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RESEARCH ARTICLE

# Molybdenum disulfide ($MoS_2$) – based, tunable passively Q-switched Thulium-Fluoride Fiber (TFF) laser

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**Abstract**

We demonstrated the tunable passively Q-switched Thulium-Flouride Fiber (TFF) laser based on exfoliated $MoS_2$ saturable absorber (SA). The generation of Q-switched pulses of the proposed experiment favors the tunable operation from 1460.0 nm to 1506.0 nm, with range of 46.0 nm. The achievable maximum repetition rate and maximum pulse energy in the experiment are 35.1 kHz and 63.2 nJ, respectively. To the best of our knowledge, the first reported tunable passively Q-switched TFF laser using exfoliated $MoS_2$ as saturable absorber has been demonstrated.

***Keywords***: Fiber laser, tunable Q-switched, Q-switch, S-band, Thulium-fluoride fiber.



## INTRODUCTION

Interest on generation of Q-switched laser has increases due to their advatange of exhibiting long pulses that is useful for many applications such as nonlinear experiments, material processing, medicine and sensing [1-4]. Passively Q-switched fiber laser has gained significant attentions because of their advantages, including high efficiency, compact, flexible, cost-effective and high spatial beam quality [5]. The key feature of Q-switched fiber laser is their ability to be tuned in broadband wavelength especially in communication band region, which is important in specific applications such as spectroscopy and wavelength division multiplexing (WDM). Q-switching operation in fiber lasers can be achieved either actively or passively. However, active Q-switching fiber laser needs a bulky components and complex electronics, which makes its less suitable for laser applications as well as increasing the cost of the operation [6]. Therefore, passive Q-switching technique has become an extensive attention by the reseachers as this technique allow for compact and cost-effective operation. Passive Q-switched pulsed fiber laser is generate by inserting a saturable absorber (SA) into the laser cavity and has shown a promising result in generating pulsed laser [6]. In the generation of passive Q-switched pulsed laser, the saturable absorber act as a modulator to controlled the losses of the operation. The Q-switched pulses is formed as the energy stored in the gain medium has reached the saturation energy and the gain medium starts to saturated.

The earliest types of saturable absorbers in generating passive Q-switched pulses in fiber laser were semiconductor saturable absorber mirrors (SESAMs) [7]. Although SESAMs have a better control on the parameters of SA in generating pulses, but they had a limited bandwidth as well as being complex and high cost in fabricating SESAMs [6]. Thus, extensive studies on finding other potential SAs, especially 2-D materials which have a different electronic, optical, thermal and mechanical properties compared to 3-D materials [8]. 2-D materials can be used as photovoltaics, photoluminescence and photodetection in the field of optoelectronics due to the existance of Pauli blocking property of these materials that enables them to be used as saturable absorber to generate pulsed laser. Graphene was a well-known 2-D material and carbon-based material which proves to be a broadband functional SAs in generating Q-switched pulses [3]. Another carbon-based SAs was carbon nanotubes that was used as SA to generate Q-switched pulses [9]. Other promising materials such as topological insulator [10] and black phosphorus [11] have been succesfully used as SA to generate pulsed laser.

Transition Metal Dichalcogenides (TMDs) was a promising 2-D materials in generating pulsed laser as shown in the recent work of Refs [12-14]. Molybdenum disulfide ($MoS_2$) was one of TMDs materials that shows a high potential to be used as SA for generation of pulsed laser [15, 16]. TMDs, included $MoS_2$, possess a thickness-dependent band-gap and electronic band structure [17], which leads to the changes in photoluminescence and photoconductivity. Due to this characteristics, the photoluminescence can be increases up to a factor of $10^4$ yield from bulk to monolayer $MoS_2$ that is advantageous MoS as a saturable absorber to generate pulsed laser [18]. Other than that, $MoS_2$ also exhibit a strong light-matter interaction [18] and optical saturable absorption [19].

There are many succesfull reports on $MoS_2$ as SAs for different band regions [20, 21] due to their advantages makes $MoS_2$ as a choosen SA to generate Q-switched pulses. Exploiting $MoS_2$ as SA had succesfully reported by Luo *et. al.* at different region which are 1-, 1.5- and 2- μm region, shows the capability of $MoS_2$ as promising broadband SA [16]. Despite of that, there were only a few reports on generation of Q-switched fiber laser in S-band region using $MoS_2$

which mainly used depressed-cladding erbium-doped fiber (DC-EDFs) as gain medium [22]. However, DC-EDFs has a short bandwidth range which only covers a part of S-band region [22].

