Q-SWITCHED ERBIUM-DOPED FIBER LASER UTILIZING TUNGSTEN DISULFIDE DEPOSITED ONTO D-SHAPED FIBER AS SATURABLE ABSORBER

S. OMAR[a], N. F. ZULKIPLI[b], A. A. A. JAFRY[c], B. MUSA[a], M. I. M. ALI[a], S. W. HARUN[b], Z. JUSOH[a], M. YASIN[d*]

[a]*Faculty of Electrical Engineering, Universiti Teknologi Mara (Terengganu), 23000 Dungun, Terengganu, Malaysia*

[b]*Photonics Engineering Laboratory, Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

[c]*Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*

[d]*Department of Physics, Faculty of Science and Technology, Airlangga University, Surabaya (60115) Indonesia*

Q-switched fiber laser was demonstrated by using tungsten disulfide (WS_2), which was deposited onto D-shaped fiber as a passive saturable absorber (SA) to modulate the loss inside the laser cavity. The SA was produced by repeatedly dropping and drying the WS_2 solution onto side-polished fiber to form a nanosheets layer. The SA is inserted into the ring laser cavity configured with a 2.4 m long Erbium-doped fiber as the gain medium to generate Q-switching pulses train operating at 1557.9 nm. The Q-switched laser produced a pulse train, which the repetition rate is tunable from 77.2 to 108.9 kHz as the pump power is increased from 84.0 to 182.9 mW. The minimum pulse width of 3.25 μs and the maximum pulse energy of 14.6 nJ was obtained at 182.9 mW pump power. The generated Q-switching pulses are stable and thus it is suitable for use in many practical applications.

(Received September 13, 2019; Accepted March 3, 2020)

Keywords: Tungsten disulfide, Passive saturable absorber, WS_2, Q-switched fiber laser

1. Introduction

Q-switching is one of the main techniques to produce a train of energetic short pulses [1–3]. It can be passively achieved by deployment of saturable absorber (SA) device inside the laser cavity [4–9]. On the other hand, research on fiber lasers have been extensively carried out in recent years due to their many advantages such as simple structure, low cost, small size, and high environmental stability. Passively Q-switched fiber lasers were previously demonstrated using semiconductor saturable absorber mirrors (SESAMs) [4]. However, SESAMs have many drawbacks, such as narrow working bandwidth and complex manufacturing packages and this has greatly limited their application in the development of pulsed fiber lasers. Therefore, many Q-switched fiber lasers have been demonstrated in recent years using various types of new SAs such as carbon nanotubes (CNTs) [5], graphene oxide [6], graphene [7], black phosphorus [8] and topological insulators (TIs) [9].

Recently, transition-metal dichalcogenides (TMDs) (e.g., MoS_2 [10], and $MoTe_2$ [11]) have attracted much attention from laser researchers due to their thickness-dependent band gap and unique absorption property. TMDs are semiconductor material with direct bandgap in monolayer or few layers structures. They exhibited a good photoluminescence ability and excellent nonlinear optical property [12]. Tungsten disulfide (WS_2) is another layered TMD, which has also attracted many attentions for application in pulsed laser generation.

There are two ways to incorporate the SA into fiber laser cavity; sandwiching thin film structure in between fiber-ferrule and integrating SA material onto a special fiber such as D-

[*]Corresponding author: yasin@fst.unair.ac.id

shaped fiber and microfiber. The first approach has few drawbacks such as limited nonlinear interaction length between material and light as well as inducing thermal and mechanical damage to the end-face of fiber connector. Thus, due to long nonlinear interaction length and high optical damage threshold [13], many works have also been focused on the latter approach. Previously few works have been demonstrated to passively generate Q-switched and mode-locked pulsed laser using SA materials coated onto D-shaped fiber [14-15]. In this paper, we demonstrate a Q-switched erbium-doped fiber laser (EDFL) using WS_2 coated onto a D-shaped fiber as a SA device. The interaction between the laser light and WS_2 via evanescent field is used to realize saturable absorption in the EDFL cavity.

