Research article

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164 fs mode-locked erbium-doped fiber laser based on tungsten ditelluride

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Abstract: In recent years, the diversity of transition metal dichalcogenides (TMDs) has made them occupy the essential status in the exploration of saturable absorbing materials. WTe_2, also an important member of TMDs not only exhibits narrower band gap than MoS_2 or WS_2, but also has fast relaxation time, thus it has advantages in the realization of broadband absorption and ultrashort pulses. In this work, a WTe_2 saturable absorber (SA) fabricated by magnetron sputtering technology features nonlinear absorption coefficient of -3.78×10^{-5} cm/W and modulation depth of 37.95%. After integrating this WTe_2 SA into the ring cavity, a 164 fs mode-locked laser is achieved at 1557.71 nm. The laser remains stable about 8 h with an output power of 36.7 mW. The results show the favorable saturable absorption properties of WTe_2, and further demonstrate the potential of WTe_2 in the realization of ultrashort pulses, which indicates that WTe_2 can be regarded as a possible candidate for future ultrafast lasers.

Keywords: two-dimensional nanomaterials; saturable absorbers; mode-locked laser; fiber lasers.

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1 Introduction

Ultrafast fiber lasers have attracted considerable attention in medical treatment, material processing, femtosecond time spectroscopy, nano-scale imaging and communication due to high pulse energy, low thermal effect and outstanding spatial/temporal resolution [1]. In particular, passive mode-locking method, which employs SAs as key mode-lockers has been recognized as an economical and efficient method to implement femtosecond pulses [2–4]. Therefore, the explorations of some SAs with excellent performance may become the point of penetration in the development and innovation of ultrafast lasers.

So far, in addition to semiconductor saturable absorber mirror (SESAM) which has been commercialized, two-dimensional (2D) nanomaterials have become candidates for the next generation of SAs, because of their unique electronic and optical properties [5–8]. With the deepening of research, the types of SA materials continue to expand, such as graphene, topological insulators, black phosphorus, TMDs, etc. [9–32]. As the representative materials of TMDs, molybdenum disulfide (MoS_2), and tungsten disulfide (WS_2) have made impressive achievements in laser as SAs. It has been reported that the third-order nonlinear susceptibility of MoS_2 is higher than that of graphene at 800 nm [33]. Moreover, both mode-locked or Q-switched lasers based on MoS_2 and WS_2 have been realized in the wide band of 1–2 μm. Undoubtedly, the diversity of TMDs makes them occupy the essential status in the exploration of SA materials.

Tungsten ditelluride (WTe_2), is also an important member of TMDs, inherits the thickness-dependent band gap structure of TMDs. The band gap of bulk and monolayer WTe_2 are 0.7 and 1.18 eV, which is lower than that of commonly used MoS_2 or WS_2. This small band gap predicts high electron mobility and facilitates the application of broadband absorption [34]. In addition, the fast relaxation process of WTe_2 occurs within 1 ps as demonstrated in Ref. [35]. SAs with fast response timesare less affected by amplified spontaneous emission [36]. Moreover, the fast relaxation time of WTe_2 makes it suitable for the generation of ultrashort pulses. Although Q-switched laser based on WTe_2 has been realized in the previous work [13], the advantages of femtosecond mode-locked laser in small thermal effect, high temporal and spatial resolution inspire us to further explore the application potential of WTe_2 in mode-locked lasers.

In this work, an erbium-doped fiber laser (EDFL) based on WTe_2 is demonstrated. The WTe_2 is fabricated by the magnetron-sputtering technology (MST). WTe_2 SA adopts the structure of microfibre, which strengthens the interaction between light and materials, and avoids the direct photoablation damage of materials. The prepared WTe_2 SA shows nonlinear absorption coefficient of -3.78×10^{-5} cm/W and modulation depth of 37.95%. After the WTe_2 SA is integrated into the ring cavity, a sub-170 fs mode-locked laser is achieved at 1557.71 nm. High signal-to-noise ratio (SNR) and small standard deviation of output power indicate the stability of EDFL. Our research highlights the potential of WTe_2 in the realization of ultrafast pulses and paves the way for its further application in the field of ultrafast photonics.