This leads to the difficulty on development of S-band Q-switched fiber lasers, especially shorter wavelength S-band in finding an availability of photonics applications in S-band region. A highly potential solution for this arise problem is by using Thulium-Fluoride fibers (TFFs) as gain medium, which has been reported by Tanabe *et. al.*[23] and Caspary *et. al.* [24], shows that TFF has a large operational bandwidth that streching from 1440 nm to 1500 nm. This shows that TFFs able to cover a large part of S-band region, including shorter wavelength S-band. Yet, there are no reports on exploiting $MoS_2$ in TFF laser. To the best of authors' knowledge, this is first report on $MoS_2$-based, tunable passively Q-switched TFF laser.

## MOLYBDENUM DISULFIDE ($MoS_2$) SATURABLE ABSORBER

Simple mechnical exfoliation technique is used in preparing the $MoS_2$-based SA for this experiment, with the preparation flow shown in Fig. 1. The $MoS_2$ is obtained from Graphene Supermarket, where small piece of the $MoS_2$ crystal is cut out and placed between the two sides of small part of scotch tape as shown in Fig. 1 (a) and (b). Then, the small part of scotch tape is folded into half and repeatedly pressed for exfoliation of $MoS_2$ layers on one part of the scotch tape as shown in Fig. 1 (c). It can be seen from Fig. 1 (d), the thin layer of $MoS_2$ is formed on the other side of the scotch tape. The exfoliated thin layer is carefully removed and placed onto the fiber ferrule as shown in Fig. 1 (e).

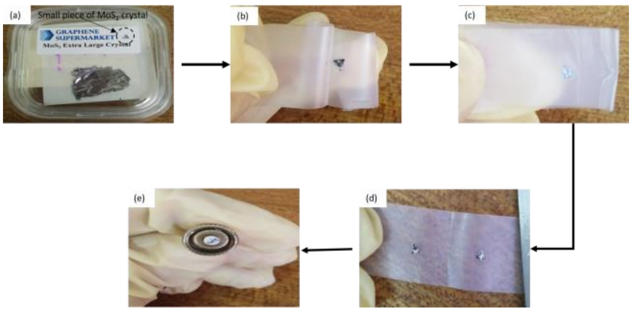


**Fig. 1** Mechanical exfolation flow in preparation of $MoS_2$-based SA.

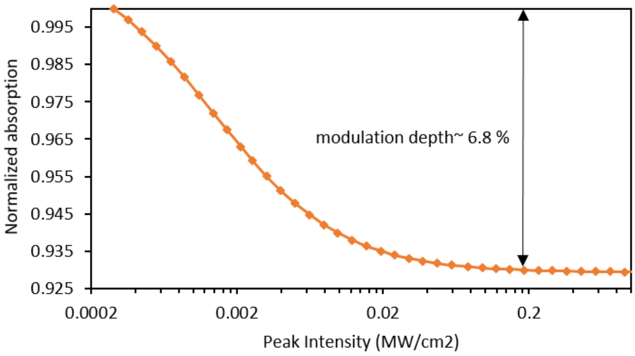


**Fig. 2** Nonlinear optical absorption curve of $MoS_2$ SA.

The nonlinear optical absorption measurement of $MoS_2$ SA was obtained by using twin-detector method. In this method, mode-locked laser seed was used as a source with the central wavelength of 1560.0 nm.The laser seed exhibit a repetition rate of 28.1 MHz and pulse width of 0.68 ps. The collected data was fitted into the saturation model formula (1) as shown below [25]:

$$\alpha(I) = \frac{\alpha_s}{1+\frac{I}{I_s}} + \alpha_{ns} \qquad (1)$$

where $\alpha(I)$ is the intensity-dependent absorption, $I$ is the input pump intensity, $I_s$ is the saturation intensity, $\alpha_s$ is the saturable loss and $\alpha_{ns}$ non-saturable loss. Fig. 2 shows the nonlinear optical absorption curve of $MoS_2$ SA based on the equation (1). From the curve, the resulted modulation depth and saturation intensity are around 6.8 % and 0.0018 MW/cm$^2$, respectively.

