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Lutetium (III) oxide film as passive mode locker device for erbium-doped fibre laser cavity

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ABSTRACT

We reported a newly fabricated saturable absorber (SA) namely Lutetium oxide (Lu_2O_3) thin film for generating a stable and compact mode-locked Erbium-doped fibre laser (EDFL) operating at 1564 nm. The film SA was synthesized by embedding Lu_2O_3 into polyvinyl alcohol (PVA) host film. By incorporating the film SA along with 200 m long single mode fibre (SMF) into an EDFL cavity, the mode-locked laser with 0.97 MHz repetition rate stably emerged at an increasing pump power, ranging within 145-187mW. The pulse width was measured to be 2.12 ps. The highest pulse energy and peak power were measured as 7.64 nJ and 3.61 kW respectively and were obtained at 187 mW pump power. The fundamental frequency was examined to have a signal to noise ratio (SNR) of 61 dB. These laser performances suggest that the Lu_2O_3 film SA is feasible for becoming an alternative passive SA in the 1.55 μm region.

1. Introduction

Mode-locked fibre lasers typically based on passive technique, have received tremendous responses in recent years owing to their great flexibility and improved simplicity. Unlike the active technique which uses electronically pulse triggering system for the pulse generation, the passive one, is generally much simpler in preparation, smaller in geometry, cheaper, and even faster [1]. Mode-locked erbium-doped fibre lasers (EDFL) have found significant potentials in several applications including telecommunication, medical diagnostics and treatments, sensing, material processing, and range finding [2,3].

In the early years, semiconductor saturable absorbers (SESAMs) [4], carbon nanotubes (CNTs) [5], graphene and black phosphorus (BP) [6] have been successfully used as the passive intracavity-loss modulators in the fibre lasers. SESAMs which debuted in 1992 [7,8], quickly became the most prominent SA for some years. However, these devices have certain drawbacks including narrow absorption bandwidth, relatively high production cost and considerably bulky for a fibrized laser source. In addition, CNTs has absorption efficiency and bandwidth that depend on its diameter, while, graphene has a relatively low optical absorption per layer that limits its usability [9,10]. Additionally, BP is a hydrophilic material that easily interacts with water, and is a polarization dependent material; thus, integrating BP as SA requires a fairly complex preparation as well as careful handling [11–13]. Thus, in recent years, several other new materials [14–17] with relatively easy preparation techniques have been proposed as SA candidates in promoting reliable and stable pulsed fibre lasers. In an earlier report, holmium oxide, a lanthanide material had been successfully revealed as a reliable SA candidate for inducing a stable Q-switched fibre laser at the 2-micron regime [18].

Lutetium oxide (Lu_2O_3) or Lutecia, another lanthanide oxide element, is a thermally stable white compound material which is suitable for glass and optical applications. It is used as cracking, alkylation, hydrogenation, polymerization, X-ray application as well as the starting material in the production of laser crystals. Experimentally, it has been tested to have sufficient optical absorption in the 1.55 μm vicinity, suggesting a suitability to be used as a potential SA candidate for the mode-locked EDFL operation. By properly embedding the Lu_2O_3 element into the polyvinyl alcohol (PVA), a very thin Lu_2O_3 PVA film with a thickness of around 30 μm could be attained. The film SA can be easily incorporated into the laser cavity by sandwiching a small size (1 mm x 1 mm) of the film between two fibre ferrules before being closely fixed with a fibre adapter. Such a mechanism allows the realization of a simple, as well as flexible all-fibrized passively mode-locked laser system.

