Few Layer Molybdenum Selenide Saturable Absorber using Optical Deposition Technique for Q-switched Ytterbium Pulses Laser Generation

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Abstract. We have successfully generated a Q-switched ytterbium-doped fiber laser pulses using few layers of Molybdenum Selenide (MoSe2) as saturable absorber (SA). The setup was a ring fiber laser cavity with few-layer MoSe2 deposited onto a fiber ferrule using an optical deposition technique. A stable pulses started at input power of 68.8 mW with repetition rate ranging from 14.2 kHz to 34.0 kHz was achieved with highest pulse energy, shortest pulse width and highest output power of 3.6 nJ, 4.4 µs and 0.12 mW were observed, respectively.

1. Introduction
Passively Q-switching fiber laser has gained popularity among scientists and laser engineers due to its broad range of applications, uniqueness, and compactness. In particular, Q-switching in ytterbium doped fiber laser (YDFL) pulses in 1-micron region has its footing in supercontinuum generation [1, 2], industrial [3] and nonlinear frequency conversion [4, 5]. In addition, pulse fiber laser in 1 µm region has been described as low deployment cost and is recognized for their compactness, small footprint and flexibility in its pattern [6, 7].

In-order to generate pulse laser, few passive techniques have been widely used. One of the techniques is to use new optical nanomaterials with Pauli blocking property. These new nanomaterials are known as saturable absorbers (SAs); where transmission increase at higher intensity. Since over the past few decades, semiconductor saturable absorber mirror (SESAM) has become the leading technology to generate Q-switching and mode-locking pulses at 1-micron region [8, 9]. However, SESAM inherit several drawbacks. For example, SESAM is high-priced and require clean room environment for fabrication and have very complicated packaging and fabrication techniques [10, 11]. Furthermore, SESAM has narrowband operating range [12]. A few years ago, carbon-based nanomaterials are gaining popularity as SA. Carbon nanotubes (CNTs) [12-15] and graphene [16, 17] have exciting characteristics;
such as ultrafast recovery time, broadband operating wavelength and simple fabrication process to make them as suitable SAs for generating passive pulse fiber laser. Yet, CNT suffers from a complex bandgap control [18], which could reduce absorption at specific wavelength while graphene has quite small optical absorption (2.3% per layer) and modulation depth [18]. Therefore, extensive research has been carried out to seek for a new SA, which can inherit both CNT and graphene features, but none of their weaknesses.

At present, new 2D and 3D-materials with similar properties inclusive of topological insulators (TIs) [19] and transition metal dichalcogenides (TMDs) [20, 21], plus other materials such as black phosphorous [22, 23] were explored for their potential. In recent progress, there have been interests in transition metal chalcogenides (TMD) based optical materials which comprise of molybdenum disulfide (MoS$_2$) [21], molybdenum selenide (MoSe$_2$) [20] and tungsten disulfide (WS$_2$). A number of reports highlighted MoSe$_2$ as a favorable material for photodetector, pulsed laser and thermoelectric applications [24-26], because of its excellent optoelectronic characteristics, for instance, ultrafast dynamic carriers for mono and few-layers form, strong photoluminescence, and high optical nonlinearity [27]. In this work, we demonstrated a passively Q-switched YDFL by utilizing few-layer Molybdenum Selenide (MoSe$_2$), which is a selenide-based TMDs as a passive SA. The pulse repetition rates of the laser ranged from 13.5 kHz to 54.3 kHz, hence determined the MoSe$_2$ has typical characteristic of SA for YDFL Q-switching pulse.

2. Preparation of MoSe$_2$ by an optical deposition technique

The few-layers MoSe$_2$ were mix with a solvent to produce few-layer MoSe$_2$ solution. One end of a fiber patchcord was immersed into the solution while another ferrule was connected to a running laser. At a correct power, the MoSe$_2$ particles are attracted to the core of the fiber ferrule by optical tweezer effect. The fabrication and preparation of SA by optical deposition technique were also implemented in our previous work [28, 29]. Commercially available bulk MoSe$_2$ and exfoliated MoSe$_2$ solution were analyzed by using Renishaw inVia confocal Raman Microscope with 488 nm laser and radiated power of 3.5 mW. The results are depicted in Figure 1(a). Bulk MoSe$_2$ shows out of plane vibration ($A_{g1}$), centered at 240 cm$^{-1}$, while the few layer MoSe$_2$ out of plane vibration ($A_{g1}'$) centered around 235 cm$^{-1}$. This shift in peak verifies the exfoliation of bulk MoSe$_2$ to few layer MoSe$_2$. Furthermore, SPECORD 210-Plus UV-Vis Spectrometer was utilized to characterize the linear absorption of MoSe$_2$ as illustrated in Figure 1(b) whereby two spectrum peaks were observed at ~697 nm and ~800 nm, respectively.

