Graphene-based passively Q-switched dual-wavelength erbium-doped fiber laser

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Received August 17, 2010; revised September 30, 2010; accepted October 6, 2010; posted October 12, 2010 (Doc. ID 133466); published October 29, 2010

We demonstrate a compact *Q*-switched dual-wavelength erbium-doped fiber (EDF) laser based on graphene as a saturable absorber (SA). By optically driven deposition of graphene on a fiber core, the SA is constructed and inserted into a diode-pumped EDF laser cavity. Also benefiting from the strong third-order optical nonlinearity of graphene to suppress the mode competition of EDF, a stable dual-wavelength *Q*-switching operation has been achieved using a two-reflection peak fiber Bragg grating as the external cavity mirror. The *Q*-switched EDF laser has a low pump threshold of 6.5 mW at 974 nm and a wide range of pulse-repetition rate from 3.3 to 65.9 kHz. The pulse duration and the pulse energy have been characterized. This is, to the best of our knowledge, the first demonstration of a graphene-based *Q*-switched laser. © 2010 Optical Society of America

OCIS codes: 140.3510, 140.3540, 060.4370.

Q-switched fiber lasers are of great interest because of their versatile applications to remote sensing, range finding, medicine, laser processing, and telecommunications. Compared to actively *Q*-switched fiber lasers, passively *Q*-switched fiber lasers possess the attractive advantages of compactness, simplicity, and flexibility in design. Passively *Q*-switched Yb^{3+}- or Er^{3+}-doped fiber lasers have been intensively investigated using different kinds of saturable absorbers (SAs) [1–4], such as transition metal-doped crystals [2], semiconductor saturable absorber mirrors (SESAMs) [3], and single-wall carbon nanotubes (SWNTs) [4]. Considering the compatibility between SAs and optical fibers, SESAMs and SWNTs are generally thought of as the ideal SAs for realizing all-fiber *Q*-switched lasers. However, SESAMs require complex fabrication and expensive packaging. Although the SWNT is simple and cost-effective, bandgap engineering or diameter/charity control of the SWNT is often demanded for obtaining a broad wavelength range of saturable absorption. Moreover, the higher surface energy of the SWNT results in a low damage threshold, poor stability, and poor long-term reliability of SWNT-based passive laser pulsation.

Bao *et al.* [5] have recently reported that graphene can provide outstanding saturable absorption, overcoming these inherent drawbacks of SWNTs and SESAMs. Because of its unique energy band properties with the Pauli blocking principle, graphene possesses significant advantages over SWNTs, including much lower saturation intensity [5,6], larger saturable-absorption modulation depth [5], higher damage threshold [7,8], ultrafast recovery time, and an ultrabroad wavelength-independent saturable-absorption range (300–2500 nm) [8]. Some techniques have been developed to integrate graphene into fiber devices to construct SAs for passive laser pulsation production [5–11]. However, all these reports are focused on graphene mode locking with a fiber ring cavity. To the best of our knowledge, the graphene-based *Q*-switched laser has not been reported previously. In this Letter, by the optically driven deposition of graphene on a fiber end to construct a SA, we report what we believe to be the first demonstration of a compact graphene-based *Q*-switched Er^{3+}-doped fiber laser (EDFL). Moreover, the strong nonlinear optical property of graphene is also used for the first time to suppress the mode competition of erbium-doped fiber (EDF) for realizing the dual-wavelength *Q*-switched output.