**Table 1** Modulation depth values of $MoS_2$ reported by previous works.

| Saturable Absorber | Modulation Depth (%) | Ref |
|---|---|---|
| $MoS_2$ | 6.3 | [26] |
| | 10.69 | [15] |
| | 4.6 | [27] |

Table 1 shows the modulation depth values of $MoS_2$ reported by previous works. It can be seen that modulation depth of SA in this works is comparable with the previous works. However, the saturation intensity in this work is lower than values reported by previous work [12], that could be advantageous in generating a pulsed laser mentioned by Woodward *et al* [26].

## EXPERIMENTAL SET-UP

The experimental set-up for the experiment is schematically shown in Figure. 3. The ring cavity has a total cavity length around 26.5 m. A 14.5 m long TFF is used as a gain medium which was obtained from Fiberlabs Inc. The TFF exhibit an absoprtion rate of 0.15 dBm and mode-field diameter of 4.5 µm at wavelength of 1400 nm. The gain medium is pumped by 1400 nm FOL1405RTD laser diode (LD) through an isolator(ISO) and 1400/1500-nm wavelength divider multiplexer. The purpose of the isolator (ISO) is to protect LD from possible back-reflections from the cavity. The end of TFF is connected to another isolator; to force unidirectional signal propagation in the cavity and into a tunable bandpass filter (TBPF), which allow central wavelength of TFFL to be tuned. Then, the TBPF output is guided into the 90:10 coupler, in which a 10% portion of the signal is extrated for analyzed. Whereby, another 90% of signal connected to $MoS_2$-based SA, then in turn linked to the 1500 nm port of the WDM, thus complete the laser cavity.

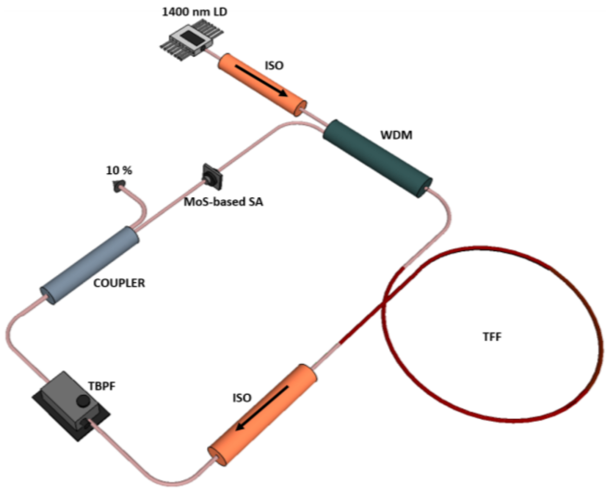


**Fig. 3** Tunable Q-switched Thulium-Fluoride Fiber Laser Set-up.

The characteristics of pulsed laser are measured by using Yokogawa DLM2054 Oscilloscope together with a 1.2 GHz photodetector. The Anritsu MS2683 Radio-Frequency Spectrum Analyzer (RFSA) is used to obtained the signal-to-noise ratio (SNR) of the pulsed laser. The spectrum of the generated pulsed laser is monitored by an Anritsu MS9740A Optical Spectrum Analyzer (OSA). The Thorlabs PM100USB powermeter is used to monitor the output power.

## RESULTS AND DISCUSSION

Initially, the operation is investigated without integrating the tunable bandpass filter (TBPF) into the cavity. Continous wave operation starts at 90.0 mW, whereby the Q-switching operations starts at a pump power of approximately 93.4 mW, with a central wavelength of 1496.0 nm. The are no observation of Q-switching operation as the SA was removed from the cavity, thus confirming that the SA plays an important role in the gereation of Q-switched pulses. Fig. 4. shows the typical characteristics of the Q-switched pulses at the pump power of 98.1 mW. The obtained pulse train illustrates the Q-switched pulses with a repetition rate of 20.2 kHz, corresponding to the time interval between each pulses of 49.5 µs as shown in Fig. 4(a). The full-width-half-maximum (FWHM) for each individual pulses is about 6.4 µs as given in Fig. 4(b). The Radio-Frequency (RF) spectrum shown in Figure 4(c) provides the corresponding Signal-to-Noise Ratio (SNR) of the generated pulses, which is measured to be about 51.8 dB. It can be seen from Figure 4 (c) that only fundamental and harmonic frequencies are present in the correspoding spectrum. Thus, this confirms that the Q-switched pulses is in a stable regime and comparable to the previous works [12, 28].

