Passively Q-Switched Erbium-Doped Fiber Laser with Brass-Based Saturable Absorber

N.N.A.A. Nik Zain[1], H. Yahaya[1], W.M.F. Wan Nawawi[2], N.B. Ahmad Khairuddin[1], S. Ambran[1], S.N.F. Zuikafly[1], H.H.J. Sapingi and F. Ahmad[1]*

[1] Malaysia Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia
[2] Department of Biotechnology Engineering, International Islamic University Malaysia, 53100 Selangor, Malaysia

E-mail: fauzan.kl@utm.my

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Abstract
The operating wavelength in the 1.5 μm region is made accessible through an Erbium-doped fiber as a gain medium. The minimum optical loss of this region has proven beneficial in the application of pulsed fiber lasers. However, the ideal material to act as passive modulator for the system is yet to be found. Therefore, this research proposed the generation of pulsed fiber laser using metal based passive saturable absorber by utilizing brass-based 3D printer filament. A free-standing film was fabricated using chitin as host polymer for ease of integration in the laser ring cavity. The Erbium-doped fiber laser with brass-chitin based polymer composite film generated Q-switched pulses within the input pump power of 135.7 mW to 172.3 mW. The repetition rate was increased from 55.80 kHz to 68.03 kHz. Meanwhile the pulse width was reduced from 3.06 μs to 2.24 μs, with corresponding maximum instantaneous pulse energy and peak power of 2.10 nJ and 882.71 μW, respectively. The signal-to-noise ratio was measured at 67 dB, indicating a highly stable pulse generation.

Keywords
brass filament, chitin, saturable absorber, Q-switch

1. Introduction

Nowadays, different fields of science and technology utilize fiber lasers due to their flexibility and ease of use [1]. Erbium-doped fiber (EDF)'s operating wavelength in 1.5 μm region serves as a huge advantage in the telecommunication fields due to the minimum possible optical loss incurred in the telecom fibers in this region [2]. In pulsed fiber lasers, a saturable absorber (SA) is introduced to control the gain modulation in the laser cavity. Through this approach, pulsed laser generation can be achieved through passive Q-switching. Q-switching in a laser leads the output signal to operate in pulsed form. Nowadays, passive Q-switching method is preferred by researchers as compared to the active approach [3]. The use of SA to modulate the cavity's intracavity loss instead of an external component made it simpler and more flexible. Many types of materials have been reported as SAs by researchers, including 1 dimensional (1D) and 2-dimensional (2D) materials, topological insulators (TIs) and transition metal dichalcogenides (TMDs) [4]. However, the search of the ideal SA is still on-going.

Recently, metal nanomaterials have attracted many researchers as the next generation of SA. Metal nanoparticles, including gold (Au), silver (Ag), copper (Cu) and brass possess strong light absorption caused by the collective oscillation of conduction electrons of metal nanoparticles, namely localized surface Plasmon resonance (LSPR). The strong resonance due to LSPR also contributes to the significant enhancement in optical nonlinearity, which is nonlinear absorption. Compared to gold and silver, copper and brass are more cost-effective and are commercially available in different forms. The lasers generated using copper-based passive saturable absorbers are reported to have operating frequencies covering from visible range to mid-infrared region with different starting materials such as copper pellets, copper nanoparticles, copper oxide (CuO) nanopowder and copper nanowires (CuNWs).

Brass is a mixture of metals or alloy, mostly referred to copper alloy and zinc element mixture [5]. A report in [6] reported a Q-switched fiber laser by employing CuO nanomaterial. The SA was prepared by embedding CuO nanoparticles (NPs) into polyvinyl alcohol (PVA) by solution casting method. The fabricated CuO-PVA film was integrated in Erbium-doped

