Passively Mode-Locked Thulium- and Thulium/Holmium-Doped Fiber Lasers Using MXene Nb₂C-Coated Microfiber

Harith Ahmad (✉ harith@um.edu.my)

University of Malaya

Rizal Ramli

University of Malaya

Nor Najwa Ismail

University of Malaya

Siti Nabila Aidit

University of Malaya

Norazriena Yusoff

University of Malaya

Muhamad Zharif Samion

University of Malaya

Research Article

Keywords: 2D, Thulium, fiber, MXene

Posted Date: February 17th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-199981/v1>

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

[Read Full License](#)

Abstract

As a result of the emergence of two-dimensional (2D) materials for various opto-electronics applications, a new class of materials named MXenes have been attracting interests due to their outstanding nonlinear properties. In this work, an MXene niobium carbide (Nb_2C) was proposed and demonstrated as a saturable absorber to induce mode-locking in thulium- and thulium/holmium-doped fiber lasers. The Nb_2C solution was first prepared using the liquid exfoliation technique, and then deposited onto a microfiber for integration into the laser cavity. Stable mode-locking operation was observed in both laser cavities, where the center wavelengths of the laser were recorded at 1944 nm for the TDFL and 1950 nm for the THDFL. The generated pulses in the TDFL and THDFL had repetition rates of 9.35 and 11.76 MHz respectively, while their corresponding pulse widths were 1.67 and 1.34 ps. Both of the lasers were highly stable, having SNR values of more than 52 dB and showed no major fluctuations when tested for their long-term stabilities. The results demonstrate an excellent performance of the Nb_2C as a saturable absorber, offering opportunities to further explore MXenes for future photonics devices.

Introduction

Optical fiber based devices are a major area of interest within the development of optical fiber amplifiers and lasers. These devices generally cover a wavelength range stretching from the S-band (1460 nm to 1530 nm)^{1–3} to L-band region (1565 nm to 1625 nm)^{4–6}. The advancement of optical fiber lasers has seen variety of laser output reported in a various laser configuration including pulsed^{7–12} and multi-wavelength^{13–16}. Tremendous achievement in the field of near-infrared (IR) fiber lasers have kept this field growing to cater the ever-growing demands from laser end-users. This include expanding the wavelength operation to 2.0 μm region. Eye-safe 2.0 μm laser sources are of particular interest due to its potential in medical, space, defence and industrial applications. A key aspect of 2.0 μm light sources is its ability to be strongly absorbed in the human eye's vitreous part, reducing the possibility to harm the retina¹⁷. This property is much needed in free-space optical communication system¹⁸ or in LIDAR (Light Detection and Ranging)^{19–21}. Additionally, 2.0 μm laser sources play a critical role in the near-infrared (IR) gas spectroscopy and sensing owing to the efficient light absorption of atmospheric gaseous (e.g., carbon dioxide, CO_2) at 2.0 μm wavelength range^{22–24}. 2.0 μm fiber laser source can be generated from thulium-doped²⁵ and thulium/holmium-doped fiber lasers²⁶. The thulium and thulium/holmium doped fiber, exhibit broad bandwidth covering almost 500 nm, from 1.7 μm to 2.2 μm . This feature allows a wide selection range of laser operations in the eye-safe spectral region, including the continuous-wave (CW) mode and the Q-switching mode. Such broad bandwidth is also known to be capable of generating femtosecond pulses in the mode-locking regime^{27–32}.

Mode-locked fiber lasers as highly versatile light sources have attracted enormous attention due to its ability to access a wide range of scientific and industrial processes including optical communications, sensing, material processing and medical treatment^{33–38}. So far, two main approaches utilized in the operation of mode-locked fiber lasers are based on active and passive techniques. Compared to active,

passive technique has the intrinsic advantages of high stability and reproducibility for robust ultrashort optical pulses. Saturable absorber (SA) plays a vital role in passive mode-locking technique. Presently, SA can be classified into two broad types namely, artificial, and real. Artificial SAs such as nonlinear loop mirrors^{39–43} and nonlinear polarization rotation^{44,45} are based on nonlinear effects with the properties of high damage threshold and low cost. These SAs provide a good platform for operation of high energy laser. However, the vulnerability of the laser system towards environmental perturbation has limit its practical applications. Real SAs, made up of materials that exhibit intensity-dependent transmission are regarded as a more effective way to generate mode-locked pulses. Specifically, two-dimensional (2D) material-based SAs have been widely employed as effective SAs due to their excellent optical properties, including wide absorption band and ultrafast recovery time. Following the successful exfoliation of graphene and its first ultrafast application, other 2D materials including topological insulators (TIs)^{31,46–49}, transition metal dichalcogenides (TMDs)^{50–55}, metal chalcogenides⁵⁶, antimonene⁵⁷ and MXenes have been explored for their unique saturable absorption property in ultrafast laser generation.

