Graphene-based Q-switched pulsed fiber laser in a linear configuration

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Received August 30, 2011; accepted October 25, 2011; posted online January 6, 2012

A pulsed laser system is realized with graphene employed as a Q-switch. The graphene is exfoliated from its solution using an optical deposition and the optical tweezer effect. A fiber ferrule that already has the graphene deposited on it is inserted into an erbium-ytterbium laser (EYL) system with linear cavity configuration. We successfully demonstrate a pulsed EYL with a pulse duration of approximately 5.9 μs and a repetition rate of 20.0 kHz.

OCIS codes: 140.3540, 140.3538.
doi: 10.3788/COL201210.041405.

Graphene, an allotrope of carbon whose structure is one-atom-thick planar sheets of sp^2-bonded carbon atoms densely packed in a honeycomb crystal lattice (i.e., consisting of a hexagonal array of sp^2-bonded carbon atoms similar to those found in bulk graphite) is currently a major research topic of interest due to its uniqueness as a two-dimensional (2D) material. Bonaccorso *et al.* presented a detailed description on various aspects of graphene as well as its many possible applications in photonics and optoelectronics, where the combination of its unique optical and electronic properties could be fully exploited in the absence of a bandgap[1]. The linear dispersion of the Dirac electrons in graphene allows for ultra wideband tunability[1]. Its thin dimension and electronic properties make it suitable for electronic devices such as transistors and gas sensors. Graphene's resistivity to acids and alkalines provides an opportunity for its use in inert coatings as well. In optoelectronics, its special optical properties enable graphene to have an ultrashort recovery time in saturation absorption. In addition, it displays smaller non-saturable loss and a higher damage threshold. The unique absorption of light by graphene can become saturated when the input optical intensity is above a specific threshold value. Graphene can be readily saturated under strong excitation over the visible to near-infrared region due to the universal optical absorption resulting from the zero band-gap structure. This behavior is relevant for the mode-locking and Q-switching of fiber lasers, where short pulses have been achieved by using graphene-based saturable absorbers[2−6]. The first mode-locked laser in a ring configuration was reported by Hasan *et al.*[7], whose research observed saturation absorption over at least a 20-nm range with a pulse duration of ∼800 fs. Using graphene as a saturable absorber, Sun *et al.* successfully produced a mode-locked pulse train at a repetition rate of 19.9 MHz from a ring erbium-doped fiber laser (EDFL)[8]. Graphene has also been used to mitigate the mode competition in EDFLs as well as stabilize the multi-wavelength oscillation[9].

In this letter, we describe the successful production of a Q-switched pulsed laser using graphene inserted into a laser oscillation system within a linear cavity configuration. Thus far, as optical pulse generation by graphene has been reported primarily in a ring laser configuration, this device is, to the best of our present knowledge, the first ever Q-switched pulsed fiber laser using graphene achieved in a linear laser cavity configuration. One motivation of the present work is to propose a simple and efficient setup for short pulse generation (i.e., mode-locked operation) in a linear configuration.

The graphene flakes (in a solution) used in this research were supplied by Graphene Research. The graphene had to be deposited onto a fiber ferrule; we employed the optical tweezer effect for this purpose. The setup for depositing graphene onto the fiber ferrule is shown in Fig. 1. The fiber was prepared by removing the PVC coating, cleaving, and then placing it into the solution. Optical radiation from a 980-nm laser diode (LD) at 10 dBm was then propagated through the fiber; the laser was left on for 30 min. The laser beam has a very high intensity; therefore, at the end face of the fiber ferrule, it produces a very strong electric field gradient, resulting in the attraction of the graphene flakes along the field-gradient into the region of the strongest electric field. The laser beam exerts a force on the flakes that are in the beam, along the direction of beam propagation. The LD was then turned off, and the fiber was removed from the solution.

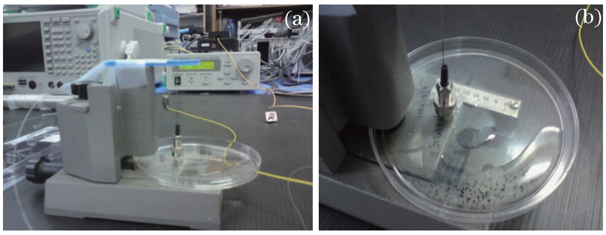

Fig. 1. (a) Experimental setup for deposition of graphene onto the end face of the fiber ferrule; (b) graphene flakes could be clearly seen in the solution. The flakes were deposited onto the ferrule by an attractive force caused by the gradient of the strong electric field near the end of the ferrule.

