Q-switched Erbium-doped fiber laser using multi-layer graphene oxide based saturable absorber

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A stable passive Q-switched Erbium doped fiber laser (EDFL) operating at 1533 nm is demonstrated using a multi-layer graphene oxide (GO) based saturable absorber. The GO was synthesized via chemical oxidation of graphite flakes at room temperature using a simplified Hummer's method. By dipping a fiber ferrule end face onto the GO suspension, GO is successfully coated onto the end face, making it a simple saturable absorption device. At 980 nm pump power of 40 mW, the EDFL generates an optical pulse train with a repetition rate of 12.98 kHz and pulse width of 13 μs. The highest energy of 0.46 μJ is achieved at the maximum pump power of 90 mW. The pulse width ranges from 5.14 to 14.63 μs.

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1. Introduction

Lasers operating in CW or quasi-CW regime have limited optical output power, which depends on the maximum available pump power. By concentrating the available energy in a single short optical pulse, or in a periodic sequence of optical pulses, higher peak power is viable. Q-switch is a technique that enables the generation of a short optical pulse by sudden switching of the cavity Q factor, i.e., of the cavity loss [1-3]. Compared to CW fiber lasers, high-peak-power Q-switched fiber lasers are practically useful in numerous applications, such as range finding, remote sensing, industrial processing, and medicine [4-6]. Active Q-switching is typically achieved by inserting an acoustic-optic or an electro-optic modulator into the cavity [2]. On the other hand, passive Q-switching is attained by employing saturable absorbers (SAs). It is a convenient technique that simplifies the cavity design and eliminates the need for external Q-switching electronics. Semiconductor saturable absorber mirrors (SESAMs) [7-8], and carbon nanotubes (CNTs) [9-10] are normally used as the SA for the Q-switched fiber lasers. However, the fabrication of SESAMs is complex and costly. While constructing CNTs SA is relatively simple and cheap, when operating the CNTs at a particular wavelength, band-gap tuning must be done by controlling their diameters and chirality. Moreover, the surface tension of the CNTs is too large, resulting in them having a low damage threshold [11].

More recently, novel nano-material graphene has been utilized as broadband functional SAs [12-13]. Graphene is a two-dimensional crystal of carbon atoms arranged in a honeycomb lattice. It has outstanding linear and nonlinear optical properties, such as low threshold level of saturable absorption (~0.7 MW cm^{-2}), ultrafast recovery time (200 fs) and an ultra-broad wavelength independent saturable absorption range, which covers the wavelength range from the visible to mid-IR. Compared with CNTs, graphene is expected to have a higher damage threshold due to its two-dimensional structure [14]. However, till now most reports on graphene have focused on mode locked fiber lasers [14-16] while graphene Q-switched fiber lasers have rarely been investigated [17-18]. Recent demonstrations on Q-switched fiber lasers are mainly based on graphene film, which is obtained by chemical vapor deposition (CVD) approach [18].

In this paper, a Q-switched Erbium doped fiber laser (EDFL) operating at 1533 nm is demonstrated using a simple and inexpensive graphene-oxide (GO) based SA. The GO is synthesized via chemical oxidation of graphite flakes at room temperature. First, we coat a fiber ferrule with GO by dipping its end surface into a GO suspension. Then it is matched with another clean ferrule to fabricate an SA. The SA is integrated in the EDFL to achieve a stable pulse train with a repetition rate of 12.98 kHz and pulse width of 13 μs at 980 nm pump power of 40 mW.

2. Fabrication of GO based SA and experimental set-up

In constructing the GO-based SA, the first step is to prepare GO suspension using the simplified Hummer's method as described in ref. [19]. This method offers the advantage of much shorter mixing time for the reactants necessary for chemical oxidation. In addition, the whole

process can be carried out without any temperature control. Oxidation of graphite flakes was carried out by mixing H_2SO_4:H_3PO_4, graphite flakes and potassium permanganate using a magnetic stirrer. The mixture was stirred at room temperature for three days. Then, sulfuric acid was added to the mix to stop the oxidation process and form graphite oxide. The GO was subsequently washed with 1 mol hydrochloric acid aqueous solution followed by repeated washing with de-ionized water until its pH is within 4 to 5. The washing process was carried out using simple decantation of supernatant via centrifugation. When washed with de-ionized water, the graphite oxide experienced exfoliation, resulting in the thickening of the graphene solution, forming a GO gel. Finally, a fiber ferrule end face was immersed onto the GO and left to dry. The GO coated ferrule was then mated to another clean ferrule via a fiber connector to form a simple saturable absorption device, suitable for Q-switching of fiber laser.