Transition metal carbides and/or nitrides, which are widely known as MXenes, are a member of the 2D material group that possess unique properties that could be altered by simply manipulating the composition and surface termination elements^{58,59}. In general, MXenes consist of few-atoms-thick layers of transition metal carbides, nitrides, or carbonitrides with composition of $M_{n+1}X_nT_x$, where M stands for an early transition metal (such as: Ti, V, Cr, Nb, etc.), X stands for carbon and/or nitrogen, $n = 1, 2$, or 3 , and T_x is the surface termination groups ($(-O)$, $(-F)$, and $(-OH)$)⁶⁰. Being in the family of MXene, niobium carbide (Nb_2C) has received extensive research attention in the last few years due to its unique physical and chemical properties that are valuable in various applications⁶¹. Theoretically, it has been predicted that Nb_2C demonstrate a great reduction of lattice thermal conductivity resulted from the abnormal electron–phonon scatterings with intensities close to that of phonon–phonon scatterings⁶². In a study conducted by *Lin et. al.*⁶³ has revealed that the Nb_2C possess strong optical response in the near infrared region as it shows high photothermal conversion efficiency that can be used in biomedicine, particularly for cancer phototherapy. In another report, *Wang et. al.*⁶⁴ has investigated the broad-band nonlinear optical response and the ultrafast carrier dynamics of Nb_2C over the wavelength ranging from visible to the near-infrared region. Their finding discloses the dependency of the nonlinear optical response of Nb_2C on wavelength and excitation intensity. The unique nonlinear absorption response inversion properties of Nb_2C , that is the ability to shift from saturable absorption to two-photon absorption in near infrared region has facilitate its vast applications in nonlinear photonics, in particular as an optical switch⁶⁵.

In this work, high-quality few layer Nb_2C nanosheets were fabricated by the liquid phase exfoliation method and deposited onto a tapered fiber using a drop-casting method, forming an all-fiber SA device. Based on Nb_2C -coated microfiber SA, passive mode-locking operation in TDFL and THDFL were successfully generated. Both laser systems show stable mode-locked pulses with the former system operating at 1948 nm and the later operating at 1952 nm. These results suggest that the Nb_2C -coated microfiber could perform as a practical and a high-performance SA for an ultrafast fiber laser generation

in the 2.0 μm region. This could further promote the development of MXene-based optical devices in the photonics technology.

Characterization Of Nbc Mxene

The surface morphology of the Nb_2C MXene in the powder form was investigated by field emission scanning electron microscopy (FESEM) and the elemental composition of Nb_2C MXene was determined by energy dispersive X-ray (EDX) analysis. These studies were performed using a Hitachi Model SU8220 FESEM which was equipped with EDX detector and operating at 2.0 kV. Figure 1 shows the FESEM image of Nb_2C Mxene captured at the magnification of 20.0k. It can be observed that Nb_2C MXene exhibits a sheet-like structure with multiple layers stacked together, whose size was about 2.0 μm .

Figure 2 represents the EDX elemental mapping images of Nb_2C MXene where the distribution of each element can be clearly seen. The Niobium (Nb) and Carbon (C) maps verified the presence of Nb and C elements, thus confirming the successfully formation of Nb_2C MXene.

An atomic force microscope (Park System NX-10 AFM) was used to measure the thickness of the Nb_2C MXene. The measurement was done under non-contact mode. Initially, 10 μL of Nb_2C MXene solution was deposited on the Si substrate using the spin coating technique. The sample was dried at room temperature overnight before being used for thickness measurement. The AFM topography image of Nb_2C MXene together with its corresponding lateral height measurement were presented in Fig. 3(a) and Fig. 3(b), respectively. The obtained result demonstrates that the Nb_2C MXene exhibits few-layer structure of the Nb_2C sheet with a thickness of about 28 nm and lateral size of approximately 1.2 μm .

