Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Mode-locked fiber laser operating in the C and L bands with immobilized molybdenum disulfide saturable absorber over etched SMF

Zhihao Wang
Liaocheng University
Chao Liu
Liaocheng University
Guoru Li
Liaocheng University
Xiancui Su
Liaocheng University
Yiran Wang
Liaocheng University
Yiyan Xie
Liaocheng University
Feilong Gao
Liaocheng University
Santosh Kumar
Liaocheng University
Bingyuan Zhang (bingyuanzhang@yahoo.com.cn)
Liaocheng University

Research Article

Keywords: Mode-locked laser, molybdenum disulfide-saturable absorber, etched fiber, erbium-doped fiber laser

Posted Date: February 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1232593/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Abstract

In this work, a passively mode-locked erbium-doped fiber laser with layers of molybdenum disulfide saturable absorber (MoS_2 -SA) immobilized etched single mode fiber (SMF) is developed. MoS_2-SA are synthesized via liquid phase exfoliation then transferred to etched fiber (EF). SA is used to achieve mode-locked operation in an erbium-doped fiber laser. With a pump power of 250 mW, a repetition rate of 11.07 MHz produces a pulse width of 388 fs and a maximum average output power of 16.9 mW. This work demonstrates the potential of SA based on EF in C and L band mode-locked fiber lasers.

1. Introduction

Laser communication has garnered considerable attention due to its high capacity, high level of confidentiality, and low cost. The most effective method for generating ultrashort pulses in the communication band is considered to be the passive mode-locked erbium-doped fiber laser [1–3]. Saturable absorber (SA) is a critical component of mode-locked operation in fiber lasers [4–6]. Various types of SAs have been used in passively mode-locked fiber lasers in the past. Two-dimensional (2D) materials, such as graphene [7], carbon nanotubes [8], topological insulators (TIs) [9], and other 2D materials [10–13], are among the most representative and studied. As an ideal and powerful candidate material for SA, it should exhibit the following properties: controllable modulation depth, a high damage threshold, broadband saturable absorption capacity, and fiber compatibility [14]. Currently, the most common method of transferring SA to fiber is via optical fiber patch cords and microfiber. To increase the efficiency of SA transfer, we propose a novel and effective method for fabricating microfibers with a controllable core diameter via etching. In comparison to flame drawing and machine control, this method has the advantage of being simple to prepare and inexpensive [15]. The LPE technique is used to create liquid dispersions enriched with a few layer molybdenum disulfide (MoS_2) flakes, then that are transferred to the Etched single mode fiber (E-SMF) and used as the SA to generate mode-locked pulses in an Er-doped fiber laser. MoS_2 has been demonstrated to be suitable for mode-locked fiber lasers due to its numerous advantages, including switchable bandgap, broadband saturable absorption, increased nonlinear optic response, and low saturation intensity [16–18]. E-SMF is a low-cost fiber design that allows for a sufficient amount of nanomaterial coating along the fiber's surface. When a material is superimposed on the E-SMF, light from the fiber core can couple to the overlay at specific resonant wavelengths depending on its polarization. By etching the optical fiber, it is possible to obtain a more precise interaction length between SA and light, as well as improved mode locking performance, in comparison to the more common thin film method [19–21]. MoS_2 produced via the LPE method is transferred to E-SMF to form MoS_2-SA.

We developed a 1568 nm Er-doped fiber mode-locked laser using MoS_2-SA. The corresponding pulse duration and maximum output power are 388 fs and 16.9 mW, respectively. The experimental results demonstrate that MoS_2-SA immobilized E-SMF has a favorable optical modulation capability.

2. Fabrication Process Of The Multilayer Mos And Etched Fiber

We produce the E-SMF in this experiment by etching it with hydrofluoric (HF) acid [22]. The diameter of the optical fiber decreases as it is etched, allowing an increasing number of evanescent waves (EWs) to escape. To validate the etching experimental results, the diameter of the E-SMF is measured using a Combiner Manufacturing System (CMS, 3SAE CMS Technologies, USA). The EF was prepared to facilitate EW interaction between the MoS_2-SA and the core light while increasing the SA's damage threshold. The etching reactor is illustrated in detail in Fig. 1(a).