Raman spectroscopy was performed to confirm the presence of graphene layer in the fabricated GO based SA and the result is shown in Fig. 1. As seen in the figure, three prominent peaks are observed at approximately 1360 cm^{-1}, 1593 cm^{-1} and 2930 cm^{-1}, which are generally referred as the D, G and 2D band, respectively. The G band contributes to an E_{2g} mode of graphite and is related to the in-plane vibration of sp^2-bonded carbon atoms, while the D band is associated with the vibrations of carbon atoms with sp^3 electronic configuration of disordered graphite. 2D Raman peaks change in shape, position and relative intensity with number of graphene layers. The Raman spectroscopy reveals a broad 2-D peak, which indicates that the graphene has a multi-layer structure. Another method of determining the graphene layer structure is by calculating the intensity ratio between the G and 2-D peak. It was reported that single-layer graphene has a low intensity ratio, usually lower than 0.5 while multi-layer graphene shows higher intensity ratio (≥1) [20]. In our work we obtain a G/2-D peak ratio of 0.9, which indicates that we have multi-layer graphene on the fabricated SA.

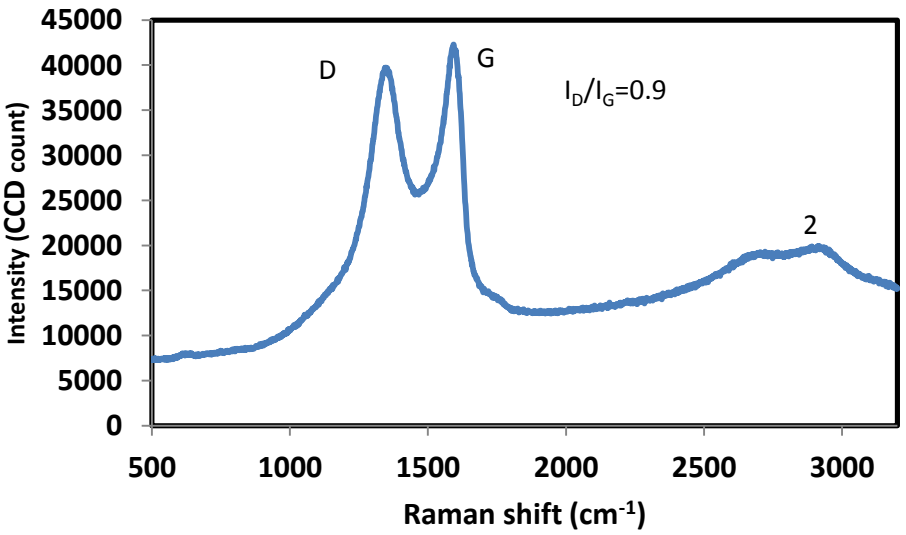

Fig. 2. Raman spectrum from the GO based SA.

The experimental setup of the proposed Q-switched EDFL is shown in Fig. 2, which consists of a 1 m long EDF, a 980/1550 nm wavelength division multiplexer (WDM), a GO based SA, an optical isolator, polarization controller and 95/5 output coupler in a ring configuration. The insertion loss of the SA is measured to be around 2 dB at 1550 nm. The EDF used has core and cladding diameters of 4 µm and 125 µm respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm. It is pumped by a 980 nm laser diode via the WDM. An isolator is incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser. A polarization controller (PC) is used to adjust the polarization state of the oscillating light and the birefringence inside the ring cavity. The output of the laser is tapped from the cavity through a 95/5 coupler while keeping 95% of the light to oscillate in the ring cavity. The optical spectrum analyzer (OSA) is used to inspect the spectrum of the EDFL with a spectral resolution of 0.05 nm whereas the oscilloscope is used to observe the output pulse train via a 460 kHz bandwidth photo-detector (Thor lab, PDA50B-EC). The total cavity length of the ring resonator is measured to be around 3 m.

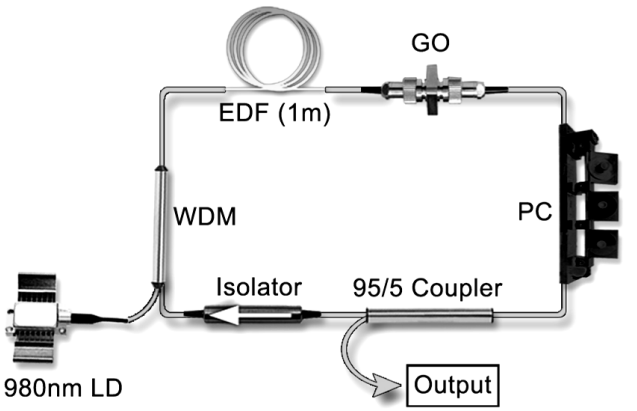

Fig. 2. Schematic configuration of the Q-switched EDFL.