Graphene used in our experiment was prepared by the solution-based route [12] reported by Li *et al.* Initially, graphene oxide (GO) was synthesized from natural graphite powder by a modified Hummers method. In a typical experiment for chemical conversion of GO to graphene, 20 ml of GO aqueous dispersion (0.25 mg/ml) was mixed with 10 μl of hydrazine solution (80 wt.%) and 70 μl of ammonia solution (28 wt.%) in a 50 ml round-bottom flask. After being stirred for a few minutes, the flask was transferred to an oil bath (~95 °C) and stirred overnight. The average thickness of the as-prepared graphene characterized by atomic force microscopy is around 1 nm. In addition, the transmission of the graphene film sprayed on a glass plate was measured to be ~90% in the wavelength range of 1000 to 2500 nm. Because the theoretical thickness of single-layer graphene is ~0.34 nm and the absorption loss of per layer is 2.3%, the as-prepared graphene is estimated to have three to five layers. Then the key problem is how to transfer the graphene in the aqueous suspension on a fiber core. Two methods, i.e., graphene film deterministic replacement on the fiber end [5,10] and graphene solution deposited on the side-polished fiber [8], have been previously used to construct graphene-based SAs. Alternatively, here we employed the optically driven deposition method [13], as shown in Fig. 1(a), because it is a cost-efficient and easy-to-operate technique for transferring the graphene on the fiber end. When 25 mW of laser radiation from a 974 nm laser diode (LD) was propagating in a fiber, the fiber was dipped into the graphene aqueous suspension for 25 min and then moved out to evaporate for ~20 min in a heating gun operating at 40 °C. Graphene was easily deposited on the fiber core,

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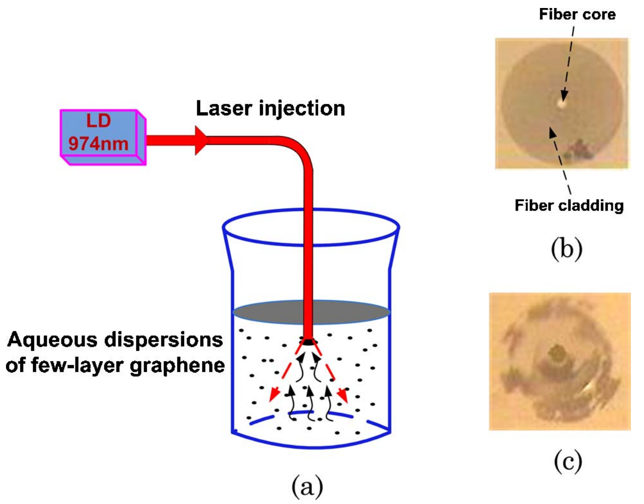

Fig. 1. (Color online) (a) Schematic diagram for depositing graphene on the fiber end face by optical radiation. Images of the fiber end face (b) before and (c) after the graphene was deposited.

benefiting from the efficient thermophoresis due to optical absorption of the graphene solution. Using an optical microscope, we recorded the images of the fiber end face before and after graphene was deposited, respectively, as shown in Figs. 1(b) and 1(c). It is obvious from Fig. 1(c) that the graphene has been well deposited on the fiber core. The insertion loss of the graphene-deposited fiber device is 1.8 dB at 1550 nm. Using a 1550 nm pulsed fiber laser as a probe laser, we measured the saturation intensity of the graphene fiber device as 0.66 MW/cm^2, and the relative saturable-absorption modulation depth was 45%.

Figure 2 shows the experimental setup of the compact graphene-based passively Q-switched dual-wavelength EDFL. A 3 m long EDF with peak absorption of 27–30 dB/m at 1530 nm was used as the gain medium. The EDF was backward pumped by a 974 nm LD through a wavelength division multiplexer (WDM). The as-prepared graphene-deposited fiber device played the key role of a passive Q switcher. A polarization controller (PC) was utilized for optimization of the laser output. The wavelength-selective element was composed of a fiber Bragg grating (FBG) in combination with an optical circulator, which also ensured clockwise unidirectional operation. The transmission spectrum of the FBG is given in the inset of Fig. 2. There are two reflection peaks with

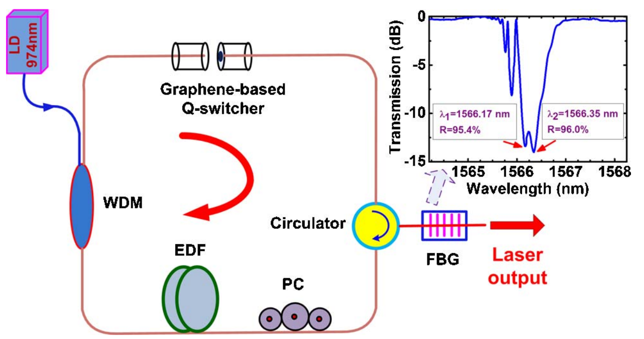

Fig. 2. (Color online) Experimental setup of the proposed graphene-based dual-wavelength Q-switched EDFL. Inset, transmission spectrum of the FBG with two reflection peaks.

