Laser Physics Letters

LETTER

Mode-locked thulium fiber laser with MoS_2

To cite this article: Zhen Tian *et al* 2015 *Laser Phys. Lett.* **12** 065104

IOP Publishing | Astro Ltd Laser Physics Letters

Laser Phys. Lett. **12** (2015) 065104 (5pp) doi:10.1088/1612-2011/12/6/065104

Mode-locked thulium fiber laser with MoS_2

Zhen Tian[1,2], **Kan Wu**[3], **Lingchen Kong**[1], **Nan Yang**[1], **Yao Wang**[1],
Rong Chen[1], **Weisheng Hu**[2], **Jianqiu Xu**[1,4] **and Yulong Tang**[1,4]

[1] Department of Physics and Astronomy, Key Laboratory for Laser Plasmas (Ministry of Education), Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[2] School of Physics Science and Information Engineering, Shandong Key Laboratory of Optical Communication Science and Technology, Liaocheng University, Liaocheng 252000, People's Republic of China
[3] Department of Electronic Engineering, State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[4] IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China

E-mail: yulong@sjtu.edu.cn and jqxu09@sjtu.edu.cn

Received 19 March 2015, revised 15 April 2015
Accepted for publication 17 April 2015
Published 30 April 2015

Abstract

Liquid-phase exfoliated 2D material multilayer MoS_2 is transferred onto a gold mirror and its saturable absorption at the 2 μm wavelength region is experimentally observed. This transferred MoS_2 saturable absorber has a modulation depth of 13.6% and a saturation intensity of 23.1 MW cm^{-2}. This saturable absorber is integrated into a linear Tm^{3+} fiber laser cavity, and stable fundamental-frequency mode-locking operation is realized at 2 μm with pulse energy of 15.5 nJ, pulse width of ~843 ps, and a repetition rate of 9.67 MHz. The laser spectral width is ~17.3 nm with a center wavelength of 1905 nm. This first presence of mode-locking with multilayer MoS_2 sheets in the 2 μm wavelength region verifies that multilayer MoS_2 is a good candidate for broadband mode-locking comparable to graphene, as well as a good mode-locker for achieving high pulse energy.

Keywords: thulium-doped fiber laser, mode-locking, multilayer MoS_2, dissipative soliton

(Some figures may appear in colour only in the online journal)

1. Introduction

Tm^{3+}-doped fiber lasers (TDFLs) at 2 μm have received wide research interests in recent years due to their valuable applications in sensing, medical surgery, industrial machining and scientific experiments [1, 2]. To meet these application requirements, high-peak-power and/or high-energy 2 μm laser pulses are needed, which are generally produced by using Q-switching [3, 4] or mode-locking [5, 6] methods. Compared with Q-switching, mode-locking can provide much narrower pulse duration and higher peak power, as well as higher stability in the time domain.

Passive mode-locking, due to its simple configuration, has been a much preferred choice to obtain short pulses from 2 μm TDFLs, especially with the maturely developed semiconductor saturable absorbers (SAs) as modulators [7]. However, semiconductor SA has some drawbacks such as a complex design for improving damage threshold [8], a narrow working wavelength range, etc. Recently, graphene (a monolayer of two-dimensional (2D) carbon atoms in a honeycomb structure) has attracted great attention and has been extensively used for mode-locking of TDFLs [9, 10] due to its advantages of large absorption per layer [11], wide operation spectral range [12], and moderate damage threshold and ultrafast recovery time [13]. Another kind of 2D material MoS_2 has also attracted wide attention in the fiber laser community, and has been extensively explored to mode lock fiber lasers [14–18]. Owing to the semiconductor characteristics of layered MoS_2, especially the monolayer MoS_2 a direct band semiconductor, the band gap determines the energy of photons to be absorbed. However, studies have proven that layered MoS_2, in particular when stoichiometric defects (non-ideal atomic ratio) are introduced, also possesses wideband absorption and saturable absorption features [19], which are prerequisites for mode-locking of lasers. Thereafter, extensive researches have been dedicated to exploring of mode-locking operation and related characteristics of fiber lasers in the 1 μm [14, 15] and 1.5 μm [16–18] wavelength regions. However, mode-locking with MoS_2 in the 2 μm regime has not been reported to date. Owing to large anomalous dispersion of the gain fiber and lower absorption of layered MoS_2 at 2 μm, mode-locking operation with this kind of 2D material and corresponding behaviors in the near mid-infrared spectral region still need further verification and investigation.

