Q-switched fiber laser based on transition metal dichalcogenides MoS$_2$, MoSe$_2$, WS$_2$, and WSe$_2$

Bohua Chen,$^1$ Xiaoyan Zhang,$^2$ Kan Wu,$^1$* Hao Wang,$^1$ Jun Wang,$^2$ and Jianping Chen$^1$

$^1$State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
$^2$Key Laboratory of Materials for High-Power Laser, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

* kanwu@sjtu.edu.cn

Abstract: In this paper, we report 4 different saturable absorbers based on 4 transition metal dichalcogenides (MoS$_2$, MoSe$_2$, WS$_2$, WSe$_2$) and utilize them to Q-switch a ring-cavity fiber laser with identical cavity configuration. It is found that MoSe$_2$ exhibits highest modulation depth with similar preparation process among four saturable absorbers. Q-switching operation performance is compared from the aspects of RF spectrum, optical spectrum, repetition rate and pulse duration. WS$_2$ Q-switched fiber laser generates the most stable pulse trains compared to other 3 fiber lasers. These results demonstrate the feasibility of TMDs to Q-switch fiber laser effectively and provide a meaningful reference for further research in nonlinear fiber optics with these TMDs materials.

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1. Introduction

The discovery of graphene in 2004 [1] has opened up a door to a novel world of 2-dimensional materials. Since then, many researchers have investigated all kinds of optical and electrical characteristics of graphene such as saturable absorption, four wave mixing, etc [2–7]. Many novel photoelectric devices have been invented based on graphene [8, 9]. The prevalence of graphene has also guided researchers in exploring more analogous 2-dimensional materials, among which transition metal dichalcogenides (TMDs) are well-known. Typical TMDs include molybdenum disulfide (MoS2), molybdenum diselenide...
(MoSe₂), tungsten disulfide (WS₂) and tungsten diselenide (WSe₂). They are actually semiconductors with indirect bandwidth in bulk states. When split into monolayer or few layers, they turn into semiconductors with direct bandgap, which indicates good photoluminescence ability [10–12]. Besides, they own some potential optoelectronic properties, especially the nonlinear optical property [13–17].

Q-switched fiber laser is a kind of pulse laser which could generates high energy pulses up to several milli-joules [18]. It has gained significant applications in science researches and medical treatment [19–22]. Q-switching operation can be classified into 2 categories: active Q-switching and passive Q-switching. The former usually utilizes an acousto-optic or electro-optic modulator to modulate the loss of laser resonator [23], while the latter works with a saturable absorber, which could be semiconductor saturable absorber mirror (SESAM) [24, 25], carbon nanotubes (CNTs) [26, 27], graphene [28] and others. Some new saturable absorbers such as topological insulator [29, 30] and black phosphorus [31] can also be used in fiber lasers. Recently, lots of researches with TMDs to generate Q-switched laser pulses have been reported. R. I. Woodward et al. reported a tunable ytterbium-doped Q-switched fiber laser based on few layer MoS₂, tunable from 1030nm to 1070nm [32]. Besides MoS₂, their team has also researched Q-switched MoSe₂ fiber lasers with Yb-, Er-, and Tm-doped fiber [33]. Z. Luo et al. used a broadband few-layer MoS₂ saturable absorber to Q-switch 1, 1.5 and 2 μs fiber laser [34]. Sahar Hosseinzadeh Kassani et al. reported a WS₂ based Q-switched laser with tunable repetition rates from 82 kHz to 134 kHz [35]. Besides Q-switching operation, some researchers have achieved mode-locking operation with TMDs. H. Zhang et al. reported a MoS₂ based mode-locked fiber laser, which could generate pulses centered at 1054.3 nm with bandwidth of 2.7 nm and pulse duration of 800ps [36]. H. Liu et al. used MoS₂ to generate 710fs mode-locked pulses in an erbium-doped fiber laser [37]. Reza Khazaenezhad et al. reported a mode-locked fiber laser based on WS₂ [38]. Peiguang Yan et al. reported a 675 fs WS₂ based mode-locked fiber of which the signal-to-noise ratio is 65dB [39]. Other works related to mode-locked fiber laser based on WS₂ saturable absorber have been reported this year [40, 41]. These results encourage us to investigate optoelectronic characteristics of more similar TMDs materials.

