Dual-wavelength Q-switched thulium doped fiber laser with TiO_2 film saturable absorber

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We report a dual-wavelength Q-switched Thulium doped fiber laser based on a Titanium dioxide (TiO_2) saturable absorber. The TiO_2 was embedded in polyvinyl alcohol (PVA) film, which was then sandwiched in between two fiber ferrules in the cavity. By using a Thulium-doped fiber with a slightly larger core, it functions as intra-cavity spectral filter to allow dual-wavelength Q-switching regime to be achieved in the cavity. Our experimental results show that the fiber laser can simultaneously generate Q-switched microsecond pulses at 1954.43 nm and 1957.27 nm, which have the repetition rate varying from 12.89 kHz to 21.93 kHz and 0.54 µJ maximum pulse energy. Our proposed scheme is quite simple and thus it can be implemented at a low cost

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1. Introduction

Q-switching technology has been widely studied to generate short laser pulses with high-energy for a wide range of applications ranging from range finding, microfabrication and metal cutting to medical treatment [1]. The Q-switched lasers were normally demonstrated by passive technique employing saturable absorbers (SAs) due to their excellent mechanical stability and compactness. The SA functions to periodically modulate the intracavity loss and turning the continuous wave (CW) laser into pulse trains. 2D nanomaterials such as graphene [2-3], topological insulators (TIs) [4], transition metal di-chalcogenides (TMDs) [5], and black phosphorus [6] have been widely reported in recent years as the SA. It is owning to their flexibility in design, rugged, compactness, and low cost.

Recently, an emerging nanomaterial, titanium dioxide (TiO_2) has also gained wide attention as a thin film material for potential application in all-optical switching devices [7]. Many investigations on TiO_2 optical properties such as recovery time [8], nonlinear property [9] and spectral absorption [10] have also been conducted. Remarkably, its spectral absorption can be extended up to the near-infrared (NIR) region [11]. This can be explained by the quantum size effect of TiO_2, where the absorption depends on the crystal form and particle size [12]. Likewise, polyvinyl alcohol (PVA) has been extensively used in many applications because of its capability to form film and favourable physical properties such as good chemical resistance, biocompatibility and hydrophilicity [13].

Both the emission spectrum of the gain fiber and the absorption spectrum of TiO_2 are rather broad, compared to the bandwidth of a Q-switched output, so it is possible to realize passively Q-switched fiber lasers at different wavelengths. On the other hand, the multi-wavelength Q-switched lasers, which can simultaneously generate synchronized Q-switched pulse trains at different center wavelengths, can be useful in terahertz generation, airborne Lidar, multiphoton dissociation of molecules and other sensing or nonlinear optics applications [14].

Previously, Q-switched fiber lasers generating a single peak at 1558.9 nm and 1935 nm have been demonstrated based on Erbium-doped fiber laser (EDFL) [15] and Thulium-doped fibre laser (TDFL) [16] respectively, using TiO_2 embedded in polymer film as the passive newly saturable absorber (SA). In another work, passively Q-switched dual-wavelength ytterbium-doped fiber laser (YDFL) was demonstrated using a TiO_2, which was coated onto a side-polished fiber as SA [17]. The YDFL operated at 1034.7 and 1039.0 nm, with a maximum pulse energy of 2.0 nJ, and a shortest pulse width of 3.2 µs. More recently, a Q-switched Raman fiber laser (RFL) was also demonstrated using a TiO_2 film based SA to operate at 1558.5 nm [18]. In this paper, we demonstrate a dual-wavelength Q-switched Thulium-doped fiber laser (TDFL) operating at 1954.43 and 1957.27 nm by inserting a TiO_2 embedded in PVA film as an SA. This is the first demonstration of dual-wavelength TDFL by using TiO_2 film SA.

