APPLIED PHYSICS LETTERS **95**, 253102 (2009)

A compact, high power, ultrafast laser mode-locked by carbon nanotubes

Z. Sun, A. G. Rozhin, F. Wang, T. Hasan, D. Popa, W. O'Neill, and A. C. Ferrari[a)]
Department of Engineering, University of Cambridge, Cambridge CB3 0FA, United Kingdom

(Received 25 November 2009; accepted 30 November 2009; published online 21 December 2009)

We report ultrafast highly chirped pulses from an erbium doped, nanotube-mode-locked fiber oscillator. We generate 1.6 W average power and 11 kW peak power by seeding a fiber amplifier. This paves the way to mode-locked all-fiber master oscillator amplifiers as economic and compact sources for high-power applications, such as micromachining and laser surgery. © *2009 American Institute of Physics*. [doi:10.1063/1.3275866]

Ultrafast fiber lasers attract considerable interest as alternative to bulk solid state lasers, due to their efficient heat dissipation and alignment-free waveguide format.[1–3] Fiber based amplification is a viable route to reach high output power.[2,3] Erbium doped fiber amplifiers (EDFAs) are widely used in telecommunications for their large bandwidth and gain. However, in direct amplification, i.e., when the source output is directly seeded into an amplifier input, the peak power (P_{peak}) can become so high that nonlinear spatial, spectral, and temporal pulse-shape distortions or damage may occur.[3] The output intensity, i.e., power per unit area, is further limited by the saturation fluence and energy storage capacity of the gain medium.[3] One solution is to increase the effective confined mode area (A_{eff}), using large mode area (LMA) fibers[2,4] to reduce the intensity. However, increasing A_{eff} can lead to large losses, even for small fiber imperfections, or bending during operation.[4] Alternatively one can work on the pulse width by introducing a chirp, i.e., a time dependence of the instantaneous frequency, by using a propagating medium where the group velocity is frequency dependent.[4] Before amplification, the input pulse is widened by chirping with a stretcher (e.g., a grating),[2–4] decreasing P_{peak}.[2–4] The chirped pulse can then be amplified until P_{peak} reaches the maximum allowed before the onset of nonlinearities.[5] After amplification, the chirp of the output pulse is removed, i.e., dechirping with a compressor, recovering a pulse width close to the original one, but now with a much higher P_{peak} and, thus, much higher average power, P_{avg}. This method is called chirped-pulse amplification (CPA).[2,3,5] While direct amplification of undistorted ultrafast pulses has not been achieved for energies (E) above $\sim$1 nJ,[3] fiber based CPA can work up to hundreds μJs, by widening the input pulse duration up to 10^5 times.[3] However, the stretcher complicates the design,[6] eliminating the alignment-free waveguide format, due to the use of free-space components.[6] Ultrafast fiber lasers at normal group velocity dispersion (GVD) can achieve chirped output pulses up to few hundred times the transform limited duration[7–12] and can thus be amplified without a stretcher, offering a compact and low cost high power system.[10,11]

Saturable absorbers based on single wall carbon nanotubes (SWNTs) are promising passive mode-lockers with low fabrication cost, subpicosecond recovery time, broad operation range, low saturation power, polarization insensitivity, and mechanical and environmental robustness.[13–27] Highly chirped pulses with $E=3$ nJ and $P_{avg}=155$ mW were generated using a normal GVD oscillator,[27] but with a loss of performance after a few days due to mode-locker damage.[12] $P_{avg}=250$ mW, $E=6.5$ nJ were reported for SWNT mode-locked pulses from a fiber oscillator, using anomalous intracavity GVD to favor solitonlike pulse shaping.[18] However, the soliton area theorem $[E\times\tau\propto(\beta_2/n_2)]$ states that the product of E and pulse duration (τ) is fixed by the cavity dispersion (β_2) and nonlinearity (n_2),[28] therefore E is typically limited by the system design, with a trade-off between E and pulse width.[28] LMA fibers were also used to amplify SWNT mode-locked pulses to $P_{avg}=1.5$ W, $E=67$ nJ.[29] However, as discussed above, this approach is prone to losses.[4] Also, mode-matching LMA and single-mode fibers increases cost, eliminating the advantages of the fiber waveguide format.[6,10]

