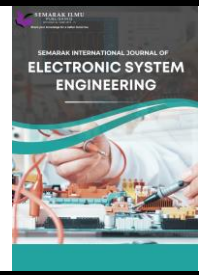




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Exploring Organic-Based Saturable Absorption Focusing on Spider Silk in Q-Switched Pulse Fiber Laser Applications: A Mini Review

Nur Ainnaa Mardhiah Muhammad^{1,*}, Noor Azura Awang¹, Agus Muhamad Hatta²

¹ Photonics Devices Sensors Research (PDSR), Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, KM1 Jalan Panchor, 84600 Panchor, Johor, Malaysia

² Department of Engineering Physics, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

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ABSTRACT

The fiber laser combines the fiber gain medium's function as a fiber amplifier, transforming it into laser output through integration within a cavity configuration. Meanwhile, a pulsed fiber laser is capable of generating short bursts of laser emission characterized by high peak power levels. This concept is known as Q-switching. A saturable absorber material is essential for passive Q-switching, as it is integrated into the laser cavity to produce an instantaneously Q-switched pulse fiber laser. While these materials have been effective in generating pulsed lasers, they often come with unresolved issues, such as long-term exposure to two-dimensional materials can pose health risks. To address this gap, researchers have shifted their interest toward natural or organic materials in the quest for new saturable absorbers. This mini-review provides a comprehensive overview of the saturable absorber mechanism, including essential theoretical equations and key measurement parameters. The next section continues by exploring the fundamentals and early development of saturable absorbers, followed by an in-depth explanation of the Q-switched pulse generation process using erbium-doped fiber as the gain medium and saturable absorber. Critical parameters influencing the performance of Q-switched pulse fiber lasers are discussed, with special attention given to recent advancements in organic-based saturable absorbers for Q-switching. The potential of spider silk as an innovative saturable absorber in Q-switched pulse fiber laser applications is highlighted. Finally, the review delves into the wide-ranging applications of these lasers, including tunable and switchable dual-wavelength fiber lasers with sensor for temperature measurement and to detect adulteration in pure kelulut honey and sucrose solution.

1. Introduction

The fiber laser combines the fiber gain medium's function as a fiber amplifier, transforming it into laser output through integration within a cavity configuration. Meanwhile, a pulsed fiber laser is capable of generating short bursts of laser emission characterized by high peak power levels. Since its establishment by Fred J. McClung in 1962, the idea of pulse creation in lasers has gained significant

* Corresponding author.

E-mail address: researchainnaa@gmail.com

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traction, leading to a proliferation of research in the field of pulsed laser technology. His theory is referred to as Q-switching. Initially, this technique involved the utilization of Kerr cell shutters to generate significant pulses, resulting in peak power approximately 100 times greater than that produced by ruby lasers [1]. The foundations of both active and passive approaches are also recognized [2–4]. Using passive saturable absorbers has been regarded as a viable approach for achieving narrow pulse widths and broad spectral ranges [5]. The investigation of high-performance saturable absorbers is widely pursued in the field of ultrafast photonics research. High-performance saturable absorbers possess notable attributes such as efficient heat dissipation, a high threshold for laser damage, and wavelength independence. In addition, their compact size makes them suitable for analyzing small-scale samples and accessing limited or hard-to-reach areas [6,7]. A saturable absorber material is essential for passive Q-switching, as it is integrated into the laser cavity to produce an instantaneously Q-switched pulse fiber laser. While these materials have been effective in generating pulsed lasers, however, they often come with some unresolved issues such as the challenging and expensive fabrication processes for transition metal dichalcogenides material [8–10], and their low damage threshold [11–15]. Additionally, long-term exposure to two-dimensional materials, including topological insulators, can pose health risks [16–18].

To address this gap, researchers have shifted their interest towards natural or organic material in the quest for new saturable absorber. Therefore, this mini review exploring organic-based saturable absorbers, focusing on spider silk to generate the Q-switched pulse erbium-doped fiber laser source. Natural spider silk is a protein-based biological material produced by spiders naturally through silk glands in their bodies [19]. Interestingly, these silks serve as photon carriers, with light guiding through dragline silk recently proven to have transmission losses of only a few dB/cm [20–22], paves the way for its incorporation as natural biological saturable absorber to generate Q-switched pulse fiber laser applications.

2. Saturable Absorber

2.1 Saturable Absorber Mechanism

A saturable absorber is an optical device or material that exhibits a nonlinear response to incident light. It is essential for passively Q-switched fiber lasers as it facilitates the formation of optical pulses (initiating operation in the pulsed state), regulates the output intensity of lasers, and controls characteristics such as repetition rate, pulse width, and pulse energy. It significantly contributes to stabilizing laser output by reducing fluctuations and providing consistent pulse parameters. It is characterized by its ability to modulate the light intensity passing through it, depending on the intensity of the incident light. The mechanism of a saturable absorber is based on the concept of intensity-dependent transmission or absorption of light [23]. Specifically, understanding this mechanism relates to the framework of the saturable absorber material's energy levels and their interaction with light.

When saturable absorber material is placed within the laser cavity under low light intensity, it remains in its ground state with relatively high absorption. During this stage, most electrons are in the ground state and absorb photons at low intensity, exciting them to higher energy levels. As the intensity of the incident light continues to increase, the electrons within the saturable absorber material continues to excite, transitioning to higher energy states, resulting in a decrease in the saturable absorber material's absorption. At sufficiently high light intensities, the absorption becomes saturated due to the fully-occupied of electrons in higher level.

2.2 Saturable Absorber Parameters

As discussed in Subsection 2.1, saturable absorption is a phenomenon that occurs in certain materials or devices, wherein the degree of light absorption relies on the optical intensity of the incoming light, causing a decrease as the light intensity increases. Understanding the parameters of a saturable absorber is important for assessing the desired performance of the resulting laser output. The nonlinear behaviour exhibited by saturable absorber material can be effectively characterized by utilizing a straightforward two-level saturable absorption model. This model serves as a resource for identifying the significant parameters such as the saturable absorption, non-saturation absorption, saturation intensity, and recovery time. The expression of the two-level saturable absorption model is given by Wang *et al.*, and Xing *et al.*, [24,25]:

$$\alpha(I) = \frac{\alpha_s}{1 + \frac{I}{I_{sat}}} + \alpha_{ns} \quad (1)$$

where $\alpha(I)$ denotes the absorption coefficient that is dependent on the intensity of the incident light, α_s is the linear limit of saturable absorption (modulation depth), I is the input laser intensity, I_{sat} is the saturation intensity, and α_{ns} is the non-saturable absorption coefficient.

Saturable absorption, also known as modulation depth, can be experimentally measured using the twin-detector method, also known as the twin-balanced or balanced twin-detector technique [26–30], Z-scan measurement [31], and P-scan measurement [32]. The experiment for the twin-detector method is carried out with the help of an ultrafast pulse source of a specific wavelength transmitted into a saturable absorber. The modulation depth is determined by measuring the maximum change that can occur in the induced optical loss. A saturable absorber with a modulation depth of 10 % or higher is preferred, as this allows for a more stable pulse laser function [33–35]. In addition, a saturable absorber with a larger modulation depth can produce significant pulse shaping, which is necessary for achieving short pulse durations. The only disadvantage of a saturable absorber with high modulation depth is its propensity towards Q-switched instabilities. Furthermore, saturable absorption can be expressed as:

$$\alpha_s = \alpha_{sg}N \quad (2)$$

where α_{sg} is the absorption cross-section at the ground state of the saturable absorber and N is the concentration of the saturable absorber material. The saturable absorption is determined by the relative number of photons absorbed per unit distance by the saturable absorber material. A high saturable absorption coefficient means more photons are absorbed by the saturable absorber rather than penetrating deeper, over a relatively short distance. This concept is illustrated in Figure 1, which shows the distance, X for two different absorption coefficient values versus photon intensity, I_{v0} .

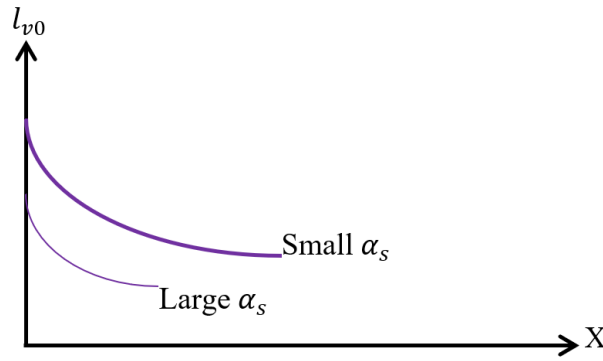


Fig. 1. The distance for two different absorption coefficient values versus photon intensity

Meanwhile, the loss that cannot be saturated by the saturable absorber material, known as non-saturable absorption, is expressed as a percentage of linear absorption due to normalization [36]. This loss can be attributed to transmission loss, free carrier absorption, Auger recombination, and scattering loss. Scattering loss can occur due to surface roughness of the material, lattice defects, and rough interfaces. Additionally, the modulation depth of the saturable absorber material is related to the minimum pulse width of the Q-switched laser, which is regulated by the properties of saturable absorption and non-saturable loss.

