

Titanium tin carbide as saturable absorber in C-band fiber laser

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Abstract: In this work, the Q-switched Erbium-doped fiber laser (EDFL) is visualized using Ti_2SnC as saturable absorber. The thin layer of Ti_2SnC is mechanically exfoliated from a bulk material and pasted onto a fiber ferrule and integrated into EDFL by sandwiched method. The proposed Q-switched EDFL successfully achieved a stable pulse train, and the smallest pulse width of 1.26 μs and the highest pulse energy of 43.76 nJ are obtained at low operational pump power of 110 mW. The pulse energy obtained is comparable to other metal–ceramic based SA, with relatively low pump power. Owing to the strength of thermal shock resistance and oxidation resistant, the proposed saturable absorber is more feasible to cater the commercialization requirements.

Keywords: Q-switching operation; Fiber lasers; Metal–ceramic; Saturable absorber

1. Introduction

MAX phase is a machinable metal–ceramic material that possesses the strength of both metal and ceramic. Even though MAX phase is more known as precursor to produce MXene, it also exhibits exceptional material characteristic that has attracted a great interest in various applications, including hazardous pollutants removal, nuclear engineering, aerospace, and high temperature applications [1–3]. In general, MAX phase materials have excellent electrical, mechanical and thermodynamics properties [4, 5]. Furthermore, they have good structural stability, thermal shock resistance, damage tolerance, lightweight and good oxidation resistant [6].

The titanium tin carbide (Ti_2SnC) is one of the early founded MAX phase materials. The Ti_2SnC structure was first proposed based on powder diffraction X-ray data (space group: P63/m.m.c.; hexagonal axes $a = 0.31626$ nm, $c = 1.36789$ nm) [7]. Inheriting the remarkable properties of MAX phases, Ti_2SnC exhibits impressive material self-healing capabilities. For instance, it can be employed as a healing material, effectively restoring electrical and

mechanical properties while mending cracks and flaws at relatively low temperatures (as low as 800 °C) [8]. Furthermore, Ti_2SnC has displayed promise in energy storage applications. In Li-ion battery, Ti_2SnC nanosheets function as anode exhibits an increasing specific capacity with cycling. After 1000 charge–discharge cycles, Ti_2SnC nanosheets delivered a high specific capacity of 735 mA h g^{-1} at a current density of 50 mA g^{-1} , which surpassing the performance of most other MAX phase materials [9]. The exceptional mechanical and electrical properties of Ti_2SnC have been widely utilized; however, the exploration of photonic application is still relatively intangible.

In photonics application, pulsed laser is one of the primary research topics due to the feasibility in material processing [10], medical treatment [11, 12] and telecommunication [13, 14]. The development of low-dimensional material spurs the exploration of passively pulsed laser using saturable absorber (SA). Many emerging materials have been reported as SA in pulsed laser system, such as graphene [15], transition metal dichalcogenide (TMD) [16], MXene [17], topological insulator [18] and vanadium pentoxide [19]. Recently, MAX phase has also been reported as SA [20]. From the reported results, the performance of MAX phase SA is comparable to other low-

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dimensional material. Owing to the nature of ceramic, MAX phase SA could perform better in hazardous environment due to its thermal shock resistance and oxidation resistant. Therefore, it is more feasible to cater the commercialization requirements.

In this work, we report the application of Ti_2SnC as SA in Erbium-doped fiber laser (EDFL) system to induce Q-switching operation. The Ti_2SnC thin layer is mechanically exfoliated from a bulk material and integrated into EDFL by sandwiched method. The proposed Q-switched EDFL achieved 1.26 μs pulsed width and highest pulse energy of 43.76 nJ at low operational pump power of 110 mW.

