Q-switched Raman fiber laser with titanium dioxide based saturable absorber

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We demonstrate a Q-switched Raman fiber laser (RFL) using a newly developed Titanium dioxide (TiO_2) film based saturable absorber (SA). The SA is fabricated by mixing the dispersed TiO_2 suspension into a polyvinyl alcohol solution to form a precursor which is then transformed into a thin film through a drying process at room temperature. It is sandwiched between two fibre ferrules and inserted in a Raman fiber laser cavity with a total cavity length of about 8 km. Self-started pulse train operating at 1558.5 nm is generated as the pump power is increased from 398 mW to 431 mW with a repetition rate that can be tuned from 131.4 to 142.5 kHz. The smallest pulse width of 2.97 μs and the highest energy of 5.81 nJ are obtained at pump power of 431 mW and 427 mW, respectively. These results show that the TiO_2 embedded in polymer film has a great potential to be used for pulse generation in Raman fiber laser system.

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1. Introduction

Raman fiber lasers (RFLs) have gained a tremendous interest in recent years especially for operation at wavelengths that are difficult to access directly with conventional gain media. They are developed based on Stimulated Raman scattering (SRS) effect. In the process, the amount of the Stokes frequency shift is intrinsically determined by the irradiated medium in which a quantum conversion increases proportionally with the complex part of the third-order nonlinear permittivity [1]. To date, various RFLs have been fabricated and demonstrated using various gain media such as germanosilicate or phosphosilicate glass fiber. Most of the proposed lasers are operating with a CW mode with high output power. On the other hand, Q-switched fibre lasers were also intensively investigated for many potential applications such as LIDAR, remote sensing, communication and medicine [2]. Compared with the active technique, the passive approach is better in terms of simplicity, compactness, and flexibility of implementation [3, 4]. The passive Q-switching generation can be realized by using either nonlinear polarization rotation or passive saturable absorber (SA) techniques.

Up to date, various SAs have been implemented such as semiconductor saturable absorber mirrors (SESAMs), two-dimensional (2D) materials (graphene, topological insulators, transition-metal dichalcogenides) and doped-fibre SA for Q-switching generation in various fibre lasers and cavities [5]. However, the applications of these SAs are restricted due to their drawbacks such as complex optical alignments, environmentally sensitive, limited operating bandwidth and complicated fabrication. Therefore, there is many new attempts in recent years to develop new SAs with better performance for Q-switching laser operation .

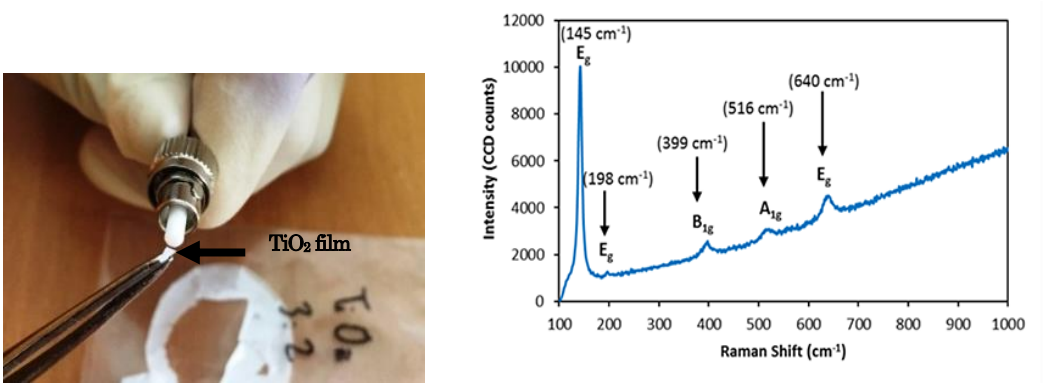
On the other hand, titanium(IV) oxide (TiO_2) is a transition metal oxide nanomaterials which having a low electrical resistivity [6] and exhibits high efficiency as a diffusion barrier against the interdiffusion of aluminium and silica. It is also reported that conductive TiO_2 film is useful for microelectronic applications [7]. Recovery time is an important parameter to determine the Q-switching ability of saturable absorber. Elim et al. reported the TiO_2 polymer film has a recovery time of ~ 1.5 ps [8] and thus it could provide saturable absorption ability due to the Pauli-blocking principle. Of late, many investigations on TiO_2 optical properties such as the light absorption have been conducted [9]. For instance the light absorption properties of blue titanium sub-oxide nanoparticles was investigated by [10] On the other hand, Polyvinyl alcohol (PVA) has been intensively used in many applications because of its capability to form film and favourable physical properties such as good chemical resistance, biocompatibility and hydrophilicity [11].

