The generation of nanosecond pulses at C-band region with titanium dioxide as a saturable absorber

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Abstract. A passive mode-locked in an erbium-doped fiber laser with titanium dioxide (TiO2) film as a saturable absorber (SA) has been successfully demonstrated. The film is fabricated using a liquid phase exfoliation, which offers a simple and low-cost method. The self-starting mode-locked was created by inserting a 200-meter-long single-mode fiber into the laser cavity to balance the nonlinearity and dispersion of the cavity. The pulses operate stably at a central wavelength of 1560 nm. The pulse repetition rate was almost fixed at 988 kHz at a tunable pump power from 145.83 mW to 187.04 mW. The repetition rate shows excellent stability with a signal-to-noise ratio (SNR) of 69 dB whilst the pulse width was virtually constant at 230 ns. The maximum output power was measured at 2.17 mW, eliciting maximum pulse energy of 2.19 nJ. This experiment demonstrates that stable mode-locked pulsed can be generated using TiO2-SA.

1. Introduction

The pulses with a nanosecond-duration generated by mode-locked fiber lasers have attracted broad attention in many applications in a variety of fields, including remote sensing, welding industries, and medical [1–3]. Beforehand, electro-optic and acousto-optic modulators were used to actively generate nanosecond pulses. However, this active modulation approach necessitates a large and costly component. Therefore, passive techniques are preferable to active techniques for producing mode-locked EDFLs because they are less expensive, simple, flexible, and have better performance. Various saturable absorbers (SAs) have been widely investigated using mode-locking schemes in the passive approach. The construction of the mode-locked operation with an extended cavity fiber laser to generate the desirable nanosecond pulse train has adopted semiconductor saturable absorber mirrors (SESAMs) [4], graphene [5], single-walled carbon nanotubes (SWCNTs) [6], topological insulator (TIs) [7], and transition metal dichalcogenides (TMDs) [8]. However, these SAs have disadvantages and drawbacks that limit their potential as mode-lockers. For SESAMs, the complex fabrication makes it very costly. Apart from that, a limited response time, narrow operating wavelength region, and low damage threshold...
are also being highlighted as the limitations of SESAMs. As for graphene, its zero-bandgap structure has limited its applications in ultrafast optics. SWCNTs depend on their tube sizes for their absorption efficiency, which determines the bandwidth operation. The intricate fabrication process of TIs is its main flaw, and TMDs' application in the mid-infrared region is limited by large direct bandgaps.

The search for a potential material to provide the next laser generation with low cost, wideband absorption, a high damage threshold, and a reliable SA continues in this work. The selection of suitable SAs and their parameter control are crucial subjects for the mode-locking performance. Amongst many transition metal oxides (TMOs), titanium dioxide (TiO$_2$) still holds strong attention in various applications, including photonic, photovoltaic, photocatalytic, electrochromic devices, and sensing [9]. Available in three different polymorphs: anatase, rutile, and brookite, TiO$_2$ possesses many advantageous qualities to offer, such as high chemical and optical stability, nontoxicity, and low cost [10]. Anatase, which is more favored than the other polymorphs, has shown a great deal of interest in solar cells due to the possibility of a higher conduction band edge energy and a lower electron-hole pair recombination rate. In an ultrafast fiber laser, a fast recovery time is an important factor in determining a saturable absorber's pulsing capability. As reported by Elim et al., TiO$_2$ has a very fast recovery time of 1.5 ps, resulting from the Pauli-blocking principle [11]. Rusdi et al. demonstrated the use of a TiO$_2$ film with a thulium-holmium-doped fiber laser, mentioning that its spectral absorption can be extended to the near-infrared (NIR) region, in which absorption is affected by crystal form and the particle size of TiO$_2$ [12]. To reaffirm this fact, recent research on TiO$_2$ has been conducted, with the results remaining significantly promising [13,14]. In addition, with a bandgap of 3.2 eV, anatase TiO$_2$ has been reported to exhibit significant nonlinear optical response [15], thus making it an ideal candidate as a saturable absorber.

