Graphene saturable absorber power scaling laser

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Abstract: A solution-processed graphene-film coated on a fiber-based connector is used for stable, mode-locked femtosecond-duration pulses with 16 mW average output power.

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1. Introduction

Graphene and carbon nanotubes (CNTs) are promising saturable absorbers (SAs) for mode-locking of fiber lasers [1–3]. Broadband operation is achieved with CNTs by combining tubes of different diameters [4], while it is an intrinsic property of graphene, due to the linear dispersion of Dirac electrons [5]. This, along with the ultrafast recovery time [6], and low saturation fluence [1, 7], makes graphene an excellent broadband SA [1, 7–9]. A variety of approaches have been used to make graphene-based SA (GSA) mode-locked lasers [10], with output power ranging, e.g., from∼3W [11] for a graphene oxide SA to∼270mW for a chemical vapor deposited GSA [12], generated in solid-state lasers [11, 12], to few-mW directly generated from fiber oscillators with GSAs coupled between fiber connectors [10]. The most commonly used GSA for fiber lasers [10] are fabricated from liquid phase exfoliation (LPE) of graphite [13, 14] in water [15] or organic solvents [13, 16]. Graphene produced by LPE can be embedded into polymer composites [2], which can be integrated into various systems [1, 2, 5, 7, 8]. Here we use LPE graphene in a polymer-free film coated onto a fiber based connector. This reduces non-saturable losses, making it suitable for high average-power applications and device miniaturization [8]. Based on this, we demonstrate a mode-locked fiber laser, achieving stable sub-250 fs pulses with a repetition rate of 21 MHz. The output power ranges from∼0.8 mW to more than 15 mW.

2. Results

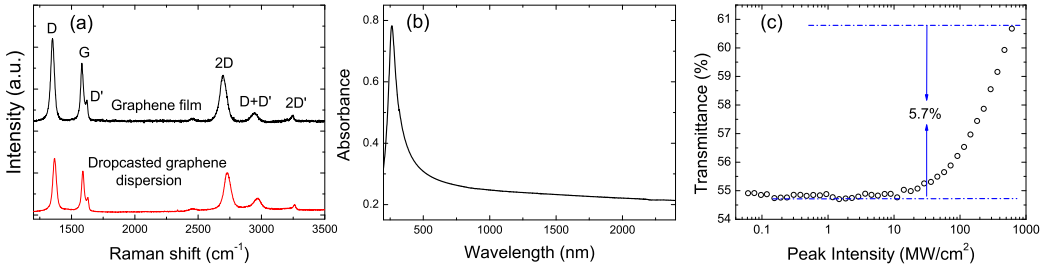

Fig. 1. (a) Raman spectrum of dropcast-graphene and GSA. (b) Linear absorbance and (c) Nonlinear transmittance.

We fabricate a GSA by exfoliating graphite flakes via ultrasonic treatment in a solution of deionised water and sodium cholate (SC) (0.9wt%) [1, 15], followed by ultracentrifugation at 10000 rpm for 1 hour. The resulting top 70% dispersion is then filtered in vacuum through a nitrocellulose membrane (Millipore 100 nm pore-size filter). This blocks the flakes, while allowing water to pass through, resulting in a film on the top of the membrane. This is then transferred on the tip of a fiber connector and the membrane is dissolved in an acetone/water mixture. A control sample for optical characterization is also prepared by transferring the film on a quartz plate and annealing (∼90°C, to improve adhesion) for 1 hour, followed by dissolution of the filter in acetone/water. To investigate the flakes' quality before and after film fabrication, and to monitor defects, we measure the Raman spectra at 457, 514.5, and 633 nm. Fig.1(a) plots a typical Raman spectrum of a drop-cast graphene dispersion on a Si wafer and the resulting film. Besides the G and 2D peaks, significant D and D' bands as well as their combination mode D+D' at ∼2950 cm^{-1} are also present [17]. We assign the D and D' peaks to the sub-micrometer edges of our flakes [18], rather than to disorder within the flakes. This is corroborated by a multi-wavelength Raman analysis: the resulting G peak dispersion is below 0.05 cm^{-1}/nm [16]. There is no significant change in the spectrum of the film with respect to that of the drop-cast dispersion. Thus, the fabrication process does not affect the structure or quality of the flakes. The 2D peak is still single Lorentzian, thus,

even if the flakes are multi-layers, they are electronically decoupled and, to a first approximation, behave as a collection of single layers [17, 19]. The GSA has a featureless linear absorption from 500 to 2000 nm, Fig.1(b), save the UV van Hove singularity peaks [20], and∼5.7% non-linear transmittance change at 1.5 μm, Fig.1(c).

