Nonlinear optical property measurements of rhenium diselenide used for ultrafast fiber laser mode-locking at 1.9 μm

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An experimental investigation into the nonlinear optical properties of rhenium diselenide (ReSe₂) was conducted at a wavelength of 1.9 μm using the open-aperture and closed-aperture Z-scan techniques for the nonlinear optical coefficient (β) and nonlinear refractive index (n²) of ReSe₂, respectively. β and n² measured at 1.9 μm were ~ −11.3 × 10⁻³ cm/GW and ~ −6.2 × 10⁻² cm²/GW, respectively, which to the best of our knowledge, are the first reported measurements for ReSe₂ in the 1.9-μm spectral region. The electronic band structures of both ReSe₂ and its defective structures were also calculated via the Perdew–Becke–Erzenhof functional to better understand their absorption properties. A saturable absorber (SA) was subsequently fabricated to demonstrate the usefulness of ReSe₂ for implementing a practical nonlinear optical device at 1.9 μm. The 1.9-μm SA exhibited a modulation depth of ~ 8% and saturation intensity of ~ 11.4 MW/cm². The successful use of the ReSe₂-based SA for mode-locking of a thulium–holmium (Tm–Ho) co-doped fiber ring cavity was achieved with output pulses of ~ 840 fs at 1927 nm. We believe that the mode-locking was achieved through a hybrid mechanism of saturable absorption and nonlinear polarization rotation.

Nonlinear optical materials have been an essential part of realizing various nonlinear functions in optical and photonic devices, such as frequency conversion¹⁻², parametric processes³, optical switching⁴, and saturable absorption⁵. The aforementioned nonlinear optical functions require different nonlinear optical effects of the material; for example, the χ⁽²⁾ effect is used for the implementation of optical wavelength converters⁶, χ⁽³⁾ is for optical switches⁷, and nonlinear absorption is for saturable absorbers (SAs)⁸.

SAs can be broadly categorized into fast and slow devices. It is well-known that fast SAs are suitable for generating ultrashort pulses owing to their immediate response time⁹. Optical fiber-based nonlinear transmission devices comprising a nonlinear optical loop mirror (NOLM), a nonlinear amplifying loop mirror, or nonlinear polarization rotation (NPR) are commonly known as fast SAs¹⁰⁻¹². However, mode-locking with the aforementioned optical fiber-based nonlinear devices has a self-starting difficulty. On the other hand, one of the latest developments in the field of materials science, nonlinear saturable absorption materials, are known to be relatively slow SAs compared to optical fiber-based nonlinear transmission devices. The saturable absorption phenomenon usually occurs because of Pauli's blocking principle within semiconductors¹³. It is well-known that nonlinear material-based SAs are suitable for self-starting mode-locking operations. Until now, many nonlinear optical materials can be used as relatively slow SAs, such as carbon nanotubes¹⁴⁻¹⁵, graphene¹⁶⁻¹⁷, topological insulators (TIs)¹⁸⁻¹⁹, transition metal dichalcogenides (TMDCs)²⁰⁻²⁸, lead sulfide (PbS)²⁹, and MXenes³⁰⁻³⁹.

Hybrid mode-locking techniques have been widely investigated to solve the difficulty with self-starting for conventional mode-locking in optical fiber-based nonlinear transmission devices. They can induce self-starting mode-locking with ultrafast and stable pulses by combining an optical fiber-based nonlinear transmission device and a nonlinear material-based SA: the former can induce ultrashort pulse duration while the latter can easily initiate self-starting for the mode-locking process to enhance the overall mode-locking stability.

Among the saturable absorption materials, TMDs have received much attention. TMDCs have the chemical formula MX₂ (M: transition metal, X: chalcogen). Zhang et al.²⁰ first investigated the saturable absorption
property of molybdenum disulfide (MoS₂), after which this property has been extensively investigated in various other TMDCs.

