Graphene Q-switched, tunable fiber laser

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We demonstrate a wideband-tunable Q-switched fiber laser exploiting a graphene saturable absorber. We get ~2 μs pulses, tunable between 1522 and 1555 nm with up to ~40 nJ energy. This is a simple and low-cost light source for metrology, environmental sensing, and biomedical diagnostics. © *2011 American Institute of Physics*. [doi:10.1063/1.3552684]

Q-switching and mode-locking are the two main techniques enabling pulsed lasers.[1] In mode-locking, the random phase relation originating from the interference of cavity modes is fixed, resulting in a single pulse,[1] with typical duration ranging from tens ps to sub-10 fs,[2] and a repetition rate corresponding to the inverse of the cavity round-trip time.[2] Many aspects, including the dispersive and nonlinear proprieties of the intracavity components, need to be precisely balanced in order to achieve stable operation.[1,2] Q-switching is a modulation of the quality factor, Q, of a laser cavity,[1] Q being the ratio between the energy stored in the active medium and that lost per oscillation cycle[1] (thus, the lower the losses, the higher the Q). In Q-switching, the active medium is pumped while lasing is initially prevented by a low Q factor.[1] The stored energy is then released in a pulse with duration ranging from μs to ns when lasing is allowed by a high Q factor.[1] The time needed to replenish the extracted energy between two consecutive pulses is related to the lifetime of the gain medium, which is typically ~ms for erbium-doped fibers.[1] Thus the repetition rate of Q-switched lasers is usually low [~kHz (Ref. 1)], much smaller than mode-locked lasers.[1,2] On the other hand, Q-switching enables much higher pulse energies and durations than mode-locking.[1] Q-switching has advantages in terms of cost, efficient operation (i.e. rate of output pulse energy to input power), and easy implementation, compared to mode-locking, which needs a careful design of the cavity parameters to achieve a balance of dispersion and nonlinearity.[1,2] Q-switched lasers are ideal for applications where ultrafast pulses (<1 ns) are not necessary, or long pulses are advantageous,[3,4] such as material processing, environmental sensing, range finding, medicine, and long-pulse nonlinear experiments.[3–5]

Q-switching can be active (exploiting, e.g., an acousto-optic or electro-optic modulator[1]), or passive [using, e.g., a saturable absorber (SA)[1]]. Passive Q-switching features a more compact geometry and simpler setup than active, which requires additional switching electronics.[1] For Q-switching the SA recovery time does not need to be shorter than the cavity round-trip time, since the pulse duration mainly depends on the time needed to deplete the gain after the SA saturates,[1,2] unlike mode-locking.[2] Doped bulk crystals,[5] and semiconductor SA mirrors (SESAMs)[3,6] are the most common SAs in passive Q-switching.[1] However, the use of doped crystals as SAs requires extra elements (mirrors, lenses) to focus the fiber output into the crystal.[5] SESAMs have limited operation bandwidth, typically few tens nm,[7] thus are not suitable for broad-band tunable pulse generation. Broadband SAs enabling easy integration into an optical fiber system are thus needed to create a compact Q-switched fiber laser.

Single wall carbon nanotubes (SWNTs) and graphene are ideal SAs, due to their low saturation intensity, low-cost and easy fabrication.[8–23] Broadband operation is achieved in SWNTs using a distribution of tube diameters,[8,18] while this is an intrinsic property of graphene, due to the gapless linear dispersion of Dirac electrons.[19–22,24] Q-switching was reported using SWNTs: Ref. 25 achieved 14.1 nJ pulse energy and 7 μs width, while Ref. 26 reported 13.3 nJ and 700 ns. After our demonstration of a graphene-based mode-locked laser,[18] various group implemented graphene SAs in a variety of cavity designs.[19–23,27–29]

Here, we demonstrate a fiber laser Q-switched by a graphene SA (GSA). The broadband absorption of graphene enables Q-switching over a 32 nm range, limited only by our tunable filter, not graphene itself. The pulse energy is ~40 nJ, for ~2 μs duration.

