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Sc_2O_3 Thin Film for Q-Switching Application in Erbium-Doped Fiber Laser

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ABSTRACT

This study demonstrates the utilization of a Scandium Oxide (Sc_2O_3) film as a passive saturable absorber (SA) for pulse generation within the C-band region in an Erbium-Doped Fiber Laser (EDFL) cavity for possible applications in metrology, sensing, and medical diagnostics. The SA was fabricated using Sc_2O_3 powder, with polyvinyl alcohol (PVA) employed to form the film. The experimental setup utilized an all-fiber ring cavity configuration. Q-switching was achieved over a range of pump powers from 48.8 mW to 84.8 mW. It is observed that as the pump power increased, the repetition rate rose from 42.3kHz to 82.8 kHz, accompanied by a reduction in pulse width from 5.04 µs to 2.82 µs. At a pump power of 84.8 mW, the system achieved a maximum output power of 6.75 mW and a maximum pulse energy of 81.6 nJ. The EDFL also has a high signal-to-noise ratio (SNR) at the fundamental frequency which is 55.4 dB, highlighting the stability of the Q-switched pulses.

Keywords: Fiber laser; Q-switching; saturable absorber; scandium oxide

INTRODUCTION

Recent decades have witnessed significant advancements in fiber laser research, particularly in enhancing erbium-doped fiber lasers (EDFL). Fiber lasers are increasingly favoured over traditional bulk lasers due to their robustness and alignment-free operation. Moreover, the higher surface area-to-volume ratio of fiber facilitates efficient heat dissipation. EDFLs, utilizing erbium-doped fibers (EDF) for amplification, have garnered substantial attention for their applications.

Q-switching, which enables the generation of high-energy pulses at low repetition rates, has found widespread use in diverse fields such as laser materials processing, range finding, and medical applications(Adachi & Koyamada 2002; Goel 2008; Sharma, Kim & Kang 2004; Skorczakowski et al. 2010). While Q-switching traditionally relies on costly and complex modulators like acousto-optic or electro-optic devices (El-Sherif & King 2003), recent interest has turned toward simpler and more cost-effective passive techniques employing saturable absorbers (SAs).

Commonly, doped crystals and semiconductor SA mirrors (SESAMs) have been utilized for passive Q-switching in commercial laser systems (M. Wang, Chen, Huang & Chen 2014; Yu et al. 2007). However, their complex synthesis processes and narrow operational wavelength bands limit their versatility. This has spurred extensive research into alternative SA materials with simpler fabrication processes and superior performance characteristics.

Carbon-based nanomaterials such as graphene and single-walled carbon nanotubes (SWCNTs) have shown remarkable nonlinear optical responses (Bao et al. 2009; Cui & Liu 2013; Jun-Qing et al. 2012; Liu, Xu & Wang 2012; Z. T. Wang, Chen, Zhao, Zhang & Wen 2012). Despite their promise, challenges like diameter control for SWCNTs and limited modulation depth for graphene exist. Recently, new types of SAs including topological insulators and transition metal dichalcogenides have emerged as promising alternatives for generating Q-switched pulses

(Chen et al. 2015; Luo et al. 2013; Luo et al. 2016; Meng et al. 2015; Mohanraj, Velmurugan & Sivabalan, 2016).

Furthermore, rare earth materials such as Eu, Nd, Sm, and La have demonstrated nonlinear optical responses suitable for Q-switching applications (Kumar 2003). As for now, there are limited studies regarding Sc_2O_3 in the use of Q-switching application and this study would be aiming to the objective of filling in those study gap. Notably, Gadolinium Oxide (Gd_2O_3) has been successfully employed for stable Q-switched pulses (Yusoff et al. 2020). In this study, this study explores Scandium Oxide (Sc_2O_3) as a SA material by incorporating Sc_2O_3 nano powders into a polyvinyl alcohol (PVA) host polymer within an EDFL cavity. This research demonstrates Q-switching operation at a wavelength of 1562.4 nm, highlighting Sc_2O_3 as a promising candidate for fiber laser pulse technology.