The optical peak intensity that equates to a 50 % reduction of the saturated region of its absorption is known as the saturation intensity. Additionally, the Eq. (1) for saturation intensity, represents the intensity required in a steady state to reduce the absorption to half of its unsaturated value:

$$l_s = \frac{hf}{\sigma_{sg}\tau_{se}} \quad (3)$$

where h is Plank's constant, f is the light frequency of operation, σ_{sg} is the absorption cross-section at the ground state of the saturable absorber, and τ_{se} is the absorber recovery time or excited state lifetime. According to Eq. (3), less continuous-wave intensity is needed to saturate the saturable absorber when the excited state lifetime is longer before recombination.

Figure 2 shows a graph of the normalized nonlinear absorption, based on Eq. (1), at different normalized light intensity [37]. According to the Figure 2, the absorption is high, and lasing is disallowed when the laser resonator (pump diode source) light intensity is lower than the saturable absorber saturation intensity ($l < l_s$). The absorption reduces, and transmissivity gradually becomes higher when the light intensity is $l \geq l_s$. Overall, the absorption is saturated when $l \gg l_s$ because of the high Q-value of the resonator, initiating Q-switched laser oscillation. Due to non-saturable loss property, α_{ns} of the saturable absorber, the nonlinear saturable absorption cannot reach 0 %.

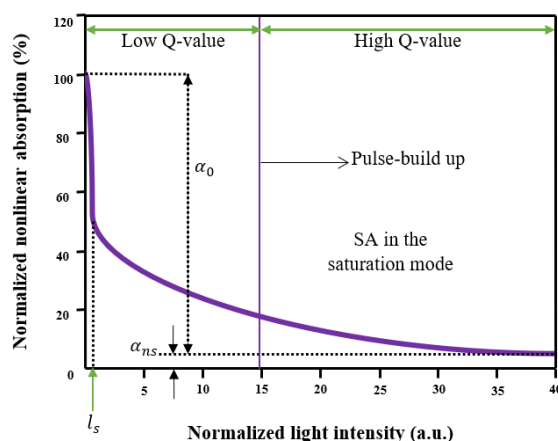


Fig. 2. Light intensity versus nonlinear absorption in Q-switching

3. Overview of the Saturable Absorber

3.1 Graphene

The research on two-dimensional materials has seen rapid development since the first graphene saturable absorber was introduced in 2009 [38,39]. It is ideally suited as a saturable absorber in pulsed fiber laser systems due to its significant fast response times and broad wavelength range [40–45]. Despite its potential, graphene has certain drawbacks, including a low modulation depth, as the absorption per layer is only 2.3 % [46–52]. Apart from that, because graphene is easily oxidized, a hydrogen ambient atmosphere is necessary during its manufacture using chemical vapour deposition [53]. Thus, further investigations into other materials are needed to find high-performing saturable absorbers.

3.2 Topological Insulators

Topological insulator (TI) materials with the formula Y_2X_3 , where Y can be either Bi or Sb, and X can be either Te or Se. A HgTe is an example of a two-dimensional material, while Bi_2Te_3 , Bi_2Se_3 , and Sb_2Te_3 are examples of three-dimensional materials. Hsieh *et al.* reported the initial discovery of three-dimensional TI material in 2008 [54]. Numerous studies have been conducted to generate pulsed fiber laser-based TIs material [55–66]. TIs are quantum states of matter in which the interior is an insulator, whereas the surface states are conductive, allowing electrons to only travel along the surface of the material [67,68]. The electronic configurations of TI films are affected by film thickness due to electron quantum confinement, which drives the TI materials to generate pulsed fiber lasers in the range of visible, near-infrared, and mid-infrared wavelengths [69]. However, there are still challenges to overcome, primarily in understanding how the electronic structure of TI materials works. These materials exhibit intricate electronic structures due to the strong spin-orbit interaction, making it challenging to theoretically predict their bandgap energies and verify them experimentally [69]. Furthermore, the pulse bandwidth and high non-saturable loss are affected not only by the nonlinearity of the fibers, but also by the presence of impurities, defects, and dislocations in the material [69–71]. Additionally, material preparation for compounds such as Bi_2Te_3 , Bi_2Se_3 , Sb_2Te_3 is complex because they are made of two different elements [72,73]. Moreover, TI saturable absorbers are restricted with a low damage threshold, meaning they can only tolerate a relatively small amount of energy before becoming saturated [11,74,75].

3.3 Transition Metal Dichalcogenides

Transition metal dichalcogenides (TMDs) belong to the category of two-dimensional materials and have attracted attention due to their layer-dependent bandgap, which allows the bandgap to be controlled by manipulating the number of material layers. This property enables saturable absorption over a broad wavelength range and is accompanied by high optical nonlinearity [15,76–81]. TMDs are a family of anisotropic semiconductor materials with the common formula MX_2 , where M represents a transition metal element from groups IV to X, including Ti, Zr, and Hf (group IV), group V contains V, Nb, and Ta, group VI involves Mo and W, group VII consists of Mn, Tc and Re, group VIII (Fe, Ru, and Os), group IX (Co, Rh, and Ir), and group X (Ni, Pd, and Pt). The X represents chalcogen elements such as S and Se [82]. TMD materials from groups IV to VII are typically layered, while those from groups VIII to X are often non-layered. The layer-dependent bandgap in TMD materials makes them an appealing target for study in the approach of exploiting saturable absorbers for pulse generation [76,83]. Active research on TMDs-based saturable absorbers and their application in fiber lasers is ongoing. Studies have demonstrated that materials such as titanium trisulfide [84], hafnium sulfide [81], platinum [85], molybdenum ditelluride [86], rhenium disulfide [87], and antimony sulfide [79] act as saturable absorbers to produce Q-switched pulses in an erbium-doped fiber laser cavity. Despite the fact that their bandgaps can be adjusted by changing the layer numbers, their absorption in the mid-infrared wavelength is relatively poor, which might further increase the optical loss [88]. Additionally, TMDs may be inhaled as airborne particles during the fabrication or disposal of two-dimensional TMD-based products, necessitating an evaluation of their biosafety. The preparation methods for TMDs are also somewhat complicated [8–10]. Moreover, these materials are susceptible to low optical damage thresholds [11–15], which can impact their laser generation performance.

3.4 Black Phosphorus

Two-dimensional mono-elemental materials, such as black phosphorus (BP), have piqued the interest of researchers due to their natural characteristics [89–93]. In 2014, experiments conducted by Ye and Zhang independently discovered that BP exhibits anisotropic properties with a variable bandgap [94,95]. Anisotropy refers to materials exhibiting properties that vary with the direction in which they are observed. Along with its layered orthorhombic structure, through which electrons, phonons, and their interactions with photons propagate in an anisotropic manner within the layers' plane. The anisotropic structure of BP thin films is disclosed using angle-resolved Raman and infrared spectroscopies, as well as angle-resolved transport research by Xia *et al.*, [96]. Both theoretical calculations and experimental evidence indicate that BP has direct bandgap characteristics depending on the number of layers (layer-dependent bandgap), with values ranging from 0.10 eV to 0.35 eV for bulk BP and 1.0 eV to 1.7 eV for monolayer BP. Another remarkable aspect of this material, which has garnered considerable research interest, is its ability to absorb light across a wide range of wavelengths, from ultraviolet to infrared [97–99]. In 2021, a Q-switched erbium-doped fiber laser using exfoliated BP as a saturable absorber, was demonstrated by Alghamdi *et al.* achieving a highest pulse energy of 171.7 nJ [72]. Despite its numerous impressive qualities, BP has two major drawbacks that hinder its widespread use. One of these drawbacks is the low stability of two-dimensional BP in ambient conditions. Although the phosphorus allotrope BP is most stable in bulk form, when exfoliated into a few-layer structure, it rapidly reacts with oxygen and moisture in the air, leading to the breakdown of its crystal structure [9,100–103]. Another issue is the difficulty in producing high-quality, large-area few-layer BP using existing synthesis techniques [104,105].

