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PASSIVELY Q-SWITCHED YTTERBIUM-DOPED FIBER LASER EMPLOYING SAMARIUM OXIDE AS SATURABLE ABSORBER

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ABSTRACT: The rapid developments in transition metal dichalcogenide materials as saturable absorbers (SAs) have been reported to be efficient materials for generating Q-switched fiber lasers. In this paper, we report on the use of samarium oxide (Sm_2O_3) saturable absorber (SA) for 1-micron Q-switched fiber laser generation. The Sm_2O_3 thin film SA was constructed in-house through which the Sm_2O_3 powder was mixed and stirred in polyvinyl alcohol (PVA) solution. It was then integrated into the ytterbium-doped fiber laser (YDFL) ring cavity, hence producing a sequence of Q-switched pulsed lasers at 1062.49 nm wavelength. The stable pulse train appeared from 69.97 to 111.1 kHz between the applied pump power of 57 mW to 96 mW. The signal-to-noise ratio (SNR) of 38.56 dB was recorded at the 57 mW pump power, whereas the pulse energy raised until 15.21 nJ at 96 mW. These results showed that the Sm_2O_3 could be a favourable SA material to iniatiate Q-switched ytterbium-doped pulsed fiber laser.

ABSTRAK: Perkembangan pesat dalam bahan logam peralihan *dichalcogenide* sebagai bahan penyerap boleh larut (SAs) telah dilaporkan sebagai kaedah yang berkesan bagi menjana laser fiber *Q-switched*. Kajian ini menggunakan *samarium* oksida (Sm_2O_3) *saturable absorber* (SA) bagi menjana laser gentian *Q-switched 1-Micron*. Filem nipis Sm_2O_3 SA telah dihasilkan melalui campuran serbuk Sm_2O_3 ke dalam cecair polivinil alkohol (PVA) dalam persekitaran makmal. Kemudian, ia diintegrasi ke dalam rongga gelang laser gentian *dop-ytterbium* (YDFL), lalu menghasilkan denyut laser *Q-switched* stabil pada jarak gelombang 1062.49 nm. Denyutan stabil muncul dari 69.97 kepada 111.1 kHz pada kuasa pam yang dikenakan antara 57 mW hingga 96 mW. Nisbah isyarat-hinggar (SNR) pada 38.56 dB telah direkodkan pada pam kuasa 57 mW, sementara denyut tenaga ditingkatkan kepada 15.21 nJ pada 96 mW. Keputusan menunjukkan Sm_2O_3 merupakan bahan SA penggalak yang memuaskan bagi menjana denyut laser gentian *dop-ytterbium Q-switched.*

KEYWORDS: *Q-switched; Sm_2O_3 saturable absorber; Samarium oxide; Ytterbium-doped fiber pulsed laser*

1. INTRODUCTION

A Q-switched laser operating in the 1 to 2 μm region have gained research attention due to their vast applications in material fabrication, radar transmission, corrective eye surgery, remote sensing and biomedicine [1-5]. Generation of Q-switched lasers takes place once the losses inside the resonator surpass the gain in active medium, therefore bringing the quality factor to a low level. The losses are often introduced by acousto- or electro-optic active modulation that require externally driven components such as shutters, mirrors, and chopper wheels. These components are necessary as a voltage-controlled modulator to control the intracavity losses [6, 7]. Although the frequencies of these active modulation techniques for pulsed laser generation are reliable and adjustable, they however acquired disadvantages; e.g being bulky and costly [8]. On the other hand, the passive method introduces simpler techniques and low fabrication costs. Normally, a material-based saturable absorber (SA) is preferred for fabricating a real SA. Its simpler implementation is such that the fabricated SA can be placed within the laser cavity for pulse generation. This simpler technique might stimulate the research on new SA materials for generating a pulsed fiber laser.

