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Q-Switching in an Erbium-Doped Fibre Laser Using a Saturable Absorber Based on Vanadium Pentoxide Polyethylene Glycol in the Long-Wavelength Range

***Abstract**. The laser generation was produced at a wavelength of 1562.4 nm with a small spectral bandwidth of 0.4 nm using a short-pulse erbium-doped fibre laser with unique group delay dispersion. This process was generated by Q-switching, which was accomplished using a vanadium oxide polyethylene glycol (V2O5-PEG) film saturable absorber (SA) within an all-fiber ring cavity arrangement. The laser generated a peak output power of 0.4 mW, a maximum pulse energy of 3.2 nJ, and an astonishingly brief pulse width of 4.7 s. These results highlight the possibility of the V2O5 film as a workable SA substitute for producing pulsed lasers.*

***Streszczenie.**Generowanie lasera zostało wytworzone przy długości fali 1562,4 nm z małą szerokością pasma widmowego 0,4 nm przy użyciu krótkoimpulsowego lasera światłowodowego domieszkowanego erbem z unikalną dyspersją opóźnienia grupowego. Proces ten został wygenerowany przez przełączanie Q, które zostało osiągnięte przy użyciu nasycalnego absorbera (SA) z tlenku wanadu, glikolu polietylenowego (V2O5-PEG) w układzie wnęki pierścieniowej z wszystkich włókien. Laser generował szczytową moc wyjściową 0,4 mW, maksymalną energię impulsu 3,2 nJ i zdumiewająco krótką szerokość impulsu 4,7 s. Wyniki te podkreślają możliwość zastosowania folii V2O5 jako wykonalnego substytutu SA do produkcji laserów pulsacyjnych. (**Q-Switching w laserze światłowodowym domieszkowanym erbem przy użyciu nasycalnego absorbera na bazie glikolu polietylenowego pięciotlenku wanadu w zakresie długich fal**)*

Keywords: Q-swiched, fiber laser, V_2O_5, PEG
Słowa kluczowe: Przełączanie Q, laser światłowodowy, V_2O_5, PEG

Introduction

Due to their inherently align-free construction, excellent mode confinement, and great stability, Q-switched fibre lasers have attracted a lot of interest in recent years [1]. They have a wide range of uses, such as in the processing of materials, microfabrication, range finding, remote sensing, optical communications, skin care, and medical procedures [2–5]. An electro-optic or acousto-optic modulator can provide a Q-switched pulse to actively regulate the loss inside the cavity [6–8]. However, the complexity and cost of the laser system's production are increased by the modulator's expensive and bulky component construction. A portable, inexpensive, straightforward, and reliable alternative approach to create Q-switched is provided by the passive technique with a saturable absorber (SA) [8]. Additionally, it is more practical for some portable devices, such a range finder and a laser marker, due to its lightweight characteristics and low energy consumption.

Because of their outstanding nonlinear optical responses, semiconductor saturable absorber mirrors (SESAM) [9] and carbon-based nanomaterials [10, 11] are commonly used as SA in laser cavities for Q-switched pulse production. However, the synthesis of these materials is costly and time-consuming. Furthermore, SESAMs have a small operating wavelength spectrum, limiting their usefulness and versatility. Carbon-based materials such as carbon nanotubes [10], graphene [12], and graphene oxide [11] each have their own drawbacks, such as the necessity for diameter control in carbon nanotubes and a lesser modulation depth in graphene. Consequently, a significant amount of research has been dedicated to the exploration of novel alternative superconducting materials that exhibit both great operational efficiency and straightforward production techniques.

Recently, 2D nanomaterials such as Transition metal dichalcogenides (TMDs) and Black phosphorus (BP) have also been reported as alternative SAs in many laser systems [13] [14]. TMDs have excellent physical properties such as fast response time, good electron mobility, and high superconductivity [15]. For instance, Molybdenum disulfide and Tungsten disulfide have a relaxation time of about 30 fs, and thus they were widely explored for pulse generation [16, 17]. These materials require a particular fabricating procedure based on mechanical exfoliation to obtain a monolayer structure, which has a bandgap corresponding to the production of the near-infrared laser [18]. But this fabrication procedure is complex because the mechanically exfoliated material contains an inconsistent powder-like layer that is difficult to handle. On the other hand, BP has these unique properties but it is sensitive to air and water, which affects its performance [14].