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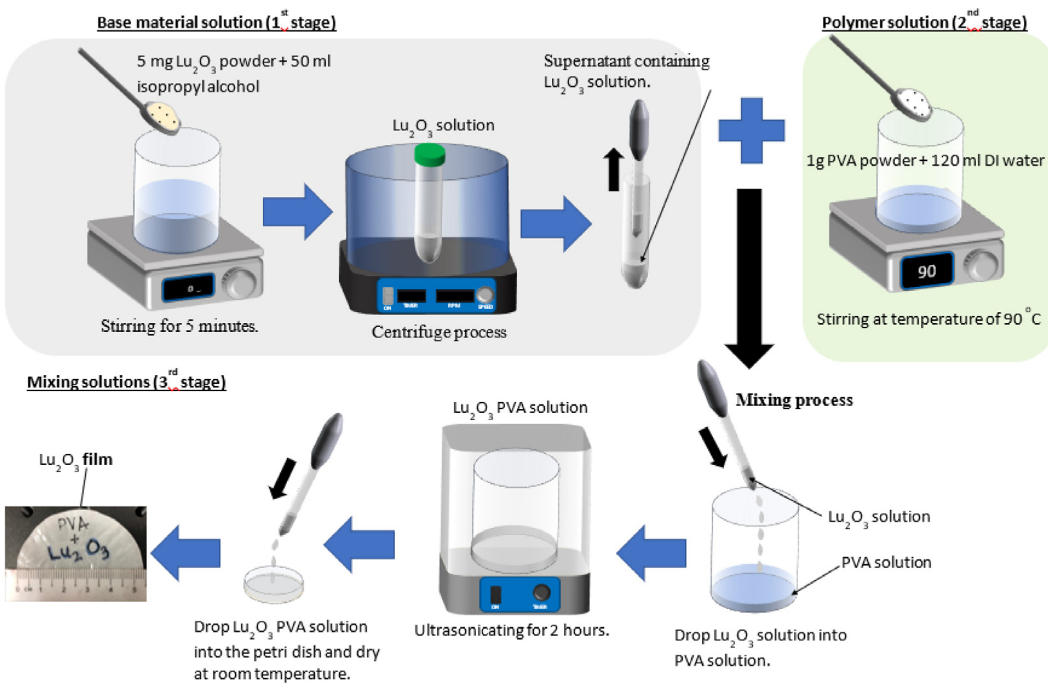

Fig. 1. The proposed fabrication process of the Lu_2O_3 thin film SA.

In this regard, we report for the first time, to the best of our knowledge, a passively stable and compact mode-locked EDFL by integrating Lu_2O_3 PVA composite thin film in the ring cavity. A stable mode-locked EDFL operating at 1564.92 nm with a corresponding pulse repetition rate of 0.97 MHz and a pulse width of 2.12 ps were achieved at a pump power range of 145–187 mW. The mode-locked laser had a slope efficiency of 8.65%, while the highest pulse energy was obtained as 7.64 nJ.

2. Lutetium oxide film fabrication and characterization

The Lu_2O_3 powder (CAS No. 12032-20-1, 99.9% traces metal basis) used in the Lu_2O_3 thin film SA fabrication was obtained from Sigma Aldrich (Malaysia) without further purification. The fabrication process of the Lu_2O_3 film SA is illustrated in Fig. 1. The Lu_2O_3 solution was prepared by dissolving 5 mg Lu_2O_3 into 50 ml isopropyl alcohol (IPA). The solution was constantly stirred for 5 min using a magnetic stirrer. Then, the Lu_2O_3 solution was centrifuged for 6 h using an ultrasonic bath machine. Upon completion of these processes, the supernatant containing Lu_2O_3 solution could be seen emerging on the surface of the Lu_2O_3 residue. The Lu_2O_3 solution was then transferred into a test tube for later use. On the other hand, the PVA solution was prepared by dissolving 1 g of PVA powder with 120 ml deionized (DI) water. The mixture was stirred at a stirring temperature of 90 °C for 30 min. Then, the PVA solution was cooled down to room temperature. Next, the pre-prepared Lu_2O_3 solution was carefully mixed with the PVA solution. The mixed solution was ultrasonicated for 2 h to form a homogenous composite precursor solution. The solution was then transferred onto a petri dish and left to dry at room temperature for 3 days, to form ~30 μm thick of Lu_2O_3 PVA composite film SA. For brevity, the composite film SA is regarded as Lu_2O_3 film SA in this paper. Our observation shows that the fabricated film SA is quite easy to prepare and relatively simple in fibre integration. Unlike BP material which is hydrophilic and tends to react with water more easily, the fabricated Lu_2O_3 film SA is more reliable, robust and quite easy to maintain.