Compared to conventional group VI TMDCs (molybdenum- or tungsten-based ones), rhenium-based ones (group VII TMDCs) are known to possess quite different optical and electronic characteristics. Very recently, several rhenium-based TMDCs, such as rhenium disulfide (ReS₂) and ReSe₂, for use as nonlinear SAs have been reported. These SAs have been implemented in Q-switching or mode-locking, and their nonlinear absorption coefficients have been obtained using Z-scan techniques conducted at wavelengths of 515, 1030, or 1560 nm.

In this work, we measured the nonlinear optical properties of ReSe₂ at a wavelength of 1.9 μm. First, the nonlinear absorption coefficient (β) of ReSe₂ was measured using the open-aperture (OA) Z-scan technique (~ - 11.3 × 10⁻³ cm/GW). Next, the nonlinear refractive index (n²) of ReSe₂ was measured using the closed-aperture (CA) Z-scan technique (~ - 6.2 × 10⁻² cm²/GW). To the best of our knowledge, these are the first measurements of β and n² of ReSe₂ in the 1.9-μm spectral region.

Density functional theory (DFT) calculations were conducted to determine the electronic band structures of ReSe₂ for different ratios of Re and Se atoms. Finally, a composite of ReSe₂ and polyvinyl alcohol (PVA) was fabricated to assess the practicability of using ReSe₂ as an SA at 1.9 μm. Ultrafast ~ 840 fs pulses could readily be obtained after incorporating the prepared SA into a 1.9 μm fiber ring cavity as a mode-locker.

Results

Material characterization and bandgap calculation of ReSe₂ particles. ReSe₂ bulk flakes were first suspended in 10 mL distilled water, after which the solution was sonicated for 16 h to obtain nano-sized particles. Scanning electron microscopy (SEM) was conducted on the sonicated particles, and the SEM image in Fig. 1a clearly illustrates that the particle size varied from hundreds of nanometers to a few micrometers, indicating that the ReSe₂ particles were still in the bulk state.

Characterization of the sonicated ReSe₂ particles was conducted via energy dispersive spectroscopy (EDS). From the two distinct peaks corresponding to Re and Se, it can be clearly observed in the EDS spectrum in Fig. 1b, the atomic ratio between Re and Se was 1:2. Stoichiometric analysis of the ReSe₂ particles was performed via X-ray photoelectron spectroscopy (XPS). The two peaks in the Re 4f₇/₂ and Re 4f₅/₂ spectra (Fig. 2a) at ~ 41 and ~ 43.5 eV, respectively, are consistent with previously reported values, while two peaks at ~ 53.9 and ~ 54.8 eV in the Se 3d spectrum (Fig. 2b) signify the presence of Se 3d₅/₂ and Se 3d₃/₂, respectively.

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Figure 1. (a) An SEM image and (b) an EDS spectrum of ReSe₂ particles.

Figure 2. XPS core-level spectra: (a) Re 4f and (b) Se 3d.
Raman spectroscopy (Fig. 3a) revealed three peaks corresponding to the $E_g$ ($\sim 125$ cm$^{-1}$) and $A_g$ ($\sim 160$ cm$^{-1}$) and $\sim 173.7$ cm$^{-1}$ modes. Many other small peaks in the spectrum can be attributed to the low lattice symmetry and complex lattice vibrations of the particles$^{35-39}$. The size of the ReSe$_2$ particles used in this experimental investigation ranged from tens of nanometers to a few micrometers rather than just a few layered evenly sized nanoparticles. To enable the facile formation of a thin film, we combined the ReSe$_2$ solution with polyvinyl alcohol (PVA). The ReSe$_2$/PVA composite film was then characterized via linear optical absorption (Shimadzu, UV-3600PLUS) measurements after the ReSe$_2$/PVA solution had been dropped onto a glass slide and then dried for 1 hour. As shown in Fig. 3b, it is clear that the prepared film had wide spectral band absorption.