2. Preparation and optical characterization of the SA device

The interaction between the evanescent light field and layered WS_2 material should be efficiently established within the SA device for Q-switched pulses generation. In this work, a D-shaped optical fiber is used to induce light-matter interaction so that an efficient fiber laser with excellent Q-switching performance can be realized. The D-shaped fiber is produced using a polishing wheel technique. Fig. 1 shows the fabrication setup, which uses rough and fine abrasive papers for efficient polishing process of D-shaped fiber. At first, an 800-grid and 1500-grid sandpapers are pasted around the rotating wheel. Then, a single mode optical fiber (Corning SMF-28) with core/cladding diameter of 9/125 µm is fixed with two fiber holders. The holders are used to clamp the fiber at both ends to ensure less vibration during the polishing process. Before polishing, approximately 3 mm of the fiber's jacket is stripped off in advance at the polishing region of optical fiber. Amplified spontaneous emission (ASE) light source is launched into the optical fiber while optical power meter (THORLABS) is connected to observe insertion loss during polishing process.

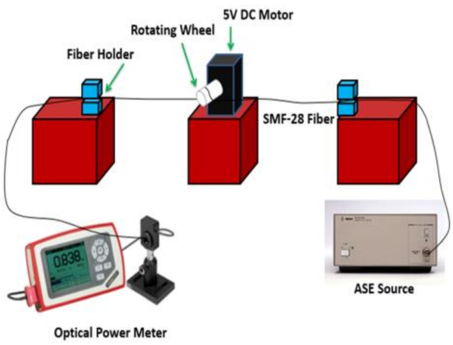

Fig. 1. Experimental setup of polishing wheel technique to produce D-shaped fiber.

In this work, we implement two steps polishing process using rough sandpaper, followed by fine sandpaper to obtain a smoother polished surface of the D-shaped fiber. At first, the stripped part is polished with 800-grid sandpaper until the desired insertion loss is observed on the optical power meter. This process normally takes around 10 minutes. The rotating wheel is then adjusted so that the polished region is in contact with fine sandpaper with 1500-grid. The fine polishing is conducted for about 5 minutes. Figs. 2(a) and (b) shows the optical fiber before and after polishing, respectively. The waist diameter of the fiber reduces from 125.0 µm to 97.3 µm after the polishing process.

WS_2 solution was prepared by dissolving WS_2 flakes into ethanol and distilled water. The mixture was then treated by a high power sonification process for about 2 hours. The dispersed solution obtained was then centrifuged at 3000 rpm for 30 min to remove large agglomeration. The upper supernatant was collected for use in the experiment as WS_2 solution. The concentration of WS_2 nanosheets in the solvent was about 26 mg/l. The solution was dropped onto the prepared D-shaped fiber using micropipette and then left to dry in room temperature for about 48 hours. This step was repeatedly done until it formed WS_2 nanosheets layer onto the polished surface of the D-shaped fiber. Fig. 3 show the linear absorption profile of the WS_2 coated D-shaped fiber, which was obtained within 1200 nm to 1600 nm wavelength region. It is observed that the SA device has an absorption loss of about 4.5 dB at 1550 nm region.

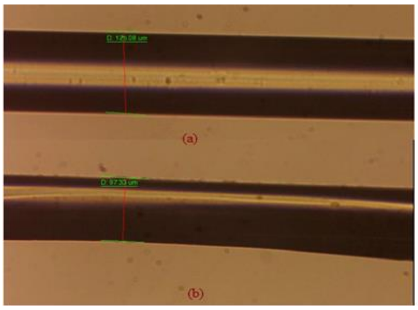

Fig. 2. Images of optical fiber (a) before and (b) after polishing.

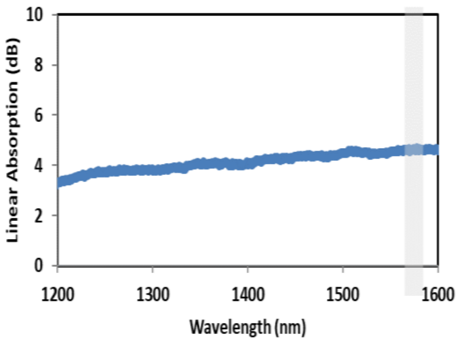

Fig. 3. Linear absorption profile of the fabricated SA device based on D-shaped fiber deposited with WS_2.