The measurement of nonlinear optical absorption of MXene Nb_2C -coated microfiber SA was examined using the twin-detector measurement technique. A 1950 nm Toptica FemtoFerb femtosecond laser with a repetition rate of 30 MHz and a pulse width of 100 fs was employed as the seed laser. The laser source was connected to a variable attenuator and subsequently to a 3 dB optical coupler for beam splitting. One port of the 3 dB coupler was connected to the Nb_2C -coated microfiber SA and another port was connected directly to a microfiber without the SA as the reference port. Both transmitted powers were measured using optical power meter. The experimental data was recorded and fitted using the saturation model equation below:

$$\alpha(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}$$

where I , I_{sat} , α_{ns} , α_s signify the laser input intensity, saturation intensity, non-saturated loss and modulation depth. From the fitting of the measured data shown in Fig. 4, the saturation intensity and modulation depth obtained were 0.4 MW/cm² and 6.77 %, respectively.

Experimental Setup

To prepare the SA device, the Nb₂C solution was drop-casted onto a microfiber with a waist diameter and tapered length of around 8 μm and 3 cm, respectively. The insertion loss of the microfiber at 2000 nm was initially measured to be 6 dB without the Nb₂C, while the value increased to 7.5 dB after the material was deposited. The MXene-coated microfiber was incorporated into the THDFL and TDFL cavities that utilized the dual pumping mechanism as shown in Fig. 5. Both lasers had the same cavity design, except for the different active fibers being used as the amplifying medium. Two laser diodes (LDs) with center wavelengths at 1560 nm were used as the pump source to pump the active fiber. Each LD was then connected to a 1550 nm isolator to protect the LD from back-reflections. A 1550/2000 nm wavelength division multiplexer (WDM) was placed after each of the 1550 nm isolator to guide the 1560 nm pump light to the active fiber. A 2000 nm isolator was placed after WDM₂ to allow the light to only propagate in the clockwise direction. The output of the isolator was then connected to a 90:10 coupler, where 10% of the signal was taken as the output whereas the 90% was looped back to the cavity. A polarization controller (PC) was connected to the 90% port of the coupler and was used to adjust the polarization states of the circulating light. The other end of the PC was connected to the Nb₂C-coated microfiber, then to the 2000 nm port of the first WDM₁. Thus, completing the ring laser cavity.

The total length of the TDFL was measured around 22.1 m, consist of 4 m of the TDF and 18.1 m single mode fiber (SMF-28), whereas the THDFL had a total cavity length of 17.4 m, involving of 1.5 m of the THDF and 15.9 m of SMF-28. The group velocity dispersions (GVDs) of the TDF and THDF were - 0.0222 ps²/m and - 0.0675 ps²/m, respectively. The GVD of SMF-28 was - 0.0663 ps²/m at 1944 nm and - 0.0672 ps²/m at 1950 nm. By computing the $L_{SMF-28}GVD_{SMF-28} + L_{Active\ fiber}GVD_{Active\ fiber}$, the net cavity dispersion of -1.28 ps² and - 1.17 ps² were obtained for TDFL and THDFL, respectively, indicating that the operation of both lasers were in the anomalous dispersion regime. The characteristics for the gain medium for both cavities are given in Table 1.

Table 1
Characteristics of the active fibers used in the TDFL and THDFL cavities.

Cavity	Thulium-doped Fiber Laser	Thulium/Holmium-doped Fiber Laser
Active fiber	OFS Thulium doped fiber (TmDF200)	CorActive Thulium/Holmium doped fiber (TH512)
Length	4 meter	1.5 meter
Numerical aperture	0.26	0.16
Absorption	22 dB/m at 1550 nm	15 dB/m at 1550nm
GVD	-0.0222 ps ² /m	-0.0675 ps ² /m

Results And Discussion

Mode-locked Thulium-doped fiber laser (TDFL) using Nb₂C.

The performance of the Nb₂C coated microfiber for the generation of mode-locking was first studied using the TDFL cavity. Mode-locked laser was initiated at pump power of 123 mW, with a suitable adjustment of PC. Figure 6 summarizes the characteristics of mode-locked TDFL at pump power of 476 mW. The soliton spectrum, which is a typical spectrum of mode-locked fiber laser operating in the anomalous regime, is depicted in Fig. 6(a). The spectrum was centered at 1944 nm with a 3-dB bandwidth of 2.8 nm. The mode-locked pulse train is depicted in Fig. 6(b), having a repetition rate of 9.35 MHz. The pulse train exhibits a uniform pulse intensity with a pulse interval of 107 ns, which matched well with the cavity round-trip time. This validates the fundamental operation of the mode-locked laser. Figure 6(c) shows the autocorrelation trace fitted by a hyperbolic-secant (Sech²) function, showing a pulse duration of 1.67 ps. With values obtained from the mode-locked, the computed time bandwidth product (TBP) is 0.320 which is marginally higher than 0.315 indicating that the pulse is slightly chirped. Figure 6(d) shows the RF spectrum with a resolution bandwidth of 1 kHz. A distinct and sharp peak was observed at 9.35 MHz with signal-to-noise ratio of more than 52 dB.