4. Passively Q-Switched Pulse Fiber Laser

A pulsed fiber laser is a subset of fiber laser technology that generates optical pulses, or light pulses, as its output. It can produce more powerful energy than a continuous-wave laser. One technique for generating optical pulses is the passively Q-switched fiber laser, where saturable absorption serves as the essential element [106,107]. Q-switching is a technique used to produce energetic and short pulses, also known as giant pulses. This pulse is not ultrashort. The first experimental works on Q-switched were conducted at Hughes Research laboratories [108]. Hellwarth [109] predicted that a laser would emit short pulses if the loss in an optical resonator was rapidly changed from a high to a low value. This prediction was experimentally confirmed a year later by Collins and Kisliuk [110] and McClung and Hellwarth [111].

By adjusting a laser resonator's quality factor (Q-factor), Q-switching enables the generation of short-duration laser pulses ranging from nanoseconds to picoseconds with high pulse energy. The Q-factor is a dimensionless variable that measures the strength measurement of its oscillation damping. It is determined by:

$$Q = \frac{2\pi f_0 \varepsilon}{P} \quad (4)$$

where f_0 is the resonant frequency, ε the stored energy in the cavity and $P = -\frac{dE}{dt}$ is the power dissipated.

The quality factor (Q-factor) indicates a laser cavity's ability to preserve its energy. A higher Q-factor signifies lower intracavity losses. The term Q-switching describes the process of switching the laser setup from a low Q to a high Q to create a short pulse duration. Initially, the Q-factor is kept low (with large losses) to prevent lasing. The gain medium provides constant pumping, leading to the accumulation of spontaneous emissions in the cavity, and thereby storing energy. When the Q-factor is suddenly increased to a high level and the necessary amount of energy is collected, the laser pulse begins to build up in the cavity following spontaneous emission, becoming a laser. The pulse intensifies until the losses equal the gain. The laser can no longer oscillate when the pulse peak power is exceeded and the gain is fully depleted. The Q-switch is then opened again (low Q), and the process starts over to build up more inversion for the next consecutive pulse [112].

Passively Q-switched pulse fiber lasers are increasingly useful and relevant in real-life applications. For example, in industrial settings, they are extensively used for precise material processing tasks such as cutting [113,114], engraving [115–119], and marking [120–122]. These lasers deliver high peak powers (ranging from several kilowatts to tens of kilowatts) and short pulse widths (in the nanoseconds range), enabling precise, high-quality processing with minimal thermal effects on ceramics, metals, and polymers. Q-switched pulse fiber lasers are also practical in the aerospace sector [123,124], and electronics industries [125] for manufacturing components with complex designs and precise dimensions. Next, these lasers are highly useful in dermatology [126–130], ophthalmology [131,132], and precision surgery [133–137]. They are employed in operations where meticulous control over energy delivery and minimal thermal damage are essential, such as eye surgery, skin resurfacing, and tattoo removal [138,139]. These lasers enable medical professionals to conduct delicate and precise treatments with little to no damage to surrounding tissues. Additionally, they are used in LIDAR systems for atmospheric research, environmental monitoring, and remote sensing applications [140–144]. In telecommunications, a passively Q-switched pulse fiber laser is necessary for high-speed data transmission, wavelength conversion, signal amplification, signal processing, and data routing [145]. Their stability and reliability, combined with their ability to

operate continuously, compact size, lightweight design due to the use of optical fiber as the gain medium, and high efficiency in converting a significant portion of input light energy into laser output, help reduce operating costs and power consumption. These attributes make them indispensable components in fiber optic networks and communication systems, supporting the growing demands of modern telecommunications technologies. Passively Q-switched pulse fiber lasers can create high-energy pulses with good temporal characteristics and narrow linewidths over long distances, making them applicable for military and security devices. These applications include target designation, range finding, and active imaging, all of which require intense bursts of energy [146–148]. In scientific research, this technique is used by researchers to explore ultrafast processes, analyze material properties, and carry out accurate spectroscopic analyzes. It is instrumental in broadening the understanding of basic scientific ideas and opening doors for innovations across various fields of study. Passively Q-switched pulse fiber lasers offer additional key advantages that make them highly desirable, including relatively low maintenance requirements compared to other laser types. They do not require frequent sophisticated component repairs or replacements, resulting in minimized downtime and reduced operational costs over the long term [149,150]. This laser exhibits high beam quality, characterized by strong focusing ability, low divergence, and a well-defined mode structure [130,151–153]. The high beam quality ensures accurate and precise material processing, measurement, and imaging, making them appropriate for applications requiring high spatial resolution and beam manipulation. Passively Q-switched pulse fiber lasers are comparatively easy to operate, unlike several other types of lasers that require complex external modulators [154]. They have a simpler design and are less prone to failure because they do not require alignment to generate a Q-switched pulse [155,156].

4.1 The Principal Process in Generating Q-Switched Pulse Fiber Laser with Saturable Absorber

The generation of Q-switched pulses occurred when a photon of light entered the core of the erbium-doped fiber. This erbium-doped fiber served as the gain medium in the laser cavity to amplify the light. Erbium ions in the fiber absorbed the energy supplied by the pump diode, transferring the energy to the erbium ions and creating a population inversion. This means that the exceeded ions were in a higher state rather than the ground state ions.

The pump diode continuously supplied energy to the gain medium, thus maintaining the population inversion. Following that, the light passed through the area containing the saturable absorber material. The saturable absorber material was designed to have high absorption, creating significant losses within the laser cavity and thus inhibiting lasing from occurring.

As mentioned before, the pump diode continuously supplied energy to the gain medium. After a specific time, the energy within the gain medium achieved a threshold value higher than the loss in the cavity created by the saturable absorber. This caused the absorption of the saturable absorber to suddenly become saturated and then transition to a transparent state.

At that moment, the loss of the cavity was reduced, and the accumulated energy in the gain medium was released, forming the Q-switched pulse with high energy and short duration (Figure 3).

After the pulse was generated, the saturable absorber entered the recovery phase, preparing for the next round of lasing. During this time, the saturable absorber returned to its high absorption state, causing high losses of the cavity and inhibiting lasing. The pump diode continued to supply energy to the gain medium, preparing for the next cycle.

The entire process repeated itself. As the saturable absorber recovered, the loss in the cavity increased, inhibiting lasing. The energy in the gain medium continued to accumulate until it reached

the threshold value, at which point the saturable absorber switched states, leading to the generation of the Q-switched pulses.

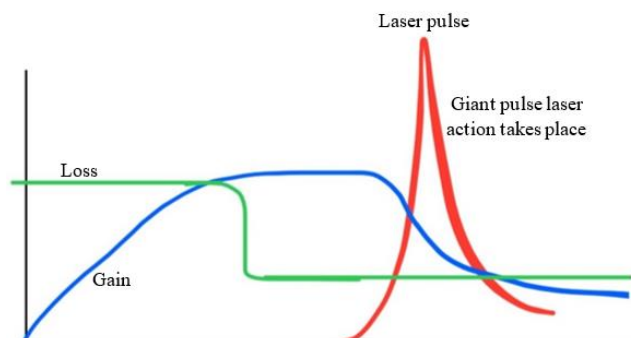


Fig. 3. A visualization depicting the creation of a Q-switched pulse

4.2 Q-Switched Pulse Fiber Laser Key Parameters

The temporal characteristics of Q-switched pulse fiber laser is typically characterized by several key parameters, such as repetition rate, pulse width, pulse energy, and peak power (Figure 4), measured using an oscilloscope.

The first parameter, repetition rate, indicates the number of pulses emitted by the laser within a given time interval, often measured in seconds. This repetition rate can be simply measured from the oscilloscope by monitoring the duration between the output pulse trains. The Q-switched pulse repetition rate typically ranges from a few kilohertz to 100 kHz, representing its fundamental feature [157–159].

Secondly, the pulse width, also known as pulse duration, is identified as the full width at half-maximum, which represents 50 % of the time interval between the rising edge-marking the initiation of the pulse and a drop edge, signifying the end point of the pulse, within the framework of laser pulses. According to Herda *et al.*, the pulse width exhibits a decreasing trend with an increase in pump power [160]. Typically, the pulse width occurs within the microseconds range [10,161].

The term pulse energy pertains to the amount of energy encapsulated within each pulse produced by the laser. It is calculated by dividing the average power by the repetition rate. The measurement of pulse energy is commonly expressed in units of nanojoules [162–164].

Another criterion of a Q-switched pulse is peak power. The peak power of an optical pulse refers to the maximum optical intensity that the pulse can achieve. Peak power is commonly measured in milliwatts or decibel-milliwatts [165].

Meanwhile, an optical spectrum analyzer is used to measure the spectral properties of the laser output, including the main wavelength at which the laser operates. This helps identify the lasing medium and assess the tuning capabilities of the Q-switched laser.