In this paper, we demonstrate the feasibility of Q-switching operation with 4 typical TMDs MoS₂, MoSe₂, WS₂, and WSe₂. The TMDs-PVA saturable absorbers are fabricated and characterized with Raman spectroscopy and Transmission Electron Microscopy. The saturable absorption experiment is carried out to measure the modulation depth of home-made saturable absorbers. Lastly, with these saturable absorbers we construct a ring-cavity erbium-doped Q-switched fiber laser and the results of different materials are compared. The analysis of different Q-switch performance of 4 TMDs materials provides guidance for selecting suitable TMD saturable absorber to satisfy specific requirements of Q-switched fiber lasers and offer a good reference for future researches on nonlinear optical characteristics of TMDs.

2. Material preparation and characterization

Saturable absorber with thin-film form has advantages in the mass preparation, uniform quality and flexibility of usage. In our experiment, all the four TMDs are embedded in polyvinyl alcohol (PVA) to fabricate TMDs-PVA saturable absorber films. The whole fabrication process has been shown in Fig. 1 (a). For a meaningful comparison among these TMDs materials, all four TMDs are processed with the same procedures and parameters to keep the sample concentration constant. Therefore, the conclusions of comparison of four samples in this work should indicate the difference of the samples. Here MoS₂ is used as an example in Fig. 1 (a). First of all, 5mg/ml MoS₂ water dispersions are prepared with sodium cholate (SC) as surfactant. The detailed preparation of MoS₂ dispersions can be referred to Ref [42]. Meanwhile, 50mg/ml polyvinyl alcohol (PVA) aqueous solution is also prepared. Then we mix 2ml MoS₂ dispersions with 10ml PVA aqueous solution for 24 hours with a magnetic stirrer. After that, the mixture is processed for another 4 hours by ultrasonic water
bath device. The uniform mixture is then dropped onto the surface of a clean plastic dish and dried under 50°C air condition for 3~4 days. Finally, the high quality transparent films are obtained. Figures 1(b)-1(e) show the well-fabricated 4 types of TMDs-PVA polymer films. Although there is corrugation on the films, the films are cut into very small pieces (1x1 mm) for experimental usage. Moreover the light beam diameter is 10 μm and the films are very flat on this scale. Scanning electron microscope (SEM) is used to confirm this, shown in the insets of Figs. 1(b)-1(e). Very flat edges can be observed of four TMDs-PVA films.

Fig. 1. (a) Fabrication procedures of TMDs-PVA films, taking MoS₂ for example. (b)-(e) show the photos of fabricated TMDs-PVA polymer films. Insets: SEM images of film edges with x1500 magnification.

Fig. 2. (a)-(d) Raman spectroscopy and (e)-(h) Transmission Electron Microscopy photos of four TMDs materials.

Raman spectroscopy is utilized to characterize the atomic structures of the fabricated films. The Raman spectra of 4 types of TMDs-PVA films are displayed in Fig. 2. According to [43], the \( E_{12g} \) mode is related to an in-plane motion of TMD molecular and \( A_{1g} \) mode is corresponded to out-of-plane motion of TMD molecular. And the separation between the two modes is positively correlated to material thickness and is a good indicator of TMDs material layers. \( B_{2g} \) mode is due to the breakdown of translation symmetry in few-layer TMD material. The details for determining layers of different TMDs materials can be referred to Ref [44, 45]. For MoS₂, \( A_{1g} \) mode is observed at 407.2 cm\(^{-1}\) and \( E_{12g} \) mode is observed at 381.3 cm\(^{-1}\).
For MoSe₂, \(A_{1g}\), \(E_{12g}\) and \(B_{2g}\) modes are observed at 239.6 cm\(^{-1}\), 283.9 cm\(^{-1}\) and 354.0 cm\(^{-1}\), respectively. For WS₂, \(A_{1g}\) mode is found at 419.5 cm\(^{-1}\) and \(E_{12g}\) mode is found at 355.4 cm\(^{-1}\). For WSe₂, \(A_{1g}\), \(E_{12g}\) and \(B_{2g}\) modes are observed at 250.7 cm\(^{-1}\), 245.1 cm\(^{-1}\) and 315.6 cm\(^{-1}\), respectively. The measuring results are analogous to the results of few-layer TMDs materials reported at Ref [43], which mean a good thickness of these TMDs films. The Transmission Electron Microscopy (TEM) gives an auxiliary demonstration of thickness of TMDs films. TEM photos are gathered in Figs. 2(e)-2(h). The darker a region is in TEM photo, the thicker it is and the more layers exist in that region. There are 1–5 layers in these TMDs films, as indicated by TEM photos.

