# Passively mode-locked erbium-doped fiber laser via a D-shape-fiber-based $MoS_2$ saturable absorber with a very low nonsaturable loss*

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We report on the generation of conventional and dissipative solitons in erbium-doped fiber lasers by the evanescent field interaction between the propagating light and a multilayer molybdenum disulfide ($MoS_2$) thin film. The $MoS_2$ film is fabricated by depositing the $MoS_2$ water–ethanol mixture on a D-shape-fiber (DF) repetitively. The measured nonsaturable loss, saturable optical intensity, and the modulation depth of this device are 13.3%, 110 MW/cm$^2$, and 3.4% respectively. Owing to the very low nonsaturable loss, the laser threshold of conventional soliton is as low as 4.8 mW. The further increase of net cavity dispersion to normal regime, stable dissipation soliton pulse trains with a spectral bandwidth of 11.7 nm and pulse duration of 116 ps are successfully generated. Our experiment demonstrates that the $MoS_2$-DF device can indeed be used as a high performance saturable absorber for further applications in ultrafast photonics.

**Keywords:** fiber laser, nano-sheet materials, saturable absorber, mode locking

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## 1. Introduction

Fiber-based pulse laser has received special attention in the field of scientific research due to the growing needs of industry.[1–5] In the past decades, passively mode locking technique has been proved to be a simple and effective way to achieve the ultrashort pulses.[6,7] For such a technique, saturable absorber (SA) is a crucial device and has experienced rapid development from semiconductors to nano-sheet materials.[8–11] Especially, remarkable researches based on two-dimensional (2D) nanomaterial (including grapheme and topological insulator) have been reported for their advantages of easy fabrication, wide working wavelength, and controllable modulation.[12] Recently, it is found that molybdenum disulfide ($MoS_2$) could also be fabricated as 2D nanosheet, which exhibits stronger saturable absorption and higher relaxation time (30 fs) than graphene at the wavelength of 800 nm.[13] Zhang *et al.* have obtained mode-locked dissipative soliton (DS) at 1 μm by a fiber pigtailed $MoS_2$ SA which possessed a modulation depth of 9.3% and a saturable intensity of 15.9 MW/m$^2$.[14] Moreover, by introducing suitable defects, Wang *et al.* have fabricated broadband few-layer $MoS_2$ SAs at the wavelengths of 1.06, 1.42, and 2.1 μm.[15] On the other hand, in order to improve the performance of the SA, particularly the damage threshold, a new fabricating method known as evanescent-light deposition was introduced.[16–20] Owing to the evanescent wave working mechanism, only part of the transmitting light power interacted with the SA, so the SA device could endure much higher power than the SA fabricated with a quartz plate or on the fiber end facet. Moreover, the interaction length between the light and the SA was controllable as needed. In summary, the evanescent-light deposition is usually based on microfiber or D-shape-fiber (DF). Compared with the microfiber, the DF presents a high flexility. By combining the DF with $MoS_2$ SA, the bound-state and single-pulse-state conventional solitons have been obtained in Ref. [21]; moreover, dissipative soliton mode locking and conventional soliton were both achieved in Ref. [22]. However, in those reports, due to the high nonsaturable losses (∼75% and ∼89%) of the $MoS_2$-DF SA, the laser thresholds of conventional soliton mode locking are very high (43 mW and 56 mW). So lowering the nonsaturable loss of such an SA device is still a challenge to researchers.

In this paper, we are to answer this question. We report on the generations of conventional and dissipative solitons in erbium-doped fiber lasers with different net cavity dispersions by inserting an $MoS_2$-DF SA. The nonsturable loss, saturable optical intensity, and the modulation depth of the $MoS_2$-DF SA are measured to be 13.3%, 110 MW/cm$^2$, and 3.4% respectively. The mode locking of bunch-state conventional soliton can be self-started at a very low pump threshold of 4.8 mW. By reducing pump to 3.2 mW, single pulse operation can be obtained, which features a 3-dB spectral bandwidth of 1.99 nm, a pulse duration of 2.08 ps, a repetition rate of 4.17 MHz, and an average output power of 34.67 μW. By further increasing

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the net cavity dispersion to normal regime, the stable DS pulse trains are successfully generated at a pump power of 150 mW. The spectral bandwidth, pulse duration, repetition rate, and average output power are 11.7 nm, 116 ps, 7.45 MHz, and 6.91 mW respectively. Our experiment demonstrates the high performance of the $MoS_2$-DF SA.

