Few-layer MoS_2 grown by chemical vapor deposition as a passive Q-switcher for tunable erbium-doped fiber lasers

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We report an erbium-doped fiber laser passively Q-switched by a few-layer molybdenum disulfide (MoS_2) saturable absorber (SA). The few-layer MoS_2 is grown by the chemical vapor deposition method and transferred onto the end-face of a fiber connector to form a fiber-compatible MoS_2 SA. The laser cavity is constructed by using a three-port optical circulator and a fiber Bragg grating (FBG) as the two end-mirrors. Stable Q-switched pulses are obtained with a pulse duration of 1.92 μs at 1560.5 nm. By increasing the pump power from 42 to 204 mW, the pulse repetition rate can be widely changed from 28.6 to 114.8 kHz. Passive Q-switching operations with discrete lasing wavelengths ranging from 1529.8 to 1570.1 nm are also investigated by using FBGs with different central wavelengths. This work demonstrates that few-layer MoS_2 can serve as a promising SA for wideband-tunable Q-switching laser operation.

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1. INTRODUCTION

Passively Q-switched fiber lasers have received considerable attentions due to their versatile applications in optical imaging, micromachining, medicine, and telecommunications [1,2]. In recent years, different kinds of saturable absorbers (SAs) have been used in fiber lasers to achieve passively Q-switched pulses, such as transition-metal-doped bulk crystals [3], semiconductor saturable absorber mirrors (SESAMs) [4], and single-wall carbon nanotubes (SWCNTs) [5]. Due to the compatibility with optical fibers, SESAMs and SWCNTs are widely used in passively Q-switched fiber lasers. However, SESAM is regarded as an expensive SA for passively Q-switched fiber lasers because of its complex fabrication and packaging design. Although the fabrication of SWCNT is simple and cost-effective, bandgap engineering or diameter/chirality control of the SWCNT is often necessary for realizing a broadband saturable absorption. Thus, there are always strong motivations to explore new high-performance SAs for pulsed laser systems. Graphene, a well-known two-dimensional (2D) nanomaterial, has been successfully used as an excellent SA for pulsed laser applications [6–8]. The success of graphene greatly motivates scientific researchers to seek other graphene-like nanomaterials for photonics applications.

Atomic-layered molybdenum disulfide (MoS_2) is a representative 2D material of transition metal dichalcogenides (TMDs) [9], which is now attracting continuous attention of the scientific community due to its exceptional optical properties, including saturable absorption behavior [10] and ultrafast carrier dynamics [11]. Recently, taking its advantage of the excellent saturable absorption, few-layer MoS_2 has been successfully exploited as a promising SA used in pulsed lasers [12–18]. Woodward *et al.* demonstrated a passively Q-switched ytterbium-doped fiber laser (YDFL) with MoS_2–polymer composite and achieved stable Q-switched pulses at 1.06 μm wavelength [13,14]. Wang *et al.* reported broadband few-layer MoS_2 SAs by introducing suitable atomic defects, which were successfully used in passively Q-switched solid-state lasers operating at 1.06, 1.42, and 2.1 μm [15]. By using a few-layer MoS_2 SA, we firstly demonstrated a passively mode-locked erbium-doped fiber laser (EDFL) emitting 1.28 ps pulses at 1568.9 nm [16]. Then, a MoS_2 SA was used to Q-switch an EDFL that had a short linear cavity with two fiber Bragg gratings (FBGs) as the end-mirrors [17]. These experimental results paved the way for few-layer MoS_2 used as a promising broadband SA for pulsed laser applications. Most recently, Luo *et al.* demonstrated 1, 1.5, and 2 μm fiber lasers Q-switched by a few-layer MoS_2–polymer composite as broadband SA [18]. It should be noted that the few-layer MoS_2 SAs used in Refs. [12–14,18] were prepared by liquid-phase exfoliation (LPE), which contain MoS_2 nano-flakes with different layers, and the prepared MoS_2 films are not always uniform. The chemical vapor deposition (CVD) technique allows growing high-quality MoS_2 films with precisely controlled number of layers. However, to date, the CVD-grown few-layer MoS_2 as a broadband Q-switcher for pulsed fiber lasers has not yet been fully explored.