Fig. 2 shows the important optical characteristics of the Lu_2O_3 film SA. The film SA modulation depth was measured using twin detector measurement method. In the experiment, a stable 1 MHz amplified self-generated passively mode-locked EDFL (1550 nm) with a constant 2 ps pulse width was used as the input pulse light source. The output powers from both detectors (with and without SA integrated into) were recorded as the optical power gradually increased. The results were then fitted with the Gamire et al. saturation model formula [19],

$$\alpha(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}$$

where $\alpha(I)$ is the absorption rate, α_s is the saturable absorption or modulation depth, I is the input intensity, I_{sat} is the saturation intensity, and α_{ns} is the non-saturable absorption. As given in Fig. 2(a) the Lu_2O_3 film SA has saturable absorption of 10%, saturation intensity of 100 MW/cm^2 and non-saturable loss of 58%, respectively. In comparison with certain 2D materials [20]; MoS_2 (2.15%), $MoSe_2$ (6.73%), WS_2 (2.53%) and WSe_2 (3.02%), the obtained modulation depth of Lu_2O_3 film SA (10%) is relatively higher. Next, the composition of the fabricated Lu_2O_3 film SA was investigated via energy dispersive spectroscopy (EDS). As provided in Fig. 2(b), the presence of the Lu_2O_3 is confirmed through several high peaks dominated by the Lu and O elements that appear on the plot. Fig. 2(c) illustrates the scanning electron microscopy (SEM) image of the fabricated Lu_2O_3 film SA, which shows the Lu_2O_3 component randomly distributed in the polymer composite. The linear absorption profile of the Lu_2O_3 film SA is provided in Fig. 2(d). As demonstrated, the peak absorption (20.7 dB) is observed to be at 1308 nm wavelength, while the optical absorption at the mode-locked operating wavelength (1564 nm) is found to be 4.6 dB. The inset of Fig. 2(d) illustrates the set-up used for the linear absorption measurement.

3. EDFL ring cavity

The mode-locked EDFL experimental configuration is illustrated in Fig. 3. The gain medium (2.8 m EDF, IsoGain I-25(980/125) has peak core absorption of 35–45 dB/m at 1531 nm wavelength. In addition to that, it also has a core diameter of 4 μm, a cladding diameter of 125 μm and numerical aperture (NA) of 0.23–0.26. As shown, the gain medium is optically pumped by a single wavelength 980 nm laser diode (LD) through a 980/1550 nm wavelength division multiplexer (WDM). The