## 2. Fabrication and characterization of the $MoS_2$-DF SA device

To integrate the $MoS_2$ nanosheets onto the DF, we firstly disperse the $MoS_2$ in a water-ethanol mixture. The preparation of the $MoS_2$ solution is similar to that in Ref. [21]. By depositing the $MoS_2$ solution on a quartz plate, we measure the scanning electron microscope (SEM) image of the $MoS_2$ nanosheets as shown in Fig. 1(a).

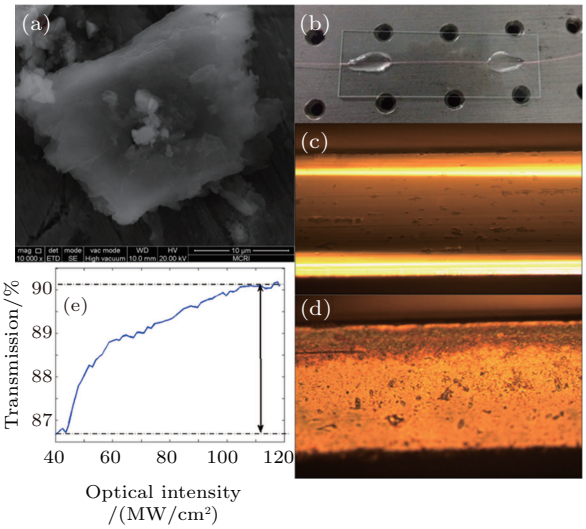



**Fig. 1.** (color online) SEM image of $MoS_2$ (a), the DF injected with visible light (b), the DF under microscope (c), the DF coated with $MoS_2$ under microscope (d), and the measured saturable absorption curve of the $MoS_2$-DF SA (e).

For the DF, the distance between the surface of the D-shape plane and the upper surface of the fiber core is 5 μm, the length of D-shape plane is 10 mm. The DF is fixed on a glass plate. Firstly, we inject a visible light into the DF, and no distinct evanescent wave can be observed as shown in Fig. 1(b). It may be due to the fact that the transmitting loss of the DF is very low (∼3%); the evanescent visible light is too weak to be seen by our naked eyes. Secondly, we observe the DF under a microscope with a magnification of 50-fold objective lens (combined with a 10-fold eyepiece) as shown in Fig. 1(c). Thirdly, we inject a continuous wave (CW) laser into the DF to speed up the deposition process. With the pump power working at 400 mW unchanged, the $MoS_2$ solution is dripped on the glass plate until it covers the DF. It takes about 30 min for the water and ethanol in the $MoS_2$ solution to evaporate completely. To make the $MoS_2$ deposition on DF more uniform and overall, such a deposition process is repeated about 30 times. Then we take off the DF and observed it under the same microscope as shown in Fig. 1(d). The $MoS_2$ deposition on DF is uniform and overall. Then we detect the saturable absorption data of the $MoS_2$-DF SA via a power-dependent transmission technique based on a balanced twin-detector measurement. The pulse laser features an operation wavelength of 1550 nm, a pulse duration of 950 fs, and a repetition rate of 12.8 MHz. The measured nonlinear saturable absorption curve is shown in Fig. 1(e), so the nonsaturable loss, modulation depth, and saturable optical intensity of the $MoS_2$-DF SA are 13.3%, 3.4%, and 110 MW/cm$^2$, respectively. Compared with the results in Refs. [21] and [22], the inserting loss is greatly reduced, and the modulation depth is improved.

## 3. Experiment setup

Having prepared the $MoS_2$-DF SA, we insert the mode-locking device into the fiber laser cavity. The configuration of proposed fiber laser system is schematically shown in Fig. 2. One 976-nm single-mode laser diode (LD) with a maximum power of 650 mW is used to provide pump through a 980/1550-nm wavelength-division-multiplexer (WDM). A segment of EDF acts as a gain medium in the oscillator. The other fibers in the laser system together with the pigtail of the passive components are denoted as SMF. The group velocity dispersions for the EDF and SMF are 17 ps/(nm·km) and −16 ps/(nm·km), respectively. One polarization insensitive isolator (ISO) is used to ensure unidirectional operation in the oscillator. A polarization controller (PC) is used in the oscillator for adjusting the linear cavity birefringence and selecting laser wavelength. A fused optical coupler (OC) with 10% output is used as an output port. The fabricated $MoS_2$-DF device works as an absorber. The output prosperities of the laser oscillator are monitored by a power meter (YOKOGAWA, AQ2180), an optical spectrum

