TUNGSTEN DISULFIDE COATED MICROFIBER AS SATURABLE ABSORBER FOR Q-SWITCHED PULSES GENERATION

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Q-switched fiber laser was demonstrated by using tungsten disulfide (WS_2) two-dimensional nanomaterials 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 microfiber to form a nanosheets layer. The WS_2 coated microfiber is inserted into the ring laser cavity configured with a 2.4 m long Erbium-doped fiber (EDF) as the gain medium to generate Q-switching pulses train operating at 1568 nm. The Q-switched laser produced a pulse train, which the repetition rate is tunable from 62.0 kHz to 78.0 kHz as the pump power is raised from 151 to 193 mW. The minimum pulse width of 4.72 µs and the maximum pulse energy of 20.5 nJ was obtained at 193 mW pump power. The generated Q-switching pulses are stable and thus it is suitable for use in many practical applications.

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1. Introduction

Passively Q-switched fiber lasers that typically provide large accumulated gain and high beam quality have received tremendous interest in recent years due to their many advantages including high flexibility and great durability against environmental changes. They offer great demands in applications like micro-cutting, laser spectroscopy, human tissue surgery as well as range finding [1-3]. These Q-switched lasers can be obtained via various active and passive methods. The passive technique via the use of saturable absorber (SA) is more desirable over the active technique as they are more simple, flexible and compact. Up to date, various SAs that able to facilitate Q-switched fiber lasers have been demonstrated, including semiconductor saturable absorber mirrors (SESAMs) [4], graphene [5] and carbon nanotubes [6]. SESAMs are widely used due to their flexibility and robustness. However, their applications are limited by narrow operating bandwidth and high fabrication cost. On the other hand, graphene has gained a better interest in recent years. This is due to its inherent capabilities that a single atomic layer of graphene can produce Q-switched pulses without the high costs and complexity as incurred by SESAMs. Besides, graphene based SAs also have their own advantages such as a very broad operational wavelength range and fast recovery times due to the gapless behavior of the graphene atomic layer [7]. Carbon nanotubes, which are created from graphene layers, additionally possesses the similar advantages as graphene. However, the absorption wavelength of the carbon nanotubes is strongly depended on the nanotube diameter, and thus the efficiency of this material is not really high.

On the other hand, another two-dimensional (2D) material, transition metal dichalcogenides (TMDs) have also drawn growing interest for photonics applications. This is

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attributed to their complementary electronic and optical properties, which are useful for short pulse generation [8-9]. TMDs can display metallic, semiconducting, and even super-conducting behaviors due to their layered materials. They have indirect band gap in bulk form and thus many works have been conducted to investigate its characteristic in mono-layered structure, where the band gap can be shifted from indirect to direct. The TMDs are generally have a layered structure with chemical formula of MX2. It comprises of stacked X-M-X slabs, where X and M represent chalcogen and transition metal element, respectively. These elements are strongly bonded in hexagonal order with a weak out-of-plane van der Waals interactions as a monolayer, while interlayer bonds are held together by the strong covalent bond [10]. These features are useful in fabrication of a new photonic devices in term of compactness, efficiency and flexibility.

When the input light intensity is high, the nonlinear absorption property can be changed from saturable absorption to reverse saturable absorption with a monolayer tungsten disulfide (WS_2). This is due to the broken opposite symmetry in the WS_2 structure, which cause the carrier mobility becomes higher and the orbital coupling becomes stronger. This characteristic is useful for photonic applications such as frequency comb spectroscopy, material preparation and lasers [11]. In this paper, a new Q-switched fiber laser is demonstrated by using a microfiber coated with tungsten disulfide (WS_2) as the SA device. The SA was fabricated by repeatedly dropping the WS_2 solution onto microfiber to form a nanosheets layer. The WS2 coated microfiber is then incorporated in the ring laser cavity to generate Q-switching pulsed laser operating at 1568 nm using a 2.4 m long Erbium-doped fiber (EDF) as the active medium.

2. Preparation and optical characterization of SAs

At first, fused optical microfiber was fabricated from a bare standard silica single mode fibers (SMFs) using a flame brushing technique. In the process, the heat from a butane-oxy flame was moved and brushed across a narrow region of the fiber while stretching the fiber using a computer-controlled stepper motor stage. During the heating and stretching process, a broadband light source was launched into the microfiber while monitoring the output using an optical spectrum analyzer (OSA) to control its loss and spectral response. The microfiber with a waist diameter of around 2.3 µm over a length of about 50 mm was successfully fabricated for this study. The microfiber was connected to un-tapered fiber via adiabatic, conical transitions at both ends. In this work, the linear WS_2 pristine flakes with purify of more than 99% was used. It was obtained by the liquid-phase exfoliation method [12]. The WS_2 flakes was dissolved by mixing with ethanol and distilled water before it was treated by a high power sonification process for 120 min. 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 microfiber as illustrated in Fig. 1 and then dried using air dryer. This step was repeatedly done until it formed WS_2 nanosheets layer surrounding the microfiber region. Inset of Fig. 1 shows the microfiber, which was coated by the WS_2 layer.

