Q-switched pulse generation in a bidirectionally pumped EDFL utilizing Lu_2O_3 as saturable absorber

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In this paper, we have successfully demonstrated a Q-switched pulse generation utilizing lutetium oxide (Lu_2O_3) thin film based saturable absorber (SA) in all-fiber erbium-doped fiber laser (EDFL) cavity with a bidirectional pumping. The Lu_2O_3 powder is mixed with isopropyl alcohol (IPA) solution before we add polyvinyl alcohol (PVA) as our host polymer to make the Lu_2O_3 into a thin film. By inserting the Lu_2O_3-PVA thin film into a bidirectional pumped EDFL cavity, a stable Q-switched pulse is realized with repetition rate in a range of rose from 43.67 kHz to 57.74 kHz whereas the pulse width decreased from 14.48 μs to 11.20 μs. This result indicates that the Lu_2O_3 can be implemented as an SA device in an EDFL as it owns a linear absorption of around 3 dB at 1 567 nm.

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Q-switched laser has been widely investigated and applied in vast applications due to its capability to generate pulses operating at the low repetition rate and high pulse energy. Q-switched pulses can be used in various areas including laser materials processing, range finding, remote sensing, microfabrication, tattoos removal, skin treatment, medical surgery, and pumping source for nonlinear frequency conversion devices[1-4]. Q-switching can be realized by using acousto-optic or electro-optic optical modulators to actively modulate the Q-factor within the laser cavity. However, the modulators are costly, complex, and bulky, which may increase the complexity and cost of production of the Q-switched laser system[5]. Therefore, the interest has shifted to the simpler, low cost and reliable saturable absorber (SA) based passive techniques. The Q-switched pulses can be generated passively by modulating the cavity Q-factor by using the nonlinear optical absorption properties of some materials.

Typically, doped crystals and semiconductor saturable absorber mirror (SESAM) were used to passively induce Q-switched pulse generation in various commercial laser systems[6,7]. However, the synthesis processes of these commercial SAs generally involve costly and complicated crystal growth and metal oxide chemical vapor deposition (MOCVD) methods. Additionally, operation wavelength band for the doped crystals and SESAMs is relatively narrow and thus reduces the flexibility and applicability of the laser. Therefore, enormous research attempts have been dedicated to searching new SA materials which has a simpler fabrication method and can provide a higher operation performance. The carbon-based nanomaterials, e.g. graphene[8-10], graphene-oxide[11] and single-walled carbon nanotubes (SWCNT)[12] have attracted great research interests since they have demonstrated exceptional nonlinear optical responses. However, the carbon-based nanomaterials have their own limitations, e.g. diameter control required for SWCNT, lower modulation depth for graphene. Recently, other new types of nonlinear optical materials have also been reported as SAs, including topology insulators[13,14], transition metal dichalcogenides (TMDCs)[15]. For example, TMDCs, such as WS_2, WSe_2, $MoSe_2$ and MoS_2 have been reported as a promising SA to produce Q-switched pulses[15,16].

On the other hand, nonlinear optical response and saturable absorption behaviour can also be obtained in various rare earth materials such as Nd, Eu, Sm and La[17]. In our earlier work, we have demonstrated a stable pulse of Q-switched using rare earth oxide such as Scandium Oxide (Sc_2O_3)[18], Gadolinium Oxide (Gd_2O_3)[19]. Bidirectional pumping is also widely deployed in both Erbium-doped fiber amplifier (EDFA) and Erbium-doped fiber laser (EDFL) designs to enhance the gain and reduce the noise in the devices. In this paper, lutetium oxide (Lu_2O_3) is used as SA to modulate a Q-factor and

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generate a Q-switched pulse in a bidirectionally pumped EDFL cavity. In this laser, two laser diodes are used to pump Erbium-doped fiber (EDF) simultaneously. One is launched in forward direction and another pump in backward direction. Lu_2O_3 has an excellent thermal stability and optical absorption at 1.55 μm region and thus suitable for SA application. The results suggest that Lu_2O_3 could be served as a promising material for fiber laser pulse technology.

