Passively Q-switched Erbium-doped Fiber Laser using Tungsten Disulfide deposited D-shaped Fiber as Saturable Absorber

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Abstract. This paper generates a stable Q-switching output wavelength 1560 nm by utilizing tungsten disulfide (WS₂) as saturable absorber on D-shaped fiber in erbium-doped fiber laser. D-shaped fiber was prepared by using polishing wheel technique with rough and fine polishing is conducted to ensure efficient light-matter interaction inside D-shaped optical fibre. Proposed Q-switched erbium-doped fiber laser generates shortest pulse duration of 3.25 μs with repetition rate of 108.90 kHz. Q-switched generated was stable under pump power of 84.02 mW to 182.92 mW. Obtaining signal-to-noise ratio of 40.58 dB, Q-switched induced contain pulse energy of 14.60 nJ with output power of 0.64 mW to 1.59 mW. Therefore, proposed D-shaped fiber-WS₂ as saturable absorber was stable and efficient for making a portable laser source based on Q-switched.

1. Introduction

The avalanche development in the short-pulse laser had attracted tremendous research interest in recent years. Thanks to their usefulness in numerous industrial applications, including corrective eye surgery [1], material cutting technology [2], and micromachining of material [3], vast research efforts were conducted to make them faster and efficient. That attempt includes the development of a well-aligned laser configuration to reduced power loss and the incorporation of a material as a pulse initiator to induce a short pulse laser. The ability of the first method requires a few complicated steps involving lens arrangement, careful laser beam confinement, and harmful to eyes as well. In contrast, the latter which manipulates nonlinear optical properties of a material is an eye-safe approach with ease of preparation, which makes it favorable to emit short-pulse laser for various applications. This method configured an all-fiberized laser cavity with a low signal loss, which makes a bunch of photons confined in an optical fiber before they were absorbed by a saturable absorber (SA). Further, the SA modulate the loss and release the light to trigger a train of short pulse in the microsecond to nanosecond pulse duration.

The modulation of loss (Q-factor) triggered by a SA was called a Q-switched. The Q-factor of a laser modulator was express via the ability of a SA to realized pulsed generation in a broad optical
bandwidth and a fast response time. In 2004, carbon nanotube (CNT) was utilized as a SA in an all-fiberized laser cavity [4]. It seems promising with excellent optical and physical properties such as ultrafast recovery time, high optical damage threshold, and polarization-insensitive SA. However, chirality and shape-dependent bandgap have always been a limitation for CNT. Several geometry adjustments were needed to expand its operational wavelength in a near-infrared spectrum. Later, Bao et al. demonstrated a pulsed laser via the incorporation of graphene as a SA [5]. Graphene owns an ultrafast relaxation time (~200 fs) and bandgap independent operation as it is a zero-bandgap semi metal. Despite its excellencies, graphene possesses a low modulation depth, which leads to weak second-order susceptibility during pulsed generation [6].

Hence, other 2-dimensional materials were introduced to replace graphene such as topological insulator, black phosphorus, and transition-metal dichalcogenides (TMDs). TMDs comprise of one transition metal element sandwiched between two chalcogenide ions. They were profoundly incredible with fast response time, and a strong second harmonic generation denotes excellent nonlinear absorption properties in the laser cavity. Tungsten disulfide (WS₂) is one of TMDs which was frequently investigated to perform as a suitable SA for wide near-infrared window (1-, 1.55- and 2-μm) [7]. It mimics the physical properties of graphene, such as high charge-carrier density, and strong orbit coupling with the ability to undergo frequency doubling effectively, therefore it was better than graphene.

Here, we demonstrated WS₂ coated D-shaped fiber as a SA in an erbium-doped fiber laser (EDFL) cavity. Unlike thin film as SA, D-shaped fiber revealed a long nonlinear optical response between light and material. Thus, it introduced a SA device with high saturable absorption ability and optical damage threshold. The mechanical and thermal stability of the proposed SA was also excellent as we eliminate the parasitic reaction, which was usually induced by a fiber-ferrule [8]. The absence of fiber-ferrule produced an all-fiberized laser cavity without any optical fiber adapter and pigtail, thus decrease splice loss within the cavity. In this work, we obtained a Q-switched EDFL using WS₂ coated D-shaped fiber with a pulse width of 3.25 μs corresponds to a repetition rate of 108.90 kHz. A step-by-step fabrication of the D-shaped fiber was also elaborated to established excellent evanescent field interaction between light and material.

2. Experimental setup

To fabricate the D-shaped fibers, a two-stage polishing process is employed which is adopted from the report by Ahmad et al. [9]. While they were using different polishing depth to indicate the amount of core removed, our technique further improves the process by incorporating a more efficient two-stage polishing method using rough and fine sandpapers. The first stage involves polishing with a rough 600-grid sandpaper followed by a fine sandpaper of 3000-grid. Figure 1 shows the set-up of the polishing wheel technique used to fabricate D-shaped fibers.
In this set-up, a standard single-mode optical fiber (Corning SMF-28) with core and cladding diameters of 9 and 125 μm, respectively are used to produce D-shaped fibers. The protective jacket of the fiber is removed for approximately 3 mm and then fixed with two fiber holders. The fiber’s vibration is kept at minimum during the polishing by maintaining a good tension between the fiber holders. Insertion loss during the polishing process is monitored using the optical power meter (THORLABS, PM 100D). Initially, the stripped part is polished with 600-grid sandpaper until desired insertion loss is observed on the optical power meter. The process normally takes about three minutes to complete. Then, the rotating wheel is adjusted so that the polished region is in contact with 3000-grid fine sandpaper and the fine polishing is conducted for five minutes. Note that, in producing the D-shaped fibers, a careful observation needs to be made as to ensure the interaction between light and material are maximized which in turn will results in a good lasing performance of the generated Q-switched pulses. The fine polishing stage is very crucial to establish efficient light-matter interaction via evanescent field inside D-shaped fiber during lasing. A typical D-shaped fiber fabricated using this method has a length of about 1500 mm with the diameter of around 97.33 μm. The insertion loss recorded for these fibers is about 3 dB.

