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Q-Switched Thulium-Doped Fiber Laser with Pure Titanium-Film-Based Saturable Absorber

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ABSTRACT
We demonstrate the generation of Q-switching pulse train in thulium-doped fiber laser (TDFL) cavity by employing titanium-based saturable absorber (Ti-SA). The Ti-SA was fabricated by depositing titanium particles molecules using electron beam evaporation on the surface of a polyvinyl alcohol (PVA) film. Subsequently, stable Q-switched pulses were obtained within the 1,552 nm pump power range from 272.1 to 467 mW, with repetition rate tuned from 21.8 to 39.1 kHz. At the maximum pump power, the TDFL showed that the pulse duration of 2.22 µs and the maximum pulse energy of 124 nJ.

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KEYWORDS
Q-switching; passive saturable absorber; metal nanoparticles

Introduction
Q-switched pulse lasers are extensively used in various applications which require high pulse energy such as telecommunications, micromachining, remote sensing, and medical industries [1–3]. With their characteristics of compact in size, together with the capability to produce a high beam quality and high output power, Q-switched fiber lasers have attracted great attention from many researchers [4]. In recent decades, Q-switched fiber lasers operating in the wavelength regions of 1 and 1.5 µm have been massively explored. These fiber lasers configurations and performances have been reported in literatures where the Q-switching operations were achieved via the integration of several fiber-based and polymer film SAs. Despite these regions, in recent years, Q-switched thulium-doped fiber laser (TDFL) has also gained growing interests owing to their broad emission spectrum from 1.6 to 2.05 µm and wide absorption band, from 1.5 to 1.9 µm, which is particularly attributed to the $^3\text{H}_6-^3\text{F}_4$; Tm$^{3+}$ energy transition [5, 6].

In addition to that, thulium-doped fiber (TDF) has been revealed as an effective and high-power laser source near the 2 µm regime [7, 8]. Pulsed fiber lasers in this region have huge potentials in various applications including eye-safe light detection and ranging (LIDAR), spectroscopy, remote sensing. Furthermore, many molecules such as carbon dioxide (CO$_2$), nitrous oxide (N$_2$O), and hydrogen bromide (HBr) have absorptions resonances that overlap well with the TDF fluorescence band, suggesting a possibility of designing cost-effective optical gas sensing based on the generated TDF pulsed laser [9].

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addition to that, biological tissues that largely contain water such as animal and human tissues show relatively excellent absorption line around 2 µm, which enables TDF pulsed laser to serve as accurate and effective optical scalpels in dermatology and surgical treatments [9, 10].

Recent development in optical fiber pulse generation have led to a renewed interest in materials-based saturable absorber. This can be realized with the development of one-dimensional (1D) materials such as carbon nanotubes (CNT) [11] and two-dimensional (2D) materials such as graphene [12]. Ensuing to this, progress in the development of 2D material has steered to the discovery of transition metal di-chalcogenides (TMD) such as few-layer black phosphorus (BP), [13] molybdenum diselenide (MoSe₂), [14] and few-layer MXene [15]. This family of materials acts as promising substances as they have a direct band gap characteristic resulting in a wideband absorption which offers advantages over graphene and topological insulator (TI) [16].

Thus, in this paper, a newly developed titanium thin film is proposed and demonstrated as a functional saturable absorber (SA) for promoting stable Q-switched TDFL. The Ti-SA was fabricated by depositing titanium molecules using electron beam evaporation on the surface of a polyvinyl alcohol (PVA) thin film. By using pure titanium saturable absorber, pulse can be realized from the plasmonic characteristic of the transition metal. When the incident light is directed toward the titanium particles, the collective oscillations of electron in the conduction band leads to a saturation effect. This occurs as the incoming electric field frequency and the titanium electron frequency were in resonance which consequently leads to a collective oscillation until it reaches a realization of saturated state and saturable absorption mechanism of pure titanium [17]. The all-fiber TDFL was core-pumped at 1,552 nm and passively Q-switched at 1,955 nm using the newly developed Ti-SA.

**Preparation of titanium saturable absorber (Ti-SA)**

In this work, pure titanium (Ti) pellet was used as our SA material while PVA was used as the host material to hold the titanium particles during the coating process. The preparation process of the SA film is illustrated in Figure 1. At first, a PVA film was prepared by dissolving 1 g of PVA powder in 120 mL deionized water. The solution was sonicated at 90°C temperature for 5 min before it was carefully poured into a petri-dish and left dry for 3 days in the room temperature to form a PVA film with 30-µm thickness. The PVA film was then placed inside E-beam evaporation chamber together with titanium pellet for deposition process. During the process, Ti pellet were put under intense heat using Joule effect until the Ti particles evaporated and deposited onto the surface of the PVA film. The thickness of the Ti layer was pre-set at 16 nm.