Studies on two-dimensional (2D) materials found that they have strong optical saturable absorption as is the case with carbon nanotubes (CNT) and graphene which are used as saturable absorbers (SA) that function as the nanotube film thickness. Transition metal dichalcogenides (TMDs) for instance; molybdenum diselenide ($MoSe_2$), tungsten diselenide (WSe_2), molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) have shown a good nonlinear absorption ability [9-11]. In view of the fact that layered TMDs have a bandgap in the perceptible frequency range, they developed a strong saturable absorption at visible wavelengths. With bandgap modification for laser generation through mechanical exfoliation, the few-layers of TMDs are turned into atomically thin layers. This then makes them compatible with pulsed initiation in the near-infrared region [12, 13]. Likewise, black phosphorus (BPs) was also proposed to initiate Q-switching and mode-locked operation [14,15]. An orthorhombic structure of BPs exhibits excellent chemical stability with the absence of high heat supply, and wide optical tunability in the near-infrared region [16]. However, according to [17] BPs are highly sensitive to their environment, especially water, which can disrupt its stability as an effective SA for all-fiber laser configurations. Hisyam et al. [15] reported a stable generation of mode-locked ytterbium-doped fiber lasers (YDFL) using BP layers as a SA, subsequently producing stable mode-locked pulses centered at 1085.58 nm with a repetition rate and pulse energy of 13.5 MHz and 5.93 nJ, respectively. Besides, Luo et al. [18] also reported on generating all-fiber pulsed lasers at visible-wavelengths using 2D materials based on layered TMDs (WS_2, MoS_2 and $MoSe_2$) as a SA. The work successfully generated a visible-wavelength passive Q-switching laser at 635 nm with a repetition rate of 232 to 512 kHz, and pulse width and pulse energy of ~200 ns and 28.7 nJ, respectively. Of all reported 2D material-based SAs for pulsed fiber laser generation, very few reported a Q-switched laser generation for the 1-micron region that utilize TMD materials.

Use of ytterbium (Yb) ions for 1 μm laser generation is widely known for its wide spectral coverage in short-band wavelengths from 0.98 to 1.2 μm [19, 20]. Ytterbium-doped fiber possesses a low quantum defect due to its 2-level energy diagram and is therefore capable of providing high optical efficiencies and producing very low thermal load [21]. Apart from that, aluminosilicate glass containing Yb ions has broader emission with wavelengths longer than 1070 nm. It will be more susceptible to obtain lasing in the longwave spectral region allowing the glass to achieve a high level of inversion population which is needed to make the YDF transparent [20]. Therefore, most reported works for high-

power YDFLs operated in 1060 to 1090 nm for the low absorption of Yb ions [22-24]. This distinct optical characteristic of YDF and the wide application in the wavelength region has attracted much attention for researchers to focus on YDF. The Q-switching generation in the 1-micron region using TMD materials as a Q-switcher is not widely reported. Apart from exhibiting excellent choice for Q-switching generation, most of the TMDs present complex fabrication procedures, low damage threshold, low modulation depth, and wavelength-dependent emission ability. Thus, the search for a new material as SA in the all-fiber laser cavity is ultimately relevant. Previously, rare-earth oxide (REO) had also been manipulated as SA in near-infrared pulsed laser generation (1-2 μm) [25, 26]. Das et al. [27] demonstrated Samarium-doped fiber as SA for ytterbium-doped fiber lasers which successfully generated pulses in the 1 μm range. With a fast response time of 5 ns, Samarium oxide (Sm_2O_3) has excellent nonlinear absorption ability of 33% in a 1.5 μm regime [28, 29]. Its thin film is reported to have high chemical and thermal stability, making it efficient for pulsed laser generation due to its ability to withstand high power illumination from laser pumps [30]. The excellent performance of Sm_2O_3 thin film suggests its capability to initiate pulses in the near-infrared region as a new SA. In view of this, we demonstrated the Sm_2O_3 thin film as SA in YDFL generating Q-switched with a pulse width as short as 4.9 to 2.86 μs corresponding to a repetition rate of 69.97 to 111.1 kHz. To the best of our knowledge, this work marks among the earliest demonstrations employing Sm_2O_3 as SA for Q-switching operation of ytterbium doped fiber laser. We hope that this work will open up other insights into research on 2D material photonics.