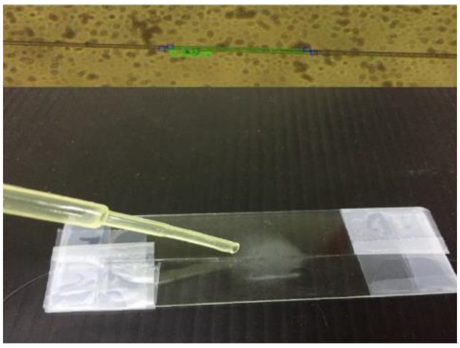
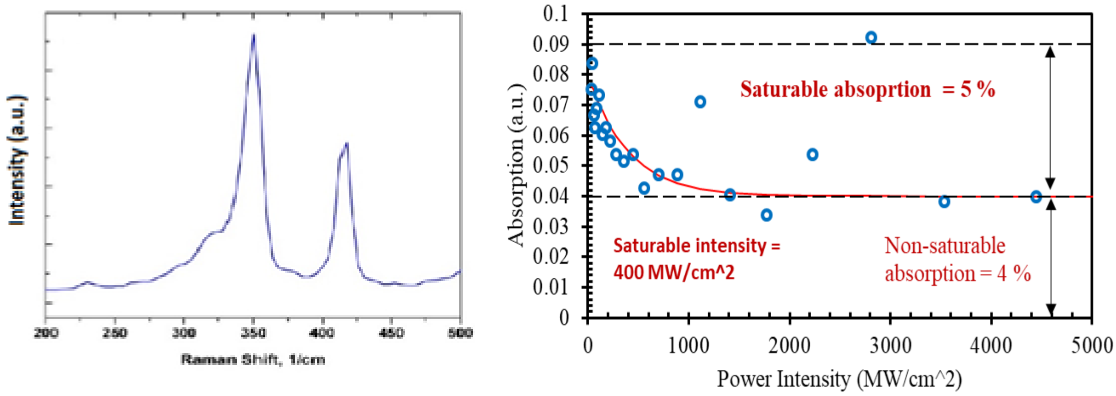


Fig. 1. Preparation of SA from the WS2 flakes solution by dripping the SA solution onto a microfiber using a pipette. Inset shows an image of the microfiber after the drying process.

Fig. 2 (a) illustrates the Raman spectrum of the deposited WS_2 nanosheets layer. The Raman spectroscopy employed Argon ion laser operating at 514 nm as a light source. The Raman spectrum shows two peaks at 350.8 and 420.7 cm^{-1} band, which are assigned to the in-plane (E_{2g}) and out-of-plane (A_{1g}) vibrational modes of WS_2, respectively. The nonlinear saturable absorption of the WS_2 SA was also measured using a balanced twin-detector measurement system based on a power-dependent absorption technique. In the measurement, a stable homemade passively mode-locked fiber laser at 1560 nm was used as the input light source. The laser operated at a repetition rate of 26 MHz and pulse width of 600 fs. The output powers from both arms with and without the SA device were recorded by different detectors as we gradually decreased the attenuation value. Fig. 2(b) illustrates the measurement curve and its curve fitting as the absorption was plotted at various input intensities. As shown in the figure, the saturable absorption or modulation depth was obtained at 5.0 % while the saturation intensity was 400 MW/cm^2. This result indicates that the developed WS_2 SA can be used for pulsed laser generation.



(a) *(b)*

Fig. 2. Optical characteristics of the WS_2 SA (a) Raman spectrum of WS_2 nanosheets layer after the solution was used to form a thin film to cover the microfiber (b) Nonlinear saturable absorption profile of the WS_2 SA.