In this letter, we report 2 μm Tm^{3+} fiber lasers mode-locked with multilayer MoS_2 with 15.5 nJ pulse energy. Simple linear cavity incorporated with gain fiber and the multilayer MoS_2 modulator is constructed to achieve mode-locking operation, showing that mode-locking capability of layered MoS_2 sheets can be definitely extended to the 2 μm wavelength region. With normal net cavity dispersion, fundamental mode-locking in the dissipative soliton regime is achieved with maximum output power of >150 mW, pulse width of 843 ps and pulse repetition rate of 9.67 MHz. This is the first time mode-locking in the 2 μm wavelength region with 2D MoS_2 materials has been realized.

2. Material characterization and experimental setup

The multilayer MoS_2 was synthesized with the liquid-phase exfoliation method (LPE). The MoS_2 powder was dispersed in ethanol solvent and sonicated for 1 h to produce few-layer MoS_2 nano-sheets. The dispersions were then put for 5 h so that the unexfoliated large-size flakes can sink to the bottom and be separated. The top 2/3 dispersions were collected for experimental use and separately transferred onto one side of a gold mirror by drop coating and air drying. After transfer, the MoS_2 on the mirror was detected by Raman spectroscopy (Renishaw Invia, 488 nm) and saturable absorption test. A representative Raman spectrum of the transferred sample is shown in figure 1(a). E^1_{2g} and A_{1g} modes are nearly coincident with those of bulk MoS_2 (~383 cm^{-1} for E^1_{2g} and ~408 cm^{-1} for A_{1g}), showing that the MoS_2 sample has a thickness of ~4 layers [20]. The transmittance of the multilayer MoS_2 on the gold mirror is shown in figure 1(b). Here, we used a reflection method to measure the saturable absorption of the sample, i.e. the incident probe laser beam was incident on the sample, transited the MoS_2 sheets, reflected by the gold mirror, then transited the MoS_2 sheets once more, and finally the retro-reflected laser beam was measured. A self-constructed ps (~800 ps) fiber laser at 1940 nm with a repetition rate of ~55 MHz was used as the input pulse source. The power-dependent absorption measurement was carried out through changing the input laser power. To obtain the nonlinear optical parameters, a simple saturable absorption model of $T(I) = 1 - \alpha_0 \times \exp(-I/I_{sat}) - \alpha_{ns}$ [14] was used to fit the measured data. $T(I)$ is the transmission, α_0 is the modulation depth, I is the input intensity, I_{sat} is the saturation intensity, and α_{ns} is the non-saturable absorbance. As shown in figure 1(b), the modulation depth α_0, non-saturable loss α_{ns} and saturation intensity I_{sat} were obtained to be 13.6%, 16.7% and 23.1 MW cm^{-2}, respectively. The modulation depth achieved here (at the 2 μm wavelength region) is comparable to that measured in the 1 μm [14, 15] region and much larger than that in the 1.5 μm [17, 18] wavelength region. This large modulation depth of the MoS_2 saturable absorber at the 2 μm wavelength region can be made advantage of to suppress wave breaking in mode-locking operation [16, 21], and thus indicates that this sample can be used as an effective saturable absorber in the 2 μm wavelength range to realize large pulse energy.

