Q-switched fibre laser using Samarium oxide for C-band region

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We demonstrated the usage of samarium oxide (Sm_2O_3) polymer film as a saturable absorber (SA) for generating stable Q-switched fibre laser at the C-band region. The SA was prepared by embedding a commercial Sm_2O_3 powder into polyvinyl alcohol (PVA) solution to form a Sm_2O_3-PVA film. The obtained film was then cut into a square shape of 1 mm x 1mm and adhered to the tip of fibre ferrule by using index matching gel. A stable Q-switching operation presence from 52 mW to 164 mW pump power at 1568 nm wavelength. Under this pump power, the repetition rate increased from 24.34 kHz to 55.80 kHz, while the pulse width reduced from 13.29 µs to 6.96 µs. The obtained Q-switching operation has a signal-to-noise ratio (SNR) of 38 dB with a maximum output power and pulse energy of 8.58 mW and 123.27 nJ, respectively. This finding shows that the Sm_2O_3 has good potential to be used as an alternative passive SA for the C-band all-fibre laser seed pulse.

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1. Introduction

Passively Q-switched fibre lasers have received growing attention in recent years as they are lightweight, flexible, robust, and offer less cost. The pulsed laser can be used in many applications including, telecommunication, medical treatment, remote sensing, metrology, and material processing. The Q-switched laser is generated by modulating intra-cavity loss or Q-factor of the cavity. In comparison with the mode-locking, the Q-switched laser is cheaper and much simple in operation as it does not need careful design to balance the nonlinearity and the dispersion. In the early years, active techniques have been widely used for the Q-switching purpose. To generate the Q-switching, they use quite bulky optical devices such as electro-optic or acousto-optic modulators for controlling the optical intensity.

Conversely, the passive technique based on saturable absorber (SA) provides significant benefits in terms of cost-efficiency, simplicity, and reliability. In the 2010s, carbon nanotubes, (CNTs) [1] and graphene [2, 3] SAs have been highly pursued and demonstrated for pulse generation in the Erbium-doped fibre laser (EDFL). These SAs have been considered as great SAs due to their easiness in fabrication as well as low cost. However, CNTs SA was reported to have operating wavelengths that determined by their nanotubes diameter and chirality [4]. Additionally, graphene was reported to have a low saturable absorption of 2.3% at 1550 nm [3], which is due to its wideband saturable absorption. These limitations have encouraged researchers to find alternative SAs such as topological insulators (TIs) [5, 6] transition-metal dichalcogenides (TMDs) [7, 8] and transition metal oxides (TMO) [9-12], which have similar optical characteristics and ability to promote passive Q-switching. Although most of these SAs are functional, many of them are quite complex to fabricate; thus, new SA materials with easy fabrication, low cost, and reliable performance would provide significant potential for real applications. Samarium oxide (Sm_2O_3) is one of the TMO members. It has a thermally stable Samarium source that suitable for glass and optic applications. Recently, Sm_2O_3 film SA was demonstrated in the Thulium-doped fibre laser (TDFL) for promoting stable Q-switching. The Q-switched laser has a tunable repetition rate within 17.62 kHz to 29.20 kHz [13].

In this paper, we demonstrated a stable and reliable performance of a passively Q-switched EDFL with the incorporation of Sm_2O_3 film material. The film SA was fabricated in the lab by embedding Sm_2O_3 with the PVA solution. The fabricated film has a modulation depth of about 37% and shows approximately 3.8 dB linear absorption loss. The generated Q-switched fibre laser has a maximum repetition rate of 55.8 kHz and a minimum pulse width of 6.96 µs. The details of the film fabrication, film characteristics as well as the Q-switched laser performances are elaborated further in the following subsequent topics.

