Q-Switched Ytterbium doped fiber laser with graphene oxide embedded in polyethylene oxide film based saturable absorber

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A stable passive Q-switched Ytterbium doped fiber laser (YDFL) is demonstrated by using a graphene oxide (GO) embedded in polyethylene oxide (PEO) film a as saturable absorber (SA). The SA was fabricated by mixing a dispersed GO composite with PEO solution thoroughly through an ultra-sonification process. The mixture solution is dried to form a film, which is then put in between two FC/PC fiber ferrule so that it can be easily incorporated in YDFL's ring cavity. A stable Q-switched laser operating at wavelength of 1040.7 nm was self-started at pump power of 93 mW with the SA. At pump power of 111 mW, the YDFL generates an optical pulse train with a repetition rate of 28.75 kHz and pulse width of 9.1 μs. The maximum pulse energy of 20.6 nJ was obtained at pump power of 99 mW while the maximum output power of 0.24 mW was obtained at pump power of 128 mW.

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1. Introduction

Pulse fiber lasers have undergone tremendous development in the past few decades since they have quite different characteristics compared with continuous wave lasers. The high peak power, controllable repetition rate, and pulse duration enable the pulse fiber laser to contribute significantly to laser development for practical applications, including material processing, LIDAR, laser communications, environmental detection, medical care, nonlinear frequency conversion, and laser acceleration [1-2]. Q-switching is one of the approaches to realize the pulse fiber lasers, which are of great interest in recent years for the above mentioned applications. In addition, Q-switched all-fiber lasers have advantages in term of their flexibility, large accumulated one-trip gain, high beam quality and intense power confined in mode field diameters of only a few micrometers [3-5]. Q-switching in all-fiber lasers has been achieved passively by modulating of the Q-factor of the laser cavity using semiconductor saturable-absorber mirrors (SESAMs) [5-6]. However, they require complex manufacturing techniques, such as metal–organic chemical vapor deposition and molecular beam epitaxy.

In recent years, single-walled carbon nanotubes (SWCNTs) and graphene have been intensively investigated for saturable absorber (SA) applications because of their advantageous characteristics, such as low cost, broad spectral ranges, and so on [7-8]. Compared with SESAMs, both SWCNTs and graphene can be fabricated in much simpler and cheaper ways. For instance, SWCNTs can be fabricated using well-known techniques based on spin coating and spray methods. Graphene is superior to SWCNT in broadband Q-switching and mode-locking due to its gapless linear dispersion of Dirac electrons. As the precursor for graphene, graphene oxide (GO) has also been widely investigated for its physical and chemical characteristics. Different from graphene, GO has strongly hydrophilic and water solubility, but it has a fast energy relaxation of hot carriers and strong saturable absorption comparable to those of graphene [9-10]. These properties make GO as potential SA material for pulsed fiber lasers. Recently, the GO SAs have been used to diode-pumped solid-state lasers at 1 μm [11] and fiber lasers near 1.5 μm [12].

In this paper, a simple and stable Q-switched Ytterbium doped fiber laser (YDFL) operating at 1040.7 nm is demonstrated using a simple and inexpensive GO-polyethylene oxide (GO-PEO) film as SA. The function of polyethylene oxide (PEO) in SA fabrication is to serve as the host polymer in order to produce SA in thin film form. The graphene is oxidized first in the experiment to produce GO. Then, the GO will be put into a solution of 1 g PEO in deionized water and thoroughly mixed using an ultra-sonification process to produce GO-PEO film. The simple SA was constructed by cutting a small piece of this film and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The SA is incorporated in the proposed YDFL cavity to realize a stable pulse train with a repetition rate

of 28.75 kHz and pulse width of 9.1 µs at 1480 nm pump power of 110.85 mW.

2. Fabrication of GO based SA

At first, we mix sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), graphite flakes, and potassium permanganate ($KMnO_4$) by using a magnetic stirrer. After adding all the materials gently, the mixture was then stirred for about 3 days to allow the oxidation of graphite. After oxidation of graphite is achieved, hydrogen peroxide (H_2O_2) solution was added to stop the oxidation process. Finally, bright yellow color mixture is obtained indicating a high oxidation level of graphite. The graphite oxide formed was washed three times with 1 M of hydrogen chloride (HCl) aqueous solution and repeatedly with deionized (DI) water until a pH of 4–5 was achieved. The washing process was carried out using simple decantation of supernatant via a centrifugation technique. During the washing process with DI water, the graphite oxide underwent exfoliation, which leads to in the thickening of the graphene solution, forming a GO gel. The GO gel was then mixed with DI water to obtain a GO solution.

