Titanium dioxide-based picoseconds pulsed fiber laser performances comparison in the 1.5-micron region

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Abstract. We demonstrated and compared picoseconds pulsed fiber lasers based on Titanium dioxide based saturable absorbers (SAs); 20 cm long Titanium dioxide-doped fiber (TiO_2DF) and Titanium dioxide PVA film (TiO_2PF) in the 1.5-micron region. The laser cavity utilized 2.4 m long Erbium-doped fiber (EDF) as the gain medium. A self-starting pulsed laser with a consistent repetition rate of ~1 MHz emerged stably with the incorporation of TiO_2 based SAs. The TiO_2DF SA produced 9.74 ps pulsed laser at a central wavelength of 1553 nm within a pump power range of 106-142 mW. The fiber SA promoted slightly higher slope efficiency and maximum pulse energy of 13.17% and 8.56 nJ, respectively in comparison with the film SA. On the other hand, the TiO_2PF SA generated stable 3.89 ps pulsed laser at an operating wavelength of 1560 nm within 86-142 mW pump power range. The film SA also produced slightly greater maximum output power of 12.17 mW and maximum peak power of 3.43 kW, respectively at the maximum pump power. The results confirmed that both TiO_2 SAs can be good alternative pulse modulator in the 1.5-micron region.

Keywords. Optical fiber laser, fiber saturable absorber, Titanium dioxide, thin film

1. Introduction

Passive pulsed fiber lasers have several advantages in comparison with the active one, which includes, simplicity, flexibility and compactness. They also have significant potentials for use in many applications, such as telecommunication, biomedical and material engraving. Numerous methods have been claimed able to facilitate passively pulsed fiber lasers such as nonlinear polarization rotation [1], semiconductor saturable mirror (SESAMs) [2], carbon nanotubes (CNT) [3], graphene [4, 5], transition metal dichalcogenides (TMD) [6] and several others [7-26] including those which have been reported by our research group lately.

Although SESAMs have been successfully developed for commercial use in the last past two decades, they suffer from a relatively narrowband operation and has to be designed for explicit

wavelength. In addition to that, they are also quite bulky for fiber lasers and have a complex fabrication. NPR based lasers are environmentally unstable and have to be securely located in limited movements surroundings. On the other hand, CNT requires quite a complex bandgap engineering or diameter control for obtaining broader operation bandwidth. Additionally, graphene has a small absorption of 2.3% at 1550 nm. Thus, in this regard, new SA material that is small, easy to integrate, possessing quite a fast recovery time and can perform well in a robust environment is highly desirable.

Titanium dioxide (TiO_2), that belongs to transition metal oxides (TMO) have seized attention in recent years as alternative SAs in several regions; 1 [27], 1.55- [28, 29] and 2-micron [30]. It has a recovery time of ~1.5 ps at room temperature [31], while Z scanning performed on anatase and rutile TiO_2 proved that it has saturable absorption feature. The modulation depth (35.41%) and the saturation intensity (0.013%) of TiO_2 [29] also are comparable to the others SAs [6]. Although it has a bandgap of ~3.2 eV (~387 nm), it was claimed able to operate in the visible [32] and infrared [33] regions.

In this report, we demonstrated and compared TiO_2DF SA and TiO_2PF SA based picoseconds lasers performances in the EDFL cavity. The TiO_2PF was fabricated in-house, using polyvinyl alcohol (PVA) as the polymer film. On the other hand, the TiO_2DF was fabricated by doping TiO_2 element into silicate glass fiber core. Experimentally, we obtained about the same value of pulse repetition rates (~1 MHz) for both TiO_2 based SAs. The fiber laser performances of these TiO_2 based SAs are summarized and elaborated in the following topics to come.

2. Fabrication and Characterization of the Titanium dioxide-based SA

2.1. TiO_2DF SA (fiber) fabrication

The TiO_2DF was fabricated by doping TiO_2 element into silica glass matrix via a conventional modified chemical vapor deposition (MCVD) through bubbling of Helium (He) and Oxygen (O_2) gases into Titanium tetrachloride ($TiCl_4$) and Silicon tetrachloride ($SiCl_4$) containing bubbles. The developed TiO_2DF has core diameter and numerical aperture (NA) of ~40 μm and 0.21, respectively. The fabricated fiber also contains 4.0 mol % doping levels of TiO_2. To effectively works as fiber SA, the TiO_2DF was cut into 20 cm length. Both of its arms were then fusion spliced with 10 cm long single-mode fiber (SMF28), to form 10 cm SMF28 – 20 cm TiO_2DF – 10 cm SMF28. However, in this report, the whole piece is regarded as TiO_2DF SA only. The TiO_2DF fabrication process in details, along with its important fiber characteristics can be found in [13].

