

Graphene Oxide saturable absorber for generating eye-safe Q-switched fiber laser

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Abstract. This paper reports the generation of Q-switched fiber laser using thulium doped fiber (TDF) as a gain medium and graphene oxide (GO) as a saturable absorber (SA). The GO powder is embedded into polyvinyl alcohol (PVA) to form an SA film based on a drop-casting technique. GO-SA film is sandwiched between two fiber connectors and tighten by FC adapter before it is incorporated into an TDF laser cavity for Q-switching pulse generation. At 344 mW pump level, a stable Q-switching regime presence at 1943 nm with a 3-dB spectral bandwidth of 9 nm. The maximum repetition rate, pulse width, and pulse energy are at 25 kHz, 4.2 μ s, and 0.68 μ J, respectively. All finding results are comparable with other reported pulse fiber lasers.

1. Introduction

Q-switched thulium doped fiber laser (TDFL) operating at 2 μ m region have gained many research interests in recent years due to their wide range of potential applications in the fields such as medicine, remote sensing and LIDAR. The TDFL operates at wavelengths near atmospheric transparency window of 2 μ m with a broad emission spectrum ranging from 1.8 μ m to 2.1 μ m. Basically Q-switched laser can be obtained by either active or passive methods [1-3]. The active method normally requires the insertion of bulk modulator such as acoustic-optic and electro-optic modulator into the laser cavity, thus make the laser configuration complex and expensive. Passively Q-switched fiber lasers serve many advantages over the active one including low cost, simplicity and flexibility. Previously, several saturable absorbers (SAs) have been reported to operate at the 2 μ m wavelength including crystal of Cr²⁺: ZnSe, semiconductor saturable absorber mirror (SESAM). However, the crystal SAs required an additional component to couple the light into the fiber, which conceding the key benefit of the compactness of the fiber. Even though SESAMs are widely commercialized and matured in the field, however it is considered to be expensive, narrow bandwidth operation and complex in device fabrication especially for 2 μ m wavelength operation. Recently, carbon materials such as carbon nanotubes (CNTs) and graphene show promising performances as saturable absorber (SA). For CNTs, it is required to control the diameter of nanotubes for obtaining saturable absorption in the desired wavelength [4]. Graphene is



a dirac two-dimensional nanomaterial which offers high performance saturable absorption characteristics with wide band operation from visible to near infrared region, ultrafast recovery time and low non-saturable loss [5]. The chemical synthesis of graphene oxide (GO) is cheaper than that of the pure graphene and thus it can serve as an alternative SA material with ultra-fast relaxation and strong nonlinear saturable absorption. GO also has inherent advantages such as good solubility in water and easy in fabrication [6].

Thulium doped fibers (TDFs) have a very broad emission spectrum, which spanning the wavelength range from 1700 nm to 2100 nm [7, 8]. It can provide great flexibility in the operating wavelength and serve as an excellent pump wavelength for nonlinear frequency conversion to the mid-infrared wavelength [9]. Recently, there are also several reports on generating of Q-switching pulse using graphene based saturable absorber [10-12]. In this paper, a Q-switched TDFL is demonstrated by using GO SA as a Q-switcher. The Q-switched laser produces pulse train, which repetition rate can be tuned from 15.76 kHz to 25.08 kHz as the pump power increases from 344 to 491 mW.

2. Fabrication and Characterization of GO SA

For constructing the GO based SA, the first step is to produce graphene flakes by using electrochemical exfoliation process. During the exfoliation process, a pair of electrodes was placed in electrolyte. When electrical potential was applied between the electrodes, the negative ion move towards anode while the positive ion to the cathode. This results in the loosening of the graphene layers from the graphite rod. The exfoliation process continues for two hours to obtain a stable graphene suspension in the sodium dodecyl sulfate (SDS) solution. The stable graphene suspension was centrifuged at 3000 rpm for 30 minutes to remove large agglomerates. Afterwards, the supernatant portion of the suspension was decanted. The graphene obtain from the electrochemical exfoliation was then mix with PVA solution at the ratio of 1:4 with drop casting technique for SA film. Then the solution was dried in the petri dish at room temperature to obtain free standing film with thickness of around 50 μm . The nonlinear absorption properties of GO SA was investigated by two level SA model. Figure 1 shows the absorption profile of GO SA. These data are fitted based on a simple two-level SA model [13];

$$\alpha(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}$$

where $\alpha(I)$ is the absorption, α_s is the modulation depth, α_{ns} is the non-saturable absorption, I_{sat} is the saturation intensity, and I is the input intensity. From the analysed graph, the value of modulation depth, non-saturable absorption, and saturation intensity obtained to be 11 %, 9 % and 1.3 MW/cm^2 , respectively.