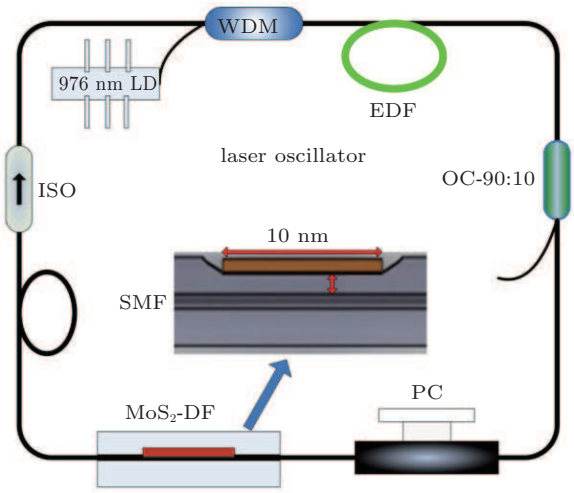



**Fig. 2.** (color online) Schematic diagram of the fiber laser setup.

analyzer (YOKOGAWA, AQ7375), an autocorrelation (Alnair Labs, HAC-200), a 44-GHz radio-frequency analyzer (Agilent, PSA), and a 200-M digital oscilloscope (RIGOL, DS1024B) together with a home-made 2.5-GHz photodiode detector. In addition, a 25-GHz digital storage oscilloscope (LeCroy, SDA-825Zi-A) together with a 70-GHz photodiode detector ($U^2T$, XPDV3120R) is specially used to detect the pulse duration of DS, which is expressly illustrated when used.

## 4. Experimental results and discussion

Firstly, we set the intra-cavity dispersion at the anomalous regime to confirm the potential of the $MoS_2$-DF SA for conventional soliton pulse shaping. The lengthens of EDF and total SMF are 6 nm and 49 m respectively, the net dispersion is estimated at $-0.82$ ps$^2$. Self-starting mode-locking of multiple pulses is successfully obtained with appropriate PC orientation and a pump power of 4.8 mW. As shown in Fig. 3(a), the output spectrum is centered at 1566.14 nm with a 3-dB spectral bandwidth of 1.99 nm. The spectrum displays Gaussian profile and Kelly sidebands, which are typical characteristics of conventional solitons. On the spectrum, the middle peak with the coordinate of (1565.39, $-15.18$) is a composition of continuous waves (CWs). As is well known, it is common and sometimes necessary in conventional soliton mode locking state. Owing to the nonzero third order dispersion, the sidebands with the coordinates of (1561.71, $-30.88$) and (1571.07, $-32.17$) are not precisely symmetrical,[23] but their difference is not large. The autocorrelation trace is given in Fig. 3(b), the blue curve represents the experimental result, and the red one refers to the sech$^2$-fit result. The full width at half maximum (FWHM) of the autocorrelation trace is determined to be ~3.2 ps. Under the assumption of sech$^2$ temporal profile, the pulse width is estimated to be ~2.08 ps. The time bandwidth product is calculated to be ~0.51, indicating that the output pulse is a little chirped. In this state, there are nine pulses in the fiber cavity as shown in the upward image of Fig. 3(c). As the pump power decreases to 3.4 mW, the pulse number drops to two as shown in the middle image of Fig. 3(c). With further reducing the pump power to 3.2 mW, the pulse number drops to one as shown in the lower image of the Fig. 3(c). The corresponding radio frequency (RF) spectrum is shown in Fig. 3(d) with a resolution of 1 Hz and a span of 1 kHz. The fundamental repletion rate is ~4.17 MHz, matching with a cavity length of ~49 m. It means that the laser works at fundamental repetition rate. The signal-to-noise ratio (SNR) is higher than 60 dB, indicating a good mode locking stability. The corresponding output power is 34.67 μW. In the condition of laboratory, the mode locking state of conventional soliton can be maintained for more than 24 h.