2 Preparation and characterization of WTe_2 SA

In the preparation process, WTe_2 is coated on microfiber to form WTe_2 SA. The microfiber used is uniformly stretched from single-mode fiber (SMF 28e), its waist diameter and effective interaction length are 15 μm and 1 cm. Considering the difficulty of adhesion in the fragile microfiber, MST is suitable for the preparation, which not only has a high film formation rate, but also prepares films with great uniformity and large scale. The detailed preparation process is as follows. First, the microfiber and WTe_2 target with the purity of 99.99% are fixed in a vacuum chamber, the vacuum degree of that chamber is 9×10^{-4} Pa. Then, argon ion ionized at high pressure bombards the target surface. Because of the high energy of sputtered target atoms, the diffusion ability of atoms during deposition is strong, which leads to the compactness of the deposited structure and the strong adhesion between the film and the substrate. Meanwhile, the microfiber rotates at a constant speed of 20 r/min to guarantee the uniformity of coating.

The nanoscale observation of surface morphology of prepared WTe_2 is realized by scanning electron microscope (SEM). As shown in Figure 1A and B, WTe_2 particles are compact and uniformly arranged. The thickness of WTe_2 film is 100 nm as shown in Figure 1C. Furthermore, the linear transmission of the WTe_2 is shown in Figure 1D, the transmittance near 1550 nm is about 61.6%. We found that WTe_2 shows absorption in a wide wavelength range from 1100 to 1800 nm. Therefore, the corresponding relationship between band gap and summation of phonon energy can be given by the Tauc plot [37, 38]. From Figure 1E, the band gap of the prepared WTe_2 is about 0.2 eV, it is probably due to the phase type of the WTe_2. According to Ref. [34], bulk WTe_2 in the Td (or 1T) structure has a 0.21 eV band by using the density functional theory (DFT). From the Raman spectrum of WTe_2 mentioned in the previous work [13], the vibration modes of WTe_2 here is consistent with that of Td-WTe_2 [39], which indicates that the phase of WTe_2 in our experiment is Td. Thus, the band gap of 0.2 eV is attributed to the Td phase of the bulk WTe_2. The nonlinear absorption properties of WTe_2 film is investigated by an open-aperture (OA) Z-scan measurement. A 100-fs Ti: sapphire amplifier at 800 nm with a repetition rate of 1 kHz pumps the measurement system. The excitation power of the mentioned driving laser is 0.4 mW. The traditional OA Z-scan data and fitting trace are shown in Figure 1F. The nonlinear absorption coefficient (β) of WTe_2 is -3.78×10^{-5} cm/W. The power-dependent nonlinear absorption of WTe_2 is exhibited by balanced twin-detector measurement. The light source is a 600 fs home-made nonlinear polarization evolution mode-locked laser with a repetition rate of 120 MHz at 1550 nm. Typical power-dependent nonlinear absorption trends and fitting curve are indicated in Figure 1F. The modulation depth (α_s) of WTe_2 SA is up to 37.95%, other details of saturation intensity (I_{sat}) and non-saturable loss (α_{ns}) are listed in Figure 1G. The modulation depth is slightly improved compared with the previous work [13], which is related to the increase in the relaxation time and the enhancement of light-matter interaction caused by the increase in thickness [40–43]. The nonlinear behavior of WTe_2 and some commonly used SAs are listed in Table 1. From Table 1, Sb_2Te_3 has the strongest nonlinearity. In addition, the nonlinear absorption of $MoTe_2$ and WTe_2 are remarkable, while the modulation depth of WTe_2 is slightly better than that of $MoTe_2$.

