

# Terawatt Cr:LiSrAlF<sub>6</sub> laser system

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We have developed a compact flash-lamp-pumped Cr:LiSrAlF<sub>6</sub> (Cr:LiSAF) laser system capable of producing peak powers in excess of 1 TW. Chirped-pulse amplification in a Cr:LiSAF regenerative amplifier produces 8-mJ pulses at a 5-Hz repetition rate. Further amplification in Cr:LiSAF yields recompressed pulse energies of 150 mJ and a pulse duration <135 fs at a 0.5-Hz repetition rate.

The technique of chirped-pulse amplification<sup>1</sup> has made possible the production of terawatt-class pulses from tabletop laser systems. First applied to Nd:glass-based systems,<sup>2</sup> the technique has since been applied to Ti:sapphire<sup>3</sup> and alexandrite.<sup>4</sup> The neodymium-based systems are limited to pulse widths greater than ~500 fs at the terawatt level because of gain narrowing.<sup>5</sup> The Ti:sapphire-based systems do not exhibit this limitation because of the material's broad emission spectrum. However, the short upper-state lifetime of Ti:sapphire (3.2  $\mu$ s) requires rapid pumping, most commonly achieved with a secondary pump laser. The cost and complexity of laser pumping has limited Ti:sapphire systems to ~100-mJ pulses. The relatively new material Cr:LiSrAlF<sub>6</sub> (Cr:LiSAF; Ref. 6) has a broad emission cross section (750–950 nm), comparable with that of Ti:sapphire, and has a sufficiently long upper-state lifetime (67  $\mu$ s) to allow direct flash-lamp pumping.

Since it has become commercially available, Cr:LiSAF has been demonstrated in many applications. As an oscillator, self-mode-locked pulses <50 fs have been observed,<sup>7</sup> diode-pumped oscillation has been achieved,<sup>8</sup> and pulsed operation as a Q-switched laser has been demonstrated to the 30-mJ level. Flash-lamp-pumped regenerative amplifiers have been demonstrated,<sup>9</sup> and a large energy-storage Cr:LiSAF power amplifier was recently used to amplify the output of a Ti:sapphire system to the terawatt level.<sup>10</sup> In this Letter we describe what is to our knowledge the first completely Cr:LiSAF-based amplifier system to produce terawatt-class femtosecond pulses. With this compact system, we have obtained, at a 0.5-Hz repetition rate, recompressed pulses of 150 mJ and transform-limited pulse widths of 135 fs.

The system begins with a self-mode-locked Ti:sapphire oscillator that produces transform-limited 110-fs pulses ( $\Delta\nu\Delta\tau = 0.38$ ) of 10 nJ at 76 MHz (Fig. 1). This pulse train enters a diffraction-grating pulse stretcher based on the design of Martinez.<sup>11</sup> This stretcher uses 1800-line/mm gold-coated holographic diffraction gratings and two 60-cm focal-length cemented achromatic doublet lenses, corrected for spherical and chromatic aberration at 825 nm. Four passes through the stretcher produce enough positive group-velocity dispersion to widen the pulses

from 110 fs to 400 ps. This pulse stretching is necessary to avoid deleterious effects associated with the intensity-dependent refractive index in the amplifier chain (i.e., self-focusing, filamentation, and self-phase modulation). Overall losses in the stretcher reduce the pulse energy in the mode-locked train to 2 nJ.

At this point, the *p*-polarized pulses are injected into a ring regenerative amplifier cavity through a broadband thin-film polarizer. The regenerative amplifier, described in detail previously,<sup>9</sup> uses a single 4 mm  $\times$  50 mm flash-lamp-pumped 2% doped Cr:LiSAF rod as the amplifying medium (Fig. 1). A single pulse is selected for amplification by applying half-wave voltage (5800 V) to a KD\*P Pockels cell placed inside the cavity. Combined with a zero-order half-wave plate, the trapped pulse experiences full-wave retardation between the two polarizers while the Pockels cell is on. Dropping the voltage on the Pockels cell to ground cavity dumps the amplified pulse after the desired number of round trips in the cavity. Timing synchronization with the Pockels cell is achieved with the use of a slow diode monitoring the pulse train from the self-mode-locked Ti:sapphire oscillator. A frequency scalar is used to fire the Pockels cell with subnanosecond accuracy. The single-pass gain in the Cr:LiSAF head follows the flash-lamp pulse and reaches a maximum at

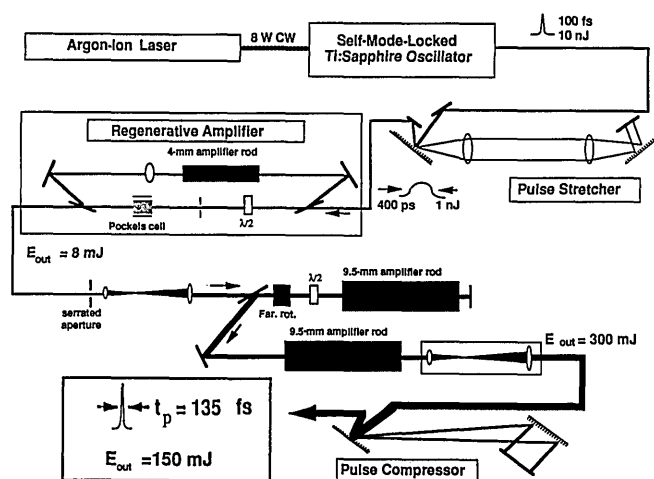


Fig. 1. Cr:LiSAF laser system layout.