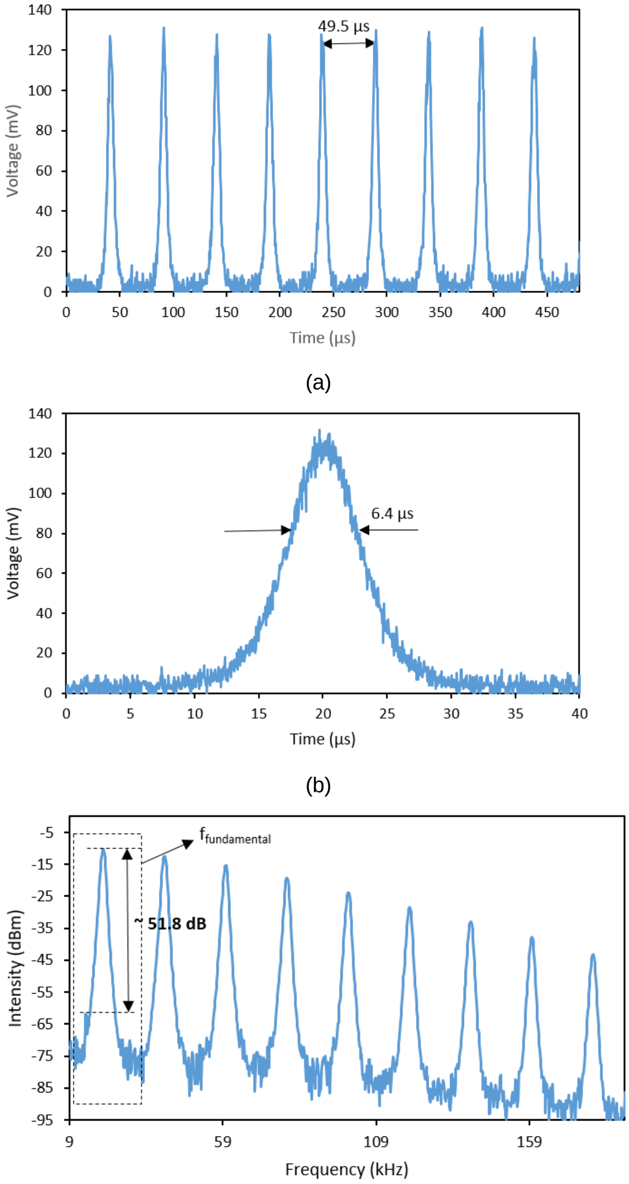


**Fig. 4** Characteristics of Q-switched pulses at a pump power of 98.1 mW showing (a) the pulse train, (b) the single pulse profile and (c) the RF spectrum of the operation.

Fig. 5 (a) shows the repetition rate and pulse width of the generated pulses as a function of pump power. It can be observed that the repetition rate increases almost linearly from 19.9 kHz to 35.1 kHz as a function of pump power. Whereby, the pulse width decreases from 6.5 µs to 3.8 µs as a pump power increases from 93.4 mW to 149.9 mW, until the pulse width remained unchanged and maintain at 3.7 µs starts from 154.6 mW until the maximum pump power of 159.3 mW. This behaviour is attributed to the full saturation of the SA. The trends average output power and pulse energy of the pulses as a function pump power is shown in Figure. 5 (b). It can be seen that both average output power and pulse energy increase linearly as the pump power rises. From the results, the maximum average output power and maximum pulse energy are 2.2 mW and 63.2 nJ, respectively. Figure 5 shows that our results behave typically as an output operation of Q-switched pulses which is comparable to the work of Refs. [10, 12].