The power dependent nonlinear transmission is the key parameter to evaluate a saturable absorber. The saturable absorption of our TMDs-PVA polymer films are investigated by standard two-arm experiment. The experiment setup is given in Fig. 3(a). The mode-locked laser generates femtosecond laser pulses with a repetition rate of 37 MHz and pulse width of 560 fs. The output power of mode-locked laser can be tuned with a maximum power of 20 mW and a single pulse energy of 0.54 nJ. The output pulses propagate through a 90:10 coupler so that 10% optical power is measured by power meter 1 as a reference and 90% optical power passes through the TMDs-PVA polymer films, which are cut into 1 mm × 1 mm squares and sandwiched by a pair of FC/PC connectors. The power of light transmitted through the sample is measured by power meter 2. A 10-dB attenuator is applied before the
power meter 2 to adapt to the measurement range of the power meter. The transmission at different optical intensity is obtained by adjusting the output power of mode-locked laser.

The results of saturable absorption experiments of 4 types of materials are shown in Figs. 3(b)-3(e). Fitting with the formula [31]:

\[ T(I) = 1 - \Delta T \times \exp\left(-\frac{I}{I_{sat}}\right) - A_{ns}, \]

where \( T \) is transmittance, \( \Delta T \) is modulation depth, \( I \) is intensity of laser, \( I_{sat} \) is saturation power intensity and \( A_{ns} \) is non-saturable absorbance. The modulation depths of MoS\(_2\), MoSe\(_2\), WS\(_2\), WSe\(_2\) are 2.15%, 6.73%, 2.53% and 3.02% respectively. The corresponding saturation intensities are 129.4, 132.5, 148.2 and 270.4 MW/cm\(^2\), respectively. And the non-saturable absorbances of 4 TMDs saturable absorbers are 63.1%, 39.2%, 58.3% and 61.5%, respectively. It can be observed that MoSe\(_2\) exhibits the highest modulation depth and smallest non-saturable absorbance among these materials. By contrast, MoS\(_2\)-PVA polymer film has a relatively poor modulation depth and a quite high non-saturable absorbance. WSe\(_2\)-PVA polymer film might suffer from two-photon absorption (TPA) under high incident optical power since its transmittance drops when the intensity of input light exceeds around 550 MW/cm\(^2\) [36]. TPA is a process where two photons are absorbed simultaneously by the material. The strength of TPA is proportional to the optical intensity and therefore TPA is usually observed under high input optical intensity. TPA has been reported in TMDs materials by a few works [16, 46] as well as in other saturable absorber materials [47]. To demonstrate that the reverse saturable absorption observed in our work is caused by TPA, a modified formula with a TPA term is used to fit the data of WSe\(_2\) in Fig. 3 (e):

\[ T(I) = 1 - \Delta T \times \exp\left(-\frac{I}{I_{sat}}\right) - A_{ns} - \beta I, \]

where \( \beta \) is the TPA coefficient. We find a better fitting result (the green line) with this modified formula than the original one (the red line) and \( \beta \) is approximately \( 7 \times 10^{-5} \) cm\(^2\)/MW.