fiber laser (EDFL) to generate stable Q-switching pulses with operating wavelength at 1560 nm within the input pump power from 70 mW to 159 mW. The shortest pulse width of 2.6 μs, with the maximum pulse energy of 66 nJ and pulse repetition rate of 83 kHz were obtained. Its metal counterpart, zinc oxide (ZnO), was first reported as SA to generate pulsed laser in 2016 [7]. Stable Q-switched pulses were generated with increasing repetition rate from 41.7 kHz to 77.2 kHz while the pulse width was decreased from 9.6 μs to 3.0 μs as the pump power was increased from 60 mW to 360 mW. Recently, Soboh et al. [8] reported zinc phthalocyanine (ZnPc) films based SAs. The film was prepared in three ways in which ZnPc were embedded into, casted onto and spin-coated onto the PVA film. Stable Q-switching pulses operating at 1561.4 nm, 1560.4 nm, and 1559.5 nm were obtained from embedded ZnPc:PVA, casted ZnPc/PVA, and spin-coated ZnPc/PVA SAs, respectively. The shortest pulse width of 3.6 μs and 71 nJ of maximum pulse energy were obtained using the embedded ZnPc/PVA SA. These works using the metals based SAs showed good Q-switching performance in the 1.5 μm wavelength region. This inspired the use of brass based SA as there was also a report of it exhibiting SA properties [9]. To the best of our knowledge, this is the first report on brass based SA in pulsed fiber laser.

A simple fabrication process of the brass based film is demonstrated and reported in this work. Chitin was used as the host polymer to promote a sustainable and environmentally friendly SA.

2. Methodology

a. Brass Chitin SA Fabrication and Characterization

Chitin was prepared from oyster mushroom (*Pleurotus Ostreatus*) and used as the host polymer in this work. The preparation of chitin was reported by Wan Nawawi et al. [10]. The mushroom was blended for 5 minutes, followed by the extraction process by using hot water (85 °C, 30 min, 1:40 mushroom dry weight to water ratio). This step is to remove any water-soluble components. The excess water together with the soluble components was then vacuum filtered using muslin cloth to obtain the filtration cake. The cake was then drenched in alkaline solution to initiate deproteination process (1M NaOH, 65 °C, 3 hours) before it was neutralized in excess water. Then, the neutralized cake was then resuspended in water (0.8% w/v) and dispersed by final blending for another minute. The suspension was stored at 4 °C until further use.

A commercially available brass-Polylactic Acid (PLA) 3D printer filament was used as the starting material in the fabrication process of the SA. The filament consists of PLA with 15% brass powder. To reduce the filament's size, it was extruded at 210°C through a 3D printer nozzle. 25 mg of the brass filament and 1 ml of tetrahydrofuran (THF) was mixed until the PLA was fully dissolved. The mixture was then ultrasonicated for 10 minutes to produce a brass-THF suspension.

The brass-THF suspension was then mixed with the chitin by using 1:1 ratio. The mixture of brass-THF and chitin was then placed in ultrasonic bath for 30 minutes to ensure that the even dispersion of the brass in the biopolymer host matrices. The mixture was then poured into a petri dish and left in ambient temperature for 3 days. After 3 days, the dried film was peeled off and a small part of the film was cut to be used in the laser cavity as SA for pulsed laser generation.

Once the brass-chitin SA was produced, the thickness of the SA was measured by using 3D Measuring Laser Microscope (LEXT OLS4100). The thickness of brass-chitin film based SA was measured at 152.52 μm which was larger compared to the previous study [6] using a CuO-PVA film of about 2 μm thick. This is because the film thickness of chitin itself is 25–80 μm [19]. The increase in thickness of the SA with respect to material to polymer ratio can cause the optical bandgap to decrease [20]. Therefore, the modulation depth of the SA shows a

positive dependence on thickness [20]. Thicker SA with higher modulation depth would require higher input pump power for pulsed laser initiation. However, an SA too thin with less material to host polymer ratio, may not be sufficient to modulate the intracavity loss in order to self-start lasing operation. On the other hand, too thick SA of more than 200 μm may cause higher insertion loss [11]. Figure 1 shows the thickness of prepared SA.

Then, the surface morphology and topology of the sample was tested using Field Emission Scanning Electron Microscope (FESEM) (JEOL JSM-7800F). The sample was first coated with platinum by using Auto-Fine Coater (JEOL JEC-3000FC). The purpose of this step is to avoid charging effect at which the electrons are focused at one site, causing low quality image. Figure 2 shows the FESEM image of the fabricated brass-chitin film. The bumpy surface as observed in Figure 2(a) shows the chitin which act as a host polymer while the brass particles can be seen on top of the chitin. Chitin topological characteristic can be seen in Figure 2(b), where it can be observed that the surface of the sample are bumpy, mainly due to the clusters of chitin agglomerating together due to its fibrous nature. This can be further refined during the fabrication process in which longer ultrasonication or the use of tip sonicator may be needed.