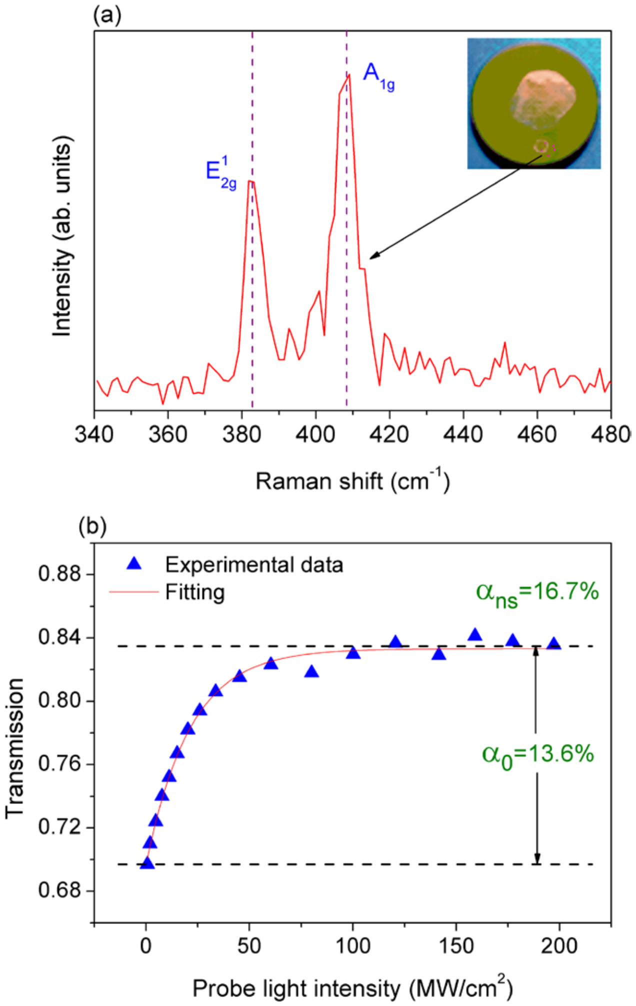

Figure 1. Raman spectrum of the adopted multilayer MoS_2 sheets and (b) nonlinear absorption of the multilayer MoS_2 sheets coated on a gold mirror.

The experimental setup for the MoS_2 mode-locked TDFL is shown in figure 2. The gain fiber was 12 cm highly doped single-cladding Tm^{3+}-doped silica fiber (5/125 μm, 0.24 NA) with core absorption of ~350 dB m^{-1} at ~1550 nm. The pump source was a CW erbium/ytterbium-codoped fiber laser (EYFL) with maximum output of 1 W centered at 1550 nm. The pump light was delivered into the gain fiber by a 1550/2000 nm wavelength division multiplexing coupler (WDM), which is made by SMF-28 fiber. After the gain fiber, a piece of 4.6 m dispersion compensating fiber (DCF) (2.2 μm, 0.35 NA core) was used to provide total net normal cavity dispersion for achieving dissipative soliton mode-locking. At the output end, a piece of 4 m SMF-28 fiber was spliced to decrease the fundamental mode-locking frequency.

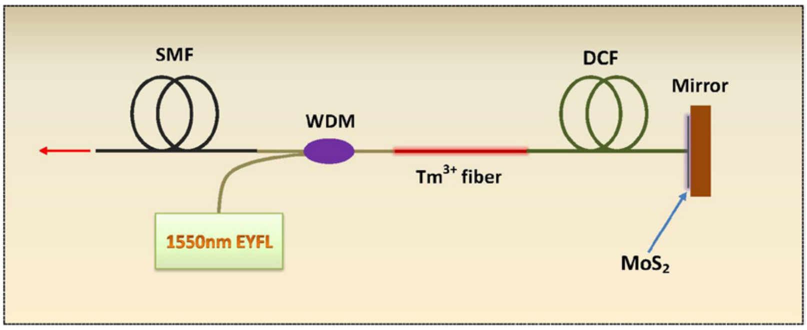

Figure 2. Experimental setup of the mode-locked Tm^{3+} fiber laser. LD: laser diode; SMF: single-mode fiber; DCF: dispersion compensating fiber; EYFL: erbium/ytterbium-codoped fiber laser; WDM: wavelength division multiplexing coupler.