2. Preparation and characterization of Ti_2SnC

Mechanical exfoliation is a method to physically separate layers from a bulk material using mechanical force. Ti_2SnC is a ternary compound that belongs to the family of MAX phases, which are layered materials with a unique combination of metallic and ceramic properties. The most common mechanical exfoliation technique is the “scotch tape” method, which involves repeatedly pressing and peeling a piece of adhesive tape on the surface of the bulk material. As the tape is peeled off, it can pull away thin layers of Ti_2SnC and then be transferred onto a substrate for further analysis or device fabrication. The general steps for performing mechanical exfoliation of Ti_2SnC using the scotch tape method are shown in Fig. 1. The first step was to obtain a piece of bulk Ti_2SnC material, which is clean and free of any contaminants. The next step was to cut a small piece of adhesive tape (such as scotch tape) and stick it onto the surface of the bulk material. The third step was to use a finger to press the tape firmly onto the surface of the bulk material, making sure to apply even pressure across the entire area. The fourth step was to slowly peel the tape off the surface of the bulk material, taking care not to tear the

tape or leave any residue on the surface. Lastly, the previous steps were repeated with a fresh piece of tape each time, pressing, and peeling in different directions and locations on the surface of the bulk material to obtain thinner flakes. Overall, mechanical exfoliation is a relatively simple and low-cost method of processing layered materials.

The presence and quality of the Ti_2SnC on the tape were checked by examining its field emission scanning electron microscopy (FESEM) image. As shown in Fig. 2a, the field emission scanning electron microscopy (FESEM) image of Ti_2SnC has a high density of microrods and micrograins, which can be clearly viewed and distributed randomly on the substrate surface. These microrods and micrograins are in irregular shapes. The presence of the Ti_2SnC layers on the tape was affirmed by analyzing the energy-dispersive X-ray spectroscopy (EDX) of the FESEM image. The EDX spectrum of Ti_2SnC is recorded in Fig. 2b. It indicates the presence of 26.38 wt.% titanium (Ti), and 12.54 wt.% Carbon (C). The linear absorption of Ti_2SnC SA was obtained by utilizing an optical spectrum analyzer (OSA) and a white light source, as shown in Fig. 2c. At the wavelength of 1559.5 nm, the linear absorption was around 1.12 dB. On the other hand, the nonlinear absorption of the Ti_2SnC SA was then characterized by utilizing a twin balance detection approach. In the measurement, we used a home-built mode-locked fiber laser as the light source. The output pulse train of the laser worked at a center wavelength of 1557 nm with a repetition rate and pulse duration of 1 MHz and 3.63 ps, respectively. The output port of the laser was connected to optical amplifier and then to the variable optical attenuator (VOA) to tune the output intensity of the laser. A 3 dB coupler was used after the VOA to split the beam power equally into two portions. The first portion was directly connected to the optical power meter as a reference power. While the other portion passed through Ti_2SnC SA and the transmission power was recorded by another optical power meter. Figure 2d shows