3 Experiment

The experimental device diagram of the WTe_2-based EDFL is shown in Figure 2, including a laser diode (LD), a wavelength division multiplexer (WDM), a section of erbium-doped fiber (EDF), an optical coupler (OC), a polarization controller (PC), and an isolator (ISO). The LD pumps the whole system through a 980/1550 nm WDM. As the gain fiber, EDF amplifies the pulse. PC generates stress birefringence through the mechanical extrusion of the fiber

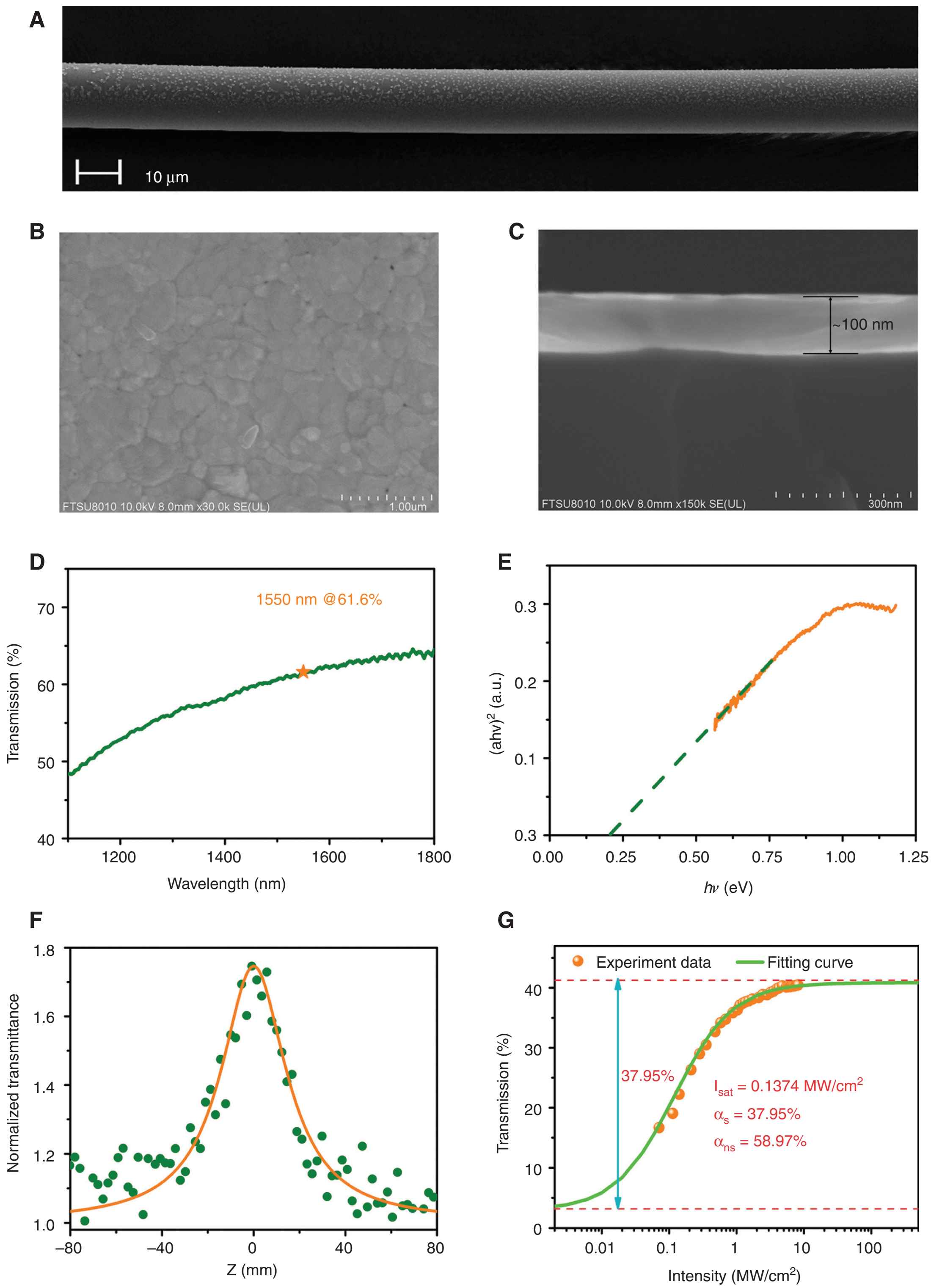

Figure 1: Characterization and nonlinear characteristics of WTe_2.
(A) SEM image of WTe_2-coated microfiber, (B) surface morphology, (C) vertical thickness, (D) linear absorption spectra, (E) Tauc plot, (F) OA Z-scan, (G) power-dependent absorption of WTe_2.

