Characterization of short-pulse oscillators by means of a high-dynamic-range autocorrelation measurement

A. Braun, J. V. Rudd, H. Cheng, and G. Mourou

Center for Ultrafast Optical Science, University of Michigan, Room 1006, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109-2099

D. Kopf, I. D. Jung, K. J. Weingarten, and U. Keller

Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg HPT, CH-8093 Zürich, Switzerland

Received April 14, 1995

A high-dynamic-range autocorrelation technique was used to characterize the temporal pulse shape of ultrashort laser pulses produced from four separate oscillators. These lasers included two Kerr-lens mode-locked Ti:sapphire oscillators as well as a Nd:glass and a Ti:sapphire oscillator, each passively mode locked by an antiresonant Fabry–Perot semiconductor saturable absorber. It was shown that the Nd:glass oscillator supported a pulse that was temporally clean over 8 orders of magnitude.

By the method of chirped-pulse amplification,[1] it is now possible to amplify ultrashort (<1-ps) laser pulses to the joule energy level and to achieve focused intensities exceeding 10^{18} W/cm^2.[2] With these peak intensities, new laser–matter interactions can be studied,[3] including the creation of solid-density plasmas[4] and the generation of short-pulse x-ray emission.[5] In such experiments a high-peak-power short pulse must interact directly with a solid target.[6] If the amplified pulse contains a temporal prepedestal with an intensity greater than the ionization threshold of the target, the main pulse will interact with a preplasma, altering the physics of the experiment. Therefore the intensity level of any long-time-scale structure under the pulse must be below the ionization intensity of the target. Inasmuch as the target material has an ionization threshold of roughly 10^{11} W/cm^2, an amplified laser pulse with a focused peak intensity of 10^{18} W/cm^2 has to be temporally clean over at least 7 orders of magnitude. For an amplified pulse with a high temporal contrast ratio to be produced, a clean seed pulse needs to be generated.[7] The availability of a clean, short pulse directly from an oscillator would be a great benefit to chirped-pulse amplification laser systems.

High-dynamic-range autocorrelation measurements[8] were used to characterize the temporal quality of pulses generated from four short-pulse laser oscillators. This technique was used because of the much larger dynamic range obtained[9] than in those measurements that give information on the symmetry of the pulse.[10] Two of the oscillators studied were Kerr-lens mode-locked (KLM) Ti:Al_2O_3 (Ti:sapphire) lasers. The other two oscillators were a Nd:glass (fluorophosphate) and a Ti:sapphire laser, each passively mode locked by an antiresonant Fabry–Perot semiconductor saturable absorber (A-FPSA). The pulses supported in all the oscillators had temporal duration ranging from 100 to 300 fs FWHM with output powers from 100 to 300 mW. The pulse with the best temporal fidelity was produced by the Nd:glass oscillator, with an intensity contrast ratio of 10^8:1.

The experimental setup used to measure the high-dynamic-range autocorrelations is shown in Fig. 1. The basic arrangement is that of a Type I phase-matched, background-free scanning autocorrelator. The delay rail in one arm consisted of a computer-controlled Klinger CC1 translational stage. A standard photomultiplier tube (PMT) was used to measure the second-harmonic signal. To improve the signal-to-noise ratio and detect the high range autocorrelation signal, a difference frequency lock-in technique was used. A dual-frequency chopping wheel was inserted before the focusing lens to modulate one beam at frequency f_1 and the other at a frequency f_2. Therefore the second-harmonic signal was modulated at both the sum frequency $f_1 + f_2$ and the difference frequency $f_1 - f_2$. The PMT signal was sent to the input of a Stanford Research Systems digital lock-in amplifier, which was referenced from the chopper wheel to detect signals modulated at the difference frequency $f_1 - f_2$. The signal level detected from the lock-in amplifier was collected by a computer via a GPIB analog-to-digital interface, making the entire process of pulse delay and signal acquisition computer controlled.

