CHIN. PHYS. LETT. Vol. 35, No. 11 (2018) 114202

Using Reduced Graphene Oxide to Generate Q-Switched Pulses in Er-Doped Fiber Laser *

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(Received 19 July 2018)

Using the reduced graphene oxide (rGO) as a saturable absorber (SA) in an Er-doped fiber (EDF) laser cavity, we obtain the Q-switching operation. The rGO SA is prepared by depositing the GO on fluorine mica (FM) using the thermal reduction method. The modulation depth of rGO/FM is measured to be 3.2%. By incorporating the rGO/FM film into the EDF laser cavity, we obtain stable Q-switched pulses. The shortest pulse duration is 3.53 μs, and the maximum single pulse energy is 48.19 nJ. The long-term stability of working is well exhibited. The experimental results show that the rGO possesses potential photonics applications.

PACS: 42.55.Wd, 42.60.Gd, 42.70.−a DOI: 10.1088/0256-307X/35/11/114202

In recent years, the remarkable electrical and optical properties of two-dimensional (2D) materials have been attracting tremendous interest in basic and application research fields.[1−4] Due to excellent saturable absorption characteristics and ultrafast dynamics, the 2D materials have been used as saturable absorbers (SAs) to generate laser pulses. Over the decades, semiconductor saturable absorber mirrors (SESAMs)[5] are considered to be one of the most mature and commercial SAs. However, SESAMs are limited by complex fabrication processes and narrow operation bandwidth. In 2004, carbon nanotube based SAs have been proposed, which exhibit fast recovery time, large saturable absorption, and easy fabrication.[6−8] However, the operation bandwidth relies on the diameters and chirality of carbon nanotube, which would lead to large non-saturable losses. Therefore, researchers have tried to find ideal SAs with excellent properties such as wide band nonlinear absorption, low losses, ultrafast response and high damage threshold.[9,10] Graphene, with 2D layered structure, has been studied in-depth and has opened up new opportunities in the optoelectronic field due to its atomic layer thickness, strong light-material interaction, ultrafast carrier dynamics, high third-order nonlinear susceptibility and broadband absorption.[11−13] The successful demonstrations of mode-locked and Q-switched lasers using graphene as SA have stimulate researchers to explore the 2D materials as the next-generation high performance SAs.[14−16] Current research on 2D material based SAs mainly focus on graphene,[17,18] topological insulators (TIs),[19,20] transition-metal dichalcogenides (TMDs)[21−23] and black phosphorus,[24−26] which have been widely used to passively Q-switched or mode-locked fiber lasers in a wide range of visible-to-infrared wavelengths.[27−29]

Motivated by graphene development, graphene oxide (GO) has attracted much attention as an alternative SA nanomaterial.[30−32] Because of its reduced structure, reduced graphene oxide (rGO) also exhibits broadband absorption property, making it a promising SA material.[33,34] Different from graphene, it possesses the advantages of ease functionalization, water solubility, and aggregate resistance. By the reduction process, it can control the transformation from sp^{3-} to sp^{2-} hybridized domain flexibility, therefore, realizing the manipulation of material structure and optical property.[35] To date, rGO has attracted tremendous interest for its application in pulsed fiber lasers. The thermal reduction method, i.e., controlling the reaction temperature to reduce the part of functional groups, is a good way to prepare the rGO. This method shows the advantages of flexibility and processibility at large-scale production.[36]

In this work, we prepare the rGO SA by the thermal reduction method. With the spin-coating method, the GO is deposited on the fluorine mica (FM) surface. For the next reduction process, we put the GO/FM into a vacuum tube furnace at a high temperature. This film-type rGO/FM SA has advantages of mass preparation, uniform quality and flexibility of usage. The modulation depth (MD) of the rGO/FM SA is measured to be 3.2%. The resultant fiber laser can work in Q-switched operation with the pump range of 50–170 mW. The shortest pulse duration is 3.53 μs, and the maximum single pulse energy is 48.19 nJ.

Here the liquid exfoliation method has been used for fabricating the GO nanosheet solution. The 10 mg GO nanoplates are dispersed in deionized water. The dispersion is ultrasonically agitated for 8 h and the

*Supported by the National Natural Science Foundation of China under Grant No 61705183, the Central University Special Fund Basic Research and Operating Expenses under Grant No GK201702005, the Natural Science Foundation of Shaanxi Province under Grant No 2017JM6091, and the Fundamental Research Funds for the Central Universities under Grant No 2017TS011.
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power of ultrasonic cleaner is set as 360 W. To isolate the large GO nanosheets, the dispersion is centrifuged at 7000 rpm. Then, we deposited GO on the FM surface. Finally, the GO/FM is put into a vacuum tube furnace for reduction, and the temperature is set at 800℃. It takes about 1 h to complete the reduction process. Figure 1 shows the SEM image of the rGO, and the rGO surface presents serious folding and curling, due to the fact that the oxygen-containing functional groups on the surface are eliminated by reduction.

