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Q-SWITCHED ERBIUM-DOPED FIBER LASER WITH GRAPHENE OXIDE EMBEDDED IN PMMA FILM

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Passively Q-switched erbium-doped fiber laser (EDFL) based on graphene oxide saturable absorber (SA) is experimentally demonstrated at pump power threshold as low as 11.8 mW. The GO was prepared by chemical oxidation and embedded into PMMA to fabricate a high quality SA device. By inserting the SA into an EDFL ring cavity, stable Q-switched operation can be achieved with the shortest pulse width of 6.12 μs, the maximum pulse energy up to 145 nJ and pulse repetition rates varying from 21.5 kHz to 68.7 kHz. The Q-switching pulse shows no spectral modulation with a peak-to-pedestal ratio of 62.6 dB, which indicates the high stability of the laser. The experimental results further verify that GO possesses the potential advantage for stable Q-switched pulse generation at 1.5 μm

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1. Introduction

Q-switched fiber lasers, because of their high peak power, are of great interest in various applications for remote sensing, medicine, marking and machining, laser ranging and optical time domain reflectometry [1-2]. The lasers can be realized either in an active or a passive way [3-4]. The active Q-switching is easy to control the pulse repetition rate as well as the pulse width, whereas the use of an optical modulator for active Q-switching in the laser cavity is disadvantageous because of its cost and complex operation. Compared with the active operation, the passive Q-switching owns the unique advantage of simple structure in all-fiber designing. Usually, a saturable absorber (SA) is adopted in operations of all-fiber passive Q-switching. Many kinds of SAs for Q-switching have been reported, such as semiconductor saturable absorber mirrors (SESAMs) [5], carbon nanotubes (CNTs) [6-7] and graphene [8]. SESAM has a narrow wavelength tuning range (tens of nanometers), and its modulation depth is typically less than 10% [9]. The CNTs and graphene are ideal SAs for Q-switching because of their low saturation intensity, low cost and broadband wavelength operation [10].

Graphene is a potential absorber to take the place of the SESAMs for Q-switched or mode locked lasers. However, it is difficult to grow graphene film with high quality, which makes graphene absorbers expensive. Furthermore, graphene cannot be dissolved in water so that the efficiency for film fabrication by graphene aqueous solution is decreased. Graphene oxide has traditionally served as a precursor for graphene because of its very low cost and simple fabrication method [11]. In this paper, we demonstrate a Q-switched fiber laser using a new graphene oxide material as SA. The SA device is fabricated by embedding a graphene oxide material, which was obtained through chemical oxidation of graphite into PMMA film. The graphene absorber can be applied in a broad wavelength range because of its unselective absorption. By incorporating a

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*Correspopnding author: swharun@um.edu.my small piece of the film in an Erbium-doped fiber laser (EDFL) cavity, stable and high power Q-switching pulses were obtained.