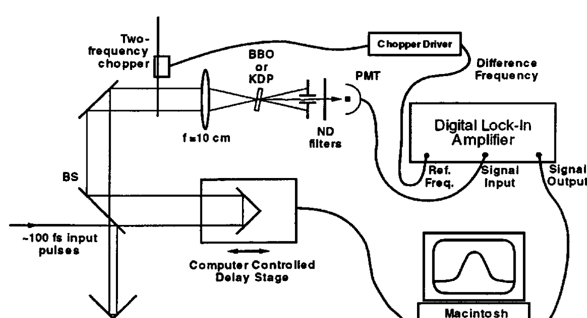

Fig. 1. Experimental arrangement to generate the high-dynamic-range autocorrelation traces: BBO, KDP, crystals; ND, neutral density; BS, beam splitter.

0146-9592/95/181889-03$6.00/0

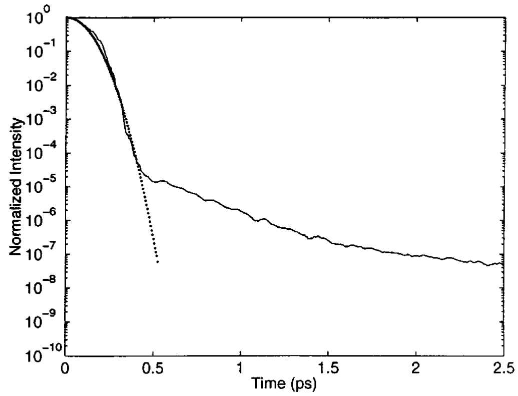

Fig. 2. Autocorrelation trace of a pulse generated from a 1.053-μm KLM Ti:sapphire oscillator fitted to a 150-fs (FWHM) Gaussian profile.

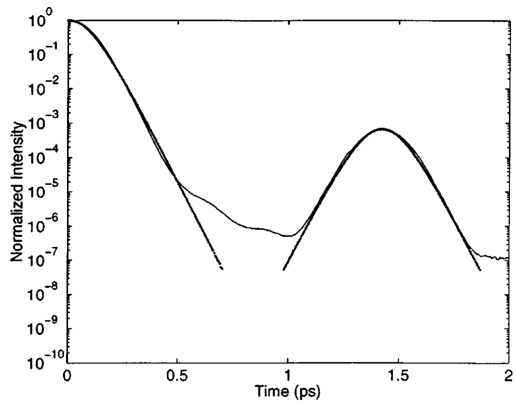

Fig. 3. Autocorrelation trace of a pulse generated from a 780-nm KLM Ti:sapphire oscillator shown with a 115-fs (FWHM) sech^2 fit. The second peak is a reflection from the normal-incidence doubling crystal.

The first oscillator studied was a KLM Ti:sapphire laser[11–13] with a spectrum centered at a wavelength of 1.053 μm. The gain guiding effect was not strong enough to mode lock the laser, so a slit was inserted near the output coupler. The average output power was 150 mW. The high-dynamic-range autocorrelation trace for this oscillator is shown in Fig. 2. The plot shows a single-sided autocorrelation trace that contains two time-scale structures. A 150-fs (FWHM) Gaussian profile is shown to be a good fit through 5 orders of magnitude below the peak. A long exponential tail then dominates to 1.5-ps, where it begins to approach the background signal level.

The second measurement was performed on a KLM Ti:sapphire laser running at a center wavelength of 780 nm. The average output power from this oscillator was 300 mW. There were no hard apertures seen by the pulse in the cavity.[14] The single-sided high-dynamic-range autocorrelation trace is shown in Fig. 3. Again, a wing begins to appear after ~5 orders of magnitude below the peak. However, for this oscillator the pulse fits a sech^2 pulse shape (115 fs FWHM) rather than a Gaussian profile over the first five decades. The second peak is a reflection that is due to the 130-μm-thick normal-incidence doubling crystal.

In acquiring data for both of these traces we kept the signal level to the PMT in a constant range by placing various calibrated filters into the second-harmonic beam path. This way neither the gain of the PMT nor the lock-in amplifier varied over several orders of magnitude. We collected the data by making a series of 100-fs scans and using the computer to compile and average the data of many scans. The difference frequency from the chopping wheel was 43 Hz. For both of these measurements the Klinger stage used had a minimum step size of 0.1 μm. It should be noted that there are many parameters that determine the pulse shape from a self-mode-locked laser (dispersion, saturable absorption, cavity geometry, material properties, etc.); to see how the background pedestal changes with some of these variables, see the related research in Ref. 15