The fabricated titanium thin film-based SA (Ti-SA) was analyzed using the energy-dispersive X-ray (EDX) method to identify the existence of the Ti element. The result is shown in Figure 2(a). The resulting spectrum reveals that C, O, and Ti are present in the SA film. C is the most abundant as it forms the base material of the PVA thin film (C₂H₄Oₓ). It was also traced that about 28.8 wt% of Ti element exists on the surface of the PVA film. A homogenous distribution of Ti particles in a PVA film surface was observed through the high-resolution image by FESEM measurement as depicted in Figure 2(b).
Figure 2(c) shows the absorption characteristics of the Ti-SA PVA, which has an absorption loss of ~3.2 dB/m at vicinity of 1-micron region.

**Laser configuration**

The fabricated SA was added in the TDFL cavity for realizing a Q-switching pulse train as described in Figure 3. The proposed TDFL uses a 5-m-long TDF, which was core-pumped by a laboratory made 1,552 nm fiber laser via fused wavelength division multiplexer (WDM), as a gain medium. This pump provides a continuous wave pump power of up to 1.5 W. The TDF has a numerical aperture (NA) of 0.16 with a core and cladding diameters of 9 and 125 μm, respectively. The thulium ion absorbances of this fiber are 9 and 27 dB/m at 1180 and 793 nm, respectively. To achieve a Q-switching operation, a small piece of the fabricated Ti-SA film (1 mm × 1 mm) was
adhered on the fiber ferrule tip with a help of an index matching gel before it was sandwiched between two fiber connectors and incorporated inside the laser cavity. A 10 dB coupler was used to allow about 90% of the Q-switched laser to oscillate inside the cavity while 10% of the laser was tapped out for measurement. The laser performances were measured from 10% port of the output coupler. An optical spectrum analyzer (OSA) with spectral resolution of 0.05 nm was employed to observe the output spectrum. For temporal performances, a 7 GHz bandwidth InGaAs photodetector was used in conjunction with a 500 MHz oscilloscope (OSC) and a 7.8 GHz radio frequency spectrum analyzer (RFSA) for time-domain and frequency-domain analysis, respectively. The laser’s output power was measured using an optical power meter (OPM). The total cavity length was about 12 m consisting 5-m-long TDF and SMF-28 fiber for

Figure 2. Characterization of Ti-SA thin film (a) EDX spectrum, (b) FESEM image, and (c) linear absorption.
the rest of the cavity. In this experiment, we do not incorporate a polarization-dependent isolator (PDI) and a polarization controller (PC) inside the cavity. This prevents the Q-switching operation through a balancing of dispersion and nonlinearity effects.

**Result and discussion**

Initially, the operation started in a continuous wave (CW) regime as the input pump power reached the CW laser threshold of 235 mW. The CW laser operated at 1,948 nm. As the pump power is further increased to 272.1 mW, a stable Q-switched pulsed laser was self-started, and its operation was maintained up to the maximum pump power of 467.3 mW. As the pump power is increased slowly to 272.1 mW, a stable Q-switched pulsed laser was self-started, and its operation was maintained up to the maximum pump power of 467.3 mW. **Figure 4** shows the optical spectrum of the Q-switched TDFL at 272.1 mW pump power. As shown in the figure, the laser operates at center wavelength of 1,955 nm with a 3 dB bandwidth of around 1.3 nm and optical signal to noise ratio (OSNR) of 39 dB. As shown in figure, the red-shifted wavelength of 1,948–1,955 nm was caused by the absorption loss of the Ti-SA film, which reduces because of saturation effect above the threshold pump power. This loss reduction causes the operating wavelength can shift to a longer wavelength, which has a lower gain. Meanwhile, as we increase the input pump power from 272.1 to 467.3 mW, the central wavelength steadily operated in 1955 nm.

The typical pulse trains of the laser at the pump powers of 272.1, 378.6, and 467.3 mW are illustrated in **Figure 5(a)**, (b), and (c), respectively. They indicate the periods of 45.8, 31.9, and 25.6 μs without noticeable timing jitter, which correspond to a pulse repetition rate of 21.8, 31.4, and 39.1 kHz at pump powers of 272.1, 378.6, and 467.3 mW, respectively. The pulse widths are approximately 5.62, 2.77, and 2.22 μs, which are
comparable to the values obtained by other SAs. It is also worthy to note that the output pulses from the laser are stable and no noticeable intensity fluctuation can be observed. To verify that the Ti-SA film was responsible for the Q-switching pulse generation for the laser, the film was removed from the set-up. In this case, no Q-switching pulse was observed on the oscilloscope trace at any pump powers, which further confirms that the Q-switching operation was due to the employment of the proposed SA. In addition, beyond maximum input pump power of 467.3 mW, pulse train totally absent which indicating that the fabricated SAs has reach their saturation. However, pulsed operation recovered back as it operates within 272.1–467.3 mW input pump range. This indicates that the optical damage threshold is above 467.3 mW.