![Cavity arrangement for the generation of Q-switched erbium-doped fiber laser.](image)

The laser cavity of the proposed Q-switched fiber laser is depicted in Figure 2. A 980 nm laser diode is used to pump the cavity through a 980/1550 nm wavelength division multiplexer (WDM). A 2.4m erbium-doped fiber (EDF) is introduced in the cavity as a gain medium to generate 1.55 μm region pulse fiber laser. The EDF used 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. An isolator is included in the cavity to ensure unidirectional light propagation in which the interactions with D-shaped fiber coated WS2 to produce Q-switched pulse laser. The fabricated saturable absorber (SA) is optimized by repeatedly depositing 3 μL WS2 solution by means of micropipette on D-shaped fiber until stable pulses are generated on the digital oscilloscope. WS2 solution was bought from Sigma Aldrich Malaysia. A 90:10 optical coupler is used to couple out 10% of the light for analysis while another 90% of the light is allowed back to the cavity. Total length of developed erbium-doped fiber laser cavity is 13.8 m. The output characteristics of the fiber laser are monitored by a digital power meter and an optical spectrum analyzer (YOKOGAWA, AQ6370D) with resolution of 0.02 nm. Temporal laser characteristics are measured 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.
3. Result and discussion

Figure 3(a) shows a typical pulse train displayed on the oscilloscope at pump power of 51 mW. A stable pulse train is obtained within the pump power region of 84.02 mW to 182.92 mW. The enlarged two pulses enveloped of the pulse train indicates the pulse width of 5.25 μs with a pulse duration of 9.2 μs. It is also observed that the Q-switched output is stable with no observable amplitude modulation in the pulse train, indicating the absence of self-mode-locking during the Q-switching operation. The output spectrum of the Q-switched laser at the pump power of 182.92 mW was shown in Figure 3(b), indicates that the laser operates at a wavelength of 1560 nm. The repetition rate of the fundamental pulses is measured as 182.92 kHz with a signal to noise ratio (SNR) of about 38.89 measured using an RF spectrum analyzer with the 10MHz span.

![Figure 3](image)

**Figure 3.** Temporal and spectral characteristics of the WS\textsubscript{2} based Q-switched EDFL; (a) typical pulse train, (b) output spectrum, and (c) RF spectrum with a 10 MHz span.

Lasing performance of Q-switched induced by D-shaped fiber-WS\textsubscript{2} implemented in EDFL is investigated over a variation of input pump power. As depicted in Figure 4 (a), by tuning the pump power within 84.02 mW to 182.92 mW, the pulse duration of 5.25 μs to 3.25 μs captured, while the repetition rate increases. The behavior of the repetition rate and the pulse width indicates typical features of passively Q-switched laser. Within the same pump power, Q-switched pulses record repetition rate of 77.16 kHz to 108.90 kHz. As shown in Figure 4 (b), output power recorded by our ring cavity shows promising performance within the attainable pump power which is from 0.64 mW to 1.59 mW. Those values exhibit maximum pulse energy of 14.60 nJ within the same range of pump power which is also plotted in Figure 4 (b). By referring to the graph of output power as a function of pump power, 1 % of slope efficiency is obtained from generated Q-switched using D-shaped fiber-WS\textsubscript{2} as SA. This is attributed to the excellence configuration of the ring cavity and the effectiveness of D-shaped fiber-WS\textsubscript{2}.
as a SA. Finally, peak power obtained by varying the pump power from 84.02 mW to 182.92 mW is comparable to other passively Q-switched EDFL which is from 1.53 mW to 4.56 mW as shown in Figure 4 (c).

![Figure 4. Q-switching performances (a) Repetition rate and pulse width against pump power (b) output power and pulse energy as a function of pump power, and (c) peak power as a function of pump power.](image)

4. Conclusion
Generating Q-switched EDFL was successfully demonstrated using a reliable D-shaped fiber-WS$_2$ as saturable absorber. Side-polished technique with rough and fine polishing is conducted to ensure efficient light-matter interaction inside D-shaped optical fibre and coarse efficient light-WS$_2$ interaction via evanescent field to ensure good propagation of light inside ring cavity. Stable pulse train is observed within pump power of 84.02 mW to 182.92 mW with maximum repetition rate of 108.90 kHz corresponds to shortest pulse duration of 3.25 $\mu$s. With maximum pulse energy of 14.60 nJ, Q-switched pulses exhibit maximum output power of 1.59 mW. Stability of Q-switched EDFL is proven with SNR of 38.89 dB. D-shaped fiber with insertion loss of 3 dB has obtained diameter of 97.33 $\mu$m which is suitable for making a portable, robust and stable Q-switched laser source. This result showed Q-switched lasers can be realized by utilising the WS$_2$ based SA inappropriate cavity design.

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