a fiber-compatible SA device. The $CaCO_3$ -PVA film was characterized to have bandgap with 3.91 eV.

A Q-switched Erbium-doped fiber laser operating at 1568.64 nm was realized by incorporating the $CaCO_3$ SA into the EDFL cavity with a pump power of 25.968 mW. The EDFL produced a series of Q-switched microsecond laser pulses with an additional 30.069 mW of pump power. The output spectrum of the laser at 36.069 mW of pump power is centered at 1568.64 nm. The accompanying RF spectrum showed a maximum repetition rate of 34 kHz at 30.069 mW pump power, with a signal-to-noise ratio greater than 45 dB which 70.4 dB, confirming the stability of Q-switched operation.

Furthermore, the typical oscilloscope traces at pump powers of 2.00 mW, 2.36 mW, and 2.98 mW demonstrated that the pulse trains have consistent strength and contour. The pulse rates were 27.38, 30.71, and 33.92 kHz, corresponding to pulse durations of 36.52, 32.56, and 29.48 μs, respectively. This indicates the passive Q-switching characteristic, with an increasing repetition rate and decreasing pulse width as pump power increases. The pulse amplitude remained constant, showcasing the exceptional stability of the Q-switching state.

The performance parameters of the Q-switched fiber laser, depicted in the accompanying graph, focused on the relationship between pump power, output power, and pulse energy. The output power increased linearly from 26 mW to 36 mW, indicating a 10% slope efficiency. This steady increase in output power suggested stable efficiency across the testing range. The pulse energy, represented by red circles, remained stable and slightly increased from 0.7 nJ at 26 mW to over 1.0 nJ at 36 mW. This stability indicated the laser's ability to produce uniform pulse characteristics, necessary for applications requiring consistent pulse energy, such as material processing and scientific research. Overall, the graph highlighted the efficiency and consistency of the Q-switched fiber laser for demanding applications.

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5.2 Future Works

Exploring the potential use of clam shell ($CaCO_3$) can build on the successful implementation as an alternative saturable absorber (SA) in pulsed fiber laser technology. Given its promising characteristics, $CaCO_3$ can be further investigated to enhance fiber laser performance by shortening pulse width, increasing repetition rate, output power, and pulse energy. Achieving these improvements may involve addressing a shorter cavity length and optimizing the gain medium, thereby advancing the overall efficiency of the proposed fiber laser system.

Additionally, future research should focus on the application of $CaCO_3$-based SAs in different wavelength regions, such as 2 µm and 3 µm, using Thulium-doped fiber (TDF) and ZBLAN EDF as gain mediums, respectively. Exploring Q-switched fiber lasers operating in the 3.0 µm region with $CaCO_3$ as the SA would be particularly intriguing, as this area remains largely uncharted. Investigating the effectiveness of $CaCO_3$ in these longer wavelengths could open new possibilities for fiber laser applications and expand the current understanding of this material's capabilities.

Moreover, developing new variants of $CaCO_3$ for fiber laser applications presents another promising research direction. Through this work, $CaCO_3$ has shown attractive performance attributes in fiber laser technology. Further studies should focus on synthesizing and characterizing different forms of $CaCO_3$ to evaluate their effectiveness as SAs. This could lead to the discovery of new materials with enhanced properties, thereby contributing to the advancement of fiber laser technology and broadening its range of applications.

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