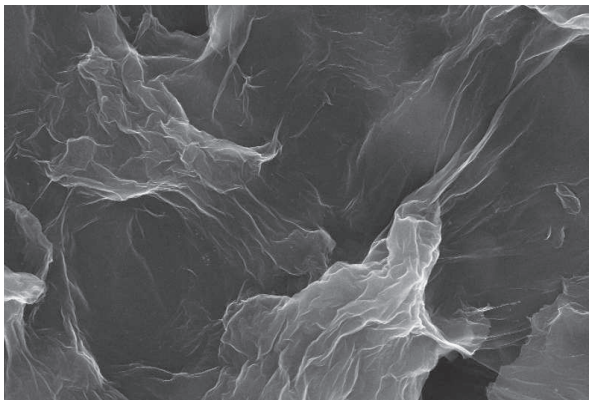

Fig. 1. The SEM image of the rGO/FM.

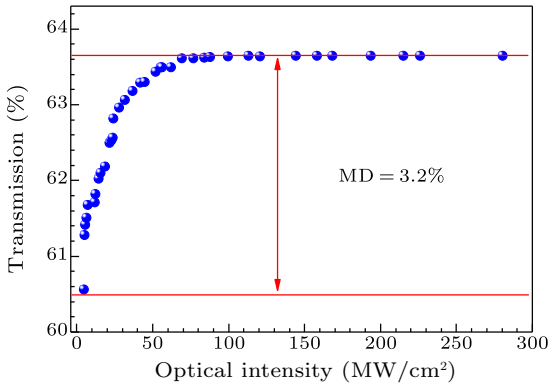

Fig. 2. Nonlinear saturable absorption of the rGO/FM SA.

To investigate the optical saturable absorption of the prepared rGO/FM SA, nonlinear transmission experiments have been conducted. A femtosecond pulsed EDF laser (central wavelength: 1560 nm, pulse duration: 530 fs, repetition rate: 27 MHz) works as the illumination source to study the nonlinear saturable absorption of the rGO/FM SA. Figure 2 shows the nonlinear transmission curve as a function of peak power intensity. As can be seen here, the MD of the rGO/FM SA is measured to be 3.2%.

The schematic diagram of EDF laser is depicted in Fig. 3. The ring laser oscillator cavity consists of a gain fiber, a wavelength division multiplexer (WDM), a polarization independent isolator (PI-ISO), an optical coupler (OC), a polarization controller (PC) and an rGO/FM SA. A 2-m-long EDF with absorption coefficient of 25 dB/m at 976 nm is employed as the gain medium. The EDF is pumped by a 976 nm laser diode (LD). The PI-ISO is used to force the unidirectional operation in the fiber ring cavity. The PC is engaged for achieving different polarization sates. The optical coupler is used and 10% portion of the laser is coupled out from the laser cavity. The other fibers and pigtails of the optical components are single-mode fibers (SMFs). The total length of laser cavity is 15.6 m.

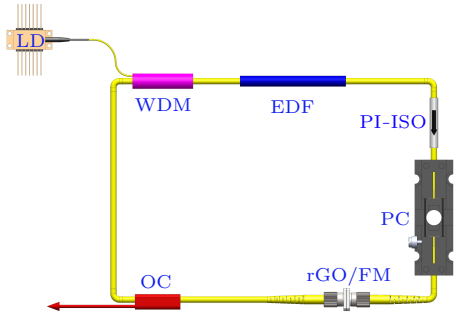

Fig. 3. Er-doped Q-switched fiber laser setup.

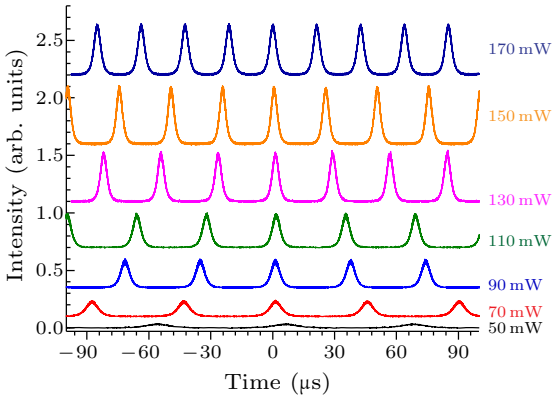

Fig. 4. The various pulse trains obtained under different pump powers.

In the experiments, the EDF laser with rGO/FM starts the continuous wave (CW) at the pump power of 9.6 mW. When the pump power reaches 50 mW, a stable Q-switching operation is obtained. The repetition rate increases as the pump power increases. The Q-switched pulse trains under different pump powers have been measured. Figure 4 records the stable pulse trains at the pump powers of 50 mW, 70 mW, 90 mW, 110 mW, 130 mW, 150 mW and 170 mW, respectively. It is also noted that the amplitude of Q-switched pulses enhances as the pump power increases to 150 mW, and the amplitude shows slightly decrease at the pump power of 170 mW. No significant pulse modulation is observed on the oscilloscope, which indicates that the Q-switching fiber laser works in a stable regime.