2.2. TiO_2PF SA (film) fabrication

The TiO_2 powder used in the film SA was purchased from Sigma Aldrich. The powder is 99 % pure and has a diameter of lower than 45 μm. First, the host solution was prepared by dissolving 1 g of polyvinyl alcohol (PVA) into 120 ml of deionized (DI) water. Then, the host mixture was stirred using a magnetic stirrer at 90ºC temperature, until the PVA powder fully dispersed. The solution was then cooled down to room temperature. Additionally, TiO_2 solution was prepared by dissolving TiO_2 powder into DI water with the help of 1% sodium dodecyl sulphate (SDS) solvent. The mixture was stirred for 5 minutes and centrifuged at 3000 rpm for ~15 minutes, to yield supernatant containing TiO_2 suspension. The TiO_2 suspension was collected and then poured onto the prepared PVA host solution. Next, the mixed solution was centrifuged to yield a composite precursor solution. The precursor solution was then transferred onto a flat and clean petri dish and left for two days at room temperature, to form TiO_2 composite film SA with a thickness of ~30 μm. The TiO_2 film fabrication details and its important characteristics are explained in [30, 34]. To be effectively served as an effective SA, the composite film (TiO_2PF SA) was cut into a square shape of 1 mm x 1 mm and sandwiched between two clean fiber ferrules with the aid of an index matching gel. Then, a clean fiber adapter was carefully fixed at the coupling spot. The whole piece was then inserted into the EDFL cavity.

2.3. Linear absorption profile of the TiO_2 based SAs.

Figure 1 depicts linear absorption profiles of the TiO_2PF SA and the TiO_2DF SA taken at their respective mode-locked operating regime. The measurements were conducted by coupling the SA between a broadband white light source (WLS) and an optical spectrum analyzer (OSA). The net reduction of the injected WLS intensity is regarded as the linear absorption of the tested SA. As shown, the TiO_2PF SA shows relatively more consistent absorption profile than the TiO_2DF SA, due to the highly uniform

structure obtained in the thin film. The TiO_2PF SA has slightly lower absorption of 1.55 dB at 1560 nm wavelength as compared to the TiO_2DF SA (that has an absorption of 2.95 dB at 1553 nm wavelength).

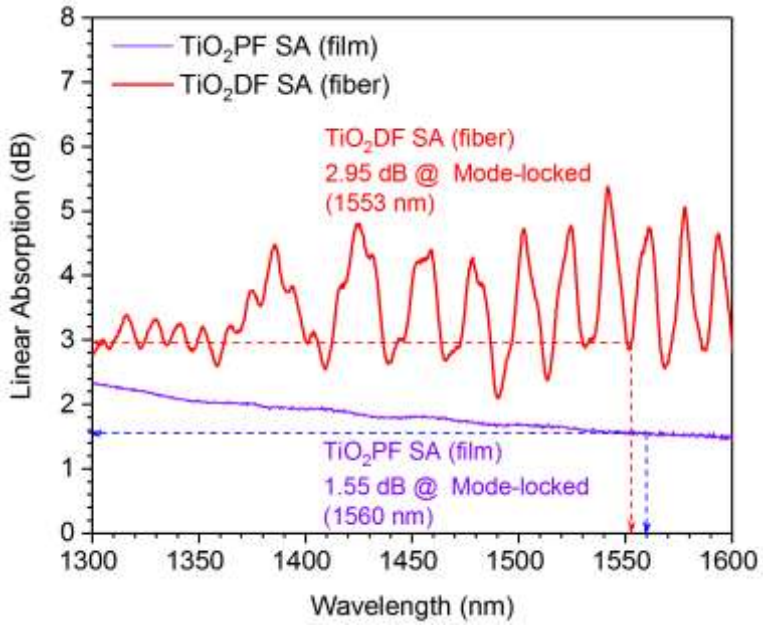

Figure 1. Linear absorption profile of TiO_2 based SAs.