The evolution of repetition rate and pulse width were also investigated against the pump power and the result is shown in Figure 6(a). As it can be seen, the pulse repetition rate increases linearly from 21.8 kHz at threshold pump to 39.06 kHz at the maximum power. Conversely, the pulse width decreases exponentially from 5.62 μs to the narrowest achievable, 2.22 μs. This corresponds to typical Q-switching pulse behavior. Figure 6(b) shows the relation between average output power and single pulse energy against pump power. Both average output laser power and pulse energy increase with pump power where the maximum pulse energy of 124 nJ was obtained at the maximum pump power of 467 mW. The average power increases from 1.63 to 4.84 mW as input pump power is tuned from 272.1 to 467 mW. This indicates the laser has an efficiency of about 1.62%. Figure 6(c) shows the peak power calculated from the data pulse energy against the pump power. The peak power is also observed to

Figure 4. Q-switching TDFL operation at 272.1 mW input pump power. The inset shows the span of Q-switching spectrum at 20 nm.
increase with pump where the maximum peak power of 55.8 mW is obtained at the maximum pump power.

The RF spectra are obtained for two different spans as shown in Figure 7 at the maximum pump power. Figure 7(a) shows the RF spectrum of the fundamental frequency of 39 kHz with the RBW of 1 kHz, which indicates a signal-to-noise ratio (SNR) of 55 dB. Figure 7(b) shows the fundamental and 11 harmonic frequencies within 500 kHz span. It is also worth to notice that the proposed laser operated stably in the laboratory condition for at least one day without any noticeable degradation of performance.

Although several studies indicated that titanium-based SA managed to generate pulsed fiber laser on 2-micron region, little attention has been given to develop

![Figure 5](image-url). Temporal performance of the Q-switched TDFL. (a) Pulse train at 21.83 kHz, (b) pulse train at 31.35 kHz, and (c) pulse train at 39.06 kHz.
a pure titanium SA mainly using E-beam evaporation. In the proposed work, pure Ti deposited on PVA film appears to generate 2-micron Q-switched TDFL with longer tunability of repetition rate, and higher SNR, when compared to prior works based on Ti-SA thin film [18]. Our finding revealed that E-beam method capable to produce a good or at least comparable pure metal-based SA in addition to their simple and easy fabrication process when compared to [18–20]. The comparison performance for different SA preparation is presented in Table 1.

Compared to other materials, the use of titanium nanoparticles is advantageous due to its outstanding optical and physical properties. Due to the surface plasmonic resonance, titanium nanoparticles provide a broadband linear absorption and thus it can be used for wideband operation. The SA is also robust with high optical damage threshold. This may increase the maximum attainable energy. In addition, the proposed laser produces Q-switching pulses at a significant low threshold and broad range input pump power with a relatively higher output pulses energy and peak power compared to other SAs [11, 12]. Meanwhile, with current cavity, no mode-locking operation has been observed, and we expect that this can be obtained by optimizing the dispersion and SPM parameters of the cavity.

**Figure 6.** Power performance of the Q-switched TDF laser. (a) Repetition rate and pulse width, (b) average output power and pulse energy, and (c) peak power.
Conclusion

Q-switched fiber laser operating at 2-micron region has been successfully demonstrated using a Ti-SA. The Ti-SA used was prepared by depositing particles of Ti onto the surface.
of PVA film through the electron beam deposition process. By incorporating the SA into a TDFL cavity by sandwiching between two fiber ferrules, Q-switching pulses train was generated at 1,955 nm. Stable Q-switched pulses were successfully obtained within the 1,552 nm wavelength a pump power range from 272.1 to 467 mW, with repetition rate tuned from 21.8 to 39.1 kHz. At 467 mW pump power, the TDFL showed that the pulse duration of about 2.22 μs and the average output power is about 4.84 mW. The peak power and maximum pulse energy were obtained at 55.8 mW and 124 nJ, respectively. This result confirmed the proposed Ti-SA film can be utilized as a promising new SA for operating in 2-micron region.

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References


Table 1. Comparison of recent works on typical 2-micron Q-switched TDFL with different SA fabrication method.

<table>
<thead>
<tr>
<th>SAs material</th>
<th>Method of preparation</th>
<th>Pump power (mW)</th>
<th>Wavelength (nm)</th>
<th>Rep. rate (kHz)</th>
<th>Pulse width (µs)</th>
<th>SNR (dB)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Ti</td>
<td>E-beam</td>
<td>272.1–467.3</td>
<td>1955</td>
<td>21.83–39.06</td>
<td>5.62–2.22</td>
<td>55</td>
<td>This work</td>
</tr>
<tr>
<td>Anatase TiO2</td>
<td>Drop casting</td>
<td>289–485</td>
<td>1935</td>
<td>30.12–36.96</td>
<td>3.91–1.91</td>
<td>23</td>
<td>[18]</td>
</tr>
<tr>
<td>HoDF</td>
<td>Fiber-SA</td>
<td>418–564</td>
<td>1972</td>
<td>30.61–38.89</td>
<td>3.18–2.27</td>
<td>50</td>
<td>[19]</td>
</tr>
<tr>
<td>GO</td>
<td>Tapered</td>
<td>5100–6270</td>
<td>2032</td>
<td>20–45</td>
<td>9–3.8</td>
<td>–</td>
<td>[20]</td>
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