Here, we demonstrate a compact high-power fiber laser based on direct amplification of highly chirped pulses, mode-locked by SWNTs from a normal GVD oscillator, with $P_{avg}=1.6$ W, $E=65$ nJ, $P_{peak}=11$ kW. These are comparable to what reported for LMA-based amplification of SWNT mode-locked pulses,[29] but using standard, telecom-grade, single-mode fiber components, with no specially designed fibers nor additional mode-matching devices (such as the mode transformer of Ref. 29). Furthermore, we generate a much larger chirp by inserting a dispersion component directly inside the cavity, rather than placing it outside, as typically done for the stretcher in CPA systems[3]). This paves the way to much higher amplification, in principle up to MW peak power.

We use a $\sim$2 mm^2 SWNT-based saturable absorber prepared as for Refs. 20 and 30. Power-dependent absorbance measurements at 1550 nm give a saturation intensity $\sim$18.9 MW/cm^2 and modulation depth $\sim$16.9%. The packaged composite is inserted into a fiber ring cavity. A 3.6 m erbium doped fibre (EDF) is forward pumped by a 980 nm laser diode through a fused wavelength division multiplexer to provide gain. The EDF is selected to form a normal GVD cavity. It also provides spectral filtering, cutting the pulse temporal wings introduced by normal GVD during intracavity propagation,[7,10] and keeps the pulse self-consistent,[7,10] i.e., stable after every cavity round trip. The total cavity length is $\sim$8.55 m. A fused 40/60 coupler allows 40% of the pulse out of the cavity.

Mode-locking self starts at $\sim$55 mW pump power, with an output $P_{avg}=4.6$ mW and repetition rate f_{Rep} $\sim$24.5 MHz. Figure 1(a) plots a typical output spectrum,

---

[a)]Electronic mail: acf26@eng.cam.ac.uk.

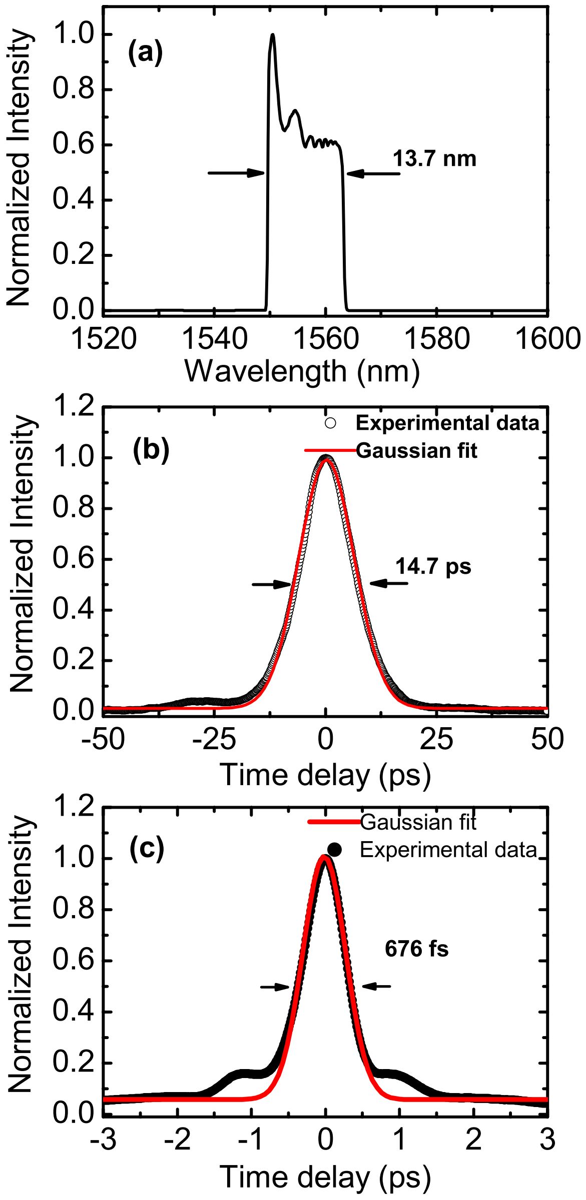

FIG. 1. (Color online) Pulses from oscillator: (a) output spectrum; [(b) and (c)] autocorrelation traces (b) before and (c) after dechirping.