cross section. The ISO is used for guaranteeing orderly unidirectional laser transmission. A small portion of the light is exported by a 20:80 OC for real-time observation and data recording. The length of the whole ring cavity is 2.98 m, which contains the EDF of 0.58 m and single-mode fiber of 2.25 m.

Table 1: The nonlinear behavior of some SAs.

Materials	Modulation depth	Saturation intensity (MW/cm^2)	$\|\beta$ (cm/W)$\|$	Refs.
Graphene	5.1%	74	10^{-7}	[44]
BP	7.57%	9870	2.5×10^{-7}	[45]
Sb_2Te_3	38%	3.3	9.0×10^{4}	[46]
$MoTe_2$	5.7%	8.3	7.4×10^{-4}	[47]
WTe_2	37.95%	0.1374	3.78×10^{-5}	This work

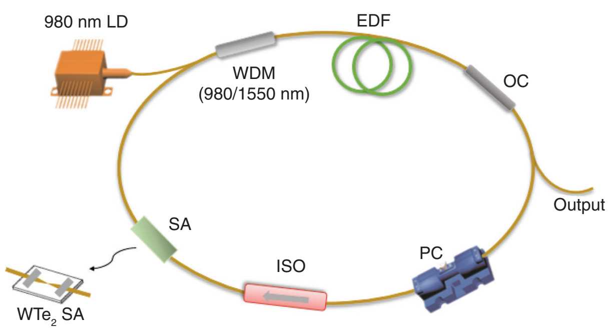

Figure 2: Experimental device diagram of the WTe_2-based EDFL.

4 Results and discussion

Although experimental devices similar to previous work are adopted [13], an additional 50 cm single-mode fiber was added, and another SA showing different nonlinearity was used. When the pump power reaches the mode-locked threshold of 244 mW, self-starting mode-locking is observed after fine-tuning the PC. And when it slowly increases to 630 mW, the main operating parameters of achieved laser are measured by the light exported through OC. The obtained mode-locked pulses are uniform and own a fixed time interval of 14 ns as shown in Figure 3A. The autocorrelation trace of the single pulse fitted by $sech^2$ profile is shown in Figure 3B, the pulse duration is 164 fs. The coefficient 1.54 is the conversion coefficient of pulse duration indicated in autocorrelation curve and actual pulse duration. Subsequently, long-term spectral samplings are presented in Figure 3C, informing the mode-locked system works at 1557.71 nm with a 3 dB bandwidth of 31.42 nm. The time-bandwidth product (TBP) is 0.6366. As shown in Figure 3D, the fundamental frequency at 71.3 MHz owns the SNR up to 75 dB with a resolution of 1 Hz. The illustrations show the distribution of frequency multiplications over a range of 800 MHz.