The third laser studied was a diode-pumped Nd:glass (flourophosphate) oscillator. This laser was passively mode locked by an A-FPSA sample[16] with a bitemporal impulse response of 180 fs and 17 ps.[17,18] The soliton perturbation theory[19,20] predicted a sech^2 pulse shape. The average output power was 90 mW, and the spectrum was centered at 1.058 μm. Figure 4 shows the high-range autocorrelation trace taken from this oscillator. The pulse is clean over 8 orders of magnitude

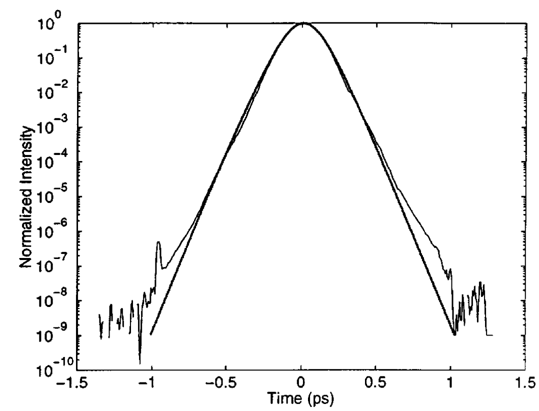

Fig. 4. Autocorrelation trace of a Nd:glass oscillator mode-locked by an A-FPSA sample fit to a 140 fs (FWHM) sech^2 pulse shape. The spectrum is centered at 1.058 μm.

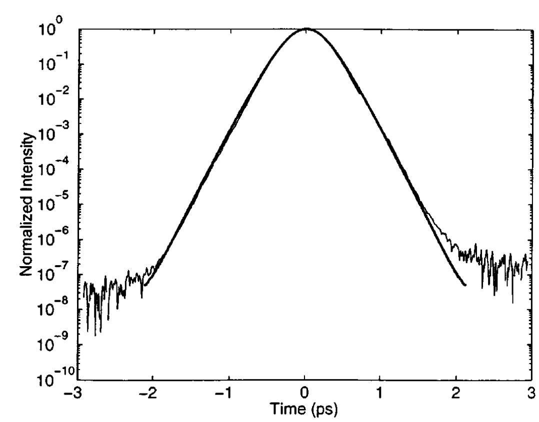

Fig. 5. Autocorrelation trace of a pulse generated from a Ti:sapphire oscillator mode locked with an A-FPSA. The spectrum was centered at 800 nm, and the fit is a 335-fs (FWHM) sech^2 pulse shape.

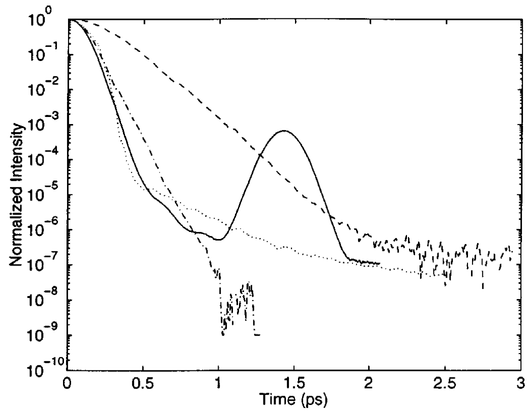

Fig. 6. Comparison of autocorrelation traces from all oscillators. Solid curve, KLM Ti:sapphire at 800 nm; dotted curve, KLM Ti:sapphire at 1.053 μm; dashed–dotted curve, Nd:glass mode locked with an A-FPSA; dashed curve, Ti:sapphire mode locked with an A-FPSA.

and matches the 140-fs sech^2 fit well over 6 orders of magnitude. The noise floor was verified to be detector limited.

The last oscillator studied was a Ti:sapphire cavity mode locked by an A-FPSA sample that had a single slow recovery time of 10 ps. The cavity was operated in a stability regime that prevented Kerr-lens mode locking. Soliton pulse shaping stabilized by the slow A-FPSA[19] generated 300-fs pulses at a central wavelength of 800 nm. The output power was 200 mW. The high-range autocorrelation of this oscillator is shown in Fig. 5. The data fit well over 6 orders of magnitude to a 335-fs (FWHM) sech^2 pulse even though the net gain window remained open after the pulse.

