Generation of Q-switched Erbium-Doped Fiber Laser Using Titanium Dioxide Film Based Saturable Absorber

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Abstract. This work demonstrates a generation of a passively Q-switched erbium-doped fiber laser with titanium dioxide (TiO₂) film as saturable absorber. The film is fabricated using a ratio of 2:1 by embedding the rutile nanoparticles (TiO₂) into a polyvinyl alcohol (PVA) host film. Short after placing the SA film on the fiber ferrule, a stable 1563.3 nm pulses appeared at a power pump range from 104.62 mW to 145.83 mW. The maximum output power was recorded at 2.05 mW, inducing a maximum pulse energy of 22.63 nJ. The repetition rate shows an increasing trendline from 81.04 kHz to 90.58 kHz while the pulse width decreases from 5.08 μs to 4.12 μs. The high signal to noise ratio (SNR) of 63 dB indicates that the TiO₂ film has a good performance in generating pulsed laser at 1550 nm wavelength.

1. Introduction

A Q-switched erbium-doped fiber lasers (EDFLs) have a very high demand in applications such as medical treatment, laser cutting technology, optical telecommunication, remote sensing, and a wide range of different applications for industry [1-2]. The excellent beam quality and cost effective of this fiber laser have attracted many researchers in recent years [3-5]. In addition, passively Q-switched technique based on saturable absorber are often preferred as they are more compact in setup and do not require an electronic controller to trigger the pulses, which makes it more favoured compared to active technique [6-7].

In general, saturable absorber can be categorized into two: real SAs and artificial SAs [8]. The artificial SAs however, have difficulties in exploiting optical fiber properties that is homogeneous to saturable absorption, hence struggling to access a better performance [9]. Real SAs, on the other hands, such as Semiconductor saturable absorber (SESAMs), 1D carbon nanotubes (CNTs), graphene, topological insulator (Tis), transition metal dichalcogenides (TMDs) and black phosphorus (BP) have been effectively used to generate pulsed lasers [10-13]. The evolution of saturable absorber technologies has growth tremendously with newly discovered material that provides a strong motivation in fulfilling the needs of photonic applications. However, these SAs have weaknesses that limits their reputation as an effective saturable absorber. SESAMs is a high cost option that have a narrow absorption bandwidth plus having a bulky size [14]. The main drawbacks of CNTs includes low modulation depth and an absorption efficiency that is dependant to their diameter while graphene suffers from a low optical absorption per layer that limits the capability in initiating laser pulses [15]. The exploration of finding...
a new material continues in providing the laser generation with a low cost, wideband absorption, high
damage threshold and a reliability SA. Meanwhile, transition metal oxide (TMOs) have been proposed
as an ideal saturable absorber that gained lots of interest in generating pulsed laser [16].

In this paper, Titanium dioxide (TiO₂) has been selected to generate passive Q-switched fiber laser
in 1550 nm wavelength. Despite of the fact that the bandgap of TiO₂ is between 3-3.2 ev, this rutile
nanoparticles has a remarkable electrical and optical properties such as high refractive index and good
transmission in the near-infrared regions [17]. Moreover, with the successful demonstration of passive
Q-switched erbium-doped fiber laser, TiO₂ is indeed a suitable candidate that has a good potential as
saturable absorber with simplicity and low fabrication cost.

2. Titanium dioxide (TiO₂) film preparation and characterization
The fabrication of taking TiO₂ into thin film was first prepared by mixing the TiO₂ powder and a de-
ionized water with a ratio of 2:1 respectively. 30 mg of TiO₂ powder and 15 ml of de-ionized water was
blended using a magnetic hot plate stirrer at room temperature for 3 hours. The mixture was then put
into the ultrasonic bath for one hour to ensure that the TiO₂ powder is blend well with the de-ionized
water. Next step is to mix the TiO₂-de-ionized water solution and the PVA solution with a ratio of
20ml:10ml. The PVA solution was prepared by mixing 1 g of PVA powder with 120 ml distilled water
as a solvent. Both solutions were stirred for 1 hour using the magnetic stirrer and again, the mixture
was put into the ultrasonic bath for 30 minutes. Finally, the TiO₂ suspension was poured carefully onto
a petri dish and left to dry at room temperature for 48 hours to form TiO₂ composite film.

