Generation of 18-fs, multiterawatt pulses by regenerative pulse shaping and chirped-pulse amplification

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Transform-limited, 18-fs pulses of 4.4-TW peak power are produced in a Ti:sapphire-based chirped-pulsed amplification system at a repetition rate of 50 Hz. Regenerative pulse shaping is used to control gain narrowing during amplification, and an optimized, quintic-phase-limited dispersion compensation scheme is used to control higher-order phase distortions over a bandwidth of ~100 nm. Seed pulses are temporally stretched >100,000 times before amplification.   © 1996 Optical Society of America

Chirped-pulse amplification (CPA) has become a common technique for the generation of energetic optical pulses of less than a picosecond in duration.[1] The use of Ti:sapphire as an amplification medium has led to the generation of terawatt-level optical pulses at repetition rates greater than 1 Hz.[2-7] Pulses of this type are useful for a variety of high-intensity ($>10^{18}$ W/cm^2) and high-field applications such as the generation of ultrafast soft- and hard-x-ray radiation,[8,9] and ultrahigh-order harmonic generation.[10] Recently even shorter-duration CPA was demonstrated by two groups of researchers, with multiterawatt pulses of the order of 30 fs reported.[4,5] Further reductions in pulse duration were previously limited by gain narrowing during amplification. In this Letter we describe a 50-Hz repetition rate CPA system that utilizes both regenerative pulse shaping[11] to control gain narrowing and an optimized, quintic-phase-limited expansion and compression system that is designed to expand a 100-nm-bandwidth pulse by more than 100,000 times and then recompress it with less than 1 fs of relative pulse delay across the entire bandwidth. To date this system has produced 18-fs 4.4-TW laser pulses with an average power of 4 W. To our knowledge, these results represent the shortest-duration terawatt level pulses yet produced, the largest expansion ratio used in a CPA system, and the highest average power generated from a multiterawatt laser system.

In most CPA systems a net amplification of $>10^8$ is necessary for reaching the final pulse energy. Because of the frequency dependence of the amplifier gain profile, this amplification leads to significant reshaping or gain narrowing of the pulse spectrum. In terawatt Ti:sapphire systems this effect has limited amplified bandwidths to ~40 nm or less and compressed pulse durations to greater than 26 fs. If saturation is neglected, the amplified pulse spectrum, $I_{out}(\omega)$, is determined by

$$I_{out}(\omega) = I_{in}(\omega)G(\omega)^n T(\omega)^n, \qquad (1)$$

where $G(\omega)$ is the frequency-dependent gain, $T(\omega)$ is the frequency-dependent transmission function of the amplifier, and n is the number of passes through the system. Equation (1) suggests two routes for the elimination of gain narrowing. First, the gain band-

width of the amplification medium could be increased. In Nd:glass amplification systems, mixed gain media with different peak gain wavelengths have been used to increase the amplified pulse spectrum significantly.[12,13] The second possibility is to introduce a frequency-dependent loss during amplification with greater attenuation at the peak of the gain profile than in the wings. This method is most practical for systems that employ multiple passes of a single gain medium, because the gain narrowing on any one pass can be relatively small. The laser system described in this Letter utilizes spectral filters placed inside a regenerative amplifier to reshape the amplified spectrum after each pass of the gain medium.[11] To control simultaneously the modulation depth and bandwidth of the attenuation, an air-spaced, angle-tuned étalon consisting of two uncoated BK7 optical flats was used. By piezoelectrically adjusting the spacing between the plates to be an odd number of quarter wavelengths, it is possible to introduce a relative attenuation at line center of the gain profile with respect to the wings. In addition, by varying the angle of incidence of the intracavity beam on the optical flats, the magnitude of the Fresnel reflection of the individual surfaces, and thus also the modulation depth of the filter, is changed. In our case an angle of incidence of ~10° was used.

