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Lutetium oxide film as a passive saturable absorber for generating Q-switched fiber laser at 1570 nm wavelength

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ABSTRACT

We report for the first time, the application of Lutetium oxide (Lu_2O_3) thin film as a saturable absorber (SA) in generating a stable and compact Q-switched Erbium-doped fiber laser (EDFL) operating at 1570 nm. The film SA was prepared by embedding the Lu_2O_3 particles into a polyvinyl alcohol (PVA) host film. By integrating the film SA in a laser cavity, a stable pulsed laser appeared when the input pump power hit the threshold at 26.3 mW. The frequency of the pulsed laser rose from 18.4 kHz to 30.4 kHz, matching the increase of pump power from 26.3 mW to 71.6 mW. The shortest pulse width of 8.47 µs and the highest peak power of 8.98 mW were obtained at the maximum available pump power of 71.6 mW. Meanwhile, the maximum output power and pulse energy were measured at approximately 2.32 mW and 76 nJ, respectively. In addition, the signal to noise ratio (SNR) was 40 dB. These indicators suggest that Lutetium oxide film is a good passive SA that can be used to generate pulsed laser operating at1.55 µm region.

1. Introduction

Q-switched fiber lasers, particularly the ones achieved via passive techniques, have seized the attention of many researchers in recent years as they are easier to generate and more compact in setup [1]. This is due to the flexibility and simplicity of the passive techniques that do not require an electronic controller to trigger the pulses. In particular, Q-switched erbium-doped fiber lasers (EDFL) have found many applications in telecommunication, medical diagnostics and treatments, sensing, material processing, and range finding [2–4].

Semiconductor saturable absorbers (SESAMs) [5,6], carbon nanotubes (CNTs) [7,8], graphene [9–12] and black phosphorus (BP) [13,14], among others [15–19] have been successfully used as intracavity-loss modulators to produce pulsed lasers passively or have been successfully used as intracavity-loss modulators to produce pulsed lasers passively or have been benefited many other photonics applications. After its debut in 1992 [6], SESAMs quickly became the most prominent SA for several years. However, they suffer from some drawbacks including narrow absorption bandwidth, relatively high production cost and considerably bulky size. The main drawback of CNT SAs is that their absorption efficiency and bandwidth are dependent on their diameter. As for graphene, its main issue is its relatively low optical absorption per layer that limits its usability. Meanwhile, BP is a polarization dependent and hydrophilic material that easily interacts with water [20]. Thus, constructing a BP SA is challenging as it requires a complex preparation as well as careful handling. In recent years, other new materials that are relatively easy to prepare have been proposed as candidates for SAs to produce cheap and stable pulsed fiber lasers [18,21–23]. In our earlier work, Holmium oxide SA was used successfully to produce stable Q-switched fiber laser at the 2-µm regime [24].

Lutetium oxide (Lu_2O_3) or Lutecia, is a lanthanide oxide element similar to Holmium oxide. It is a thermally stable white compound which has uses in making specialized glass, crystal and ceramic. Optically, it has been shown to have enough linear absorption at 1.55-µm region, suggesting that it is suitable to be used for producing Q-switched EDFL in that region. By properly embedding sufficient 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 formed. Then a small piece (1 mm × 1 mm) of the film is placed between two fiber ferrules to construct an SA. The SA can be used to realize a simple and flexible all fiber passively-Q-switched laser system. In addition, the proposed

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Lu_2O_3 SA is quite easy to prepare, and shows relatively higher modulation depth of 10% than certain of 2D materials [25]; MoS_2 (2.15%), $MoSe_2$ (6.73%), WS_2 (2.53%) and WSe_2 (3.02%). Unlike BP SA, which tends to react with water due to its hydrophilic property, the Lu_2O_3 SA is more reliable, simple and robust.