3. Picoseconds pulsed fiber laser cavity design

The proposed design of the mode-locked based TiO_2 element is shown in Figure 2. The laser cavity is driven by a 980 nm laser diode pump. The light enters into a wavelength division multiplexer (WDM) and then into 2.4 meters long Erbium-doped fiber (EDF) gain medium. An isolator ensures unidirectional light propagation in the cavity. The EDF is a commercial glass fiber (IsoGain, I-25) from Fibercore and has core diameter and NA of 4 μm and 0.23, respectively. In addition to that, the EDF has core concentricity of less than 0.5 μm and absorption of 23-27 dB/m at 980 nm wavelength. As shown, 3 dB coupler 1 is used to separate the laser output into equal halves. Half of the laser output is then channeled into 3 dB coupler 2, while the remaining half, is left to be looped inside in the cavity. The 3 dB coupler 2 divides the light into further halves, providing real-time light measurements at two different ports. The TiO_2 based SAs, acts as mode-lockers; exploiting its linear and non-linear absorption characteristic to generate stable picoseconds pulsed lasers. A commercial single-mode fiber (SMF28) with a length of 195 nm, is appended before the SA to provide sufficient intracavity nonlinear and dispersion in the cavity. At the same time, it also reduces the pulse repetition rate and improves the pulse energy. This improved pulse energy would be sufficient enough to saturate the SA for a reliable self-starting mode-locked operation. A digital oscilloscope (OSC) and a radio frequency spectrum analyzer (RFSA) with a pre-connected photo-detector were employed to measure the pulse in the time and frequency domain, respectively, while an OSA records the output laser spectrum. The output power is measured via an optical power meter.

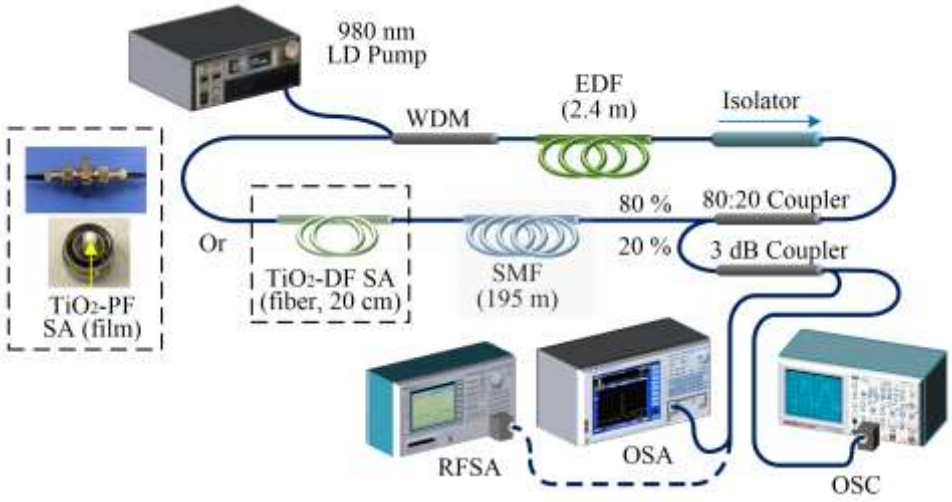

Figure 2. Mode-locked EDFL based on TiO_2 based SA cavity design.

4. Picoseconds pulsed fiber laser performances

The mode-locked EDFL based on TiO_2DF SA self-started at 106 mW threshold pump power and destructed into continuous laser (CW) laser when the pump power goes beyond 142 mW. Figure 3(a) depicts the mode-locked laser optical spectrum with a central wavelength of 1553 nm. The 3 dB spectral bandwidth (3 dB SB) is found to be 0.269 nm (33.58 GHz). The pulsed laser has a pulse repetition rate of 0.984 MHz. The autocorrelator trace as depicted in Figure 3(b), shows a single enveloped pulse with a pulse duration of ~9.74 ps (using $sech^2$ fitting analysis). Based on the obtained 3 dB SB of 33.58 GHz, the time-bandwidth product (TBP) is measured to be 0.33 which is slightly higher than the transform limit value of 0.315. This phenomenon indicates that the pulse is marginally chirped.