In this paper, we demonstrate a tunable Q-switched EDFL using few-layer MoS_2 as a SA. The CVD method was employed to grow few-layer MoS_2 film, which was sandwiched between two fiber connectors (FCs) with a fiber adapter to form a fiber-compatible MoS_2 SA. The laser cavity was constructed by using a three-port optical circulator (OC) and a FBG as the two end-mirrors. Stable Q-switched pulses were obtained with a pulse duration of 1.92 μs at 1560.5 nm. The pulse repetition rate of the laser could be widely changed from 28.6 to 114.8 kHz by increasing the pump power from 42 to 204 mW.

By using FBGs with different central wavelengths, passive Q-switching operations with discrete lasing wavelengths ranging from 1529.8 to 1570.1 nm were also achieved.

2. EXPERIMENTAL SETUP OF MoS_2 Q-SWITCHED FIBER LASER

A schematic diagram of our compact passively Q-switched EDFL is shown in Fig. 1(a). A 0.6 m long erbium-doped fiber (EDF; Liekki Er80-8/125) was used as the gain medium. The laser was pumped by a 980 nm laser diode (LD) through a wavelength division multiplexer (WDM). Other fiber used in the cavity is the standard single-mode fiber (SMF). The total cavity length is about 2.6 m. The MoS_2 SA was spliced into the laser cavity for passive Q-switching. A three-port OC and a FBG were used as the two end-mirrors of the laser. The FBG with 95% reflectivity has a 3 dB spectral bandwidth of 0.1 nm and a central wavelength of 1560.5 nm. The 5% intracavity laser was output from the FBG. With the proposed laser cavity configuration, the self-mode-locking effect can be effectively suppressed by the narrow-band filtering of the FBG. Moreover, the intracavity OC was not only used as a high-reflection mirror, but also as a router for partly recycling the residual pump light and increasing the laser pumping efficiency [19]. The laser output performance was measured using an optical power meter, an optical spectrum analyzer (Yokogawa; AQ 6370C), and a 2 GHz photodetector together with a 500 MHz oscilloscope (Tektronix; TDS3052C). The radio frequency (RF) spectrum was measured by a RF spectrum analyzer (Advantest; R3267).

Few-layer MoS_2 film used in this work was synthesized in a tube furnace by the CVD method as previously presented in Ref. [16]. The Raman spectrum of the as-grown MoS_2 film was measured using a Renishaw 100 Raman spectrometer with 514 nm laser. As shown in Fig. 1, the MoS_2 film exhibited two Raman characteristic bands at 404.0 and 379.8 cm^{-1}, corresponding to the A_{1g} and E_{2g}^1 modes, respectively [20]. The peak frequency difference (Δ) between the A_{1g} and E_{2g}^1 modes can be used to identify the number of MoS_2 layers [18]. In our case, the Δ value of the as-grown sample was 24.2 cm^{-1}, corresponding to a layer number of 4–5. The MoS_2 film was then transferred and attached onto the end-face of a FC [Fig. 1(c)]. The FC coated with few-layer MoS_2 was connected to another clean FC with a fiber adapter to form a MoS_2 SA. The SA parameters were measured by a power-dependent transmission measurement system with 250 fs pulses at a wavelength of 1550 nm, which has been elaborated in Ref. [16]. The optical transmittance of the MoS_2 SA at different input powers was recorded, as shown in Fig. 2, exhibiting saturable absorption property that the transmittance increased with incident light intensity. The experimental data for power-dependent transmittance $T(I)$ were fitted by $T(I) = 1 - \Delta T \exp(-I/I_{\text{sat}}) - T_{ns}$ [21], where ΔT is the modulation depth, I is the incident intensity, I_{sat} is the saturation intensity, and T_{ns} is the nonsaturable absorbance. The parameters ΔT and I_{sat} were determined to be 28.5% and 0.55 MW/cm^2, respectively. Our measured saturation intensity for few-layer MoS_2 is much lower than those of SWCNTs [22] and graphene [23] at 1550 nm, which could be beneficial for Q-switched pulse generation in fiber lasers.