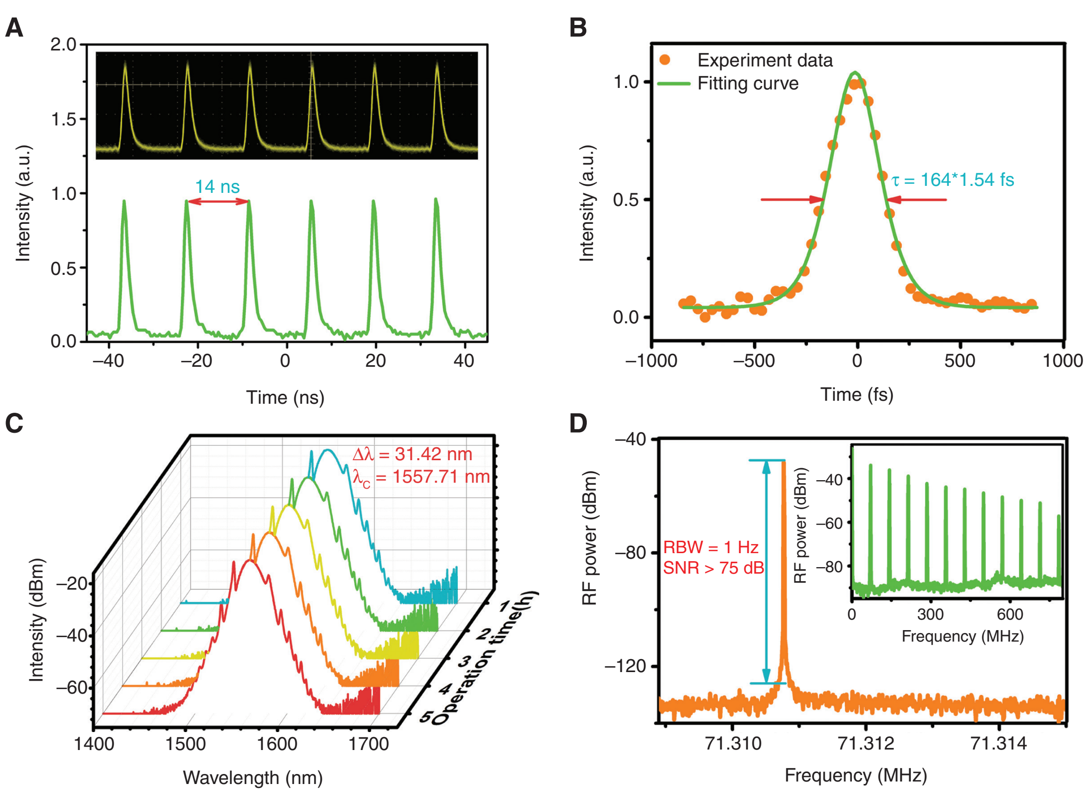

Figure 3: The operating parameters of achieved laser.
(A) Oscilloscope signals; (B) Pulse duration; (C) Spectrum; (D) Radio frequency (RF) spectrum.

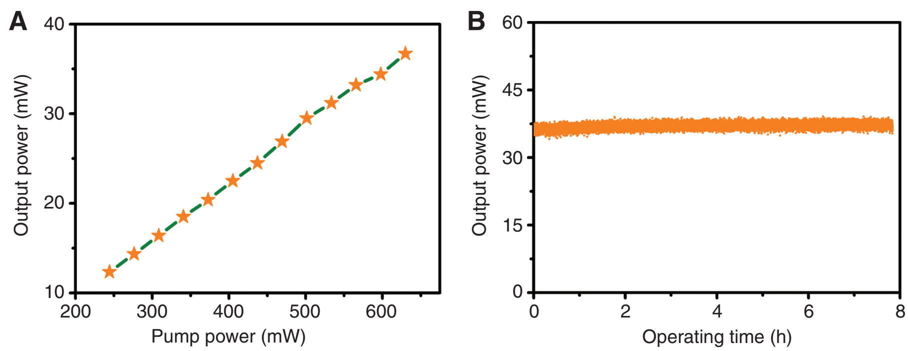

Figure 4: Output power and stability of laser.
(A) The law of output power increasing with pump power; (B) Long time output power monitoring.

Table 2: Comparisons of mode-locked lasers based on some SAs.