Seed pulses for amplification were provided by a Ti:sapphire oscillator capable of producing transform-limited, sub-10-fs pulses. This laser utilized a pair of Brewster-cut fused-silica prisms and one intracavity turning mirror possessing excess positive cubic phase distortion (Newport Corporation Model BD.2) to provide second- and third-order phase compensation for a 4-mm-long Ti:sapphire gain medium. The spectrum of the oscillator output is given in Fig. 1. This spectrum has a transform limit of ~9 fs. ~3-nJ pulses from the oscillator were stretched in a cylindrical-mirror-based pulse expander.[14] The spectrum of the stretched pulse is also shown in Fig. 1. It should be noted that at the angle of incidence used in the expander (50.2°) the 1200-groove/mm gratings (Milton Roy MR136) have a significant variation in efficiency as a function of wavelength. This leads to the reshaping of the spectrum shown in Fig. 1. The FWHM duration of the output of
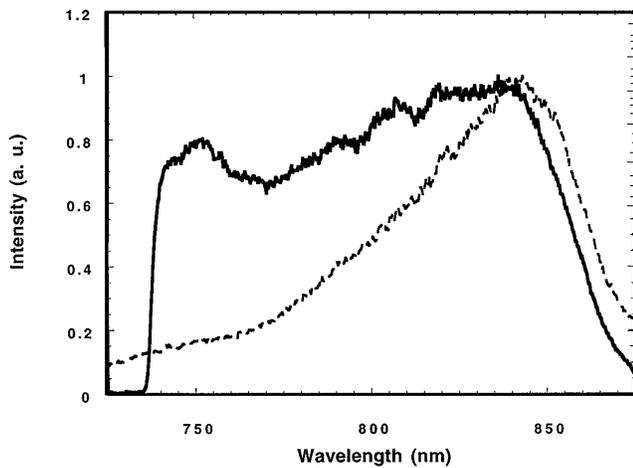
Fig. 1. Measured oscillator spectrum before (dashed curve) and after (solid curve) the stretcher. Note that the spectrum is clipped in the stretcher on the short-wavelength side.
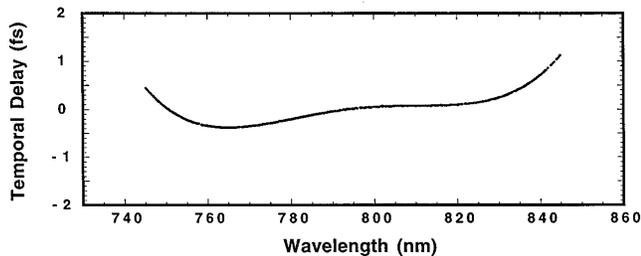

Fig. 2. Calculated relative pulse delay after compression, based on a three-dimensional ray tracing model in conjunction with a multivariable optimization routing.

the expander is ~ 950 ps, or more than 100,000 times greater than the transform limit of the oscillator output. Such large stretching ratios enable the amplifiers to be operated well above the saturation fluence of Ti:sapphire ($\sim$1 J/cm^2) without excess B-integral accumulation and intensity-dependent optical damage to dielectric coatings. This is essential for efficient, high-average-power amplification.

The exact design of the expander and compressor was similar to that described originally by Lemoff and Barty.[14] However, in our case we used a three-dimensional ray tracing routine in conjunction with a multivariable optimization to determine the correct compressor angles of incidence (62.1°) and separation (115.88 cm), expander grating angles of incidence (50.2°) and separation (21.20 cm to the first mirror and 20.06 cm to the second mirror), cylindrical mirror curvatures (99.82 cm), angles of incidence (15.0°) and separation (96.46 cm), and total material path (16.4 cm of e sapphire, 19.0 cm of o KD*P, 0.3 cm of o quartz, 3.2 cm of e calcite, 0.2 cm of CaF$_2$, 2.1 cm of TGG, and 71.9 cm of BK7) such that a 100-nm-wide spectrum would experience less than 1 fs of relative delay across its entire bandwidth after compression. The calculated pulse delay after compression for our system is shown in Fig. 2.

The stretched seed pulses were amplified first in a regenerative amplifier and then in a four-pass

power amplifier. The regenerative amplifier was pumped at 50 Hz with ~60 mJ of 532-nm radiation (Continuum 6050). The pump beam diameter at the Ti:sapphire crystal was ~1 mm. In the regenerative amplifier a Pockels cell placed between two thin-film polarizers (Alpine Research Optics) was fired to a half-wave voltage twice: once to inject the seed pulse into the cavity and once to dump the pulse after nine round trips. The output pulse energy was ~2 mJ. In addition to the angle-tuned, air-spaced étalon, a solid 3-μm-thick étalon was also placed in the cavity. With two étalons it was possible to control independently the blue and the red sides of the amplified spectrum and to increase in the amplified bandwidth by ~15% more than for a cavity with only one étalon.

Output from the regenerative amplifier was up-collimated with a Galilean reflective telescope to an ~4-mm diameter and then injected into the four-pass amplifier. This amplifier was pumped with 580 mJ of 532-nm radiation at 50 Hz (Continuum 9050) and utilized a 12-mm-diameter 10-mm-long Ti:sapphire crystal, which had ~85% absorption at 532 nm. The beam from the pump laser was split into two outputs, which were then relay imaged to opposite faces of the amplifier crystal. At ~30-W average pump power, thermal lensing in the water-cooled Ti:sapphire crystal was significant. We compensated for this lensing by placing a 12-mm-diameter singlet negative lens of $f = -1.5$ m after the second pass and before the third pass of the Ti:sapphire crystal. For high efficiency the pulse fluence on the last pass in the amplifier was designed to be ~1.7 J/cm^2. The output pulse energy was ~160 mJ.