Nonlinear optical property measurements using Z-scan techniques. The nonlinear optical properties of the ReSe$_2$ particles were studied via the Z-scan techniques$^{44}$. Figure 5 shows the Z-scan measurement setup, in which a ~ 550-fs pulsed fiber laser was employed as the input beam. A ReSe$_2$/PVA film was vertically placed on the translation stage with a laser output beam focused through the lens onto the film, after which the sample position was moved from $z = -20$ to 20 mm. The ReSe$_2$/PVA film exhibited an obvious nonlinear saturable absorption response (Fig. 6a); as $z$ approaches 0 (the intensity of the incident beam increased), the normalized transmittance ($T(z)$) of the measured graph was plotted along the $z$ position with a fitted curve based on the following formula$^{45}$:

$$T(z) = \sum_{n=0}^{\infty} (-\beta I_0 L_{\text{eff}})^n / \left(1 + z^2 / z_0^2\right)^n (n + 1)^{3/2} \approx 1 - \beta I_0 L_{\text{eff}} / 2^{3/2} (1 + z^2 / z_0^2), \quad (1)$$

where $\beta$ represents the nonlinear absorption coefficient; $I_0$ is the peak intensity at the focusing point; $z_0$ denotes the linear absorption coefficient; $z$ and $z_0$ denote the position of the film and the Rayleigh length, respectively; $L$ represents the film thickness.

We subsequently conducted a CA Z-scan analysis to measure the nonlinear refractive index of the ReSe$_2$/PVA film; Fig. 6b shows the Z-scan results as a fitted curve based on the following formula$^{46}$:

$$T(z) = \frac{1}{1 - \frac{\Delta \Phi}{\Delta \Phi} \frac{4}{\Delta \Phi} / \lambda}, \quad (2)$$

where $\Delta \Phi = 2\pi n_2 I_0 L_{\text{eff}} / \lambda$.

Figure 3. (a) A Raman spectrum of the ReSe$_2$ particles and (b) measured linear absorption spectrum of the ReSe$_2$/PVA film.
where $\omega_0$ is the beam waist, $\lambda$ is the light wavelength, and $n_2$ denotes the nonlinear refractive index.

From the measurement results and fitted curves (Fig. 6), the nonlinear absorption coefficient of the ReSe$_2$/PVA film was estimated as $\sim -11.3 \times 10^3$ cm/GW and its refractive index was $\sim -6.2 \times 10^{-2}$ cm$^2$/GW at 1.9 µm. For comparison, the reported nonlinear optical parameters for several other TMDCs are listed in Table 1. Nevertheless, it was not possible to directly compare the measured parameters of ReSe$_2$ with the ones of other TMDCs because, to the best of our knowledge, no previous measurements of the nonlinear optical parameters for TMDCs in the 2-µm wavelength area have been reported. The nonlinear absorption coefficient and nonlinear refractive index of ReSe$_2$ at 1.9 µm are twice as large as the values at 1560 nm$^{34}$. In our previous work, we

$$z_0 = \frac{\pi \omega_0^2}{\lambda}, \quad (5)$$
reported that the nonlinear absorption coefficient and nonlinear refractive index of ReSe$_2$ are $\sim -5.67 \times 10^3$ cm/GW and $\sim -2.81 \times 10^{-2}$ cm$^2$/GW at 1560 nm, respectively.

Fabrication of a ReSe$_2$/PVA-based saturable absorber. To determine the practicability of using ReSe$_2$ in a device at 1.9 μm, we fabricated a fiberized SA by dropping ReSe$_2$/PVA solution onto the surface of a side-polished SM2000 fiber and drying it for 1 day. The physical distance between the flat side and the fiber core was $\sim 5$ μm, while it had a side-polished section length of $\sim 2$ mm. After drying, we measured the insertion loss and polarization-dependent loss (PDL) ($\sim 3.4$ dB and $\sim 4$ dB, respectively). It is possible to reduce the PDL by decreasing the polished section length of a side-polished fiber and/or increasing the distance between the core and the polished fiber surface$^{47,48}$, and thus we tried to use the aforementioned methods to reduce the PDL. However, we observed that the saturable absorption did not proceed very well due to reduced interaction between the deposited ReSe$_2$/PVA layer and the oscillating beam.