The first step was to fabricate five E-SMFs using conventional SMF. The core and cladding diameter of SMF are 9 μm and 125 μm, respectively. The cladding of 3 cm length of optical fiber section was removed using an optical fiber stripper. Thereafter, the exposed portion of optical fiber was wiped with a 70% ethanol solution and then inserted into the center of 0.2 mm fiber groove, ensuring that sufficient fiber lengths on either side were available for stacking in the apparatus depicted in Fig. 1(a). Then, added 1 mL HF acid (40% weight concentration) to the etching reactor for different timings. The optical fiber removed from the etching reactor every nine minutes, wipe it with ethanol solution, and place it in a CMS machine to determine the optical fiber diameter. As shown in Fig. 1(b), a relationship between HF corrosion time and optical fiber diameter is obtained. We can easily determine the etching rate from our achieved results.

Liquid-phase exfoliation (LPE) was used to prepare the few-layer MoS_2-SA [23]. Typically, 30 mg of MoS_2 was added to 10 mL NMP and ultrasonically bathed for 3 hours. The supernatant was collected and stored at room temperature in the 50 mL glass bottle for subsequent use in the experiment. Following that, a homogeneous suspension of MoS_2 was sonicated for 10 minutes at room temperature using a high-power ultrasonicator. To avoid overheating, the output power is set to 1000 W, with a 9-second ON and 6-second OFF cycle. The dissolved solution was then centrifuged at room temperature for 1 hour at 4000 rpm. The supernatant was collected and stored at room temperature in the 50 mL glass bottle for subsequent use in the experiment.

Raman spectroscopy is a widely used technique for determining the vibration modes of MoS_2. Two distinct characteristic peaks are shown in Fig. 2(a) at 378.9 cm^{-1} and 409.6 cm^{-1}. According to previous research, the mode at 378.9 cm^{-1} is caused by an in-plane vibration associated with Mo and S atoms, whereas the mode at 409.6 cm^{-1} is caused by an out-of-plane vibration associated with S atoms. The spacing between the two peaks was found to be 21 cm^{-1} for two randomly chosen spots, indicating the formation of uniform multilayer MoS_2 [24]. The atomic force microscope (AFM) was used to characterize the surface morphology and thickness of the material, and the results are shown in Fig. 2. (b). Comparing the surface heights of different regions on the MoS_2 films reveals that the film thickness was 8 nm, as indicated in Fig. 2(b), that corresponds to 10-12 layers in the structure [25]. The linear absorption spectrum shown in Fig. 2(c) indicates that MoS_2 has a flat absorption at 1550 nm.

MoS_2 was immobilized on the fiber structure using a dip-coating technique. The E-SMF were dipped for 20 seconds in 1 mL of MoS_2 solution and dried for 2 minutes. These steps were repeated eight times to ensure uniform coating. Following that, the immobilized fiber was kept in an oven at 50°C for 2 hours to ensure the robustness of MoS_2 -SA. MoS_2 film is transferred to E-SMF, that has never been done before. Figure 2(d) shows an optical microscopic image of the boundary of the MoS_2 layer. Field emission scanning electron microscopy (FE-SEM) was used to investigate the morphological properties of the MoS_2 film. The image shows that a uniform MoS_2 atomic layer is generated by LPE. These shows that MoS_2 is evenly covered on the surface of the optical fiber.

3. Mode-locked Fiber Laser Experiments

We developed a ring fiber laser cavity by inserting the MoS_2 ESMF-SA, and the experimental setup is shown in Fig. 4. The SMF and Er-doped fiber (EDF) have lengths of 12.9 m and 5.7 m, respectively, that correspond to an overall ring resonator length of 18.6 m and a total net cavity dispersion of -0.21 ps^2. The ring cavity was pumped by a 974 nm laser diode (LD) through a 980/1550 nm wavelength division multiplexing (WDM) coupler, an 80/20 output coupler (OC) with a 20% output coupling ratio, and a polarization insensitive isolator (ISO) that ensures the laser operates unidirectionally in the cavity. A polarization controller (PC) was inserted into the laser cavity to control the polarization state. An optical spectrum analyzer (YOKOGAWA AQ6370), an autocorrelator (APE pulse check), and a digital oscilloscope (TEKTRONIX MDO3102) were used to monitor the pulse trains, pulse width, and spectrum of fiber laser.