2. SA Fabrication and characterization

The Sm_2O_3 film was fabricated by properly blending commercial Sm_2O_3 powder with a PVA solution. In this work, the PVA solution was prepared by dissolving 1 g of PVA powder into 120 ml deionized water. Then we mixed approximately 50 mg of the Sm_2O_3 powder with the 50 ml PVA solution. The mixture was then stirred using a magnetic stirrer for about two hours. Later, the solution was sonicated for one hour in an ultrasonic bath. This process would agitate Sm_2O_3 particles into the PVA solution by breaking the Van der Waals force between molecules. The obtained homogenous solution was then poured onto a clean petri dish and kept under lab environment for three days to form a composite film. The resultant polymer film was then carefully peeled off from the petri dish by using a clean tweezer. The thickness of the film was measured to be around 50 µm. Fig. 1(a) shows the image of the fabricated film SA, which has a diameter of about 50 µm. As depicted in the figure, a semi-transparent white colour which represents the Sm_2O_3 particles is observed to be fully covering the film. The fabricated film SA has certain advantages, including simple and cost-effective in both preparation and laser cavity integration. Fig. 1(b) shows the field emission scanning electron microscope (FESEM) image of the polymer film. As shown, the Sm_2O_3 particle has an average diameter of approximately 6 to 7 µm, which is comparable with the fibre core diameter. Fig. 1(c) shows the energy dispersive X-Ray spectroscopy (EDS) of the Sm_2O_3 film. As illustrated in the figure, the Samarium (Sm) element contributes about 64% of the weight percentage and 15.51% for the atomic percentage, respectively. On the other hand, the Oxygen (O) element dominates around 32.68% of the weight percentage and contributes about 74.43% of the atomic percentage. The results confirm the presence of the Sm and O elements in the composite film.

The linear absorption profile of the film SA was inspected by propagating low-density broadband white light source into the film. As shown in Fig. 2(a), the linear absorption measured at the Q-switched operating wavelength of 1568 nm is around 3.8 dB. The characteristic of the nonlinear optical response of the film was also analyzed by using a balanced twin detector measurement. The nonlinear response profile is shown in Fig. 2(b). The obtained experimental data is fitted using a curve determined from a formula [14]: $T(I) = 1 - \Delta T*\exp(-I/I_{sat}) - T_{ns}$, where, $T(I)$: transmission, ΔT: modulation depth, I: input intensity, I_{sat}: saturation intensity. As illustrated in the figure, the film SA has a modulation depth of 37%, a non-saturable absorbance of 61%, and a saturation intensity of 19 MW/cm^2. The non saturable absorption of 61% will affect the threshold pump of the Q-switching operation. This happens due to large particle size and uneven distribution of Sm_2O_3 particle on the film surface.

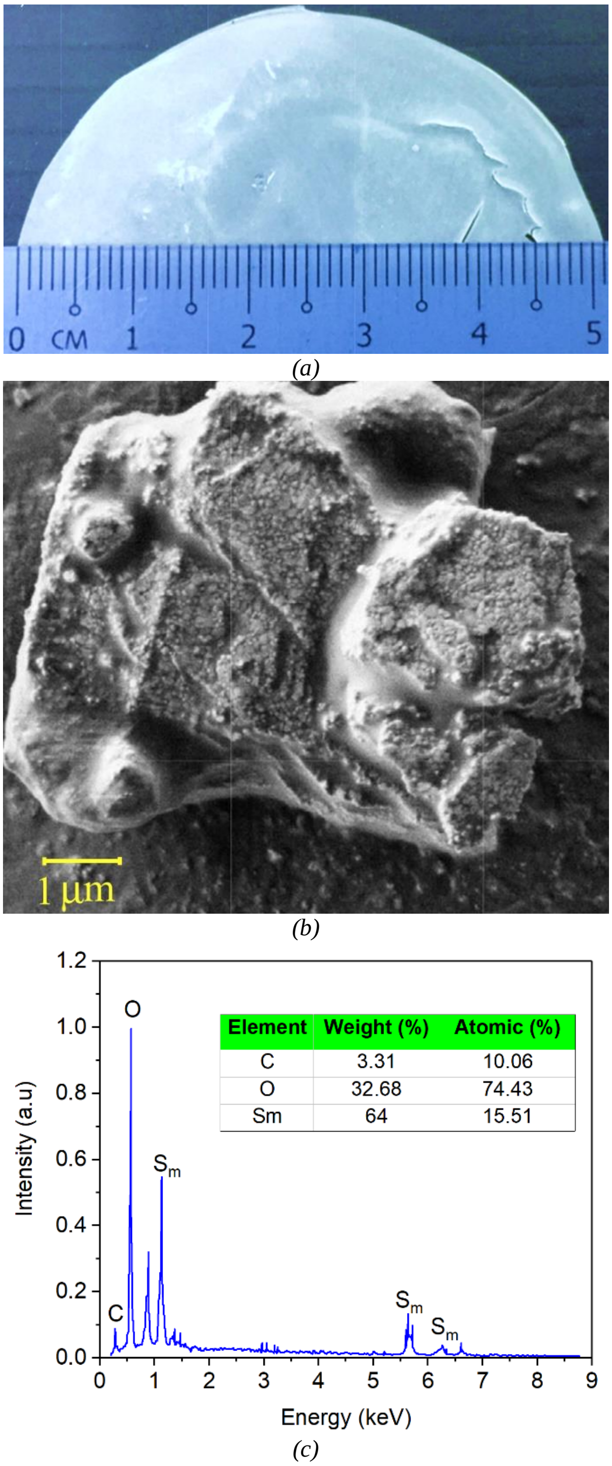


Fig. 1. Sm_2O_3 PVA film, (a) physical image, (b) FESEM image, and (c) EDS profile (color online)