Graphite flakes are exfoliated by mild ultrasonication with sodium deoxycholate (SDC).[20,22,30] A dispersion en-

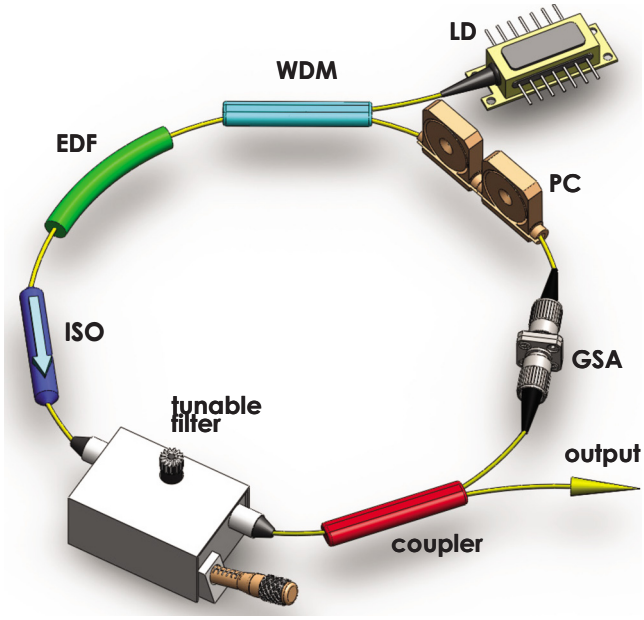

FIG. 1. (Color online) Schematic setup of our graphene-Q switched laser: laser diode (LD), wavelength division multiplexer (WDM), erbium doped fiber (EDF), isolator (ISO), graphene-based saturable absorber (GSA), and polarization controller (PC).

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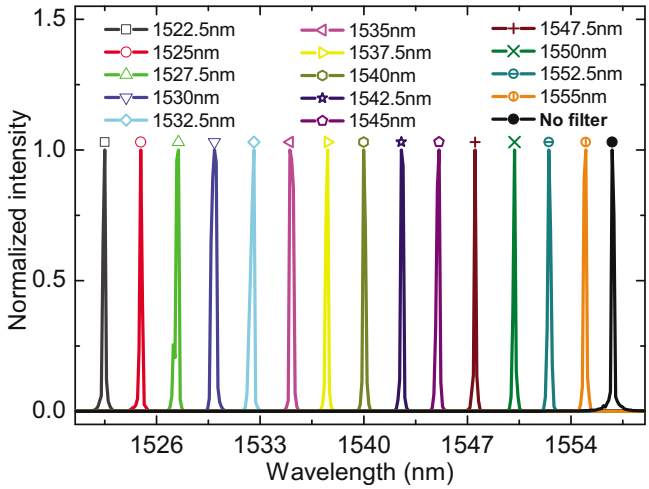

FIG. 2. (Color online) Output spectra for 14 tuning wavelengths. The curve with a filled circle corresponds to Q-switching without filter.

riched with single (SLG) and few layer graphene (FLG)[22] is then mixed with an aqueous solution of polyvinyl alcohol (PVA). After water evaporation, a ~50 μm thick graphene-PVA composite is obtained.[18,20] This is then placed between two fiber connectors to form a fiber-compatible SA, then integrated into a laser cavity, Fig. 1, with 1.25 m erbium-doped fiber (EDF) as gain medium, pumped with a 980 nm laser diode (LD), coupled via a wavelength division multiplexer (WDM). An optical isolator (ISO) ensures unidirectional light propagation. An in-line tunable optical bandpass filter is inserted after the ISO. Our EDF can support lasing between 1520 and 1560 nm.[31] The operation wavelength is selected by rotating the dielectric interference filter. The 20% port of an optical coupler provides the laser output. The rest of the cavity consists of a combination of single mode fiber (SMF) Flexcor 1060 and SMF-28. All fibers used in our cavity are polarization-independent, i.e., they support any light polarization, even if this changes as a result of outside perturbations (e.g., mechanical stresses, bending, or temperature). Thus, to improve the output pulse stability, we place in the cavity a polarization controller (PC), consisting of 2 spools of SMF-28 fiber acting as retarders. The total retardation induced by the PC is a function of the fiber geometry in the spool.[31] This allows to maintain a given polarization state after each round trip. The total cavity length is ~10.4 m. The operation is evaluated by a 14 GHz bandwidth photodetector and an oscilloscope. A spectrum analyzer with 0.07 nm resolution measures the output spectrum.