2. FABRICATION METHOD

Samarium oxide (Sm_2O_3) PVA films were synthesized by mixing the Sm_2O_3 powder into a polyvinyl alcohol (PVA) solution [29]. Initially, 120 ml of distilled water was used to dissolve 1 g of PVA powder. This was done for 30 minutes on a magnetic mixer with speed and temperature of 300 rpm and 100 ºC, respectively, until the PVA powder completely dissolved and became a solution. Next, 50 mg of Sm_2O_3 grain was immersed into 50 ml of the prepared PVA solution and stirred by magnetic stirrer at a speed of 300 rpm for 12 hours. Finally, the Sm_2O_3-PVA solution was sonicated for 1 hour using an ultrasonic bath. Upon completion, it was dispensed onto a petri dish and left to dry for 48 hours or more at room temperature, until it completely became a thin film. The synthesized Sm_2O_3 PVA film was characterized using the Field Emission Scanning Electron Microscope (FESEM), X-ray diffraction (XRD), linear absorption profile and nonlinear absorption profile. Figure 1(a) shows the XRD analysis of Sm_2O_3 film.

Figure 1(a) shows the diffraction peaks observed at 29.11º, 40.79º, and 50.27º. They can be assigned at (4 0 1), (-5 1 1), and (0 2 0) planes of Sm_2O_3. The high and strong peak patterns of Sm_2O_3 film XRD proves the successful implant of the Sm_2O_3 film onto the PVA polymer. Figure 1(b) shows a homogenous distribution of Sm_2O_3 particles and PVA solution observed by FESEM image. Figure 1(c) shows the absorption loss of about 6 dB near to 1040 nm, indicating the mode-locking process mainly corresponding to Sm_2O_3. The nonlinear absorption profile of the Sm_2O_3 can be seen via the balanced twin-detector measurement as shown in Fig. 1(d). The point reference shows flat output transmission, while the Sm_2O_3 thin film SA shows the result of nonlinear transmission which fitted accordingly. The transmissions at various input intensities were recorded. The Sm_2O_3 thin film SA had a modulation depth of 33%, saturable intensity of 25 MW/cm^2 and a non-saturable absorption of 65%. The EDX data in Fig. 1(e) shows the element of samarium is 64.00% (Wt) and 15.51% (At), oxygen (O) and carbon (C) from PVA film is 32.68% (Wt) and 74.43% (At), 3.31% (Wt) and 10.06% (At), respectively. This data can confirm and

prove the presence of the samarium element in this PVA film. Such characteristics of the SA reveals the ability of Sm_2O_3 to act as good saturable absorber.