Next, we measured the nonlinear transmission of the ReSe$_2$/PVA-based SA versus the input beam peak power, for which a 1.9-μm thulium-holmium (Tm–Ho) co-doped fiber laser with a $\sim 1.2$-ps pulse width was used, as shown in the measurement setup in Fig. 7a. Figure 7b exhibits the measured transmission curve of the ReSe$_2$/PVA-based SA, from which the saturation intensity and modulation depth were estimated as $\sim 11.4$ MW/cm$^2$ and $\sim -20$ dB, respectively.

![Figure 6. Plots for the (a) open-aperture and (b) closed aperture Z-scans of the ReSe$_2$ film.](image-url)
~ 8%, respectively. Hence, the measured modulation depth is high enough for mode-locking in an anomalously dispersive fiber cavity49,50.

**Fiber laser setup and results.** The experimental setup of the fiber laser is illustrated in Fig. 8. The gain fiber was 1-m length of co-doped Tm-Ho fiber. Its peak absorption was ~ 13 dB/m at a wavelength of 1550 nm. The pumping source for the cavity was a 1550-nm pump laser diode and the pumping beam was launched into the Tm-Ho co-doped fiber through a 1550/2000 nm wavelength division multiplexer (WDM). A polarization controller (PC) was used to optimize the polarization state of the beam, while an isolator was placed in the cavity for unidirectional light propagation and the SA was inserted between the WDM and the PC. The output pulses were extracted through a 90:10 optical coupler.

Self-started optical pulses were induced at the pump power of ~ 224 mW. Our SA had a relatively high PDL, and so we believe that the mode-locking pulses were generated from the fiber laser cavity through the combined use of saturable absorption and NPR. The self-starting capability of our laser was tested by repeatedly increasing and decreasing the pump power near ~ 224 mW. The self-starting phenomenon was clearly observed, which we believed is due to the relatively slow response of the saturable absorption owing to the presence of ReSe2. Anyhow, it is very difficult to negate the contribution of NPR to the laser mode-locking due to the 4 dB PDL value of the SA. Although it is difficult to realize self-starting mode-locking in fiber lasers with NPR mode-locking, it can be readily achieved in saturable absorption mode-locking. In this experiment, the self-starting operation was easily achieved without the necessity of a precise PC adjusting procedure. Therefore, we consider that the mode-locking demonstrated in this experiment is a hybrid type of saturable absorption and NPR.

**Figure 8.** The fiber laser configuration and setup.
The measured optical spectrum with its hyperbolic secant function curve is illustrated in Fig. 9a. The 3-dB bandwidth is \(~ 4.67 \text{ nm}\) with a center wavelength of \(~ 1927 \text{ nm}\). Many Kelly sidebands were observed; it is well-known that these result from the periodic spectral interference of soliton pulses and dispersive waves in the laser cavity, depending on the phase-matching conditions. Therefore, it was possible to generate many Kelly sidebands when the phase-matching conditions were well satisfied in the laser cavity. Note that there are several reports on obtaining many Kelly peaks in passively mode-locked Tm-doped fiber lasers\(^{51-53}\). The temporal shape and spectrum of the output pulses exhibited little change when the pump power was changed from 224 to 297 mW. The measured period of the pulse train was \(~ 56.92 \text{ ns}\) (Fig. 9b) that corresponded to a repetition rate of \(~ 17.57 \text{ MHz}\), which is a fundamental resonance frequency of the cavity.

We subsequently performed autocorrelation measurements of the output pulses (Fig. 10a), for which the output temporal width was measured at \(~ 840 \text{ fs}\). Considering the 3-dB bandwidth of \(~ 4.67 \text{ nm}\), the time-bandwidth product was calculated as \(~ 0.317\), which indicates that the pulses are almost transform-limited. Figure 10b depicts the radio frequency (RF) spectrum of the output pulses; the signal-to-noise ratio (SNR) was measured as \(~ 62 \text{ dB}\) with a fundamental frequency of \(~ 17.57 \text{ MHz}\). A 1-GHz-span electrical spectrum was also measured (Fig. 10b), in which the strong harmonic signals imply that the laser output consisted of stable mode-locked pulses at the fundamental resonance frequency.