3. Experimental setup

Fig. 3 shows the schematic diagram of the proposed all-fiber Q-switched Erbium-doped fiber laser (EDFL) with a microfiber coated with tungsten disulfide (WS_2) as the SA device. The laser cavity composed of 2.4 m long erbium-doped fiber (EDF), which was pumped by 980 nm laser diode via a wavelength division multiplexer (WDM), an optical isolator, the prepared WS_2 based SA and a 10 dB output coupler. The EDF used has an absorption of 24 dB/m at 1550 nm, which equavalent to 2000 ppm Erbium concentration and a numerical aperture of 0.24. The isolator was used to ensure the unidirectional operation of the ring cavity. The output laser was tap out from the 10% port of output coupler while allowing 90% of the laser to oscillate in the cavity. The microfiber coated with WS_2 nanosheets layer was used as a SA device and it was incorporated into the cavity to act as a Q-switcher. The optical spectrum was measured by an optical spectrum analyzer (Yokogawa, AQ6370B) with the resolution of 0.02 nm. The pulse information was analyzed using a 350 MHz oscilloscope (GWINSTEK: GDS-3352) in conjunction with a 1.3 GHz photodetector (Thorlabs, DET10D/M). The laser output was measured by an optical power meter while the radio frequency (RF) spectrum was measured by a RF spectrum analyzer.

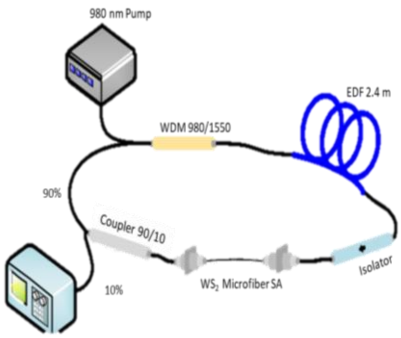


Fig. 3. Configuration of the Q-switched fiber laser with a microfiber coated WS_2 as SA.

4. Results and discussion

The EDFL starts to operate in continuous wave (CW) mode as the pump power was increased above the threshold value of 34 mW. The threshold is slightly high mainly due to the large loss of the WS_2 coated on microfiber, which was used as SA. After the pump power reaches 151 mW, Q-switched pulses train comes out and its operation is maintained up to the pump power of 193 mW. However, the Q-switched pulses diminish as the pump power is increased above 193 mW. Fig. 4(a) shows the output optical spectrum for the Q-switched pulses emitted from the EDFL at pump power of 193 mW. As shown in the figure, the Q-switched EDFL operates at wavelength of 1568 nm with the 3-dB spectral width of approximately 1.4 nm. The spectrum broadening is observed due to the self-phase modulation (SPM) effect in the laser cavity.

Fig. 4(b) shows typical oscilloscope trace of the Q-switched laser at 193 mW pump power. It indicates a pulse period of 12.8 μs while a single pulse envelop is showing a pulse width of 4.72 μs. Fig. 4(c) shows the corresponding RF spectrum, which indicates a pulse repetition rate of 78.0 kHz, matching the pulse period of 12.8 μs. The signal-to-noise ratio (SNR) of the fundamental frequency is ~55 dB, indicating the small fluctuations of pulse amplitude and good Q-switching stability. The microfiber coated with WS_2 was then changed with a new clean microfiber to investigate the effect of WS_2 on the Q-switching operation. However, there are no pulses observed on the oscilloscope trace even when the pump power was adjusted over a wide range. This result verified that the WS_2 SA is the key component for realizing the Q-switching operation of the laser.