As a nanomaterial, TiO_2 sheets can be easily exfoliated mechanically or chemically due to its strong in-plane bonding and weak van der Waals coupling between layers. In this letter, a passively Q-switched RFL is demonstrated using a TiO_2 embedded in PVA film SA as a Q-switcher. Stable pulsing with a pump power threshold of 398 mW, repetition rate tunable from 131.4 to 142.5

kHz, the highest energy of 5.81 nJ and the smallest pulsewidth of 2.97 µs is obtained in a 8 km Q-switched resonator. To the best of our knowledge, a Q-switched RFL operating in any wavelength regions using a passive SA has never been demonstrated before.

At first, we prepare TiO_2 solution by solving a commercial anatase TiO_2 powder in distilled water with an assistance of 1% sodium dodecyl sulphate (SDS) solvent. The TiO_2 powder is 99% pure and has diameter of less than 45 µm. The mixture is then stirred for 5 minutes so that the TiO_2 material is dispersed homogeneously. 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 then added into a polymer solution. The polymer solution was obtained by mixing 1 g of PVA powders with 120 ml of deionized water (DI). The mixture is stirred at 90°C until the polymer was completely dispersed. The polymer solution was then cooled down to room temperature. The TiO_2 and PVA mixture was thoroughly mixed through a centrifuging process to form a composite precursor solution. Then the precursor solution was poured onto a glass substrate and heated in an oven for nearly 2 days to form a free standing film.

The film obtained has an absorption of around 3 dB at 1550 nm with thickness of around 30 µm. Fig. 1 (a) shows how the film was transferred onto a fibre ferrule. We also performed Raman spectroscopy on the fabricated TiO_2 film sample to verify the presence of TiO_2 material. Fig. 1(b) shows the Raman spectrum, which is recorded by a spectrometer when a 514 nm beam of a Argon ion laser is radiated on the film for 10 ms with an exposure power of 50 mW. The sample exhibits five distinct Raman peaks at approximately 145, 198, 399, 516, and 640 cm^{-1}, which corresponds to the first Eg, second Eg, B1g, A1g, and third Eg band, respectively [12]. High peak intensity at 145 cm^{-1} confirms this TiO_2 is only observed in the Raman spectrum of anatase crystalline structure. By performing a balance twin-detector measurement, the modulation depth of the film is measured to be around 33 %. A stable self-constructed passively mode-locked fibre laser (1560 nm wavelength, 980 fs pulsewidth, 21.8 MHz repetition rate) is used as the input pulse source.



(a) (b)

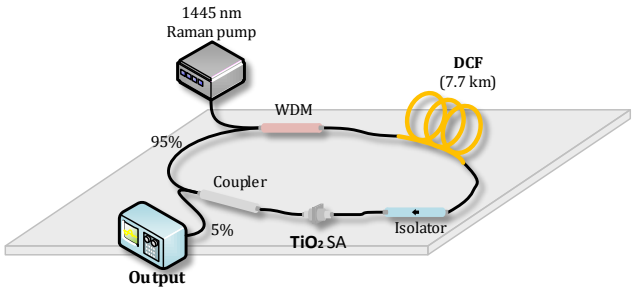
Fig. 1. Characterization of Ti O_2 film (a) Image of fabricated TiO_2 film (b) Raman spectrum of the fabricated TiO_2 film