Figure 11a demonstrates the relationship between the average power of our laser output and the pump power, in which we can see the linear increase in output power with the increase in pump power. The maximum output power was \(~ 12.7 \text{ mW}\), and the slope efficiency was \(~ 1.5\%\). Stable output pulses existed at a pump power range from \(~ 224\) to \(~ 297 \text{ mW}\).

Finally, the long-term stability of the pulse laser was examined by measuring the output spectrum every 10 min for 1 h with the pump power set at \(~ 297 \text{ mW}\) (Fig. 11b). It can be indirectly inferred from the measurements that stable mode-locking was maintained for the duration of the experiment.

**Conclusion**

We performed the Z-scan measurements at 1.9 \(\mu\text{m}\) to investigate the nonlinear optical responses in ReSe\(_2\). From the results, the nonlinear absorption coefficient of ReSe\(_2\) was approximately \(~ 11.3 \times 10^4 \text{ cm/GW}\) and the nonlinear refractive index was around \(~ 6.2 \times 10^{-2} \text{ cm}^2/\text{GW}\). Furthermore, through energy band structure calculations with the PBE functional, we showed that the bandgap of ReSe\(_2\) decreases with an increase in atomic defects, allowing for a broader saturable absorption bandwidth that can cover the mid-infrared wavelength region. Moreover, we experimentally demonstrated hybrid mode-locking with a 1.9-\(\mu\text{m}\) fiber laser with a ReSe\(_2\)/PVA-based SA. Due to both nonlinear saturable absorption and the high PDL of the prepared SA, 840-fs mode-locked pulses could be generated from a co-doped Tm-Ho fiber laser ring cavity.

We believe that this investigation will be technically meaningful from the viewpoint of providing useful data for producing promising nonlinear optical materials that could be used in the implementation of nonlinear
Figure 10. (a) An autocorrelation trace and (b) an electrical spectrum. Inset: the electrical spectrum over 1 GHz at a pump power of ~297 mW.

Figure 11. (a) Pump output characteristics with continuous wave and pulse regions shown. (b) Measured output optical spectrum with a pump power of ~297 mW for 1 h.
optical and photonic devices. Further investigations need to be conducted to fully understand the nonlinear optical properties of ReSe₂ in the mid-infrared spectral region beyond 2 μm.

Methods

Z-scan measurement. A 1.2-ps fiber laser operating at 1.9 μm was used as the input pulse. The input beam was focused through a plano-convex lens into the ReSe₂ sample, and the beam passing through the ReSe₂ sample was separated through a beam splitter. The sample was gradually moved in the propagation direction. One of the two separated beams was used for the OA Z-scan while the other passed through the aperture and was used for CA Z-scan. Power meters were used to measure the varying power of the beam while the sample moved.

Nonlinear transmission curve measurement. The fiber laser used in the Z-scan measurements was used as the input source that was adjusted using a variable optical attenuator. After a 3-dB coupler, the input pulses were separated into two ports. One was directly detected by a power meter to measure the reference beam power while the other was connected to the prepared SA to monitor the output power for comparison with the input power. A PC was employed within the setup to show the non-negligible PDL of the SA.

