Phase and intensity characterization of femtosecond pulses from a chirped-pulse amplifier by frequency-resolved optical gating

Bern Kohler, Vladislav V. Yakovlev, and Kent R. Wilson

Department of Chemistry, University of California, San Diego, La Jolla, California 92093-0339

Jeff Squier

Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109

Kenneth W. DeLong and Rick Trebino

Combustion Research Facility, Sandia National Laboratories, Livermore, California 94551

Frequency-resolved optical gating (FROG) measurements were made to characterize pulses from a Ti:sapphire chirped-pulse amplified laser system. By characterizing both the pulse intensity and the phase, the FROG data provided the first direct observation to our knowledge of residual phase distortion in a chirped-pulse amplifier. The FROG technique was also used to measure the regenerative amplifier dispersion and to characterize an amplitude-shaped pulse. The data provide an experimental demonstration of the value of FROG for characterizing complex pulses, including tailored femtosecond pulses for quantum control.

Control of dispersion over wide bandwidths is critical in ultrafast optics. Interest in devices that can be programmed to modify dispersion, such as liquid-crystal modulators,[1] has been catalyzed recently by new applications such as quantum control. These applications require femtosecond pulses that are carefully tailored in coherence for controlling the dynamics of matter.[2] Frequency-resolved optical gating (FROG) is a new technique[3] for measuring the time- or frequency-dependent phase of ultrashort pulses in addition to the pulse intensity and for providing a means of directly measuring dispersive pulse reshaping. In this Letter we apply FROG to characterize and optimize pulses produced by chirped-pulse amplification (CPA). The data constitute the first experimental measurement to our knowledge of residual phase distortion in a CPA laser system. We also report the characterization, by FROG, of a pulse that was amplitude shaped in the pulse stretcher.

In CPA[4] an ultrashort pulse is chirped by the frequency-dependent group delay of a pulse stretcher before amplification. Chirping lowers the peak intensity to prevent optical damage. After amplification, the pulse is sent through a grating-pair pulse compressor to remove the frequency chirp. Because the pulse stretcher, amplifier, and pulse compressor significantly modify the frequency-dependent phase of the pulse, dispersion must be carefully balanced to compress the pulse back to the transform limit.[5–7] Because FROG measures the intensity and phase of ultrashort pulses, imperfect phase compensation in CPA can be readily quantified. Additionally, because the dispersive effects of modifying distances and angles in the pulse compressor and pulse stretcher are well known,[5–7] a CPA laser is ideal for testing the FROG technique with a variety of real-world pulses.

A kilohertz regeneratively amplified Ti:sapphire laser system, similar to that discussed by Rudd *et al.,*[7] was used in this study. A self-mode-locked Ti:sapphire oscillator produced approximately 70-fs pulses. Pulses from the oscillator were sent into an all-reflective pulse stretcher that consisted of two 1200-line/mm gratings placed 29.7 cm from two 100-cm radius-of-curvature mirrors. After a fixed number of round trips in a Ti:sapphire regenerative amplifier, the amplified pulse was switched out and compressed with a second pair of 1200-line/mm gratings.

FROG measurements were performed after the pulse compressor in the polarization-gate geometry.[3] The probe and gate pulses were formed with a 50% beam splitter and then recombined in a 2-mm-thick piece of fused silica that served as the nonlinear optical gate. Identical calcite polarizers were used in both beams to balance the dispersion of the FROG setup. Pulse energies were kept near 1 μJ to avoid distortion in the gate material.[8] The delay between gate and probe pulses was set by a stepping-motor delay line. For each delay, the FROG signal light was analyzed spectrally with a 0.25-m spectrograph and a CCD detector. Using an exposure time of 1 s for each spectrum (an average of 1200 pulses per delay setting), we acquired an entire FROG data set in ~1 min. Finally, we retrieved the pulse intensity and phase by the generalized projections algorithm.[9]

Figure 1(a) shows the FROG image of a CPA pulse with imperfect phase compensation. Figure 1(b) displays the temporal pulse intensity (solid curve) and phase (dashed curve) retrieved from the FROG data