Mode-locked Thulium/holmium-doped fiber laser (THDFL) using Nb₂C.

Subsequently, the Nb₂C coated microfiber was incorporated into the THDFL. The properties of the mode-locked THDFL is demonstrated in Fig. 7 at pump power of 397 mW. Figure 7(a) illustrates the mode-locked THDFL spectrum, having a center wavelength at 1950.8 nm with a full-width at half maximum (FWHM) of 3 nm. Similar to the output spectrum of the TDFL, Kelly sidebands were also observed in the optical spectrum. This was the result of the gain fibers exhibiting a relatively large anomalous dispersion in the 2.0 μ m region, causing the mode-locking operation of the 2.0 μ m fiber lasers often lying in the conventional soliton regime. Figure 7(b) shows the mode-locked pulse train having a pulse interval of 85 ns, with a corresponding repetition rate of 11.76 MHz. This tallies well with the fundamental frequency estimated from the total cavity length. The pulse profile obtained from the autocorrelation measurement was fitted with a sech² profile, as illustrated in Fig. 7(c). The pulse width verified with fitted function is around 1.34 ps. The TBP was estimated to be 0.317, which was only slightly larger than the TBP limit of 0.315. This indicates that the generated pulses were close to their transform-limited operation. The RF spectrum was also measured and shown in Fig. 7(d). A distinct peak was observed at the fundamental frequency of 11.76 MHz with an SNR of more than 64 dB. Additionally, the RF spectrum on a wider range of 400 MHz shown in the inset of Fig. 7(d) was seen to be free from any spectral modulation, which eliminates possible Q-switching instabilities.

Figure 8 shows the variation of average output power against pump power for both mode-locked TDFL and THDFL cavities. Low mode-locking threshold of 123 mW was observed in the TDFL. At maximum pump power of 476 mW, the maximum output power for the mode-locked TDFL was recorded to be around 1.1 mW. The slope efficiency of TDFL is 0.3 %. The corresponding peak power was calculated

around 70 W. Meanwhile, the mode-locked THDFL had a maximum output power of around 4.6 mW at maximum pump power of 397 mW with corresponding pulse peak power of 291 W. As compared to TDFL, higher slope efficiency of 1.7 % was obtained in THDFL. It should be noted that a harmonic mode-locking operation was obtained at pump power greater than 397 mW, nevertheless it was not reported here as the interest of this work is only fundamental mode-locking operation. Both output power could be linearly fitted with minimal error, suggesting the capability of the lasers to generate a higher output power if a higher pump power were available.

The Nb₂C-coated microfiber SA also exhibited an excellent stability against degradation, maintaining stable mode-locking operation when tested for its long-term stability. This can be seen from Fig. 9, where the mode-locked spectrum of TDFL and THDFL was recorded at every 10 minutes for 1-hour. Throughout the stability measurement, the center wavelengths of the lasers were maintained at 1944 nm and 1950.8 nm for the TDFL and the THDFL, respectively. Additionally, no significant power fluctuation was observed during their operations. To further verify the generation of mode-locked pulses in both laser cavities were induced by Nb₂C-coated microfiber SA, the SA device was removed from the laser cavities. At any pump power level, only continuous-wave (CW) laser operation was observed in both TDFL and THDFL. This proves that the mode-locking operation was induced by the saturable absorption effect from the Nb₂C completely.

Methods

Preparation of Nb₂C MXene.

Initially, 50 mg of Nb₂C powder (2D Semiconductors, USA) was added in a glass vial containing 10 mL of isopropyl alcohol (IPA, Sigma Aldrich). The mixture was put under the sonication process using a Hielscher UP200Ht probe type sonicator to obtain a homogenous solution. The sonicator was operated with 5 seconds on pulse, 5 seconds off pulse and 40 % power for 4 hours. Next, the obtained black colour suspension was centrifuged for 10 minutes at 4000 rpm to separate the undissolved powder. The supernatant was collected for further use and has been labelled as Nb₂C Mxene solution.

Laser characterisation.

To analyse the output mode-locked pulses, a 2 μ m Newport 818-BB-51F photodetector was used together with a Yokogawa DLM2054 oscilloscope and a Rohde & Schwarz FPC1000 radio-frequency spectrum analyser (RFSA). The spectrum of the mode-locked laser was recorded using a Yokogawa AQ6375 optical spectrum analyser (OSA) at the highest resolution of 0.05 nm. The pulse width measurement was measured by an A.P.E Pulsecheck 150 autocorrelator while the output power was measured using a Thorlabs S148C optical power meter (OPM).