In this paper, a stable passively Q-switched EDFL employing a Lu_2O_3 SA in a ring cavity is reported. We believe that this is the first time that an all fiber Q-switched laser employing such an SA is reported. The laser operates at an L-band region of 1570 nm with an initial frequency of 18.4 kHz at a low threshold pump power of 26.3 mW. The frequency of the pulses increases as the input power is increased. At the maximum available pump power of 71.6 mW, the frequency of the pulsed laser is 30.4 kHz.

2. Lutetium oxide film fabrication and characterization

The Lu_2O_3 film was fabricated by mixing Lu_2O_3 powder and polyvinyl alcohol (PVA) solution. First, 5 mg Lu_2O_3 powder was dissolved in 50 ml isopropyl alcohol. This mixture was stirred for about 24 h by using magnetic hot plate stirrer. This was followed by 6 h of sonification process in ultra-sonic bath to break the Van der Waals force that bound the molecules and completely disperse the powder. At the same time, we also prepared the PVA solution by mixing 1 g of PVA powder with 120 ml deionized water as a solvent. To totally dissolve the solute PVA, this mixture was stirred at 90 °C, and then it was cooled down to room temperature. The Lu_2O_3 and PVA mixture was thoroughly mixed by centrifuging process to form a composite precursor solution. Finally, the precursor solution was poured onto a glass Petri dish and dried in a vacuum oven for nearly two days to form a film with a thickness of 30 µm. In this experiment, the PVA was chosen as the host material as it has excellent film-forming and adhesive properties. Furthermore, by embedding the Lu_2O_3 materials inside the PVA film, not only it would ease the film SA handling and integration into the laser cavity, but it would also securely protect the Lu_2O_3 materials from external contamination. The Q-switched operation was conducted at considerably low or moderate pump power and therefore would not damage the film SA.

Fig. 1(a) shows the real image of the Lu_2O_3 PVA thin film. The white thin film is partly transparent and the SA base-material (Lu_2O_3) seems to be distributed evenly across the film as indicated by the scanning electron microscope (SEM) image in Fig. 1(b) which shows an almost consistent topography. The Energy dispersive X-ray spectroscopy (EDS) in Fig. 1(c) affirms the presence of Lu and Oxygen elements in the film. The initial indicator of an SA is its optical absorption. Fig. 1(d) shows the linear optical absorption profile of the Lu_2O_3 PVA film which shows that the SA optically absorbs around 4.3 dB at the Q-switched laser operating wavelength of 1570 nm. No significant absorption was detected at longer wavelengths. Fig. 1(e) depicts the nonlinear transmission response of the film SA as a function of peak power intensity. As illustrated, the modulation depth, ΔT of the film SA is around 10%, while the non-saturation loss, T_{ns} and the saturation peak intensity, I_{sat} are 58% and 72 mW/cm^2, respectively. The use of Lu_2O_3 PVA film as an SA is demonstrated in the following fiber laser experiment.

The SA was made by sandwiching a tiny piece of the thin film (about 1 mm × 1 mm) between two clean FC/PC fiber ferrules. Prior to that, a small quantity of index matching gel was applied on the fiber ferrule surface, to easily stick the film SA onto the ferrule tip as well as to minimize the unwanted parasitic reflections between the coupling areas.

3. EDFL ring cavity configuration

The proposed Q-switched EDFL configuration, in a forward-pumped ring cavity scheme, is illustrated in Fig. 2. The laser cavity consists of 2.8 m long erbium-doped fiber (EDF) gain medium, a wavelength division multiplexer (WDM), an isolator and a 3 dB coupler. The components are all connected via standard SMF. The EDF has a core diameter of 4 µm, a fiber diameter of 125 µm, an absorption coefficient in the range of 23–27 dBm at an operating wavelength of 980 nm and a numerical aperture (NA) of 0.23. It is pumped by a 980 nm single wavelength laser diode (LD) via the 980 nm port of the 980/1550 nm wavelength division multiplexer (WDM). The other end of the gain medium is connected to the optical isolator which ensures unidirectional light propagation inside the cavity. Then the light goes into the thin-film SA that periodically switches the intracavity losses, as well as, the Q-factor of the cavity. After the SA, the light passes through the 3 dB coupler where 10% of the laser output is extracted while the rest (90%) is retained to circulate inside the cavity via the 1550 nm port of the WDM. An optical spectrum analyzer (OSA) with a 0.03 nm resolution is utilized to investigate the laser optical spectrum. Meanwhile, a radio frequency spectrum analyzer (RFSA) and a digital oscilloscope (OSC) that are pre-coupled with a fast photodetector (PD) are used to examine the appearance and quality of the pulsed signal in the time domain and frequency domain, respectively. An optical power meter is used to measure the output power of the pulsed laser.