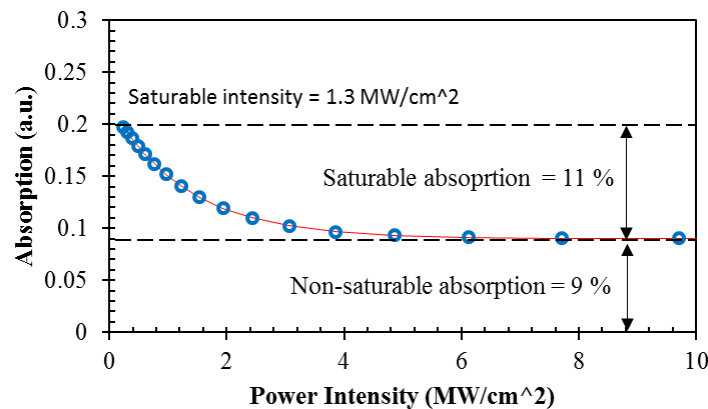


Figure 1. The nonlinear absorption profile of GO.

3. TDFL Configuration

The Q-switching pulse is generated using a TDFL ring cavity as shown in Figure 2. It uses a 5-m-long TDF as a gain medium, which is forward pumped by 1550 nm erbium–ytterbium doped fiber laser via 1550/2000 nm wavelength division multiplexer. The TDF used has numerical aperture of 0.15, core and cladding diameters of 9 and 125 μm , respectively, loss of less than 0.2 dB/km at 1900 nm, and peak core absorption at 1180 and 793 nm are 9.3 and 27 dB/m, respectively. The isolator is used for unidirectional laser propagation and maintain its direction. The Q-switched laser was measured on the 10% output coupler, and the remaining 90% of output coupler used as a feedback for laser oscillated in the ring cavity.

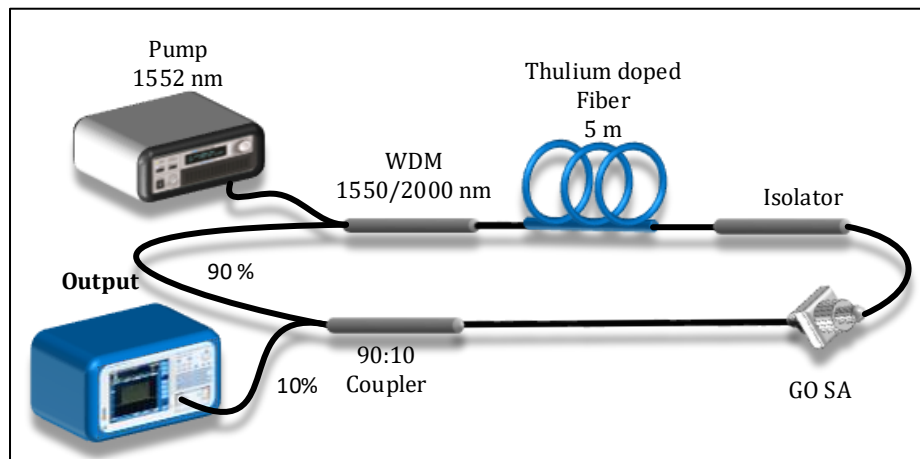


Figure 2. The experiment setup of Q-switched TDFL using GO SA.

The 1 mm x 1 mm GO film was sandwiched with a pair of fiber ferrule. Index matching gel was used as an adhesive and also as an element to reduce the back-scattering effect between the ferrules. As for confirmation of generation Q-switched laser by GO film, we remove the film from the ferrule and there is no Q-switched lasing was observed. The total cavity length of the ring cavity approximately 11 meters. The output spectrum was observed by using optical spectrum analyser (OSA, Yokogawa: AQ6375) with resolution of 0.005 nm. Power meter was measured by using optical power meter (OPM, OPHIR: AN-2) connected with thermal sensor (OPHIR: D30A-SA_V1). The temporal characteristic in time domain of the Q-switched laser was observed by using 500 MHz oscilloscope (OSC, LeCroy: WAVEJET 352 A) through 7 GHz InGaAs photodetector with rise and fall time less than 50 ps. The result from oscilloscope will be confirm with the radio frequency spectrum analyser (RFSA, Anritsu: MS2683A) for measure in frequency domain of Q-switched laser.

4. Result and Discussion

At first, we sandwiched the 1 mm x 1 mm of GO film in between two fiber ferrules and lock them by a fiber adapter. The Q-switched operation starts at the pump power of 344 mW and continues stable up to pump power of 491 mW. However, it disappears after the pump power is increased beyond 491 mW. Figure 3 shows the output characteristics of the Q-switched laser. Figure 3(a) shows the output spectrum at the maximum pump power of 491 mW, which indicates the operation of laser at the wavelength of 1943 nm. The figure also compares the output spectrum with and without the GO SA in the cavity. It is observed that the spectrum shifts to the shorter wavelength with the incorporation of the SA. This is attributed to an additional loss in the cavity created by the GO SA. The output power and pulsed energy characteristics of the Q-switched laser against the pump power are depicted in Figure 3(b). In the experiment, the pump power is varied from 344 mW to 491 mW. It is shown that the output power is decreased as the pump power is increased before it increases steadily as the pump power is

increased from 380 mW to 499 mW. The maximum output power is 17 mW at the pump power of 344 mW. On the graph, the slope efficiency of output power is 4.68% when maximum pulse energy was calculated at 1.66 nJ. The pulse energy shows the increment steadily with the increment of pump power.