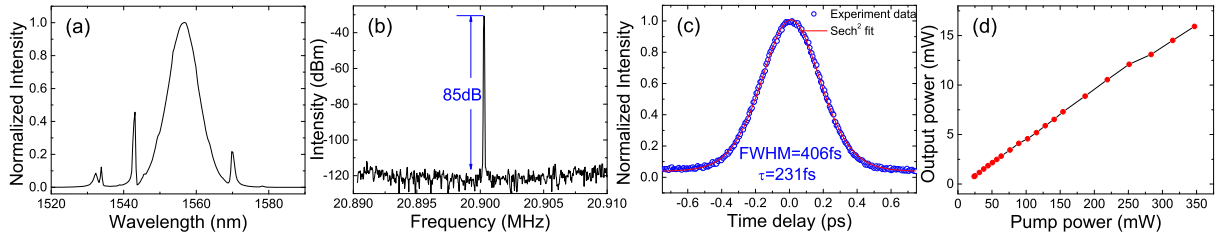

Fig. 2. (a) Optical spectrum; (b) RF spectrum (c); Autocorrelation trace and (d) Average output power vs. pump power.

We use a ring cavity with 3 m erbium doped fiber (EDF), pumped by a 980 nm diode through a wavelength division multiplexer. Unidirectional operation is enabled by an optical isolator. A polarization controller is used for mode-locking optimization. Output of the laser is provided by the 20% port of a coupler. The total cavity length is∼9 m. Mode-locking starts at ∼23 mW pump power, with∼0.8 mW output power at ∼21 MHz repetition rate. A typical spectrum is shown in Fig.2(a), with the corresponding intensity autocorrelation trace in Fig.2(c). The full width at half maximum (FWHM) is 406 fs. Assuming a sech^2 fit, deconvolution gives 231 fs pulse duration. The radio frequency (RF) spectrum in Fig.2(b) gives a signal-to-noise ratio>80 dB indicating low-amplitude fluctuations, thus stable mode-locking [21]. Mode-locked operation can be maintained up to a pump power∼350 mW. The output power scales linearly with pump power as for Fig.2(d), with a maximum∼16 mW. The output power is limited by the maximum power of our pump laser, and higher average power would be possible using a higher power laser diode.

3. Conclusions

We demonstrated a mode-locked fiber laser using a graphene film saturable absorber. The easy integration of the GSA into the fiber connector shows potential in the development of next generation compact ultrafast fiber lasers.

4. Acknowledgments

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References

1. Z. Sun, et al., "Graphene Mode-Locked Ultrafast Laser," ACS Nano **4**, 803 (2010).
2. T. Hasan, et al., "Nanotube-polymer composites for ultrafast photonics," Adv. Mater. **21**, 3874 (2009).
3. V. Scardaci, et al., "Carbon Nanotube Polycarbonate Composites for Ultrafast Lasers," Adv. Mater. **20**, 4040 (2008).
4. F. Wang et al., "Wideband-tuneable, nanotube mode-locked, fibre laser" Nat. Nano. **3**, 738 (2008).
5. F. Bonaccorso, et al., "Graphene Photonics and Optoelectronics," Nat. Photonics **4**, 611 (2010).
6. D. Brida, et al., "Ultrafast collinear scattering and carrier multiplication in graphene," Nat. Commun. **4**, 1987, (2013).
7. D. Popa, et al., "Sub 200 fs pulse generation from a graphene mode-locked fiber laser," Appl. Phys. Lett. **97**, 203106 (2010).
8. R. Mary, et al., Opt. Express **21**, 7943 (2013).
9. C. A. Zaugg, et al., Opt. Express **21**, 31548 (2013).
10. Z. Sun, et al., "Ultrafast lasers mode-locked by nanotubes and graphene," Physica E **44**, 1082 (2012).
11. C. Feng, et al., "3 W high-power laser passively mode-locked by graphene oxide saturable absorber," Opt. Commun. **298**, 168 (2013).
12. A. A. Lagatsky, et al., "2 μm Solid-State Laser Mode-locked By Single-Layer Graphene," Appl. Phys. Lett. **102**, 013113 (2013).
13. Y. Hernandez, et al., "High-yield production of graphene by liquid-phase exfoliation of graphite," Nat. Nanotechnol. **3**, 563 (2008).
14. F. Bonaccorso, et al., "Production and processing of graphene and 2d crystals," Mater. Today **15**, 564 (2012).
15. T. Hasan, et al., "Solution-phase exfoliation of graphite for ultrafast photonics," Phys. Status Solidi B **247**, 2953 (2010).
16. F. Torrisi, et al., "Inkjet-Printed Graphene Electronics," ACS Nano **6**, 2992 (2012).
17. A. C. Ferrari, et al., "Raman spectrum of graphene and graphene layers," Phys. Rev. Lett. **97**, 187401 (2006).
18. C. Casiraghi, et al., "Raman spectroscopy of graphene edges," Nano Lett. **9**, 1433 (2009).
19. A. C. Ferrari, et al., "Raman spectroscopy as a versatile tool for studying the properties of graphene," Nat. Nano. **8**, 235 (2013).
20. V. G. Kravets, et al., Phys. Rev. B **81**, 155413 (2010).
21. D. von der Linde, "Characterization of the Noise in Continuously Operating Mode-locked Lasers," Appl. Phys. B **39**, 201 (1986).