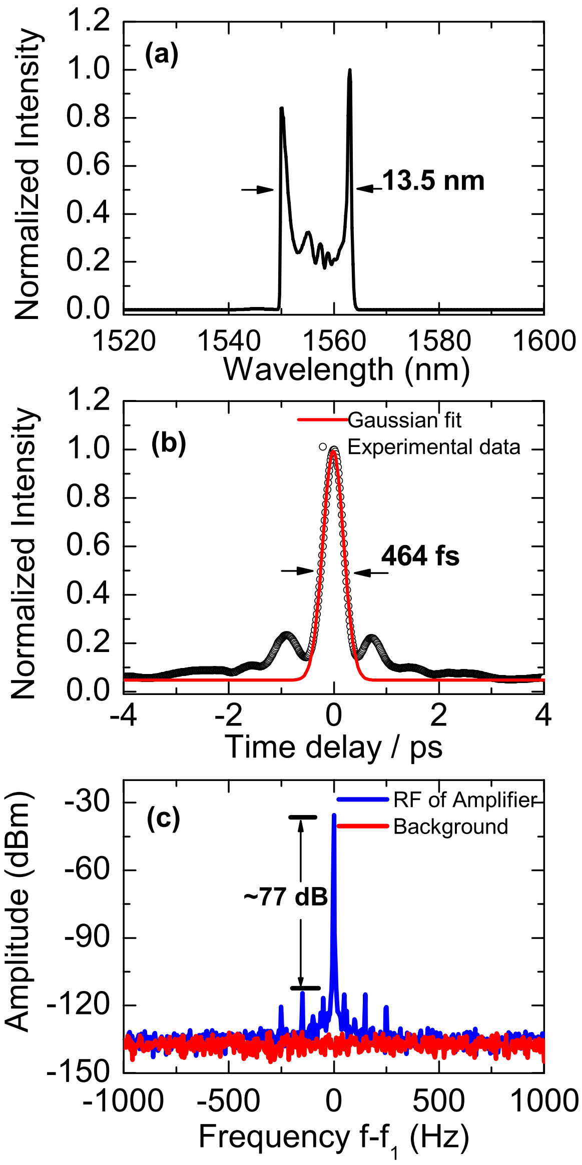

FIG. 2. (Color online) Pulses from amplifier: (a) output spectrum; (b) autocorrelation trace after dechirping; (c) rf spectra at the fundamental repetition rate.

centered at $\sim$1550 nm, with full width at half maximum (FWHM) $\sim$13.7 nm. This has steep sides, typical of mode-locked fiber lasers with significant net normal GVD.[7–9,27] Figure 1(b) is a representative second harmonic generation (SHG) autocorrelation trace. Assuming a Gaussian profile, the deconvolution gives a pulse duration $\sim$10.4 ps, with time-bandwidth product (TBP) $\sim$17.8, over 40 times the expected transform limited 0.44.[31] Figure 1(c) shows that the pulses are dechirped to 478 fs after a 46.6 m single mode fiber (SMF28), with no change of output spectrum. The autocorrelation trace has an increased pedestal, most likely due to the small nonlinearity of the long compensation fiber.[32] Figures 1(b) and 1(c) show that the pulse from the oscillator is over 20 times broader than after external dechirping, going from 10.4 ps to 478 fs, with P_{peak} 20 times lower. Therefore, we expect 20 times less nonlinear effects, being these proportional to P_{peak}.[32]