3. Q-switching operations

A ring-cavity fiber laser is constructed to verify the functionality of our home-made TMDs-PVA films as saturable absorbers. The setup is shown in Fig. 4. A 980nm diode laser with tunable output power is used as a pump source. A 980/1550nm wavelength division multiplexer (WDM) couples the pump light into the ring cavity. We use a section of erbium-doped fiber (EDF) as the gain medium. 2 polarization controllers (PC 1 & PC2) are used to adjust polarization of optical light and birefringence of fiber cavity. A 90/10 coupler extracts 10% optical power as output. A polarization independent isolator (PII) assures the unidirectional running of fiber laser. As for the output, an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) is used to monitor the optical spectrum of output laser. We also use a photodetector (PD) to transform the optical signals into electrical signals. An oscilloscope (Agilent Technologies, DSO9254A) and an electric spectrum analyzer (ESA, ROHDE & SCHWARZ) are used to monitor these electrical signals in time and frequency domain, respectively. TMDs-PVA saturable absorber is constructed by sandwiching pieces of square TMDs-PVA polymer films by a pair of FC/PC connectors. The total cavity length is approximately 17.4 m.
The setup of ring cavity Q-switched fiber laser. LD: laser diode; WDM: wavelength division multiplexer; SMF: single mode fiber; EDF: Erbium-doped fiber; PC: polarization controller; TMDs-PVA SA: transition metal dichalcogenides- polyvinyl alcohol saturable absorber; PII: polarization independent isolator.

The architecture of fiber laser is kept completely same for all 4 different TMDs-PVA polymer saturable absorbers. Q-switching operation is obtained as following: When the pump power is increased gradually, the free running of continuous wave (CW) laser is first observed which is indicated by a single narrow peak in OSA. Many longitudinal modes compete in cavity simultaneously when the pump power is further increased. Then the optical polarization is adjusted by tuning 2 PCs. Q-switched pulses will be generated at a certain pump power for different TMDs materials. Specifically, The MoS$_2$ Q-switching operation starts when pump power is higher than 50mW, MoSe$_2$ Q-switching operation starts when pump power is higher than 570mW, WS$_2$ starts Q-switching as the pump power is higher than 400mW, WSe$_2$ starts Q-switching as the pump power is higher than 280mW. Moreover, it is found that Q-switching operation can only happen when fiber laser is pumped with appropriate power and maintain stable pulses in a certain pump power range. Figure 5 shows the relationship of pump power with the output power of Q-switched lasers for four TMDs materials. The nonlinear relation between the output power and pump power is due to the generation of unstable CW lasing when Q-switching operation is still dominated.

As shown in Fig. 5, the power of Q-switched lasers rises following the increase of pump power. MoS$_2$ Q-switching operation happens in low pump power range, its output power is lowest and the maximum output power doesn’t exceed 0dBm. MoSe$_2$ and WS$_2$ Q-switching operation needs high pump power, WS$_2$ has the highest output power under identical pump condition compared to other three materials. Furthermore, WSe$_2$ has the broadest Q-switching range as it Q-switches laser starting from 280mW to 720mW and limited to the maximum output of pump LD.

Figure 6 gathers output pulses of Q-switched fiber lasers based on 4 TMDs-PVA polymer saturable absorbers. Q-switched pulses have considerable wide pulse duration [18]. In our experiment, MoS$_2$ Q-switched fiber laser generate 12.9 $\mu$s pulses when it’s pumped at 100mW. At 650mW pump power, MoSe$_2$ and WS$_2$ Q-switched fiber lasers output pulses with width 4.2 and 4.1 $\mu$s, respectively. WSe$_2$ Q-switched fiber laser generates 4.8 $\mu$s pulses under 500 mW pump power.
Fig. 5. The output power variation with pump power within Q-switching range, (a)–(d) delegates the results of MoS$_2$, MoSe$_2$, WS$_2$ and WSe$_2$, respectively.

Fig. 6. (a) Pulse train with MoS$_2$-PVA SA under 100 mW pump. (b) Pulse train with MoSe$_2$ under 650 mW pump power. (c) Pulse train with WS$_2$ under 650 mW pump power. (d) Pulse train with WSe$_2$ under 500 mW pump power. Insets are corresponding single pulse.
As for the stability of Q-switching operation in the above pump condition, we measure the
signal to noise ratio of electrical signal transformed by PD and analyze electrical spectrum
with the help of ESA. With a resolution bandwidth of 100Hz, the results are gathered in Fig.
7. It shows WS2 Q-switched fiber laser works with a highest stability, the extinction ratio of
RF signal can reach up to 54.2dB. MoSe2 Q-switched fiber laser is least stable as its
extinction ratio is only 31.3dB. MoS2 and WSe2 Q-switched fiber lasers have a moderate
performance as the extinction ratios are 48.5 dB and 41.9 dB respectively.