2. TiO_2 PVA film fabrication and characterization

The SA film fabrication process involves with a preparation of TiO_2 suspension and PVA solution. The raw material used was a commercial anatase TiO_2 powder with purity of 99% and has diameter of less than 45 µm. We prepared TiO_2 solution by solving the powder in distilled water with an assistance of 1% sodium dodecyl sulphate (SDS) solvent. The mixture was stirred for 5 minutes so that the Van der Waals forces between powders break and completely disperse. Then, the TiO_2 solution was centrifuged at 3000 rpm for 15 minutes, and the supernatant containing TiO_2 suspension in solution was collected for use. The dispersed TiO_2 solution was added into a PVA solution. The polymer solution was obtained by mixing 1 g of PVA powder with 120 ml deionized water (DI). The mixture was stirred at 90^oC until the PVA dissolved homogenously. The polymer solution was then cooled down to room temperature. The TiO_2 and PVA mixture is thoroughly mixed through a centrifuging process to form a composite precursor solution. Finally, the precursor solution was poured onto a glass petri dish and dried in a room temperature for nearly 48 hours to form a free standing film as shown in Fig. 1(a). This thickness of the film was measured to be around 30 µm.

We also performed Raman spectroscopy on the fabricated TiO_2 film sample and the result is shown in Fig. 1(b). In the experiment, an Argon ion laser operating at 514 nm was used as a light source. The laser was radiated on the film for 10 ms with an exposure power of 50 mW. The Raman spectrum exhibits five distinct peaks at approximately 145, 198, 399, 516, and 640 cm^{-1}, which corresponds to the first-Eg, second-Eg, B_{1g}, A_{1g}, and third-Eg band, respectively. High peak intensity at 145 cm^{-1} confirms this TiO_2 has an anatase crystalline structure.

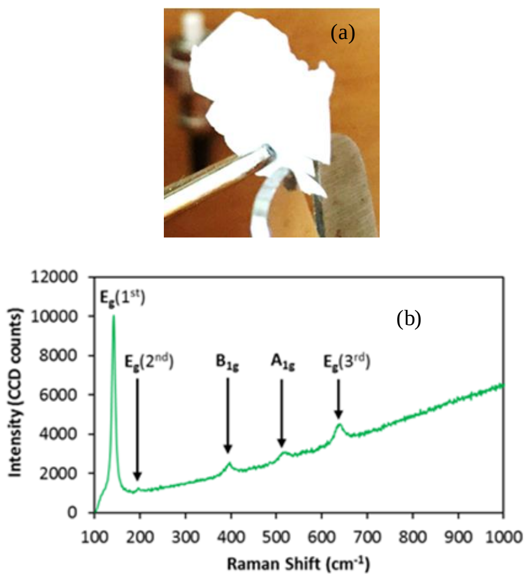

Fig. 1. (a) Actual image and (b) Raman spectrum for the fabricated TiO_2 PVA film

3. Laser configuration

Fig. 2 illustrates a schematic diagram for the proposed dual-wavelength Q-switched TDFL. The laser is based on ring configuration, which uses a 7 m long Thulium-doped fiber (TDF) as the gain medium. The TDF is pumped by a single-mode laser operating at 1552 nm via wavelength division multiplexer (WDM). The TDF used has a core size of 13.43 µm with a numerical aperture of 0.21 and a peak absorption of about 165 dB/m at 793 nm. Different core size between standard SMF and large core TDF causes a multimode interference inside the gain medium. This create a filtering effect inside the cavity for dual-wavelength generation. Polarization controller is used to adjust the state of polarization for the oscillating light in order to optimize the dual-wavelength generation. 10 dB output coupler is used to couple out the laser while allowing 90 % of light to oscillate inside the cavity. Spectral characteristic was measured by using optical spectrum analyzer (OSA) with resolution of 0.05 nm. Through high speed 7 GHz InGaAs photodetector (PD), pulse train was measured in time-domain by 500 MHz digital Oscilloscope (OSC) and in frequency-domain by 7.8 GHz RF spectrum analyzer (RFSA). Average power was measured by digital optical power meter via thermal sensor.

Q-switched operation was realized by incorporating an SA device inside the laser cavity. The SA device was obtained by sandwiching a small piece of TiO_2 film in between two fiber ferrules via fiber adaptor. By removing the SA device from the cavity, no pulse train presence on both OSC and RFSA. Total fiber length in the cavity is about 11 m.