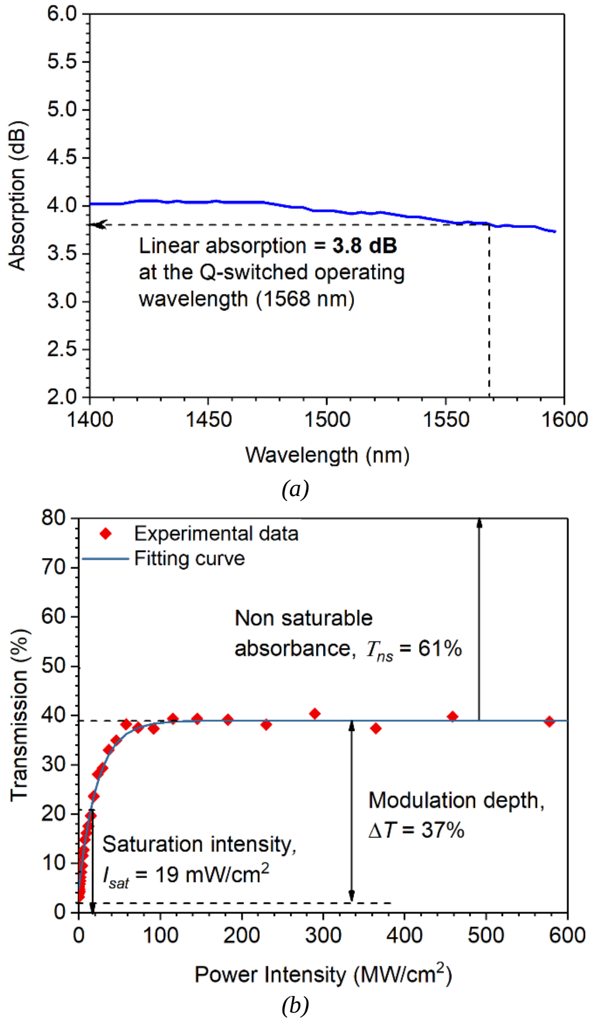


Fig. 2. Optical properties of the Sm_2O_3 film, (a) Linear absorption profile, and (b) Nonlinear optical response (color online)

3. Experimental setup

The fabricated SA was inserted in the laser cavity to inspect its workability in inducing Q-switching, using a configuration, as shown in Fig. 3. The laser cavity used 2.4 m long EDF, which was core-pumped by a lab-made 980 nm fibre laser via a 980/1550 nm fused wavelength division multiplexer (WDM). The EDF has a core and cladding diameters of nine and 125 µm, respectively, with a reported core absorption of 24 dB/m at 1550 nm. The laser diode (LD) pump able to provide a maximum continuous-wave pump power of up to 1.5 W. An isolator was used to prevent uncertain back reflections while at the same time promotes unidirectional light propagation in the cavity. The Sm_2O_3 film was sandwiched between two fibre ferrules that initially applied with index matching gel. The SA unit was then integrated between the isolator and a coupler. As shown in the figure, the 90:10 optical couple is incorporated after the SA. This coupler keeps 90% of the light oscillating within the cavity while tapping out 10% of the output for the Q-switched performance analysis. The spectral characteristic was measured using an optical spectrum analyzer (OSA), with a pre-set spectral resolution of 0.05 nm, while the temporal characteristics were measured using a 500-MHz oscilloscope. The optical power meter (OPM) was used to measure the output power, whereas the RF spectrum analyzer (RFSA) was utilized to record the RF spectrum characteristic. The rest of the ring cavity comprised of 50 m SMF-28 fibre with a total cavity length measured to be approximately 52.4 m.

