Simultaneous dual-wavelength Q-switched fiber laser utilizing tungsten sulfide as saturable absorber

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Dual-wavelength Q-switched Erbium-doped fiber laser (EDFL) was shown by using tungsten disulfide (WS_2), which was deposited onto a micro-sphere resonator (MSR) as a saturable absorber (SA). WS_2 functions to modulate the cavity loss for Q-switching while the dual-wavelength operation was realized due to MSR, which allows only two wavelengths to oscillate in the resonator. MSR with the sphere diameter of 200 μm was fabricated at the tip of a standard single mode-fiber by employing a fiber fusion splicer machine. The SA was obtained by repeatedly dropping and drying of WS_2 solution onto the MSR structure to form an active thin layer. The SA was incorporated into an EDFL cavity to realize a dual-wavelength Q-switched laser operating at 1554.0 nm and 1560.7 nm. The repetition rate of the pulse train is tunable from 72.4 kHz to 85.1 kHz as the pump power is increased from 104.6 mW to 145.8 mW. At 145.8 mW pump, the minimum pulse width and maximum pulse energy were obtained at 3.47 µs and 131.4 nJ, respectively. The dual-wavelength Q-switched laser was stable and thus it is suitable for use in airborne Lidar, environmental sensing, and terahertz applications.

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1. Introduction

Q-switching technique has been widely investigated and used to produce short laser pulses, which have many applications ranging from microfabrication, range finding and metal cutting to medical treatment [1-3]. Traditionally, active techniques based on acousto-optic and electro-optic modulators are widely used to modulate the cavity loss in the laser cavity for Q-switching [4]. The actively Q-switched lasers are often relatively complicated due to the presence of the bulky device in the cavity. Therefore, the passive techniques based on saturable absorbers (SAs) are preferable due to their compactness and simplicity [5]. Up to date, various SAs including graphene and single walled carbon nanotube (CNT) were proposed and demonstrated for passively generating Q-switched pulses due to their excellent nonlinear optical characteristic [6-7]. However, these materials own some drawbacks such as, low optical saturation absorption per layer for graphene, while the CNT has its spectral range response depending on the chirality and size of the nanoparticles. The reports on carbon-based materials have stimulated the research interests of other new materials such as black phosphorus (BP) for Q-switching applications [8-9]. BP has fast recovery time and wide spectral range that made them distinguished from other SAs. However,

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some factors such as low damage threshold and complexity in the fabrication process have limited the use of BP as a Q-switcher.

Recently, the interests on dual-wavelength Q-switched lasers are increasing. These lasers can simultaneously generate two Q-switched pulse trains at different wavelength operation and thus they have extensive applications in airborne Lidar, environmental sensing, and terahertz [10-11]. Previously, a dual wavelength Q-switched Erbium-doped fiber laser (EDFL) was demonstrated by using a graphene SA in conjunction with the birefringence-induced filtering effect [12]. A dual-wavelength Q-switched Ytterbium-doped fiber laser (YDFL) operating at around 1-micron wavelength region was also demonstrated using a Cr^{4+}: YAG as the SA [13]. These SAs have a broad absorption spectrum and thus dual-wavelength Q-switched lasers were successfully realized with this kind of fiber-compatible and low-cost SAs.

Recently, transition metal dichalcogenides (TMDs) have also been investigated for Q-switched pulse generation due to their graphene-like electronic-band structure [14]. For example, a stable Q-switched EDFL operating at 1560 nm was successfully demonstrated by employing molybdenum disulfide material, which was coated onto a side-polished optical fiber as a SA [15]. In this paper, a new dual-wavelength Q-switched EDFL is proposed and demonstrated by using another TMD material, tungsten disulfide (WS_2) coated onto a micro-sphere resonator (MSR) as SA. WS_2 was reported to have a high third-order optical nonlinearity, which is preferred to obtain a stable dual-wavelength pulsed fiber laser [16].

2. Experimental arrangement

Multi-layered WS2 was reported to have a good nonlinear absorption property and thus suitable for use as SA. It can be produced by either chemical vapor deposition (CVD) or liquid phase exfoliation (LPE). The CVD process is more complicated since it requires high temperature and complex transfer procedure. Therefore, in this work, multi-layered WS_2 pristine flakes were produced using LPE technique at room temperature. The WS_2 flakes obtained with a purity of more than 99% were used to prepare dispersed WS_2 solution by dissolving into a mixture of ethanol and distilled water. The mixture solution was then treated using a high-power ultrasonic washer for about 2 hours to properly disperse the WS_2 into the solution. After this process, the dispersed WS_2 solution was left to settle for several hours. The large agglomerations of WS_2 particles were then removed by centrifuging the dispersed solution for 30 minutes at 3000 rpm. The upper supernatant was then collected for use in preparing SA device.