3. Result and discussion

Stable and self-starting Q-switching operation is obtained just by adjusting the pump power over a threshold of 30 mW. Fig. 3 compares the output spectrum of the EDFL with and without the graphene SA when the pump power is fixed at 50 mW. As seen, the center wavelength of the laser slightly shifts to a shorter wavelength and the average output reduces with the incorporation of the SA. This is attributed to the cavity loss of the resonator, which is increased by about 2 dB with the SA. To compensate the loss, the laser operates at a shorter wavelength, which is near the peak absorption wavelength of the EDF to acquire more gain. Without the SA, the EDFL operates in CW mode.

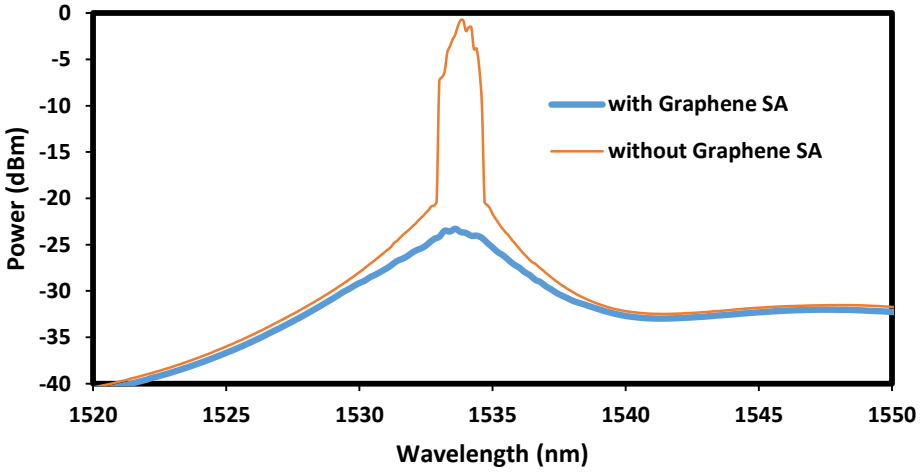

Fig. 3. Output spectra from the both EDFLs configured with and without the SA at pump power of 50 mW.

Fig. 4(a) shows the oscilloscope trace of the Q-switched pulse train at pump power of 40 mW. There is no distinct amplitude modulation in each Q-switched envelop of the spectrum, which indicates that the self-mode locking effect on the Q-switching is weak. At 40 mW pump power, a stable passively Q-switching operation starts to occur with an average output power of 4.3 mW and a repetition rate of 12.98 kHz. The pulse energy is calculated to be around 0.33 µJ at this pump power. The pulse energy could be improved by reducing the insertion loss of the saturable absorber or by optimizing the laser cavity. Fig. 4(b) shows the typical oscilloscope trace of the pulse envelop at the pump power of 40 mW. As seen in the figure, the full-width at half maximum or pulse width was obtained at 13 µs.

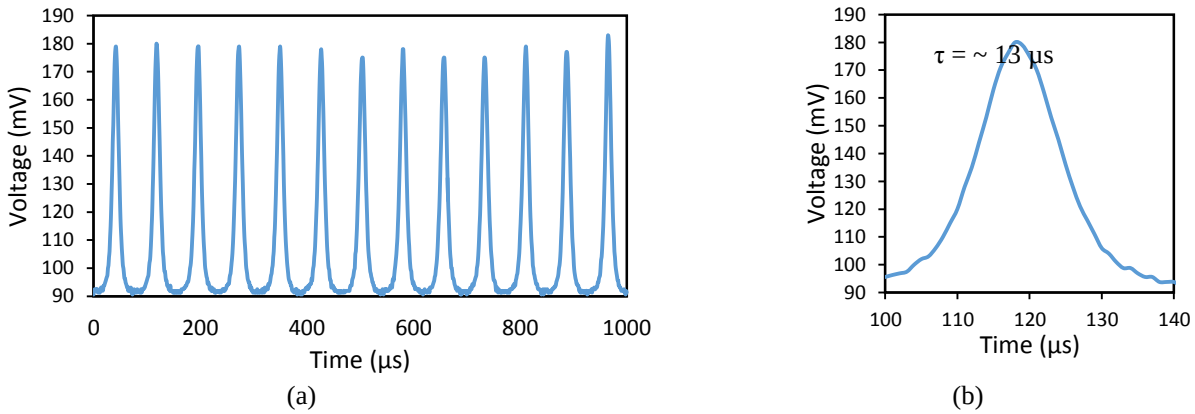

Fig. 4. (a) The pulse train for the proposed EDFL with graphene based SA at 40 mW pump power with the repetition rate of 12.98 kHz. (b) Enlarge pulse width spectrum.