0146-9592/95/050483-03$6.00/0 © 1995 Optical Society of America

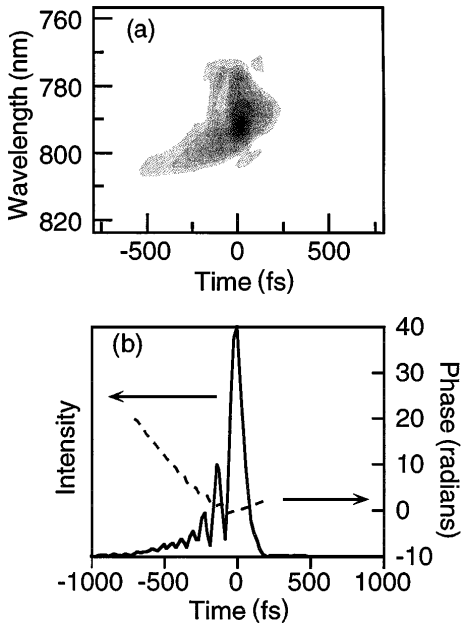

Fig. 1. (a) FROG signal of an amplified pulse from the unoptimized Ti:sapphire chirped-pulse amplifier. (b) The time-dependent pulse intensity (solid curve) and phase (dashed curve) retrieved from (a). The oscillatory structure in the pulse intensity is due to residual cubic spectral phase.

set. The pulse intensity exhibits a dramatic series of leading-edge subpeaks, which are the result of cubic spectral phase distortion. A polynomial fit to the frequency-dependent pulse phase (spectral phase) gives values of 5.6×10^3 fs^2 and -4.0×10^5 fs^3 for the quadratic and cubic dispersion terms, respectively. The negative sign of the cubic term is responsible for the appearance of the subpeaks on the leading edge of the pulse. The positive material dispersion that results from approximately 20 round trips through the regenerative amplifier cavity requires that the grating angle of incidence in the pulse compressor be made greater than that in the pulse stretcher.[7] We obtained the data of Fig. 1 by increasing the angle of incidence in the pulse compressor too much, thus decreasing the positive cubic dispersion to such an extent that the pulse after compression is left with negative cubic spectral phase. In contrast with the detailed information provided by FROG, the second-order intensity autocorrelation function of this pulse is smooth with featureless wings, and it is impossible to determine the sign of any of the dispersive terms.

Using the measured amount of phase distortion and a ray tracing model of the pulse compressor, we determined the change of grating angle required to null the spectral phase through third order. For our laser system and a stretcher angle of incidence of 23.1 deg, the required compressor angle was found to be 33.0 deg. The measured FROG trace for the conditions described above is shown as a contour plot in Fig. 2(c). The retrieved intensity (solid curve) and phase (dashed curve) are shown as a function of frequency (relative to the carrier frequency, ω_0) in Fig. 2(h). The spectral phase is nearly flat across the bandwidth of the pulse, indicating excellent phase compensation. The FWHM of the temporal intensity of this pulse is 77 fs.

Figure 2 also shows the effects of varying the grating separation in the pulse compressor about the optimal value. Increasing the distance between the gratings increases the amount of negative quadratic dispersion and leaves the pulse with a negative frequency chirp, which is clearly seen in the negative curvature of the spectral phase in Figs. 2(f) and 2(g). Conversely, when the gratings are moved closer together, the negative quadratic dispersion decreases, and the pulse is left with a residual amount of positive quadratic phase, as seen in Figs. 2(i) and 2(j). Figures 2(a)–(e) illustrate the powerful diagnostic value of the FROG image itself. The sign of the chirp is immediately apparent from the slope of the