We use a Pritel EDFA to amplify the chirped pulses. The output fiber is a traditional single-mode with $\sim$10 μm core. The input $P_{\text{avg}} \sim 7$ mW. Figure 2 plots typical characteristics of the amplified pulses with output $P_{\text{avg}}=0.6$ W. Figure 2(a) shows that the output spectrum has steep sides, derived from the pulses seeded from the oscillator. The amplified pulses duration is $\sim$13.3 ps. Figure 2(b) plots the SHG autocorrelation trace after 31.5 m single mode fiber. Its FWHM $\sim$464 fs corresponds to $\sim$328 fs for a Gaussian profile.[31] In Gaussian pulses $P_{\text{peak}} \sim (0.94 \times P_{\text{avg}})/(\tau \times f_{\text{Rep}})$.[4] From the compressed pulse width 328 fs and $P_{\text{avg}}=0.6$ W, the maximum achievable P_{peak} is $\sim$70 kW. After compensation, an increased pedestal is observed, likely due to the nonlinearity during amplification and dechirping. The maximum output is $P_{\text{avg}}=1.6$ W, with no pulse breaking, $E=65$ nJ and $P_{\text{peak}}=11$ kW. P_{avg} is only limited by our amplifier saturation, and P_{avg} up to tens of Watts would be possible using a higher saturation amplifier. P_{peak} is limited by nonlinear distortion, which results in incompressible pulses.[32] Higher P_{peak} is realizable by seeding even larger chirped pulses to further decrease the nonlinearity. Refs. 13, 14, and 27 reported SWNT-based highly chirped fiber oscillators at $\sim$1 μm, with up to $\sim$750 times the transform limited duration.[13] In principle, this could enable P_{peak} exceeding MWs.

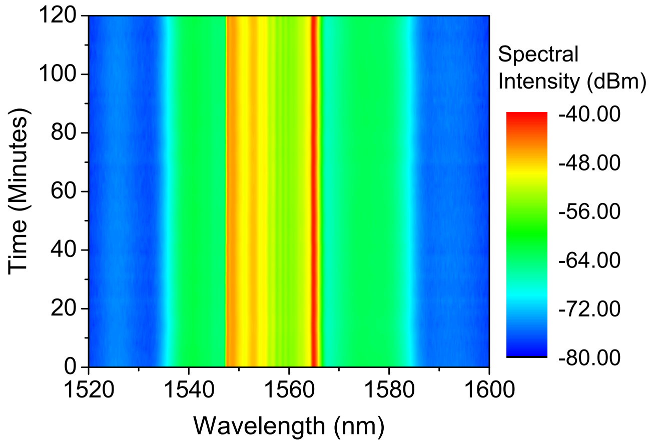

FIG. 3. (Color online) Output stability.

Fiber lasers are very sensitive to temperature variations and fiber bends.[4] We tested stability over a noncontinuous period of 4 months, finding no degeneration. Figure 3 plots a typical, stable optical spectrum recorded without temperature and vibration control over 2 h. The stability can also be probed using radio frequency (rf) measurements of the output.[33] Figure 2(c) plots the rf spectrum. A signal-to-noise ratio of 77 dB ($10^{7.7}$ contrast) is observed, highlighting the low-amplitude pulse fluctuation from oscillator and amplifier.

In conclusion, SWNTs enable highly chirped pulses in a compact ultrafast source based on direct amplification. Our system only uses single-mode fibers and standard telecom components, representing an economic and compact alternative for high-power applications, such as micromachining and laser surgery.

We acknowledge funding from EPSRC Grant No. GO30480/1, the Isaac Newton trust, and Royal Society, European Research Council Grant NANOPOTs. We thank I. H. White, F. Ye, and L. Zhao for useful discussions.