We fabricated Lu_2O_3-PVA thin film to act as an SA device in the proposed bi-directionally pumped EDFL cavity for Q-switched pulse generation. The fabrication process is illustrated in Fig.1. 5 mg Lu_2O_3 powder was added to 50 mL Isopropyl Alcohol (IPA) solution and heated on a hot plate for 24 h. While heating the solution, a magnetic stirrer was used to dissolve the Lu_2O_3 powder thoroughly. After that, the Lu_2O_3 solution was centrifuged for 6 h to distribute the Lu ions evenly. Then, the host polymer PVA solution was prepared by mixing 1 g PVA powder with 120 mL of the deionized water (DI). The PVA solution is stirred at the temperature of 90 °C using a hot plate and magnetic stirrer. Later, we mixed the Lu_2O_3 solution and the PVA solution at equal ratio to make the Lu_2O_3-PVA thin film. The mixture was sonicated for 2 h to ensure its homogeneity. Finally, the Lu_2O_3-PVA solution was poured into a petri dish and left to dry at room temperature for about 48 h to form the thin film. The physical image of the fabricated Lu_2O_3-PVA thin film SA is shown in Fig.2(a) while Fig.2(b) illustrates its linear absorption profile. As seen, the absorption at 1 567 nm is approximately 3 dB. Fig.2(c) illustrates the nonlinear absorption profile of the SA, which was obtained at 1 550 nm using a twin-detector measurement method. As shown in the figure, the Lu_2O_3 SA has non-saturable loss of 58%, saturable absorption of 10%, and saturation intensity of 100 MW/cm^2, respectively.

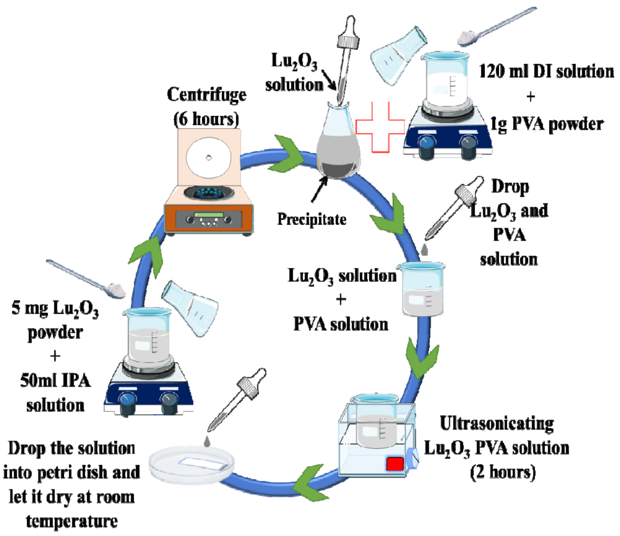


Fig.1 The preparation of the Lu_2O_3 PVA thin film

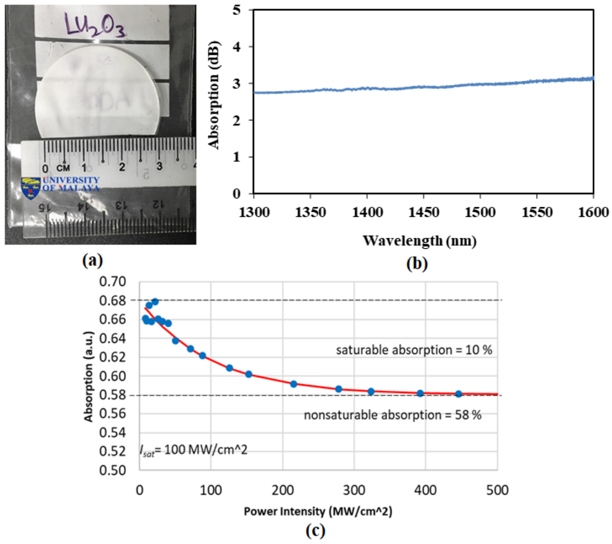


Fig.2 The characterization of Lu_2O_3: (a) Physical image of Lu_2O_3-PVA thin film; (b) The linear and (c) nonlinear absorption profiles of Lu_2O_3- PVA thin film