4. Q-switched EDFL performances

The proposed laser started to transform into a stable Q-switched laser with an initial frequency of 18.4 kHz at a threshold pump power of 26.3 mW. The pulsed laser remains stable with the increase in pump power and its frequency rose steadily up to 30.4 kHz when the pump power reached 71.6 mW. Beyond this value, the pulsed laser started to destabilize and collapsed into a continuous wave (CW) operation. The optical spectrum of the Q-switched EDFL in Fig. 3 shows a single wavelength laser, centered at 1570 nm (λ_o) with a peak power intensity of −40.54 dBm. The optical signal-to-noise ratio (OSNR) is obtained at 33.46 dB, which is acceptable. Recently, several reports demonstrated wavelength-tunable fiber laser which particularly would benefits spectroscopy and biomedical research [26,27]. Based on the obtained Q-switched laser spectrum, we believed that the central wavelength of the pulsed laser could be tuned within the spectral bandwidth of 1567–1573 nm. This can be achieved by employing a correct tunable wavelength filter and by providing sufficient pump power into the cavity.

The oscilloscope trace of the pulsed laser at 38 mW pump power in Fig. 4, shows nearly identical pulses with a repetition rate, f_1, of around 21.6 kHz. The inset of Fig. 4 is an enlarged view of the pulses, indicating a peak to peak time interval that corresponds to a pulse period of 46.2 µs. In addition to that, the pulse width taken at full wave half maximum (FWHM) is approximately 11 µs. Meanwhile, the frequency domain of the Q-switched EDFL examined via the RFSA as depicted in Fig. 5, shows that more than ten frequency harmonics generated stably within the span of 450 kHz. As expected, the fundamental frequency (f_1) of both the time and the frequency domains are identical, thus technically confirming both optical measurements. The signal to noise ratio (SNR) of the fundamental frequency (21.6 kHz) is measured to be around 40 dB, indicating a stable Q-switching operation. In addition to that, the performances of the pulsed laser at different pump powers are demonstrated in Fig. 6.

The output power of the Q-switched EDFL is provided in Fig. 6(a). It increases from 0.36 mW to 2.32 mW with the rise of pump power from 26.3 mW to 71.6 mW. Meanwhile, the slope efficiency which is related to the output power response is obtained at 3.97%, indicating an acceptable level of intra-cavity losses. The increase in pump power also increases the pulse energy from 19.4 nJ to the highest value of 76 nJ and the repetition rate from 18.4 kHz to the greatest value of 30.4 kHz as illustrated in Fig. 6(b). The pulse width, however, declines from 14.6 µs to the shortest value of 8.47 µs. In a typical Q-switched laser, by increasing the pump power, more gain is available, thus the threshold energy which is needed to saturate the SA is accomplished earlier, resulting in a higher pulse repetition rate and narrower pulse width.