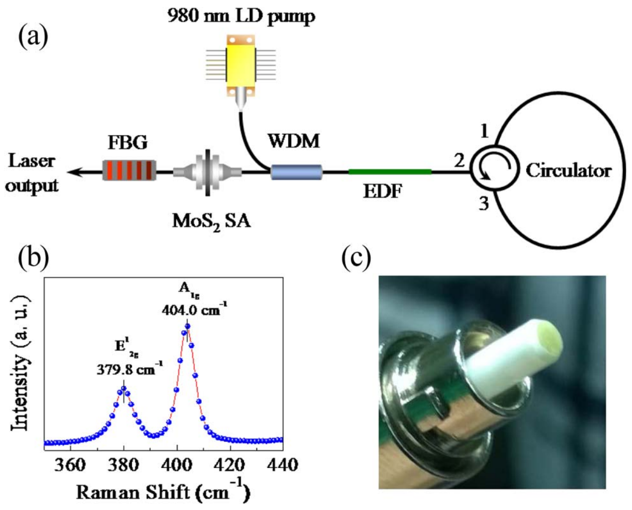

Fig. 1. (a) Experimental setup of the MoS_2 Q-switched fiber laser; (b) Raman spectrum of as-grown few-layer MoS_2; (c) photograph of a FC coated with few-layer MoS_2.

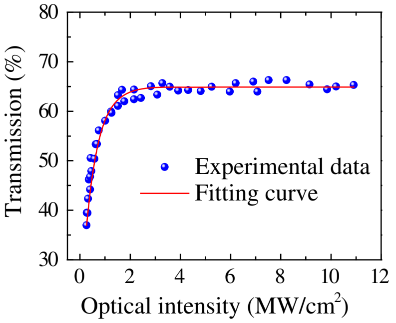

Fig. 2. Nonlinear transmission of few-layer MoS_2 SA.

We note that the direct band gap of monolayer MoS_2 is about 1.8 eV (0.66 μm) while the indirect band gap of few-layer MoS_2 is about 1.2 eV (0.99 μm) [9]. When irradiated by photons with an energy greater than the band gap, few-layer MoS_2 can be excited by absorbing one photon and exhibits saturable absorption at high excitation intensities due to the Pauli blocking effect [10]. It seems that few-layer MoS_2 are beyond the application as a SA for pulsed lasers at around 1.55 μm. However, several groups have experimentally demonstrated that MoS_2 exhibits saturable absorption property at around 1.55 μm [10,12–18], and some mechanisms have been proposed to explain the intriguing saturable absorption observed at such waveband, such as MoS_2 bandgap reduction induced by introducing suitable S atomic defects [15] and coexistence of semiconducting and metallic states [12]. Recently, Woodward *et al.* proposed a mechanism based on edge states in MoS_2 bandgap [14], which is responsible for the wideband saturable absorption exhibited by few-layer MoS_2, despite operating at photon energies lower than the material bandgap. Our experimental results show that the CVD-grown few-layer MoS_2 has significant saturable absorption at 1550 nm. Further investigation is needed to identify the detailed mechanisms for the saturable absorption we observed.