METHODOLOGY

A commercial Sc_2O_3 nano powder with a molecular weight of 137.9 g/mol was utilized to fabricate a SA thin film using an embedding technique. Initially, a PVA solution was prepared by dissolving 1 g of PVA powder in 120 ml of deionized water using a magnetic stirrer. Subsequently, 50 mg of Sc_2O_3 powder was added to 50 ml of the PVA solution and stirred vigorously for approximately 24 hours. To ensure effective binding of Sc_2O_3 to the PVA, the solution underwent ultrasonic treatment to make sure that the solution is homogeneous by using ultrasonic bath (GT SONIC-P2) at 40 kHz with ultrasonic power of 50 W for 30 minutes at room temperature. The resulting Sc_2O_3 suspension was carefully spread over a petri dish to prevent air bubble formation. After drying for 48 hours, a Sc_2O_3 PVA thin film approximately 50 μm thick was obtained. The film was cut into small pieces for use in constructing a SA device, which was then sandwiched between two fiber ferrules for easy integration into an EDFL cavity as a Q-switcher.

Figure 1 depicts the EDFL cavity configuration, which utilized a ring structure incorporating the Sc_2O_3 SA. A 14-pin laser diode operating at 980 nm pumped an 8 m long Erbium-doped fiber (EDF) via a 980/1550 Wavelength Division Multiplexer (WDM). A polarization-insensitive isolator ensured unidirectional laser propagation. An optical coupler split 40% of the optical power from the ring resonator as output, with the remaining 60% continuously circulating within the cavity. The Q-switched output spectrum was analyzed using an Optical Spectrum Analyzer (Anritsu, MS9710B). Temporal characteristics were measured with a digital oscilloscope (Agilent Technologies, DSO-X-2002A) and Radio Frequency Analyzer (PSA-3000), while power measurements were conducted using an optical power meter.

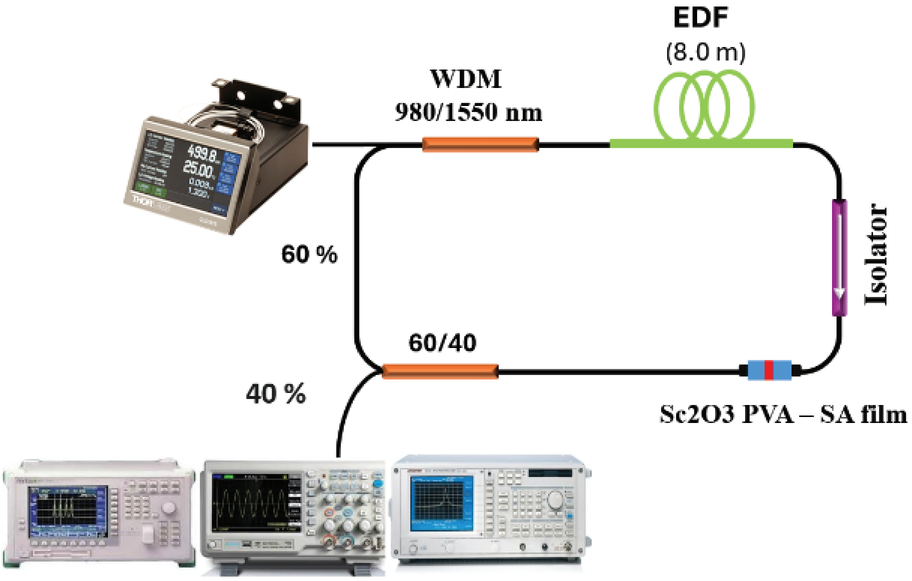

FIGURE 1. Erbium-Doped Fiber Laser configuration; which the Sc_2O_3 film was sandwiched between two fiber ferrules.

RESULTS AND DISCUSSION

In this study, Q-switched pulses were generated by integrating a Sc_2O_3-PVA thin film into the EDFL cavity setup at a threshold pump power of 48.8 mW. The Q-switching operation was sustained up to a maximum pump power of 84.8 mW. Beyond this threshold, the Q-switched pulses ceased due to the SA becoming oversaturated at high input fluences. The output spectrum of the Q-switched pulse at 84.8 mW pump power is depicted in Figure 2, centered at a wavelength of 1562.4 nm. Figure 3 illustrates a stable pulse train achieved at the maximum pump power, featuring a pulse repetition rate of 82.8 kHz and a pulse duration of 2.82 μs.