The dispersions of the DCF fiber, the SMF-28 fiber (including 1.62 m pigtail SMF-28 fiber) and the Tm^{3+} fiber at 1.9 μm are 93, −67 and −12 $ps^2 km^{-1}$, respectively [22], which give a total net normal cavity dispersion of ~0.05 ps^2. At the rear end, a high-reflection gold mirror (coated with the MoS_2 sheets) provided feedback, and this mirror combined with the perpendicularly cleaved output-end fiber facet (~3.5% Fresnel reflection) completed the laser cavity. The gold mirror, on which the MoS_2 was adsorbed, was fixed on a five-dimension stage (3D translation and 2D rotation) for fine position adjustment and the fiber end was perpendicularly butt coupled to the MoS_2 sheets.

Laser output power was measured with a power meter (FieldMate, Coherent Co.) and the laser spectrum was tested with a mid-infrared analyzer (SIR 5000, SandHouse Co.) with a spectral resolution of 0.22 nm. Laser pulsing dynamics were recorded with a 2.5 GHz Agilent oscilloscope (DSO9254A) combined with a 3.5 GHz InGaAs detector. The radio-frequency spectrum was measured with a 26.5 GHz microwave spectrum analyzer (N9938A, FieldFox).

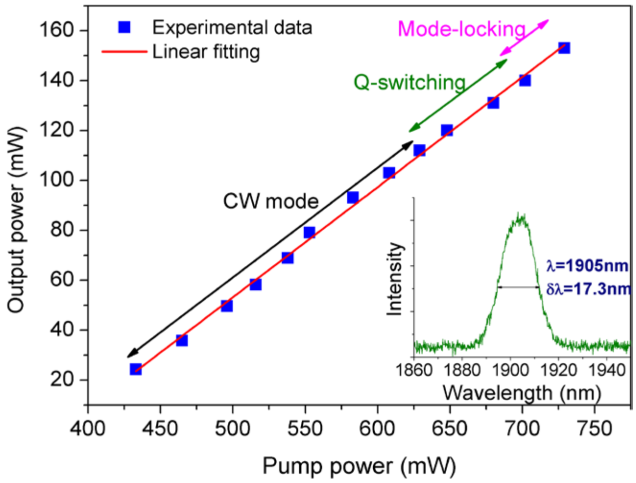

Figure 3. Output of the mode-locked Tm^{3+} fiber laser. The laser threshold is around 430 mW, and the slope efficiency is about 43.6%. Square dots are measured data and the solid line is linear fitting. Inset shows the laser spectrum of the mode-locked Tm^{3+} fiber laser (in linear scale).

3. Results and discussions

When the 2 micron laser operation was initiated with pump power over threshold (~430 mW), the laser first went to continuous wave (CW) operation. When the pump power was increased to over 630 mW and the MoS_2 sheet position was carefully adjusted, the laser came to the stable Q-switching regime. Then, further raising the pump power to over 700 mW, stable mode-locking operation of the TDFL occurred, which could be sustained up to the available maximum pump power (730 mW). The output power shows a linear increase with pump power, and the maximum output power is 150 mW, as shown in figure 3. The slope efficiency is 43.6% with respect to pump power. The laser spectrum of the mode-locked TDFL at the maximum output level is present in the inset of figure 3. The spectrum is centered at ~1905 nm with an FWHM (full width at half maximum) bandwidth of about 17.3 nm. This spectral width is much larger than that of the 1 and 1.5 µm counterparts [14–17], showing that much narrower mode-locked pulse duration can be feasible if dispersion is appropriately compensated.

The laser pulse trains obtained at the maximum output levels are shown in figure 4(a). The 103.4 ns period time corresponds well to the cavity round trip time (the total fiber length is ~10 m), showing that the mode-locking operates at the fundamental frequency of 9.67 MHz. The intensity stability between different pulses is >95%. Considering the output power of 150 mW, the output laser pulse has single pulse energy of 15.5 nJ. This is the highest pulse energy ever achieved in mode-locked fiber lasers with MoS_2 modulators, and this also demonstrates that 2D material MoS_2 has great potential in high power photoelectronics and integrated photonics.