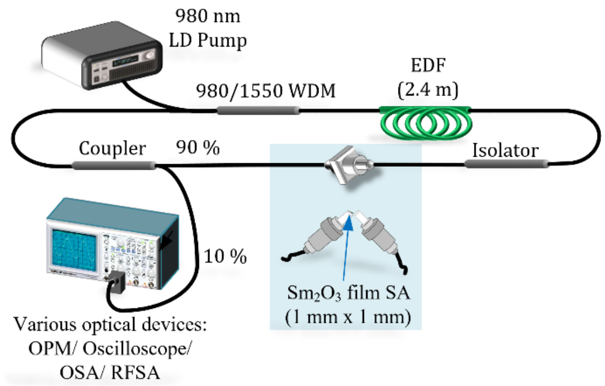


Fig. 3. Schematic configuration of Q-switched EDFL (color online)

The Q-switched EDFL with incorporated Sm_2O_3 film started to operate stably from 52 mW. Fig. 4 shows the output spectrum of the Q-switched laser. As depicted, the laser spectrum is centred at a 1568 nm wavelength (in the C-band region), with a peak intensity attained at -14.5 dBm.

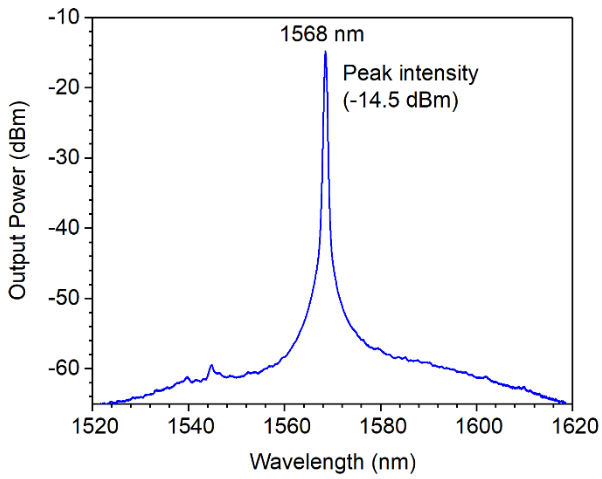
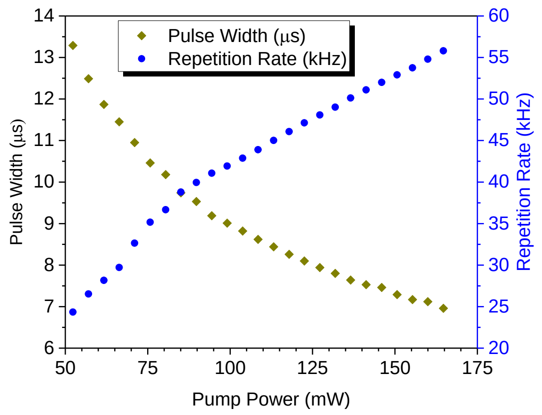


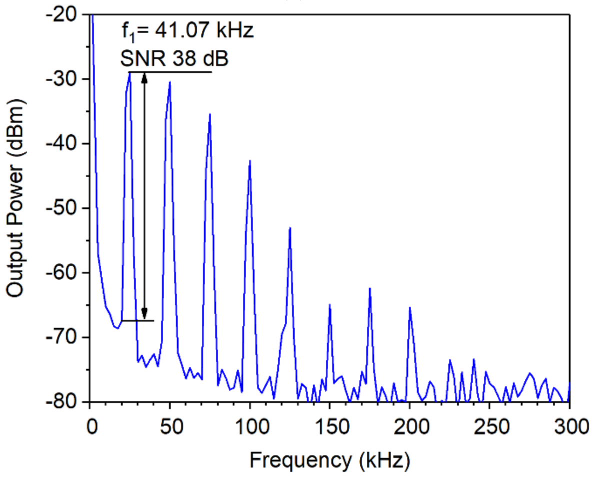
Fig. 4. The output spectrum of the Q-switched laser at 52 mW pump power (color online)

4. Result and discussion

The EDFL cavity generated a continuous wave (CW) laser once the pump power lifted to 23.5 mW. However, the laser cavity only started to produce a stable Q-switched laser at a higher pump power of 52 mW. The pulsed laser remained stable with a further pump power increment up to 164 mW. Beyond the 164 mW, the pulsed laser collapsed and transformed back into the CW. Fig. 5(a) depicts the overall temporal performance of the pulsed laser within the Q-switched operating pump power; 52 mW to164 mW. As seen, the pulse width shrinks from 12.26 μs to the shortest of 6.96 μs, when the pump power increased to the maximum value. As expected, the repetition rate increases from 24.34 kHz to 55.8 kHz, within the same operating pump power range. These attributes, which refer to the rise of the repetition rate and the decrease in the pulse width, agree well with the typical Q-switched laser characteristics. The reason for the increase in the repetition rate is due to the higher pump power provided into the cavity, which gives more available energy to saturate the SA, in a much faster way. As a result, the pulses develop more quickly, and a stable pulse train with a higher repetition rate is generated.