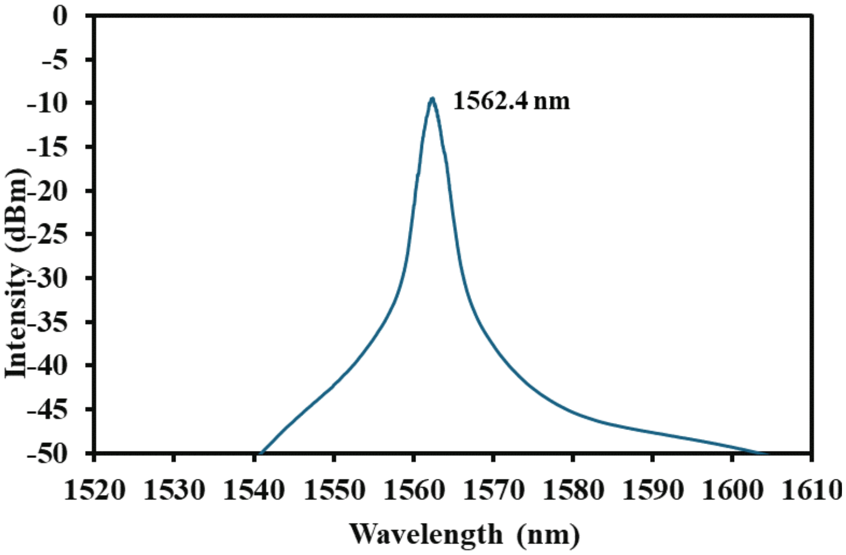

FIGURE 2. Output spectrum at 84.8 mW pump power

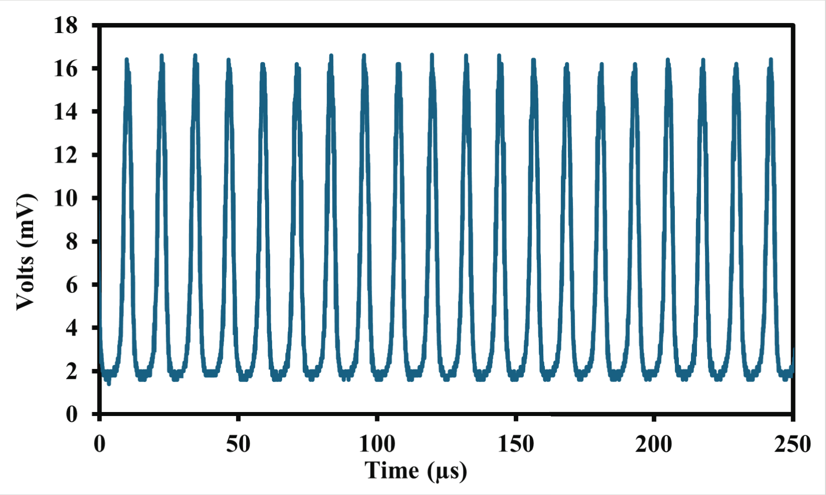

FIGURE 3. Typical pulse train at 84.8 mW pump power

Figure 4 depicts the repetition rate and pulse width as functions of incident pump power. As the pump power increased from 48.8 to 84.8 mW, the pulse repetition rate rose from 42.3 to 82.8 kHz, while the pulse width decreased from 5.02 μs to 2.82 μs. These trends confirm the characteristics of the Q-switched pulses, where the Sc_2O_3 thin film saturated at higher rates under increased pump power. Higher pump powers resulted in an increase of population inversion, which in turn increased repetition rates and decreased pulse widths. Optimization of parameters such as the EDF performance, improvement of the Sc_2O_3 thin film quality, or reduction of cavity losses could further minimize the pulse width.

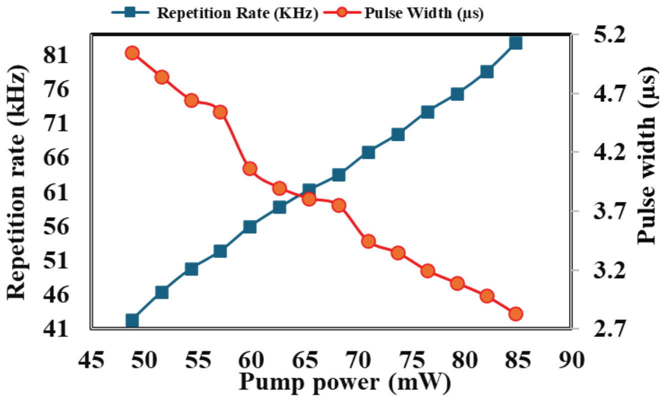

FIGURE 4. Repetition rate and pulse width as a function of pump power

Figure 5 illustrates the relationship between pulse energy, average output power, and pump power. As the pump power increases, both the average pulse energy and output power increase accordingly. These results demonstrate that higher pump power injection into the system leads to increased pulse energy generation. At a pump power of 84.8 mW, the system achieves a maximum pulse energy of 81.6 nJ and an output power of 6.75 mW.