Transition metal oxide (TMO) materials have also gained explosive growth of advertence in the past few years due to their excellent electronic and optical properties. They can enable high-performance optoelectronic devices due to their high carrier mobility and broadband light absorption. The TMO, in their low-dimensional form, demonstrates good abilities in the field of nonlinear optics. It is characterized by large third-order nonlinear interchange ability, rafast response time in a narrow range, a high damage threshold, and a broad absorption band [19]. Apart from that, the TMO bandgap can be set via the thickness and controlling particle size [20]. Several TMO-SAs have been proposed for producing Q-switched pulses, such as zinc oxide [21, 22], titanium dioxide [23], copper oxide [24], and molybdenum oxide [25].

Vanadium pentoxide (V2O5) is considered to be a crucial member of the transition metal oxide family [26]. According to the paper, the material exhibited a highly favourable nonlinear optical absorption property, making it well-suited for applications using saturable absorbers [27]. This work presents the demonstration of a Q-switched fibre laser utilising a recently designed vanadium pentoxide saturable absorber incorporated into polyethylene glycol. The surface area (SA) was generated by the incorporation of V2O5 material into polyethylene glycol (PEG) to form a film absorber. This film absorber was subsequently placed between two fibre ferrules. The use of V2O5 PEG film has the potential to serve as a nonlinear optical modulator within the cavities of Erbium-doped fibre lasers (EDFLs).

Laser EDFL V_2O_5 PEG setup

The experimental setup involves the utilization of a laser, an erbium-doped fiber amplifier (EDFA), a vanadium pentoxide (V2O5) catalyst, and polyethylene glycol (PEG).A passively Q-switched pulse is produced within an erbium-doped fiber laser (EDFL) cavity by the use of vanadium pentoxide (V2O5) as a saturable absorber (SA) for Q-switching. The Electrochemical Double-Layer Capacitor (EDFL) is designed for the purpose of investigating the effectiveness of the V2O5-PEG Solid Electrolyte Interface (SEI), as seen in Fig 1. The ring cavity is established by the fusion of two meters of erbium-doped fiber (EDF), a polarization-insensitive isolator, a vanadium pentoxide-polyethylene glycol saturable absorber (V2O5-PEG SA), a 90/10 fiber-fused optical coupler, and a 980/1550nm wavelength division multiplexing (WDM) device. To enable unidirectional light transmission within the ring resonator, an optical isolator was positioned between the gain medium and the saturable absorber (SA). The V2O5 PEG film, which had been manufactured in advance, was placed between two fiber ferrules with FC/PC connectors. This assembly was then introduced into the laser cavity, where it served the purpose of a Q-switcher. A fraction of 10% of the laser's power was extracted using a 90:10 coupler in order to conduct analysis. The optical spectrum analyzer (OSA, Yokogawa AQ6370B) was used to identify the output spectrum of the laser. The OSA has a spectral resolution of 0.02 nm. The detection of the signal's frequency and time-domain may be achieved by utilizing a 1.3 GHz photodetector (Thorlabs, DET10D/M) in combination with a 7.8 GHz RF spectrum analyzer (Anritsu) and a 350 MHz digital oscilloscope (GWINSTEK: GDS-3352), respectively. The whole length of the cavity utilized for Q-switching operation is approximately 5 meters.

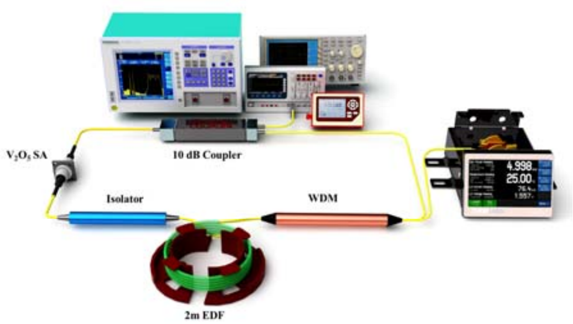

Fig.1. The experimental setup of EDFL V2O5 SA PEG.

Fabrication and experimental setup

Simple construction and characterization yielded laser performance. V2O5 and PEG polymer were chemically combined to make the clear and even saturable absorber (SA). As illustrated in Fig. 2, synthesised V2O5 was mixed with PEG solution for 2 hours, cast onto a petri dish, and dried in a vacuum oven to make the film. Fig. 2 shows an enlarged view of the SA film on the fibre. V2O5 film's linear absorption profile Fig. 3, determines its SA applicability. The V2O5 film showed linear absorption at 1.55 microns, with 7dB at 1550 nm.