2. Experimental setup

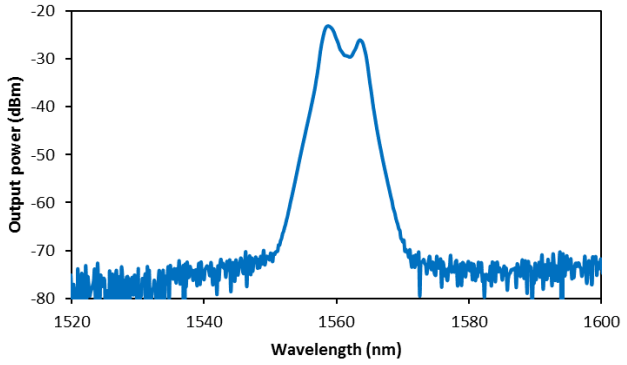
The fabricated SA is then inserted in the RFL cavity for Q-switching experiment as shown in Fig. 2(a). The fiber laser cavity employs a 7.7 km long dispersion compensating fiber (DCF) with 584 ps/nm.km of dispersion as a nonlinear gain medium. The DCF was pumped by a 1455 nm laser via a 1455/1550nm wavelength division multiplexer (WDM). The TiO_2 film was incorporated into the ring cavity by sandwiching a small portion of the film between two fiber ferrules adhered with index matching gel to act as a passive Q-switcher. The isolator is used in the setup to ensure unidirectional operation of the laser. The signal was coupled out using a 5/95 output coupler which keeps 95% of the light to oscillate in the cavity for both spectral and temporal diagnostics. The output laser was tap from a 5 % port of the coupler. The spectral characteristic was measured using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm while the temporal characteristics were measured using a 500 MHz oscilloscope and a 7.8 GHz radio-frequency (RF) spectrum analyser via a 1.2 GHz photodetector. The total cavity length of the ring laser is estimated to be around 8 km.

Fig. 2(b) shows the output spectra of the Q-switched RFL with the TiO_2 film based SA in the cavity. In the experiment, the power of 1455 nm Raman pump is fixed at 431 mW. It is obtained that the Q-switched laser operates at peak wavelengths of 1558.5 nm. Presence of peak dip at peak wavelength is due to the cavity perturbations during Q-switching regime [13]. The RFL generates a stable pulse train with an increasing repetition rate as the pump power is increased from 398 mW to 431 mW. Fig. 2(c) shows the typical pulse train of the Q-switched laser at three different pump powers. It is obtained that the repetition rate increases with pump power. At the maximum pump power of 431 mW, the pulse train indicates the period of 7.12 µs without noticeable timing jitter, which corresponds to a pulse repetition rate of 140 kHz. To verify that the TiO_2 SA was responsible for the Q-switching pulse generation for the laser, the FC fiber ferrule filled with TiO_2 film was replaced with a clean

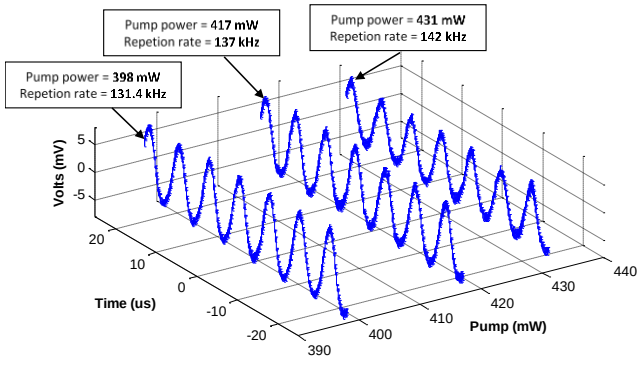
ferrule. In this case, we observe no Q-switching pulse on the oscilloscope at any pump powers, which confirms that the Q-switching operation was attributed to the TiO_2 SA.