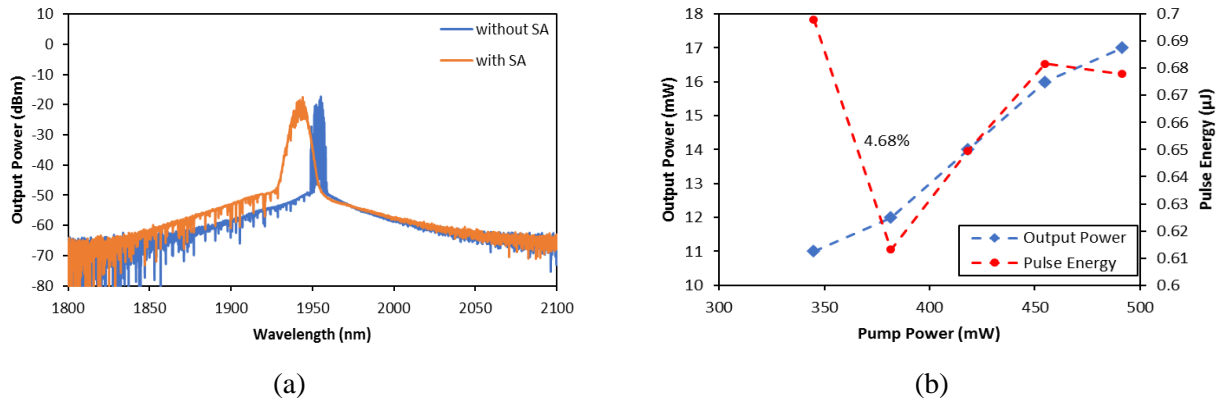


Figure 3. Performance of the Q-switched TDFL (a) Output spectrum with and without SA at pump power of 344 mW. (b) Output power and pulse energy against the pump power.

Figure 4(a) shows the repetition rate and pulse width of the Q-switched laser against the pump power. As shown in the graph, by tuning pump power from 344 mW to 499 mW the repetition rate increase from 15.76 – 25.08 kHz. Also, the pulse width is narrowed from 5.08 μs to 4.2 μs with the increasing of repetition rate. Figure 4(b) shows the radio frequency (RF) spectrum of the TDFL Q-switched laser at the maximum pump power of 499 mW with the span of 380 kHz. Signal to noise ratio (SNR) of the RF spectrum is 47 dB for the fundamental frequency.

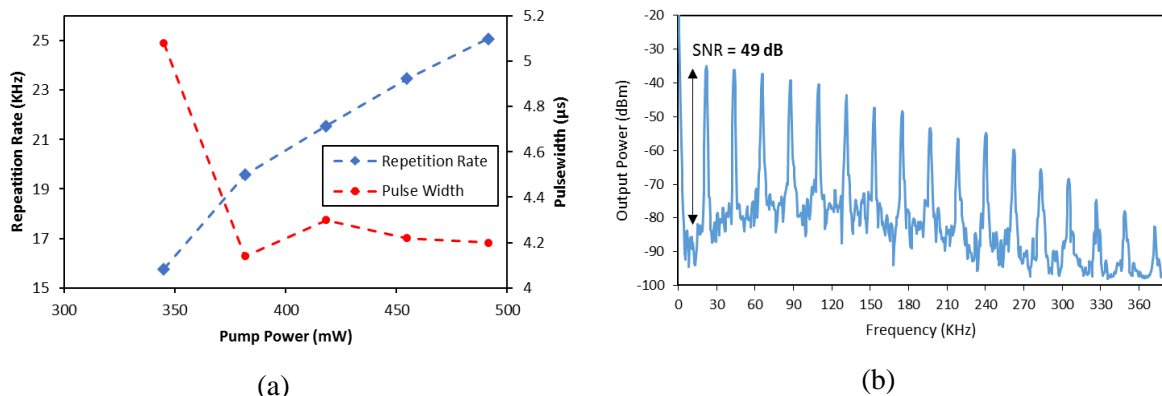


Figure 4. Temporal characteristic of the laser (a) Repetition rate and pulse width against the pump power (b) RF spectrum within 380 kHz span.

5. Conclusion

The Q-switched generation by the GO SA was successfully demonstrated with the repetition rate tunable from 15.76 – 25.08 kHz when the pump power is varied from 344 mW to 491 mW. The laser has a slope efficiency of 4.58%. The homemade GO SA was fabricated by embedding the GO into PVA to form a film by using a drop-casting technique. The pulse width decreases from 5.08 μs to 4.2 μs with the increment of pump power. At the maximum pump power, the pulse energy of 1.66 nJ was achieved.

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