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Microsecond pulse erbium-doped fiber laser using WS_2 deposited on D-shaped fiber fabricated by polishing wheel technique

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Abstract. We demonstrate a stable Q-switching pulse train output centered at 1561 nm by implementing D-shaped fiber deposited tungsten disulphide (WS_2) as a saturable absorber in erbium-doped fiber laser. D-shaped fiber was fabricated using a polishing wheel technique with two stages polishing. Proposed Q-switched EDFL generates a maximum repetition rate of 47.28 kHz at a pulse duration of 5.4 µs. Under pump power of 104.6 mW, the laser consumed pulse energy of 99.4 nJ with an output power of 4.7 mW. This WS_2-D-shaped SA is excellence for the production of Q-switched laser source.

1. Introduction

A laser operating at microsecond to nanosecond pulse duration (Q-switched) is essential for various applications in industry. Conversion of continuous-wave into energetic short pulses is dependable on a nonlinear optical element called saturable absorber (SA). Passively Q-switched is first demonstrated using semiconductor saturable absorber mirrors (SESAMs). However, SESAMs has narrow tuning range due to the limited wavelength spectrum and complex fabrication method [1]. Thus, an all-fiber laser is introduced with the implementation of various materials as a SA such as carbon nanotubes (CNTs), graphene, topological insulators (TIs), and transition metal dichalcogenides (TMDs) including several others [2-6]. The all-fiber laser has shown excellence lasing performance due to compact structure, high-quality optical pulses and adjust-free configuration [7].

Among all materials, TMDs exhibit excellent saturable absorption due to the sizable band gap structure from bulk to 2-dimensional (2D) [8]. For instance, bulk-tungsten disulphide (WS_2) has an indirect band gap (1.3 eV) which can be engineered to form 2D-WS_2 with direct band gap (2.1 eV) [9]. Recently, it is proven that nano-sheets WS_2 exhibit high second order susceptibility and saturable absorption [10]. In addition, superior properties of monolayer WS_2 including high carrier mobility and strong orbit coupling [11] make it a suitable saturable absorber for the generation of Q-switched pulse laser.

There are two ways to implement SA into all-fiber laser cavity; sandwiching thin film structure in between fiber-ferrule and implementing SA material on a special fiber such as D-shaped fiber, microfiber and photonic-crystal fiber. The first technique has few disadvantages including limited nonlinear interaction length between material and light [12] as well as inducing mechanical and thermal damage to the end face of fiber connector [13]. Therefore, the mechanism of evanescent field interaction between light and material is introduced using D-shaped fiber. D-shaped fiber has a long nonlinear interaction length and high optical damage threshold which makes it superior for the generation of Q-switched [14]. Passively Q-switched fiber laser is introduced with the implementation of WS_2 on D-shaped fiber as a saturable absorber for erbium-doped fiber laser.

2. Preparation of D-shaped fiber deposited WS_2

ASE source was launched into single mode optical fiber (CORNING SMF-28) with core/cladding diameter of 9/125 μm while optical power meter (THORLABS) was connected at the other end to observe the insertion loss of the polished fiber. Single mode optical fiber was clamped using fiber holder at both ends to ensure less vibration during polishing. Rotating wheel with 5V DC motor was set up with 800-grid sandpaper and 1500-grid fine sandpaper pasted around the wheel. D-shaped fiber was polished using 800-grid sandpaper until desired insertion loss was obtained on optical power meter. The D-shaped fiber was then polished by 1500-grid fine sandpaper for 15 minutes. Two stages polishing were carried out to ensure that the polishing surface is smooth thus allowing good propagation of light inside the D-shaped fiber. D-shaped fiber has insertion loss of 3 dB, length of 1.8 mm and diameter of 64 μm. Experimental setup for D-shaped fiber fabrication technique is shown in Figure 1. WS_2 used was bought from Graphene Supermarket. A 3 μL WS_2 solution was dropped on D-shaped fiber polished surface using micropipette (EPPENDORF) with 10 mW laser diode pump launched into the laser cavity.