Fig. 5 shows how repetition rate and pulse width are related to the pump power. The repetition rate of the graphene based Q-switched EDFL has a monotonically increasing, near-linear relationship with the pump power level. When the pump power is tuned from 30 to 90 mW, the pulse train repetition rate also increases from 6.45 to 26.11 kHz. On the other hand, the pulse width fluctuates from 5.14 to 14.63 µs within the same pump power range. The pulse width is expected to drop back by further increasing the pump power, as long as the damage threshold of the graphene SA is not exceeded. Using a higher doped fiber for a shorter cavity length of the EDFL would be an effective alternative to obtain a shorter pulse width [21]. Fig. 6 shows the average output power and pulse energy of the Q-switched EDFL as functions of pump power. The output power increases while the pulse energy fluctuates within 0.33 to 0.46 µJ as the pump power is increased from 30 to 90 mW. At the maximum pump power of 90 mW, the stable Q-switching operates with the highest average power of 12.1 mW and the highest pulse energy of 0.46 µJ. The pulse energy could be further improved by increasing the pump power. These results indicate that graphene has a big potential for superior Q-switching and saturable absorption compared to conventional light absorbing components when carefully employed in an appropriate laser system. The fabrication of the SA is also simple and thus the cost of the laser should be low. The simple and inexpensive laser is suitable for applications in metrology, environmental sensing and biomedical diagnostics.

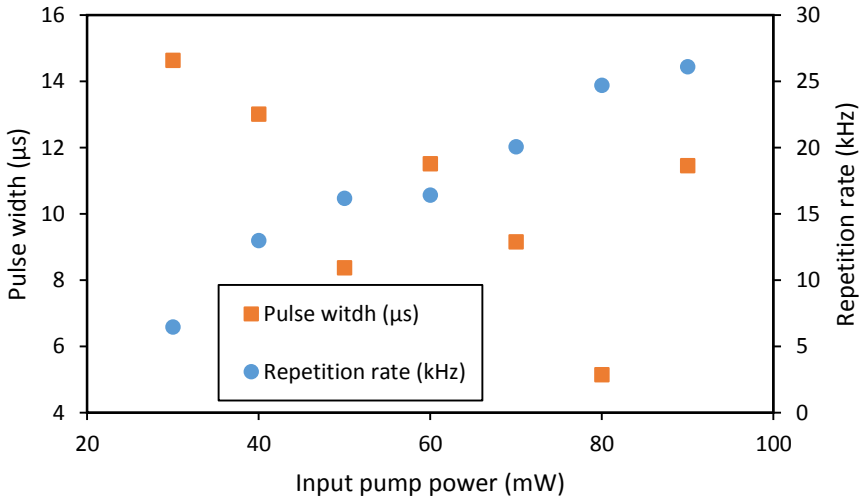

Fig. 5. Repetition rate and pulse width as a function of pump power.

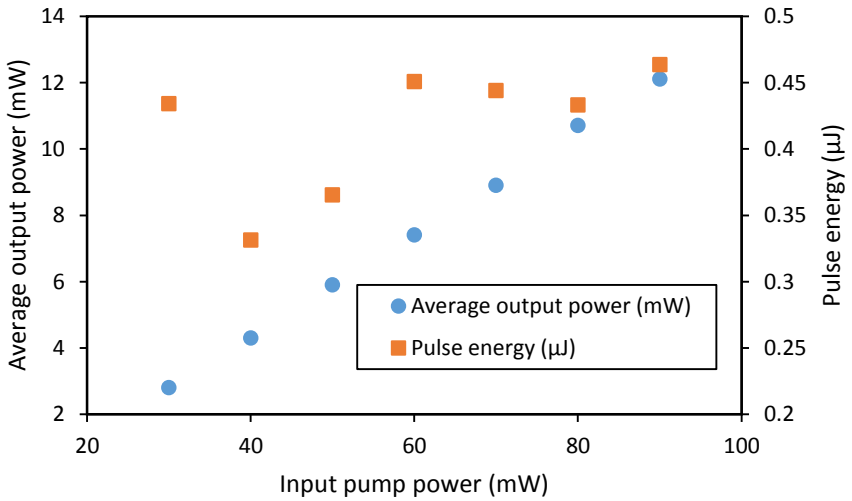

Fig. 6. Output power and pulse energy versus pump power.

4. Conclusion

The Q-switching in EDFL has been demonstrated using a multi-layer graphene oxide based SA. The SA was fabricated using a simplified Hummer's method to synthesize the GO via chemical oxidation of graphite flakes at room temperature. By dipping a fiber ferrule end face into the GO suspension and mating it with another clean ferrule a simple saturable absorption device is obtained. The proposed laser operates at 1533 nm and self-starts at pump threshold of 30 mW to produce Q-switching pulse. The repetition rate ranges from 6.45 to 26.11 kHz while the pulse width varies from 5.14 to 14.63 μs. The highest energy of 0.46 μJ is achieved at the maximum pump power of 90 mW. It is expected that a higher performance from the graphene Q-switched fiber lasers can be achieved with the optimization of the graphene SA and laser cavity.

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