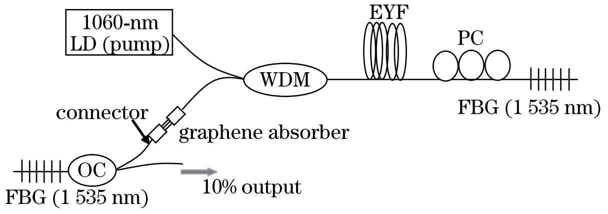

Fig. 2. Linear cavity configuration for a Q-switched laser system.

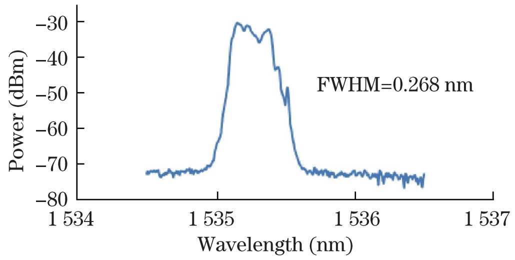

Fig. 3. Optical spectrum of the laser output with graphene inside the linear cavity. The FWHM measured is 0.268 nm.

The fiber was then inserted into the cavity of a laser system, as shown in Fig. 2. A 980/1550-nm wavelength division multiplexer (WDM) was used. The gain medium used in the setup was a 4-m-long erbium-ytterbium fiber (EYF) (Fibercore Ltd., USA) with a nominal peak absorption of 16.75 dB/m at 1 530 nm. The system was pumped with a LD operating at 1 060 nm and at a 100-mW output power level. Two fiber Bragg gratings (FBGs) with a reflection wavelength of 1 535 nm acted as the amplifier of the cavity. The graphene was inserted into the cavity using a connector. A 10-dB optical coupler (OC) enabled 90% of the light to oscillate in the cavity while allowing 10% of the light to leave the cavity as useful output. The polarization controller (PC) was carefully adjusted while the experiment was running.

Using an optical spectrum analyzer (OSA), we monitored the output laser spectrum in real time at an incident pump power level of 100 mW. By carefully adjusting the PC, the spectrum of the laser output is observed, as shown in Fig. 3. The wavelength of the laser is centered at 1 535 nm with a full-width at half-maximum (FWHM) of 0.268 nm.

Figure 4 shows the optical conversion of the pulsed laser system. The threshold pump power is 13 mW (without graphene) and 16 mW (with graphene), indicating that—due to the intrinsic loss of graphene—a higher pump power is necessary for lasing to begin.

With careful adjustment of the optical components, the Q-switched pulsed laser operation was successfully observed as soon as the pump power reached a threshold condition of approximately 25.0 mW. The average output power level was about 20 mW, corresponding to a slope efficiency of 23.3%, when the system was pumped at 100 mW. Based on the data supplied by the manufacturer (Fibercore Ltd. USA), the absorption of the pump light in the active fiber is close to 100%. We measured the 4-m-long EYF absorption efficiency to be 99.4%, which is close to the value expected from the data provided by Fibercore Ltd. The ratio of the output power levels between graphene Q-switched operation and continuous wave (CW) operation has a value of about 0.66. This value is significant and interesting to note as it indicates that graphene has a low insertion loss and, therefore, has a large potential for better Q-switching and saturable absorption compared with conventional light absorbing components, when carefully employed in an appropriate laser system.

The pulses formed by the Q-switching process in the resonator were detected using a 6-GHz photodetector (Hewlett Packard 83440B, USA) and a 500-MHz digital phosphor oscilloscope (LeCroy WaveJet 352A, USA). Figure 5 shows the relationship between the input pump power and the pulse repetition rate. The repetition rate of the graphene Q-switched laser has a monotonically increasing, near-linear dependence on the pump power level, which is consistent with the findings of Popa *et al.*[10].