Figure 1(a) shows the image of the TiO₂ thin film on a fiber ferrule. Figure 1(b) compares the
percentages of element in the thin film which contain 33.3% of Titanium and 21.61% of oxygen while
Figure 1(c) illustrated the field emission scanning electron microscopy (FESEM) of the film. As shown
in Figure 1(d), the saturable intensity, modulation depth and non-saturable absorption of TiO₂ film are
0.05kW/cm², 13% and 37%, respectively. An absorption of EDFL Q-switched around 13 dB can be
seen on Figure 1(e) that shows the linear absorption profile (LAP) of the TiO₂ film.
Figure 1. Characteristics of TiO$_2$ film (a) the fabricated film attached into an FC/PC fiber ferrule (b) EDS profile (c) FESEM image (d) nonlinear absorption profile (e) TiO$_2$ film SA’s linear absorption profile

3. EDFL ring cavity setup

The schematic diagram of the proposed laser cavity in generating the Q-switched EDFL is illustrated in Figure 2. The laser cavity consists of 980 nm laser diode, a wavelength division multiplexer (WDM), a 2.8m long erbium-doped fiber (EDF) gain medium, isolator and 90/10 coupler and a film of TiO$_2$ at the flat end of the fiber ferrule. The 980 nm laser diode pump the erbium-doped fiber (EDF) gain medium based on the forward pumping scheme via the 980/1550 nm port of the wavelength division multiplexer. An optical isolator is used to prevent unwanted feedback of light in the ring cavity. The light then goes into the fiber connector that has a SA film on it. The film is attached at the flat end of the fiber ferrule by applying index matching gel. After passes the SA, 10% of laser output was tap out by the 3dB coupler and another 90% is retained to circulate inside the ring cavity. The repetition rate and pulse width were measured using a 500-MHz digital oscilloscope while the optical spectrum of the laser is observed by an optical spectrum analyser (OSA) with 50 nm spectral resolution. The output coupler is then connected to a power meter where the average output power is recorded. The repetition rate and pulse stability of the laser is validated using an electrical radio frequency (RF) spectrum signal of a 7.8 GHz RF spectrum analyzer. The total length of ring cavity was about 13 m.

Figure 2. Schematic diagram of Q-switched erbium-doped fiber laser
4. Result and Discussion
Before we start the experiment, the laser cavity has been cleared from any form of impurities especially at the fiber connector in order to make sure that there is no self-Q-switching effect. The oscilloscope observed only continuous wave (CW) signals even when we increase the laser diode pump to the maximum. After inserting the SA into the laser cavity, the CW mode began to disappear. A Q-switching operation started at a threshold input power of 42 mW. As we increase the pump power up to 100mW, a stable pulse train was observed and maintained at a range of 104.62 mW to 145.83 mW. The repetition rate of the pulse is presented in Figure 3(a) and (b).

![Figure 3](image1.png)

**Figure 3.** Repetition rate at pump power: (a) 104.62 mW and (b) 145.83 mW

Figure 4(a) depicts the repetition rate and pulse width of Q-switched erbium-doped fiber laser pulses versus pump power. The repetition rate increases from 81.04 kHz to 90.58 kHz with the decreasing pulse width from 5.08 μs to 4.12 μs. The pump power is tuned from 104.62 mW to 145.83 mW. The inversely proportional of the repetition rate and the pulse width is consistent with the typical features of passively Q-switched lasers. Figure 4(b) shows the pulse energy and average output power versus pump power. The average output power rises linearly from 1.58 mW to 2.05 mW, and pulse energy increases from 19.5 nJ to 22.63 nJ.

![Figure 4](image2.png)

**Figure 4.** (a) Repetition rate and pulse width versus pump power. (b) Average output power and single pulse energy vary with the increasing pump power.

The output spectrum of the Q-switched laser at a pump power of 104.2 mW, is presented in Figure 5(a), indicates that the Q-switched erbium-doped fiber laser operates at a wavelength of 1563.9 nm. The RF spectrum (Figure 5(b)) shows a signal-to-noise ratio (SNR) of 63 dB for the repetition rate at 90 kHz proving that the laser pulses is very stable.
5. Conclusion

In conclusion, the fabrication ratio of 2:1 of the TiO$_2$-PVA film as saturable absorber was successfully demonstrated in generating EDFL pulse at 1.55 μm wavelength. A stable repetition rate increases from 81.04 kHz to 90.58 kHz within a range of pump power from 104.62 mW to 145.83 mW. The shortest pulse width was observed at 4.12 μs. At the maximum pump power, a high output power and pulse energy was recorded as 2.05 mW and 22.63 nJ, respectively. A high signal to noise ratio (SNR) of 63 dB validate that the Q-switched laser operation is very stable and confirms that TiO$_2$ film is an excellent saturable absorber.

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