In order to know the composition of the brass-chitin SA, Energy Dispersive X-Ray Spectroscopy (EDS) analysis has been done. Figure 3 shows the EDS analysis report. The resulting spectrum shows that the high peak corresponded to oxygen (O) element with high peak percentage weight of 68.31% and followed by carbon (C) with 23.38%. Zinc (Zn) and copper (Cu) elements have the percentage weight of 5.11% and 3.19%, respectively, indicating the presence of brass. The detection of C and O in this EDS spectrum came from the base material of the film which was penetrated by the radiation of EDS spectra during the measurement process. Nevertheless, the existence of C and O elements does not affect or lead the generation of pulse throughout the experiment.

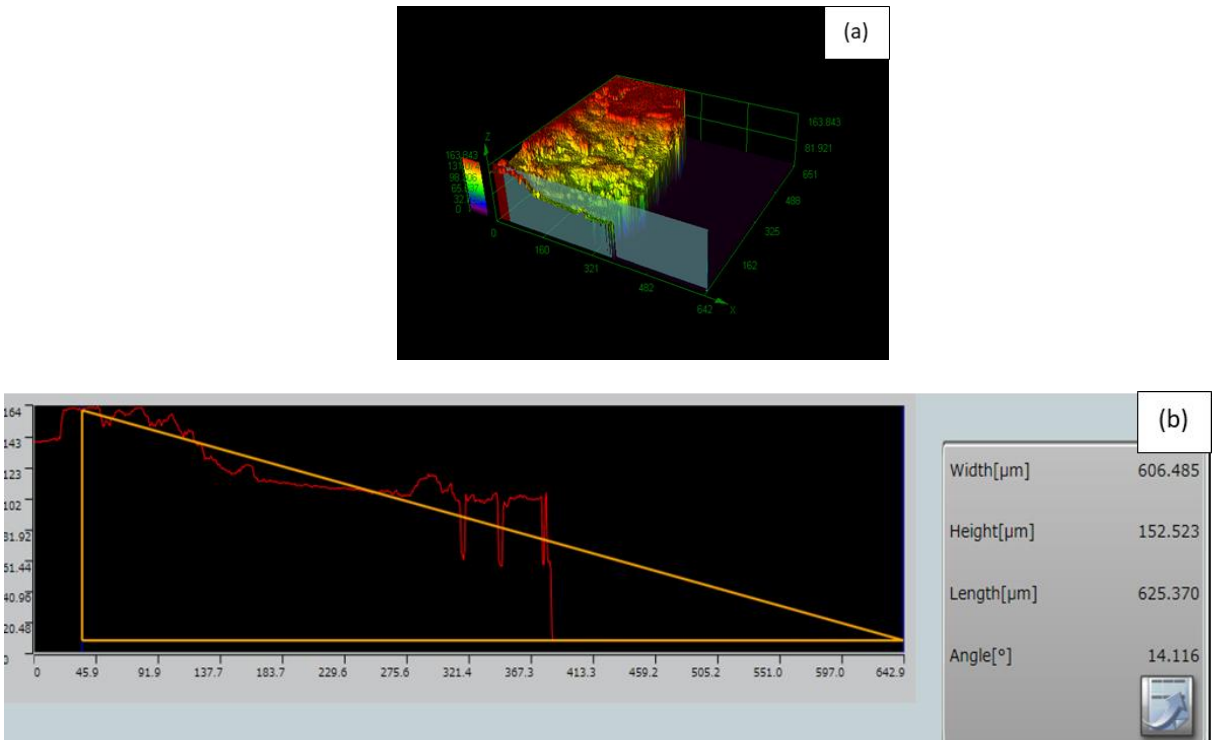

Figure 1. Thickness measurement of the brass-chitin film (a) 3D contour image of the film and (b) thickness of brass-chitin SA measured by reading the height measurement.