Before being sent to the compressor, the beam was upcollimated to ~5 cm in diameter with another Galilean reflective telescope. The compressor consisted of two 1200-groove/mm gold-coated gratings (Milton Roy MR136), which had a measured diffraction efficiency of 91.5% at a 62° angle of incidence. It should be noted that at this angle of incidence these gratings do not exhibit any strong spectral dependence with respect to diffraction efficiency, as was the case for the expander. The transmission of the compressor, including the gold-coated turning optics, was ~50%,
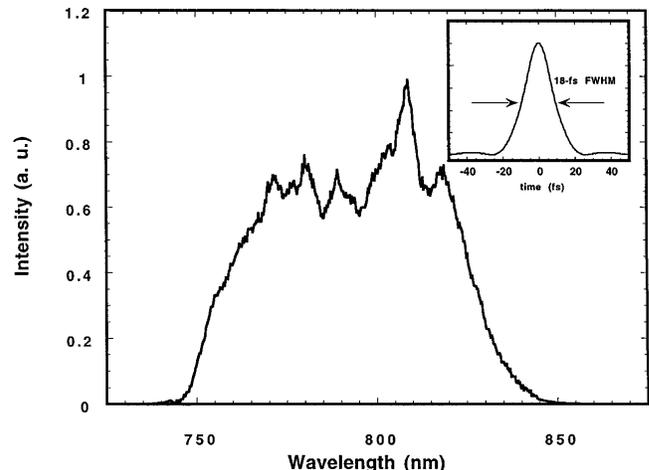

Fig. 3. Measured amplified spectrum. Inset: transform-limited pulse shape corresponding to this spectrum (FWHM 18 fs).
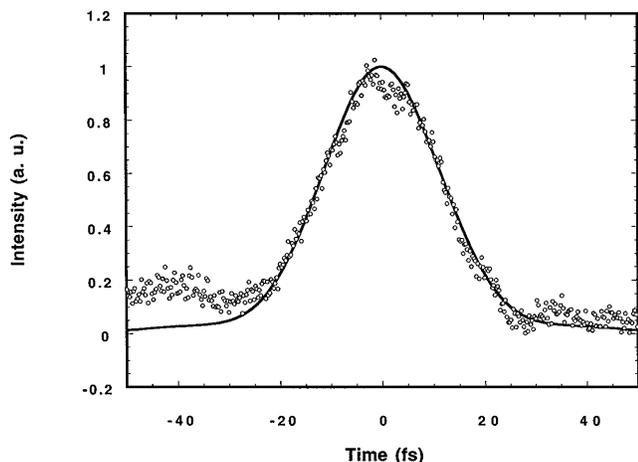
Fig. 4. Measured and calculated autocorrelation. The solid curve is the calculated, transform-limited autocorrelation based on the measured, amplified spectrum after the compressor. The circles represent the measured autocorrelation.

yielding a compressed output pulse energy of 80 mJ. The amplified spectrum is shown in Fig. 3.

Approximately 4% of the compressor output was sent to a single-shot autocorrelator, which utilized matched beam splitters to ensure balanced dispersion in the two delay lines and a 100-μm KD*P doubling crystal. The system was optimized under full power conditions. A typical autocorrelation trace is shown in Fig. 4. Also shown is the theoretical autocorrelation function corresponding to that produced by a transform-limited pulse with the same spectrum as that shown in Fig. 2. The high degree of agreement suggests that the compressed pulses are nearly transform limited. The duration of the transform limit is 18 fs FWHM. We believe that the discrepancy in the left-hand side of the trace is due to beam clipping in the autocorrelator.

It is important to note that, because of the modulation of the spectrum shown in Fig. 2, one can expect temporal wings to appear on the compressed pulse. The calculated temporal behavior of the transform-limited pulse exhibits a wing at a level of 10^{-4} of the peak intensity at a duration of ~ 200 fs on either side of the peak. High-dynamic-range autocorrelations have not yet been performed to confirm this hypothesis, nor has any attempt been made to control the modulation of the spectrum. Full characterization of the focusability of the compressed output has also not been performed. However, qualitatively the near-field beam profile, as observed with a CCD camera, was found to be smoother and less modulated than that produced at higher energies by the 532-nm-pumped, nearly diffraction-limited Ti:sapphire system[4] described in Ref. 4, which used similar amplifiers and components.

In conclusion, we have shown that with regenerative pulse shaping it is possible to overcome gain narrow-

ing in Ti:sapphire-based amplifier systems and to produce shorter-duration terawatt level pulses (18 fs) than previously reported. In addition, with optimized dispersion compensation, significantly higher expansion ratios ($>100,000$) and higher average output powers (~ 4 W) were also demonstrated. Extensions of these concepts to produce efficiently pulses of ~ 10-fs duration at average powers of >10 W should be possible.

When this research was performed, C. Barty was with the Institute for Nonlinear Science; T. Guo, F. Raksi, C. Rose-Petruck, K. R. Wilson, and V. V. Yakovlev were with the Department of Chemistry and Biochemistry; and J. Squier was with the Department of Electrical and Computer Engineering, University of California, San Diego. C. Le Blanc is now with the Ecole Nationale Superiéure des Techniques Avancées-Laboratoire d'Optique Applique, Batterie de l'Yvette, 91120 Palaiseau, France, and K. Yamakawa is now with the Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki 319-11, Japan.

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