A micro-ball resonator (MBR) was then fabricated based on the soft-compress method. A spherical structure was formed at the tip of a standard single mode fiber (SMF) using a fusion splicer (Furukawa Electric Fitel S178A) whose parameters were manually modified for this purpose. In this work, a cleaved tip of the SMF is placed in one arm of the splicer and a series of arcs were then applied. The plasma arcs heated and partially melted the fiber tip to form a spherical shape due to surface tension after multiple arcing process. The diameter of microsphere formed can be controlled by the number of arcs applied on the fiber tip. Fig. 1(a) shows the MBR fabricated with 10 times of arcing. It has a stem and microsphere diameter of 125 and 200 μm, respectively.

The previously prepared WS_2 solution was then dropped over the microsphere structure and left to dry for few hours. The process was repeated three times to ensure the microsphere was fully covered with the WS_2 layer. To allow for coupling of light to and from the microsphere coated with WS2, a microfiber was fabricated using a customized flame brushing technique. The microfiber has a waist diameter of 8 μm. Fig. 1(b) shows the microsphere coated with WS_2, which was placed directly on the microfiber to form a resonator while allowing efficient coupling of light in or out of the MSR. This is attributed to the evanescent field of a phase-matched microfiber can be easily aligned to be overlap with the evanescent field of a WGM from the microsphere.

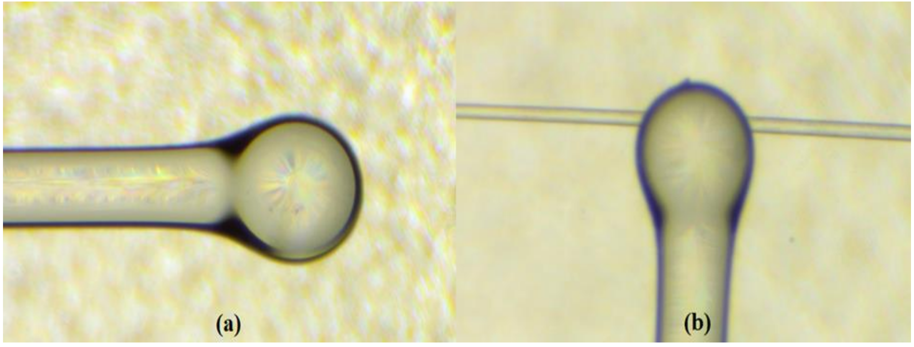

Fig. 1. Images of (a) bare microsphere (b) microsphere coated with WS2 attached on the microfiber to form MSR.

The proposed dual-wavelength Q-switched EDFL is based on a ring configuration as illustrated in Fig. 1. A 2.4 m long Erbium-doped fiber (EDF) with a cut-off wavelength of 950 nm and numerical aperture of 0.24 was deployed as a laser gain element. The EDF has an Erbium ion absorption of 90 dB/m at the pumping wavelength of 980 nm. It was pumped by a laser diode through a 980/1550 nm wavelength division multiplexer (WDM). The prepared microsphere coated with WS_2 was incorporated into the laser cavity via a microfiber to function as SA. A polarization insensitive isolator is used to ensure light to travel in one direction. 10% of the laser coming out of the 90/10 coupler was used to measure power and spectral characteristics of the Q-switched laser using an optical power meter (THORLABS, PM310D) and optical spectrum analyzer (OSA) with a resolution of 0.07 nm (ANRITSU, MS9710C), respectively. Meanwhile, the temporal characteristics of the laser in frequency and time domain was analysed using a 7.8 GHz radio frequency spectrum analyzer (ANRITSU, MS2683A) and a 350 MHz digital storage oscilloscope (GWINSTEK, GDS-3352), respectively via a 7-GHz InGaAs photodetector. The cavity of the ring laser was closed by splicing another port of coupler (90%) to the input signal port of WDM.

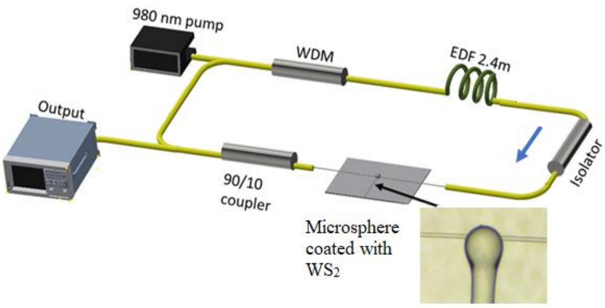

Fig. 2. The experimental setup for the dual-wavelength Q-switched laser with the microsphere coated with WS_2.