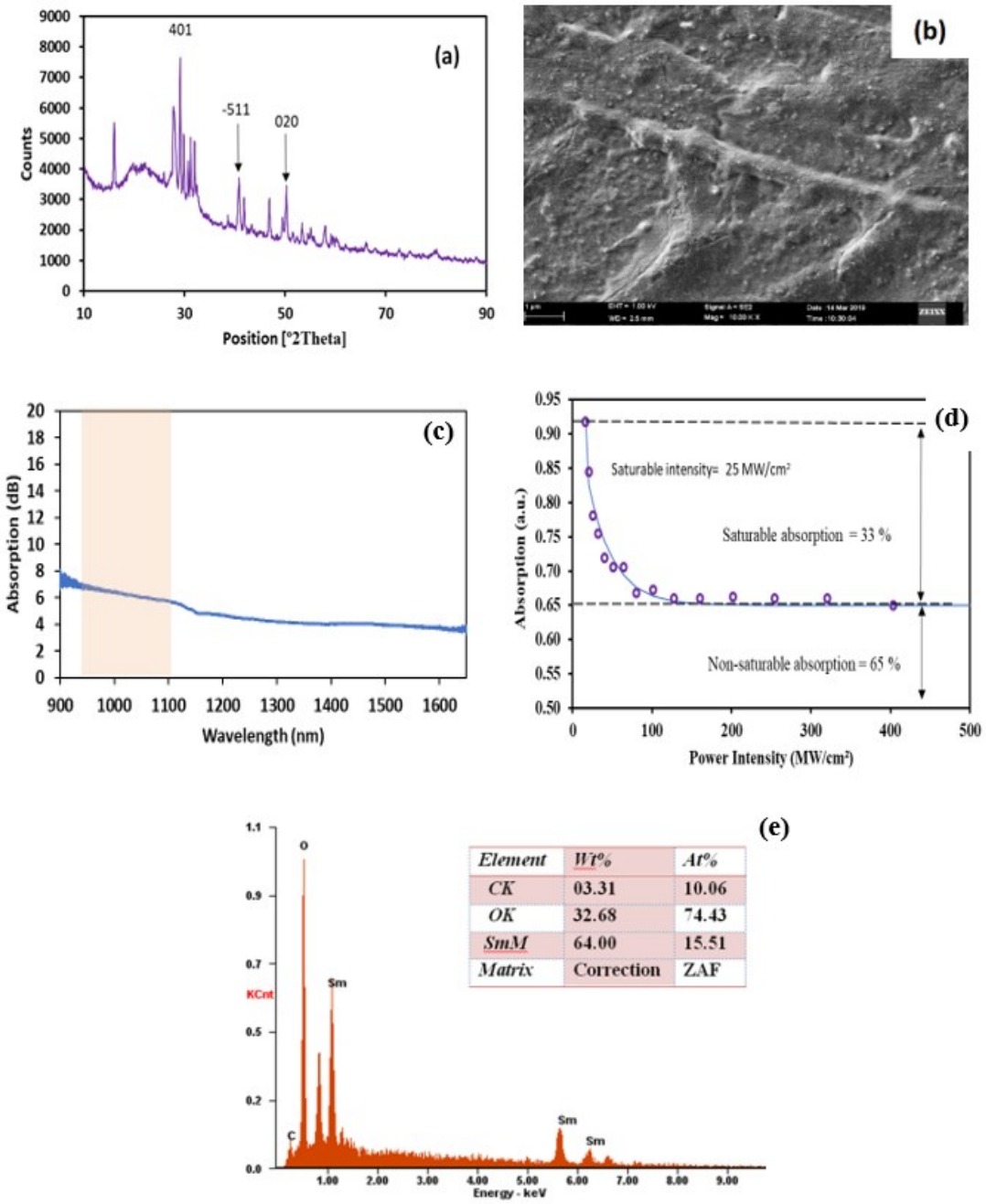

Fig. 1: Characterization of Sm_2O_3 PVA film as SA (a) XRD (b) FESEM (c) Linear absorption profile (d) Nonlinear absorption profile (e) Energy dispersive X-ray.

3. EXPERIMENTAL DEMONSTRATION

In order to perform a pulsed laser, the homemade Sm_2O_3 SA thin film was integrated in the all-fiber ring cavity laser setup. As shown in Fig. 2, the thin film SA that was placed between fiber ferrule was capped together using a fiber connector. Each end of the connector was spliced to 90/10 coupler and wavelength division multiplexing (WDM). The 90/10 coupler was used to allow 90% of the power to oscillate back in the resonator. The feedback power hit the SA when the amplified spontaneous emission gain oscillated in the resonator.

The 1064 nm wavelength division multiplexor (WDM) was spliced to the other end of the connector to form the resonator for oscillation. The 980/1064 nm WDM was used in the setup to compliment the 980nm laser diode and ~1064 nm wavelength laser that were built up from ytterbium-doped fiber (YDF) as a gain medium (2m), respectively. The isolator was placed after the YDF to prevent any unwanted signal feedback. The whole length of the YDFL cavity was approximately 9.5 m. The feedback process occurs continuously, hence accumulates the energy fed into the gain medium (YDF). When the resonator losses decrease until reaching saturation energy of the gain medium, the fiber laser will start to perform. In this experiment, an optical spectrum analyzer (Anritsu MS9710C, 0.6 - 1.75 µm) and optical power meter (PM100D THORLABS) were used to record the spectrum and power, respectively from the 10% output of the coupler. The photodetector (DET01CFC THORLABS InGaAs Biased Detector) was attached to it to record the time and frequency domain of Q-switched pulsed using an oscilloscope (GDS-3352 350 MHz 5GS/s) and radio frequency (RF) spectrum (Anritsu, 9 kHz - 7.8 GHz).