3. Laser configuration

Fig. 4 shows the proposed Q-switched EDFL configured with WS2 coated D-shaped fiber as a SA device. It uses a 2.4 m long erbium-doped fiber (EDF) as a gain medium. The EDF has a core diameter of 4 μm, an absorption coefficient of 23 dB/m at 980 nm and a numerical aperture (NA) of 0.16. It was pumped by a 980 nm laser diode based on forward pumping scheme through a 980/1550 nm wavelength division multiplexer (WDM). The forward pumped EDF produced an amplified spontaneous emission (ASE) light to oscillate in the ring laser cavity and generate laser in 1550 nm region. The oscillating laser is forced to propagate in forward direction inside the cavity by the isolator. The unidirectional propagated light is allowed to interact with WS2 in the D-shaped fiber to produce Q-switched pulses. An optical coupler with 90:10 coupling ratio is used as the output coupler. A 90 % of light is forced to turn back into the cavity thus allowing cycles of energetic pulse to continue. On the other hand, 10% of light is coupled out of the ring cavity for analysis purposes. Total cavity length of the EDFL is about 14 m. The output laser is monitored by a digital power meter and an optical spectrum analyser (YOKOGAWA, AQ6370D) with resolution of 0.02 nm. Temporal characteristic of the laser is monitored by using a 350 MHz digital oscilloscope (GWINSTEK, GDS-3352) and 7.8 GHz RF spectrum analyser (ANRITSU, MS2683A) connected via a 7-GHz InGaAS photodetector.

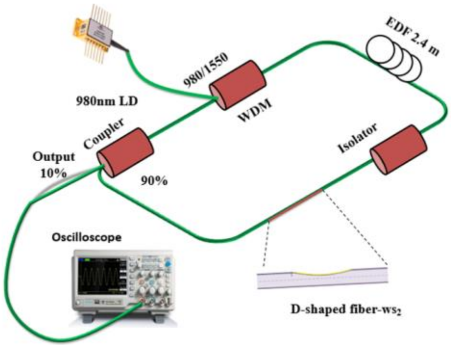

Fig. 4. Laser cavity of the Q-switched EDFL.

4. Results and discussion

In this experiment, continuous wave (CW) laser starts to develop at pump power of around 40 mW while self-started Q-switched laser starts to initiate at pump power of 84.0 mW. The Q-switching threshold pump power is relatively higher due to the high non-saturation loss of the SA device, which is based on D-shaped fiber. The Q-switching operation is maintained up to the maximum pump power of 182.9 mW. Fig. 5 shows the typical Q-switched laser output properties under the pump power of 182.9 mW. Fig. 5(a) show the output spectrum, which operates at 1557.9 nm. Fig. 5 (b) shows the typical pulse train of the Q-switched laser. The amplitude of the generated pulses is uniform over 500 μs span, denotes consistency of Q-switched pulses over a long period of time. The enlarged image of two pulses envelope is also shown in the inset figure with full-width half maximum (FWHM) of approximately 3.25 μs and peak-to-peak distance of about 9.2 μs. Fig. 5 (c) shows the measured RF spectrum for the Q-switched pulses. It indicates the fundamental frequency at 108.9 kHz with many harmonics. The signal-to-noise ratio (SNR) of the fundamental frequency is measured to be around 38 dB. This confirms that Q-switched generated is stable as the distortion of signal by the noise is minimized inside the ring cavity. It is also worthy to note that no pulses visible without the deposition of WS_2 on D-shaped fiber inside the laser cavity.