To prepare the polymer, 1000 mg of PEO with average molecular weight of 1 x 10^6 g/mol is dissolve in 120 ml deionized (DI) water using hot plate stirrer with the aid of magnetic stirrer. From the experiment, it is observed that about three hours was taken to fully dissolve the PEO in DI water. GO-PEO composite was fabricated by adding a small quantity of dispersed GO solution into a PEO solution with GO:PEO ratio of 2:3 with weight percentage of 4.76 % and thoroughly mixed them using an ultra-sonification process. In this experiment, the mixer is put into ultra-sonic bath for about one hour to produce a stable GO-PEO composite solution. This solution is then left dry at room temperature to obtain GO-PEO film.

Fig. 1 shows the field emission scanning electron microscopy (FESEM) image of the GO-PEO film, which shows three-dimensional interconnection of graphene sheets. GO synthesized from graphene flakes will produce porous-like complex which resembles layers of an onion as seen in Fig. 1. The thickness of the fabricated GO-PEO film is measured to be around 50 µm. Fig. 2 shows the Raman spectrum from the graphene oxide (GO), which clearly indicates two peaks; D and G band. As shown in the figure, the D and G peaks are located at around 1359 cm^{-1} and 1600 cm^{-1}, respectively. 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 [13]. It is found that the G band is located at a higher frequency in the GO compared to that of graphite, which normally located at1580 cm^{-1} as reported in reference [14]. 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 [15].

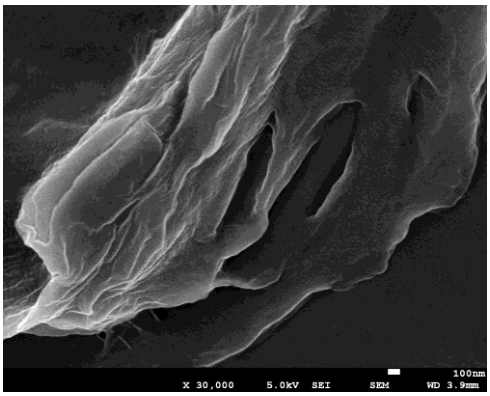


Fig. 1: FESEM image of GO-PEO film.

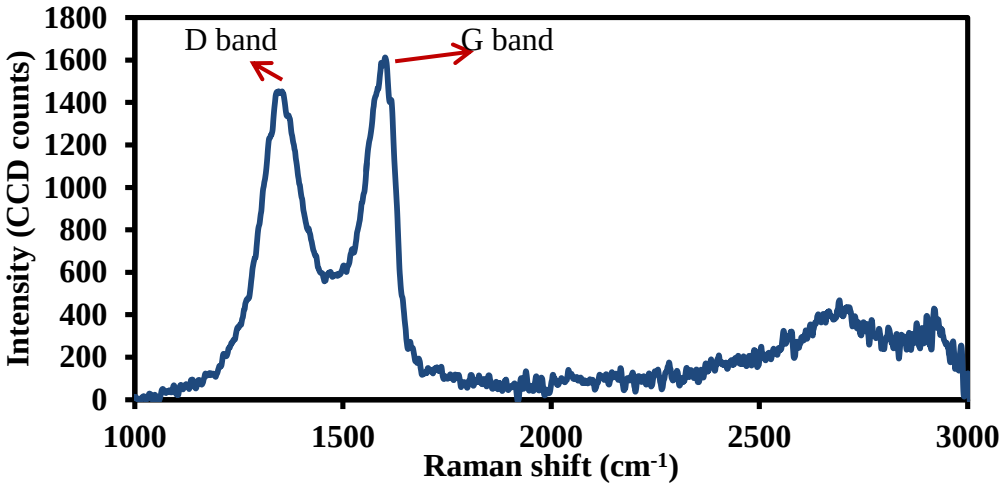


Fig. 2. Raman spectrum of graphene oxide.