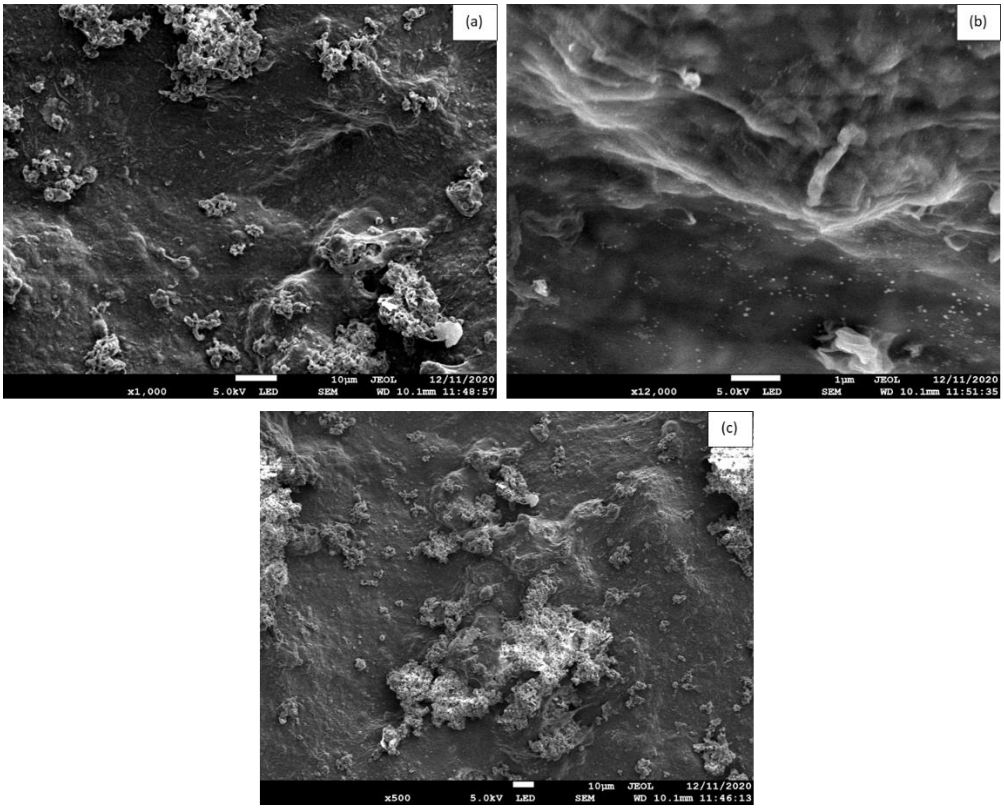

Figure 2. Brass Chitin SA morphology and topology in FESEM (a) SA with 1000X magnification, (b) 12 000X and (c) 500X magnification by using 5.0kV voltage.

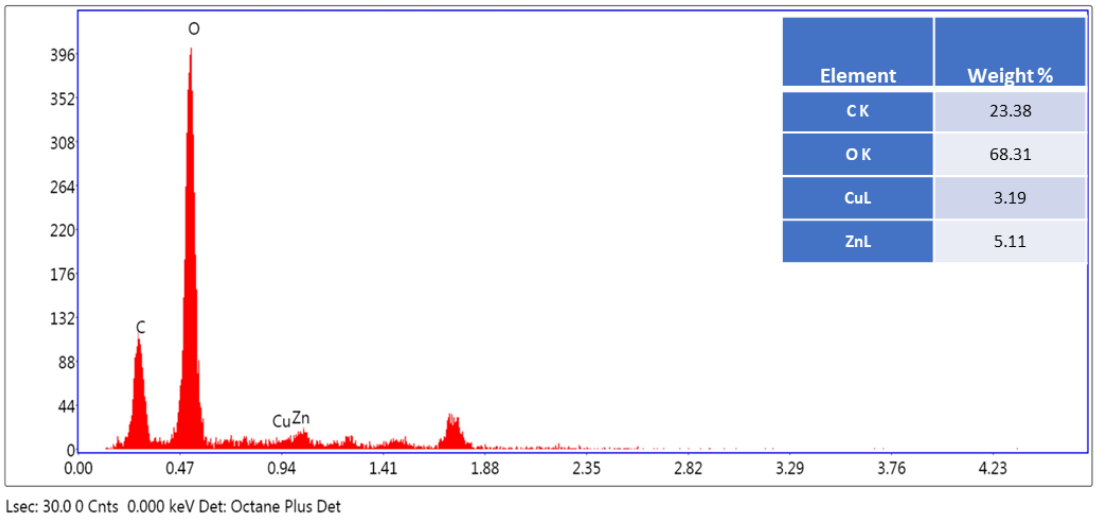

Figure 3. EDS spectrum for determination of elemental composition brass-chitin based passive SA

b. Experimental Setup

The experimental setup for the Q-switched EDFL with brass chitin film as the SA is shown in Figure 4. 980 nm laser diode (LD) was used to pump the gain medium of the laser cavity, which was a 1.5 m Erbium-doped fiber (EDF) through 980/1550 nm wavelength division multiplexer (WDM). The numerical aperture of the EDF is 0.16 with Erbium ion absorptions of 45 dB/m at 1480 nm and 80 dB/m at 1530 nm. An isolator was used in the laser cavity to prevent any backtracking of the light.