The repetition rate as a function of the pump power varies from approximately 20 kHz to approximately 70 kHz. A repetition rate of 20.0 kHz was achieved at a pump power level of about 32 mW. It is clear that, as the pump power increases, the laser output has a higher pulse repetition rate. The typical oscilloscope traces of the Q-switched pulse train at different pump power levels are shown in Fig. 6.

In Q-switched lasers, the repetition rate depends on the pump power. As the pump power is increased, more gain is provided to saturate the saturable absorber. Since pulse generation relies on saturation, the repetition rate increases with pump power[10]. In our experiment, the maximum single-pulse energy obtained was calculated to be 184.0 nJ at a repetition rate of 20.0 kHz with a pump power level of 32 mW.

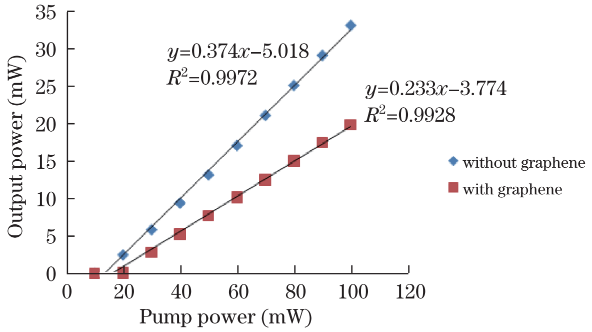

Fig. 4. Plot of output laser power against the pump power. The linear configuration with a graphene absorber inside has a lower efficiency due to the intrinsic loss of the graphene deposited on the fiber ferrule.

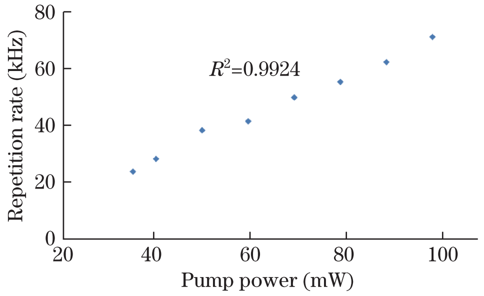

Fig. 5. Relationship between the input pump's power level and the pulse repetition rate, with a R-squared value of 0.9924.

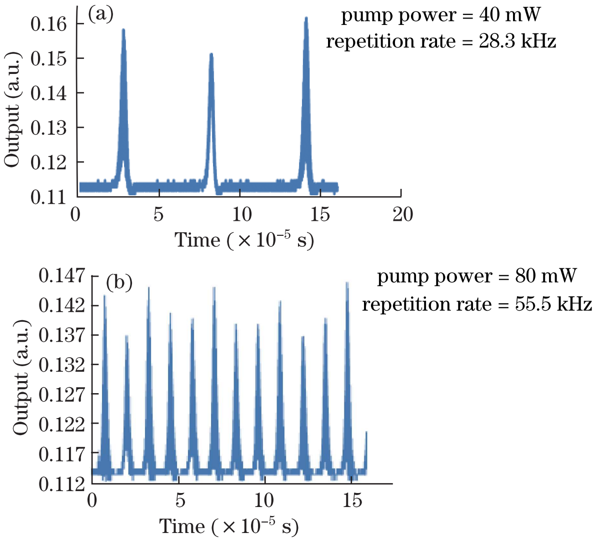

Fig. 6. Oscilloscope traces of the pulse train at different pump power levels.

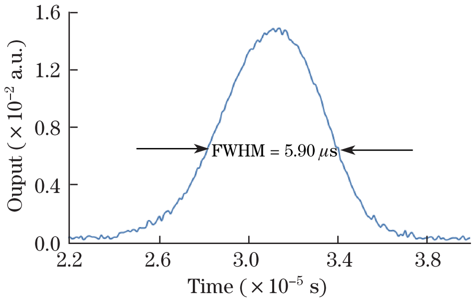

Fig. 7. Single pulse trace. The FWHM measured is 5.90 μs at a pump power of 28.9 mW.