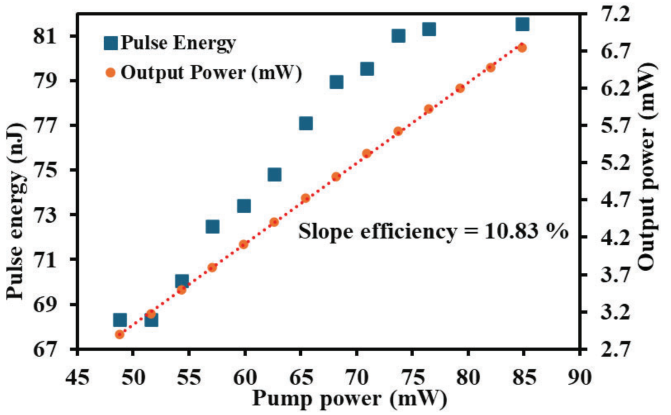

FIGURE 5. Pulse energy and output power as a function of pump power

Figure 6 demonstrates the stability of the Q-switched pulses using a Radio Frequency Spectrum Analyzer (RFSA) over a 700 kHz span. The first peak frequency at 82.8 kHz corresponds closely with the oscilloscope result shown in Figure 3. The signal-to-noise ratio (SNR) of the fundamental frequency was measured at 55.4 dB, indicating excellent stability of the Q-switched pulse. Enhancing the SNR further could be achieved by reducing non-saturable losses in the SA and minimizing cavity losses.

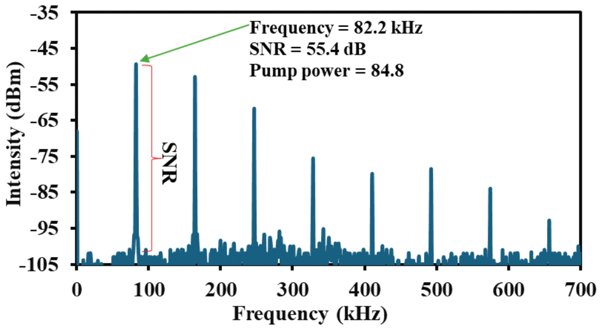

FIGURE 6. RF spectrum at 84.8 mW pump power

TABLE 1. Comparison of past Q-switched performance from different materials with current works

Materials	Repetition Rate (kHz)	Pulse Width (µs)	Pulse Energy (nJ)	Reference
Black Titanium Dioxide ($BTiO_{2-x}$)	35.77	7.48	64.39	Johari et al, 2024
Indium Tin Oxide (ITO)	37.60	5.60	12.69	Zamri et al, 2024
Boron Carbide Nanoparticles (B4C)	31.60	15.27	2.61	Jasem et al, 2024
Scandium Oxide (Sc_2O_3)	82.80	2.82	81.60	This work

Table 1 shows the comparison of Q-switched fiber laser performance between Scandium Oxide (Sc_2O_3) and other materials in the recent year. Black titanium dioxide *($BTiO_{2-x}$)*, indium tin oxide (ITO) and boron carbide nanoparticles (B4C) all have lower repetition rate compared to 82.8 kHz of that Sc_2O_3 which are 35.77 kHz, 37.60 kHz and 31.60 kHz respectively. The pulse width for all these 3 materials is also higher than Sc_2O_3 (2.82 µs) at 7.38 µs, 5.60 µs and 15.27 µs. Lastly, Sc_2O_3 produces the highest pulse energy among these 4 materials at 81.60 nJ compared to 64.39 nJ, 12.69 nJ and 2.61 nJ respectively to the other materials mentioned above.

CONCLUSION

This study has successfully demonstrated a Q-switched EDFL operating at 1562.4 nm, utilizing a Sc_2O_3 film as a passive SA. The SA was fabricated by embedding Sc_2O_3 powder into a PVA host matrix. It was integrated into an all-fiber ring EDFL cavity to generate Q-switched pulses with pump powers ranging from 48.8 mW to 84.8 mW. Increasing the pump power resulted in a corresponding increase in the repetition rate, from 42.3 to 82.8 kHz, and a decrease in pulse width, from 5.04 µs to 2.82 µs. The SNR measured at the fundamental frequency was 55.4 dB, indicating excellent stability of the Q-switched pulses. At a pump power of 84.8 mW, the system achieved a maximum output power of 6.75 mW and a maximum pulse energy of 81.6 nJ. It is found that within the resulted parameter, this material as a saturable absorber is very stable and reliable in generating Q-switched fiber laser.

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DECLARATION OF COMPETING INTEREST

None.

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