Materials	Preparation	SA structure	τ (fs)	λ/Δλ(nm)	SNR(dB)	Output power (mW)	Refs.
WS_2	MST	Tapered fiber	288	1560/19	58	18.4	[48]
MoS_2	MST	Tapered fiber	256	1563.4/13.6	75	68.3	[49]
$MoTe_2$	MST	Tapered fiber	229	1559.6/11.8	93	–	[50]
WTe_2	MST	Tapered fiber	164	1557.7/31.4	75	36.7	This work

The law of output power increasing with pump power is shown in Figure 4A, the slope of each point is approximately the same. The maximum output power is 36.7 mW. In the laboratory environment, we monitored its output power stability for about 8 h, and the output power of the laser is recorded once a second. The data of nearly 30,000 points are almost distributed in a straight line in Figure 4B, and the standard deviation of the samples is 0.56 mW. From the perspective of high SNR and small standard deviation, the system is relatively stable.

Further, comparisons of mode-locked lasers based on some SAs have also been launched in Table 2. The results in Table 2 are all based on the MST method and the structure of the tapered fiber. After eliminating the interference of preparation method and the structure of SA, we found that the pulse duration of WTe_2-based laser is relatively short. The results highlight the potential of WTe_2 in the realization of ultrafast pulses.

5 Conclusion

In conclusion, the ultrafast EDFL based on the WTe_2 SA has been implemented. The proposed WTe_2 SA has been prepared by coating WTe_2 on microfiber with MST. This WTe_2 SA has shown impressive optical nonlinearity with nonlinear absorption coefficient of -3.78×10^{-5} cm/W and modulation depth of 37.95%. After integrating it into the ring cavity, a sub-170 fs mode-locked laser has been achieved at 1557.71 nm. The laser has the maximum output power of 36.7 mW and SNR of 75 dB, and the stability of the output power has been maintained during the monitoring for nearly 8 h. In addition, after eliminating the interference of preparation method and SA structure, the proposed WTe_2-based laser is not inferior, especially in the realization of ultrashort pulses. Our work shows the potential of WTe_2 in ultrafast photonics, and opens a possible way to achieve high-performance laser with high power and ultrafast pulse.

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References

[1] Keller U. Recent developments in compact ultrafast lasers. Nature 2003;424:831–8.

[2] Liu M, Liu W, Wei Z. $MoTe_2$ saturable absorber with high modulation depth for erbium-doped fiber laser. J Lightwave Technol 2019;37:3100–5.

[3] Bao QL, Zhang H, Wang Y, et al. Atomic-layer graphene as a saturable absorber for ultrafast pulsed lasers. Adv Funct Mater 2009;19:3077–83.

[4] Luo ZQ, Huang YZ, Zhong M, et al. 1-, 1.5-, and 2-μm fiber lasers Q-switched by a broadband few-layer MoS_2 saturable absorber. J Lightwave Technol 2014;32:4077–84.

[5] Su LM, Fan X, Yin T, et al. Inorganic 2D luminescent materials: Structure, luminescence modulation, and applications. Adv Opt Mater 2019;1900978.

[6] Zhang H, Bao Q, Sun Z. Introduction to two-dimensional layered materials for ultrafast lasers. Photonics Res 2018;6:TDL1–2.

[7] Sun Z, Martinez A, Wang F. Optical modulators with 2D layered materials. Nat Photonics 2016;10:227–38.

[8] Yan PG, Chen H, Yin JD, et al. Large-area tungsten disulfide for ultrafast photonics. Nanoscale 2017;9:1871–7.

[9] Liu WJ, Liu ML, Lin S, et al. Synthesis of high quality silver nanowires and their applications in ultrafast photonics. Opt Express 2019;27:16440–8.

[10] Wu K, Zhang X, Wang J, Li X, Chen J. WS_2 as a saturable absorber for ultrafast photonic applications of mode-locked and Q-switched lasers. Opt Express 2015;23:11453–61.

[11] Liu WJ, Liu ML, Liu B, et al. Nonlinear optical properties of MoS_2-WS_2 heterostructure in fiber lasers. Opt Express 2019;27:6689–99.

[12] Zhang H, Tang DY, Zhao LM, Bao QL, Loh KP. Large energy mode locking of an erbium-doped fiber laser with atomic layer graphene. Opt Express 2009;17:17630–5.