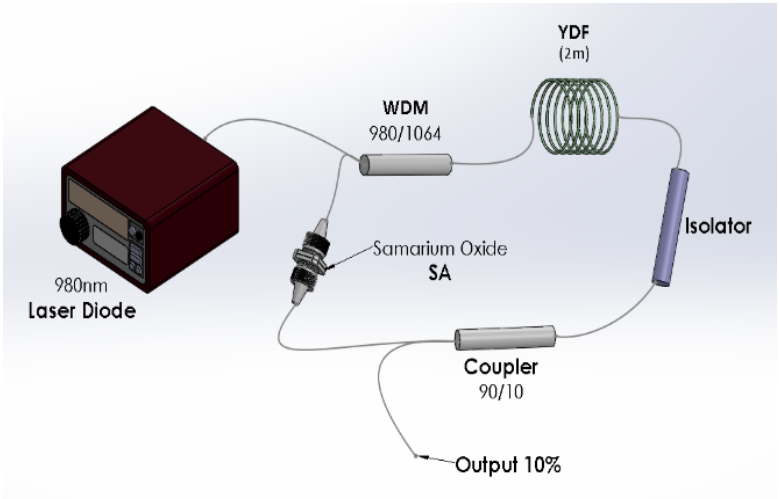

Fig. 2: The schematic for the Q-switched ytterbium laser setup incorporating Sm_2O_3 based saturable absorber (SA).

4. RESULTS AND DISCUSSION

By using homemade Sm_2O_3 SA, the stable Q-switching operation was obtained, as shown in figure 3. The generated Q-switched pulses exhibit a pulse duration between 4.9 to 2.86 µs. The pulse pattern and its characteristic display the normal features of Q-switched fiber lasers. Unlike a mode-locked laser, in Q-switching pulses, longer or shorter pulse duration is hard to determine with the modulation depth. However, it was suggested that the pulse width can be scaled down by preparing a SA with a higher modulation depth in a mode-locked case or having a short total cavity length. The inset of Fig. 3 shows a stable pulse to pulse spectral range of 14.4 µs which translates into a repetition rate of ~69.97 kHz, recorded when the pump power is 57 mW (at threshold). The pulse repetition rate shown in Fig. 4(a) rises from 69.97 to 111.1 kHz, while pulse width declines and becomes narrower, in the range of 4.9-2.86 µs, as opposed to the repetition rate. Both outputs were plotted as a function of pump power ranging from 57 to 96 mW. In case of Q-switching operation, the increase in pump power would cause the repetition rate to increase. Higher pump power will increase the amplifier gain for YDF thereby contributing to the saturation of SA. The pulse energy was calculated given 8.96 nJ using an equation of

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$$Q\ [J] = \frac{P_0}{f_r}$$

where P_0 is the average output power and f_r is the repetition rate.