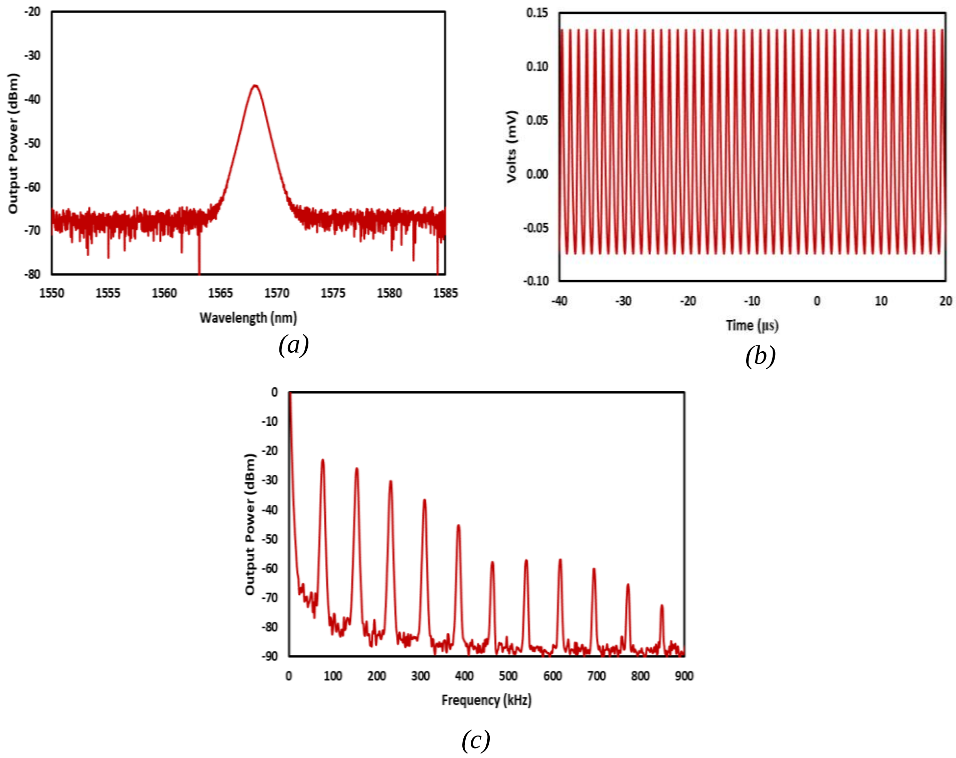
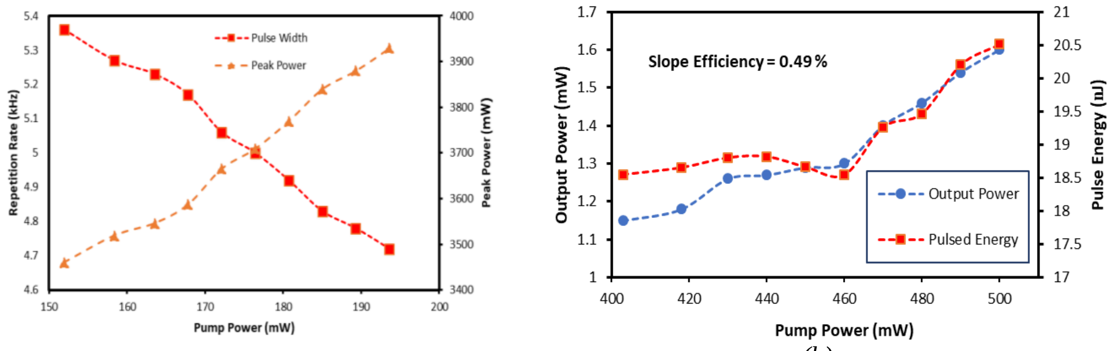


Fig. 4. Spectral and temporal characteristics of the proposed Q-switched EDFL with WS_2 SA when the pump power is fixed at 193 mW (a) Output spectrum (b) Typical oscilloscope trace (c) RF spectrum

The evolution of the repetition rates and pulse width along with the increasing pump power is shown in Fig. 5(a). As the pump power is raised from 151 to 193 mW, the repetition rate increases from 62.0 to 78.0 kHz and the pulse width decreases from 5.36 to 4.72 μs. This is the typical characteristic of passively Q-switched fiber laser. When the pump power increases above 193 mW, the pulse becomes unstable and diminish. This may be the result of cavity design. While the pump power is decreased, the Q-switched pulse reappears indicating that the SA is not destroyed. It is also observed that the Q-switched pulse output is stable at every pulse repetition rate and pump power, where no amplitude modulations are observed in these pulse trains. This indicates that there is no self-mode locking (SML) effect during the Q-switching operation. The pulse duration is strongly depended on the modulation depth of the SA and the cavity design of the Q-switched laser. Subsequently, the pulse width in this experiment could be narrowed by improving the SA fabrication and shortening the cavity length.

Fig. 5 (b) shows the average output power and single pulse energy against the pump power for the Q-switched EDFL. An shown in the figure, both output power and pulse energy increased as the pump power is raised. The output power reached 1.6 mW at a maximum pump power of 193 mW while the the maximum pulse energy is calculated to be 20.5 nJ. The slope efficiency of the laser was around 0.49%.



(a) *(b)*

Fig. 5. Q-switching performance for the WS_2 based EDFL (a) Repetition rate and pulse width as functions of pump power (b) Output power and single pulse energy as functions of pump power.

5. Conclusions

WS_2 based SA has been successfully obtained by coating a microfiber with WS_2 nanosheets layer via drop-casting method. The SA was incorporated into an EDFL ring cavity to function as a Q-switcher and generates Q-switching pulse train. A stable self-starting pulse train operating at 1568 nm was obtained at threshold pump power of 151 mW. The Q-switched EDFL produced a pulse train with repetition rate tunable from 62.0 kHz to 78.0 kHz while pulse width can be narrowed from 5.36 μs to 4.72 μs as the pump power is raised from 151 to 193 mW. The maximum pulse energy of 20.5 nJ was obtained at 193 mW pump power.

Acknowledgements

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