Conclusion

An MXene niobium carbide (Nb_2C) was successfully proven as a saturable absorber to produce stable mode-locked pulses in the 2.0 μm wavelength region. The Nb_2C solution was coated onto a microfiber by the drop-cast method to allow easy integration into thulium- and thulium/holmium-doped fiber laser cavities. The TDFL had a center wavelength at 1944 nm, while the center wavelength of the THDFL was recorded at a slightly longer wavelength at 1950 nm. The generated pulses in the TDFL and THDFL had repetition rates of 9.35 and 11.76 MHz, respectively, while their corresponding pulse widths were 1.67 and 1.34 ps. The maximum peak power generated was 70 W for the TDFL and as high as 291 W for the THDFL. The lasers were highly stable when tested for their long-term stabilities, where no major fluctuation in the center wavelength as well as the peak optical power was observed. The stability was further proven with the SNR values of both lasers recorded to be more than 52 dB. The results show the use of the Nb_2C as a promising mode-locker, offering opportunities to further explore the use of MXenes for future photonics devices.

Declarations

Acknowledgment

This work is funded by the University of Malaya under the grants RK021-2019, TOP100PRC and RU002-2020 and the Ministry of Higher Education, Malaysia under the grant HiCoE Phase II.

Author information

Affiliations

Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia.

Harith Ahmad, Rizal Ramli, Nor Najwa Ismail, Siti Nabila Aidit, Norazriena Yusoff and Muhamad Zharif Samion.

Physics Department, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia.

Harith Ahmad

Author contributions statements

Harith Ahmad proposed the study and designed the experiment. Rizal Ramli performed the TDFL experiment. Nor Najwa Ismail conducted the THDFL experiment. Siti Nabila Aidit contributed to writing of the manuscript. Norazriena Yusoff prepared the Nb_2C MXene, performed the material characterization and contributed to writing of the manuscript. Muhamad Zharif Samion contributed to data analysis.

Competing interests

The authors declare no competing financial interests.

Additional information

Correspondence and requests for materials should be addressed to H.A.

References

1. Harun, S. W., Saat, N. K. & Ahmad, H. An efficient S-band erbium-doped fiber amplifier using double-pass configuration. *IEICE Electron. Express* **2**, 182–185 (2005).
2. Rosolem, J. B. *et al.* All silica S-band double-pass erbium-doped fiber amplifier. *IEEE Photonics Technol. Lett.* **17**, 1399–1401 (2005).
3. Tanabe, S. & Tamaoka, T. Gain characteristics of Tm-doped fluoride fiber amplifier in S-band by dual-wavelength pumping. *J. Non. Cryst. Solids* **326**, 283–286 (2003).
4. Harun, S. W., Low, S. K., Poopalan, P. & Ahmad, H. Gain clamping in L-band erbium-doped fiber amplifier using a fiber Bragg grating. *IEEE photonics Technol. Lett.* **14**, 293–295 (2002).
5. Yang, J., Meng, X. & Liu, C. Accurately control and flatten gain spectrum of L-band erbium doped fiber amplifier based on suitable gain-clamping. *Opt. Laser Technol.* **78**, 74–78 (2016).
6. Ahmad, H., Shahi, S. & Harun, S. W. Bismuth-based erbium-doped fiber as a gain medium for L-band amplification and Brillouin fiber laser. *Laser Phys.* **20**, 716–719 (2010).
7. Xu, N., Ming, N., Han, X., Man, B. & Zhang, H. Large-energy passively Q-switched Er-doped fiber laser based on CVD-Bi₂Se₃ as saturable absorber. *Opt. Mater. Express* **9**, 373–383 (2019).
8. Liu, J. *et al.* Switchable dual-wavelength Q-switched fiber laser using multilayer black phosphorus as a saturable absorber. *Photonics Res.* **6**, 198–203 (2018).
9. Liu, L. *et al.* Passively Q-switched pulses generation from Erbium-doped fiber laser based on microfiber coated PbS quantum dots. *Opt. Fiber Technol.* **46**, 162–166 (2018).
10. Luo, X. *et al.* All-Fiber Mode-Locked Laser Based on Mamyshev Mechanism With High-Energy Pulse Generation at 1550 nm. *J. Light. Technol.* **38**, 1468–1473 (2020).
11. Elahi, P., Kalaycioğlu, H., Li, H., Akçaalan, Ö. & Ilday, F. Ö. 175 fs-long pulses from a high-power single-mode Er-doped fiber laser at 1550 nm. *Opt. Commun.* **403**, 381–384 (2017).
12. Li, D. *et al.* Wavelength and pulse duration tunable ultrafast fiber laser mode-locked with carbon nanotubes. *Sci. Rep.* **8**, 1–8 (2018).
13. Parvizi, R., Arof, H., Ali, N. M., Ahmad, H. & Harun, S. W. 0.16 nm spaced multi-wavelength Brillouin fiber laser in a figure-of-eight configuration. *Opt. Laser Technol.* **43**, 866–869 (2011).
14. Ahmad, H., Zulkifli, M. Z., Latif, A. A. & Harun, S. W. Tunable dual wavelength fiber laser incorporating AWG and optical channel selector by controlling the cavity loss. *Opt. Commun.* **282**, 4771–4775 (2009).
15. Zhou, Y., Lou, S., Tang, Z., Zhao, T. & Zhang, W. Tunable and switchable C-band and L-band multi-wavelength erbium-doped fiber laser employing a large-core fiber filter. *Opt. Laser Technol.* **111**, 262–270 (2019).