Fig. 1 The process of mechanical exfoliation method

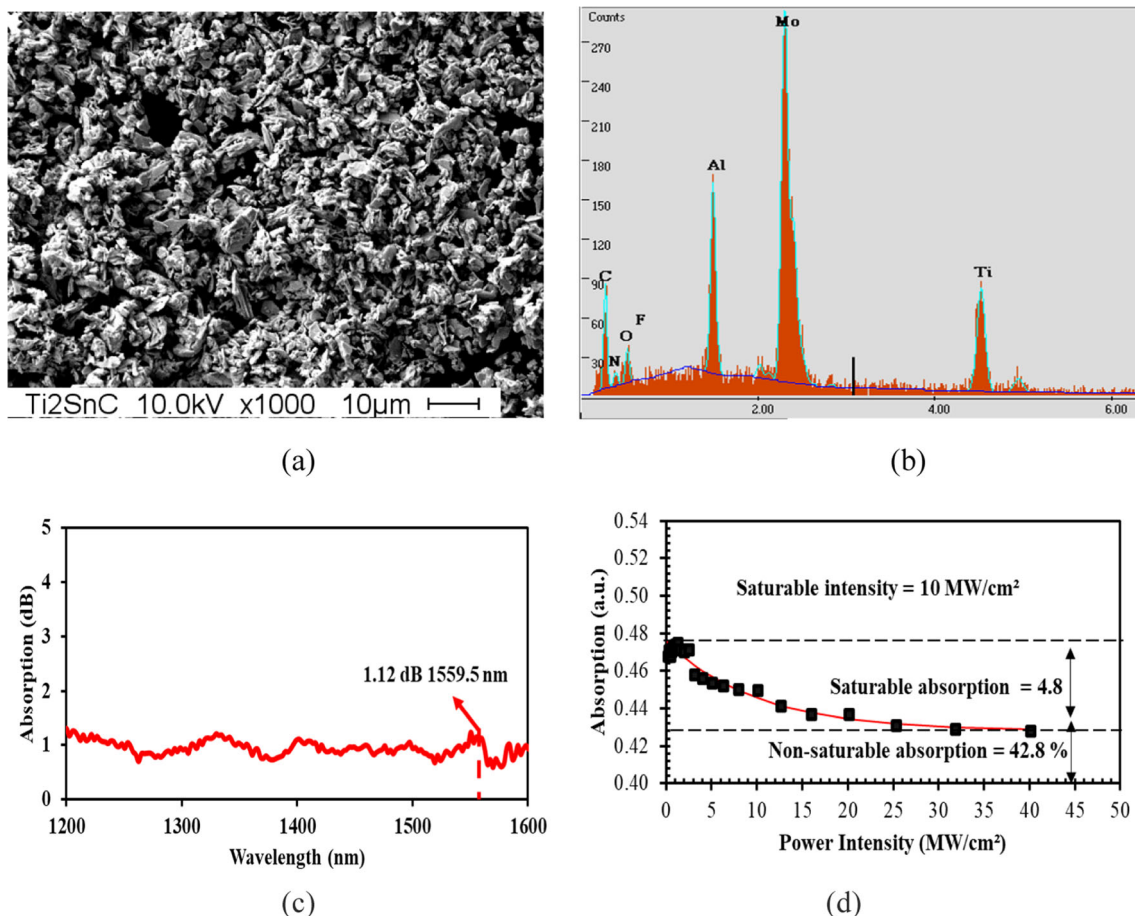


Fig. 2 (a) FESEM image, (b) EDX spectrum, (c) Linear absorption of Ti₂SnC-SA, and (d) Nonlinear absorption of Ti₂SnC-SA

the nonlinear optical profile for the Ti₂SnC SA, which was obtained by comparing the output power spectrum with and without the SA. The modulation depth and non-saturable absorption were measured to be about 4.8 and 42.8%, respectively. The saturable intensity of the film was about 10 MW/cm².

3. Experimental details

The experimental setup of proposed Q-switched EDFL is illustrated in Fig. 3. A 980 nm pump laser diode is used to excite the population inversion in the 3 m long EDF gain medium. A wavelength division multiplexer is connected between EDF and pump laser diode to couple the C-band signal and 980 nm pump light to co-propagate in the ring cavity. An isolator is incorporated into the ring cavity to ensure unidirectional signal propagation. The Ti₂SnC SA is sandwiched into the cavity using two FC/PC ferrule. A 90:10 coupler is used to channel 90% of the signal light to circulate in the cavity. Another 10% of signal is tapped out from the cavity for further analysis using power meter,

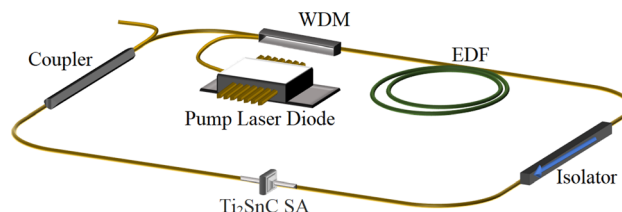


Fig. 3 Experimental setup of Q-switched EDFL using Ti₂SnC as SA

optical spectrum analyzer (OSA), oscilloscope and RF spectrum analyzer.

4. Results and discussions

Like most of the low-dimensional SA materials, Ti₂SnC SA can also self-start Q-switching operation at relatively low pump power. In the proposed cavity, the self-started Q-switched laser was obtained at a pump power as low as 51 mW with repetition rate of 37.17 kHz and pulse width of 2.92 μs. In Q-switched operation, the EDFL is pumped to produce a high population inversion in the gain medium.