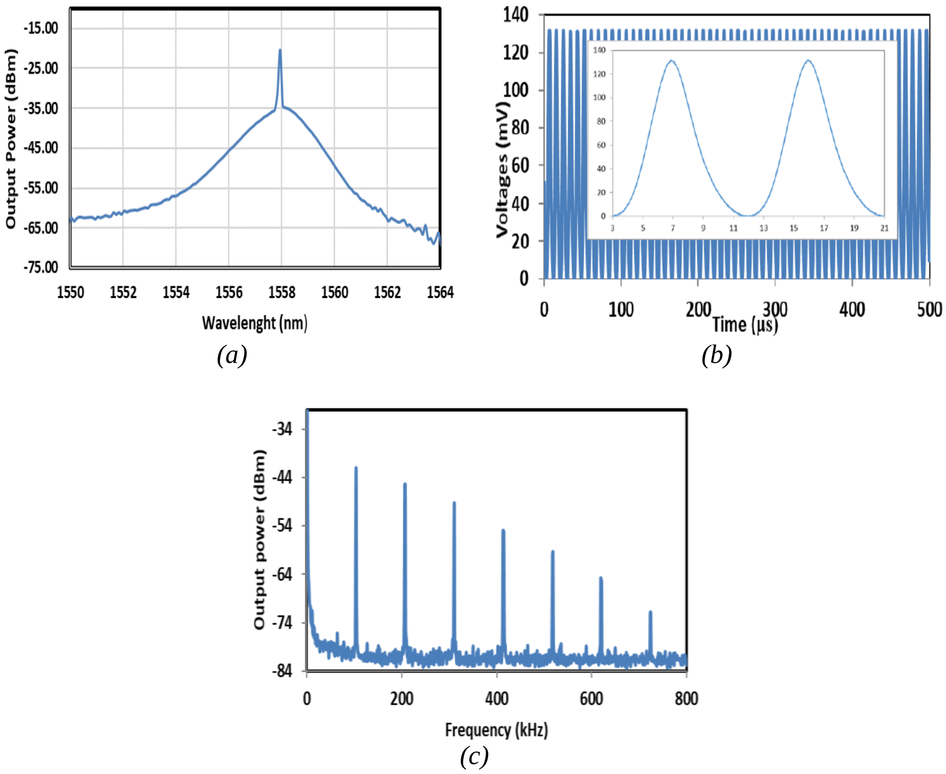

Fig. 5. (a) Output optical spectrum (b) pulse train (c) RF spectrum of the Q-switched EDFL at a pump power of 182.9 mW

Fig. 6 shows the variation of the Q-switched pulses properties with the pump power. The repetition rate and pulse width as a function of pump power is shown in Fig. 6 (a). It is observed that the repetition rate can be tuned from 77.16 to 108.9 kHz by increasing the pump power from 84.0 to 182.9 mW. The pulse width, on the other hand, reduces from 5.20 to 3.25 µs, which is due to the increase of the pump rate for the upper laser level. The increase of input pump power produced more gain to be fed to saturate the SA. Therefore, the threshold energy stored in the gain medium was reached earlier, resulting in the increase of the repetition rate and decrease of the pulse width. This presents the typical features of passively Q-switched laser. Fig. 6(b) shows the average output power and pulse energy as a function of pump power. As the pump power was increased from 84.0 mW to 182.9 mW, the output power linearly increased from 0.64 to 1.59 mW with efficiency of 0.96 % while the pulse energy increased from 8.3 to 14.6 nJ. The pulse energy can be improved by reducing the insertion loss of the SA and further optimizing the EDFL cavity. The long-term stability of the SA was also examined by monitoring the condition of the Q-switching at a moderate pump power of 182.9 mW for 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. The operating wavelength of the Q-switched EDFL can be tunable by integration of tunable filter in the cavity, however it would be limited within the area covered by the EDF emission cross section.

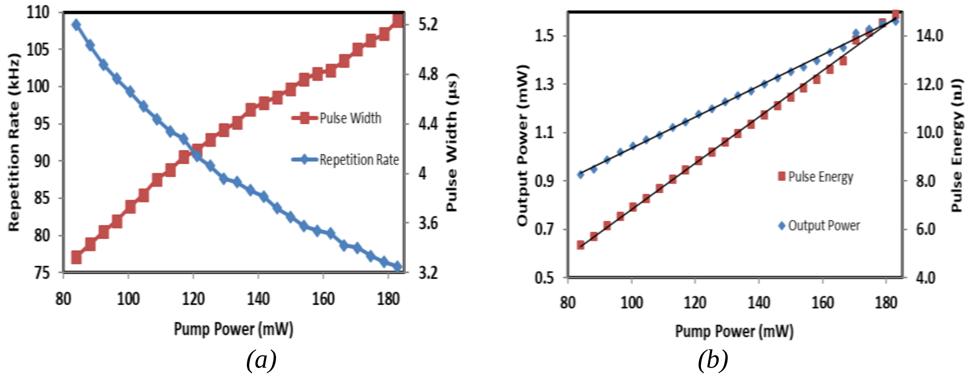

Fig. 6. (a) Pulses repetition rate and pulse width versus pump power (b) Average output power and pulse energy versus pump power.