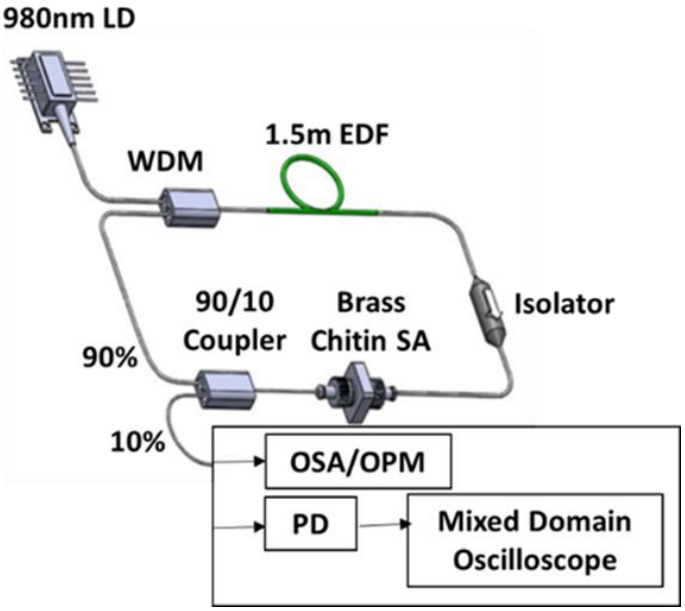

Figure 4. Laser cavity setup of Q-switched EDFL based on brass chitin SA.

The SA was inserted in the cavity by sandwiching it between two ferrules which were connected with a fiber connector. A 90/10 output coupler was used to collect the laser output where 90% of the light was kept oscillating in the cavity and the other 10% was tapped out as the output. Optical spectrum analyzer (OSA) (Yokogawa AQ6370B), an optical power meter (OPM) (Thorlab PM100D), mixed domain oscilloscope (Tektronix MDO3024) which were connected through a 460 kHz bandwidth photodetector (PD) (Thorlab DET01CFC), were used to observe and obtain the output of the laser. The total cavity length is about 10.5 m approximately.

3. Result

The integration of the brass-chitin SA in the laser cavity was able to suppress the amplified spontaneous emission. As shown in Figure 5, the EDFL started lasing at 135.7 mW with a central wavelength of 1558.8 nm, corresponding to an output power of 4.145 dBm.

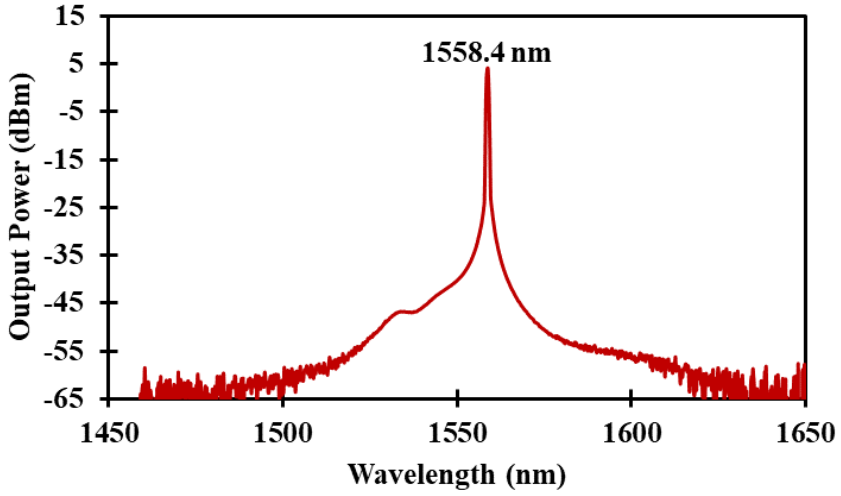

Figure 5. Optical Spectrum of EDFL in ring cavity without brass chitin SA at input pump power of 135.7 mW.