In acquiring the last two traces we took several 400-fs scans, with consecutive scans overlapped by roughly 100 fs. For these traces no filters were used, and the PMT gain was increased after each scan. It was verified that the PMT was never in saturation. The difference frequency from the chopping wheel was 66 Hz. The minimum step size of the Klinger stage used for these scans was 1.0 μm. For ease of comparison, a single-sided autocorrelation trace from each oscillator is shown on the same intensity and temporal scale in Fig. 6.

The Nd:glass oscillator supported the cleanest pulse measured, with an intensity contrast ratio of 10^8:1. This oscillator would make an excellent front end to high-energy chirped-pulse amplification laser systems, as the spectrum is well matched to the gain spectrum of glass amplifiers. It was measured that the two KLM oscillators supported different pulse shapes over the first 5 orders of magnitude. It was also shown that both of these pulses contained a temporal wing after the first 5 orders of magnitude. This wing was not present on any of the oscillators mode locked by the A-FPSA sample. Numerical simulations need to be performed that include the various saturable absorbers present in the oscillators[21] as well as the different material parameters to permit the nature of these pulse shapes and long temporal structures to be determined.

This research was supported by the National Science Foundation through the Center for Ultrafast Optical Science under grant STC PHY 8920108 and through the Swiss National Fund (21-39362.93).

References

1. P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quantum Electron. **24,** 398 (1988).
2. Z. Jiang, J.-C. Kieffer, J. P. Matte, M. Chaker, O. Peyrusse, D. Gilles, G. Korn, A. Maksimchuck, S. Coe, and G. Mourou, Phys. Plasmas **2,** 1702 (1995).
3. M. D. Perry and G. Mourou, Science **264,** 917 (1994).
4. J.-C. Kieffer, M. Chaker, J. Matte, H. Pepin, C. Cote, Y. Beaudoin, T. Johnston, C. Y. Chien, S. Coe, G. Mourou, and O. Peyrusse, Phys. Fluids B **5,** 2676 (1993).
5. M. M. Murnane, H. C. Kapteyn, M. D. Rosen, and R. W. Falcone, Science **251,** 531 (1991).
6. M. M. Murnane, H. C. Kapteyn, and R. W. Falcone, Phys. Rev. Lett. **62,** 155 (1989).
7. Y. Beaudoin, C. Y. Chien, J. S. Coe, J. L. Tapié, and G. Mourou, Opt. Lett. **17,** 865 (1992).
8. H. Roskos, A. Seilmeir, W. Kaiser, and J. D. Harvey, Opt. Commun. **61,** 81 (1987).
9. J. L. Tapié and G. Mourou, Opt. Lett. **17,** 136 (1992).
10. K. W. DeLong, R. Trebino, J. Hunter, and W. E. White, J. Opt. Soc. Am. B **11,** 2206 (1994).
11. D. E. Spence, P. N. Kean, and W. Sibbett, Opt. Lett. **16,** 42 (1991).
12. D. K. Negus, L. Spinelli, N. Goldblatt, and G. Feugnet, in *Advanced Solid-State Lasers*, Vol. 8 of 1991 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1991), paper PDP4.
13. F. Salin, J. Squier, G. Mourou, M. Piché, and N. McCarthy, in *Advanced Solid-State Lasers*, Vol. 8 of 1991 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1991), paper PDP5.
14. M. Piché and F. Salin, Opt. Lett. **18,** 1041 (1993).
15. P. F. Curley, G. Darpentigny, G. Cheriaux, J. Chambaret, and A. Antonetti, "High dynamic range autocorrelation studies of a femtosecond Ti:sapphire oscillator and its relevance to the optimisation of chirped pulse amplification systems," Opt. Commun. (to be published).
16. U. Keller, Appl. Phys. B **58,** 347 (1994).
17. L. R. Brovelli, U. Keller, and T. H. Chiu, J. Opt. Soc. Am. B **12,** 311 (1995).
18. D. Kopf, F. X. Kärtner, K. J. Weingarten, and U. Keller, Opt. Lett. **20,** 1169 (1995).
19. F. X. Kärtner and U. Keller, Opt. Lett. **20,** 16 (1995).
20. F. X. Kärtner, D. Kopf, and U. Keller, J. Opt. Soc. Am. B **12,** 486 (1995).
21. H. A. Haus, Opt. Commun. **97,** 215 (1993).