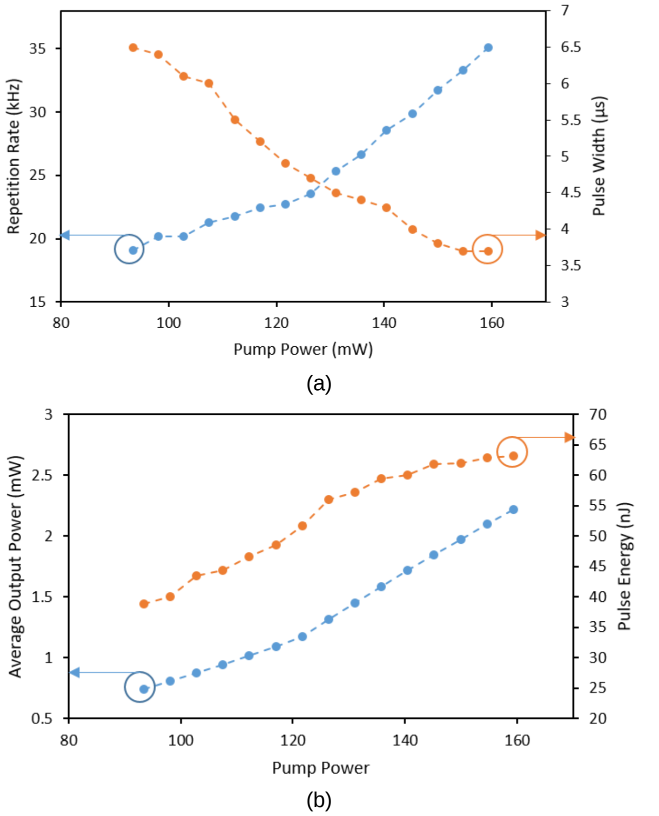


**Fig. 5** Trends of (a) repetition rate and pulse width and (b) average output power and pulse energy of Q-switched TFF laser as a function of pump power.

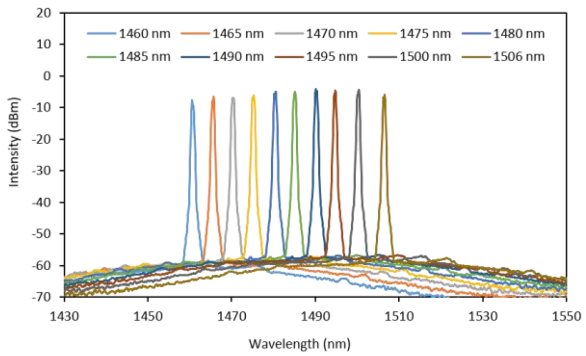


**Fig. 6** Output spectra for 10 tuning central wavelength.

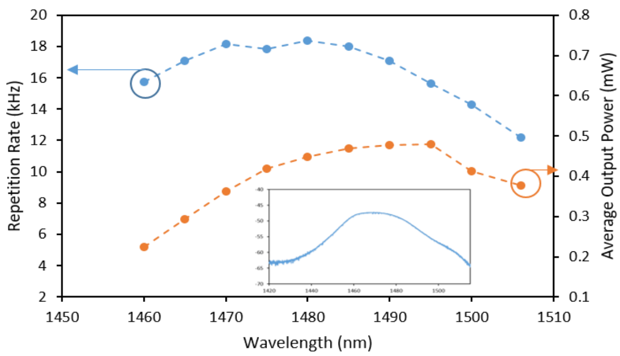


**Fig. 7** Trends of repetition rate and average output power as a function of wavelength. Inset illustrates the Amplified Spontaneous Emission (ASE) spectrum of the laser cavity.

By adjusting the TBPF, the central wavelength of the Q-switched output pulses can be tuned from 1460 nm to 1506 nm, with a tuning range of 46.0 nm as illustrates in Figure 6. From the wavelength range, it can be seen that the tuning wavelength covers the S+/S band region. Trends of repetition rate and average output power as a function of wavelength is shown in Figure 7. As shown in Figure 7, the trends is highly similar to the ASE spectrum (refer to the inset of Fig. 7). This phenomenon occur due to the variation of the ASE gain, for which the larger gain corresponding to the larger repetition rate and larger average output power [29]. No observation of Q-switched pulses was made beyond this wavelength range.

## CONCLUSION

$MoS_2$-based, tunable passively Q-switched Thulium-Flouride Fiber (TFF) laser is proposed and demostrated. The proposed experiment capable of generating Q-switched pulses that can be tuned from 1460.0 nm to 1506.0 nm, with a range of 46.0 nm. The maximum repetition rate and maximum pulse energy achieved in this experiment are 35.1 kHz and 63.2 nJ, respectively. The results of this work show tunable Q-switched pulses can be achieved in the S and S+ band by using $MoS_2$ in TFF laser system.

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