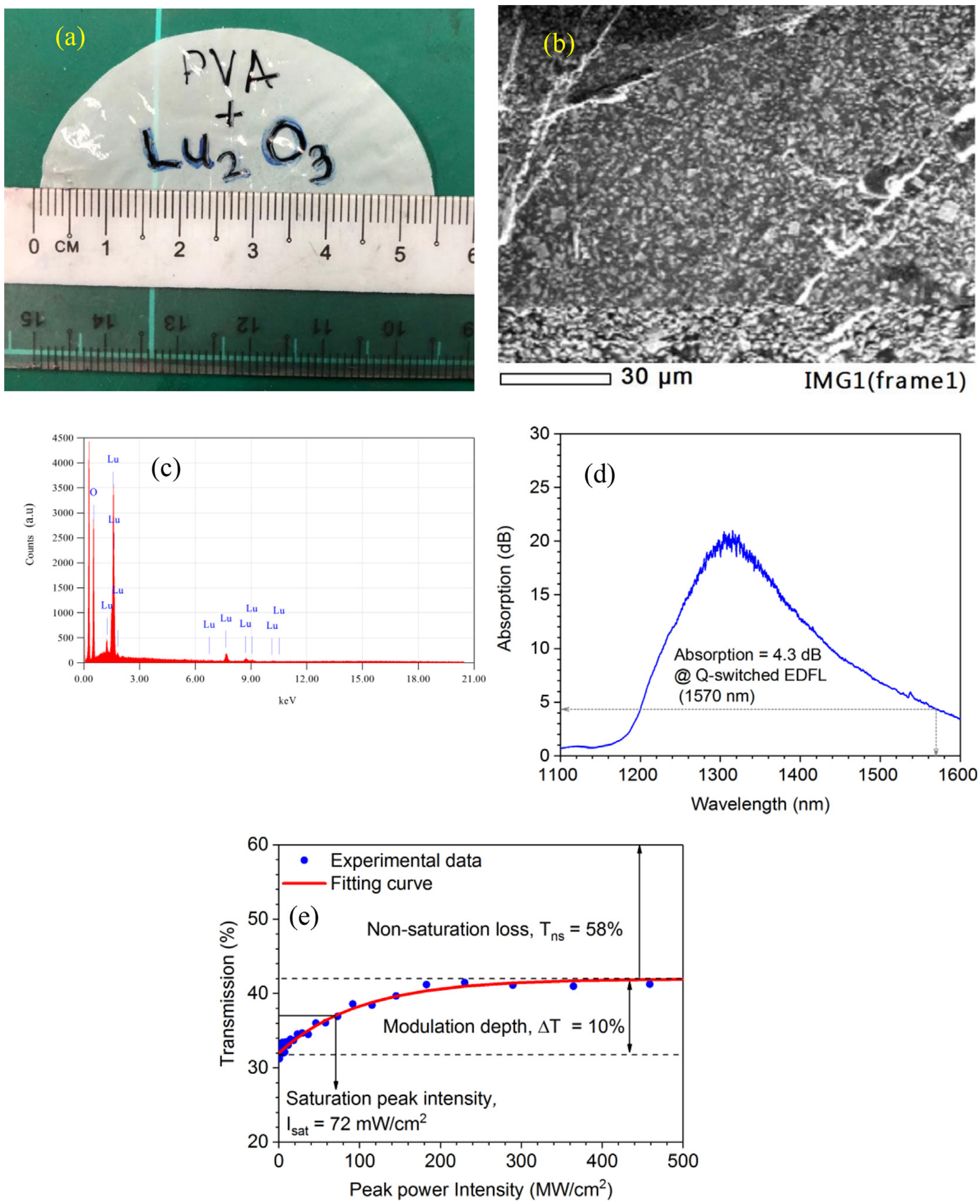

Fig. 1. Lu_2O_3 PVA thin film characteristics (a) physical image (b) SEM image (c) EDS profile (d) linear absorption profile (e) Nonlinear transmission profile.

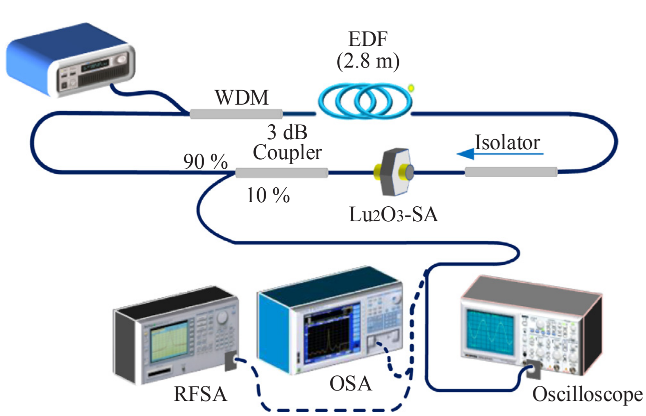

Fig. 2. Schematic diagram of the EDFL in ring-cavity configuration.