The manipulation of pump power induces noteworthy effects on the Q-switched parameters. As the pump power increases, more energy becomes available for the gain medium in the fiber laser, leading to faster population inversion and quicker recovery of the gain medium. This allows for a higher repetition rate as the laser system can undergo more cycles of energy storage and release in a given period. Simultaneously, the pulse width decreases. Increased pump power accelerates the build-up of energy in the gain medium, resulting in a higher inversion level in the gain medium that allows for quicker release of stored energy during the Q-switched process. Quicker release of energy results in shorter pulse durations, leading to a decrease in pulse width. Furthermore, the pulse energy

exhibits a notable increase, as the augmented pump power provides more energy for storage in the gain medium, resulting in a more substantial release during the Q-switched operation. Finally, the higher pump power leads to more stimulated emission events, contributing to a more intense laser output and, consequently, an increase in the overall output power, owing to the combined effects of higher repetition rates and increased pulse energy.

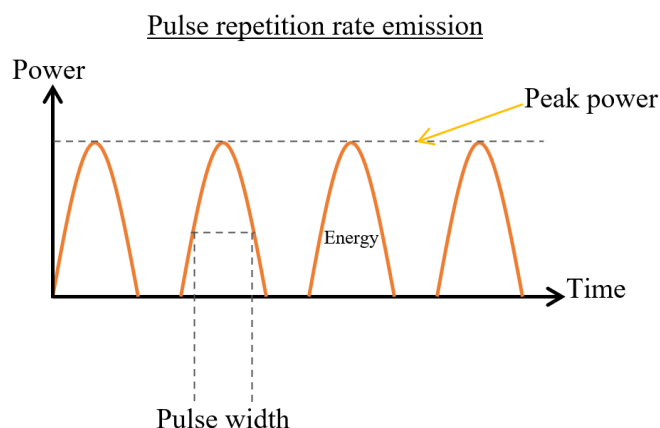


Fig. 4. An illustration of the pulse laser emission

5. Organic Based Saturable Absorber

Currently, the market for various saturable absorbers has been growing, including organic-based saturable absorbers from different classes, which have been successfully used to generate pulsed laser output in erbium-doped fiber laser systems. Over the past five years (since 2021), organic semiconductor material was made from Poly(3-hexylthiophene-2,5-diyl) regioregular, which was used to drive Q-switched pulse generation at maximum repetition rate of 78.63 kHz. In the same year (2021), the Q-switched laser output using 8-Hydroxyquinolino cadmium chloride hydrate as saturable absorber were realized in two different erbium-doped fiber laser's cavity configurations having different output couplers. Najm *et al.*, demonstrated a modulation depth of 11 % as shown in Figure 5. They prepared as saturable absorber by mechanical exfoliation technique and demonstrated Q-switched pulse output of 136 kHz using 50/50 optical coupler. In addition, the same group also used 8-Hydroxyquinolino cadmium chloride hydrate as a saturable absorber using 95/5 optical coupler, achieved 173 kHz Q-switched pulse output. Later, researchers prepared 8-Hydroxyquinolino cadmium chloride hydrate material as a saturable absorber in the thin-film form, exhibit modulation depth of 18 % which enabled Q-switched pulse generation at 150 kHz and 143 kHz, respectively. These studies suggest that organic-based saturable absorber materials can be effectively engineered to generate a broader pulse range.

The operation of the organic-based saturable absorbers was extended by using turmeric material, prepared by embedding turmeric powder into polyvinyl alcohol (PVA) film. A stable Q-switched pulse with a pulse width of 0.725 μ s and a repetition rate of 90.09 kHz was obtained at a central wavelength of 1566.96 nm (Figure 6).

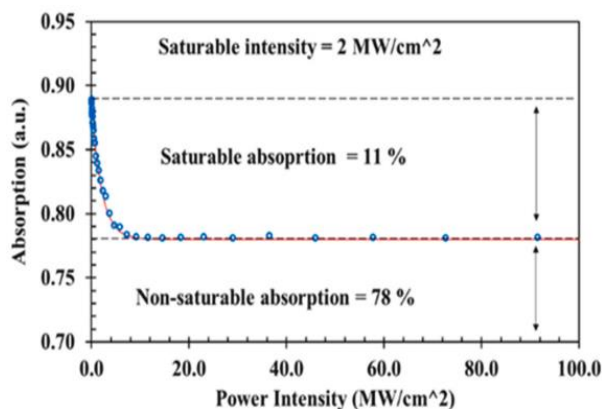


Fig. 5. The nonlinear absorption response of 8-Hydroxyquonolino cadmium chloride hydrate [166]

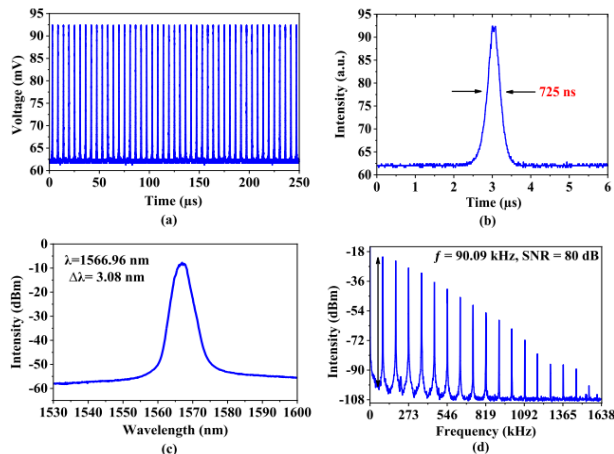


Fig. 6. (a) Pulses train, (b) single pulse envelop, (c) output spectrum, and (d) radio frequency spectrum [167]

Due to the optical response of poly (3,4 ethylenedioxythiophene): poly (4-styrenesulfonate), organic conducting material, Al-Hiti *et al.*, were fabricated thin-film saturable absorber by mixing poly (3,4 ethylenedioxythiophene): poly (4-styrenesulfonate) with polyvinyl alcohol (PVA), prepared by simple solution casting and spin-coating method. From the balanced twin detector measurement revealed that it has potential to be performed as a pulse initiator in 1.5 μm region as it owns moderate of saturable absorption of 50 % and 22 % respectively.

Natural dyes, considered among the organic-based materials, are colorants acquired from plants, minerals, and/or invertebrates. Henna (*Lawsonia inermis*) is one such dye material, obtained from the leaves of the plant, traditionally used to create intricate designs on women's hands. The leaves of the plant are dried, crushed, and then boiled with water to extract the dye. The potential of lawsone-based saturable absorbers has been highlighted due to their nonlinear optical properties at low input power. Soboh *et al.*, in 2021 reported the generation of stable Q-switched pulses at a central wavelength of 1564 nm, with the highest repetition rate of 80 kHz, and the lowest pulse width of 1.7 μs , utilizing lawsone as the saturable absorber [168].

Furthermore, phthalocyanines based saturable absorber allow for the operation wavelength for instance, S. Wadi *et al.*, demonstrated a modulation depth of 8.8 % at 1532.1 nm with repetition rate of 77.2 kHz. Additionally, the same group also used phthalocyanines film as saturable absorption (9.5 %) achieving 48.6 kHz pulse repetition rate.

Ahmad *et al.*, (2024) practically using Polyacrylonitrile film as a saturable absorber for generating Q-switched pulses with the combination of Polyacrylonitrile, a resin material, and polyvinyl alcohol. Polyacrylonitrile is a synthetic polymer derived from the monomer acrylonitrile, and it is structurally composed of a linear polymer featuring repeating units of acrylonitrile monomers. This organic polymer exhibits a semicrystalline nature and is characterized by the chemical formula $[\text{C}_3\text{H}_3\text{N}]_n$, with a nitrile (CN) functional group attached to its polyethylene backbone as the fundamental unit structure. The nitrile group, acting as a hydrogen bonding acceptor, possesses a large dipole moment between the electron-deficient carbon atom and the electron-rich nitrogen atom, facilitating relatively strong attractive interactions. The Polyacrylonitrile film saturable absorber, fabricated via a casting approach, was generated Q-switched laser pulses at a central wavelength of 1572.0 nm. The highest repetition rate and the lowest pulse width achieved was 66.1 kHz and 2.43 μs , respectively.

Q-switched pulse generation-based Poly(9-vinylcarbazole) saturable absorber was validated by Samsamun *et al.*, Poly(9-vinylcarbazole) has a bandgap energy of about 3.4 eV and it has been used

to investigate the nonlinear optical properties of Poly(9-vinylcarbazole) thin film fabricated by spin-coating approach. The highest pulse obtained at 1562 nm band characterizes a pulse width of 395 us at a repetition rate of 77.2 kHz.