This paper reports a mode-locked EDF laser that uses TiO$_2$ as a SA. The SA device is incorporated into the cavity of the ring laser to act as a mode-locker that generates nanosecond pulses in the C-band region. The prepared SA’s modulation depth, nonsaturable absorption, and saturation intensity were 5%, 37%, and 2.15 kW/cm$^2$, respectively. The mode-locked operation released pulses with a fundamental frequency of 988 kHz and a pulse width of 230 ns. The center wavelength was recorded at 1560 nm with a 3-dB bandwidth of 1.2 nm. The average output power of 2.17 mW has been obtained and pulse energy of 2.19 nJ was observed under a maximum pump power of 187.04 mW.

2. Titanium dioxide (TiO$_2$) film preparation and characterization

The TiO$_2$ powder (anatase, 25 nm, Sigma Aldrich Chemical) and de-ionized water were mixed in a 2:1 ratio to prepare the TiO$_2$ film fabrication. 30 mg TiO$_2$ powder and 15 ml of de-ionized water were blended for 3 hours at room temperature using a magnetic hot plate stirrer. The mixture was then placed in an ultrasonic bath for one hour to ensure proper mixing of the TiO$_2$ powder and de-ionized water. The following step is to combine the TiO$_2$-deionized water solution and the PVA solution in a 20ml:10ml ratio. The PVA solution was made by dissolving 1 gram of PVA powder in 120 mL of distilled water. Both solutions were stirred for 1 hour with a magnetic stirrer and then placed in a 30-minute ultrasonic bath. Finally, the TiO$_2$ suspension was put into a petri dish and allowed to dry at room temperature for 48 hours to form a TiO$_2$ composite film. Figure 1 (a) shows the real image of a TiO$_2$ PVA film whose thickness was determined to be approximately 50 µm. According to Figure 1 (b), the TiO$_2$ film’s saturable intensity, modulation depth, and non-saturable absorption are 2.15 kW/cm$^2$, 5%, and 37%, respectively. The film’s measurement provided by field emission scanning electron microscopy (FESEM) is depicted in Figure 1 (c). It can be seen from the figure that the TiO$_2$ appears to be distributed evenly throughout the film. In Figure 1 (d), an absorption of EDFL Q-switched at approximately 13 dB can be seen, which depicts the TiO$_2$ film’s linear absorption profile (LAP) at 1560 nm.
Figure 1. Characteristics of TiO$_2$ film (a) the real image of the fabricated TiO$_2$ PVA film (b) nonlinear absorption profile (c) FESEM image (d) linear absorption profile

3. EDFL ring cavity setup

Figure 2 depicts the schematic diagram of the proposed laser cavity for generating the mode-locked EDFL. The laser cavity is composed of a 980 nm laser diode, a wavelength division multiplexer (WDM), a 2.4-meter-long erbium-doped fiber (EDF) gain medium, an isolator, a standard 200-m-long single-mode fiber (SMF), a 90/10 coupler, and the prepared TiO$_2$ PVA film on the flat end of the fiber ferrule. The 980 nm laser diode forward pumps the erbium-doped fiber (EDF) gain medium via the wavelength division multiplexer's 980/1550 nm port. To prevent unwanted feedback of light in the ring cavity, an optical isolator is used. The light is then directed into the fiber connector, which is coated with a small piece of TiO$_2$ PVA film. A fiber-compatible SA device was created by sandwiching the film between two fiber ferrules using a fiber adapter. To ensure proper film attachment and to minimize parasitic reflection, an index matching gel was spread onto the ferrule tip. After passing through the SA, 10% of the laser output is tapped out by the 3dB coupler, while the remaining 90% is retained to circulate within the ring cavity. A 500 MHz digital oscilloscope was used to measure the repetition rate and pulse width while the optical spectrum was observed using a 50 nm spectral resolution optical spectrum analyzer (OSA). After that, the output coupler is connected to a power meter, which records the average output power. The stability of the pulsed laser is verified using a 7.8 GHz RF spectrum analyzer's electrical radio frequency (RF) spectrum signal. The ring cavity's total length was approximately 212 meters.
4. Result and Discussion