16. He, W., Zhu, L., Meng, F., Song, Y. & Dong, M. Selectable and stable C-band multi-wavelength ring cavity erbium-doped fiber laser employing Sagnac loop and tunable filter. *Optik (Stuttg)*. **176**, 528–534 (2019).
17. Scholle, K., Lamrini, S., Koopmann, P. & Fuhrberg, P. 2 μm laser sources and their possible applications. in *Frontiers in guided wave optics and optoelectronics* (IntechOpen, 2010).
18. Wilkins, G. D. Eye-safe free-space laser communications. in *Proceedings of the IEEE National Aerospace and Electronics Conference NAECON 1996* vol. 2 710–715 (1996).
19. Singh, U. N., Yu, J., Petros, M., Refaat, T. & Reithmaier, K. Development of a pulsed 2-micron integrated path differential absorption lidar for CO₂ measurement. in *Lidar Remote Sensing for Environmental Monitoring XIV* vol. 8872 887209 (International Society for Optics and Photonics, 2013).
20. Singh, U. N. *et al.* Airborne 2-micron double-pulsed integrated path differential absorption lidar for column CO₂ measurement. in *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing X* vol. 9246 924602 (International Society for Optics and Photonics, 2014).
21. Mizutani, K. *et al.* Conductive-cooled 2-micron laser development for wind and CO₂ measurements. in *Lidar Remote Sensing for Environmental Monitoring XIII* vol. 8526 852603 (International Society for Optics and Photonics, 2012).
22. Stepanov, E. V, Kotelnikov, S. N., Stavtsev, A. Y. & Kasoev, S. G. The best absorption lines for the detection of carbon monoxide at 2.35 micron with tunable diode lasers. in *Journal of Physics: Conference Series* vol. 1560 12053 (IOP Publishing, 2020).
23. McAleavey, F. J. *et al.* Narrow linewidth, tunable Tm³⁺-doped fluoride fiber laser for optical-based hydrocarbon gas sensing. *IEEE J. Sel. Top. quantum Electron.* **3**, 1103–1111 (1997).
24. Ghosh, A., Roy, A. S., Chowdhury, S. Das, Sen, R. & Pal, A. All-fiber tunable ring laser source near 2 μm designed for CO₂ sensing. *Sensors Actuators B Chem.* **235**, 547–553 (2016).
25. Li, Z. *et al.* Thulium-doped fiber amplifier for optical communications at 2 μm . *Opt. Express* **21**, 9289–9297 (2013).
26. Honzatko, P., Baravets, Y., Kasik, I. & Podrazky, O. Wideband thulium–holmium-doped fiber source with combined forward and backward amplified spontaneous emission at 1600–2300 nm spectral band. *Opt. Lett.* **39**, 3650–3653 (2014).
27. Wang, J. *et al.* 152 fs nanotube-mode-locked thulium-doped all-fiber laser. *Sci. Rep.* **6**, 1–7 (2016).
28. Sun, B. *et al.* 1867–2010 nm tunable femtosecond thulium-doped all-fiber laser. *Opt. Express* **25**, 8997–9002 (2017).
29. Meng, Y., Li, Y., Xu, Y. & Wang, F. Carbon nanotube mode-locked thulium fiber laser with 200 nm tuning range. *Sci. Rep.* **7**, 1–7 (2017).
30. Hoogland, H., Hänsel, W. & Holzwarth, R. Novel Robust 2- μm All-PM Thulium/Holmium Based Femtosecond Fiber Laser Oscillator. in *CLEO: Science and Innovations SM3L-4* (Optical Society of America, 2017).