Single pulse characteristics measured at the maximum power level is shown in figure 4(b). The single pulse shows a nearly Gaussian shape with FWHM pulse width of about 843 ps. This pulse width is comparable to that obtained from the 1 μm dissipative-soliton counterparts [14, 15]. This pulse duration, combined with the above mentioned spectral width, gives a time-bandwidth product of ~1200, which is by far larger than the Fourier transform limited one of 0.441 if a Gaussian pulse shape is assumed. This means that the mode-locked laser pulse is highly chirped, which also accounts for the experimentally observed high pulse energy. This large mode-locked pulse duration originates from the unique characteristics of dissipative solitons, chirping pulse to achieve high pulse energy. In fact, 2D MoS_2 (monolayer or few-layer) has ultrafast recovery times of tens of femtoseconds [23] and

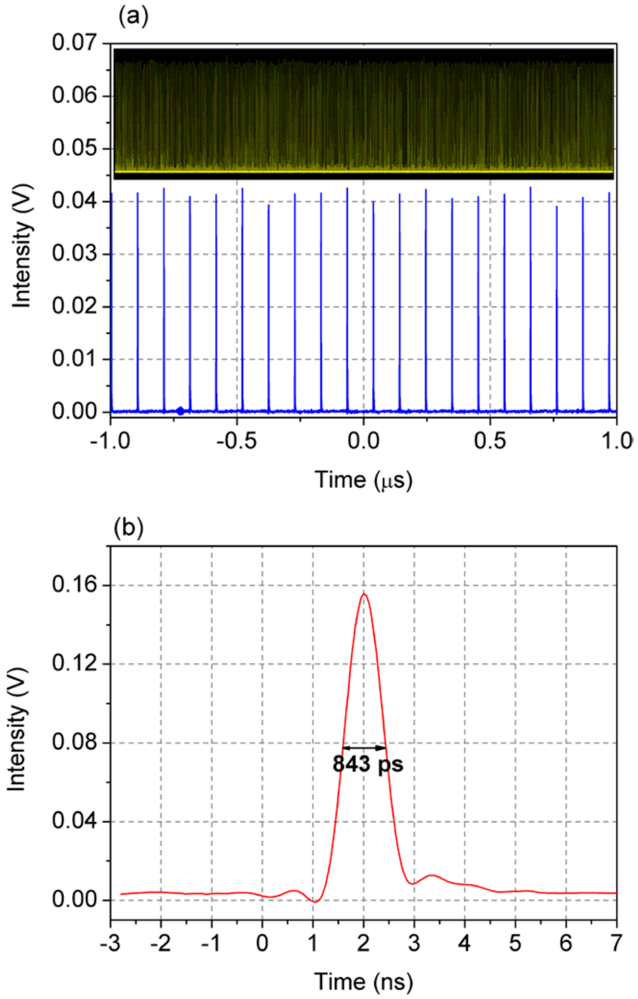

Figure 4. Laser pulse train (a) and single pulse (b) of the MoS_2 mode-locked Tm^{3+} fiber laser. Insets show the oscilloscope traces.

~100 ps [24, 25], corresponding respectively to the intraband transition and interband transition of excited free carriers. Recently, mode-locking with similar multilayer MoS_2 saturable absorbers has achieved femtosecond time-scale pulse durations [18, 26, 27]. Based on the pulse spectral width (17.3 nm) in our experiment, a Fourier transform-limited pulse width of ~247 fs is expected provided that the entire pulse chirp can be compensated. To out-cavity compensate the high pulse chirp of our solitons (843 ps), coarse calculation shows that around 1.1 km single-mode fiber (SMF-28 with dispersion of $-67\ \mathrm{ps}^2\ \mathrm{km}^{-1}$) is needed.

In order to show the stability of the mode-locking state, the radio-frequency spectrum was measured with a bandwidth resolution of 0.1 MHz and the results are shown in figure 5. Over the 100 MHz range, only the fundamental frequency of 9.67 MHz is present, and the signal-to-noise ratio is >55 dB, showing high stability of the mode-locking operation with the as manufactured MoS_2 multilayer sheets.