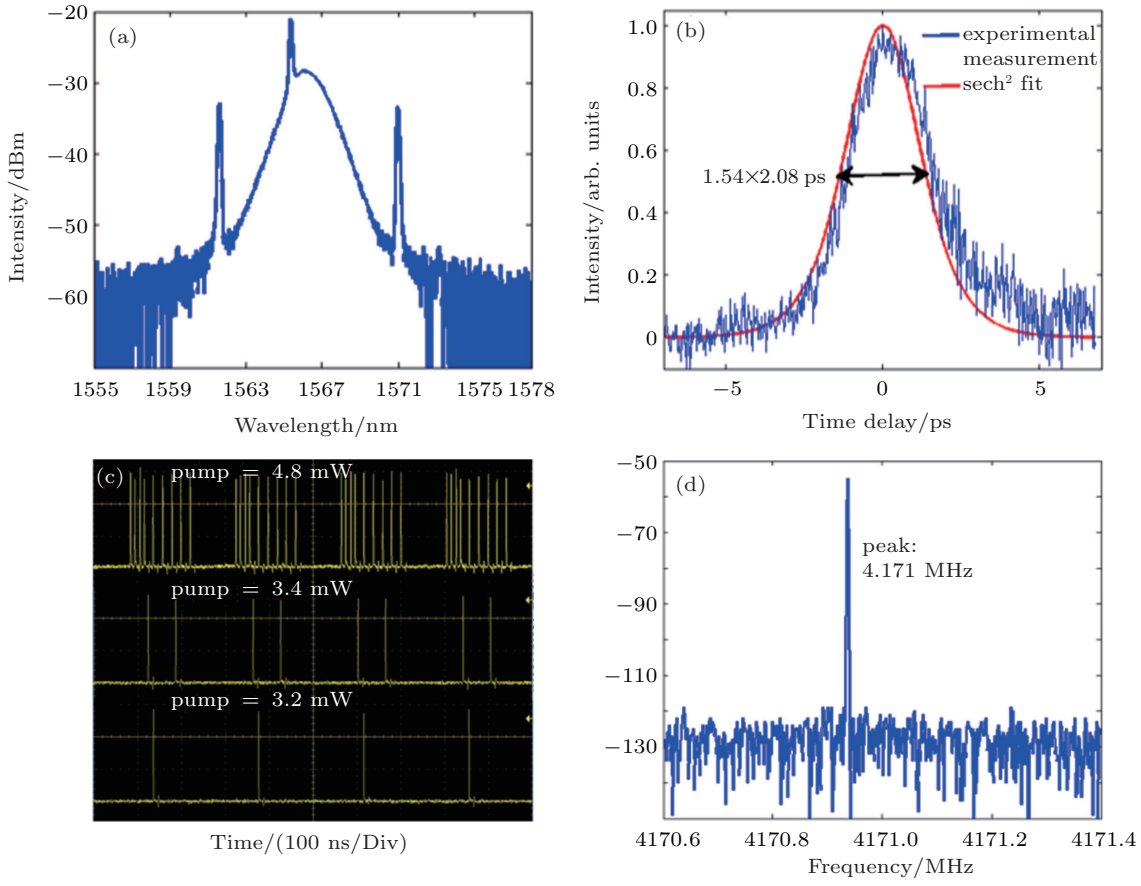



**Fig. 3.** (color online) Experimental results: (a) optical spectrum, (b) oscilloscope trace, (c) autocorrelation trace.

A notable feature of this laser is that it has the ultra-low operating pump, and single pulse mode-locking can be obtained under 3.2 mW, which is much lower than those in Refs. [21] and [22]. It is due to the very low nonsaturable loss of the $MoS_2$-DF SA device.

Furthermore, we change the intra-cavity dispersion to the normal regime to test the potential of $MoS_2$-DF SA for DS pulse shaping. The lengthens of EDF and total SMF are 17 m and 10.5 m respectively, the dispersion is estimated at 0.12 $ps^2$. Self-starting mode-locked DS is successfully generated when the pump power reaches 150 mW, and the output characteristics of the fiber laser are summarized in Fig. 4. The spectrum in Fig. 4(a) shows typical sharp edges, which verifies the operation of DS. On the basis of flat-top shape, there are two CW components on the spectrum, which may be due to the excess power in the oscillator. The 3-dB bandwidth of the spectrum is estimated to be ~11.7 nm. The pulse duration is detected by a 25-GHz digital storage oscilloscope (LeCroy, SDA-825Zi-A) together with a 70-GHz photodiode detector ($U^2T$, XPDV3120R). The resolution of the detecting system is higher than 40 ps, and the obtained pulse duration is 116 ps as shown in Fig. 4(b), which is much larger than the resolution, so the detected pulse duration is believable. The pulse train on oscilloscope manifests uniform intensity and temporal interval as shown in Fig. 4(c), displaying a stable mode-locking state. The time-band product of the DS is 161, so large a chirp exists in the pulses. The corresponding RF spectrum is shown in Fig. 4(d) with a resolution of 1 Hz and a span of 100 Hz. The SNR is about 50 dB, which is a little low due to the two CW components in spectrum. The fundamental peak is located at ~7.45 MHz, matching with the cavity length of ~27.5 m. The inset in Fig. 4(d) shows the wideband RF spectrum up to 1 GHz, which displays flat top. The corresponding output power is ~6.91 mW. In our experiment, the mode locking state of DS can be kept for more than 6 h.