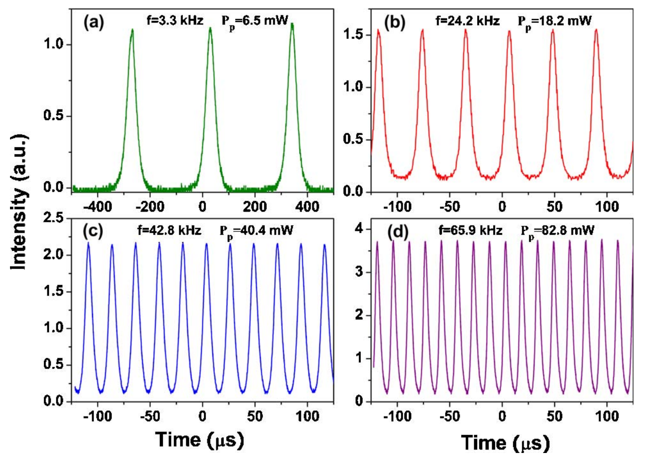

Fig. 3. (Color online) Typical oscilloscope traces of the Q-switched pulse trains under different pump powers: (a) 6.5, (b) 18.2, (c) 40.4, and (d) 82.8 mW.

reflectivity of 95.4% and 96.0%, respectively, at 1566.17 and 1566.35 nm. The overall length of the laser cavity was ~8 m. The laser output from the ~4% transmission of the FBG was measured by an optical spectrum analyzer (OSA), a power meter, and an oscilloscope together with a photodetector.

At the pump power of 6.5 mW, the EDFL started lasing with the passive Q-switching mode. The pump threshold is much lower than that of SWNT- or SESAM-based Q-switched EDFLs [3,4], mainly owing to a lower saturation intensity of the graphene. Under the different pump power, Fig. 3 shows the typical oscilloscope traces of the Q-switched pulse trains, which were measured by a photodetector with a bandwidth of 20 MHz. The pulse-repetition rate of the Q-switched EDFL can be widely tuned from 3.3 kHz to 65.9 kHz by varying the pump power from 6.5 to 82.8 mW. At every specific repetition rate and pump power, the Q-switching pulse output was stable and no significant pulse jitter was observed on the oscilloscope.

Figure 4 shows the pulse duration and the pulse energy as a function of the pump power. By increasing the pump power, the pulse duration becomes shorter and shorter and the pulse energy monotonically increases. At the incident pump power of 82.8 mW, the Q-switched EDFL has a pulse duration of 3.7 μs and pulse energy of 16.7 nJ

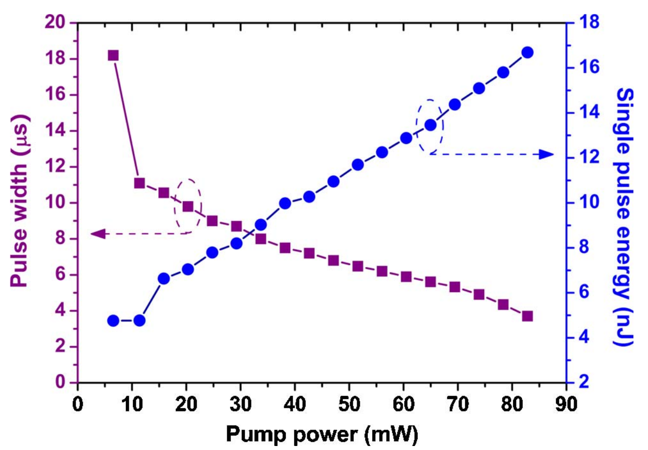

Fig. 4. (Color online) Pulse duration and pulse energy as a function of the incident pump power.