In the EDF, self-starting mode-locked pulses were successfully generated. Figure 4(a) illustrates the fiber laser's output characteristics. The typical shape of the soliton pulse spectrum was determined using a 180-mW pump power. The spectrum's central wavelength is 1568 nm, with a 3-dB bandwidth of 4.78 nm. As illustrated in Fig. 4(b), the repetition rate of the fiber laser was 11.07 MHz, that was determined by the time interval of the output pulse train with a signal-to-noise ratio (SNR) of 35.9 dB. The measured pulse duration was well-fit by a Gaussian pulse profile, and the autocorrelation trace had a full width half maximum (FWHM) of 388 fs, as shown in Fig. 4. (c). The average output power of the soliton laser was plotted as a function of the pump power in Fig. 4(d). When the pump power attained 74 mW, the laser's continuous wave (CW) operation was initiated. When the pump power was increased further to 150 mW, a stable and self-starting mode-locked operation was observed and maintained without changing the polarization controller state. These experimental results confirmed that the SA nature of MoS_2 EF enabled the fiber laser to operate in a highly stable soliton mode via EW interaction. Additionally, we demonstrated the long-term viability of the MoS_2-SA based on E-SMF.

4. Conclusion

The present work synthesized MoS_2 sheets and successfully immobilized the multilayer MoS_2 film on the E-SMF without the use of any organic binder. A pulsed Er-doped fiber laser was used to observe saturable absorption characteristics through MoS_2 on E-SMF at 1568 nm. It is demonstrated that a thin film of

MoS_2 can be used as a SA in an erbium ring fiber laser cavity operating in the C and L bands. This experiment generated a soliton pulse with a pulse width of 388 fs and a bandwidth of 4.78 nm at the center laser wavelength of 1568 nm. We found that the multilayer MoS_2 transferred to E-SMF exhibited extremely reliable SA functionality, enabling the generation of efficient and soliton-generating pulses in fiber lasers.

Declarations

Funding:

National Natural Science Foundation of China, China (61905103), Science and Technology Branch high Level Start-up Fee 2018 - Based on plasma biosensing, China (31805180301), Liaocheng University Start-up Fund for Doctoral Scientific Research, China (318051931, 318051836).

References

1. Huang, Z., Huang, Q., Theodosiou, A., et al.: Femtosecond laser direct inscribed 45° tilted fiber grating for a net-normal-dispersion mode-locked Er-doped fiber laser[J]. Optics & Laser Technology, 2021, 143(19):p. 107358
2. Krupa, K., Nithyanandan, K., Andral, U., et al.: Real-Time Observation of Internal Motion within Ultrafast Dissipative Optical Soliton Molecules[J]. Phys. Rev. Lett. **118**(24), 243901 (2017)
3. Ryczkowski, P., Nrhi, M., Billet, C., et al.: Real-time full-field characterization of transient dissipative soliton dynamics in a mode-locked laser[J]. Nat. Photonics **12**, 221–227 (2018)
4. Li, P.X.: Y.F. et al. 980-nm all-fiber mode-locked Yb-doped phosphate fiber oscillator based on semiconductor saturable absorber mirror and its amplifier[J]. Chin. Phys. B **25**(8), 1–1 (2016)
5. Li, P.X., Liang, B.X., Zhang, M.M., et al.: 978nm 1.24ps ultra-short plused large mode area photonic crystal fiber laser[J]. Opt. Commun. **352**, 19–24 (2015)
6. Morales, L., Durán-Sánchez, M., Rivera, I.A., et al.: Wide wavelength-tunable passive mode-locked Erbium-doped fiber laser with a SESAM[J]. Opt. Laser Technol. **134**(3), 106593 (2020)
7. Liu, G.X., Feng, D.J., Zhang, M.S., et al.: Mode-locked erbium-doped all fiber laser using few-layer graphene as a saturable absorber[J]. Opt. Laser Technol. **72**, 70–73 (2015)
8. Set, S.Y., Yaguchi, H., Tanaka, Y., et al.: Ultrafast fiber pulsed lasers incorporating carbon nanotubes[J]. IEEE J. Sel. Top. Quantum Electron. **10**(1), 137–146 (2004)
9. Zhang, H., Liu, C.X., Qi, X.L., et al.: Topological insulators in Bi2Se3, Bi2Te3 and Sb2Te3 with a single Dirac cone on the surface[J]. Nat. Phys. **5**(6), 438–442 (2009)
10. Feng, J., Li, X., Shi, Z., et al.: 2D Ductile Transition Metal Chalcogenides (TMCs): Novel High-Performance Ag2S Nanosheets for Ultrafast Photonics[J]. Advanced Optical Materials **8**(6), 2195–1071 (2020)