The Q-switching operation was able to be kept stable until the pump power reached 181.5 mW. The operating wavelength shows a tri-wavelength of the Q-switched pulsed laser at 1563.76 nm, 1564.36 nm, 1564.44 nm, as shown in Figure 6. It was reported that copper based SA which is one of the elements in brass [5] was also successfully used to achieve Q-switching operation at 1560 nm [6].

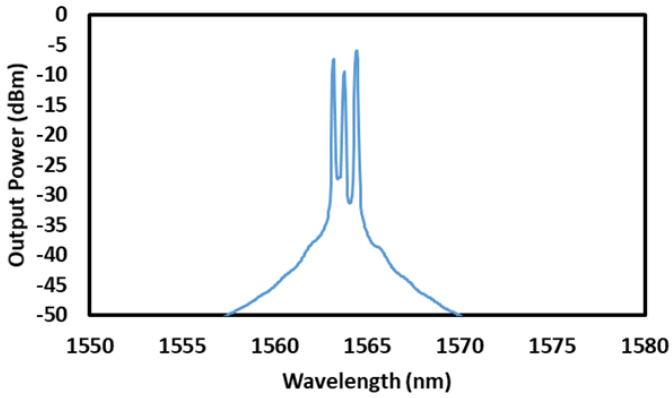

Figure 6. The optical spectrum at 172.3mW.

Highly stable pulse train of the Q-switching operation with low intensity variation in between the generated pulse, at maximum pump power is shown in Figure 7. The ability of the SA to withstand higher pump power without yet being fully saturated can also be observed. Figure 7(a) shows the pulse train repetition rates of the Q-switching operation. The brass-chitin SA produced a pulse train with 68.03 kHz repetition rate with a 15.96 µs pulse separation. The single pulse envelope as shown in Figure 7(b) indicates the pulse width measuring at 2.56 µs at the maximum pump power of 172.3 mW. Figure 7 also shows a stable Q-switched pulse generation with little to no amplitude modulation.

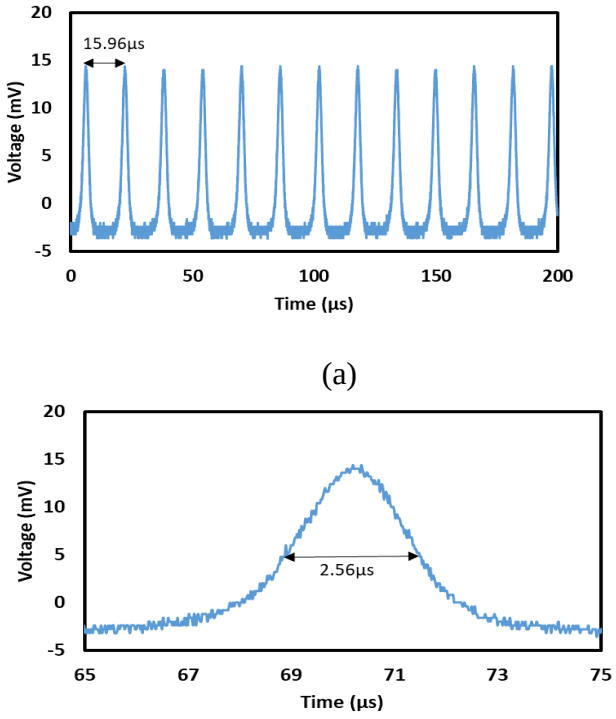

Figure 7. (a) Pulse train repetition rate of the Q-switched EDFL based on brass chitin SA (b) single pulse envelope at maximum input pump power of 172.3mW.

The dependency of the repetition rate and pulse width against the input pump power was plotted in Figure 8. As can be seen in the Figure 8, as the pump power was increased, the repetition rate which was started at 55.80 kHz continued to increase until 68.03 kHz.

On the other hand, the pulse width showed a decreasing trend as the input pump power was increased up to 172.3 mW. The recorded pulse width started to decrease from 3.06 µs to 2.24 µs as the pump power was increased from 135.7 mW to 172.3 mW. This behaviour is the same as reported in [6]. Theoretically, the increasing pump power will provide more gain to cause saturation to the SA, which causes the increase of repetition rate and the decrease in pulse width [6][18]. This behaviour is typical of Q-switched operations [16] and can also be observed in [6] in which copper was used as SA.