These changes (repetition rate and pulse width), cause the peak power to climb-up from 1.33 mW to a maximum of 8.98 mW. The experiment was then repeated without inserting the SA in the cavity, under the same condition and procedure. As expected, no pulsed laser was detected, confirming that the Q-switched laser was essentially induced by the film SA. In addition to that, the experiment was conducted by increasing the pump power beyond its maximum available pump. No Q-switched pulse could be detected as the pump power rose beyond the maximum level of 76.1 mW. When the pump power decreased back to the Q-switched operating pump power (26.3–71.6 mW), a stable pulsed laser with almost similar Q-switching characteristics as demonstrated earlier emerged again. This phenomenon, not only verified that the film SA was still in good condition but also suggested that the laser operation was conducted below the SA optical damage threshold.

The long-term stability of the SA was examined by monitoring the condition of the Q-switching at a moderate pump power of 50 mW for

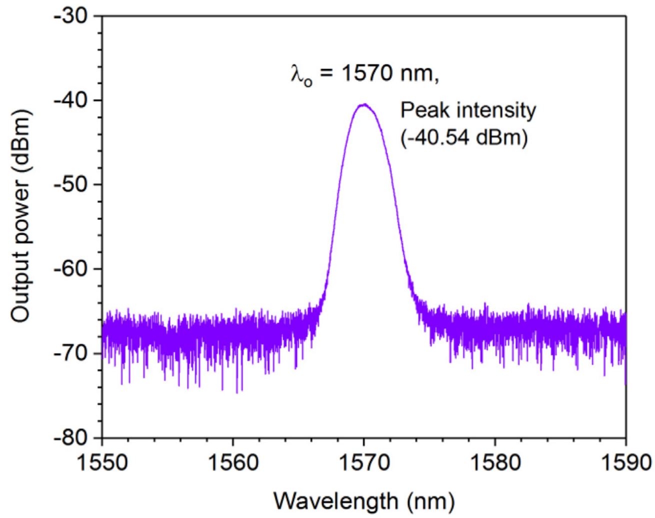

Fig. 3. Output spectrum of Q-switched EDFL at a threshold pump power of 26.3 mW.

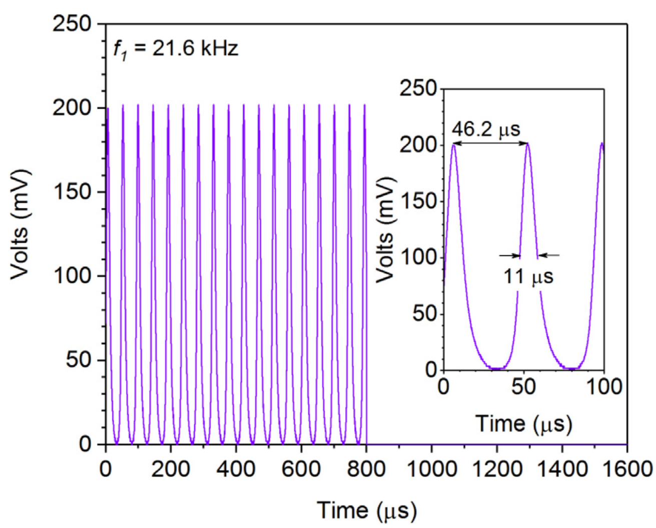

Fig. 4. Oscilloscope trace of the Q-switched EDFL at 38 mW pump power. Inset image shows the enlarged view of the enveloped pulses.