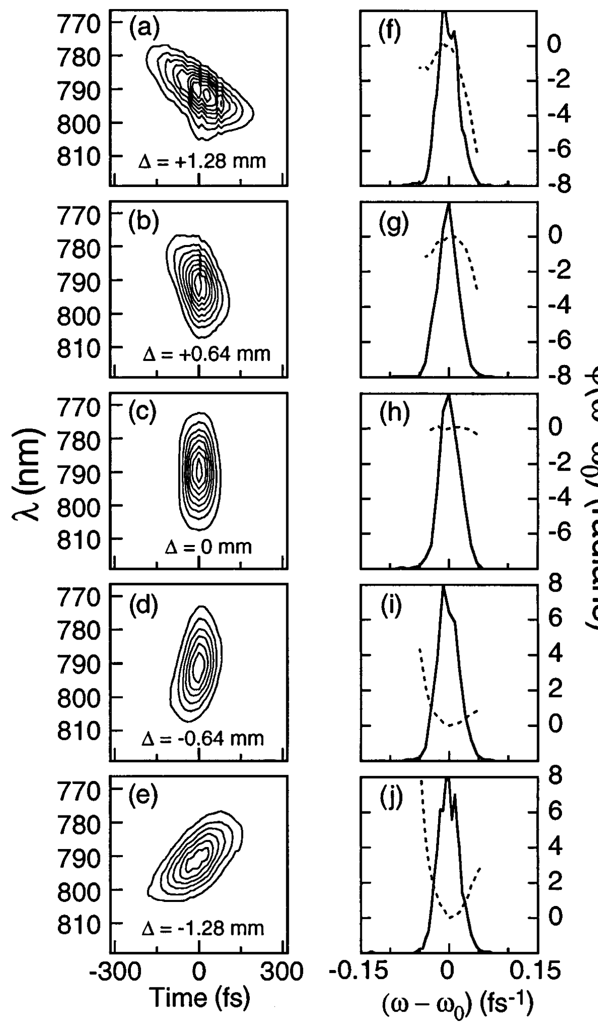

Fig. 2. (a)–(e) FROG data of CPA pulses measured at different compressor grating separations. The change in distance, Δ, from the experimentally optimal grating separation of 510 mm is shown for each measurement. (f)–(j) Frequency-dependent intensity (solid curves) and phase (dashed curves) retrieved from the data sets in (a)–(e), respectively. The spectral intensity remains nearly constant, while the pulse phase develops positive or negative curvature, according to whether the gratings are too close or too far apart. In (h) the compression is nearly optimal, and the FWHM of the time-dependent pulse intensity is 77 fs.

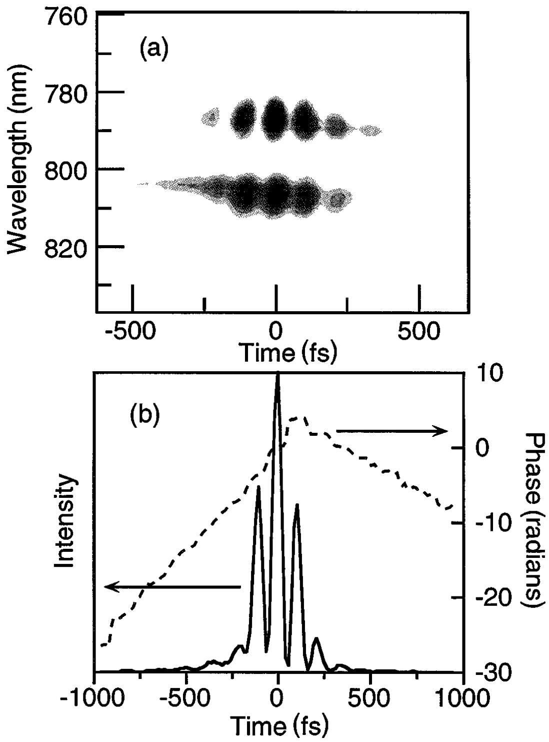

Fig. 3. (a) Measured FROG signal of amplified pulse, which was shaped by blocking the central portion of the pulse spectrum with an opaque object placed in the pulse stretcher. (b) Time-dependent intensity (solid curve) and phase (dashed curve) retrieved from the data in (a).