3. Result and discussion

Stable Q-switched pulses were noticed as the pump power was raised to the starting threshold of 104.6 mW. The threshold is relatively high due to the high cavity loss induced by the micro-sphere resonator (MSR). The Q-switching remained stable up to 145.8 mW pump power. However, the pulses became unstable and vanished with the further increase in pump power. The repetition rate was measured as from 72.4 kHz to 85.1 kHz with respect to the pump power from 104.6 mW to 145.8 mW, as shown in Fig. 3(a). The figure also shows that the pulse width reduces from 4.43µs to 3.47 µs as the pump power was changed within the same range. This is attributed to the dependence of population inversion with pump power. Higher pump power induced a higher population inversion to enhance the attainable gain and laser intensity in the proposed EDFL cavity. Subsequently, the rise and fall times of the pulses became narrower due to the saturation effect. The shorter pulse duration can be expected by reducing the total cavity length. The variation ranges of the output power and pulse energy are 6.9 mW to 11.2 mW and 95.7 nJ to 131.4 nJ, respectively as shown in Fig. 3(b). Both average output power and pulse energy increased linearly with the increase in pump power. This is caused by the increase of population inversion with the pump power. The slope efficiency was about 10.4%, which is relatively higher for a Q-switched ring fiber laser. This reveals that the insertion loss of the SA device is low.

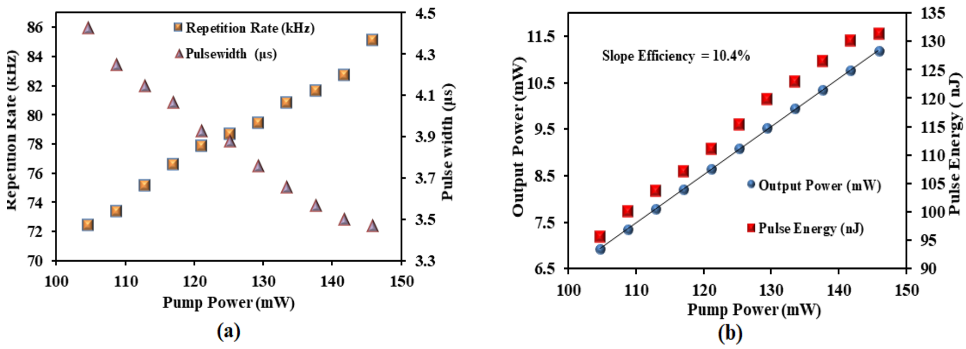

Fig. 3. (a) Repetition rate and pulse width (b) output power and pulse energy of Q-switched EDFL within 104.6 mW to 145 mW pump power.

Fig. 4(a) depicts the monitored output laser spectrum, from which one can clearly observe two wavelengths lased at about 1554.0 nm and 1560.7 nm. The optical signal to noise ratio of both wavelength is larger than 32 dB. The generation mechanism of the dual wavelength may be attributed to the MSR, which create an artificial filter in the cavity giving rise to dual wavelength generation. If absorption of light in the silica microsphere is minimal and scattering losses at the boundary of the microsphere are very low, then the input light photons can circulate on their orbit few thousand times before exiting the microsphere structure by loss mechanism. This long lifetime of the confined photons is associated to a long optical path length because of the resonant nature of the phenomenon. The interaction of WS_2 with the confined circulating light also provides a loss modulation inside the laser cavity for Q-switching operation.

Fig. 4 (b) shows a typical oscilloscope trace of the Q-switched pulse train at the pump power of 145.8 mW. It is also found that the Q-switching pulses was consistent, and no amplitude modulations can be detected in the pulse train, indicating that there is no self- mode-locking effect during the Q-switching activity. The peak-to-peak duration of the pulse train is measured to be around 11.8 µs, which corresponds to the repetition rate of 85.1 kHz. Fig. 4 (c) depicts the RF spectrum with resolution bandwidth of 3 kHz at 145.8 mW pump power. The repetition rate frequency is observed at 85.1 kHz with the signal-to-noise ratio (SNR) of 35.3 dB. The decrease in the intensity of higher order harmonics follows the typical Q-switched operation which is the opposite case to mode-locking (where the intensity is maintained at higher order harmonics). To eliminate the possibility of pulse generation using only MSR, or any nonlinear polarization rotation (NPR) affect within the cavity, the MSR was replaced with the bare MSR without WS_2 coating. Then, the pump power was increased to the maximum sustainable limit of laser diode being about 300 mW. There was no pulse observed over the oscilloscope within the pump power range of 0-300 mW by using the bare MSR. This indicates that there was no contribution of the bare MSR in the Q-switched operation.