Fig.3 illustrates the bidirectionally pumped ring configuration of the pulsed laser using Lu_2O_3 as an SA. Two 14-pin Laser Diodes (LD) with an operating wavelength of 980 nm are used to pump the 6-m-long Erbium-doped Fiber (EDF) via two 980/1550 wavelength division multiplexers (WDM) to generate a Q-switched pulse laser. The EDF was pumped at equal ratio by the two laser diodes with a total maximum pump power of 500 mW. The EDF is placed between the two WDMs. An isolator is used to deter multidirectional light propagation while a polarization controller (PC) is used to modify the light polarization state during circulation. In this work, the fabricated Lu_2O_3-PVA thin film has been cut into small pieces approximately ~1 mm×1 mm to prepare an SA device, which was incorporated into the laser ring cavity as a Q-switcher. The 90/10 coupler was used to extract output pulses. The 90 % went to the feedback of the ring cavity and continuously circulated, while for 10% went to the optical spectrum analyzer (Anritsu, MS9710B), digital oscilloscope (Agilent Technologies, DSO-X-2002A), radio frequency analyzer (PSA-3000), and optical power meter. The temporal characteristics were measured utilizing a digital oscilloscope and radio frequency analyzer, and the power measurement was carried out by using an optical power meter. It was observed that the use of polarization controller (PC) degrades the Q-switching performance of the EDFL cavity due to the increased cavity loss. Therefore, the PC was removed from the cavity in this study.

In this study, the Q-switched pulse was obtained by inserting the Lu_2O_3-PVA thin film into the EDFL cavity setup at the threshold pump power of 74 mW for each laser diode (with the total pump power of 148 mW). Two 980 nm pump diodes function to efficiently pump the EDF so that the population inversion could be increased. This improves the gain characteristic of the cavity, which in turn improves the Q-switching performance of the laser. The Q-switching operation was maintained until the maximum pump power of 127 mW for each pump (with the total pump power of 254 mW). However, when the laser diode power elevated beyond 127 mW, the Q-switched pulse was disappeared due to the over saturation of the SA at high input fluence. By increasing the pump power from 127 mW to 500 mW, we observed the continuous-wave operation. Later, we bring the LD pump back to 127 mW, and the same temporal pulse performance recovered. Thus, the SA device has an optical damage threshold which is higher than 500 mW.

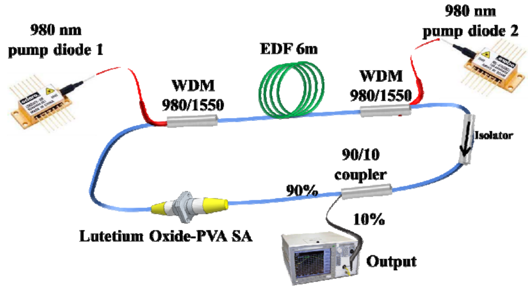
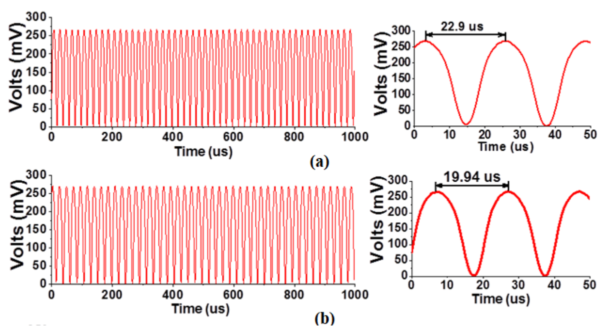