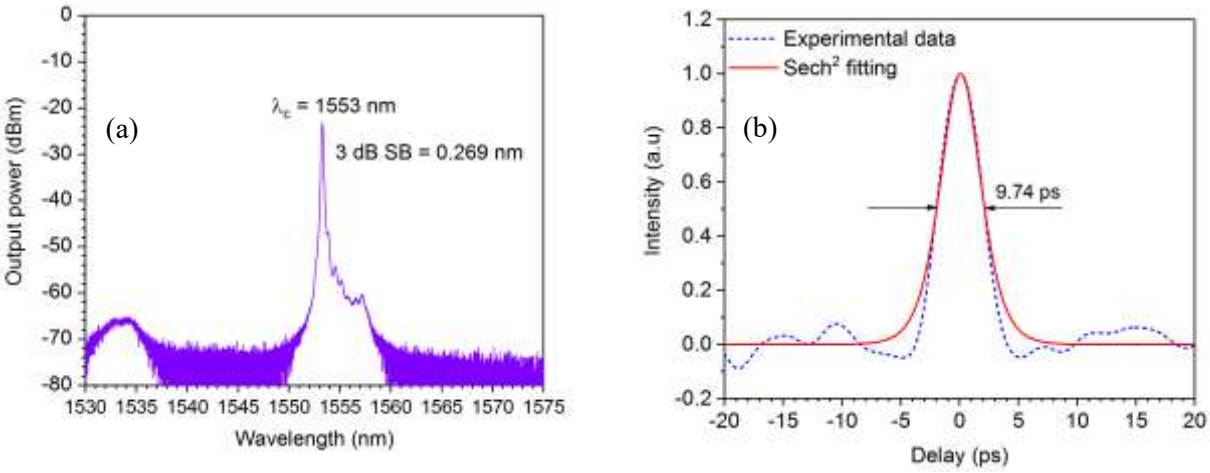

Figure 3. Mode-locked EDFL based on TiO_2DF SA (a) optical spectrum (b) autocorrelator trace

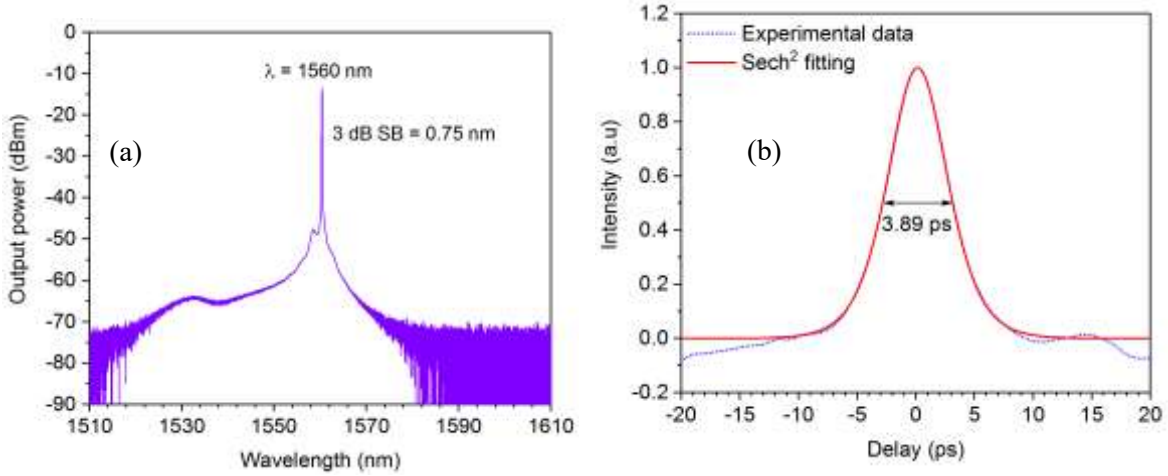

Figure 4. Mode-locked EDFL based on TiO_2PF SA (a) optical spectrum (b) autocorrelator trace

On the other hand, mode-locked EDFL based on TiO_2PF SA self-emerged at a threshold pump power of 86 mW and remained stable until 142 mW. Figure 4(a) illustrates the generated pulsed laser output spectrum, indicating a central wavelength of 1560 nm. As seen, the 3 dB SB is measured as 0.75 nm (72.57 GHz). The pulsed laser has a pulse repetition rate of 1.01 MHz. The autocorrelator trace as provided in Figure 4(b), depicts a pulse duration of ~3.89 ps (based on the $sech^2$ fitting analysis). By considering the 3 dB SB as 72.57 GHz, the time-bandwidth product (TBP) is calculated to be 0.36, slightly greater than the transform limit of 0.315, which also indicates that the pulse is chirped.

The TiO_2DF SA based pulsed laser performances as a function of pump power (106-142 mW) is demonstrated in Figure 5(a). As depicted, the output power increases linearly within a range of 3.73-8.42 mW. The pulse energy and the peak power also ascend with the increase of pump power. The maximum pulse energy and peak power are measured to be 8.56 nJ and 0.88 kW, respectively. The calculated slope efficiency is found to be 13.17 %.