FROG trace. Higher-order phase modulations give rise to other distinctive traces. With a single-shot geometry,[8] the FROG signal could be displayed on a video monitor to provide real-time feedback for fine-tuning the compressor grating separation and angles to produce a desired pulse shape.

By altering the Pockels cell timing, we recorded a series of FROG traces for pulses that differed only by the number of round trips in the regenerative amplifier. The slope of a plot of the group-velocity dispersion (obtained by differentiating the pulse spectral phase twice with respect to frequency) versus the round-trip number provided a direct measurement of the amplifier cavity dispersion. The value obtained for the quadratic dispersion was 5100 fs^2, in excellent agreement with an estimate from the refractive index data of the cavity components.[10]

To demonstrate the use of FROG for characterizing tailored pulses, a mask was placed in the Fourier plane of the pulse stretcher and used to block the central portion of the pulse spectrum. The FROG image of the resulting pulse is shown in Fig. 3(a). The missing spectral intensity is reflected in the channel in the FROG image parallel to the time axis of the figure. The broken lumps in the FROG trace indicate strong temporal modulation that is seen in the retrieved-pulse intensity shown by the solid curve in Fig. 3(b). The FROG measurement is superior to cross correlation with a second unshaped pulse, the usual technique for characterizing shaped pulses, because it provides the full pulse intensity and phase. In addition, the same polarization-gate FROG apparatus can be used to characterize pulses from the UV to the infrared, because the electronic–Kerr nonlinear optical effect used is nonresonant (instantaneous) across this spectral range.[11]

In conclusion, we have presented several FROG measurements of femtosecond pulses from a Ti:sapphire CPA laser system. The intensity and phase versus time or frequency reconstructed from these measurements provide insight into pulse distortions that result from imperfect phase compensation. The quantitative information about the pulse phase obtained by the FROG technique also allowed us to measure the round-trip dispersion of the regenerative amplifier. Measurement of the pulse phase was used to modify the compressor geometry to yield nearly transform-limited pulses. Finally, a complex, tailored pulse created by Fourier-plane filtering in the pulse stretcher was fully characterized with respect to intensity and phase. We expect FROG to be an invaluable diagnostic for the new realm of applications, such as quantum control, that require synthesized, ultrafast optical waveforms.

R. Trebino and K. W. DeLong acknowledge support from the U.S. Department of Energy, Office of Basic Energy Science, Chemical Sciences Division.

References

1. A. M Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, Opt. Lett. **15,** 326 (1990); M. M. Wefers and K. A. Nelson, Science **262,** 1381 (1993).
2. B. Kohler, J. L. Krause, F. Raksi, C. Rose-Petruck, R. M. Whitnell, K. R. Wilson, V. V. Yakovlev, Y. J. Yan, and S. Mukamel, J. Phys. Chem. **97,** 12602 (1993).
3. R. Trebino and D. J. Kane, J. Opt. Soc. Am. A **10,** 1101 (1993).
4. D. Strickland and G. Mourou, Opt. Commun. **56,** 219 (1985).
5. B. E. Lemoff and C. P. J. Barty, Opt. Lett. **18,** 1651 (1993).
6. W. E. White, F. G. Patterson, R. L. Combs, D. F. Price, and R. L. Shepherd, Opt. Lett. **18,** 1343 (1993).
7. J. V. Rudd, G. Korn, S. Kane, J. Squier, and G. Mourou, Opt. Lett. **18,** 2044 (1993).
8. D. J. Kane and R. Trebino, Opt. Lett. **18,** 823 (1993).
9. K. W. DeLong, R. Trebino, B. Kohler, and K. R. Wilson, Opt. Lett. **19,** 2152 (1994).
10. B. Kohler, V. V. Yakovlev, K. R. Wilson, J. Squier, K. W. DeLong, and R. Trebino, in *Ultrafast Phenomena IX,* G. A. Mourou, A. H. Zewail, P. F. Barbara, and W. H. Knox, eds. (Springer-Verlag, Berlin, to be published)..
11. D. J. Kane, A. J. Taylor, R. Trebino, and K. W. DeLong, Opt. Lett. **19,** 1061 (1994).