Spider silk, with its exceptional all-encompassing characteristics, has become one of the most sought-after natural biological materials among researchers. Natural spider silk is a type of protein-based biological material produced naturally by the spider through the silk gland in its body [19,169]. Spider silk shows high transmittance and sparkles in the sunlight, prompting researchers to delve deeper into its optical transmission potential. In 2013, Huby *et al.*, proved that natural spider silk can be utilized as a sustainable and efficient optical fiber, capable of propagating light. A straight spider silk fiber was found to have an attenuation coefficient of 10.5 dB/cm in air. The propagation of light was further confirmed through various arrangements, including spider silk arranged in a loop configuration, silk submerged in a physiological liquid, and the integration of silk fiber into photonic chips via a hybridization process involving synthetic polymers (photoresist) and natural silk fibers [21].

In addition, Tow *et al.*, implemented spider dragline silk as a means to use as a chemically active optical fiber to measure ambient relative humidity levels. The proposed concept was validated by a polarimetric setup consisting of a laser, polarization controller, single-mode fiber, gas chamber with controlled temperature and humidity levels, dragline silk, and polarization analyzer. They applied a polarization analyzer to measure the phase change of the transmitted light. They have demonstrated that spider silk possesses the inherent ability to effectively direct light within a certain range of wavelengths, spanning from the visible spectrum to around 1400 nm. This light-guiding capability is accompanied by minimal signal attenuation, with propagation losses measuring below 1 dB/mm. The aforementioned characteristics enable the employment of silk as a means of transmitting light, serving as a chemically responsive protein thread that functions as a fiber-optic sensor for quantifying the level of ambient relative humidity [170,171]. Those studies describe the uses of spider silk as an efficient light guide, as biological media in an integrated photonic chip, and as an optical sensor.

5.1 The Specific Properties of Spider Silk That Make It Suitable for Use as A Saturable Absorber

Natural spider silk is featured by the composition of the protein that makes up the silk. The amino acid composition, produced by the major ampullate glands of the spider and used as the primary structural material of its web, consists predominantly of glycine (30%-40%) and alanine (20%-30 %). The glutamine content exceeds 10 %, while the proline content is about 5 %, suggesting that the silk possesses both hydrophobic and hydrophilic properties [172]. Silk protein sequences exhibit a distinctive structural characteristic in which they are arranged into two types of domain sections. The first type is a β -sheet block, consisting of small repetitive units that are typically hydrophobic and form the crystalline portion of the silk. The second type is organized in α -helices, consisting of the non-repetitive hydrophilic part of the core sequence, which constitutes the amorphous regions [173,174]. The silk is a protein thread made up of repeated arrays of polypeptides that have both separate and distinct crystalline and non-crystalline sections. These sections align along the axis of the silk. The attachment between these two sections is maintained by reversible hydrogen bonds (see Figure 7), which can be modified by various types of molecules. This property makes them well-suited for detecting modifying agents including water molecules, acids, and bases. Molecules that interact will either attach to the amino acids in the α -helical section, impacting the silk ability to elongate, or attach to the amino acids in the β -sheet blocks, altering the silk crystallinity or the orientation of the crystalline blocks. These unique conformational events result in changes in the optical characteristics of the light passing through the silk [170].

The optical abilities combined with unique biocompatibility, and tensile strength of spider silk enable its manipulation for advanced optical investigations and pave the way for its incorporation as a natural biological saturable absorber material to generate pulsed fiber laser [21,170,175–194].

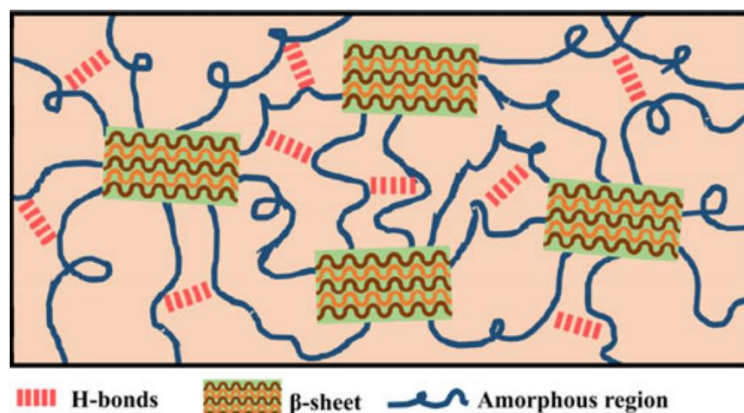


Fig. 7. This diagram illustrates the structure of silk protein, with the β -sheets (crystalline region) enclosed within the amorphous region. The crystal orientation is maintained along the silk axis by reversible hydrogen bonds (red lines) [170]

5.2 Experimental Findings

According to Muhammad *et al.*, 2024, they quantified the nonlinear absorption of spider silk saturable absorber which is evident from the fitting curve given in Figure 8 that spider silk functioning as a saturable absorber exhibits a modulation depth of $26 \pm 8 \%$ and a saturation intensity of $0.02 \pm 0.01 \text{ WM/cm}^2$. Additionally, in the design of the Q-switched erbium-doped fiber laser, Figure 9 demonstrated that the pulse width decreased as the pump power increased, while the repetition rate concurrently increased. The maximum output power and pulse energy were $0.04 \pm 0.01 \text{ mW}$ and $1.4 \pm 0.3 \text{ nJ}$ in Figure 10, respectively. The output spectrum wavelength of $1569 \pm 23 \text{ nm}$ was determined using an optical spectrum analyzer (Yokogawa, AQ6370D), with a 2 nm resolution having a wavelength range of 600 - 1700 nm, as shown in Figure 11. The pulse characteristics were observed utilizing a InGaAs biased detector (Thorlabs, DET08CFC/ M) with a 5 GHz bandwidth connected to an oscilloscope (Tektronix, MDO3104). These observations indicated that when the pump power was set at 200 mW, the minimum pulse width recorded was $10 \pm 5 \mu\text{s}$, which occurred simultaneously with the maximum pulse repetition rate of $29 \pm 6 \text{ kHz}$. A stable pulse train was observed across varying time scales, as illustrated in Figure 12, through the use of an oscilloscope. These experimental results demonstrate the effectiveness of spider silk as a saturable absorber which provide practical insights and validate the theoretical claims.

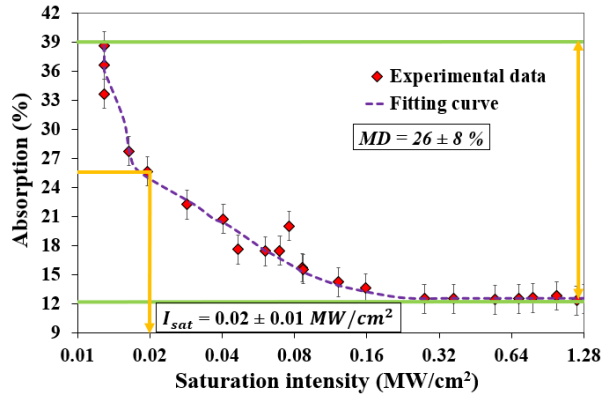


Fig. 8. The nonlinear absorption of the spider silk-based saturable absorber [195]

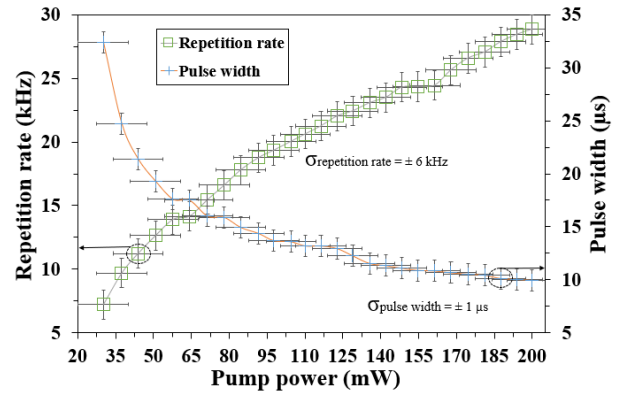


Fig. 9. Repetition rate and pulse width depends on pump power [195]

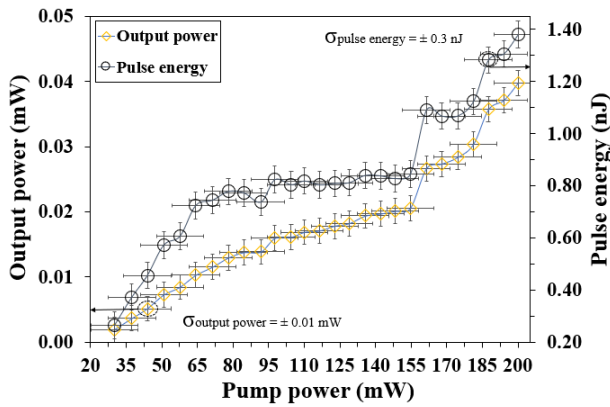


Fig. 10. Output power and pulse energy influenced by pump power [195]