[13] Liu ML, Ouyang YY, Hou HR, Liu WJ. Q-switched fiber laser operating at 1.5 μm based on WTe_2. Chin Opt Lett 2019;17:020006.

[14] Chen SQ, Zhao CJ, Li Y, et al. Broadband optical and microwave nonlinear response in topological insulator. Opt Mater Express 2014;4:587–96.

[15] Liu W, Liu M, Han H, et al. Nonlinear optical properties of WSe_2 and $MoSe_2$ films and their applications in passively Q-switched erbium doped fiber lasers. Photonics Res 2018;6:C15–21.

[16] Liu W, Liu M, OuYang Y, Hou H, Lei M, Wei ZY. CVD-grown $MoSe_2$ with high modulation depth for ultrafast mode-locked erbium-doped fiber laser. Nanotechnol 2018;29:394002.

[17] Rodin AS, Carvalho A, Neto AHC. Strain-induced gap modification in black phosphorus. Phys Rev Lett 2014;112:176801.

[18] Liu W, Pang L, Han H, Bi K, Lei M, Wei Z. Tungsten disulphide for ultrashort pulse generation in all-fiber lasers. Nanoscale 2017;9:5806–11.

[19] Na D, Park K, Park KH, Song YW. Passivation of black phosphorus saturable absorbers for reliable pulse formation of fiber lasers. Nanotechnol 2017;28:475207.

[20] Liu ML, OuYang YY, Hou HR, Lei M, Liu WJ, Wei ZY. MoS_2 saturable absorber prepared by chemical vapor deposition method for nonlinear control in Q-switching fiber laser. Chin Phys B 2018;27:084211.

[21] Han CQ, Yao MY, Bai XX, et al. Electronic structure of black phosphorus studied by angle-resolved photoemission spectroscopy. Phys Rev B 2014;90:085101.

[22] Wang ZT, Xu YH, Dhanabalan SC, et al. Black phosphorus quantum dots as an efficient saturable absorber for bound soliton operation in an erbium doped fiber laser. IEEE Photonics J 2016;8:1–10.

[23] Zhang H, Lu SB, Zheng J, et al. Molybdenum disulfide (MoS_2) as a broadband saturable absorber for ultra-fast photonics. Opt Express 2014;22:7249–60.

[24] Wu K, Guo C, Wang H, Zhang X, Wang J, Chen J. All-optical phase shifter and switch near 1550nm using tungsten disulfide (WS_2) deposited tapered fiber. Opt Express 2017;25:17639–49.

[25] Zhang M, Hu GH, Hu GQ, Howe RCT, Chen L, Zheng Z, Hasan T. Yb- and Er-doped fiber laser Q-switched with an optically uniform, broadband WS_2 saturable absorber. Sci Rep 2015;5:17482.

[26] Sun Z, Hasan T, Torrisi F, et al. Graphene mode-locked ultrafast laser. ACS Nano 2010;4:803–10.

[27] Guo B, Wang SH, Wu ZX, et al. Sub-200 fs soliton mode-locked fiber laser based on bismuthene saturable absorber. Opt Express 2018;26:22750–60.

[28] Zhang YP, Lim CK, Dai ZG, et al. Photonics and optoelectronics using nano-structured hybrid perovskite media and their optical cavities. Phys Rep 2019;795:1–51.

[29] Song YF, Shi XJ, Wu CF, Tang DY, Zhang H. Recent progress of study on optical solitons in fiber lasers. Appl Phys Rev 2019;6:021313.

[30] Jiang YQ, Miao LL, Jiang GB, et al. Broadband and enhanced nonlinear optical response of MoS_2/graphene nanocomposites for ultrafast photonics applications. Sci Rep 2015;5:16372.

[31] Song YF, Liang ZM, Jiang XT, et al. Few-layer antimonene decorated microfiber: ultra-short pulse generation and all-optical thresholding with enhanced long term stability. 2D Mater 2017;4:045010.