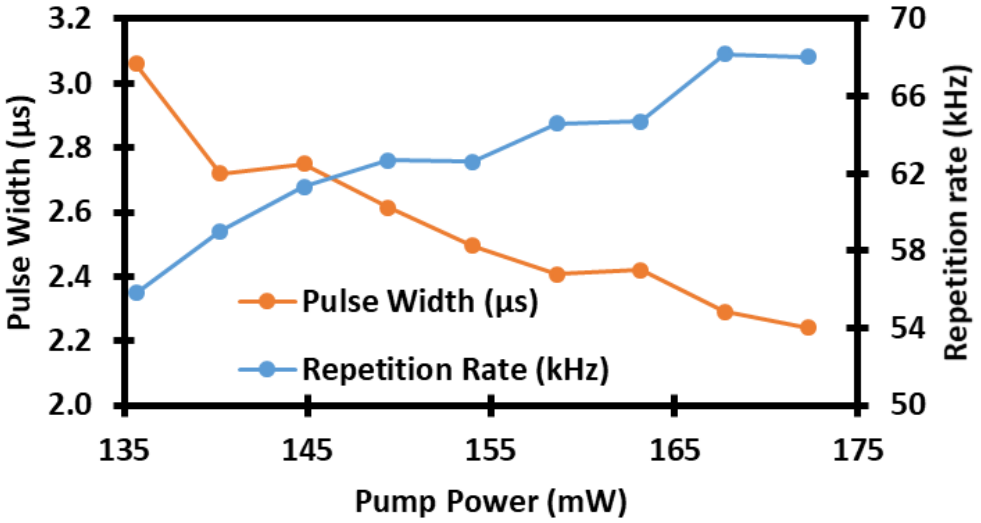

Figure 8. Repetition rate and pulse width against pump power

The instantaneous pulse energy and peak power was then calculated from the recorded repetition rate and pulse width. The function of the pulse energy and peak power against the input pump power is as shown in Figure 9. Both pulse energy and peak power was increased as the pump power was increased from 135.7 mW to 172.3 mW. This behaviour shared the same trend with reports in [6][8] which is typical in passively Q-switched fiber laser [12]. The increase in pump power causes the increase of average output power while decreasing the pulse width due to the enhanced gain inside the cavity. Since the pulse width is directly correlated to the pulse energy, the maximum pulse energy can be obtained at the maximum input pump power. However, at pump power of 154.0 mW, the pulse energy decreased from 2.09 nJ to 2.03 nJ. Then, at the pump power of 163.2 mW, it increased back to 2.08 nJ before falling to 2.02 nJ. Nevertheless, at the highest pump power of 172.3 mW, the pulse energy peaked at 2.10 nJ which was the highest pulse energy obtained. This is caused by weak saturated emission in the gain medium which leads to fluctuation of stored energy [17]. Therefore, as the fluctuation of stored energy happened, the fluctuation can be observed in the pulse energy between the pump power of 154.0 mW and 172.3 mW.

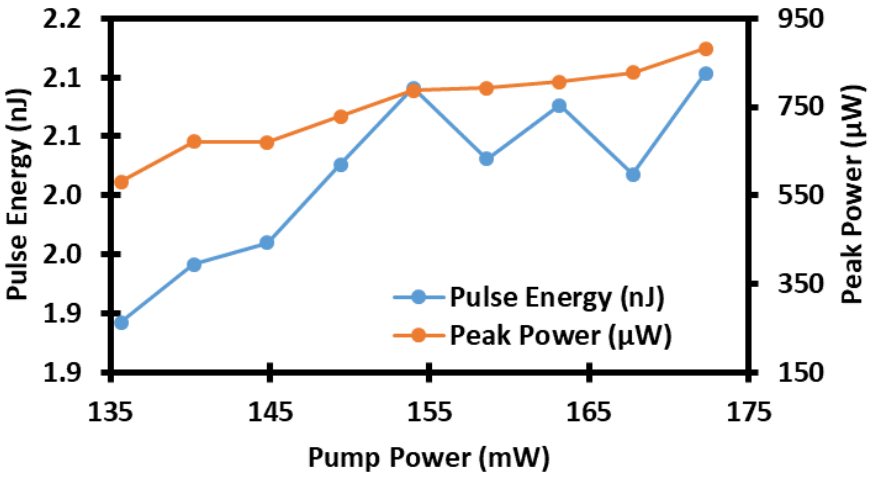

Figure 9. Instantaneous pulse energy and peak power with respect to input pump power.