(a)



(b)



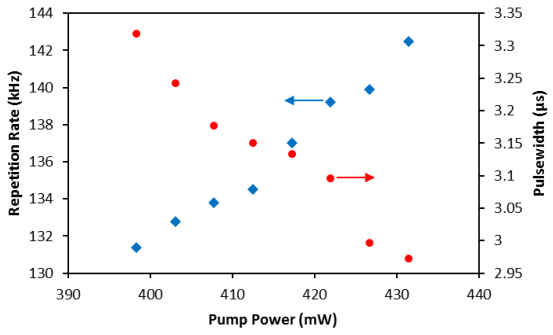
(c)

Fig. 2. (a) RFL in a ring cavity configuration. (b) Output spectrum of Q-switched RFL at 431 mW pump power. (c) Typical oscilloscope trace under different pump power between 398 to 431 mW

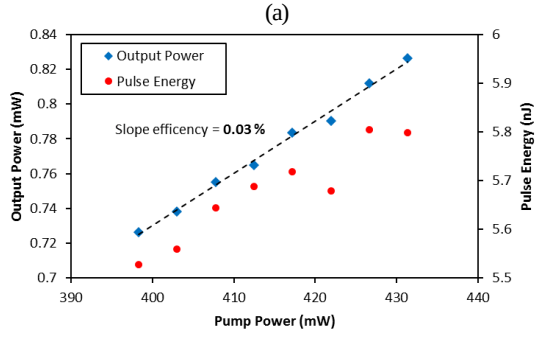
3. Experimental results and discussion

The pulse repetition rate and pulse width of the proposed Q-switched RFL are investigated as functions of pump power. The results are plotted in Fig. 3(a) where showing that the repetition rate of the Q-switching pulse train can be increased from 131.4 to 142.5 kHz as the power of the pump is varied from 398 mW to 431 mW. Concurrently, the pulse width decreased from 3.32 µs to 2.97 µs. The pulse width could be decreased further by either shortening the laser cavity length. In addition, the average output power and the corresponding single-pulse energy of the laser are also investigated at various pump powers. The results are plotted in Fig. 3(b) where showing that the average output power almost linearly increased with the input pump power up to the pump power of 431 mW. The maximum average output power of the Q-switched laser is 0.826 mW while the slope efficiency is calculated to be around 0.03%. One can observe from the figure that the pulse energy fluctuates with the maximum pulse energy of 5.81 nJ is obtained at pump power of 427 mW. The maximum peak power is calculated about 1.83 mW.

Fig. 3(c) shows the corresponding RF spectrum at the maximum pump power of 431 mW with 600 kHz span. As illustrated in the figure, the fundamental repetition rate of the laser is 142.5 kHz which agrees with the pulse period of 7.12 µs measured in Fig. 3(c). The signal-to-noise ratio of the RF spectrum is observed at 37 dB, indicating that the Q-switching operation was very stable. Throughout the experiment, we can confirm that no mode-beating frequency presence. This Q-switching performance could be improved by further optimizing the cavity design and the TiO_2 SA parameters such as modulation depth and insertion loss.



(a)



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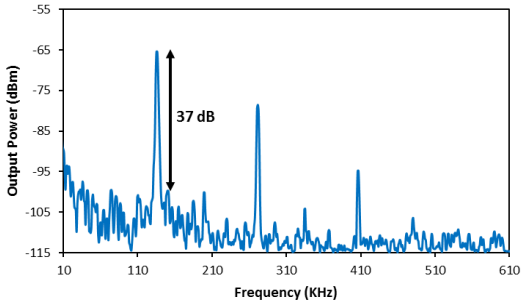

(c)

Fig. 3. (a) Repetition rate and pulse width. (b) Output power and pulsed energy. (c) Frequency domain of pulse train at 431 mW pump power

4. Conclusion

In conclusion, we have successfully demonstrated a Q-switched RFL using a TiO_2 embedded in polymer film as a passive SA. The film was prepared by mixing the dispersed TiO_2 suspension into a PVA solution to form a precursor which is then transformed into a thin film through a drying process. It is sandwiched between two ferrules via a fiber connector to form a fiber-compatible SA, which is then incorporated in RFL cavity to generate a stable Q-switched pulses at 1558.5 nm. As the pump power is increased from 398 mW to 431 mW, the repetition rate incraeses from 131.4 to 142.5 kHz while the the pulse width decreased from 3.32 μs to 2.97 μs. The highest pulse energy of 5.81 nJ is achieved at pump power of 427 mW. These results shows that TiO_2 film is a new potential SA material for pulsed laser applications.

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