On the other hand, the TiO_2PF SA based pulsed laser performances against increasing pump power (86-142 mW) is demonstrated in Figure 5(b). As illustrated, the output power ascends linearly from 7.58 mW to 12.17 mW. The pulse energy and the peak power also increases almost linearly with the rise of pump power. The maximum pulse energy and peak power are found to be 4.21 nJ and 3.43 kW, respectively. The obtained slope efficiency is measured to be 8.17 %.

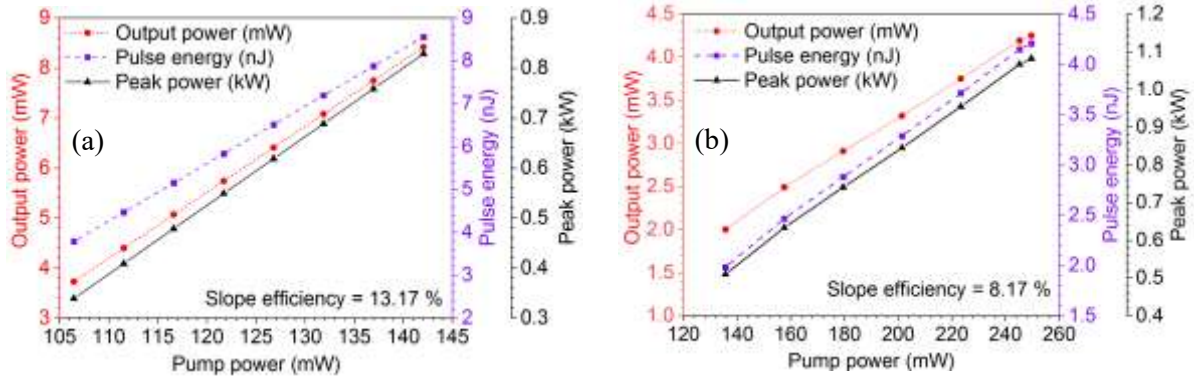

Figure 5. Pulsed laser performances based on (a) TiO_2DF SA (b) TiO_2PF SA

Table 1 summarizes and compares the TiO_2DF SA and TiO_2PF SA based pulsed laser performances and characteristics. Both TiO_2 based SAs, have about the same repetition rate of ~1 MHz, due to the same cavity length (~204 m) used in the design. The generated pulse repetition rates via these TiO_2 SAs are examined to be associated with a single cavity round trip period, suggesting that the generated pulsed lasers are mode-locked lasers. As demonstrated, the TiO_2PF SA generates higher output power and peak power as compared to the TiO_2DF SA. Conversely, the TiO_2DF SA generates better slope efficiency and higher pulse energy. Higher pulse energy generated via the film SA is attributed to a slightly broader

pulse width obtained in the optical spectrum. In summary, both SAs produces almost comparable laser performances. However, in the aspect of durability, the TiO_2DF was observed to have better pulse stability when tested under several hours of laser operation at the maximum pump power operation [13].

Table 1. Mode-locked EDFL performances comparison between TiO_2DF SA (fiber) and TiO_2PF SA (film).

Optical quantity	Unit	TiO_2DF SA (fiber)	TiO_2PF SA (film)
Central wavelength	nm	1553	1560
Pump power	mW	106-142	86-142
Output power	mW	3.73-8.42	7.58-12.17
Peak power	kW	0.39-0.88	2.14-3.43
Slope efficiency	%	13.17	8.17
Pulse energy	nJ	3.79-8.56	1.98-4.21
Repetition rate	MHz	0.984	1.01
Pulse width	ps	9.74	3.89
SNR (FF)	dB	54	67
Linear absorption	dB	1.55	2.95

5. Conclusion

We have demonstrated and compared picoseconds pulsed fiber laser at 1.5-micron by utilizing TiO_2 based SAs; fiber and film. Both pulsed fiber lasers have almost the same repetition rate of ~1MHz. The TiO_2DF SA generated 9.74 ps pulsed laser at 1553 nm wavelength. In addition, it generated higher slope efficiency and maximum pulse energy of 13.15% and 8.56 nJ, respectively, in comparison to the TiO_2PF SA. On the other hand, the TiO_2PF SA produced 3.89 ps pulsed laser at 1560 wavelength. The TiO_2 film based pulsed laser had relatively higher maximum output power and maximum peak power of 12.17 mW and 3.43 kW, respectively. In overall, the TiO_2DF provides advantages in terms of thermal damage threshold, flexibility and durability. These features are important for a portable laser source design.

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