3. Experimental set-up

Fig. 3 shows the experimental setup of the proposed Q-switched YDFL, which consists of a 1 m long Ytterbium doped fiber (YDF) as the gain medium and the homemade GO-PEO film as the Q-switcher. The YDF used has core and cladding diameters of 4um and 125 um respectively, a numerical aperture of 0.16 and Ytterbium ions absorption of 23 dB/m at 1020 nm. The YDF *was* pumped by a 980 nm laser diode via a 980/1020 nm

wavelength division multiplexor (WDM). The GO-PEO SA was fabricated by cutting a small part of the earlier prepared film (2×2 mm^2) and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The insertion loss of the SA was recorded as 1.4 dB at 1100 nm. The isolator was inserted to ensure unidirectional oscillation of the propagating light while the incorporation of the polarization controller (PC) was to adjust the polarization state of the light. Finally, the 50 % output of this proposed configuration was tapped out through a 3dB coupler while retaining 50 % of the light oscillation inside the ring cavity. An optical spectrum analyzer (OSA) was used to observe the output spectrum of the YDFL. We analyze the output pulse train using an oscilloscope and a radio frequency (RF) spectrum analyzer via a photo-detector.

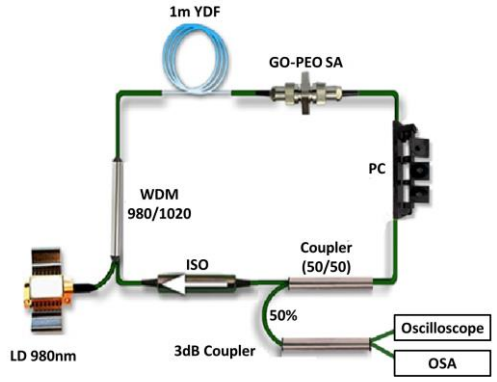


Fig. 3: Schematic configuration of the Q-switched YDFL.

4. Result and discussion

We started to observe a stable Q-switching operation when the pump power exceeded 93 mW. The output spectrum of the Q-switched YDFL with and without the GO-PEO as SA are compared as depicted in Fig. 4 at pump power of 111 mW. Without the GO-PEO as SA, the YDFL operates at a center wavelength of 1062.9 nm. However, the center wavelength shifts to 1040.7 nm when the GO-PEO based SA is incorporated inside the cavity. This is attributed to the cavity loss of the ring configuration which increases with the incorporation of the GO-PEO SA. In order to compensate for the loss, the laser operates at a shorter wavelength, approaching the peak absorption wavelength of the YDF to obtain more gain. The laser operates in continuous wave (CW) mode without the GO-PEO SA.

Fig. 5 shows the repetition rate and pulse width of the Q-switched YDFL as the 980 nm pump power is varied from 93 to 128 mW. We can observe from the figure that the pulse width becomes narrower, from 13.9 µs to 7.76 µs, as the pump power increases to its limit. On the other hand, the repetition rate of the Q-switching pulse gradually increases from 10.8 kHz to 33.2 kHz as the pump power is increased within the pump power regime. The Q-switching operation becomes unstable as the pump power increases beyond 128 mW.

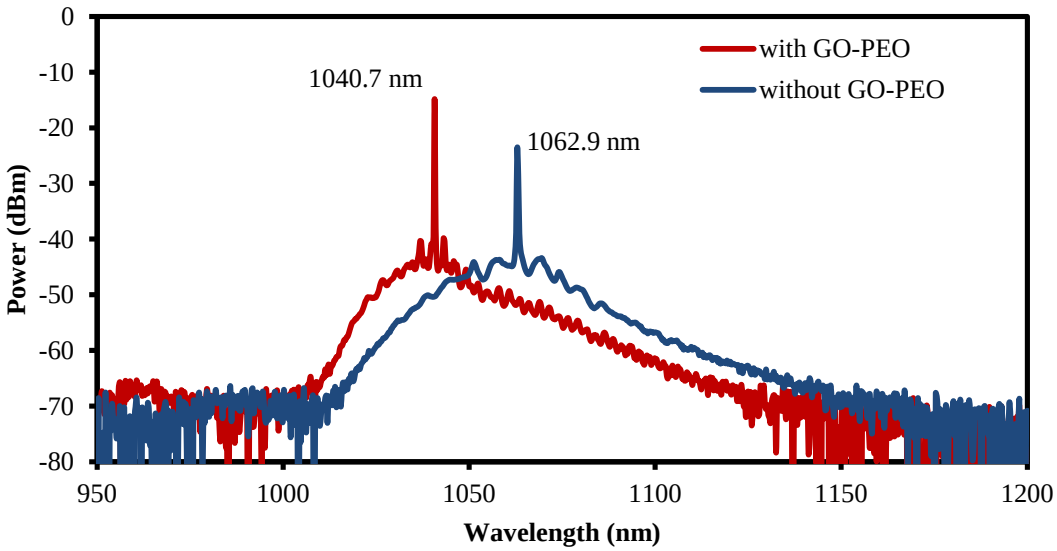


Fig. 4: The output OSA's spectra from the YDFL configuration with and without the GO-PEO SA at pump power of 111 mW