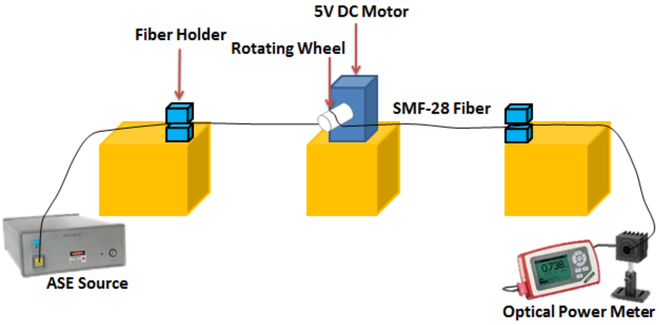

Figure 1. Experimental setup for D-shaped fiber polishing technique

3. Erbium Doped Fiber Laser Ring Cavity

Passively Q-switched erbium-doped fiber laser was generated using the setup as shown in Figure 2. A 980 nm laser diode was launched into 980/1550 nm wavelength division multiplexer (WDM). Pumped light was then propagated into 2.8 m erbium-doped fiber with an absorption coefficient of 23 dB/m, core diameter of 4 μm and numerical aperture of 0.16. The light was then directed into isolator to ensure unidirectional operation in the laser cavity. D-shaped fiber deposited WS_2 was placed inside the ring cavity and the light was then propagated to 90/10 coupler, where 90% of the light was allowed to propagate back inside the ring cavity. 10% of light was used for analysis purposes. Optical spectrum analyzer (YOKOGAWA, AQ6370D) with a resolution of 0.02 nm and optical power meter (THORLABS) was used to characterize output signal. A 350 MHz digital oscilloscope (GWINSTEK, GDS-3352) and 9 kHz-7.8 GHz RF spectrum analyser (ANRITSU, MS2683A) connected via a 1.2-GHz InGaAs photodetector were used for temporal characteristics analysis.

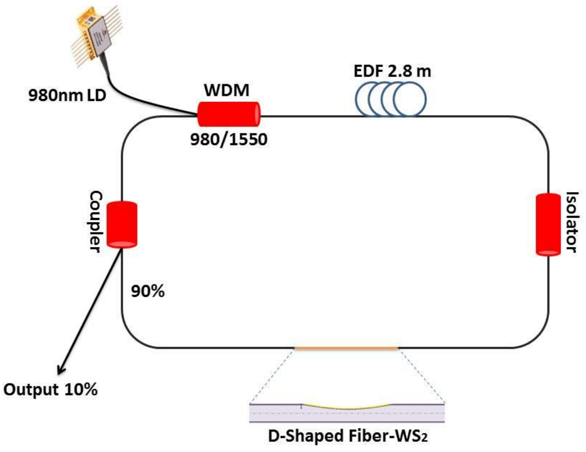

Figure 2. Experimental setup for Q-switched erbium-doped fiber laser using WS_2-D-shaped fiber as saturable absorber.

4. Result and Discussion

The laser cavity starts to generate Q-switched at pump power of 63.4 mW. Figure 3(a) shows continuous-wave spectrum centered at 1567 nm. Center wavelength shifted to shorter spectrum, 1561 nm when D-shaped fiber deposited WS_2 was incorporated into the laser cavity. This indicates lasing operation of developed laser cavity. Oscilloscope trace of Q-switched at pump power of 88 mW was shown in Figure 3(b) with inset of single pulse at the same pump power was also plotted. It is observed that the pulse generated has a full-width half maximum (FWHM) of 6.4 µs. RF spectrum shown in Figure 3(c) exhibit signal-to-noise ratio (SNR) of 52.06 dB which indicates stability of the pulses generated.