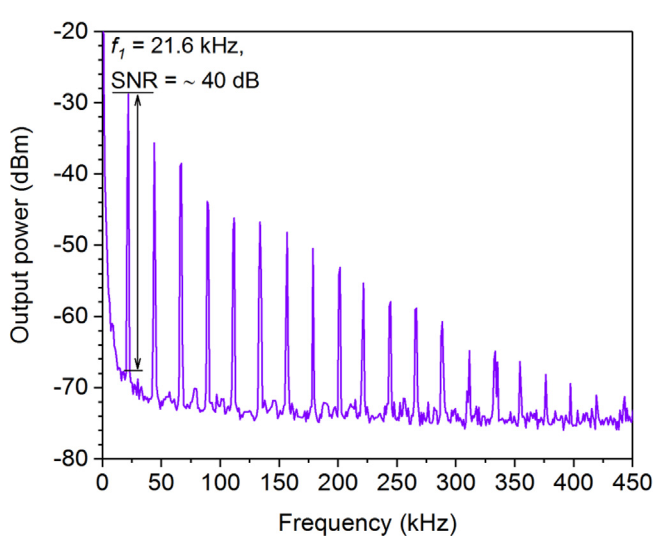

Fig. 5. RF spectrum of the Q-switched EDFL within a 450 kHz span.

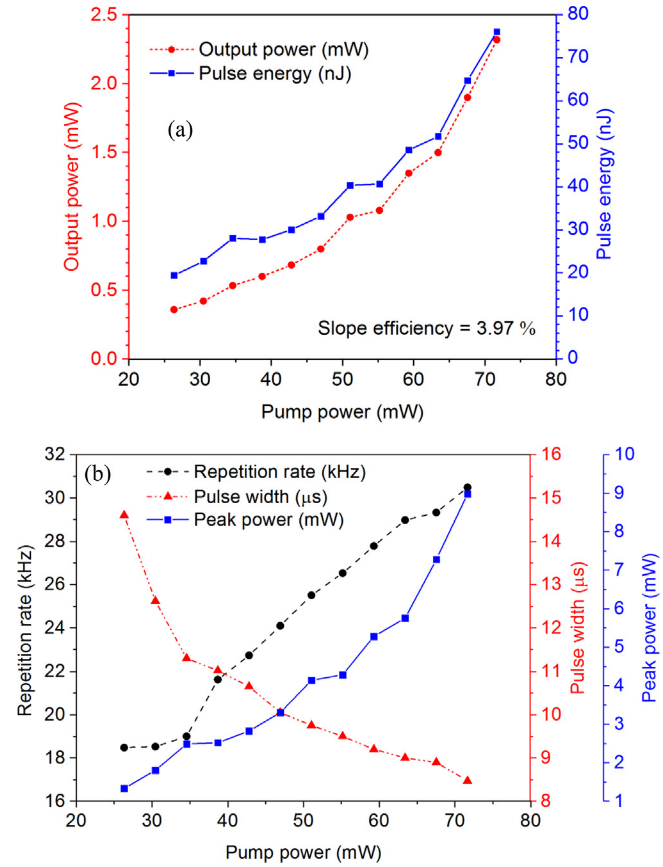

Fig. 6. Q-switched EDFL performances. (a) Output power, and pulse energy responses. (b) Pulse repetition rate, pulse width, and peak power responses.

several hours. Throughout the experiment, the Q-switched pulse remained stable without any sign of pulse destruction, indicating that the SA was still in a good condition.

5. Conclusion

A stable and reliable Q-switched EDFL was successfully demonstrated by integrating a Lu_2O_3 thin film SA (with a thickness of around 30 µm). The pulsed laser was stably operating at 1570 nm, within a frequency range of 18.4–30.4 kHz, for a pump power of 26.3 mW − 71.6 mW. At the maximum pump power, the highest output power and pulse energy of 2.32 mW and 76 nJ were attained respectively. Additionally, the maximum peak power of 8.98 mW, the shortest pulse width of 8.47 µs and the highest pulse frequency of 30.4 kHz were observed at the pump power of 71.6 mW.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yofte.2019.03.003.

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