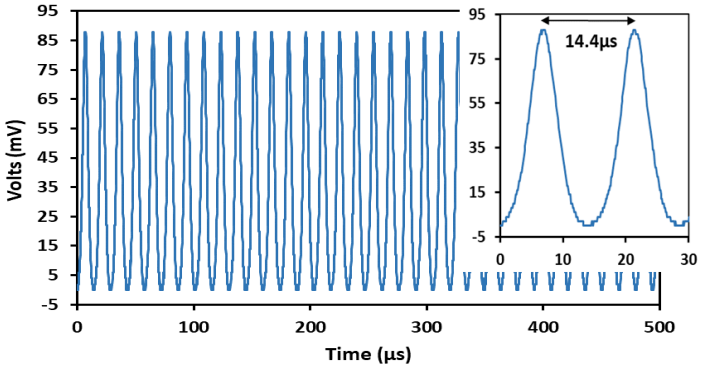
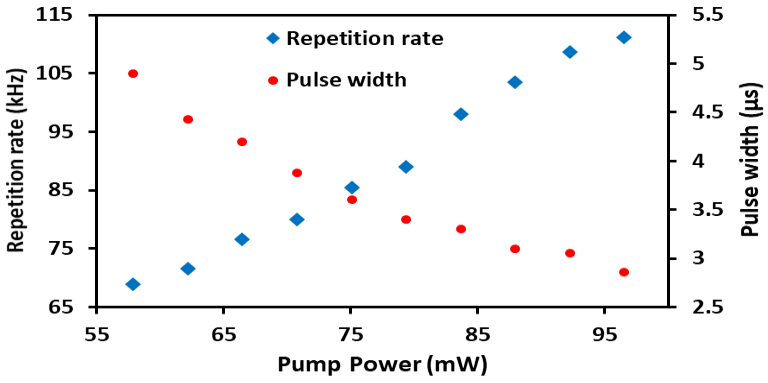
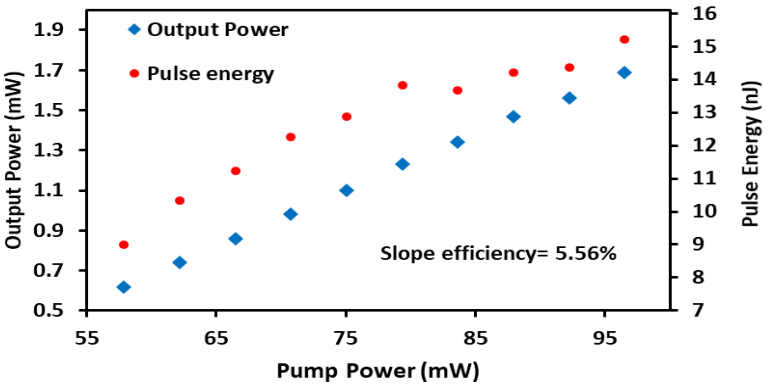


Fig. 3: The measured oscilloscope trace for the Q-switched laser at 69.97 kHz. The inset shows the free spectral range for successive pulses.



(a)



(b)

Fig. 4: Q-switched performance in terms of (a) pulse width repetition rate, (b) pulse energy and output power, versus pump power.

Stable passively Q-switched operation was successfully obtained when the pump power was tuned in the range of 57–96 mW, resulting in the output power from 0.62 to 1.69 mW, as can be seen in Fig. 4(b). The laser efficiency calculated from the output power versus pump power was 5.56% whereas the pulse energy trend was increasing from 8.96-15.21 nJ.

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Figure 5 and its inset exhibit the output laser power spectrum with and without the Sm_2O_3 thin film, respectively. The central wavelength was positioned at 1062.49 nm, similar to the one observed in the Q-switched laser (with Sm_2O_3) exhibiting FWHM of ~0.1 nm. The threshold power of the continuous wave (CW) was recorded to be 43 mW and the Q-switched laser could be observed via oscilloscope at the pump power of 57 mW after further increment. The pulsed laser was successfully detected for 10 consecutive readings and sustained up to 96 mW. However, the Q-switched pulsed laser showed instability and the pulses diminished when the pump power was increased further. In order to check whether our Sm_2O_3 SA was able to withstand higher power, the pump power was increased to the maximum allowable threshold, which is 200 mW. As we tuned back the power to 96 mW, the Q-switched pulses were observed as before. Therefore, it is confirmed that the high pump power did not cost the perseverance of our homemade Sm_2O_3 thin film SA. The excellent properties from our Sm_2O_3 SA and high bandgap energy of 4.33 eV [30] contribute to the realization of Q-switched fiber laser in the 1-micron region. Nonetheless, if the non-saturable losses could be reduced, the fiber laser performance might be improved.

Figure 6 recorded the relative RF spectrum analyzer when the pump power was 57 mW within 750 kHz span measured using a 1 kHz resolution bandwidth (RBW) and 300 Hz video bandwidth (VBD). The signal-to-noise (SNR) ratio of 38.56 dB was observed at the fundamental RF peak when the repetition rate was 69.97 kHz. This result indicates a stable Q-switching operation. The harmonics in the RF spectrum decrease linearly before disappearing at the ninth harmonic. In this work, we also verified the generation of Q-switching operation by taking out the connector that contains the SA. When the pump power was turned on up to 200 mW, no pulse was observed, however, when the SA was restored, the Q-switched pulses were detected. Hence, our Q-switched pulse is confirmed due to our homemade Sm_2O_3 SA.

