Samarium (III) oxide thin film as a saturable absorber for the passively Q-switched Tm-doped fiber laser

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Abstract. We have demonstrated a passive Q-switched Thulium-doped fiber laser (TDFL using samarium oxide (Sm₂O₃) nanomaterial as saturable absorber (SA). The Sm₂O₃ based SA was fabricated by simply mixing the Sm₂O₃ powder solution with polyvinyl alcohol (PVA) solution. The homogeneously mixed solution was spread and dry to form a thin film. A piece of 1 mm x 1 mm of the SA thin film is sandwiched between two fiber ferrules and incorporated into a TDFL ring cavity for pulses generation. By controlling the loss and gain in the cavity, stable Q-switching operation was generated. The repetition rate was tunable from 17.62 kHz to 29.20 kHz by varying the pump power from 619 mW to 784 mW. The smallest pulse width of 3.54 µs and the highest pulse energy of 0.20 uJ were obtained at the highest pump power.

Keywords: Fiber laser, Q-switched, saturable absorber

1. Introduction

Fiber lasers operating at 2-micron region have attracted much attention in recent years because of their great potential applications in telecommunication, military, spectroscopy and medical surgery [1-3]. Compared to other lasers operating at 1.0- and 1.55-micron regions, 2-micron fiber laser are advantageous due to its high absorption coefficient in water and gases. For instance, Thulium- and holmium-doped fiber lasers are operated at 1.94 µm and 2.12 µm, which have an absorption coefficient of 114 cm⁻¹ and 36 cm⁻¹, respectively. The lasers are also referred to as ‘eye-safe lasers’. Due to these characteristics, they are beneficial in many applications including material processing and biomedical diagnostics [3-5]. There are two techniques to generate the Q-switching pulses; active and passive techniques. Passive techniques require saturable absorber (SA) device and they are preferable compared to that of active techniques because of their advantages such as smaller in size, highly efficient, reliable and ease in fabrication. Furthermore, the passive technique requires no external pulse triggering signal while the active technique needs external acousto-optic modulators to actively control and modulate the intra-cavity loss [6].
Graphene, carbon nanotubes (CNTs), graphene, black phosphorus (BP), topological insulators (TIs), transition metal dichalcogenides (TMDs) and quantum dots (QDs) have been widely reported as the Q-switcher. However, these materials have some limitations in a few fields. For instance, graphene has nearly zero bandgaps and thus it has low modulation depth (2.3% per layer) which limits their application in high power laser [7, 8]. Previously, Hisyam et al. reported the mode-locked Ytterbium-doped fiber laser using BP as SA with the repetition rate and pulse energy of 13.5 MHz and 5.93 nJ, respectively [9]. However, BP has a few weaknesses such as it is hydrophilic and able to change their optical properties when contacted with water and exposed to humid air [10, 11].

To overcome this problem, many new materials have also been proposed [12-16] as alternative SAs including lutetium oxide [17] and cobalt oxide [18] which belongs to the transition metal oxide (TMO) family. Here, we proposed Sm$_2$O$_3$ thin film as the new passive SA to generate pulses at the 2-micron region.

Sm$_2$O$_3$ thin film-based SA has been fabricated through a simple process by embedding the Sm$_2$O$_3$ powder into polyvinyl alcohol (PVA) solution. The thin film is incorporated into a ring Thulium-doped fiber laser (TDFL) cavity to initiate and produce Q-switching pulses.

2. Preparation and characterization of Sm$_2$O$_3$ based SA

The Sm$_2$O$_3$ thin film was fabricated through a simple fabrication process by mixing the Sm$_2$O$_3$ powder into PVA solution. At first, the PVA solution was prepared by dissolving 1 gram of PVA powder into 120 ml of distilled (DI) water. After that, the mixing solution was stirred using a magnetic stirrer at room temperature until the PVA completely dissolved. Then, 50 ml of the PVA solution was added into the clean beaker with 50 mg of the Sm$_2$O$_3$ powder before putting them on the magnetic stirrer for 3 hours. Next, the solution was placed into the ultrasonic bath for 10 minutes. Lastly, the Sm$_2$O$_3$ PVA solution was poured into a petri dish and let the solution to dry at room temperature for about 48 hours. The thin film was then formed, and it was peeled off from the petri dish and cut to 1 mm x 1 mm in size, before sandwiching it between two FC/PC fiber ferrules.