11. Zhao, Y., Guo, P., Li, X., et al.: Ultrafast photonics application of graphdiyne in the optical communication region[J]. Carbon **149**, 336–341 (2019)

12. Liu, J., Li, X.: SnSe2 Nanosheets for Subpicosecond Harmonic Mode-Locked Pulse Generation[J]. Small **15**(38), 1613–6810 (2019)

13. Niu, K., Sun, R., Chen, Q., Man, B., Zhang, H.: Passively mode-locked Er-doped fiber laser based on SnS_2 nanosheets as a saturable absorber [J]. Photon. Res **6**, 72–76 (2018)

14. Harith, A., et al.: S-band Q-switched fiber laser using molybdenum disulfide (MoS_2) saturable absorber[J]. Laser Phys. Lett **13**, 035103 (2016)

15. Zhenhong, Wang, et al.: Generation of trapezoidal envelope pulses and soliton rains from passively mode-locked fiber laser with MoS_2 saturable absorber on microfiber[J]. Appl. Phys. Express **11**, 072504 (2018)

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

17. Wang, S., u, Y., Zhang, H., Wang, H., Zhao, A., Chen, M. Y and Wang, J.: Broadband few-layer MoS_2 saturable absorbers[J]. Adv. Mater **26**, 3538–3544 (2014)

18. Sun, Z., Popa, D., Hasan, T., Torrisi, F., Wang, F., Kelleher, E.J., Ferrari, A.C.: A stable, wideband tunable, near transform-limited, graphene-mode-locked, ultrafast laser[J]. Nano Res, 2010, 3653–60

19. Ahmad, H.B., Soltani, S., Thambiratnam, K., Yasin, M.: Highly stable mode-locked fiber laser with graphene oxide-coated side-polished D-shaped fiber saturable absorber[J]. Opt. Eng. **57**(5), 56110 (2018)

20. Coleman, J.N., Lotya, M., O'Neill, A., Bergin, S.D., King, P.J., Khan, U., Smith, R.J.: Two-dimensional nanosheets produced by liquid exfoliation of layered materials[J]. Science, 2011, 331568–71

21. May, P., Khan, U., Hughes, J.M., Coleman, J.N.: Role of solubility parameters in understanding the steric stabilization of exfoliated two-dimensional nanosheets by adsorbed polymers[J]. Phys. Chem. C **116**, 11393–11400 (2012)

22. Hong, S., Haddock, P.M., Shankar, R., Mutharasan: Fabrication of biconical tapered optical fibers using hydrofluoric acid[J]. Materials Science and Engineering: B **97**, 87–93 (2003)

23. Wang, Z., Singh, R., Marques, C., Jha, R., Zhang, B., Kumar, S.: Taper-in-taper fiber structure-based LSPR sensor for alanine aminotransferase detection[J]. Opt. Express **29**(26), 43793–43810 (2021)

24. Al-Masoodi, A.H.H., Ahmed, M.H.M., Latiff, A.A., Azzuhri, S.R., Arof, H., Harun, S.W.: Passively mode-locked ytterbium-doped fiber laser operation with few layer MoS2 PVA saturable absorber[J]. Optik **145**, 543–548 (2017)

25. Khazaeizhad, R., Kassani, S.H., Jeong, H., Yeom, D.I., Oh, K.: Mode-locking of Er-doped fiber laser using a multilayer MoS2 thin film as a saturable absorber in both anomalous and normal dispersion regimes[J]. Opt. Express **22**(19), 23732–23742 (2014)

Figures

Figure 1

Etching reactor and etching rate curve. (a) etching reactor structure (b) relationship between etching time and optical fiber diameter

Figure 2

(a) Raman spectra of the MoS_2 thin film, (b) thickness measurements of MoS_2 thin film through AFM, (c) absorption spectrum of MoS_2 by LPE, (d) SEM image of E-SMF surface transferred silica film at 5 μm scanning scale.

Figure 3

LD, laser diode, 974 nm; WDM, wavelength division multiplexer; EDF, er-doped fiber; ISO, isolator; PC, polarization controller; OC, optical coupler; SMF, Single mode fiber; MoS_2 ESMF-SA, MoS_2 etched single mode fiber saturable absorber; OSA, optical spectrum analyzer.

Figure 4

Dissipative soliton pulses characteristics: (a) optical spectrum, (b) fundamental frequency of RF spectrum, (c) autocorrelator trace of laser output and fitting Gaussian shape pulse, (d) average output power versus pump power. Inset of (b) shows typical pulse train of laser output.