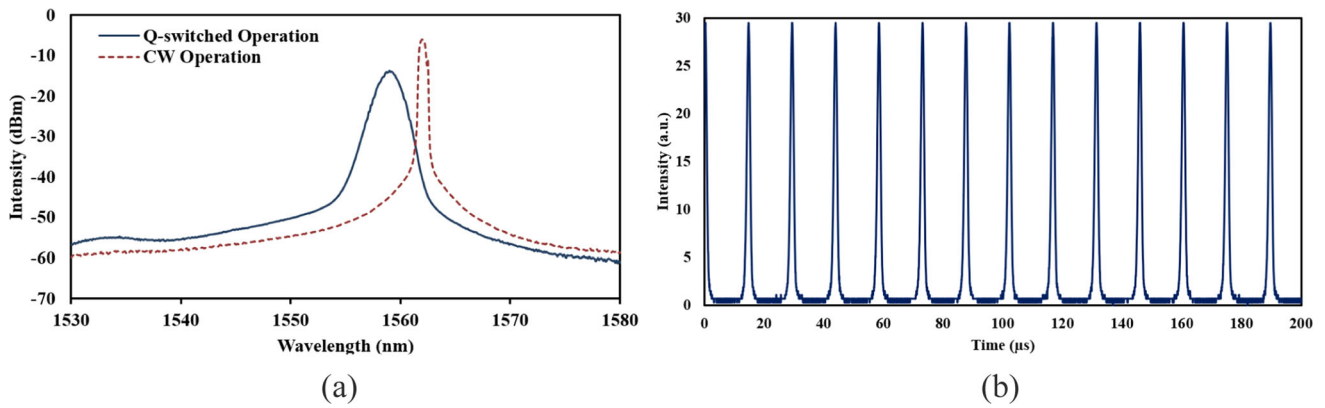


Fig. 4 (a) Optical spectrum of fiber laser cavity and (b) Q-switched pulse train in time domain at pump power of 110 mW

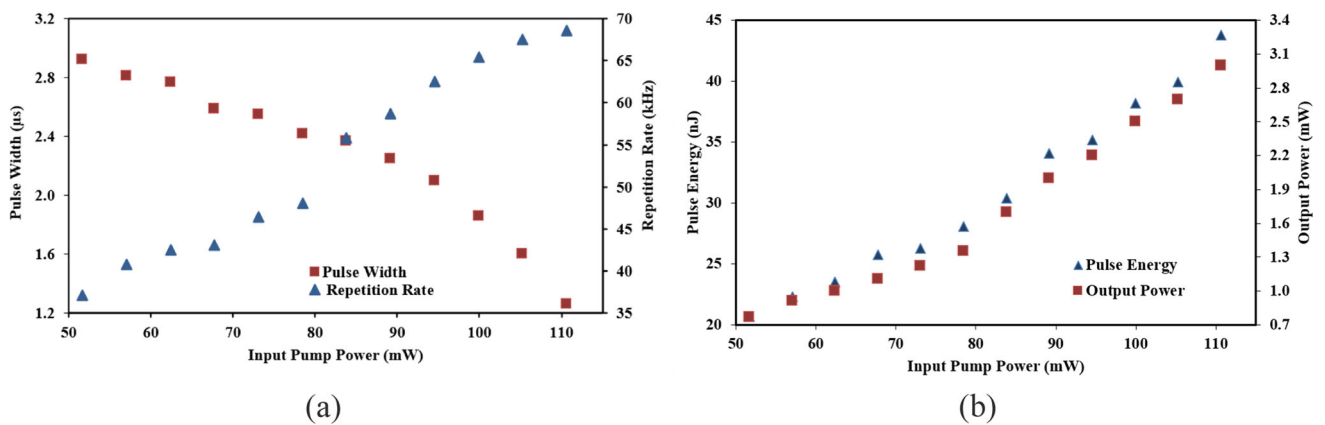
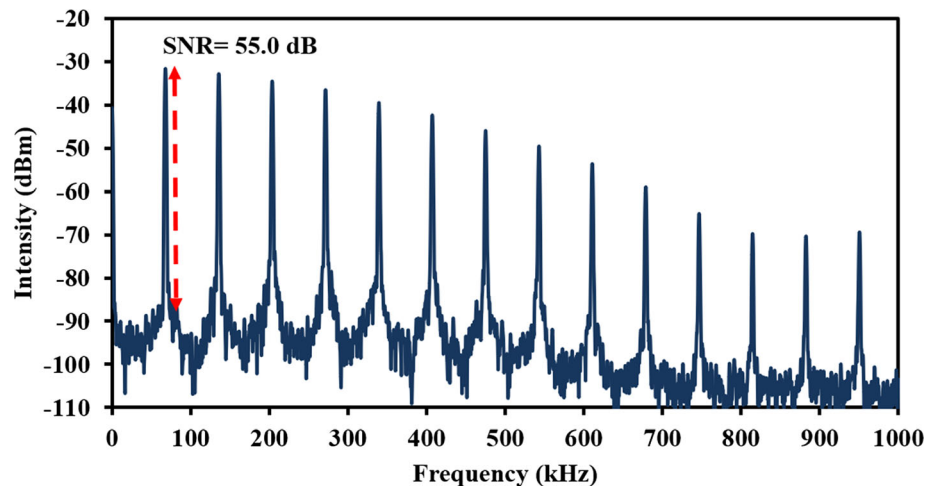