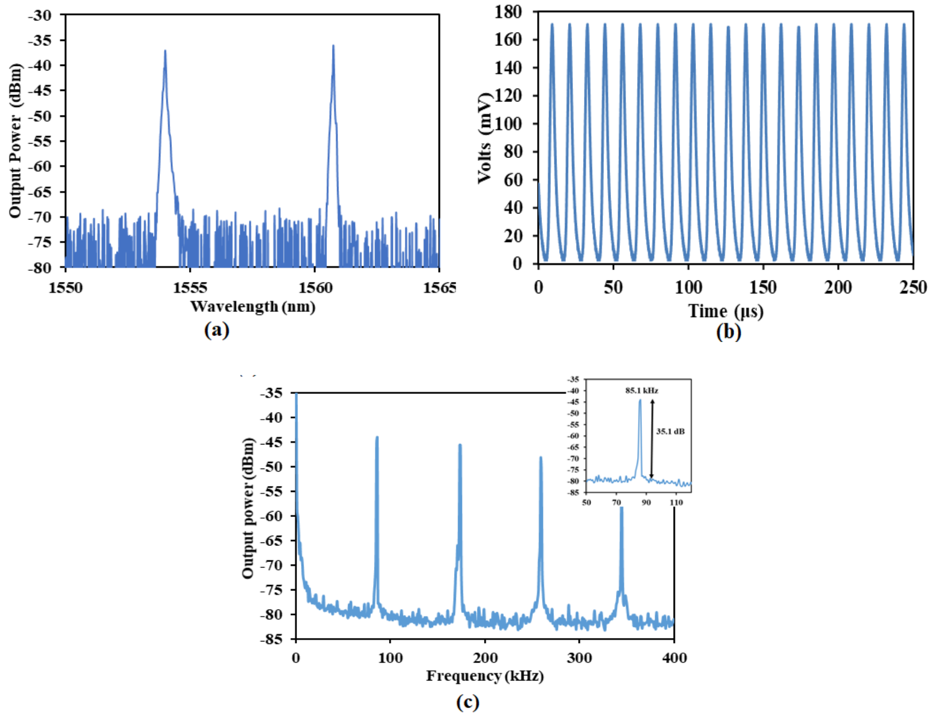

Fig. 4. (a) Output spectrum showing dual-wavelength operation (b) typical oscilloscope trace (c) RF spectrum at a pump power of 145.8 mW

5. Conclusion

WS_2 based SA has been successfully obtained by depositing WS_2 layer onto a MSR via drop-casting method. The MSR also functioned as a wavelength selective filter for realizing a dual-wavelength Q-switched operation at 1554.0 nm and 1560.7 nm. Stable pulse train is observed within pump power of 104.6 mW to 145.8 mW with maximum repetition rate of 85.1 kHz corresponds to shortest pulse duration of 3.47 μs. The maximum pulse energy of 131.4 nJ was obtained at 145.8 mW pump power. The dual-wavelength Q-switched laser has potential applications in airborne Lidar, environmental sensing, and terahertz generation.

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References

[1] W. Shi, Q. Fang, X. Zhu, R. A. Norwood, N. Peyghambarian, Applied Optics **53**, 6554 (2014).
[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] Y. Wang, C. Q. Xu, Progress in Quantum Electronics **31**, 131 (2007).
[5] 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).
[6] S. N. F. Zuikafly, F. Ahmad, M. H. Ibrahim, A. A. Latiff, S. W. Harun, Photonics Letters of Poland **8**, 98 (2016).
[7] N. A. Aziz, Z. Jusoh, M. Q. Lokman, M. Yasin, E. Hanafi, S. W. Harun, Digest Journal of Nanomaterials and Biostructures **12**, 325 (2017)
[8] S. N. F. Zuikafly, A. Khalifa, F. Ahmad, S. Shafie, S. W. Harun, Results in Physics **9**, 371 (2018)
[9] H. Song, Q. Wang, D. Wang, L. Li, Results in physics **8**, 276 (2018).
[10] S. Chen, B. Lu, Z. Wen, H. Chen, J. Bai, Infrared Physics & Technology **111**, 103519 (2020).
[11] G. Hu, L. Zhu, K. Chen, G. Chen, Z. Wang, G. Guo, Infrared Physics & Technology **117**, 103821 (2021).
[12] Z. T. Wang, Y. Chen, C. J. Zhao, H. Zhang, S. C. Wen, IEEE Photonics Journal **4**, 869 (2012).
[13] L. Pan, I. Utkin, R. Fedosejevs, Optics express **16**, 11858 (2008).
[14] A. A. A. Jafry, H. Arof, N. Kasim, Y. Munajat, R. Apsari, S. W. Harun, Nonlinear Optics, Quantum Optics: Concepts in Modern Optics **49**, 285 (2018).
[15] S. Omar, N. F. Zulkipli, A. A. A. Jafry, B. Musa, M. M. Ali, S. W. Harun, Z. Jusoh, M. Yasin, Chalcogenide Letters **17**, 99 (2020).