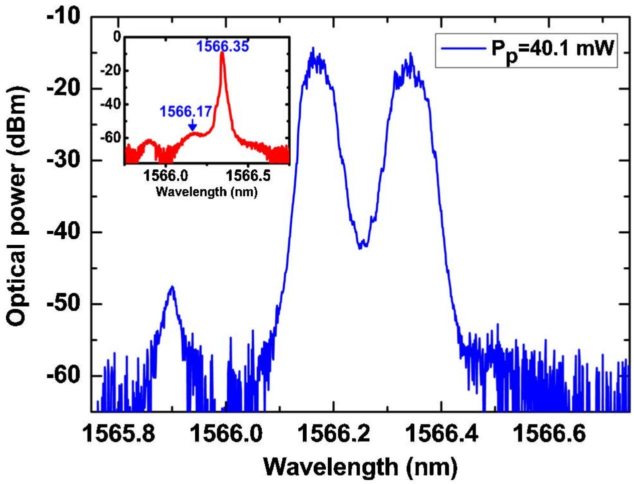

Fig. 5. (Color online) Typical dual-wavelength lasing spectrum of the graphene *Q*-switched EDFL at the pump power of 40.1 mW. Inset, cw laser output spectrum without the graphene-based *Q* switcher in the cavity.

with an average output power of 1.1 mW. Considering the only ~4% transmission of the FBG as the laser output and the insertion losses of the circulator and the FBG, the intracavity average power at the position of the graphene-based SA has been up to ~34 mW at the pump power of 82.8 mW. To protect the graphene-based *Q* switcher from the thermal damage, we did not use a higher pump power in our experiments. The pulse duration could be further reduced and the pulse energy could be scaled up by (i) optimizing the *Q*-switched laser system, including the cavity length, the cavity loss, and the coupling output and (ii) increasing the pump power and improving the damage threshold of the as-prepared graphene, such as by depositing the graphene on a D-shape fiber or a tapered fiber.

Using an OSA with spectral resolution of 0.01 nm, we measured the typical output optical spectrum at the pump power of 40.1 mW. As shown in Fig. 5, the graphene-based *Q*-switched EDFL shows a dual-wavelength simultaneous oscillation at 1566.17 and 1566.35 nm. Both the lasing wavelengths have a 3 dB linewidth of ~0.04 nm. It is surprising that the dual-wavelength lasing can be achieved without any specialized technique to suppress the mode competition of EDF. In contrast, the cw EDFL without the graphene-based SA in the cavity was also measured and always showed a single-wavelength lasing at 1566.35 nm. As a result, it is confirmed that the dual-wavelength output results from the graphene. Recently, Hendry *et al.* have shown that graphene possesses a strong third-order nonlinear optical property ($|\chi^{(3)}| \sim 10^{-7}$ esu), especially for generating highly efficient four-wave mixing (FWM) [14]. Moreover, FWM has been verified to be helpful for multiwavelength generation in EDFLs by the self-stabilizing effect [15,16]. Therefore, the FWM from the graphene is helpful for the simultaneous generation of dual-wavelength *Q*-switching pulses in our system. In addition, the output pulse performances (including pulse duration and repetition rate) at the two different wavelengths are close to those of the total pulses, as shown in Figs. 3 and 4. Moreover, the output dual-wavelength can be tuned from ~1566 to ~1570 nm by applying axial strain on the FBG.

In conclusion, a compact graphene-based *Q*-switched EDFL with dual-wavelength output has been proposed and experimentally demonstrated. The strong optical nonlinearity of graphene is helpful for eliminating the mode competition of EDF for stabilizing the dual-wavelength lasing. The laser has a low pump threshold of 6.5 mW at 974 nm, a wide range of repetition rate from 3.3 to 65.9 kHz, pulse energy of up to 16.7 nJ, and pulse duration of 3.7 μs. All these performances with this preliminary design of graphene-based *Q*-switched EDFL are superior or comparable to the results obtained with a SWNT-based SA [4].

This work is supported by the National Natural Science Foundation of China (NSFC) (grant 20701031).

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