Continuous wave operation starts at ~43 mW pump power; pulsed operation at ~74 mW. The repetition rate is pump-dependent up to ~200 mW [Fig. 4(b)], a typical signature of Q-switching.[1] The output spectrum is tunable from ~1522 to 1555 nm. This is comparable to the 31 nm range reported for doped crystal Q-switched tunable lasers,[5] but much larger than the 5 nm thus far achieved for SWNT Q-switched lasers.[25,26] Our tuning range is limited by the filter and by the EDF gain, not by the GSA. Figure 2 shows the output spectra for 14 wavelengths at ~2.5 mW output power. Without filter, the laser exhibits Q-switching at 1557 nm. The full width at half maximum (FWHM) spectral width is 0.3 ± 0.1 nm over the whole tuning range, much shorter than thus far achieved for graphene mode-locked lasers.[18–23,27–29]

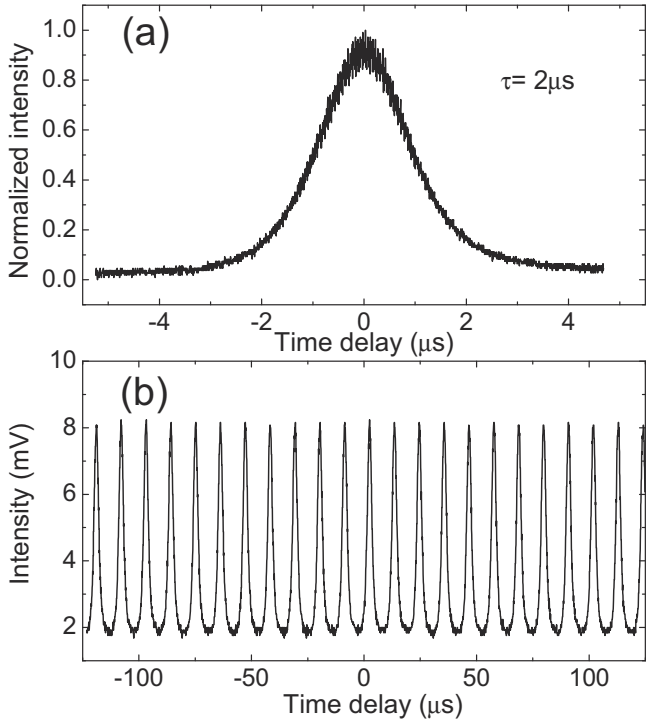

FIG. 3. (a) Single pulse envelope. (b) Typical pulse train for 2.8 mW output power.

Figure 3(a) plots a typical pulse envelope, having FWHM ~2 μs, comparable to fiber lasers Q-switched with other SAs (e.g., SESAMs,[3,6] doped crystals,[5] and SWNTs[25,26]), but much longer than thus far achieved in graphene mode-locked fiber lasers.[19–23,27–29] The output pulse duration has little dependence on wavelength, possibly due to the flat gain coefficient of our EDF.[31] Figure 3(b) shows the pulse train for a typical laser output at 158 mW pump power.

The output power varies from 1 to 3.4mW as a function of pump power [Fig. 4(a)]. The slope efficiency, i.e., the slope of the line obtained by plotting the laser output power against the input pump power,[1] is ~2%. The repetition rate as a function of pump power varies from 36 to 103 kHz [Fig. 4(b)], with a 67 kHz change for a 2.4 mW output power variation. Unlike mode-locked lasers, where the repetition