31. Lee, J. & Lee, J. H. Femtosecond Tm–Ho co-doped fiber laser using a bulk-structured Bi₂Se₃ topological insulator. *Chinese Phys. B* **27**, 94219 (2018).
32. Jung, M. *et al.* A femtosecond thulium holmium co-doped fiber laser based on graphene oxide evanescent filed interaction. in *2014 Conference on Lasers and Electro-Optics (CLEO)-Laser Science to Photonic Applications* 1–2 (IEEE, 2014).
33. Whitenett, G., Stewart, G., Yu, H. & Culshaw, B. Investigation of a tuneable mode-locked fiber laser for application to multipoint gas spectroscopy. *J. Light. Technol.* **22**, 813 (2004).
34. Mingareev, I. *et al.* Welding of polymers using a 2 μ m thulium fiber laser. *Opt. Laser Technol.* **44**, 2095–2099 (2012).
35. Fried, N. M. & Murray, K. E. High-power thulium fiber laser ablation of urinary tissues at 1.94 μ m. *J. Endourol.* **19**, 25–31 (2005).
36. Marcinkevičius, A. *et al.* Femtosecond laser-assisted three-dimensional microfabrication in silica. *Opt. Lett.* **26**, 277–279 (2001).
37. Kondo, Y. *et al.* Fabrication of long-period fiber gratings by focused irradiation of infrared femtosecond laser pulses. *Opt. Lett.* **24**, 646–648 (1999).
38. Chou, S. Y., Keimel, C. & Gu, J. Ultrafast and direct imprint of nanostructures in silicon. *Nature* **417**, 835–837 (2002).
39. Runge, A. F. J., Aguergaray, C., Provo, R., Erkintalo, M. & Broderick, N. G. R. All-normal dispersion fiber lasers mode-locked with a nonlinear amplifying loop mirror. *Opt. Fiber Technol.* **20**, 657–665 (2014).
40. Kim, D., Kwon, D., Lee, B. & Kim, J. Polarization-maintaining nonlinear-amplifying-loop-mirror mode-locked fiber laser based on a 3×3 coupler. *Opt. Lett.* **44**, 1068–1071 (2019).
41. Szczepanek, J., Kardaś, T. M., Michalska, M., Radzewicz, C. & Stepanenko, Y. Simple all-PM-fiber laser mode-locked with a nonlinear loop mirror. *Opt. Lett.* **40**, 3500–3503 (2015).
42. Ou, S., Liu, G., Qiu, D., Guo, L. & Zhang, Q. All-polarization-maintaining, all-normal-dispersion mode-locked fiber laser with spectral filtering in a nonlinear optical loop mirror. *Opt. Express* **28**, 23670–23678 (2020).
43. Chernysheva, M. A., Krylov, A. A., Kryukov, P. G. & Dianov, E. M. Nonlinear Amplifying Loop-Mirror-Based Mode-Locked Thulium-Doped Fiber Laser. *IEEE Photonics Technol. Lett.* **24**, 1254–1256 (2012).
44. Gao, C., Wang, Z., Luo, H. & Zhan, L. High energy all-fiber Tm-doped femtosecond soliton laser mode-locked by nonlinear polarization rotation. *J. Light. Technol.* **35**, 2988–2993 (2017).
45. Szczepanek, J., Kardaś, T. M., Radzewicz, C. & Stepanenko, Y. Ultrafast laser mode-locked using nonlinear polarization evolution in polarization maintaining fibers. *Opt. Lett.* **42**, 575–578 (2017).
46. Yin, K. *et al.* Soliton mode-locked fiber laser based on topological insulator Bi₂Te₃ nanosheets at 2 μ m. *Photonics Res.* **3**, 72–76 (2015).
47. Sotor, J., Sobon, G., Macherzynski, W. & Abramski, K. M. Harmonically mode-locked Er-doped fiber laser based on a Sb₂Te₃ topological insulator saturable absorber. *Laser Phys. Lett.* **11**, 55102 (2014).