As the pump power is increased, the mode locking of DS is destroyed and noise-like mode locking state appears. However, the noise-like mode locking state can be maintained even if the pump power is increased to a maximum available value of 650 mW. Moreover, with further reducing the pump power to a suitable level, mode locking of DS can be obtained again. It demonstrates that the $MoS_2$-DF SA possesses an ultra-high optical damage threshold.

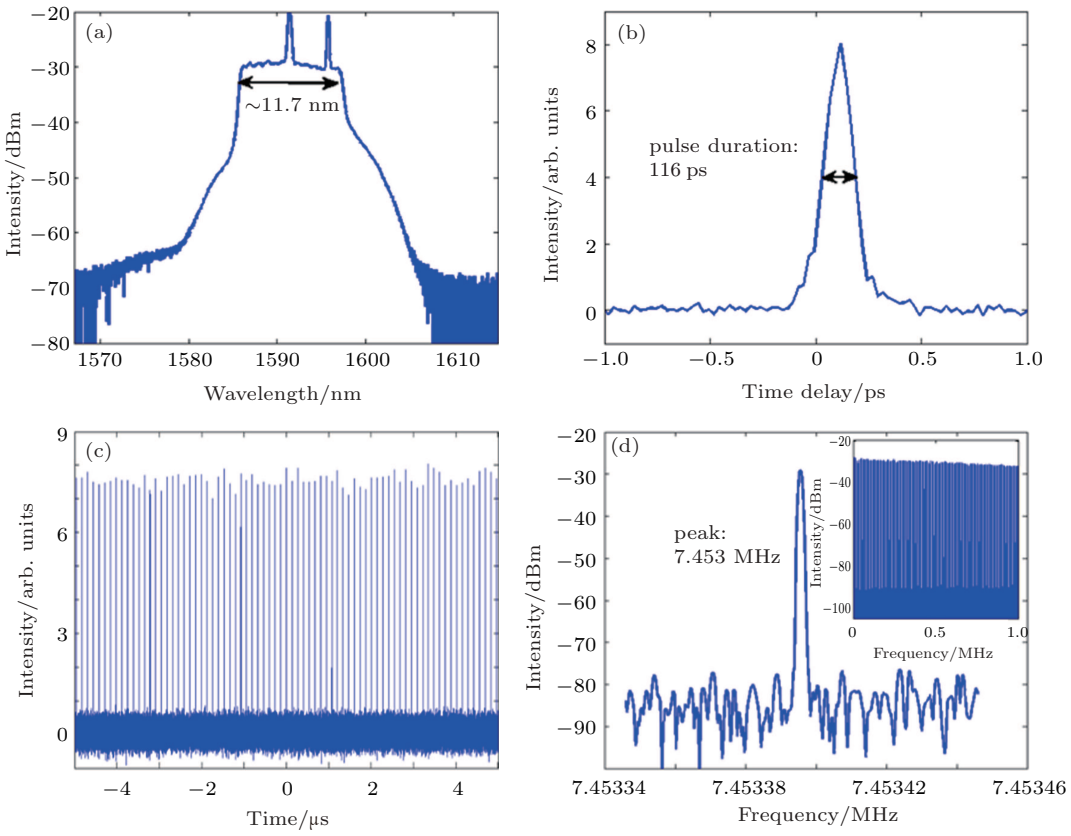



**Fig. 4.** (color online) Optical spectrum (a), pulse shape (b), oscilloscope trace (c), and RF spectrum (d) of the mode-locked DS.

## 5. Conclusions

In this work, we obtain both conventional soliton and DS in the EDF laser by inserting a $MoS_2$-DF SA. Taking advantage of the low nonsaturable loss and high saturable absorption effect of the SA device, the laser threshold for mode locking is much lowered. Moreover, the optical damage is not observed even under a largest pump power of 650 mW, which proves

the high performance of the SA device in our fiber laser.

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