References

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1. Langrock, C., Kumar, S., McGeehan, J. E., Willner, A. E. & Fejer, M. M. All-optical signal processing using χ(2) nonlinearities in guided-wave devices. J. Lightwave Technol. 24, 2579–2592 (2006).
2. Li, L., Abdukerim, N. & Rochette, M. Mid-infrared wavelength conversion from As₂Se₃ microwires. Opt. Lett. 42, 639–642 (2017).
3. Armengol, D. J., Alford, W. J., Raymond, T. D., Smith, A. V. & Bowers, M. S. Parametric amplification and oscillation with walkoff-compensating crystals. J. Opt. Soc. Am. B 14, 460–474 (1997).
4. Asobe, M., Kanamori, T. & Kubodera, K. Ultrafast all-optical switching using highly nonlinear chalcogenide glass fiber. IEEE Photon. Technol. Lett. 4, 362–365 (1992).
5. Set, S. Y., Yaguchi, H., Tanaka, Y. & Jablonski, M. Laser mode locking using a saturable absorber incorporating carbon nanotubes. J. Lightwave Technol. 22, 51–56 (2014).
6. Singh, K. D., Sohn, J. E. & Lalama, S. J. Second harmonic generation in polycrystal polymers. Appl. Phys. Lett. 49, 248 (1986).
7. Petropulos, P. et al. 2R-regenerative all-optical switch based on a highly nonlinear holey fiber. Opt. Lett. 26, 1233–1235 (2001).
8. Lee, J., Kim, K., Lee, J., Jhon, Y. I. & Lee, J. H. Topological insulators for mode-locking of 2-μm fiber lasers. Nano Res. 4, 297–307 (2011).
9. Bao, Q. et al. Monolayer graphene as a saturable absorber in a mode-locked laser. Nano Lett. 12, 769–773 (2012).
10. Cui, Y., Lu, F. & Liu, X. Nonlinear saturable and polarization-induced absorption of rhenium disulfide. Adv. Electron. Mater. 8, 1901762 (2020).
11. Zhang, H. et al. Molybdenum disulphide (MoS₂) as a broadband saturable absorber for ultra-fast photonics. Opt. Express 22, 7249–7260 (2014).
12. Huang, B. et al. Metallic MXene saturable absorber for femtosecond mode-locked lasers. Adv. Mater. 29, 1702496 (2017).
13. Jiang, X. et al. Broadband nonlinear photonics in few-layer MXene Ti₃C₂Tx (T = F, O, or OH). Laser Photon. Rev. 12, 1700229 (2018).
14. Fan, T. et al. MXene: Two dimensional inorganic compounds, for generation of bound state soliton pulses in nonlinear optical system. Nanophotonics 9, 2505–2513 (2020).
15. Cui, Y., Li, F. & Liu, X. Nonlinear saturable and polarization-induced absorption of rhenium disulfide. Sci. Rep. 7, 40080 (2017).
16. Xu, X. et al. Broadband rhenium disulfide optical modulator for solid-state lasers. Photon. Res. 6, 498–505 (2018).
17. Su, X. et al. Few-layer rhenium diselenide: An ambient-stable nonlinear optical modulator. Opt. Mater. Express 8, 926–935 (2018).
18. Li, Z. et al. Invited article: Mode-locked waveguide lasers modulated by rhenium diselenide: As a new saturable absorber. Appl. Photon. Photon. Technol. Lett. 8, 080802 (2018).
19. Lee, J., Lee, K., Kwon, S., Boo, B. & Lee, J. H. Investigation of nonlinear optical properties of rhenium diselenide and its application as a femtosecond mode-locker. Photon. Res. 7, 984–993 (2019).
35. Cober, C. M., Sonde, S. S., Tutuc, E. & Benerjee, S. K. Improved contact resistance in ReSe₂ thin film field-effect transistors. Appl. Phys. Lett. 108, 162104 (2016).
36. Qi, F. et al. Self-assembled chrysanthemum-like micropheres constructed by few-layer ReSe₂, nanosheets as a highly efficient and stable electrocatalyst for hydrogen evolution reaction. Electrochim. Acta 224, 593–599 (2017).
37. Wolverson, D., Crampin, S., Kazei, A. S., Flie, A. & Bending, S. J. Raman spectra of monolayer, few-layer, and bulk ReSe₂: An anisotropic layered semiconductor. ACS Nano 8, 11154–11164 (2014).
38. Yang, S. et al. Layer-dependent electrical and optoelectronic responses of ReSe₂, nanosheet transistors. Nanoscale 6, 7226–7231 (2014).