3. RESULTS AND DISCUSSION

Continuous wave (CW) operation of the proposed laser started at a pump power of about 30 mW, and self-starting Q-switching operation was achieved when the pump power was increased to 41.8 mW. As shown in Fig. 3, typical pulse

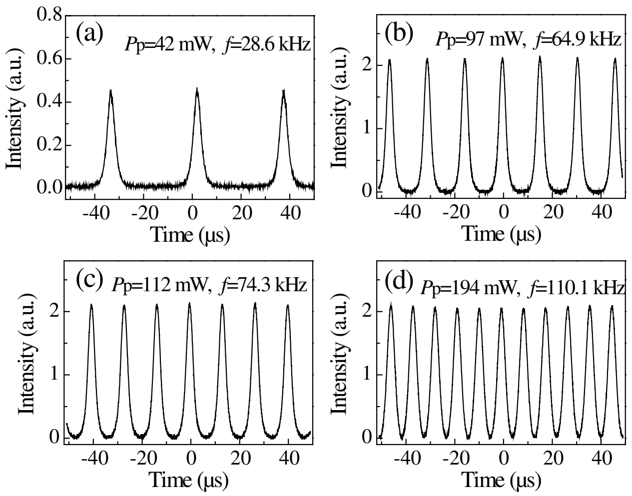

Fig. 3. Oscilloscope traces of the Q-switched pulses under different pump powers Pp; (a) $Pp = 42$ mW; (b) $Pp = 97$ mW; (c) $Pp = 112$ mW; (d) $Pp = 194$ mW.

trains were achieved under different pump powers. The pulse repetition rate monotonously increases from 28.6 to 110.1 kHz by varying the pump power from 42 to 194 mW. Unlike mode-locking operation where the pulse repetition rate is determined by the cavity length, the proposed MoS_2 Q-switched fiber laser has a tunable repetition rate, which is dependent on the pumping strength [8].

Figure 4 shows typical characteristics of Q-switched pulses generated at a pump power of 102 mW. The optical spectrum [Fig. 4(a)] of Q-switched pulses is centered at 1560.5 nm and the 3 dB spectral width is about 0.06 nm. A recorded oscilloscope trace of the Q-switched pulse train is shown in Fig. 4(b). The time interval between adjacent pulses is about 14.9 μs. Figure 4(c) presents a zoom-in single pulse profile. The pulse has a symmetric intensity profile with a pulse duration (FWHM) of 2.18 μs. Figure 4(d) shows the corresponding RF spectrum with a 40 kHz span and 30 Hz resolution bandwidth. The pulse repetition rate is 66.9 kHz, matching with the pulse period of 14.9 μs. The signal-to-noise ratio (SNR) is ~41.1 dB, indicating good Q-switching stability. Moreover, as shown in the inset of Fig. 4(d), the RF spectrum in a wider span has no other frequency component except the fundamental and harmonic frequency, further confirming the stability of the Q-switching operation. We have also tested the long-term stability of the Q-switching operation at the pump power of 102 mW. In this case, the laser was turned on over 4 h in the conventional laboratory condition. Relative fluctuation of average output power was about ±3.5%. This indicated that the MoS_2 Q-switched fiber laser exhibited the good stability in the room environment.

Figure 5(a) shows the pulse repetition rate and pulse duration of the Q-switched fiber laser as functions of incident pump power. By increasing the pump power from 42 to 204 mW, the pulse repetition rate increased monotonously from 28.6 to 114.8 kHz, but the pulse duration decreased from 3.7 to 1.92 μs, which are typical features of passive Q-switching [8]. At every specific pump power and repetition rate, the Q-switched pulse output was stable and no significant pulse-intensity fluctuation was observed on the oscilloscope. Figure 5(b) presents the average output power and correspondingly calculated pulse energy of the proposed laser versus pump power. The average output power almost increased linearly with the pump power and single-pulse energy changed from 5.8 to 8.2 nJ. Experimentally, we found that the pulse duration, and pulse energy remained almost unchanged at higher pump power (>160 mW), suggesting that the SA