4. Summary

In conclusion, stable mode-locked 2 μm TDFL with multilayer MoS_2 sheets has been realized with 150 mW output power in a compact linear cavity. Fundamental-frequency mode-locking operation provides >15 nJ pulse energy and ~10 MHz repetition rate. This highly chirped dissipative soliton pulse has a temporal width of 843 ps, which can be dechirped outside the cavity. This first stable mode-locking operation with multilayer MoS_2 in the 2 μm region clearly indicates that few-layer transition metal dichalcogenides can also function as wide-band optoelectronic elements, comparable to graphene. The achieved >15 nJ pulse energy, in addition, shows that this 2D material can be high power photonic devices, even in the 2 μm wavelength region.

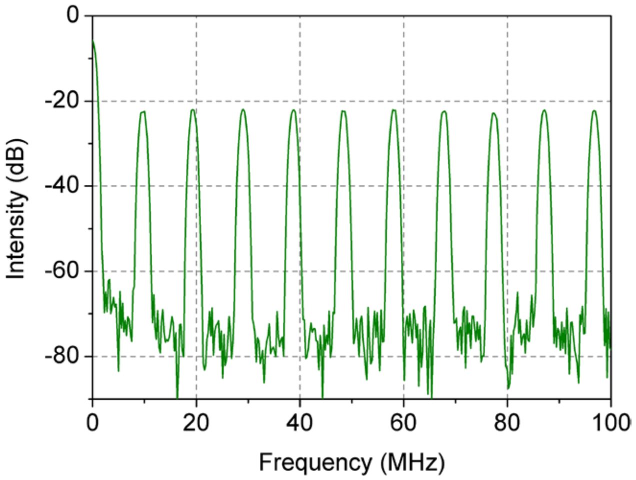

Figure 5. Radiofrequency spectral profile of the mode-locked Tm^{3+} fiber laser.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 61275136, 61138006, 11121504), the State Key Program for Basic Research of China (Grant No. 2010CB630703), and the Research Fund for the Doctoral Program of Higher Education of China (No. 20120073120085).

References

[1] Zhang Y, Tian Y, Wang W and Yao B 2010 Tunable narrow linewidth Tm^{3+}-doped silica fiber laser with an intracavity taper *Laser Phys. Lett.* **7** 225
[2] Wang F, Shen D Y, Fan D Y and Lu Q S 2010 High power widely tunable Tm^{3+}: fiber laser with spectral linewidth of 10 pm *Laser Phys. Lett.* **7** 450
[3] Tang Y, Yu X, Li X, Yan Z and Wang Q J 2014 High-power thulium fiber laser Q switched with single-layer graphene *Opt. Lett.* **39** 614
[4] Eichhorn M and Jackson S D 2007 High-pulse-energy actively Q-switched Tm^{3+}-doped silica 2 μm fiber laser pumped at 792 nm *Opt. Lett.* **32** 2780
[5] Nelson L E, Ippen E P and Haus H A 1995 Broadly tunable sub-500 fs pulses from an additive-pulse mode-locked thulium-doped fiber ring laser *Appl. Phys. Lett.* **67** 19
[6] Sharp R C, Spock D E, Pan N and Elliot J 1996 190 fs passively mode-locked thulium fiber lase with a low threshold *Opt. Lett.* **21** 881
[7] Wang Q, Geng J, Jiang Zh, Luo T and Jiang Sh 2011 Mode-locked Tm-Ho-codoped fiber laser at 2.06 μm *IEEE Photon. Technol. Lett.* **23** 682

[8] Saraceno C J, Schriber C, Mangold M, Hoffmann M, Heckl O H, Baer C R E, Golling M, Südmeyer T and Keller U 2012 SESAMs for high-power oscillators: design guidelines and damage thresholds *IEEE J. Sel. Top. Quantum Electron.* **18** 29

[9] Sobon G, Sotor J, Pasternak I, Krajewska A, Strupinski W and Abramski K M 2013 Thulium-doped all-fiber laser mode-locked by CVD-graphene/PMMA saturable absorber *Opt. Express* **21** 12797

[10] Wang Q, Chen T, Zhang B, Li M, Lu Y and Chen K P 2013 All-fiber passively mode-locked thulium-doped fiber ring laser using optically deposited graphene saturable absorbers *Appl. Phys. Lett.* **102** 131117