39. Jiang, S. et al. Application of chemical vapor-deposited monolayer ReSe₂ in the electrocatalytic hydrogen evolution reaction. Nano Res. 11, 1787–1797 (2018).
40. Virtual Lab. Inc. Materials Square (2017). https://www.materialsquare.com/
41. Liu, F. et al. Optoelectronic properties of atomically thin ReSe₂ with weak interlayer coupling. Nanoscale 8, 5826 (2016).
42. Mao, D. et al. WS₂ saturable absorber for dissipative soliton mode locking at 1.06 and 1.55 μm. Opt. Express 23, 27509–27519 (2015).
43. Koo, J. et al. Near-infrared saturable absorption defective bulk-structured WTe₂ for femtosecond laser mode-locking. Adv. Funct. Mater. 26, 7454–7461 (2016).
44. Sheik-Bahae, M., Said, A. A. & Van Stryland, E. W. High-sensitivity, single-beam n² measurements. IEEE J. Quantum Electron. 34, 1502908 (2017).
45. Ge, Y. et al. Broadband nonlinear photoresponse of 2D TiS₂ for ultrashort pulse generation and all-optical thresholding devices. Adv. Opt. Mater. 6, 1701166 (2018).
46. Jiang, X. et al. Ultrathin metal-organic framework: and emerging broadband nonlinear optical material for ultrafast photonics. Adv. Opt. Mater. 6, 1800561 (2018).
47. Zapata, J. D. et al. Efficient graphene saturable absorbers on D-shaped optical fiber for ultrashort pulse generation. Sci. Rep. 6, 20644 (2016).
48. Kowalczyk, M. et al. Sb₂Te₃-deposited D-shaped fiber as a saturable absorber for mode-locked Yb-doped fiber lasers. Opt. Mater. Express 6, 2273–2282 (2016).
49. Jeon, J., Lee, J. & Lee, J. H. Numerical study on the minimum modulation depth of a saturable absorber for stable fiber laser mode locking. J. Opt. Soc. Am. B 32, 31–37 (2015).
50. Lee, J., Kwon, S. & Lee, J. H. Numerical investigation of the impact of the saturable absorber recovery time on the mode-locking performance of fiber lasers. J. Lightwave Technol. 38, 4124–4132 (2020).
51. Qiangsong, J. et al. Mode-locking thulium-doped fiber laser with 1.78-GHz repetition rate based on combination of nonlinear polarization rotation and semiconductor saturable absorber mirror. IEEE Photon. J. 9, 1502808 (2017).
52. Wang, P., Xiao, X., Grelu, P. & Yang, C. Subsideband generation associated with period-N pulsations in Tm soliton fiber lasers. IEEE Photon. J. 9, 1502908 (2017).
53. Wang, T. et al. Passively mode-locked fiber lasers based on nonlinearity at 2-μm band. IEEE J. Sel. Top. Quantum Electron. 24, 1102011 (2018).
54. Zhang, J. et al. Ultrafast saturable absorption of MoS₂ nanosheets under different pulse-width excitation conditions. Opt. Lett. 43, 243–246 (2018).
55. He, M. et al. Enhanced nonlinear saturable absorption of MoS₂/graphene nanocomposite films. J. Phys. Chem. C 121, 27147–27153 (2017).
56. Zhang, S. et al. Direct observation of degenerate two-photon absorption and its saturation in WS₂ and MoS₂ monolayer and few-layer films. ACS Nano 9, 7142–7150 (2016).
57. Bikorimana, S. et al. Nonlinear optical response in two-dimensional transition metal dichalcogenide multilayer: WS₂, WSe₂, MoS₂ and MoSe₂, Materials Express 24, 20685–20695 (2016).
58. Zheng, X. et al. Z-scan measurement of the nonlinear refractive index of monolayer WS₂. Opt. Express 23, 15616–15623 (2015).
59. Wang, J. et al. Mode-locked thulium-doped fiber laser with chemical vapor deposited molybdenum ditelluride. Opt. Lett. 43, 1998–2001 (2018).
60. Cheng, C. et al. Tin diselenide as a new saturable absorber for generation of laser pulses at 1 μm. Opt. Express 25, 6132–6140 (2017).

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Author contributions

J.L. and J.H.L. conceived the idea of the experiment, J.L. and S.K. conducted the measurements, J.L. performed the numerical simulations. J.L., T.K., L.Z. and J.J. analyzed the results, J.L. and J.H.L. wrote the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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