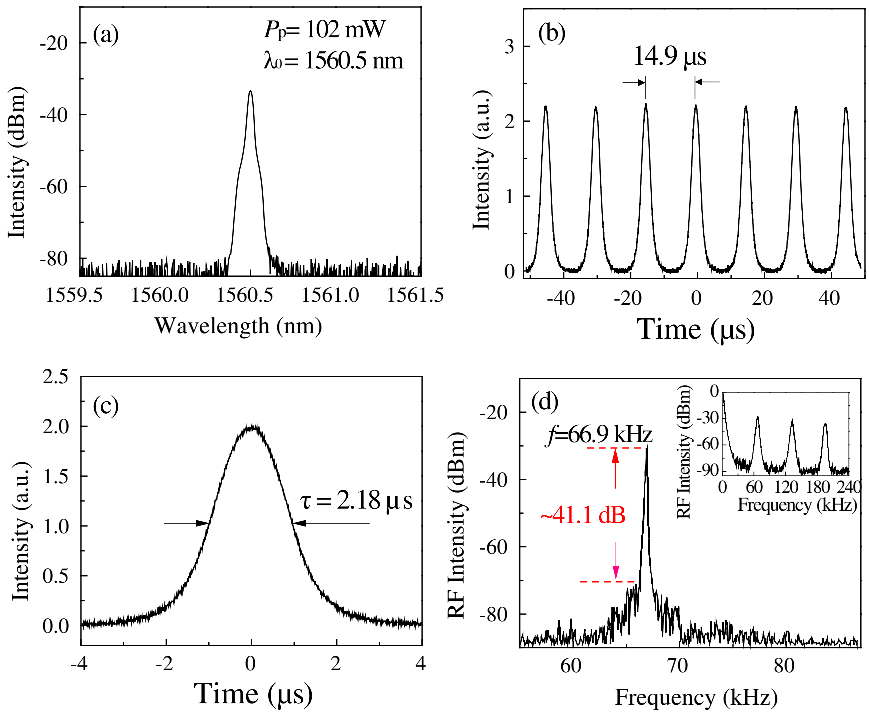

Fig. 4. Typical characteristics of the Q-switched pulses emitted from the fiber laser at the pump power of 102 mW; (a) output optical spectrum; (b) oscilloscope trace of the Q-switched pulse train; (c) single-pulse profile; (d) RF spectrum.

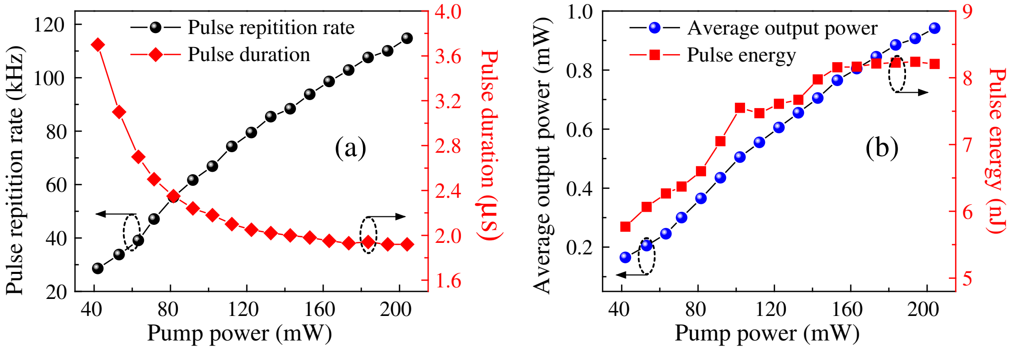

Fig. 5. (a) Pulse repetition rate and pulse duration versus incident pump power; (b) average output power and single-pulse energy versus incident pump power.

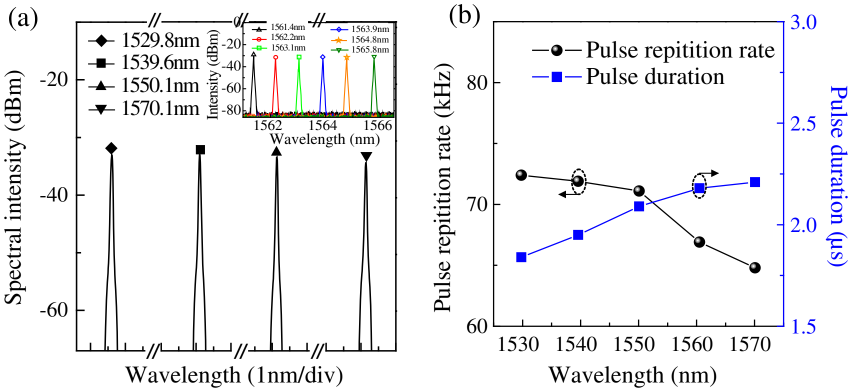

Fig. 6. (a) Laser output spectra at different wavelengths by using different FBGs under a pump power of 102 mW. Inset, axial strain induced wavelength tuning; (b) pulse repetition rate and pulse duration as a function of the wavelength.