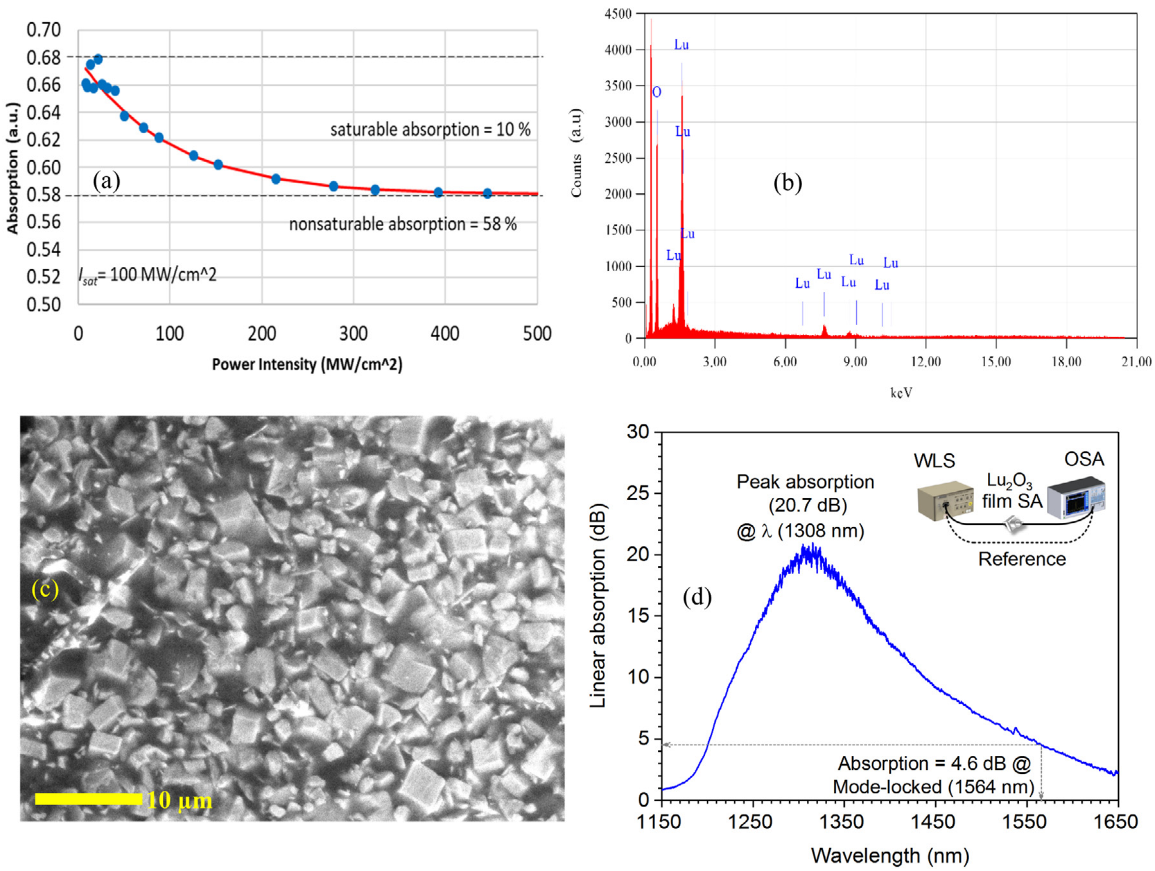

Fig. 2. The important characteristics of the Lu_2O_3 film SA (a) modulation depth (b) EDS profile (c) SEM image (d) Linear absorption profile.

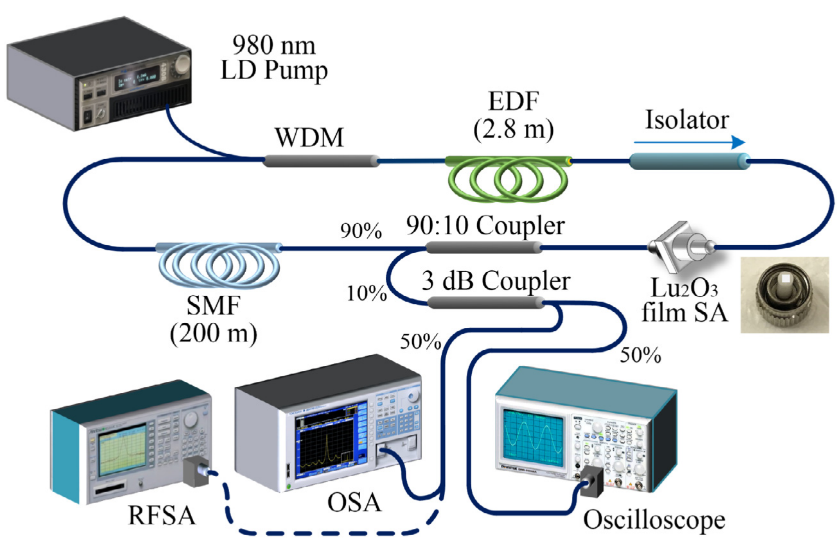

Fig. 3. The proposed EDFL mode-locked experimental setup.

light is then channelled into an isolator and the Lu_2O_3 film SA. The isolator preserves unidirectional light propagation within the cavity, whereas the film SA promotes the necessary loss modulation. The integration of the Lu_2O_3 film SA into the cavity is done by sandwiching the pre-cut film SA (1 mm x 1 mm) between two FC/PC fibre ferrules. The joining was then closely fitted with a clean fibre adapter. A small quantity of index matching gel was pre-applied onto the surface of the fibre ferrule where the film SA to be located. The application of the gel would minimize the unwanted parasitic reflections. After transmitting out from the SA, the light is then directed into a 90/10 optical coupler, where 10% of the laser output is channelled out into a 3 dB coupler. The 3 dB coupler further divides the laser output into 50:50 separations, enabling simultaneous data collections. In the meantime, 90% of the laser output (from the 90/10 coupler) is propagated through 200 m single mode fibre (SMF28). The laser is then directed into the WDM through the 1550 nm port for a complete closed-loop light propagation. The additional length of SMF28 is used to assist the Lu_2O_3 film SA for a stable self-starting mode-locked laser generation by providing sufficient dispersion and nonlinearity in the cavity. As in the mode-locked operation, both of these two parameters; dispersion and nonlinearity need to