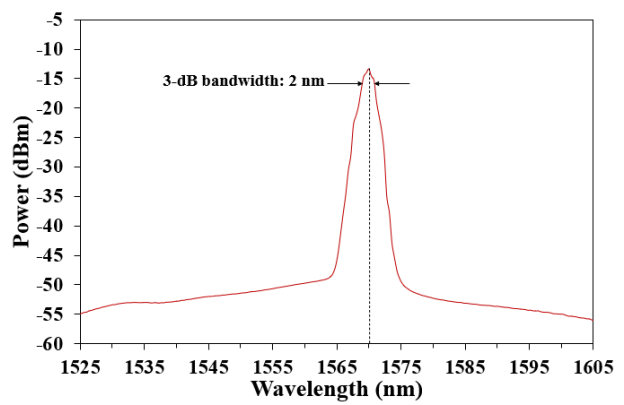


Fig. 11. The output spectrum of the Q-switched pulse fiber laser at a pump power of 200 mW with a 3-dB bandwidth of 2 nm and a central wavelength of 1569 ± 23 nm [195]

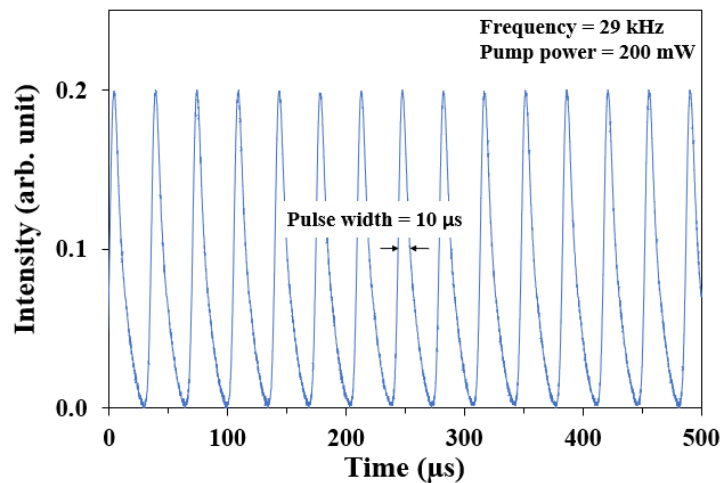


Fig. 12. A stable pulse train at the highest pump power [195]

Table 1 below shows the summarize of the results on the performance of Q-switched pulse fiber laser exploiting different organic-based saturable absorbers.

Table 1

Summarization results on the performance of Q-switched pulse fiber laser exploiting different organic-based saturable absorbers

SA category	SA material	MD (%)	Saturation intensity (MW/cm ²)	L_{EDF} (m)	PP_T (mW)	λ_C (nm)	Max. RR (kHz)	Min. PW (μ s)	SNR (dB)	PE (nJ)	Ref.
Organic material (semiconductor)	Poly(3-hexylthiophene-2,5-diyl) regioregular	11	80.45	2.4	63	1562	78.63	3.79	49.72	15	[16]
Organic material	8-Hydroxyquonolino cadmium chloride hydrate (50/50 OC)	11	2	1	50	1530.49	136	2.076	81	172	[166]
Organic material	8-Hydroxyquonolino cadmium chloride hydrate (95/5 OC)	11	2	1	101	1530.49	173	1.66	75	10	[166]
Organic material	8-Hydroxyquinolino cadmium chloride hydrate	18	0.1	1	101	1530	150	726 ns	72	4.5	[196]
Organic material	Turmeric	23	0.16	2	119	1566.96	90.09	0.725	80	150.96	[167]
Organic material	Poly(3,4 ethylenedioxythiophene): poly (4-styrenesulfonate)	50	0.14	2	113	1568.03	108.69	9.2	79	192.11	[8]
Organic material (natural dye)	Lawson (2-hydroxy-1,4-naphthoquinone)	12	3.5	2.4	26	1564	80	1.7	71	53.7	[168]
Organic material	Poly(3,4- ethylenedioxythiophene): poly(styrenesulfonate)	22	0.21	2	87	1563.3	85.91	1.97	65	155.51	[197]
Organic compound	Copper phthalocyanines	8.8	7	2.4	66.3	1532.1	77.2	3.95	55.4	49.2	[15]
Organic compound	Iron phthalocyanines	9.5	0.01	1.8	35.2	1531.3	48.6	4.34	60.28	53.6	[198]
Organic thin film	8-HQCdCl ₂ H ₂ O	18	0.1	1	71	1531	143	1.85	82	167	[199]
Organic polymer	Polyacrylonitrile	11.4	20	0.7	113.3	1572	66.1	2.43	52.1	52	[200]
Organic semiconductor	Poly (9-vinylcarbazole)	4	202.07	2.4	63.4	1562	91.91	3.43	51.14	8.73	[201]
Organic (natural biological)	Spider silk	26 $\pm$ 8	0.02 $\pm$ 0.01	3	30 $\pm$ 1	1569 $\pm$ 23	29 $\pm$ 6	10 $\pm$ 5	54 $\pm$ 14	1.4 $\pm$ 0.3	[195]

6. Q-Switched Pulse Fiber Laser Applications

Q-switched pulse fiber laser is versatile tools with a wide range of applications. It can be tuned to different wavelengths, which is useful as tunable laser source. It also supports dual-wavelength switching. In temperature sensing, Q-switched laser provide accurate measurements by detecting subtle changes in temperature. Additionally, it is used to detect adulteration in pure kelulut honey, offering a quick and non-invasive method to ensure its purity. These applications highlight the adaptability and precision of Q-switched pulse fiber laser, making them a focus of ongoing research and innovation.

6.1 Tunable and Switchable Dual-Wavelength

6.1.1 Wavelength tunable

Wavelength tunable refers to the ability of a laser to adjust its output to various specific wavelengths within a certain range. This adjustment can be achieved using different tunable filters, which are frequently used to tune the wavelength of the pulsed laser. Examples include curved multimode fiber [202], fiber Bragg grating (FBG) [203], multimode interference filter [204], rotating mirrors in combination with a diffraction grating [205,206], Sagnac interferometer [207,208], tilted fiber Bragg grating [209], and tunable bandpass filter (TBF) [28,210–219]. A wavelength tunable laser is imperative in applications where the precise matching of the laser wavelength to specific absorption lines or material properties is necessary. Such lasers are extensively applied in the treatment of pigmented lesions, teeth whitening procedures, and multiphoton microscopy technology.

A wavelength-tunable device using TBF has been designed to possess an adjustable transmission band, enabling it to selectively transmit light within a certain range of wavelengths. The operational mechanism of the TBF has its foundation based on the Fabry-Perot interferometer, as described by Frankel *et al.*, [220]. To modify the incident angle of the beam, the wavelength must be identified according to the expression given below [220]:

$$\lambda = \left(\frac{2nL}{m}\right)(\cos \theta) \quad (5)$$

The variables in the Eq. (5) are defined as follows: λ is the wavelength of interest, n represents the refractive index of the etalon, L represents the thickness of the etalon filter, m is an integer, and θ represents the angle between the incident beam and the normal axis. The model of the fiber-coupled TBF is shown in Figure 13 (a), whereas Figure 13 (b) depicts the light propagation via the Fabry-Perot etalon filter. The light beam emitted by the single-mode fiber is directed through a collimator. The light subsequently passes through a region of free space, which serves as a filter when it encounters a Fabry-Perot etalon. Before entering the second single-mode fiber, the propagating beam recombines in the second collimator. By adjusting the Fabry-Perot etalon, it is possible to change the angle at which the beam propagates, allowing for the selection of a specific wavelength. The adjustability of the TBF allows for precise tuning to select any desired wavelength within its operational range. This adjustment results in the rotation of the Fabry-Perot etalon, resulting in the desired output.

In another view, the tuning of wavelength to various specific wavelengths within a certain range is achieved with the support of a tunable bandpass filter. The operational mechanism of the tunable bandpass filter is based on the Fabry-Perot etalon, an optical device, in the experimental setup. This Fabry-Perot etalon is designed with two parallel mirrors that are partially reflective and separated by

a spacer. When light enters the etalon, a portion of it is partially reflected while the rest is transmitted at each mirror. Constructive interference occurs when the optical path difference (the distance between two light paths) between the reflected beams multiple with an integer of the wavelength, leading to reinforcement and the creation of a bright fringe. Destructive interference, on the other hand, occurs when the optical path difference between the reflected beams is multiple with half of the integer wavelength, causing the waves to cancel out and resulting in a dark fringe. Next, the desired wavelength is selected by adjusting the spacer thickness (distance), which is designed to be adjustable. Adjusting this spacer thickness changes the interference, thereby producing the desired wavelength output. Overall, the measurement of the resulting tunable wavelength is caused by the light transmitting through the etalon, which produces interference fringes. By analyzing these fringes, the desired output of a wavelength-tunable Q-switched pulse erbium-doped fiber laser is achieved.