5. Conclusions

WS_2 based SA has been successfully obtained by depositing WS_2 nanosheets layer via drop-casting method onto side-polished D-shaped fiber. The SA was incorporated into an EDFL ring cavity to function as a Q-switcher and generates Q-switching pulse train operating at 1557.9 nm. Stable pulse train is observed within pump power of 84.0 mW to 182.9 mW with maximum repetition rate of 108.9 kHz corresponds to shortest pulse duration of 3.25 µs. The maximum pulse energy of 14.6 nJ was obtained at 182.9 mW pump power. This SA is suitable for making a portable, robust and stable Q-switched laser source

Acknowledgements

This work is financially supported by Airlangga Research Group Grant (RG-2020) and Ministry of Higher Education Grant Scheme (PRGS/1/2017/STG02/UITM/02/1) as well as the University of Malaya (GPF005A-2018).

References

[1] R. Paschotta, R. Haring, E. Gini, H. Melchior, U. Keller, H. L. Offerhaus, D. J. Richardson, Opt. Lett. **24**, 388 (1999).
[2] M. Skorczakowski, J. Swiderski, W. Pichola, P. Nyga, A. Zajac, M. Maciejewska, L. Galecki, J. Kasprzak, S. Gross, A. Heinrich, T. Bragagna, Laser Phys. Lett. **7**, 498 (2010).
[3] J. Ren, S. X. Wang, Z. C. Cheng, H. H. Yu, H. J. Zhang, Y. X. Chen, L. M. Mei, P. Wang, Opt. Express **23**, 5607 (2015).
[4] U. Parali, X. Sheng, A. Minassian, G. Tawy, J. Sathian, G. M. Thomas, M. J. Damzen, Optics Communications **410**, 970 (2018).
[5] S. N. F. Zuikafly, F. Ahmad, M. H. Ibrahim, A. A. Latiff, S. W. Harun, Photonics Letters of Poland **8**, 98 (2016).
[6] N. A. Aziz, Z. Jusoh, M. Q. Lokman, M. Yasin, E. Hanafi and S. W. Harun, Digest Journal of Nanomaterials and Biostructures 12 325 (2017)
[7] S. N. F. Zuikafly, A. Khalifa, F. Ahmad, S. Shafie, S. W. Harun, Results in Physics **9**, 371 (2018)
[8] H. Song, Q. Wang, D. Wang, L. Li Results in physics **8**, 276 (2018).
[9] U. N. Zakaria, S. W. Harun, P. H. Reddy, D. Dutta, S. Das, A. Dhar, M. C. Paul, Z. Jusoh, M. Yasin, Chalcogenide Letters **15**, 181 (2018).
[10] H. Haris, S. W. Harun, A. R. Muhammad, C. L. Anyi, S. J. Tan, F. Ahmad, R. M. Nor, N. R. Zulkepely, H. Arof, Opt. Laser Technol. **88**, 121 (2017).
[11] Y. Huang, Z. Luo, Y. Li, M. Zhong, B. Xu, K. Che, H. Xu, Z. Cai, J. Peng, J. Weng, Optics Express

22(21), 25258 (2014).
[12] M. Liu, W. Liu, P. Yan, S. Fang, H. Teng, Z. Wei, Chinese Optics Letters **16**, 020007 (2018).
[13] R. I. Woodward, R. C. T. Howe, T. H. Runcorn, G. Hu, F. Torrisi, E. J. R. Kelleher, T. Hasan, Optics express **23**(15), 20051 (2015).
[14] D. Steinberg, R. M. Gerosa, F. N. Pellicer, J. D. Zapata, S. H. Domingues, E. A. T. de Souza, L. A. M. Saito, Optical Materials Express **8**, 144 (2018).
[15] M. F. M. Rusdi, M. B. H. Mahyuddin, A. A. Latiff, H. Ahmad, S. W. Harun, Chin Phys Lett. **35**, 4 (2018).
[16] J. Zapata, D. Steinberg, L. Saito, R. De Oliveira, A. Cárdenas, E. T. De Souza, Scientific Reports **6**, 20644 (2016).