3. Experimental Setup

The configuration of Q-Switching-based 2D MoSe$_2$ SA in YDFL is schematically shown in Figure 1(c). The ytterbium active medium comprises of 70 cm length of ytterbium doped fiber (Fibercore DF1100), with a peak absorption of 1300 dB/m at 977 nm. Then, a 974 nm, 600 mW pumping laser diode (Oclaro model LC96A74P-20R) was spliced to a 980 nm port of wavelength division multiplexing (WDM), while the common port of WDM was attached to 70 cm YDF, and then spliced to an isolator to guarantee uni-directional propagation. Then, the isolator output was linked to a few layers of the few-layer MoSe$_2$ SA which was placed between two fiber ferrules, and then spliced to the input port of 90:10 optical coupler 1 (OC1). The output port of 90% portion of the optical coupler was spliced to signal port of 1060 nm WDM to complete the ring cavity configuration. The other 10% output signal is extracted from the cavity was used to analyze the pulse lasing behavior. This portion of pulse lasing signal is then split equally by using 50:50 optical coupler 2 (OC2) to monitor signal in both wavelength-based and time-based observation. Therefore, the Q-switched pulses can be observed concurrently using an optical spectrum analyzer (OSA) model AQ6373 YOKOGAWA and a fiber optic photo detector connected to the digital oscilloscope (YOKOGAWA DLM2054). Beside that, a spectrum analyzer model MS2693A Anritsu with specification of 9 kHz - 7.8 GHz frequency and an optical power meter (THORLABS) were employed to characterize the extracted signal generated from the cavity.

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4. Results and Discussion

With the MoSe$_2$ SA was incorporated into cavity ring, the pump power was increased by increasing the drive current of the laser diode gradually. At 68.8 mW pulsing threshold, self-started Q-switched pulse was observed with a repetition rate of 14.2 kHz, as shown in Figure 2(a). Figure 2(b) and Figure 2(c) show pulses at 82.7 mW and 115.2 mW, respectively. The pulse duration of 70.4 μs was recorded at 68.8 mW, and the result decreases to a narrower duration of 29.4 μs at 115.2 mW due to gain compression mechanism in the Q-switched pulse laser.
Figure 2. The repetition rate of Q-switched pulses train traced at various pump power: (a) 14.2 kHz at 68.8 mW, (b) 19.3 kHz at 82.8 mW and (c) 34 kHz at 115.2 mW respectively.

Figure 3(a) shows an optical spectrum when pump power was set at 86.8 mW. It is centered at 1040.8 nm with an output power of -37.8 dBm. The corresponding signal recorded from the oscilloscope trace shows 21.4 kHz of repetition rate and 46.8 μs of time between pulses (Figure 3(b)). Its pulse width shown in Figure 3(c), in which the full half width maximum (FHWM) was measured to be 5.6 μs. Radio frequency spectrum analyzer (RFSA) was used to monitor frequency domain traces, as depicted in Figure 3(d), with 21.4 kHz fundamental harmonic frequencies (inset) and 44 dB peak-to-base ratio were recorded. Furthermore, in Figure 3(d), no spectral modulation recorded by the RF output spectra, demonstrating a steady pulse repetition rate was achieved using our proposed setup.

Figure 4(a) indicates the variation of pulse duration and pulse repetition rate against increasing pump power. Since the pumping power was increased from 68.8 mW up to 115.2 mW, Q-switched repetition rate had also increased from 14.2 kHz to 34 kHz accordingly, while the pulse width had decreased from 8.8 μs down to 4.4 μs. In our opinion, the pulse width could be narrowed down by improving modulation depth of the MoSe₂ and by using shorter cavity length. However, as shown in Figure 4(b), the pulse energy and average output power were also measured and were observed to be linearly increased as the pumping power increased. The highest pulse energy (9.4 nJ) was obtained at maximum pump power of 333.4 mW. Higher peak power can be enhanced by using dual-clad gain fiber and by minimizing loss of the laser cavity.
Figure 3. Characterization of generating a Q-switched pulse: (a) centered wavelength spectrum at 1040.8 nm, b) pulse trace at a repetition rate of 21.4 kHz and pulse duration of 46.8 µs, c) FWHM pulse width measurement of 5.6 µs and (d) RF output spectrum with peak-to-pedestal ratio 44 dB at a pump power of 86.8 mW.

Figure 4. The Q-switched pulse of (a) repetition rate and the pulse width, and (b) average output power and pulse energy corresponding to pump power.
5. Conclusion
As a conclusion, we have demonstrated a passive Q-switched YDFL pulses using a few layers MoSe$_2$ as saturable absorber. A stable Q-switched pulse was observed with the repetition rates from 14.2 kHz up to 34 kHz were accomplished. The results of the shortest pulse width and the highest pulse energy were measured to be 4.4 µs and 3.6 nJ, respectively. These findings have demonstrated that few layers MoSe$_2$ SA has potential to be used in generation laser pulses in 1-micron region and could encourage many more development in the photonic field.

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