48. Sotor, J., Sobon, G. & Abramski, K. M. Sub-130 fs mode-locked Er-doped fiber laser based on topological insulator. *Opt. Express* **22**, 13244–13249 (2014).
49. Liu, W. *et al.* 70-fs mode-locked erbium-doped fiber laser with topological insulator. *Sci. Rep.* **6**, 19997 (2016).
50. Li, L., Pang, L., Zhao, Q., Liu, W. & Su, Y. VSe₂ nanosheets for ultrafast fiber lasers. *J. Mater. Chem. C* **8**, 1104–1109 (2020).
51. Cheng, P. K. *et al.* Ultrafast Yb-Doped Fiber Laser Using Few Layers of PdS₂ Saturable Absorber. *Nanomaterials* **10**, 2441 (2020).
52. Liu, W., Liu, M., Liu, X., Lei, M. & Wei, Z. SnSSe as a saturable absorber for an ultrafast laser with superior stability. *Opt. Lett.* **45**, 419–422 (2020).
53. Lee, J., Koo, J., Lee, J., Jhon, Y. M. & Lee, J. H. All-fiberized, femtosecond laser at 1912 nm using a bulk-like MoSe₂ saturable absorber. *Opt. Mater. Express* **7**, 2968–2979 (2017).
54. Liu, W. *et al.* Tungsten disulfide saturable absorbers for 67 fs mode-locked erbium-doped fiber lasers. *Opt. Express* **25**, 2950–2959 (2017).
55. Liu, W. *et al.* Tungsten diselenide for mode-locked erbium-doped fiber lasers with short pulse duration. *Nanotechnology* **29**, 174002 (2018).
56. Feng, J. *et al.* 2D ductile transition metal chalcogenides (TMCs): novel high-performance Ag₂S nanosheets for ultrafast photonics. *Adv. Opt. Mater.* **8**, 1901762 (2020).
57. Song, Y. *et al.* Few-layer antimonene decorated microfiber: ultra-short pulse generation and all-optical thresholding with enhanced long term stability. *2D Mater.* **4**, 45010 (2017).
58. Ahmad, H. *et al.* Tunable passively Q-switched erbium-doped fiber laser based on Ti₃C₂T_x MXene as saturable absorber. *Opt. Fiber Technol.* **58**, 102287 (2020).
59. Hart, J. L. *et al.* Control of MXenes' electronic properties through termination and intercalation. *Nat. Commun.* **10**, 1–10 (2019).
60. Gogotsi, Y. & Anasori, B. The rise of MXenes. *ACS Nano* **13**, 8491–8494 (2019).
61. Gao, L. *et al.* Applications of Few-Layer Nb₂C MXene: Narrow-Band Photodetectors and Femtosecond Mode-Locked Fiber Lasers. *ACS Nano* **15**, 954–965 (2021)
62. Huang, Y., Zhou, J., Wang, G. & Sun, Z. Abnormally Strong Electron–Phonon Scattering Induced Unprecedented Reduction in Lattice Thermal Conductivity of Two-Dimensional Nb₂C. *J. Am. Chem. Soc.* **141**, 8503–8508 (2019).
63. Lin, H., Gao, S., Dai, C., Chen, Y. & Shi, J. A two-dimensional biodegradable niobium carbide (MXene) for photothermal tumor eradication in NIR-I and NIR-II biowindows. *J. Am. Chem. Soc.* **139**, 16235–16247 (2017).
64. Wang, Y. *et al.* Niobium carbide MXenes with broad-band nonlinear optical response and ultrafast carrier dynamics. *ACS Nano* **14**, 10492–10502 (2020).

65. Gao, L. *et al.* Ultrafast Relaxation Dynamics and Nonlinear Response of Few-Layer Niobium Carbide MXene. *Small Methods* **4**, 2000250 (2020).

Figures

Figure 1

FESEM image of Nb₂C MXene in the powder form.

Figure 2

EDX elemental mapping of Nb₂C MXene.

Figure 3

(a) AFM topography image of Nb₂C MXene and (b) the corresponding lateral height measurement.

Figure 4

Nonlinear absorption curve of MXene Nb₂C-coated microfiber SA.

Figure 5

Schematic diagram of 2.0 μm passively mode-locked fiber laser cavity.

Figure 6

Mode-locked TDFL output at 476 mW. (a) Enlarged optical spectrum (Inset shows full soliton spectrum); (b) oscilloscope trace; (c) autocorrelation trace and; (d) radio frequency (RF) spectrum (Inset shows RF spectrum on wider span range of 400 MHz).

Figure 7

Mode-locked THDFL output at 397 mW. (a) Enlarged optical spectrum (Inset shows full soliton spectrum); (b) pulse train; (c) autocorrelation trace and; (d) radio frequency (RF) spectrum (Inset shows RF spectrum on wider span range of 400 MHz).

Figure 8

Variation of output power against pump power for TDFL and THDFL.

Figure 9

Stability measurement of (a) TDFL at 476 mW and (b) THDFL at 397 mW over a period of 1-hour.