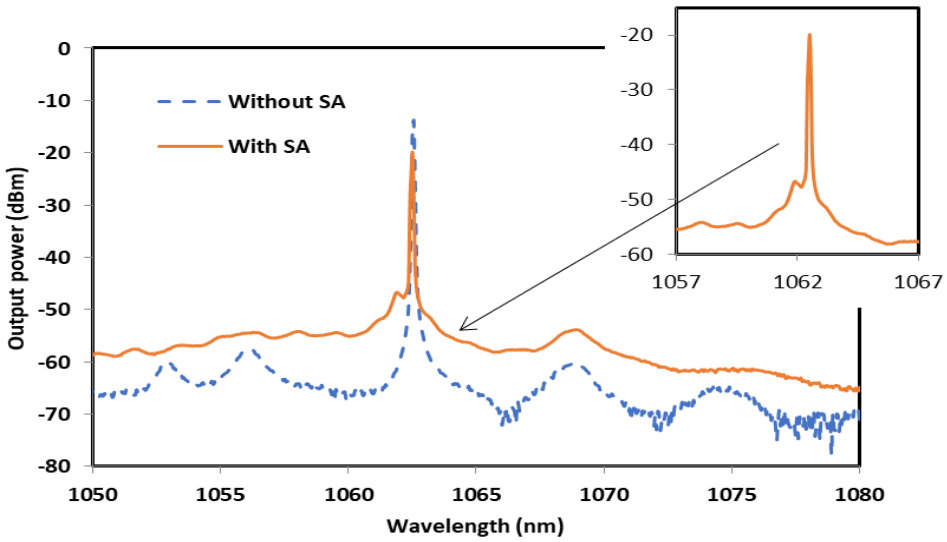

Fig. 5: Spectrum of CW laser (without SA) and Q-switched laser (with SA).

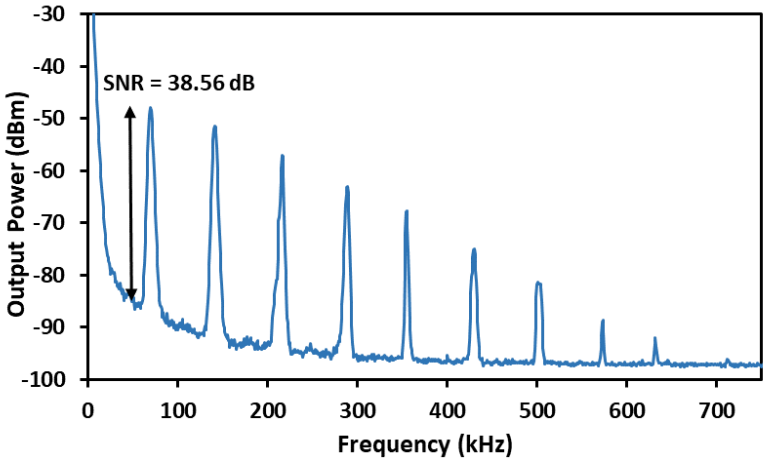

Fig. 6: Q-switched YDFL RF spectrum when the pump power is 57 mW.

5. CONCLUSION

This work successfully demonstrated a new 2D material, Sm_2O_3 as a SA to generate passive Q-switching operation for YDFL. The Sm_2O_3 based SA was embedded with a PVA solution to form the Sm_2O_3 thin film. A piece of Sm_2O_3 SA was attached between connectors and placed in the YDFL resonator. The Q-switching operation was observed at a 1062.49 nm wavelength and the pulsed fiber laser was initiated at 57 mW. The pulse width and repetition rate were obtained in the range of 4.9-2.86 µs and 69.97-111.1 kHz, respectively. The pulse energy was calculated as a change in output power over repetition rate, therefore giving the acceptable pulse energy ranging from 8.96 to 15.21 nJ. A stable pulse generation was confirmed by a high SNR of 38.56 dB. Our results suggest that the excellent properties of Sm_2O_3 has led to the pulsed fiber laser generation in the 1-micron region. The outcome of this research may promote other related research and applications in the area of material cutting and manufacturing processes.

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