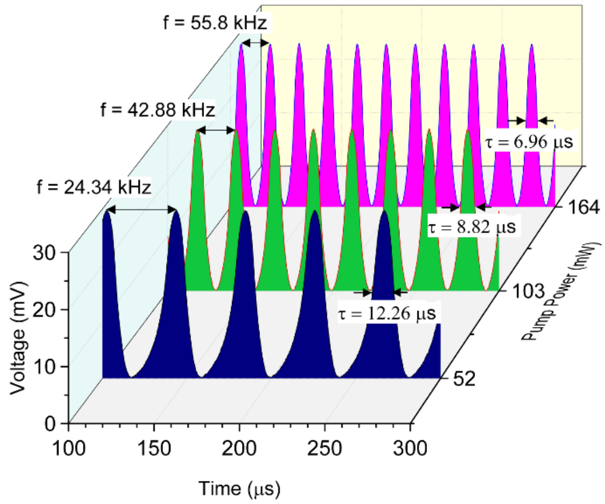
(a)



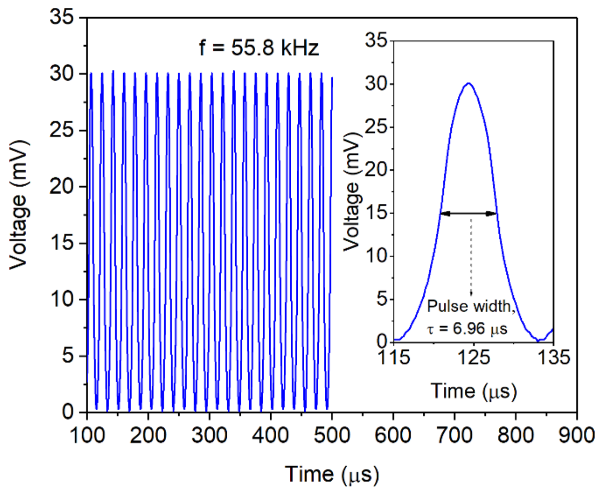
(b)

Fig. 5. Overall temporal performances. (a) Repetition rate and pulse width, and (b) RF spectrum observed within 300 kHz span (color online)

Fig. 5(b) shows the frequency domain of the Q-switched laser, recorded at 94.43 mW pump power. As depicted, the RF spectrum has a fundamental component, f_1 of 41.07 Hz, with a signal to noise ratio (SNR) measured to be 38 dB. This considerably high SNR indicates that the Q-switched laser is stable.



(a)



(b)

Fig. 6. Q-switched laser pulse train, (a) observed and compared at different pump powers of 52 mW (lowest), 103 mW (middle), and 164 mW (highest), and (b) recorded at the highest pump power of 164 mW, while the inset shows the single pulse envelope in detail (color online)

Fig. 6 illustrates the pulses train observed at certain pump powers. Fig. 6(a) shows and compares three modes of pulse trains taken at different pump powers of 52 mW (lowest), 103 mW (middle), and 164 mW (highest). As can be observed in the figure, when the pump power increases to the maximum value, the pulse train shrinks, which also causes the pulse width (τ) to shorten to the lowest of 6.96 μs. At the same time, the repetition rate (f) increases to the maximum of 55.8 kHz. Fig. 6(b) depicts the pulse train recorded at the maximum power, while the inset shows the enlarged view of the pulse envelope component. As illustrated, the pulse train has an even intensity distribution with considerably precise shapes repeated within the observed span. The result indicates that the Q-switched laser is operated in a stable regime.