Optical spectrum measurement results are given in Fig. 8. The pump condition is identical
with Fig. 6. Results show all four Q-switched fiber laser output spectra centered on the
vicinity of 1560 nm. These Q-switched operations have different optical spectrum profile. The
optical spectrum of MoS2 has a strong continuous wave which superposes in the center of
spectrum. This continuous wave occupies much power and leads to a relatively low output
power of Q-switched pulses as well as degraded stability. Similarly, the optical spectrum of
MoSe2 and WSe2 show some superposition of continuous wave while WS2 has a smoother
optical spectrum. As a result, the Q-switching operation of WS2 is more stable and effective
than other saturable absorbers.

Repetition rate and pulse duration are another two parameters of Q-switched fiber laser.
Here, pulse duration is measured with oscilloscope by measuring the full width at half
maximum (FWHM) of a pulse. These two parameters vary with pump power, as shown in
Fig. 9. It concludes that WS2 shows an obviously stable variation trend than other three
materials which is consistent with the analysis that an optical spectrum without parasitic CW
lasing has the best stability. The fluctuation of pulse duration with increasing pump power of
MoS2-PVA saturable absorber is related to parasitic CW operation. Parasitic CW operation
competes with normal Q-switching operation. The existence of parasitic CW can partially
bleach the saturable absorber, change its saturable absorption and affects the pulse duration of
Q-switched pulses [48, 49]. Therefore, under different pump power, the power of parasitic
CW operation fluctuates and thus causes pulse duration to oscillate with increasing pump
power.
Fig. 8. Optical spectra of Q-switched pulses. (a)–(d) show the measurement results of MoS$_2$, MoSe$_2$, WS$_2$ and WSe$_2$, respectively.

Fig. 9. Variation of repetition rate and pulse duration with pump power. (a)–(d) show the measurement results of MoS$_2$, MoSe$_2$, WS$_2$ and WSe$_2$, respectively.
4. Discussion

The photon energy of generated 1550nm Q-switched pulses is approximately 0.8 eV. However, the bandgap values of four TMDs materials are larger than 0.8 eV. The bandgap values of these TMDs materials are summarized in Table 1. This sub-bandgap absorption is attributed to the edge states and the defect states of the TMDs nanosheets.

Table 1. Bandgap values of four TMDs materials.

| Materials   | MoS$_2$ [32] | MoSe$_2$ [43] | WS$_2$ [35] | WSe$_2$ [43] |
|-------------|--------------|---------------|-------------|--------------|
| Bandgap (eV)| Monolayer    | 1.80          | 1.57        | 2.1          | 1.65         |
|             | Bulk         | 1.29          | 1.1         | 1.3          | 1.2          |

The bandgap for TMDs materials is obtained in the assumption of an infinite lattice without any defect. However, TMDs nanosheets prepared in our work have limited size and thus high edge-to-surface ratio, which results in the existence of edge states with sub-bandgap absorption. In the early experiment, it has been shown that the sub-bandgap absorption in MoS$_2$ increases with the decrease of MoS$_2$ platelet size [50]. Similar analysis has also been performed in [32]. Defects in the materials can also create defect states and result in sub-bandgap absorption. Wang et al. have demonstrated the reduction of the bandgap of MoS$_2$ from 1.08 eV to 0.08 eV and transformed this material into a broadband saturable absorber by adding defects to the material [51]. Because MoSe$_2$, WS$_2$ and WSe$_2$ have similar structure and material properties as MoS$_2$, it is reasonable to deduce that the sub-bandgap absorption in these three TMDs materials are also due to the absorption induced by the edge states and defect states.