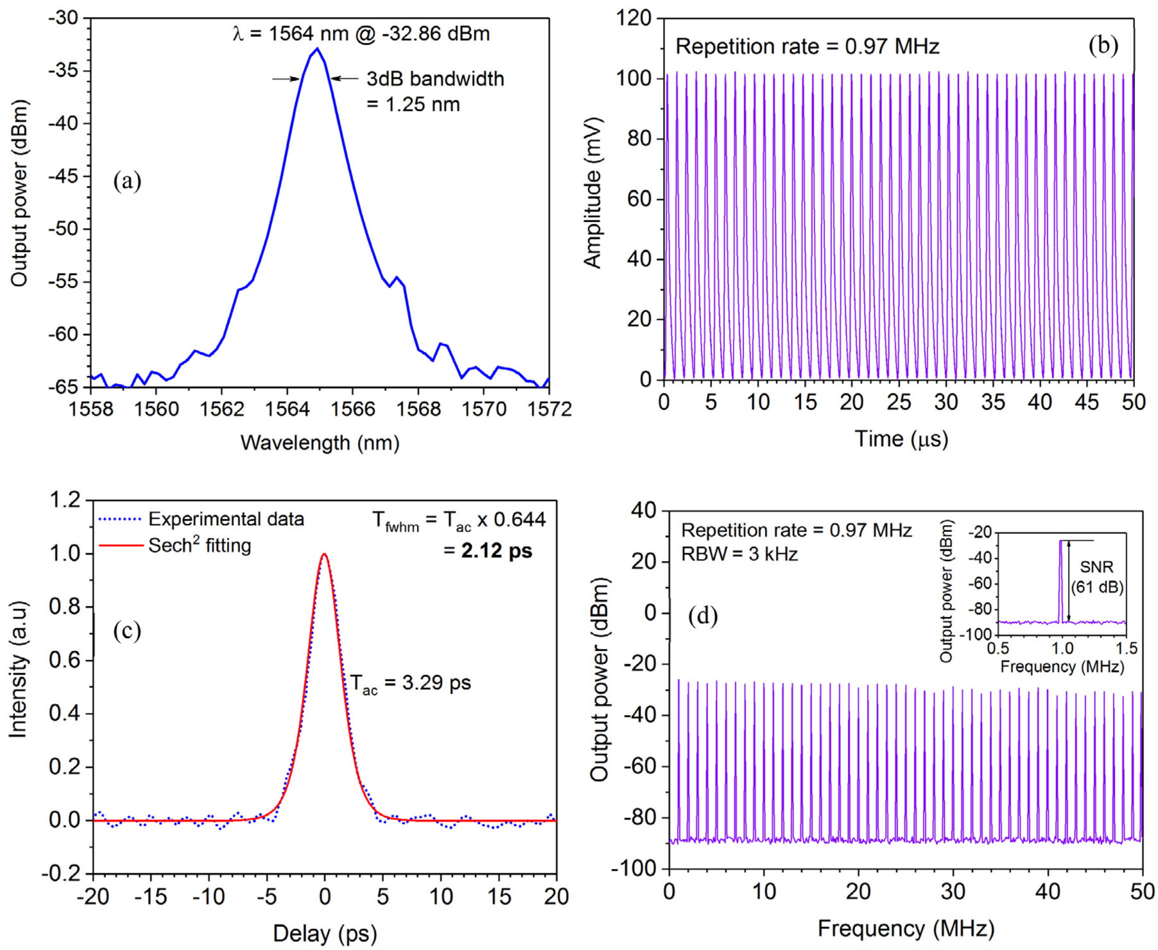

Fig. 4. Mode-locked EDFL via Lu_2O_3 film SA important characteristics at 145 pump power (a) Output spectrum (b) Oscilloscope trace (c) Autocorrelator trace (d) RF spectrum, while the inset shows the fundamental frequency in detail.

be well balanced. Furthermore, it would also enhance the pulse energy by slightly broadening the pulse width. This enhanced pulse energy would be sufficient enough to saturate the Lu_2O_3 film SA at a moderate pump power.

The EDFL cavity was observed to operate in the anomalous dispersion regime with a group velocity dispersion (GVD) of ~21.9 ps^2 /km. The total net dispersion was calculated to be approximately ~−4.464 ps^2/km. An optical spectrum analyzer (OSA) with a 0.03 nm resolution was utilized to investigate the laser optical spectrum. Meanwhile, a radio frequency spectrum analyzer (RFSA) and a digital oscilloscope (OSC) that pre-coupled with a fast photodetector (PD) was used to examine the presence and quality of the pulsed signal in the time domain and frequency domain, respectively. An optical power meter was also used to measure the laser output power.