The optical spectrum with multi-peak structure is shown in Fig. 5, which is recorded under the pump powers of 50 mW, 80 mW, 110 mW, 140 mW and 170 mW. It can be seen that the optical spectrum broadens as the pump power increases and the optical spectrum at the pump power of 170 mW is narrower. It is understood that the rGO/FM is saturable at the pump power of 170 mW. The changes in repetition rate and pulse duration with the pump powers from 50 mW to 170 mW are shown in Fig. 6(a). The repetition rate increases from 18.42 kHz to 47.04 kHz

almost linearly with the pump power increasing from 50 mW to 170 mW, which is consistent with the typical properties of Q-switched pulses. The pulse duration goes down from 13.66 μs to 3.53 μs with a nearly exponentially declining, and then goes up to 3.89 μs with increasing the pump power from 50 mW to 170 mW. The shortest pulse duration of 3.53 μs is achieved at the pump power of 160 mW. As shown in Fig. 6(b), the average output power and the single pulse energy are plotted versus the pump power. The average output power and pulse energy have values of 0.06 mW and 3.33 nJ at an initial pump power of 50 mW. With increasing the pump power, the average output power increases linearly to 2.27 mW, while the single pulse energy goes up from 3.33 nJ to 48.19 nJ with the pump power increases from 50 mW to 170 mW. To evaluate the Q-switching stability, the experiments have been performed over 48 h with the pump power fixed at 140 mW. We have noted that the optical spectral contour and pulse train remained reasonably stable over the time period. The pulse width of 3.73 μs and the repetition rate of 38.27 kHz remains unchanged.

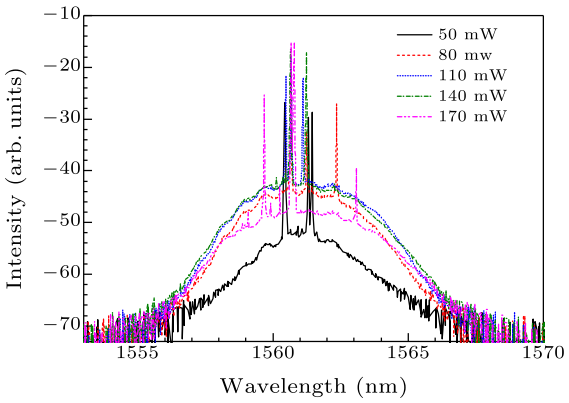

Fig. 5. Optical spectrum under different pump powers.

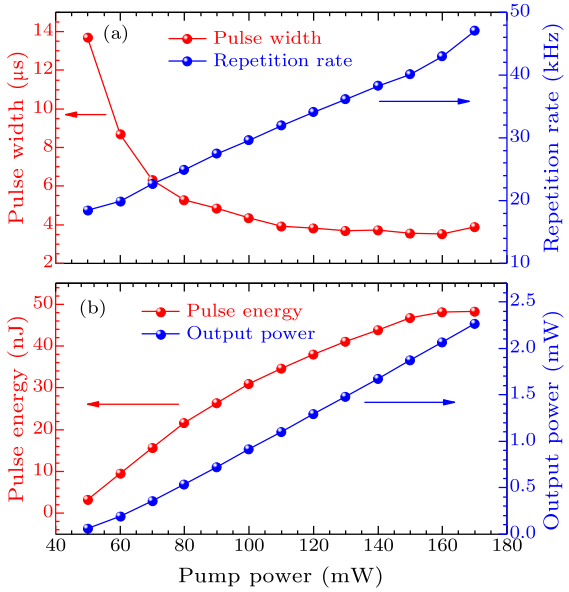

Fig. 6. (a) The pulse repetition rate and duration versus incident pump power, (b) the pulse energy and output power versus incident pump power.

In addition, we have verified that the Q-switching operation is purely contributed to by the saturable absorption of the rGO/FM SA. For this purpose, the rGO/FM SA is removed from the fiber laser. In this case, we could not observe Q-switching operation despite rotating the PC and adjusting the pump power. The comparative results show that the Q-switching operation is purely contributed to by the saturable absorption of the rGO/FM SA.

In conclusion, we have demonstrated a stable passively Q-switched EDF laser with rGO/FM as Q-switcher. The rGO is prepared by the thermal reduction method. By inserting the rGO/FM film into the laser cavity, the passively Q-switched EDF laser is obtained with generating the stable pulses. The single pulse energy goes up from 3.33 nJ to 48.19 nJ with the pump power increasing from 50 mW to 170 mW. The shortest pulse duration is 3.53 μs. These results show the feasibility and effectiveness of rGO/FM to Q-switched fiber laser and provide a meaningful reference for further research in nonlinear materials.

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