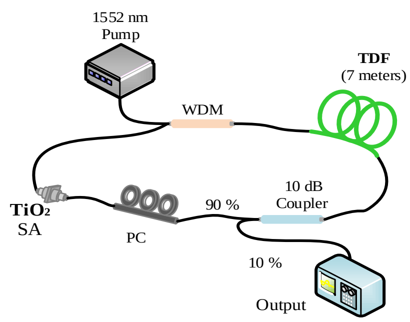

Fig. 2. Configuration of the proposed dual-wavelength Q-switched TDFL

4. Q-switching performance

The dual-wavelength Q-switched TDFL performances are discussed in this section. We measure spectral and temporal characteristics under 711 mW to 821 mW pump power, where Q-switching regime is dominant. Above 821 mW, the Q-switching regime disappears and normal continues-wave will be back dominant. Fig. 3 shows output power spectrum of the Q-switched TDFL. As shown in the figure, two wavelength peaks of 1954.43 nm and 1957.27 nm are obtained by 2.84 nm apart to each other with 0.046 nm 3dB spectral bandwidth. The residual pump power at 1552 nm is also significantly lower than both peak lasers. Different core size between SMF and TDF has induced Mach-Zehnder interferometer (MZI) effects which then generate stable dual-wavelength. At maximum pump power, we obtained 11 mW of output power corresponds to 0.5 μJ of calculated pulse energy as shown in Fig. 4. The Q-switched laser has 3.9 % of slope efficiency (SE). It is also observed in Fig. 4 that the pulse energy suddenly drops as the pump power exceeds 730 mW before it rises back at the pump power of 766 mW. This is attributed to the increased noise level, which reduces the pulse energy.

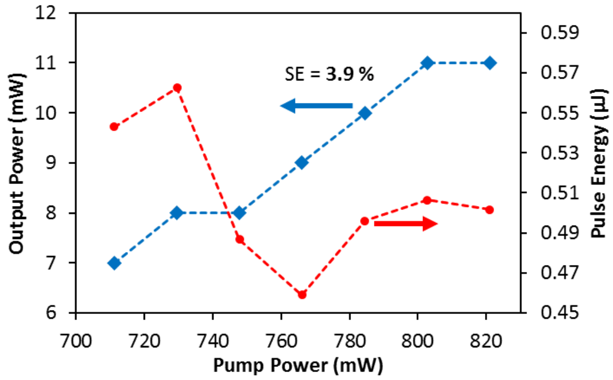

Fig. 4. Output power and pulse energy of the laser against the pump power

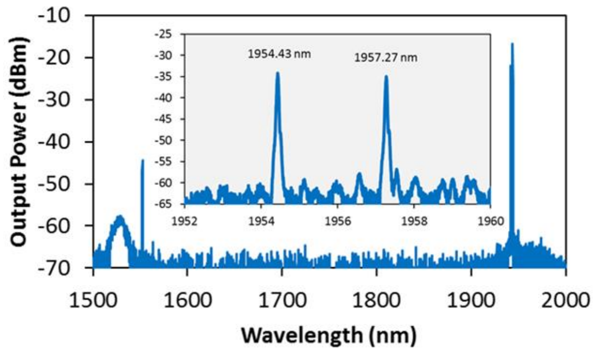

Fig. 3. Output spectrum of the Q-switched laser at threshold pump power of 711 mW. Inset shows the enlarge figure at both lasing peaks