Fig.3 The setup configuration for generating pulse utilizing Lu_2O_3-PVA SA

Fig.4(a)—(c) show the typical pulse trains at three different input pump power. The enlarged image of the oscilloscope trace was given on the right side of each figures. As shown in these figures, the pulse period was obtained at 22.90 μs, 19.94 μs and 17.32 μs, which corresponds to the repetition rate of 43.67 kHz, 50.15 kHz and 57.74 kHz when the pump power of each pumps was set at 74 mW, 101 mW and 127 mW, respectively. The output spectrum of the Q-switched pulse has been obtained in Fig.4(d) at starting threshold of 74 mW. The laser operated at centre wavelength of 1 567 nm. The Q-switched pulses' stability has been demonstrated in Fig.4(e) using radio frequency spectrum analyzer (RFSA) within a 500 kHz span. The first peak of the frequency is obtained at 43.67 kHz, which well corresponded to the oscilloscope result in Fig.4(a). The signal-to-noise ratio (*SNR*) of the fundamental frequency was recorded at 50.33 dB, indicating the stability of the Q-switched pulse. It is expected that the *SNR* can improved by minimizing the non-saturable loss of the SA and the cavity loss.



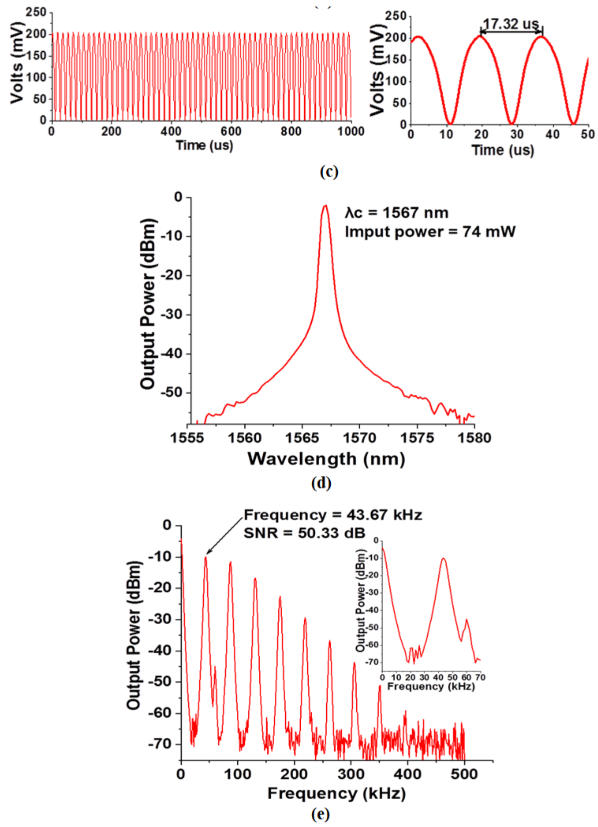


Fig.4 The temporal and spectral characteristics of the Q-switched output: Oscilloscope traces at (a) 74 mW, (b) 101 mW and (c) 127 mW pumping; (d) Output spectrum; (e) RF spectrum within 500 kHz span

The average output power was recorded by a power meter at various input pump power and the result is shown in Fig.5(a). As seen, the output power is linearly increased with the pump power with a slope efficiency of 3.92%. The maximum output power of 5.77 mW was obtained when the laser diode power was set at 127 mW for each pump. The pulse energy was then calculated based on the average output power and the repetition rate. The pulse energy improved from 83.12 nJ to 99.93 nJ when the input laser pump is escalated from 74 mW to 127 mW as shown in Fig.5(a). The repetition rate and pulse width were recorded by an oscilloscope. As shown in Fig. 5(b), when the pump power increased from 74 mW to 127 mW, the repetition rate can be tuned from 43.67 kHz to 57.74 kHz and the pulse width reduced from14.48 μs to 11.20 μs. This is a typical trend for a Q-switched laser. The stability of the Lu_2O_3 based Q-switched EDFL was investigated by recording the change of the maximum output power in the output spectra for about 24 h as shown in Fig.6. The output power fluctuation was about 0.5%, indicating the Q-switched laser has the high stability. Additionally, we kept the Lu_2O_3 SA in the ambient conditions for about 2 weeks. After two weeks, there was no obvious change in the Q-switching performance of the laser, indicating the high stability of Lu_2O_3 SA in ambient. Tab.1 shows a comparison table, which summarizes the