The experiment began by varying the pump power at 980nm that was directed into the gain medium via the WDM. The TiO$_2$-SA and 200m of SMF were incorporated into the ring cavity to compensate for cavity dispersion. The pump power was adjusted over a threshold of 145.83 mW to achieve stable and self-starting mode-locked operation. As a result of increasing the pump power to the maximum allowable value of 187.04 mW, the optical spectrum of mode-locked EDFL was obtained as plotted in Figure 3 (a). As can be seen, the central peak of the wavelength is at 1560 nm with a 3-dB spectral bandwidth of approximately 1.2 nm and a peak power intensity of -2.97 dB. The slight spectral bandwidth is caused by the cavity’s self-phase modulation (SPM). Figure 3 (b) shows the mode-locked pulse oscilloscope trace at 187.04 mW pump power. The repetition rate was measured at 988 kHz with a pulse width of 230 ns.

The RF spectrum obtained at maximum pump power is shown in Figure 4, where the pulsed laser’s stability was examined further. The figure also included an expanded pulse view that corresponds to a repetition rate of 988 kHz. The harmonic trend indicates that the mode-locking pulses are in the nanosecond range. The RF spectrum shows that the SNR is very high at 69 dB, indicating a stable regime. The measured RF spectrum demonstrates unequivocally that the obtained mode-locked pulses are extremely stable over a wide span of 50 MHz with harmonics up to more than 20$^\text{th}$ harmonics. To test the stability of the mode-locking operation, an observation was conducted for 24 hours with the pump power maintained at 187.04 mW. The optical spectrum taken every 5 hours at a pump power of 187.04 mW is depicted in Figure 5. The spectra demonstrate how the spectrums are generated in a stable mode-locking regime over a 24-hour period without causing any damage to the TiO$_2$-PVA thin film. Furthermore, to demonstrate that the TiO$_2$-SA was responsible for the laser’s mode-locking pulse generation, the TiO$_2$-PVA film was removed from the cavity. At any pump power setting, no pulse was visible on the oscilloscope. This confirms that the prepared film is in charge of the mode-locking operation.

Figure 6 depicts the single pulse energy and output power performances at various pump power inputs. The plot shows that as the input pump power increased from 145.83 mW to 187.04 mW, the output power increased linearly from 1.68 mW to 2.17 mW. The plot shows a slope efficiency of 1.16%. The high insertion loss of the SA caused the relatively low efficiency. Cavity optimization, which is dependent on intra-cavity loss, can be used to improve efficiency. As can be seen in the graph, when the pump power increases, so does the pulse energy. At 187.04 mW pump power, the maximum pulse energy of 2.19 nJ was obtained. These results reinforce that TiO$_2$ material has the potential to be used as a mode-locker in an EDFL cavity for C-band operation. The proposed TiO$_2$-based laser’s pulse performance was also compared to similar approaches based on other SAs, as shown in Table 1. In comparison to graphene and SWCNT materials, TiO$_2$ has a higher achievable pulse energy.
based laser also provides a shorter pulse width, higher repetition rate, and excellent SNR performance when compared to most of the materials in the table.

**Figure 3.** The characteristics of the mode-locking pulses (a) wavelength and (b) pulse train at 187.04 mW

**Figure 4.** RF spectrum at a pump power of 187.04 mW

**Figure 5.** Long-term operation stability of the optical spectrum at the pump power of 187.04 mW
5. Conclusion
The success of this demonstration led to the conclusion that the TiO$_2$-SA could generate stable nanosecond pulses in an EDFL that operates at a central wavelength of 1560 nm. The repetition rate recorded was almost constant at 988 kHz within a range of pump power from 145.83 mW to 187.04 mW. The pulse duration was observed at 230 ns. The maximum pump power draws an output power and pulse energy of 2.17 mW and 2.19 nJ, respectively. A very high signal-to-noise ratio (SNR) of 69 dB and a spectral bandwidth of 1.2 nm suggest that TiO$_2$-SA exhibits comparable performance and gives advantages of stability, simplicity in fabrication, and low cost.

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