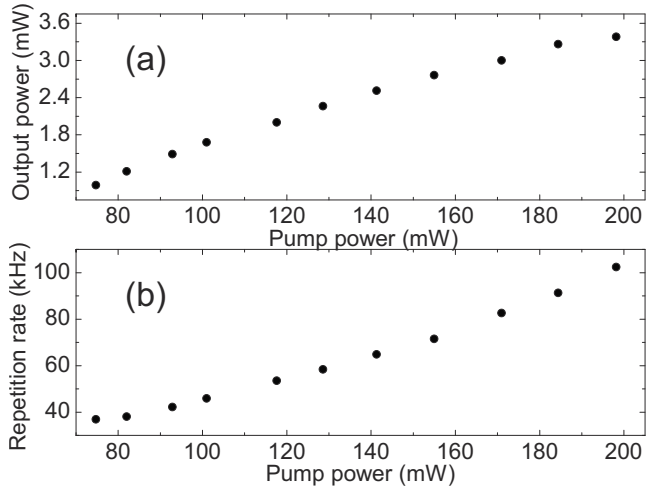

FIG. 4. (a) Output power and (b) repetition rate, as a function of input pump power at 1540 nm

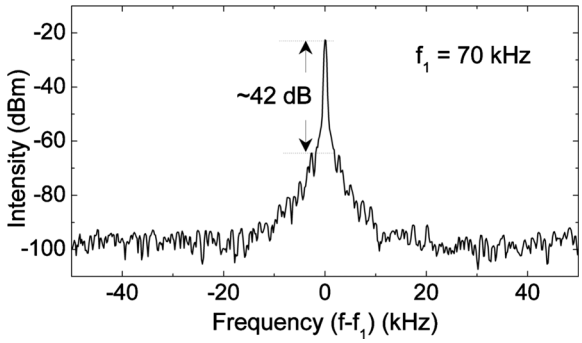

FIG. 5. Output rf spectrum measured around ~70 kHz at 1540 nm.

rate is fixed by the cavity length,[1] in Q-switched lasers this depends on pump power.[1] As this increases, more gain is provided to saturate the SA. Since pulse generation relies on saturation, the repetition rate increases with pump power.[1] The maximum output pulse energy is ~40 nJ for ~60 kHz repetition rate, similar to that achieved using other SAs.[26] Compared to graphene mode-locked fiber lasers,[19–23,27–29] our pulse energy is ~6 times larger, but with less peak power, due to the larger pulse duration. It is also much larger than thus far achieved in SWNT Q-switched lasers.[25,26] Even higher energies, thus peak powers, could be enabled by evanescent field interaction with GSA[28] and high-gain fibers (e.g., cladding-pumped fibers[5] or large mode area fibers[3]).

The radio-frequency (rf) measurement of the output intensity at 70 kHz, corresponding to a period of ~143 μs, is shown in Fig. 5. The peak to pedestal extinction is ~40 dB (10^4 contrast), confirming pulse stability.

In conclusion, we achieved Q-switching exploiting a graphene-based SA, using standard, telecom grade, fiber components. The wideband operation of graphene enables broad-band tunability. Such wideband Q-switched laser could provide a simple, low-cost, and convenient light source for metrology, environmental sensing, and biomedical diagnostics.