To measure the slope efficiency, the graph of average output power against the input pump power is plotted as shown in Figure 10. Agreeing with the typical Q-switched pulsed laser trend, the average output power's linear increase with the increase in input pump power [21] can be seen in Figure 10 as the average output power was increased from a minimum of 105.6 µW to a maximum of 143.1µW. The slope efficiency was measured at 91.38%. Cole et al. has reported that by using Cr:Zns as the saturable absorber have recorded 46% of slope efficiency [22] which is lower compared to the brass as the saturable absorber.

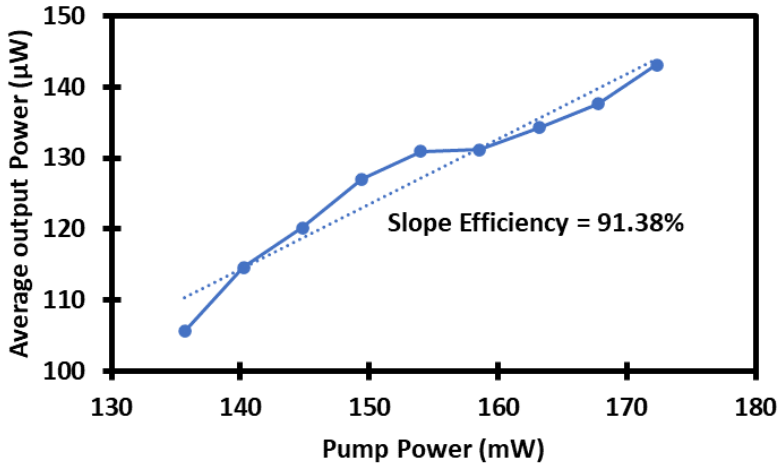

Figure 10. Average output power with respect to input pump power.

The radio frequency spectrum analyzer (RFSA) was used to check the stability of the generated Q-switched pulse. Figure 11 shows the plotted graph of the RFSA spectrum. At maximum input power of 172.3 mW, the first beat note at 64.67 kHz was recorded at 67 dB, indicating high pulse stability. The signal-noise-ratio (SNR) was higher compared to a previously reported SNR using copper nanoparticles with 54 dB [15] and zinc oxide with 31.2 dB [13] and 62 dB [14].

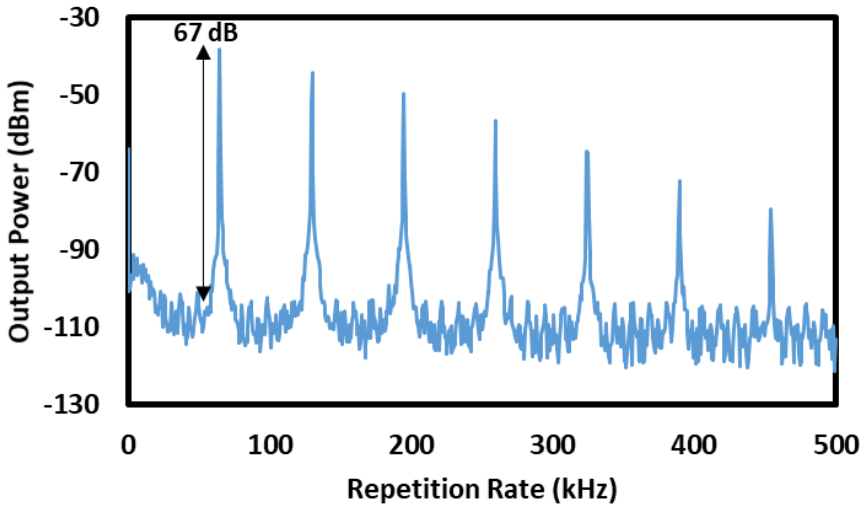

Figure 11. RFSA measurement of the Q-switched EDFL based on brass chitin SA.

4. Conclusion

The proposed experimental work using brass as a passive SA to generate an Erbium-doped Q-switched pulsed laser was successfully demonstrated. This work revealed a high maximum repetition rate of 71.33 kHz. At maximum input pump power, the pulse width was reduced to 2.24 µs, with pulse energy of 2.10 nJ and instantaneous peak power of 882.71 µW. The high laser stability was also proven by a high SNR value of 67 dB. Passive Q-switching in this region can find applications in remote sensing, range finding, medicine, material processing and telecommunications [3].

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