4. Mode-locked laser performances

A stable self-starting mode-locking operation was observed, emerging at a threshold pump power of 145 mW. The mode-locked laser remained stable as the pump power rose to 187 mW. In the mode-locking process, Lu_2O_3 SA is utilized to obtain self-amplitude modulation (SAM) in the cavity. The film SA creates some loss inside the cavity, which is relatively large for low intensity, however, fairly small for a short pulse with high intensity. Hence, a short pulse creates a loss modulation due to high intensity at the pulse's peak saturates the absorber strongly than its low intensity wing [21].

Fig. 4 shows the mode-locked EDFL important characteristics examined at the threshold pump power of 145 mW. Fig. 4(a), illustrates the optical spectrum of the mode-locked EDFL. The laser has a central wavelength of 1564 nm and a peak power intensity of −32.86 dBm. The 3 dB spectral bandwidth is approximately 1.25 nm. The total net cavity dispersion is calculated as −4.34 ps^2. The mode-locked pulses train as depicted in Fig. 4(b), has a nearly constant repetition rate of 0.97 MHz and has a considerably small amplitude fluctuation (below than 5%). The obtained repetition rate was examined, to be related with the overall EDFL cavity length of 206.18 m, indicating that the pulsed laser was a mode-locked laser. The autocorrelator trace of the mode-locked EDFL along with the $sech^2$fitting is illustrated in Fig. 4(c). The pulse width after deconvolution is 2.12 ps. Based on the obtained 1.25 nm (153 GHz) spectral bandwidth, the time-bandwidth product (TBP) is calculated as 0.325. The transform limit derived from the obtained bandwidth is around 2.05 ps, which suggests that the output pulses are slightly chirped. Fig. 4(d) depicts the radio frequency (RF) spectrum of the mode-locked laser in the span of 50 MHz and taken at resolution bandwidth (RBW) of 3 kHz. The presence of many harmonics within the span, confirms that the generated pulse is considerably narrow. As shown in the inset of Fig. 4(d), the signal to noise ratio (SNR) is around 61 dB, which affirms the stability of the mode-locked pulses.

Fig. 5, shows the mode-locked EDFL performances. The output power increases almost linearly from 3.88 mW to the maximum of 7.42 mW, as the pump power increased from 145 mW to 187 mW. The corresponding slope efficiency is obtained as 8.65%. The increase of the pump power causes the pulse energy and peak power to rise accordingly, to reach the maximum value of 7.64 nJ and 3.61 kW, respectively. The mode-locked operation was examined for 1 h duration at room temperature. Observation of the laser output showed no significant fluctuations in the optical spectrum and pulse amplitude, thus

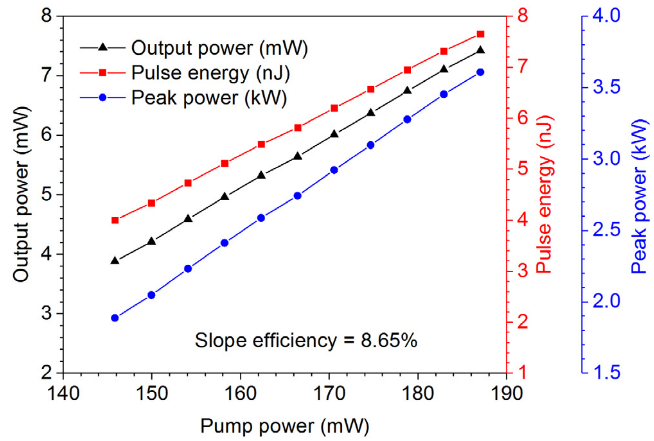

Fig. 5. The output power, pulse energy and peak power of the mode-locked EDFL as a function of pump power (145–187 mW).

validating the long stability of the designed system. This also suggests that the SA was still in good condition, indicating that the SA has higher thermal damage threshold than the laser output.

5. Conclusion

We have successfully demonstrated, a stable and reliable mode-locked EDFL by integrating Lu_2O_3 thin film SA in the EDFL cavity. The pulsed laser has a repetition rate of 0.97 MHz and stably operated at 1564 nm wavelength within a pump power range of 145–187 mW. The highest attainable output power, pulse energy and peak power were 7.42 mW, 7.64 nJ and 3.61 kW, respectively, and were achieved at the maximum pump power of 187 mW. Additionally, the pulse width was 2.12 ps, while the RF signal possessed a considerably high signal to noise ratio of 61 dB. The results suggest that Lu_2O_3 is viable of promoting a stable mode-locked laser in the 1.55-micron region, and can be utilized to fabricate low cost and a compact pulsed laser module.

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