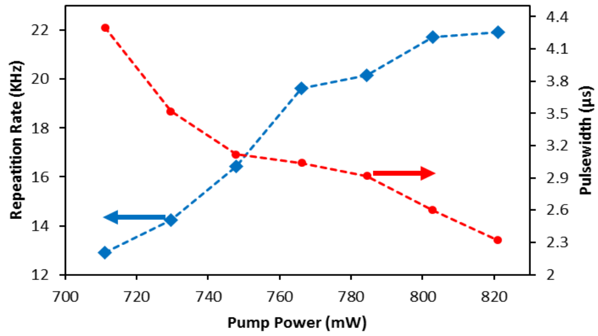

Fig. 5. Repetition rate and pulse width against the pump power

The pulse repetition rate and pulse width of the Q-switched laser are shown in Fig. 5 at varying pump powers. It is observed that repetition rate is closely related to the pump power level where the higher repetition rate is obtained at the higher pump power. This trend is similar to many other passively Q-switched lasers and it is attributed to high pump power leads to a shorter time for the inversion number of the gain medium to reach the threshold. Repetition rates from 12.89 kHz to 21.93 kHz can be achieved, when the pump power is increased from 711 mW to 821 mW. On the other hand, the pulse width decreases from 4.3 μs to 2.3 μs as the pump power is increased within the above pump power range. The long pulse duration of ~μs is due to the long cavity lifetime related to the long length of the cavity, which can be reduced by decreasing the cavity length with a highly doped TDF or other more compact components.

Fig. 6 shows the pulse traces measured by the oscilloscope at the threshold and the maximum pump powers. The pulses trains show the repetition rates of 12.89 kHz and 21.93 kHz at pump powers of 711 mW and 821 mW, respectively. Fig. 7 illustrates the RF spectrum of the laser showing a signal to noise ratio of around 40 dB. This indicates that the Q-switching pulse is stable. While current output power is relatively low, further optimization on SA fabrication and cavity design may increase in the output power and would facilitate more potential applications. Further boosting the power with an optical amplifier is a feasible solution to those application demanding even higher pulse energies. The energy distribution of the two pulses can be further adjusted by introducing extra controlled optical loss in the cavity.

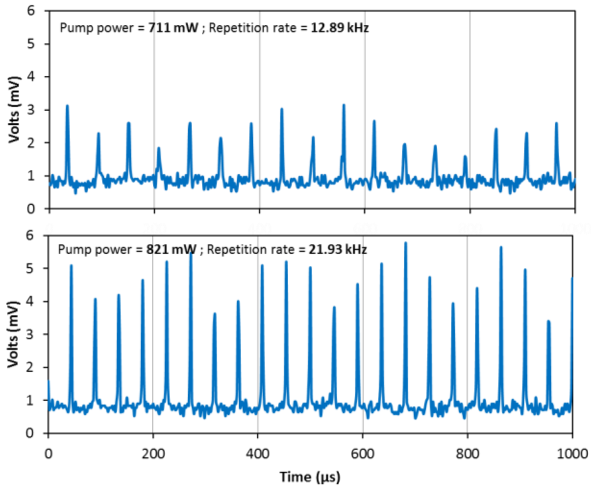

Fig. 6. The oscilloscope trace operation at different pump level

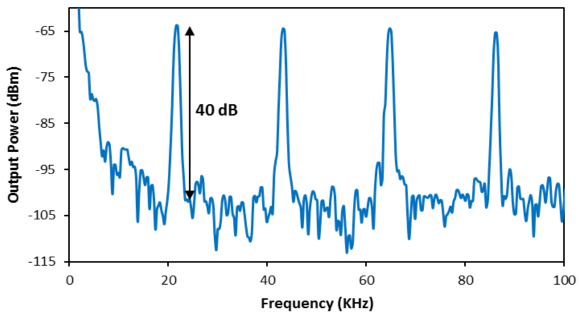

Fig. 7. RF spectrum at pump power of 711 mW

5. Conclusion

We have successfully demonstrated a dual-wavelength Q-switched TDFL based on a TiO_2 which was embedded in PVA film as saturable absorber. By using a slightly large core TDF to create intra-cavity spectral filter, dual-wavelength Q-switching pulses operating at 1954.43 nm and 1957.27 nm are obtained with the incorporation of TiO_2 SA. The repetition rate varying from 12.89 kHz to 21.93 kHz with the increase of pump power from 711 to 821 mW. The maximum pulse energy was obtained at 0.54 µJ. The laser could find applications where multiple synchronized short optical pulses are needed. Considering the all-fiber structure, simple realization and low cost, it is expected that more attractive applications could be realized using such multi-wavelength Q-switched short pulse lasers.

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