could be obviously saturated. At the pump power of 204 mW, a minimum pulse duration of 1.92 μs was achieved, comparable to the Q-switched fiber lasers using SWCNTs [5], graphene [8], and topological insulators (TIs) [24]. The minimum pulse duration obtain in our work could be further narrowed through shortening the cavity length and increasing the modulation depth of the MoS_2-based SA [25,26].

Further increasing the pump power over 204 mW, the Q-switched pulse trains became unstable with strong amplitude fluctuation, and ultimately the Q-switching operation disappeared. This phenomenon was also observed in a Q-switched fiber laser with a TI-based SA, and explained by the thermal damage to the SAs [27]. Subsequently, as we decreased the incident pump power below 204 mW, stable Q-switched pulses were observed again on the oscilloscope screen, which indicated that the MoS_2-based SA had not been thermally damaged. In our experiment, the unstable Q-switching operation could be caused by the over-bleaching of MoS_2 SA under a strong pumping intensity [24]. In addition, to check whether the passive Q-switching was attributed to the as-fabricated MoS_2 SA, the FC coated with few-layer MoS_2 was replaced with another common clean FC in the laser cavity. In this case, no Q-switched pulses were observed on the oscilloscope no matter how we adjusted the pump power in a wide range. This finding verified that the few-layer MoS_2 SA played a key role in passive Q-switching. We believe that the performance of Q-switched pulses emitted from our laser could be further improved by optimizing the SA parameters of few-layer MoS_2 and the cavity design.

To verify whether the few-layer MoS_2 SA could operate as a broadband passive Q-switcher, we replaced the FBG in the cavity with other ones that have the central wavelengths of 1529.8, 1539.6, 1550.1, and 1570.1 nm. At the same pump power of 102 mW, stable passively Q-switched pulses were achieved at different wavelengths ranging from 1529.8 to 1570.1 nm, as shown in Fig. 6(a). We also recorded the pulse repetition rate and pulse duration at different lasing wavelengths shown in Fig. 6(b). As the lasing wavelength varied from 1529.8 to 1570.1 nm, the repetition rate deceased from 72.4 to 62.8 kHz, and the pulse duration increased from 1.84 to 2.21 μs. This finding implied that the characteristics of Q-switching operation were wavelength-dependent, which could be attributed to the gain difference of EDF at different wavelengths [21]. On the other hand, the central wavelength of Q-switching could be continuously tuned by applying an axial strain on the FBG. As an example, a wavelength range tunable from 1561.4 to 1564.8 nm was achieved when the FBG with a central wavelength of 1560.5 nm was used as the cavity mirror, as shown in the inset of Fig. 6(a). The tunable wavelength range can be further extended by using strain-induced tunable cascaded FBGs or highly stretchable FBGs [28].

4. CONCLUSION

We experimentally demonstrated a passively Q-switched EDFL based on a few-layer MoS_2 SA. The few-layer MoS_2 was prepared by the CVD method and sandwiched between two FCs with a fiber adapter to form a fiber-compatible

MoS_2-based SA. Stable Q-switched pulses at 1560.5 nm have been successfully obtained with a pulse duration of 1.92 μs and a pulse repetition rate tunable from 28.6 to 114.8 kHz. Passive Q-switched pulses at discrete lasing wavelengths ranging from 1529.8 to 1570.1 nm have been achieved. Our experimental results suggest that few-layer MoS_2 can serve as a promising SA for wideband-tunable pulsed laser applications.

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