Based on the above experiments, material properties and Q-switching operations of four TMDs-PVA saturable absorbers are summarized in Table 2, which is meaningful to compare material characteristics of different TMDs materials. In this table, MoSe$_2$ has the highest modulation depth and the least non-saturable absorbance, but the extinction ratio in RF spectrum of MoSe$_2$ based laser is low which means suffering much noise during Q-switching operation. WS$_2$ based laser exhibits the best performance: the extinction ratio of RF signal reaches to 54.2 dB, optical spectrum has little glitch compared with other materials indicating a weaker influence by continuous wave. Besides, repetition rate and pulse duration vary with pump power smoothly and give a clear variation trend. MoS$_2$ and WSe$_2$ based lasers have more stable Q-switching operation than MoSe$_2$ based laser, but are not as good as WS$_2$ based laser.

This difference in the laser behaviors indicates that four lasers suffer different noise levels. The different noise levels come from different thermal stability of TMDs materials. Thermal stability is dominated by the thermal conductivity of a material. Material with higher thermal conductivity can dissipate heat faster and thus can endure higher absorption loss, allow higher input optical intensity and have a higher damage threshold. The high-thermal-conductivity material can sustain a stable optical property in the laser cavity and results in a low-noise laser operation. On the contrary, material with lower thermal conductivity becomes less stable and results in a noisy laser operation. It is also easy to be damaged at high input optical intensity. The thermal conductivity is 1.05 Wm$^{-1}$K$^{-1}$ for MoS$_2$, 0.85 Wm$^{-1}$K$^{-1}$ for MoSe$_2$, 2.2 Wm$^{-1}$K$^{-1}$ for WS$_2$ and 0.9 Wm$^{-1}$K$^{-1}$ for WSe$_2$, respectively [52]. WS$_2$ has the highest thermal conductivity, meaning a best thermal stability among four materials. This is consistent with the experimental results that WS$_2$-based laser has the best noise properties, shown in Table 2. It can also be noted that although MoSe$_2$ has the lowest non-saturable loss, MoSe$_2$ based laser does not has the best performance due to the low thermal conductivity of MoSe$_2$. Besides, since the maximum single pulse energy of femtosecond laser is 0.54 nJ, while in the Q-switched fiber laser, the intra-cavity pulse energy can exceed several hundreds of nJ or even a
few μJ. Therefore the thermal stability of four TMDs-PVA SAs cannot be observed in the nonlinear transmission experiments, but can be observed in the Q-switched fiber laser cavity.

Table 2. Comparison of four TMDs-polymer PVA saturable absorbers

| Properties                  | MoS₂-PVA | MoSe₂-PVA | WS₂-PVA | WSe₂-PVA |
|-----------------------------|----------|-----------|---------|----------|
| Modulation depth            | 2.15%    | 6.73%     | 2.53%   | 3.02%    |
| Saturation intensity        | 129.4 MW/cm² | 132.5 MW/cm² | 148.2 MW/cm² | 270.4 MW/cm² |
| Non-saturable absorbance    | 63.1%    | 39.2%     | 58.3%   | 61.5%    |
| Thermal stability           | Low      | Low       | High    | Low      |
| Output power                | −13.06~−1.16 dBm | 3.51~3.9dBm | 7.44~8.07dBm | 3.51~5dBm |
| Pulse duration              | 9.92~13.53 μs | 4.04~6.506 μs | 3.966~6.707 μs | 4.063~9.182 μs |
| Repetition rate             | 7.758~41.452 kHz | 60.724~66.847 kHz | 47.026~77.925 kHz | 46.281~85.365 kHz |
| Extinction ratio in RF spectrum | 48.5dB   | 31.3dB    | 54.2dB  | 41.9dB   |
| Pump range                  | 50~170mW | 570~720mW | 400~720mW | 280~720mW |
| Intra-cavity pulse energy   | 63.7~184.7 nJ | 367.2~369.5 nJ | 822.9~1179.4 nJ | 366.2~484.8 nJ |