[1] O. Okhotnikov, A. Grudinin, and M. Pessa, New J. Phys. **6**, 177 (2004).
[2] F. Dausinger, F. Lichtner, and H. Lubatschowski, *Femtosecond Technology for Technical and Medical Applications* (Springer, Berlin, 2004).
[3] M. E. Fermann, A. Galvanauskas, G. Sucha, and D. Harter, Appl. Phys. B: Lasers Opt. **65**, 259 (1997).
[4] R. Paschotta, *Encyclopedia of Laser Physics and Technology* (Wiley, Weinheim, Germany, 2008).
[5] D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
[6] P. K. Mukhopadhyay, K. Ozgoren, I. Budunoglu, and F. Ilday, IEEE J. Sel. Top. Quantum Electron. **15**, 145 (2009).
[7] L. M. Zhao, D. Y. Tang, and J. Wu, Opt. Lett. **31**, 1788 (2006).
[8] A. Chong, W. H. Renninger, and F. W. Wise, Opt. Lett. **32**, 2408 (2007).
[9] B. Ortac, O. Schmidt, T. Schreiber, J. Limpert, A. Tunnermann, and A. Hideur, Opt. Express **15**, 10725 (2007).
[10] W. H. Renninger, A. Chong, and F. W. Wise, Opt. Lett. **33**, 3025 (2008).
[11] X. Tian, M. Tang, X. Cheng, P. Shum, Y. Gong, and C. Lin, Opt. Express **17**, 7222 (2009).
[12] M. Schultz, H. Karow, O. Prochnow, D. Wandt, U. Morgner, and D. Kracht, Opt. Express **16**, 19562 (2008).
[13] E. J. R. Kelleher, J. C. Travers, S. V. Popov, J. R. Taylor, Z. Sun, A. G. Rozhin, and A. C. Ferrari, Appl. Phys. Lett. **95**, 111108 (2009).
[14] E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Opt. Lett. **34**, 3526 (2009).
[15] 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).
[16] Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G. C. Wang, and X. C. Zhang, Appl. Phys. Lett. **81**, 975 (2002).
[17] S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, IEEE J. Sel. Top. Quantum Electron. **10**, 137 (2004).
[18] Y. W. Song, S. Yamashita, and S. Maruyama, Appl. Phys. Lett. **92**, 021115 (2008).
[19] 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).
[20] T. Hasan, Z. Sun, F. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, Adv. Mater. (Weinheim, Ger.) **21**, 3874 (2009).
[21] 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).
[22] G. Della Valle, R. Osellame, G. Galzerano, N. Chiodo, G. Cerullo, P. Laporta, O. Svelto, U. Morgner, A. G. Rozhin, V. Scardaci, and A. C. Ferrari, Appl. Phys. Lett. **89**, 231115 (2006).
[23] K. H. Fong, K. Kikuchi, C. S. Goh, S. Y. Set, R. Grange, M. Haiml, A. Schlatter, and U. Keller, Opt. Lett. **32**, 38 (2007).
[24] 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).
[25] A. Schmidt, S. Rivier, G. Steinmeyer, J. H. Yim, W. B. Cho, S. Lee, F. Rotermund, M. C. Pujol, X. Mateos, M. Aguilo, F. Díaz, V. Petrov, and U. Griebner, Opt. Lett. **33**, 729 (2008).
[26] Y. W. Song, S. Yamashita, C. S. Goh, and S. Y. Set, Opt. Lett. **32**, 430 (2007).
[27] K. Kieu and F. W. Wise, Opt. Express **16**, 11453 (2008).
[28] L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. Ippen, Appl. Phys. B: Lasers Opt. **65**, 277 (1997).
[29] J. C. Jasapara, A. DeSantolo, J. W. Nicholson, A. D. Yablon, and Z. Várallyay, Opt. Express **16**, 18869 (2008).
[30] V. Scardaci, Z. Sun, F. Wang, A. G. Rozhin, T. Hasan, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, Adv. Mater. (Weinheim, Ger.) **20**, 4040 (2008).
[31] W. Koechner, *Solid-State Laser Engineering* (Springer, Berlin, 1999).
[32] G. P. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic, Boston, 2007).
[33] D. Von der Linde, Appl. Phys. B: Lasers Opt. **39**, 201 (1986).