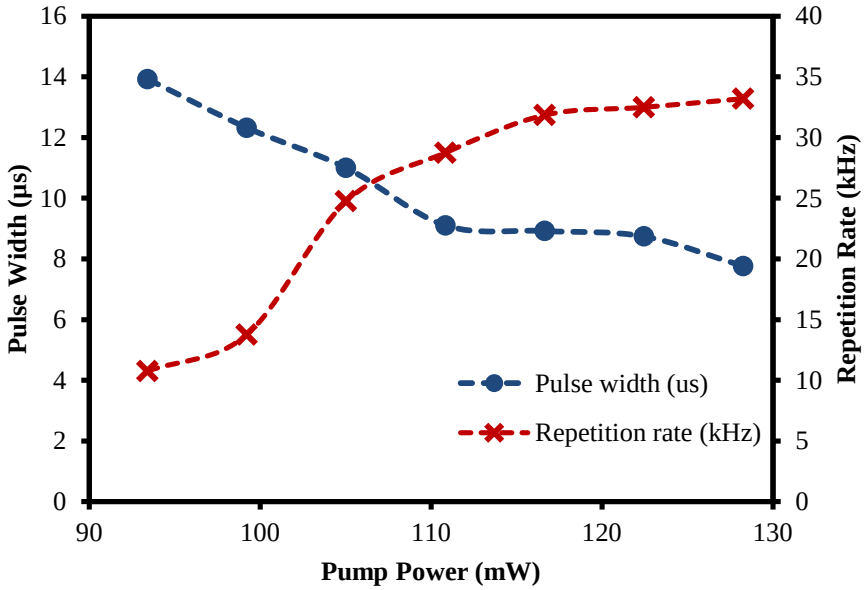
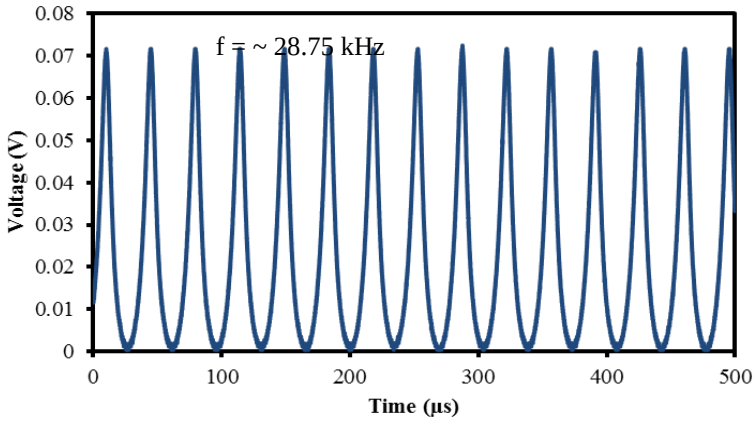


Fig. 5: Repetition rate and pulse width as a function of pump power.

Fig. 6 (a) shows the oscilloscope trace of the Q-switched pulse train at pump power of 111 mW. The measured peak to peak spacing (t_{ptp}) is 34.8 µs and this translates to a repetition rate of 28.75 kHz. 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 frail. Fig. 6 (b) shows the typical oscilloscope trace of the pulse envelop at the same pump power. As seen in the figure, the full-width at half maximum or pulse width was obtained at 9.1 µs. Fig. 6 (c) shows the RF spectrum of the Q-switched YDFL which was measured by the RF spectrum analyzer. It shows a stable repetition rate of ~ 28 kHz and peak-to-peak background ratio of ~ 53 dB to indicate that the produced pulses are stable.