[32] Xing CY, Jing GH, Liang X, et al. Graphene oxide/black phosphorus nanoflake aerogels with robust thermo-stability and significantly enhanced photothermal properties in air. Nanoscale 2017;9:8096–101.

[33] Wang R, Chien HC, Kumar J, Kumar N, Chiu HY, Zhao H. Third-harmonic generation in ultrathin films of MoS_2. ACS Appl Mater Interfaces 2014;6:314–8.

[34] Lee CH, Silva EC, Calderin L, et al. Tungsten ditelluride: a layered semimetal. Sci Rep 2015;5:10013.

[35] Dai YM, Bowlan J, Li H, et al. Ultrafast carrier dynamics in the large-magnetoresistance material WTe_2. Phys Rev B 2015;92:161104.

[36] Herda R, Okhotnikov OG. Effect of amplified spontaneous emission and absorber mirror recovery time on the dynamics of mode-locked fiber lasers. Appl Phys Lett 2005;86:011113.

[37] Xu X, Guo Y, Zhao Q, et al. Green and efficient exfoliation of ReS_2 and its photoelectric response based on electrophoretic deposited photoelectrodes. Mater Des 2018;159:11–9.

[38] Jian W, Cheng X, Huang Y, et al. Arrays of ZnO/MoS_2 nanocables and MoS_2 nanotubes with phase engineering for bifunctional photoelectrochemical and electrochemical water splitting. Chem Eng J 2017;328:474–83.

[39] Walsh LA, Yue R, Wang Q, et al. WTe_2 thin films grown by beam-interrupted molecular beam epitaxy. 2D Mater 2017;4:025044.

[40] Newson RW, Dean J, Schmidt B, van Driel HM. Ultrafast carrier kinetics in exfoliated graphene and thin graphite films. Opt Express 2009;17:2326–33.

[41] Gao W, Huang L, Xu J, et al. Broadband photocarrier dynamics and nonlinear absorption of PLD-grown WTe_2 semimetal films. Appl Phys Lett 2018;112:171112.
[42] Wang J, Jiang Z, Chen H, et al. Magnetron-sputtering deposited WTe_2 for an ultrafast thulium-doped fiber laser. Opt Lett 2017;42:5010–3.
[43] Huntington ST, Katsifolis J, Moar PN, et al. Evanescent field characterisation of tapered optical fibre sensors in liquid environments using near field scanning optical microscopy and atomic force microscopy. IEE Proc Optoelectronics 1999;146:239–43.
[44] Zhang H, Virally S, Bao Q, et al. Z-scan measurement of the nonlinear refractive index of graphene. Opt Lett 2012;37:1856–8.
[45] Zhang R, Zhang Y, Yu H, et al. Broadband black phosphorus optical modulator in the spectral range from visible to mid-infrared. Adv Opt Mater 2015;3:1787–92.
[46] Wang J, Yin J, He T, Yan P. Sb_2Te_3 mode-locked ultrafast fiber laser at 1.93 μm. Chin Phys B 2018;27:084214.
[47] Wang J, Chen H, Jiang Z, et al. Mode-locked thulium-doped fiber laser with chemical vapor deposited molybdenum ditelluride. Opt Lett 2018;43:1998–2001.
[48] Liu ML, Liu WJ, Pang LH, Teng H, Fang SB, Wei ZY. Ultrashort pulse generation in mode-locked erbium-doped fiber lasers with tungsten disulfide saturable absorber. Opt Commun 2018;406:72–5.
[49] Jiang Z, Chen H, Li J, Yin J, Wang J, Yan P. 256 fs, 2 nJ soliton pulse generation from MoS_2 mode-locked fiber laser. Appl Phys Express 2017;10:122702.
[50] Wang J, Jiang Z, Chen H, et al. High energy soliton pulse generation by a magnetron-sputtering-deposition-grown $MoTe_2$ saturable absorber. Photonics Res 2018;6:535–41.