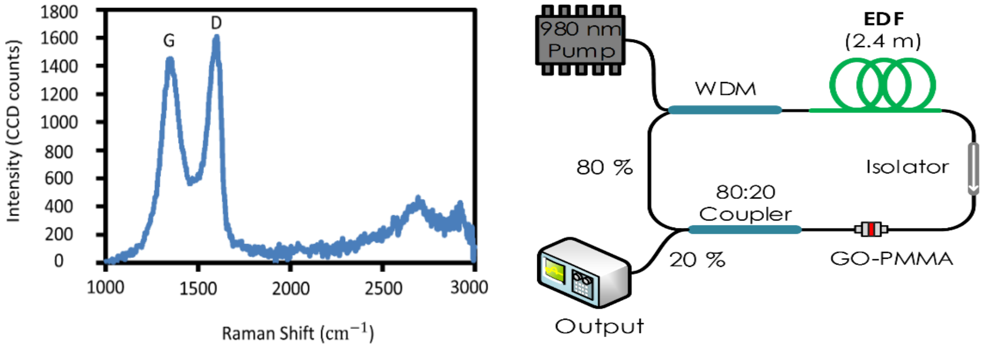
2. Experiment

The graphene oxide (GO) used in this experiment was fabricated by chemical oxidation of graphite. It was was carried out by mixing sulfuric acid: Phosphoric acid (H2SO4:H3PO4) in ratio of 320 mL:80 mL, graphite flakes, and Potassium permanganate (KMnO4), 18 g, using a magnetic stirrer. After adding all the materials slowly, the one-pot mixture was left for stirring for 3 days to allow the oxidation of graphite. The color of the mixture changes from dark purplish green to dark brown. Later, H2O2 solution was added to stop the oxidation process, and the color of the mixture changes to bright yellow, indicating a high oxidation level of graphite. The graphite oxide formed was washed three times with 1 M of HCl aqueous solution and repeatedly with deionized water until a pH of 4–5 was achieved. The washing process was carried out using simple decantation of supernatant via a centrifugation technique with a centrifugation force of 10,000 g. During the washing process with deionized (DI) water, the graphite oxide experienced exfoliation, which resulted in the thickening of the graphene solution, forming a GO gel. The GO gel was then mixed with DI water to obtain a graphene oxide solution. The mixture is then stirred for 2 hours to obtain homogenous GO solution.

To prepare the polymer, 2g of polymethylmethacrylate (PMMA) was dissolved in 60 ml of acetone and heated at 30°C with slow stirring until the PMMA completely dissolved. To fabricate the thin film, GO oxide solution was mix with PMMA and followed by slow stirring for 2 hours. Then, the mixture solution was poured into petri dish and left dry in ambient for 2 days. After dry, the film was slowly peeled.

We verify the quality of the GO PMMA film, we investigate its Raman spectrum as shown in Fig. 1(a). As shown in the figure, it's clearly discerned that the D peak of GO located at 1359 cm^{-1} and the G peak located at around 1600 cm^{-1}. The D band is due to defect-induced breathing mode of sp^2 rings and the G band is due to the first order scattering of the E_{2g} phonon of sp^2 carbon atoms [12]. As observed the G band of the GO is located at a higher frequency compare to graphite 1580 cm^{-1} and corresponds to the finding reported by [13]. The (I_D/I_G) intensity ratio for GO is 0.85 which is the measure of disorder degree and is inversely proportional to the average size of the sp^2 clusters [14]. Then, the fabricated GO film is sandwiched between two fiber ferrules inside a physical contact ferrule connector to form an all-fiber SA device. Index-matching gel is deposited in between the fiber ferrules to reduce insertion loss. The insertion loss of GO based SA device is measured to be around 3 dB at 1550 nm.

The schematic setup of our laser with a ring cavity is shown in Fig. 1(b). The laser cavity consists of a 2.8m long erbium doped fibre (EDF) as the gain medium, a wavelength division multiplexer (WDM), an isolator, the fabricated GO PMMA SA and an 80/20 output coupler. A fiber-coupled laser diode with center wavelength of 980 nm was used as the pump source. It is launched into the EDF via WDM. The EDF used has a numerical aperture (NA) of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm with a core and cladding diameters of 4 μm and 125 μm respectively. To ensure unidirectional propagation of the oscillating laser in the ring laser cavity, a polarization independent isolator was used. The laser signal was coupled out using 80:20 output coupler which keeps 80% of the light oscillating in the ring cavity for both spectral and temporal diagnostics. The output laser was tap from a 20 % port of the coupler. The spectral characteristic was measured using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm while the temporal characteristics were measured using a 500 MHz oscilloscope and a 7.8 GHz radio-frequency (RF) spectrum analyser via a 1.2 GHz photodetector.