Fig. 7 shows the output power and pulse energy profile at various pump powers, observed within a range of 52 mW to 164 mW. As seen in the figure, the output power increases linearly from 1.63 mW to 8.58 mW. The pulse energy, which is determined by dividing the output power by the pulse width, also increases from 12.26 nJ to the maximum value of 123.27 nJ. The optical to optical efficiency outlined from the output power profile is obtained as 6.14%. The performance of the film SA in inducing stable Q-switched laser at the maximum pump power was inspected by leaving the Sm_2O_3 SA to operate under the lab environment for one hour. Within the entire test period, the Q-switched pulse train remained stable at the appropriate repetition rate, without noticeable intensity destruction. This result indicates that the film SA operated well under its thermal damage threshold. The test was conducted again by replacing the Sm_2O_3 film SA with a pristine layer of PVA. The pump power was increased gradually to the maximum value. Our observation showed that no pulsed laser could be detected, and the laser remained in the CW mode. This result strongly suggested that the Q-switched laser, which presented earlier, was initiated by the effect of Sm_2O_3.

In addition to that, the performance of the pulsed laser is also compared with other SAs reported in the literature. As shown in Table 1, the proposed Sm_2O_3 film SA has a comparable Q-switched laser performance with the listed SAs.

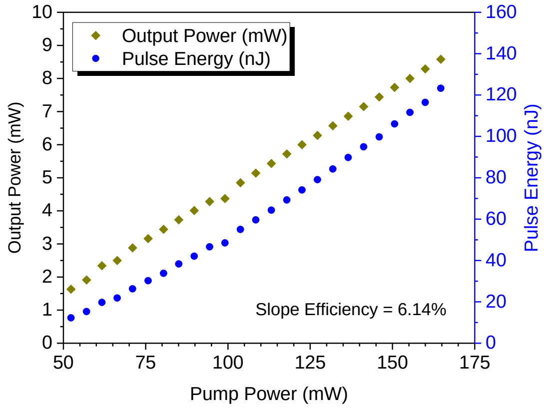


Fig. 7. The output power and pulse energy corresponding to pump power (color online)

In comparison with other materials, the Sm_2O_3 provides easiness in the film SA preparation, where the material itself is commercially available. In order to avoid the Sm_2O_3 from being contaminated during and after preparation, the film SA was prepared in a controlled lab environment, and the obtained film was then stored in a unique cabinet.

For future work, we will enhance the laser cavity by integrating a polarization controller (PC) and a piece of nonlinearity fibre. Furthermore, the film SA fabrication process will also be improved to achieve a higher particle distribution ratio on the film and to obtain a greater modulation depth, which may help in promoting a sustainable mode-locking operation.

Table 1. Q-switched EDFL performances with different SA materials

Gain Medium	SA material	Maximum pulse energy (nJ)	Minimum pulse width (µs)	Repetition rate (kHz)	The centre wavelength, λ_c (nm)	Reference
EDF	Samarium oxide (Sm_2O_3)	123.27	6.96	24.34 to 55.8	1568	This work
EDF	Black Phosphorus (BP)	94.3	10.32	6.893 to 15.47	1562.87	[15]
EDF	Gold nanostars (GNSs)	120	5.3	10 to 17	1564.5	[16]
EDF	Indium tin oxide (ITO)	21.19	1.15	37.24 to 81.28	1530.3	[17]
EDF	PbS quantum dots	586.1	3.9	21.46 to 68.04	1567.8	[18]
EDF	Titanium selenide ($TiSe_2$)	~75	1.126	70 to 154	1530	[19]
EDF	Tin (IV) oxide (SnO_2)	72.11	2.92	35.4 to 65.6	1521 to 1565 (tuneable)	[20]
EDF	Tungsten disulfide (WS_2)	~10	1.44	27.2 to 84.8	1560.7	[21]

Abbreviations: EDF, erbium-doped fibre; SA, saturable absorber; PbS, lead sulfide

5. Conclusion

The Sm_2O_3 film has been successfully demonstrated to work as a new SA in generating the Q-switched EDFL. This SA film has a linear absorption of 3.8 dB at 1568 nm wavelength and a modulation depth of 37%. To achieve the Q-switching operation, the Sm_2O_3 film was integrated into the EDFL ring cavity. A stable Q-switched laser was obtained at 1568 nm wavelength, within a pump power range of 52-164 mW. At the highest pump power of 164 mW, the pulsed laser attained the highest repetition rate of 55.8 kHz and recorded the smallest pulse width of 6.96 µs.

The maximum pulse energy was 123.27 nJ, while the SNR of the fundamental component was 38 dB. The proposed Q-switched laser mechanism is cheap and easy in fabrication and, thus, has a great potential to be used as a pulsed laser source in many applications such as medical, remote sensing, and metrology.

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