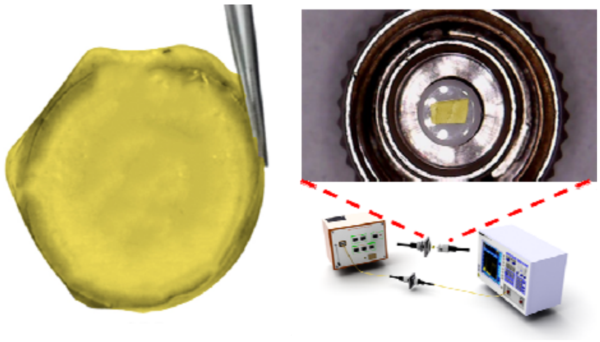

Fig.2. V2O5 SA PEG incorporates into ring cavity.

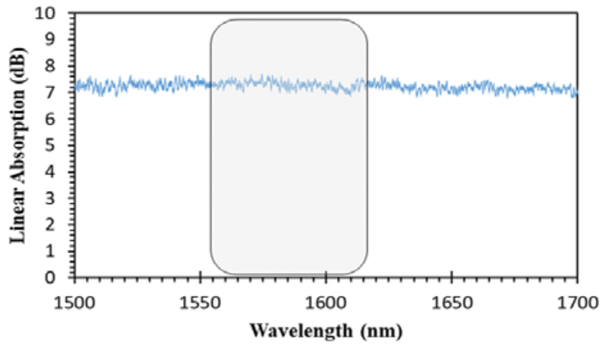

Fig.3. Linear saturable absorption curve for the V_2O_5-SA film

Q-switching EDFL V_2O_5 PEG Performance

V2O5-PEG SA thin films EDFL lasers start with 40 mW pump power. The EDFL produces Q-switched microsecond laser pulses at 110.9 mW pump power. At 138.7 mW pump power Fig. 4(a), the laser output spectrum is centered at 1562.4 nm with a 3-dB bandwidth of 0.4 nm and a peak intensity of -33.4 dBm. The RF spectrum Fig. 4(b) shows 97.2 kHz pulse repetition. The fundamental frequency's signal-to-noise ratio surpasses 45 dB, confirming Q-switched stability. As pump power increases from 110.9 mW to 166.5 mW, Q-switched pulse repetition rate increases from 91.7 kHz to 128.2 kHz Fig. 4(c). Passive Q-switched operation reduces pulse duration from 10.6 to 4.7 µs. Nevertheless, this process exhibits instability, resulting in the emergence of a continuous wave at the upper end of the spectrum when subjected to larger pump outputs. Figure 4(d) illustrates the depiction of the average power and computed single pulse energy of the Q-switched EDFL in relation to the pump power. It can be shown that the output power exhibits a nearly monotonic rise, ranging from 0.24 mW to 0.40 mW. Similarly, the single pulse energy demonstrates an increase from 2.6 nJ to 3.2 nJ. The upper limit of light conversion efficiency is around 0.3%. The potential cause for the poor efficiency might be attributed to the significant cavity loss resulting from the presence of the saturable absorber (SA) layer. Fig 5 illustrates the graphical representation of the pulsed laser oscilloscope traces obtained at a pump power of 166.6 mW. It is evident that the pulse trains have a consistent contour and strength. The duration of each pulse is measured to be 7.82 µs, indicating a repetition rate of 128.2 kHz. The minimum duration of a pulse is 4.71 microseconds.

In order to verify whether the Q-switching operation is solely caused by the V2O5 PEG film, we conducted an experiment where the saturable absorber (SA) was substituted with a pure PEG film. However, Q-switched pulses were not observed in any of the cases, even after tuning the laser diode over its full range. The results suggest that the proposed material has the potential to serve as an alternative saturable absorber (SA) for the development and application of fibre lasers.