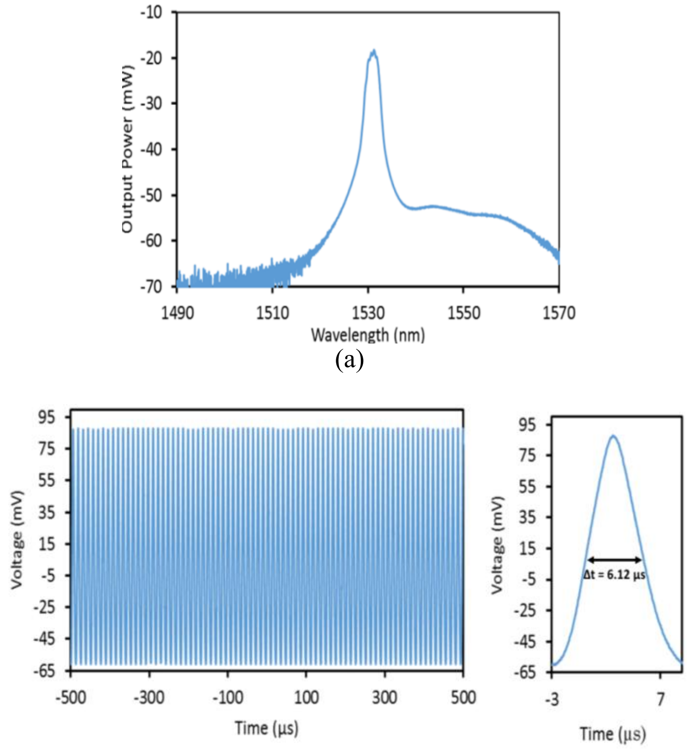
(a) (b)

Fig. 1. (a) Raman spectrum of the GO PMMA film (b) The proposed Q-switched EDFL configuration with the GO based SA device

3. Result and discussion

Stable and self-starting Q-switching operation was obtained just by increasing the pump power over 11.8 mW. There was no lasing below the threshold pump power. Such a low threshold power for Q-switching operation was most probably due to the small intra-cavity loss of the GO PMMA SA. A stable pulse train with an increasing repetition rate was observed within the pump power from 11.8 to 83.0 mW, which is a typical characteristic for the Q-switched laser. Fig. 2(a) shows the output spectrum of the EDFL at pump power of 83.0 mW. As seen in the figure, the laser operated at center wavelength of around 1531.6 nm. Spectral broadening was observed in the spectrum due to the Self-Phase Modulation (SPM) effect in the laser cavity. Fig. 2(b) shows typical oscilloscope trace of the Q-switched pulse train at pump power of 83.0 mW. It shows the peak to peak duration of 14.55 µs, which is equal to the repetition rate of 68.7 kHz. It is also observed that the Q-switched pulse output was stable and no amplitude modulations in the pulse train was observed, which indicates that there was no self-mode locking effect during the Q-switching operation. A single envelop of the Q-switching pulse is shown in the inset figure of Fig. 2(b). It has an almost symmetric shape with a pulse width of approximately 6.12 µs. To verify that the passive Q-switching was attributed to the GO PMMA SA, the film was removed from the ring cavity. In this case, no Q-switched pulses were observed on the oscilloscope even when the pump power was adjusted over a wide range. This finding confirmed that the GO film was responsible for the passively Q-switched operation of the laser.

Fig. 3 shows the relationship between the pulse repetition rate and pulse width with pump power. As pump power increases from 11.8 mW to 83.0 mW, the repetition rate increases almost linearly from 21.5 kHz to 68.7 kHz. As pump power increases, more gain is provided to saturate the SA and thus increases repetition rate. In contrast, pulse duration decreases from 20.44 µs to 6.12 µs as the pump power increases. We observe a smaller change of pulse width with the pump power at higher pump power. This is attributed that the SA is becoming saturated when more photons circulates inside the laser cavity as the pump power increased. The minimum attainable pulse duration is 6.12 µs, which is believed to be related to modulation depth of the SA. The pulse duration can be further decreased by shortening the cavity length and improving the modulation depth of the SA.



(a)

(b)

Fig. 2. (a) Output spectrum and (b) typical oscilloscope trace of the Q-switching pulse. Inset of (b) shows the single pulse envelop with pulse duration of 6.12 µs.