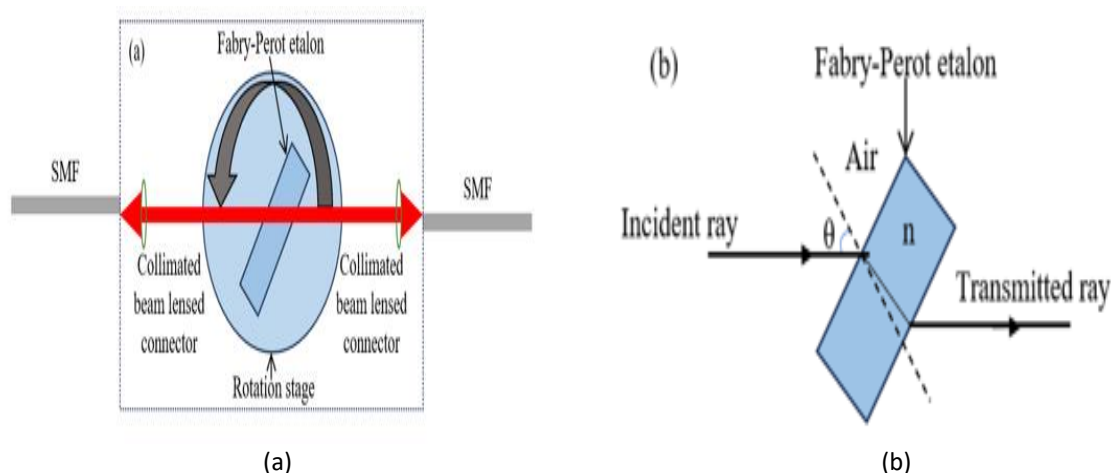


Fig. 13. (a) The model of fiber-coupled tunable bandpass filter; (b) The propagation of light via the Fabry-Perot etalon filter

6.1.2 Switchable dual-wavelength

Switchable dual-wavelength refers to the ability to rapidly and discretely adjust the laser emission from one fixed wavelength to another dominant wavelength. This feature is beneficial in applications where swift switching between different wavelengths is demanded, such as in modern communication networks, including terahertz signals [221]. It facilitates the effective and adaptable administration of optical signals, particularly in situations where multiple channels must be accessed consecutively for data transmission or processing.

To obtain switchable dual-wavelength operation, the polarization controller is required to manipulate the polarization state of light, impacting the Q-switched operation with two fiber Bragg gratings [222]. This assists in generating dual-wavelength pulses by reflecting different wavelengths. A fiber Bragg grating operates as a wavelength-selective mirror, carefully structured with distinct grating periods that align with the targeted wavelengths at which they reflect light [223,224]. The fiber Bragg grating's design parameters, such as the period and amplitude of the refractive index variation, determine the specific wavelength that the grating reflects. When light travels through an optical fiber, the fiber Bragg grating causes the reflection of the Bragg wavelength, leading to a distinct reflection peak at that specific wavelength while transmitting all others.

6.2 Sensor Applications

The pulse generated remains stable due to the gain and modulated loss of the saturable absorber. At the same time, the pulse can detect external stimuli, such as changes in temperature or the presence of adulterants in honey solutions, making it function as an optical sensor. This can be achieved by integrating sensing elements like side-polished fiber or fiber Bragg grating within the cavity.

6.2.1 Sensing element

6.2.1.1 Side-polished fiber

The investigation of side-polished fiber (SPF) has spanned four decades since its initial development by Bergh *et al.*, in 1980 [225]. Side-polished fiber provides a flexible and adaptable framework for developing optical fiber devices and sensors. It exhibits dependable mechanical features and effective immunity to electromagnetic interference, making it suitable for various applications, including temperature sensing [226]. Figure 14 portrays the structure of side-polished fiber, which comprises three distinct segments: the lead-in and lead-out optical fiber (the transitional area), and the flat area. During the fabrication of side-polished fiber, it is necessary to remove a portion of the cladding through polishing. The distance between the polished surface and the core is typically on the order of a few microns, so the evanescent field of the light propagating through the fiber will escape or leak from this polished region [227]. The flat area is in the middle of the polished region, situated between the two transition regions. The residual thickness refers to the measurement of the distance between the polished surface and the bottom surface of the fiber. This parameter identifies the interaction strength between the transmitted light in the side-polished fiber and the surrounding media [228].

Side-polished fiber is prevalently used as a sensing device to detect temperature variation. As mentioned earlier, the surface of the side-polished fiber is partially polished in the centre area to facilitate the propagation of light. The polished region acts as a sensing area, confining light within the core due to the high refractive index of the core. However, when the side-polished fiber is immersed in hot water, for example, a portion of light leaks from the core to the cladding or surrounding medium. The outcome of this process leads to the formation of an evanescent wave [229]. An evanescent wave is a near-field electromagnetic wave that exhibits an exponential decay as it propagates into a medium [226]. It is a unique characteristic of wave propagation that occurs when a wave, such as light, moves from a medium with a higher refractive index to one with a lower refractive index. This occurs when the angle of incidence surpasses the critical angle [230]. When this happens, instead of being transmitted over the interface, a fraction of the wave's energy is preserved and propagates along the interface in the form of an evanescent wave. The evanescent wave undergoes interaction with the external medium, and variations in the surrounding environment, such as fluctuations in temperature due to immersion in hot water, can affect this interaction [231]. The changes in the properties of the evanescent wave due to temperature changes can be identified and measured such as monitoring the wavelength or radio frequency change of the light that is transmitted through the fiber.

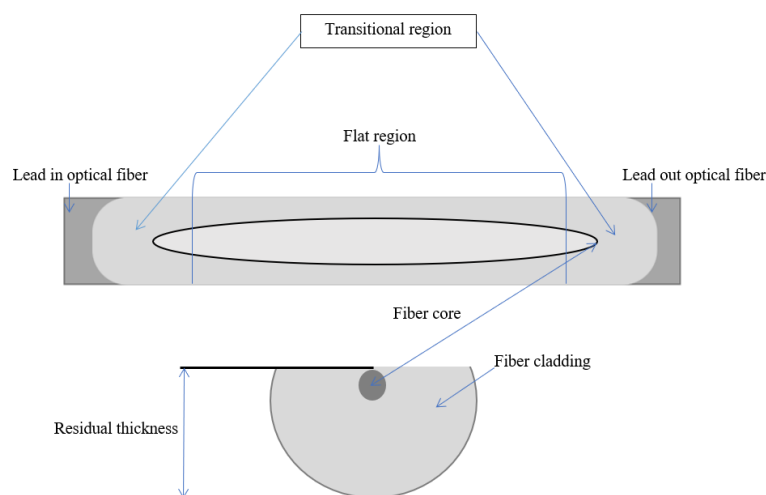


Fig. 14. The polished area's cross-section and top view of the side-polished fiber

6.2.1.2 Fiber Bragg grating

A fiber Bragg grating is a type of fiber optic component that incorporates a distributed Bragg reflector within a tiny section of the fiber core. This section is manufactured and incorporated within the optical fiber using an ultraviolet lithography technique. It is designed to selectively reflect a particular range of wavelengths associated with the guided modes while allowing the transmission of all other wavelengths. Figure 15 portrays the basic structural arrangement of fiber Bragg grating, which is manufactured with a periodically uniform grating structure. This grating constitutes the core of the optical fiber, characterized by refractive index variation with constant segments from one grating to another. These gratings are recognized as fundamental components in the manufacture of most Bragg grating structures, which periodically modulate the phase or intensity of a light wave that is reflected or transmitted by them [232–235].