To further confirm the thermal stability of four TMDs-PVA SAs, an auxiliary experiment has been carried out to compare the stability of linear optical transmission of four SAs under different input power, shown in Fig. 10. Here an EDFA is used to amplify the output of a 1550nm CW laser. The amplified 1550 nm optical light passes through a 99:1 coupler, 1% optical light is measured by a power meter (Power Meter 1) as reference. 99% optical light passes through the TMDs-PVA saturable absorbers and is measured by another power meter (Power Meter 2). A 20-dB attenuator is added before the power meter to meet its measurement range. The maximum output power of EDFA is 500 mW, corresponding to an optical intensity of ~6.3 MW/cm² in optical fiber, which is much smaller than the saturation intensity of the SAs. Therefore this experiment investigates the linear optical transmission of the SAs. If the SAs can maintain a stable material properties under different incident power, a linear relationship between input power and output power is expected. The experimental results are shown in Figs. 10(b)-10(e). It can be observed that WS₂-PVA SA has the best linearity, meaning a stable optical transmission in the whole range of input power. However, change of the linearity can be clearly observed for MoS₂-PVA, MoSe₂-PVA and WSe₂-PVA SAs. Especially, MoSe₂-PVA SA significantly changes its transmission near the input power
of 337.8 mW, meaning the worst stability among the samples. These results are consistent with the discussion about thermal stability of 4 TMDs materials.

![Diagram](image)

**Fig. 10.** (a) Experimental setup for comparing the stability of the linear optical transmission of 4 TMDs materials under high input power and (b)-(c) measurement results of 4 TMDs materials. CW: continuous wave; EDFA: erbium doped fiber amplifier; SA: saturable absorber; Att.: attenuator.

Actually, TMDs-PVA polymer films were sandwiched between fiber connectors and illuminated by lasers perpendicularly in our scheme. This required high thermal stability for our home-made films and became a challenge for the saturable absorbers under high pump power. Some other schemes may help to overcome this problem. For example, TMDs can be deposited on the surface of a tapered fiber or side-polished fiber to construct saturable absorber which interacts with the evanescent field of light beam [53–55].

Moreover, Table 2 may provide a reference for us to fabricate TMDs-based Q-switched fiber laser to meet special requirements. For example, to obtain high-power and stable Q-switched pulses, WS2 is a good choice. To get wide pump tuning range or wide repetition rate tuning range of Q-switched pulses, WSe2 seems better. MoSe2 may be a good candidate to mode-lock a fiber laser as long as solving the problem of thermal stability and would become a next research hotspot.

Our work demonstrates the feasibility of four typical TMDs to Q-switch a ring-cavity fiber laser. The mode locking operations based on MoS2 and WS2 have been reported [37, 38, 40, 42]. The non-saturable absorbance of our saturable absorbers is slightly high. The values of non-saturable absorbance for MoS2, WS2 and WSe2 are around 60%. High non-saturable absorbance can cause laser to become less efficient and increase the tendency for Q-switched instabilities [56]. Therefore, Q-switching operation is more favorable than mode-locking.
operation in the laser cavity based on our TMDs saturable absorbers. Although MoSe₂ has a smaller non-saturable absorbance of 39.2%, the weak thermal stability of this material leads to the noisy Q-switched operation. An improvement on the material preparation may help to reduce the non-saturable absorbance and increase the possibility of obtaining mode-locking operation. Other meaningful nonlinear optical phenomenon such as four wave mixing [57], which has been generated with graphene, is also expected to be observed with these TMDs materials [58, 59].

5. Conclusions

We have fabricated 4 typical TMDs-PVA polymer saturable absorber (MoS₂, MoSe₂, WS₂, and WSe₂) and utilize them to Q-switch the same ring-cavity erbium-doped fiber laser. The saturable absorption of these SAs is characterized and MoSe₂ exhibits the highest modulation depth. Q-switching operations of a same erbium-doped fiber laser based on these SAs are achieved and compared in the aspects of RF spectrum, optical spectrum, repetition rate and pulse duration. WS₂ Q-switched fiber laser outputs the most stable pulse trains with the cleanest optical spectrum and highest extinction ratio in the RF spectrum. These results demonstrate the feasibility of TMDs to Q-switch fiber laser effectively and provide a meaningful reference for further research in nonlinear fiber optics with these TMDs materials.

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