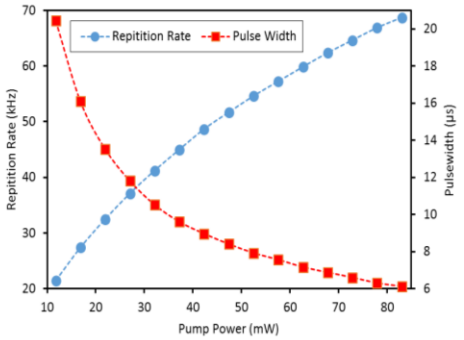


Fig. 3. Pulse widths and repetition rates versus incident pump powers

Fig. 4 shows the relationship between the average output power and pulse energy with pump power in the proposed *Q*-switched EDFL. As the pump power increases, the average output power also increases, which gives rise to pulse energy. It is observed that the output power can be linearly increased from 1.00 mW to 9.96 mW with slope efficiency of 12.52% by tuning the pump power from 11.8 to 83.0 mW. The pulse energy was increased from 46.6 nJ to 145.0 nJ when the pump power increases from 11.8 mW to 83.0 mW. The increment of pump power leads to a raise of average output power and shorten the pulse width and hence higher pulse energy is extracted in the Q-switching process. To investigate the stability of our Q-switched pulse, the radio-frequency (RF) spectrum is obtained at the pump power of 83.0 mW as shown in Fig. 5. The RF spectrum shows the fundamental frequency of 68.7 kHz with a high signal to noise ratio (SNR) of 62.6 dB. The SNR indicates good pulse train stability, comparable to Q-switched fiber lasers based on CNT and graphene [6-8].

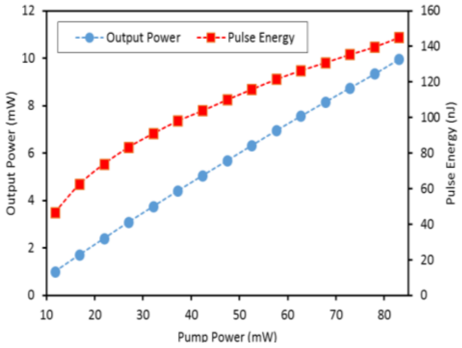


Fig. 4. Average output powers and pulse energies versus incident pump powers

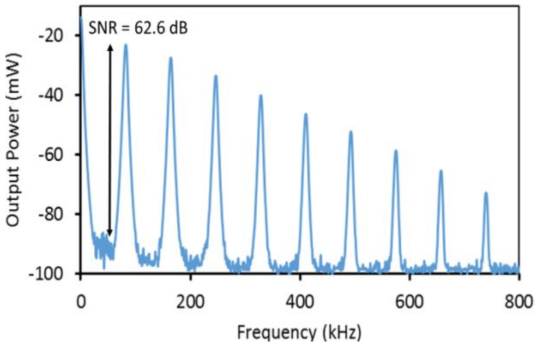


Fig. 5. RF spectrum of the Q-switching pulse at pump power of 83.0mW

The proposed laser is observed to be highly stable, with no significant changes observed in any of the output parameters after two hours of operation, and repeated cycles of operation in the two days following. When the pump power was over 83.0 mW, the Q-switched pulses became unstable and switched to CW mode, as usually observed in some passively Q-switched fiber lasers reported previously [6-8]. We think one possible reason for the unstable Q-switched is the over-saturation of the GO film at high incident intensity. That means, two-photon absorption (TPA) process in the GO layer has been excited under the higher optical intensity. Thus, the absorption coefficient increased as continually increasing of pump power and Q-switched operation could not be maintained. However, after the pump power was decreased from 200 mW, the stable Q-switched operation observed again at the pump power of 83.0 mW and below. This phenomenon indicated that the sample was not damaged in the relative high power. In the lasers, there was no thermal damage observed in the GO film sample and the output power was stable during laser operation up to 83.0 mW. Limited by the maximum output power of the pump 200 mW, we could not measure the exact damage threshold. It is expected that a better Q-switched pulse can be obtained by optimizing the design of the cavity, including reducing the cavity length and cavity losses as well as optimizing its cavity structure and using higher quality GO based SAs.

4. Conclusions

We have demonstrated a passively Q-switched EDFL based on GO SA. The SA device is fabricated by embedding a GO material, which was obtained through chemical oxidation of graphite into PMMA film. Employing this device into an EDFL cavity, we have achieved stable Q-switched pulses generation. It operates at 1531.6 nm within a pump power range of 11.8 to 83.0 mW. Through fine increasing the pump power, the repetition rate could be changed from 21.5 kHz to 68.7 kHz, and pulse duration from 20.44 μs narrow to 6.12 μs. The pulse energy was 145 nJ at pump power of 83.0 mW. These results shows that GO is a new potential SA material for pulsed laser applications.

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