Fiber Bragg grating works based on constructive interference, meaning that as the incident light travels along the fiber Bragg grating and matches with the Bragg condition (twice the grating spacing multiplied by the effective refractive index of the core), a portion of the incident light will undergo reflection. However, due to destructive interference (when the incident light travelling along the fiber Bragg grating does not match the Bragg condition), the light continues to be transmitted along the fiber. The incident wavelength that satisfies the Bragg condition, or the Bragg wavelength, is denoted as λ_B . The effective refractive index of the mode propagating in the fiber is denoted as n_{eff} , and the grating period, Λ has an impact on the Bragg wavelength. The wavelength at which a significant reflection will occur is determined by Eq. (6), [236]. The reflection of light can be attributed to changes in refractive index, which can be comprehended through a physical perspective. If the reflections from points that are spaced apart by a spatial period are in phase, then the cumulative reflections combine coherently to produce a robust reflection. Eq. (6) indicates that any change in the physical or mechanical properties of the grating region has an impact on the reflected wavelength, λ_B . The Bragg wavelength experiences a shift due to perturbations of the external medium that surrounds the fiber.

$$\lambda_B = 2\Lambda n_{eff} \quad (6)$$

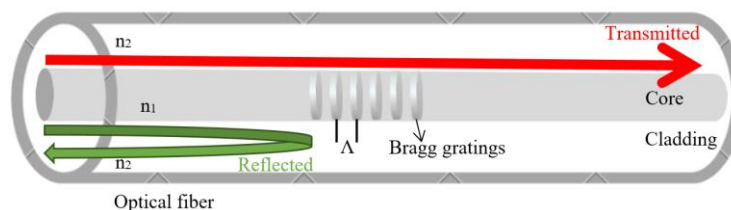


Fig. 15. The basic structure of fiber Bragg grating [237]

6.2.2 Temperature Sensor

Temperature monitoring is prominent in several industries such as the aerospace domain, metallurgical sector, medical profession, and nuclear energy generation [238,239]. The implementation of temperature monitoring inside the turbines and combustion chambers of an aircraft or aero-engine can contribute to the prolongation of its operational lifespan [240–242]. On the contrary, monitoring the interior temperature of high-temperature boilers in the metallurgical industry is critical for accurately assessing the combustion rate and ensuring safety measures are in place [243,244]. In recent times, there has been a significant surge in attention given to temperature monitoring instruments within the medical sector. This heightened interest is mostly attributed to the emergence of COVID-19, which has necessitated the constant monitoring of individuals' temperatures in public areas [245,246].

Fiber temperature sensors have the flexibility to endure challenging conditions of higher temperatures and pressures, as well as the potential to perform distributed remote measurements [247]. They are also beneficial in terms of compact size and immunity to electromagnetic interference [248]. Temperature sensing often depends on either the wavelength shift or radio frequency shift of the transmission spectrum or the fluctuation of transmitted power. To date, different techniques have been employed for temperature sensing, encompassing standard fiber types such as single-mode fiber and multi-mode fiber [249], photonic crystal fiber [250], fibers based on gratings structure such as fiber Bragg grating [251], long-period grating, and tilted fiber Bragg grating [252], Fabry-Perot interferometer fiber [253], as well as side-polished fiber [254]. In comparison to alternative fiber optics for sensor measurement, grating-based and side-polished fiber as the sensing element exhibit advantages such as excellent linearity and stable operation. Consequently, these sensors have found extensive use in commercial applications. Muhammad *et al.*, (2024) proposed and demonstrated temperature sensing device incorporating side-polished fiber and fiber Bragg grating as the sensing element within the passively Q-switched pulse fiber laser source [255]. The structure converts the continuous wave generated by a self-constructed erbium-doped fiber ring cavity with a spider silk saturable absorber into a pulsed laser of Q-switched. The Q-switched laser shows good characteristics, including a high damage threshold and resistance to oxidization, deformation, or environmental factors. The side-polished fiber and fiber Bragg grating temperature sensing area are inserted into the ring cavity, whose characteristics are experimentally investigated by monitoring the oscilloscope trace of the pulse train and radio frequency shifts, as well as assessing the stability, sensitivity, and linearity of the device.

6.2.3 Detection of Adulteration in Pure Kelulut Honey

Pure kelulut honey is highly valued in Malaysia as a versatile health supplement. Numerous claims are associated with it, including its potential as an antibacterial agent, antidiabetic compound, anti-inflammatory substance, antioxidant, and antitumor agent. These observed effects are due to the numerous bioactive constituents, which include acids, flavonoids, minerals, and phenolics [256–260].

In addition, the presence of trehalulose has been discovered in kelulut honey, which is widely distributed in kelulut bee farms in Malaysia. Trehalulose, an infrequent disaccharide, is an isomer of sucrose that has a lower glycemic index [261]. These facts support the traditional claim that kelulut honey is suitable for consumption by diabetics, as it has the potential to help lower blood glucose levels [262].

The constituents of pure kelulut honey include minerals, proteins, natural sugars, and water [263]. However, in order to profit through unethical means, the purity of honey is compromised by adding various cheaper ingredients such as beetroot sugar, cane sugar, or other sugar derivatives such as high fructose corn syrup, high fructose inulin syrup, or invert sugar syrup [264–268]. These compounds alter the biochemical properties and flavour of honey and have a negative impact on its nutritional composition, which in turn affects human health negatively [269–271].

In response to the growing need for robust methods to detect adulteration in pure honey, researchers have been working intensively on this aspect [272–274]. A variety of techniques have been developed to detect adulteration in pure honey. These include Fourier transform infrared spectroscopy [275], Fourier transforms Raman spectroscopy [276], gas chromatography [277], liquid chromatography [278,279], liquid chromatography coupled with isotope ratio mass spectrometry [280], near-infrared spectroscopy [281–283], nuclear magnetic resonance spectroscopy [284], stable carbon isotope ratio mass spectrometry [285,286], and thermal analysis [287]. Despite their effectiveness, these methods require specialized laboratory equipment and labour-intensive sample preparation, time-consuming procedures, and incur significant costs [288]. Therefore, it is imperative to develop and implement a robust method for the detection of adulteration in pure honey that not only ensures the quality, safety, and reliability of pure honey but is also stable and easy to use.

The application of fiber optic structures has been extensively researched for detecting various adulterants and contaminants in food. They represent a compelling alternative to other methods that address the challenges [289–291]. Techniques such as fiber Bragg grating [292], lossy resonance [293,294], and surface plasmon resonance have been investigated [295].

In 2024, Muhammad *et al.* presents the development of pulse fiber laser sensor structure for the detection of adulteration in pure kelulut honey using fiber Bragg grating technology as the sensing element [237]. The sensor is based on a Q-switched pulse erbium-doped fiber laser and uses spider silk as the base material. The functionality of the proposed sensor is based on the principles of Bragg grating fiber, wherein the Bragg wavelength is determined by the grating period and the effective refractive index of the fiber. Changes in the concentration of the adulterated analyte result in changes in the composition of the solution, leading to a shift in the refractive index of the adulteration solution [296,297]. Variations in the refractive index of the adulteration solution affect the overall effective refractive index, producing a response in the form of a resonance shift in the fiber Bragg grating curve. The resonance shift is influenced by different frequencies associated with the different optical wavelengths, altering the resonance angle and half-width of the fiber Bragg grating. This intricate interplay between the optical parameters enables a detailed understanding of the sensor's response to changes in adulterant concentrations in kelulut honey solutions, ranging from 0 % to 50 %. This dual mathematical and optical analysis greatly improves the precision and sensitivity of the proposed pulse fiber sensor, making it a valuable tool for detecting subtle changes in complex solutions.

7. Limitations

The use of spider silk as a saturable absorber brings intriguing possibilities, but it is not without limitations. One significant issue is related to material sourcing. Natural spider silk is difficult to obtain in large quantities due to spiders' territorial and cannibalistic nature, making large-scale production

impractical. Although synthetic production methods, such as genetic engineering in bacteria or plants, offer promise, ensuring scalability and uniformity remains a challenge. Additionally, integration challenges further complicate the use of spider silk as a saturable absorber. Its delicate and fibrous nature makes handling and incorporation into optical systems more complex, often requiring additional treatments to ensure compatibility and durability. These extra steps can increase production costs and complicate the manufacturing process. These challenges highlight the need for further research and development to address the limitations of spider silk and enhance its potential as a viable saturable absorber.

8. Conclusions

In conclusion, we were driven by the need for novel solutions in the realm of Q-switched pulse fiber laser applications. Traditional approaches often rely on saturable absorbers of synthetic origin or inorganic material, presenting limitation in terms of environmental impact. The exploration of organic-based saturable absorber such as spider silk stemmed from its unique properties, including its biocompatibility, potential for cost-effective material without compromising the pulse fiber laser generation, and interestingly, it has been proved that this spider silk served as photon carriers and light guiding with transmission losses of a few dB/cm. Recognizing these attributes, researcher were inspired to investigate its viability within the context of Q-switched pulse fiber lasers, aiming to not only advance the field of photonics but also contribute to environmentally friendly and sustainable technologies. This motivation guided our research endeavours, propelling us to explore innovative avenues in the use of saturable absorber material for Q-switched pulse fiber laser development.

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