[11] Nair R R, Blake P, Grigorenko A N, Novoselov K S, Booth T J, Stauber T, Peres N M R and Geim A K 2008 Fine structure constant defines visual transparency of graphene *Science* **320** 1308

[12] Zhang Y Z, Liu T, Li X H, Liang G, Meng B, Hu X and Wang Q J 2013 Broadband high photoresponse from pure monolayer graphene-based photodetector *Nat. Commun.* **4** 1811

[13] Bao Q, Zhang H, Wang Y, Ni Z, Yan Y, Shen Z X, Loh K P and Tang D Y 2009 Atomic-layer graphene as a saturable absorber for ultrafast pulsed lasers *Adv. Funct. Mater.* **19** 3077

[14] Du J, Wang Q, Jiang G, Xu C, Zhao C, Xiang Y, Chen Y, Wen S and Zhang H 2014 Ytterbium-doped fiber laser passively mode locked by few-layer molybdenum disulfide (MoS_2) saturable absorber functioned with evanescent field interaction *Sci. Rep.* **4** 6346

[15] Zhang H, Lu S B, Zheng J, Du J, Wen S C, Tang D Y and Loh K P 2014 Molybdenum disulfide (MoS_2) as a broadband saturable absorber for ultra-fast photonics *Opt. Express* **22** 7249

[16] Xia H, Li H, Lan C, Li C, Zhang X, Zhang S and Liu Y 2014 Ultrafast erbium-doped fiber laser mode-locked by a CVD-grown molybdenum disulfide (MoS_2) saturable absorber *Opt. Express* **22** 17341

[17] Liu H, Luo A, Wang F, Tang R, Liu M, Luo Z, Xu W, Zhao C and Zhang H 2014 Femtosecond pulse erbium-doped fiber laser by a few-layer MoS_2 saturable absorber *Opt. Lett.* **39** 4591

[18] Khazaeizhad R, Kassani S H, Jeong H, Yeom D and Oh K 2014 Mode-locking of Er-doped fiber laser using a multilayer MoS_2 thin film as a saturable absorber in both anomalous and normal dispersion regimes *Opt. Express* **22** 23732

[19] Wang S, Yu H, Zhang H, Wang A, Zhao M, Chen Y, Mei L and Wang J 2014 Broadband few-layer MoS_2 saturable absorbers *Adv. Mater.* **26** 3538

[20] Li H, Zhang Q, Yap C C R, Tay B K, Edwin T H T, Olivier A and Baillargeat D 2012 From bulk to monolayer MoS_2: evolution of Raman scattering *Adv. Funct. Mater.* **22** 1385

[21] Cabasse A, Martel G and Oudar J L 2009 High power dissipative soliton in an erbium-doped fiber laser modelocked with a high modulation depth saturable absorber mirror *Opt. Express* **17** 9537

[22] Wang Q, Chen T, Li M, Zhang B, Lu Y and Chen K P 2013 All-fiber ultrafast thulium-doped fiber ring laser with dissipative soliton and noise-like output in normal dispersion by single-wall carbon nanotubes *Appl. Phys. Lett.* **103** 011103

[23] Wang K *et al* 2013 Ultrafast saturable absorption of 2D MoS_2 nanosheets *ACS Nano* **7** 9260

[24] Korn T, Heydrich S, Hirmer M, Schmutzler J and Schuller C 2011 Low-temperature hotocarrier dynamics in monolayer MoS_2 *Appl. Phys. Lett.* **99** 102109

[25] Wang R, Ruzicka B A, Kumar N, Bellus M Z, Chiu H Y and Zhao H 2012 Ultrafast and spatially resolved studies of charge carriers in atomically thin molybdenum disulfide *Phys. Rev.* B **86** 045406

[26] Liu H, Luo A P, Wang F Z, Tang R, Liu M, Luo Z C, Xu W C, Zhao C J and Zhang H 2014 Femtosecond pulse erbium-doped fiber laser by a few-layer MoS_2 saturable absorber *Opt. Lett.* **39** 4591

[27] Wu K, Zhang X, Wang J and Chen J 2015 463 MHz fundamental mode-locked fiber laser based on few-layer MoS_2 saturable absorber *Opt. Lett.* **40** 1374