Q-switched laser performances for various materials with a similar cavity design and operating at 1.5 μm region. The proposed Lu_2O_3 SA based laser reported the highest pulse energy. These results indicate that Lu_2O_3 has great potential as a Q-switcher for operation in 1.5 μm region. It is also worthy to note that there is no mode-locking operation observed even if we tuned the LD pump towards the maximum values. However, the extension of cavity length might introduce mode-locking operation, as it enables a balance between dispersion and nonlinearity inside the laser cavity.

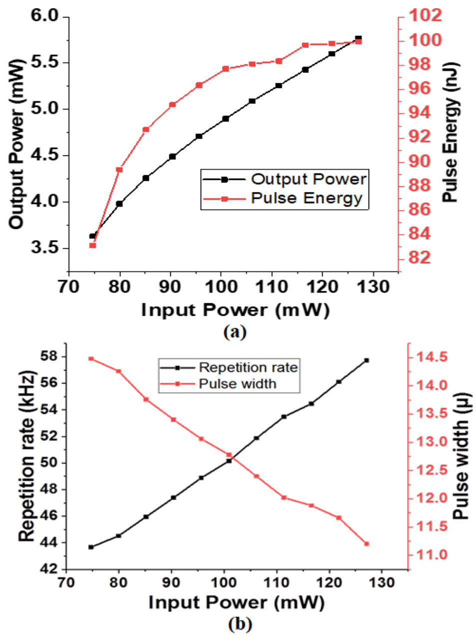


Fig.5 The Q-switching performances: (a) The average output power and pulse energy against the input pump power; (b) Repetition rate and pulse width variation with input pump power

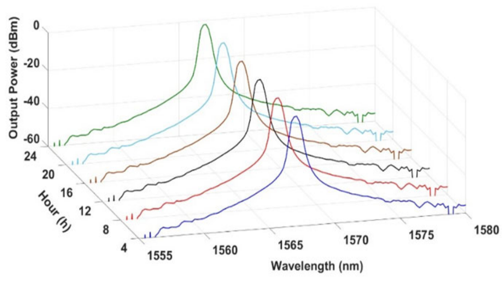


Fig.6 The output spectrum variation within 24 h

Tab. 1 Performance comparison of passively Q-switched fiber lasers with various SAs

SA material	Max pulse energy (nJ)	Min pulse width (μs)	Max repetition rate (kHz)	λ (nm)	Reference
BP	94.3	10.32	15.78	1 563	[20]
MoS_2	63.2	5.4	27.0	1 565	[21]
Sm_2O_3	26	5.60	66.0	1 567	[22]
Lu_2O_3	99.93	11.20	57.74	1 567	This work

In conclusion, the Q-switched laser operating at 1 567 nm was realized by using a Lu_2O_3 SA in a bidirectionally pumped EDFL cavity. The SA was realized by embedding the Lu_2O_3 into PVA film. By increasing the power of each 980 nm pump from 74 mW to 127 mW, the repetition rate of the Q-switched pulses can be raised from 43.67 kHz to 57.74 kHz while the pulse width reduced from 14.48 μs to 11.20 μs. The maximum average power was 5.77 mW at the pump power of 127 mW and the fluctuation of output power was about 0.5%. The corresponding single pulse energy was calculated to be 99.93 nJ. The experimental results indicated that Lu_2O_3 is a promising SA material for operation in 1.5 μm region.

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