The pulse duration was measured to be 5.90 μs at an incident pump power level of 28.9 mW, as shown in Fig. 7. The relatively long pulse duration is consistent with the findings of Popa *et al.*, who obtain a pulse duration of approximately 2 μs and pulse energy of approximately 40 nJ with a 1.25-m-long EDFL gain section, demonstrating that Q-switched fiber lasers typically exhibit long pulse durations and low repetition rates[10]. Graphene has zero bandgap, and saturable absorption is due to the Pauli blocking of electrons and holes for occupation of the energy levels in the conduction and valence bands[4]. At low light intensity levels, equilibrium is re-established through electron-hole recombination, which is the dominant process. In addition, compared with a ring configuration, the linear cavity is not as stable, possibly due to stronger mode competition effects. Shorter pulse durations can be achieved by optimizing the cavity length, cavity loss, and perhaps the coupling output as well. The use of greater pump power could also be attempted.

Figure 8 shows the pulse width variation as a function of the input pump power level. Figure 9 shows pulse measurements at 50 and 80 mW. Figure 8 clearly shows that increasing the pump power level reduces the pulse duration. In our case, this reduction is limited by the available pump power. In our experiments, the pump power level was not increased beyond 100 mW, as the thermal damage threshold of the graphene on the ferrule is a matter of concern. Tapered fiber or D-shaped fiber could be one means of improving the damage threshold. By down-tapering the fiber, the mode field diameter (MFD) can be increased[11], which could cause the light intensity at the tapered end to decrease, thereby improving the thermal threshold. The use of D-shaped fiber makes it possible to employ evanescent field interaction of the light with graphene[6] and would probably increase the durability of the graphene. Bae *et al.* demonstrated a graphene-based picosecond pulsed laser using a D-shaped fiber without any apparent degradation of the graphene in either physical damage or nonlinear functionality[6], thereby clearly highlighting the significance of the evanescent field interaction of the guided light with graphene.

The deposition of graphene could be optimized by monitoring the back-reflection of light from the graphene solution into the ferrule. Manipulating the duration of deposition could monitor the thickness of the graphene desired and its uniformity around the ferrule. In addition, the length of the gain medium and cavity could be optimized in order to maximize the propagation of single-mode light in the system.

In conclusion, we produce a Q-switched pulsed laser that uses graphene as a passive Q-switch. Pulsing occurs at a pump power level of approximately 25 mW. The

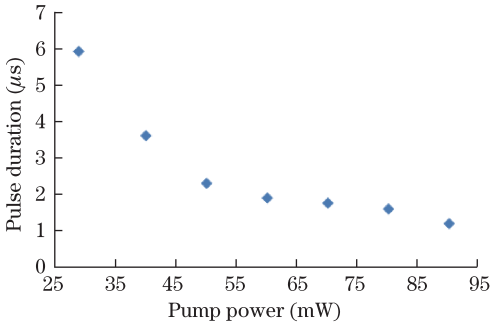

Fig. 8. Pulse width at FWHM as a function of input pump power at 1 535 nm. The pulse duration and the pump power clearly have an inverse relationship, namely, the pulses are shorter at higher pump power levels.

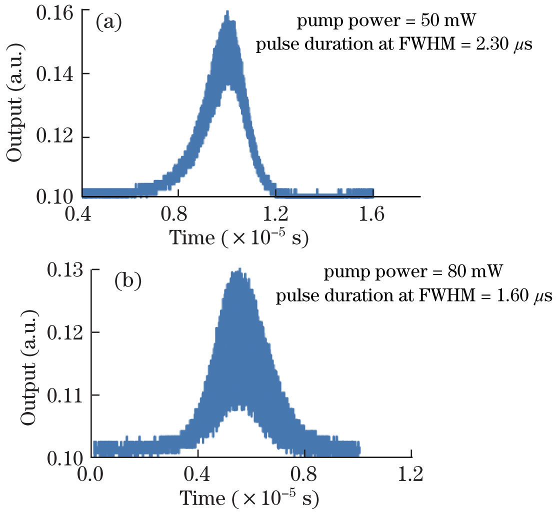

Fig. 9. Oscilloscope traces of a single pulse at different pump power levels.

pulses produced have a repetition rate of 20 kHz at an incident pump power of 32.2 mW. The pulse duration measures approximately 5.9 μs when pumped at 28.9 mW. The maximum pulse energy obtained is approximately 184 nJ. This device is, to the best of our current knowledge, the first ever graphene-based *Q*-switched pulsed laser in a linear oscillatory configuration.

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