Figure 1 shows the linear absorption profile of the Sm$_2$O$_3$ film SA. As shown, there is some absorption of about 7 dB occurs around the TDFL Q-switched laser operating region.

3. Pulsed fiber laser configuration

Figure 2 shows the experimental configuration of the proposed Q-switched TDFL. As shown in the figure, 5 m long Thulium-doped fiber (TDF) was used as the gain medium and it was pumped by a 1550 nm Erbium-Ytterbium-doped fiber laser (EYDFL) through a 1550/2000 wavelength division multiplexer (WDM). TDF used is Nuferm SM-TSF-9/125 commercial fiber with the numerical aperture (NA) of 0.15
and thulium ion absorption of 9.3 dB/m and 27 dB/m at 1180 nm and 793 nm, respectively. The 90/10 optical coupler kept 90% of the light in the ring cavity, while 10% of the light was tapped out for the optical measurement and analysis. All the optical connection in the ring cavity were directly spliced to minimize the optical loss in the cavity except for the SA device. The SA device was constructed by sandwiching 1 mm x 1 mm of the Sm$_2$O$_3$ thin film in between two FC/PC fiber ferrules while applying some index matching gel at the surface of fiber ferrules. The equipment used in this experiment for analysis were optical spectrum analyzer (OSA-500 MHz Yokogawa AQ6375), a digital oscilloscope (500 MHz LeCroy Wavejet 352A), a radio frequency spectrum analyzer (RFSA-7.8 GHz Anritsu MS2683A), a digital power meter (THORLABS PMD100D) and a photodetector (PD-EOT ET-5010F InGaAs). The total cavity length in this proposed Q-switched TDFL was 13.1 m.

![Figure 2. The schematic diagram of the pulsed TDFL setup with Sm$_2$O$_3$-SA](image)

4. Result and discussion
With the SA device placed inside the ring cavity, a passively Q-switched TDFL started to appear when the pump power increased above the threshold pump power of 619 mW. Figure 3(a) compares the output spectrum of the Q-switched EDFL with the continuous-wave (CW) laser, which was obtained without the SA at a pump power of 619 mW. As shown in the figure, the Q-switched laser operated at a wavelength of 1935.25 nm, which was at the shorter wavelength compared to the CW laser. The CW laser operated at 1965.77 nm. The operating wavelength shifted to a shorter region with the insertion of the SA device inside the cavity due to the increase in cavity loss of the resonator. The operating laser shifted to a shorter wavelength with a higher gain to compensate for the loss. Figure 3(b) shows the output power and pulse energy versus pump power of the Q-switched TDFL using Sm$_2$O$_3$ as SA. As the pump power increased from 619 mW to 784 mW, the output power and the pulse energy increase linearly from 1.3 mW to 5.9 mW and 0.073 µJ to 0.20 µJ, respectively. The calculated slope efficiency is 2.73 % as shown in Figure 3(b). Figure 3(c) shows the typical pulse train of the Q-switched TDFL observed at the maximum pump power of 784 mW. The pulses train has a peak-to-peak separation of 36 µs corresponding to the maximum pulse repetition rate of 29.2 kHz. At a pump power of 784 mW, the output power and pulse energy are measured to be around 5.9 mW and 0.20 µJ, respectively. By optimizing the cavity, the insertion loss of the SA could be reduced thus increasing the pulse energy. The frequency-domain of the pulsed signal at maximum pump power is illustrated in Figure 3(d), showing several frequency harmonics of the Q-switched laser. The pulsed laser has a signal to noise ratio (SNR) of 34.5 dB at the fundamental frequency of 29.2 kHz, which is good matching with the pulse repetition rate obtained in the time domain in Figure 3(c).
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Figure 3. Q-switched laser performances. (a) output spectrum at a pump power of 619 mW. (b) Output power and pulse energy against pump power (c) Typical pulse train (d) RF spectrum.

5. Conclusion
We have successfully demonstrated a stable Q-switched TDFL by integrating Sm$_2$O$_3$ thin film as SA in a ring cavity. The Q-switched laser started to appear as the pump power increased to the threshold of 619 mW and remain stable until the pump power up to 784 mW. At the maximum pump power of 784 mW, maximum output power and pulse energy are obtained at 5.9 mW and 0.20 µJ, respectively. The fundamental frequency of 29.2 kHz has a signal to noise ratio (SNR) of 34.5 dB. The results indicate that Sm$_2$O$_3$ can become an excellent alternative SA for laser applications.

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