Fig. 7 shows the pulse energy and output power as a function of pump power when the pump power is varied from 93 to 128 mW. The highest pulse energy of 20.6 nJ was obtained at the pump power of 99 mW with the corresponding average output power of 0.16 mW, pulse repetition rate of 13.77 kHz and pulse width of 12.32 µs. However, the output power drops to 0.12 as the pump power is increased to 105 mW. As the pump power further increases to 128 mW, the output power shows almost linear relationship with the pump power level. The highest output power of 0.24 mW is obtained at the maximum pump power of 128 mW.

These results indicate that GO-PEO has a big potential for superior Q-switching and saturable absorption in 1 micron region compared to conventional light absorbing components when carefully employed in an appropriate laser system. The fabrication of the GO-PEO SA is also simple and thus the cost of the laser should be low. Further refinement of the fabrication process is required to obtain mode locking operation in this region. The simple and low cost laser is suitable for applications in metrology, environmental sensing and biomedical diagnostics.



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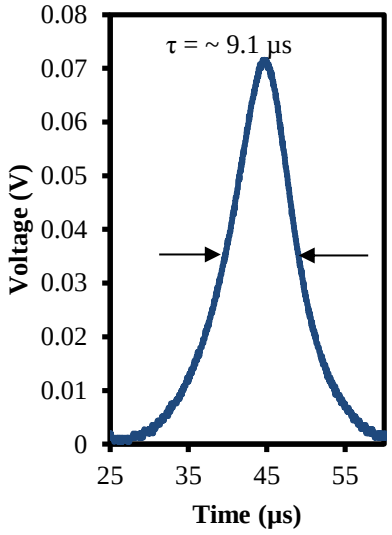

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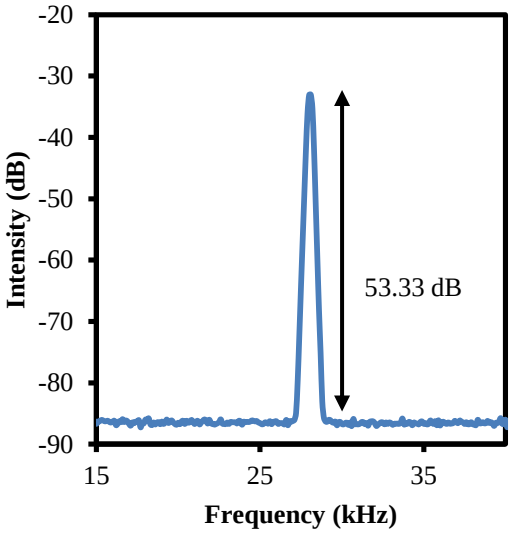

c

Fig. 6: (a) Oscilloscope trace for the YDFL with GO-PEO based SA at 111 mW pump power showing a repetition rate of 28.75 kHz; (b) Enlarged single envelop of the pulse (c) RF spectrum

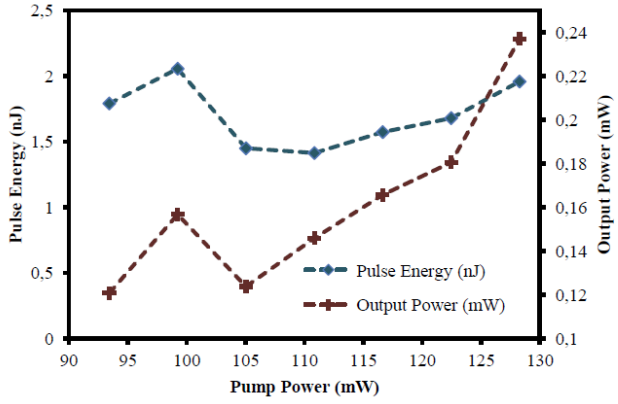

Fig. 7: Pulse energy and output power as a function of pump power

5. Conclusion

The Q-switching in YDFL is demonstrated using a GO-PEO polymer as SA. The proposed YDFL operates at 1040.7 nm and self-starts at pump threshold of 93 mW to produce Q-switching pulse. The repetition rate increases from 10.8 kHz to 33.2 kHz while the pulse width reduces from 13.9 µs to 7.76 µs as the 980nm pump power is varied from 93 to 128 mW. The highest pulse energy obtained is 2.06 nJ at pump power of 99 mW. Besides showing good Q-switching performance, the saturable absorber is easy to fabricate and cheap. It is expected that a higher performance from this Q-switched fiber lasers can be achieved with the optimization of the GO-PEO SA and laser cavity.

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