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[1]O. Svelto, *Principles of Lasers*, 4th ed. (Plenum, New York, 1998).
[2]U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Honninger, N. Matuschek, and J. A. der Au, IEEE J. Sel. Top. Quantum Electron. **2**, 435 (1996).
[3]R. Paschotta, R. Haring, E. Gini, H. Melchior, U. Keller, H. L. Offerhaus, and D. J. Richardson, Opt. Lett. **24**, 388 (1999).
[4]M. Siniaeva, M. Siniavsky, V. Pashinin, A. Mamedov, V. Konov, and V. Kononenko, Laser Phys. **19**, 1056 (2009).
[5]M. Laroche, A. M. Chardon, J. Nilsson, D. P. Shepherd, W. A. Clarkson, S. Girard, and R. Moncorge, Opt. Lett. **27**, 1980 (2002).
[6]S. Kivistö, R. Koskinen, J. Paajaste, S. D. Jackson, M. Guina, and O. G. Okhotnikov, Opt. Express **16**, 22058 (2008).
[7]O. Okhotnikov, A. Grudinin, and M. Pessa, New J. Phys. **6**, 177 (2004).
[8]F. Wang, A. G. Rozhin, V. Scardaci, Z. Sun, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, Nat. Nanotechnol. **3**, 738 (2008).
[9]G. Della Valle, R. Osellame, G. Galzerano, N. Chiodo, G. Cerullo, P. Laporta, O. Svelto, A. G. Rozhin, V. Scardaci, and A. C. Ferrari, Appl. Phys. Lett. **89**, 231115 (2006).
[10]S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, IEEE J. Sel. Top. Quantum Electron. **10**, 137 (2004).
[11]A. G. Rozhin, V. Scardaci, F. Wang, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, Phys. Status Solidi B **243**, 3551 (2006).
[12]A. Martinez, K. Zhou, I. Bennion, and S. Yamashita, Opt. Express **18**, 11008 (2010).
[13]M. A. Solodyankin, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, A. V. Tausenev, V. I. Konov, and E. M. Dianov, Opt. Lett. **33**, 1336 (2008).
[14]Z. Sun, A. G. Rozhin, F. Wang, V. Scardaci, W. I. Milne, I. H. White, F. Hennrich, and A. C. Ferrari, Appl. Phys. Lett. **93**, 061114 (2008).
[15]Z. Sun, T. Hasan, F. Wang, A. G. Rozhin, I. H. White, and A. C. Ferrari, Nano Res. **3**, 404 (2010).
[16]Z. Sun, A. G. Rozhin, F. Wang, T. Hasan, D. Popa, W. O'Neill, and A. C. Ferrari, Appl. Phys. Lett. **95**, 253102 (2009).
[17]T. R. Schibli, K. Minoshima, H. Kataura, E. Itoga, N. Minami, S. Kazaoui, K. Miyashita, M. Tokumoto, and Y. Sakakibara, Opt. Express **13**, 8025 (2005).
[18]T. Hasan, Z. Sun, F. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, Adv. Mater. **21**, 3874 (2009).
[19]Z. Sun, D. Popa, T. Hasan, F. Torrisi, F. Wang, E. J. R. Kelleher, J. C. Travers, V. Nicolosi, and A. C. Ferrari, Nano Res. **3**, 653 (2010).
[20]Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, ACS Nano **4**, 803 (2010).
[21]F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, Nat. Photonics **4**, 611 (2010).
[22]T. Hasan, F. Torrisi, Z. Sun, D. Popa, V. Nicolosi, G. Privitera, F. Bonaccorso, and A. C. Ferrari, Phys. Status Solidi B **247**, 2953 (2010).
[23]D. Popa, Z. Sun, F. Torrisi, T. Hasan, F. Wang, and A. C. Ferrari, Appl. Phys. Lett. **97**, 203106 (2010).
[24]A. K. Geim and K. S. Novoselov, Nature Mater. **6**, 183 (2007).
[25]D. Zhou, L. Wei, B. Dong, and W. Liu, IEEE Photon. Technol. Lett. **22**, 9 (2010).
[26]B. Dong, C. Liaw, J. Hao, and J. Hu, Appl. Opt. **49**, 5989 (2010).
[27]H. Zhang, D. Y. Tang, L. M. Zhao, Q. L. Bao, and K. P. Loh, Opt. Express **17**, 17630 (2009).
[28]Y. W. Song, S. Y. Jang, W. S. Han, and M. K. Bae, Appl. Phys. Lett. **96**, 051122 (2010).
[29]A. Martinez, K. Fuse, B. Xu, and S. Yamashita, Opt. Express **18**, 23054 (2010).
[30]Y. Hernandez, V. Nicolosi, M. Lotya, F. M. Blighe, Z. Y. Sun, S. De, I. T. McGovern, B. Holland, M. Byrne, Y. K. Gun'ko, J. J. Boland, P. Niraj, G. Duesberg, S. Krishnamurthy, R. Goodhue, J. Hutchison, V. Scardaci, A. C. Ferrari, and J. N. Coleman, Nat. Nanotechnol. **3**, 563 (2008).
[31]G. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic Press, San Diego, CA, 2001).