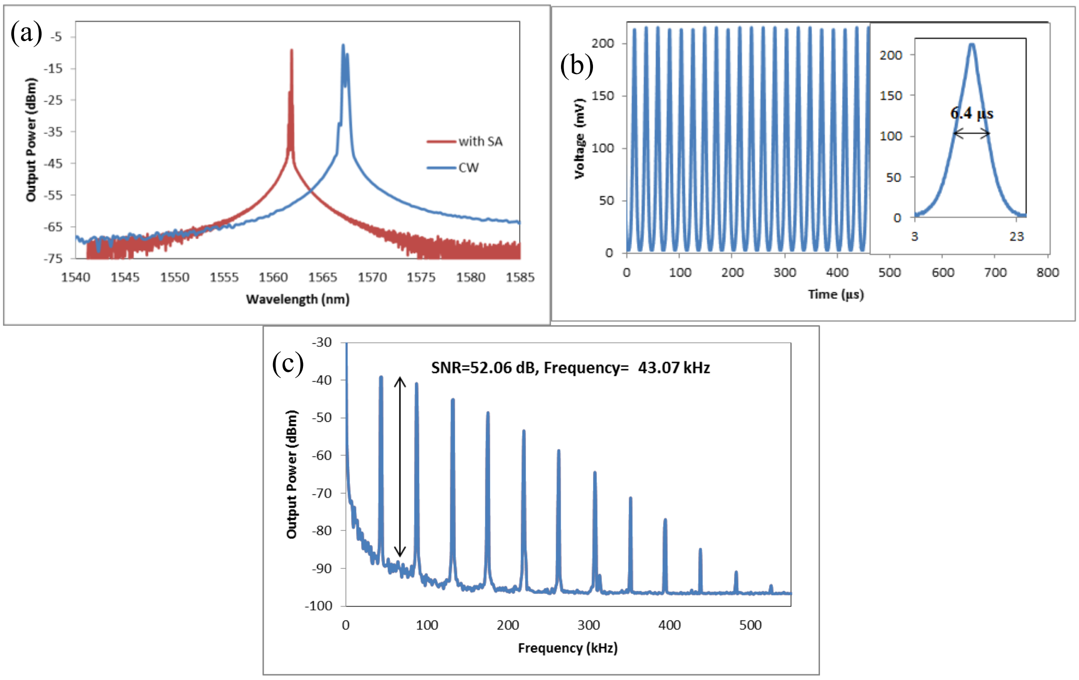

Figure 3. Spectral and temporal performances of the Q-switched laser at 88 mW pump power. (a) Output spectrum. (b) Typical oscilloscope trace with two pulses envelops (c) RF spectrum.

Self-started Q-switching visible at the input pump power of 63.4 mW and disappeared above pump power of 104.6 mW. As the pump power increased from 63.4 mW to 104.6 mW, the repetition rate of the pulses increases from 39.22 kHz to 47.28 kHz whereas the pulse width decrease from 8.1 µs to 5.4 µs. The relationship between pulse width and repetition rate with pump power was shown in Figure 4(a). Figure 4(b) shows measured output power which was 3.5 mW to 4.7 mW plotted against pump power. Whereas, calculated pulse energy from 88.73 nJ to 99.40 nJ was also shown in Figure 4(b).

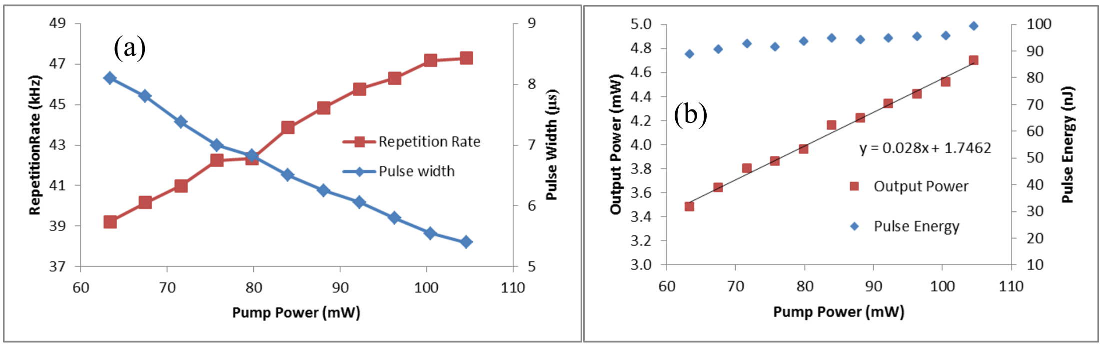

Figure 4. Q-switching performance (a) Repetition rate and pulse width against pump power (b) Output power and pulse energy against pump power.

5. Conclusion

We present Q-switched erbium-doped fiber laser with WS_2 deposited on D-shaped fiber incorporated into laser cavity as a saturable absorber. D-shaped fiber was prepared by polishing wheel technique with improved two stages polishing to ensure efficient light-matter interaction inside D-shaped fiber. With an appropriate amount of WS_2 deposited onto D-shaped fiber, stable Q-switched was initiated within 63.4 mW to 104.6 mW. The generated pulses exhibit the highest repetition rate of 47.28 kHz and the shortest pulse width of 5.4 µs. SNR measured was 52.06 dB indicating the stability of the laser. The maximum pulse energy generated was 99.4 nJ corresponds to pump power of 104.6 mW.

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