Fig. 5 (a) Pulse repetition rate and pulse width against pump power and (b) Pulse energy and output power against pump power

Fig. 6 RF spectrum of Q-switched EDFL at pump power of 110 mW



However, the laser light is initially absorbed by the Ti_2SnC SA, preventing it from circulating in the ring cavity. As the laser light intensity builds up, the SA begins to saturate, becoming increasingly transparent to the laser light. Once

the Ti_2SnC SA reaches its saturation point, the laser light is allowed to circulate in the cavity, producing a high-intensity, short-duration pulses. Successively, the Ti_2SnC SA recovers from saturable stage and continue to absorb light.

Figure 4a shows the optical spectra obtained from the fiber laser cavity with and without Ti_2SnC SA. Without the Ti_2SnC SA, the laser cavity generated continuous wave (CW) laser operating at wavelength of 1562 nm. With the incorporation of Ti_2SnC SA, the laser operation is red shifted to compensate the additional loss of Ti_2SnC SA. Besides, the circulation of short pulses in the cavity induced self-phase modulation (SPM), causing the spectrum broadening as shown in Fig. 4a. As the absorb-saturate-recover processes repeated sequentially, the Q-switched pulse train was realized in time domain as illustrated in Fig. 4b.

The Q-switching operation is observed within the pump power range of 51–110 mW. The details of Q-switched analysis are presented in Fig. 5. In Q-switched operation, the pulse width decreases, and the pulse repetition rate increases with increasing pump power. This is due to the increased energy stored in the laser gain medium, which leads to more efficient and faster population inversion and energy build-up. The result is narrower and more frequent laser pulses with higher energy. The phenomenon is observed in our analysis, as shown in Fig. 5a. With the increase in pump power from 51 to 110 mW, the pulse repetition rate increases from 37.17 to 68.56 kHz, whereas the pulse width decreases from 2.92 to 1.26 μs . The output power and pulse energy exhibit a linear increasing trend with pump power as shown in Fig. 5b. At pump power of 51 mW, the pulse energy and output power are 20.72 nJ and 0.77 mW, respectively. Both parameters increase linearly to 43.76 nJ and 3 mW at pump power of 110 mW. The pulse energy obtained is comparable to other metal-ceramic based SA [20, 21], which were generated with relatively low pump power.

With further increase in pump power, the Ti_2SnC SA forced to absorb circulation light while it is not fully recovered from saturation stage. Eventually, the SA becomes transparent (maintain in saturation stage), and the Q-switching operation dismissed. In Fig. 6, we have recorded the signal-to-noise ratio (SNR) at pump power of 110 mW. The RF spectrum is recorded at 68 kHz, which is well agreed with the pulse repetition rate that recorded in time domain (Fig. 4b). The SNR obtained is reported as 55 dB, which indicates the Q-switching operation circulates stably in the EDFL.

5. Conclusion

The Q-switched EDFL was successfully realized using Ti_2SnC as SA. The SA was fabricated using a thin layer of Ti_2SnC , which was obtained by a mechanical exfoliation method. As the SA is integrated into an EDFL cavity, it produced stable Q-switched pulses operating at 68.56 kHz

repetition rate with 1.26 μs pulse width and 43.76 nJ pulse energy at operational pump power as low as 110 mW. Our finding offers exciting prospects for advancements in Q-switched fiber laser technology.

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