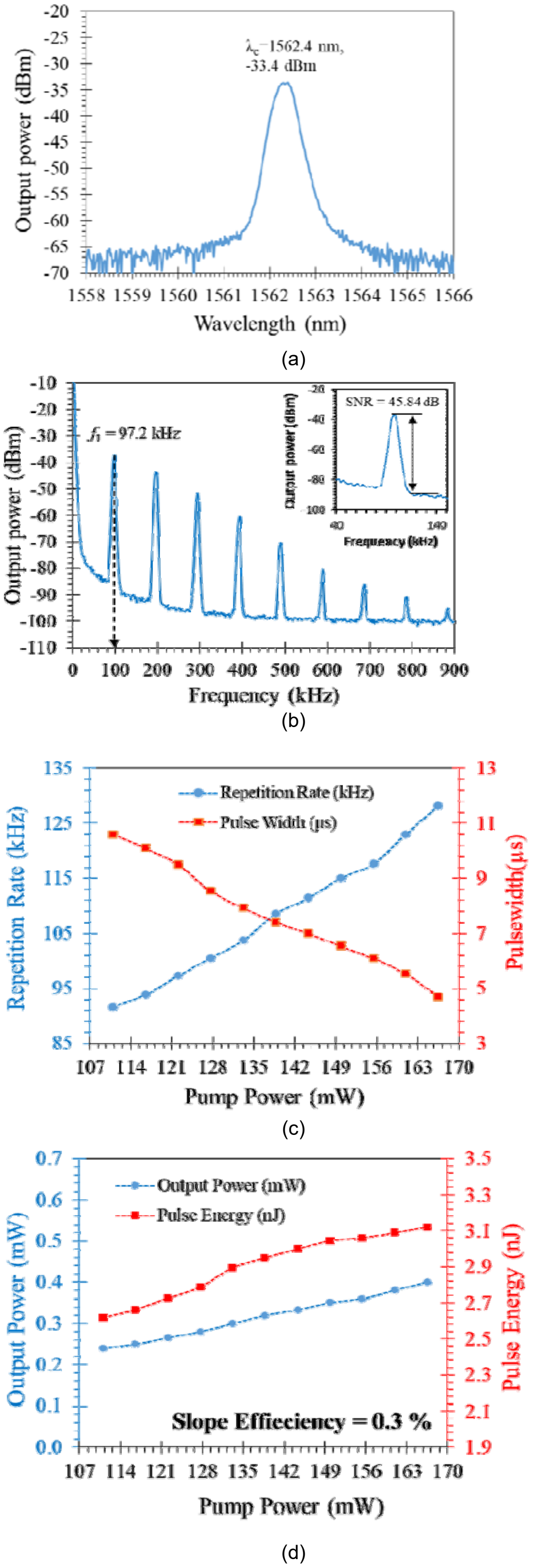

Fig. 4: (a) Output spectral and (b) RF spectrum characteristics of the Q-switched EDFL at at a pump power of 138.7 mW Q-switching performances of the V_2O_5 based EDFL against pump power (c) Repetition rate and pulse width (d) Average output power and single pulse energy.

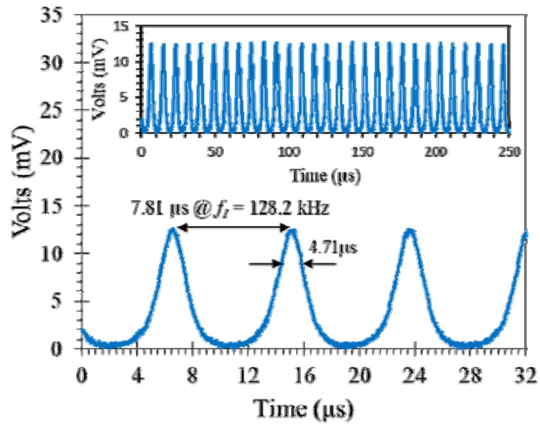

Fig. 5: Typical pulse train of the Q-switched EDFL at 166.5 mW.

Conclusion

A demonstration of a Q-switched fiber laser employing a V2O5 film as a saturable absorber (SA) was successfully accomplished. The synthesis of V2O5 was incorporated onto a PEG polymer film to generate the SA. The experiment demonstrated the use of a Q-switched Erbium-Doped Fibre Laser (EDFL) with a Vanadium Pentoxide (V2O5) Saturable Absorber (SA). The experiment successfully operated within a pump power range of 110.9 – 166.5 mW. The pulse repetition rate exhibited an increase from 91.7 kHz to 128.2 kHz, while concurrently, the pulse width shown a drop from 10.6 µs to 4.7 µs. The maximum pulse energy achieved was 3.2 nanojoules (nJ) when the pump power was set at 166.5 milliwatts (mW). The V2O5-based surface acoustic wave (SA) devices possess several advantageous characteristics, including user-friendly manufacturing, high stability, and a sturdy construction. These properties make them highly suitable for a wide range of nonlinear photonic applications, with a particular emphasis on ultrafast photonics, optical telecommunications, and measurement applications.

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