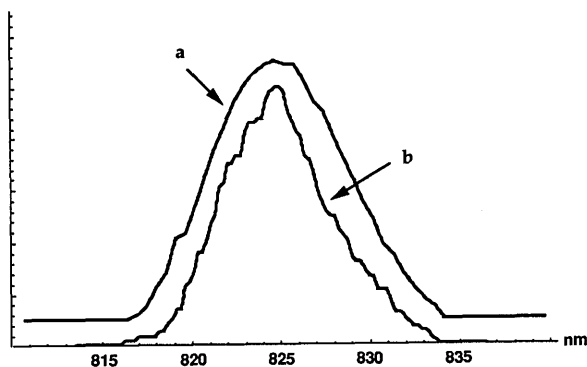


Fig. 2. Spectrum from the Ti:sapphire oscillator (curve a) and the amplified pulse (curve b).

$\sim 50 \mu\text{s}$ . At this point, the Pockels cell is triggered with a rise time to a half-wave voltage of 2.5 ns.

The 4-m-long ring cavity is TEM<sub>00</sub> stable, defined by a 1.5-m lens and a 1.5-mm aperture in the cavity. This design is superior to the confocal design, because this cavity lies well within the cavity stability diagram ( $g_1 g_2 = 0.33$ ), and the effective spot size is larger inside the amplifier head than for the confocal design. Furthermore, the cavity exhibits lower divergence than the confocal design, desirable when many passes through polarization-dependent elements are required. The mode size in the amplifier rod for our cavity is 1.9 mm (full width at  $1/e^2$ ), and the cavity divergence is 0.86 mrad.

The LiSAF amplifier head is pumped by 40 J of electrical energy and exhibits a single-pass gain of 3.1. This corresponds to a pump efficiency of 2.4%. Gain narrowing in the LiSAF is negligible. The multipass transmission function of the wave plate and polarizers, however, limit the effective gain profile to an FWHM of 20 nm centered at 832 nm with 34 round trips in the cavity. Consequently, a small amount of narrowing is imposed on the output spectrum and accounts for the fact that recompression results in 135-fs pulses and not the initial input 110 fs (Fig. 2).

After the regenerative amplifier, the Gaussian spatial profile is truncated with a 2.5-mm serrated aperture, and the image of this aperture is relayed through the remainder of the system. Relay imaging permits greater energy extraction in the *B*-integral-limited amplifier chain, because the near-flat-top profile allows a greater fill factor in the amplifier rods without significant diffraction effects. The aperture truncates 60% of the 8-mJ output from the regenerative amplifier. The image of this aperture is relayed by an air spatial filter ( $f$ -number = 120 and  $M = 2.5$ ) to the next amplification stage.

The pulse is then amplified in two 9.5 mm  $\times$  115 mm LiSAF rods. We modeled the expected gain profile of LiSAF laser rods in an isotropic flash-lamp-pump field, and our calculations suggest that a uniform gain profile is achieved with a Cr concentration of 0.8 mol %, corresponding to an ion concentration of  $\sim 1.0 \times 10^{20}$  ions/cm<sup>3</sup>. Unfortunately, the assumption of an isotropic pump field is not fully achieved with the commonly available two-lamp close-coupled

pump chambers. A four-lamp pump chamber with intermediate coupling, however, yields a nearly isotropic pump field, resulting in uniform pumping for 1-cm-diameter rods while maintaining a high pump efficiency. Detailed measurements of the gain uniformity of these 9.5-mm Cr:LiSAF amplifiers are presented elsewhere.<sup>12</sup> The essential result is that the four-lamp intermediately coupled head with a 0.8% doped rod yields a gain profile that is spatially uniform to within a few percent.

We also modeled the efficiency of flash-lamp pumping LiSAF and examined the effects of flash-lamp pulse width on the pump efficiency. This model determines the time-dependent stored energy density in the LiSAF amplifier rod as a function of the flash-lamp pulse duration and efficiency. Our calculations indicate that the lamps used in our system exhibit maximum pumping efficiency in a 9 mm  $\times$  115 mm LiSAF rod for pump durations between 80 and 120  $\mu\text{s}$ . For this reason, we have developed a flash-lamp pulse-forming network that produces a 140- $\mu\text{s}$  critically damped flash-lamp pulse. Our model predicts an 18% increase in pump efficiency by shortening the flash-lamp pulse duration from 200 to 140  $\mu\text{s}$ . Such an 18% increase in pump efficiency increases the small-signal gain as  $G^{1.18}$ . This modeling agrees well with our observed efficiency increase of 15% when we reduced the flash-lamp pulse duration.

The pulse is first double passed through a 9.5 mm  $\times$  115 mm LiSAF amplifier. This LiSAF rod is pumped in a four-lamp head by 600 J of electrical energy in a 140- $\mu\text{s}$  flash-lamp pulse. The result is a single-pass gain of 7.5 in this amplifier and a pump efficiency of 1.7%. Double pass through the rod and a Faraday rotator results in a net gain of 47. The pulse is then single passed through a second 9.5-mm LiSAF rod. This rod, pumped by 360 J in a two-lamp head with a 200- $\mu\text{s}$  flash-lamp pulse, exhibits a single-pass gain of 3. The resulting pulse is 300 mJ. The repetition rate of these amplifiers is 0.5 Hz, limited by the power supply's

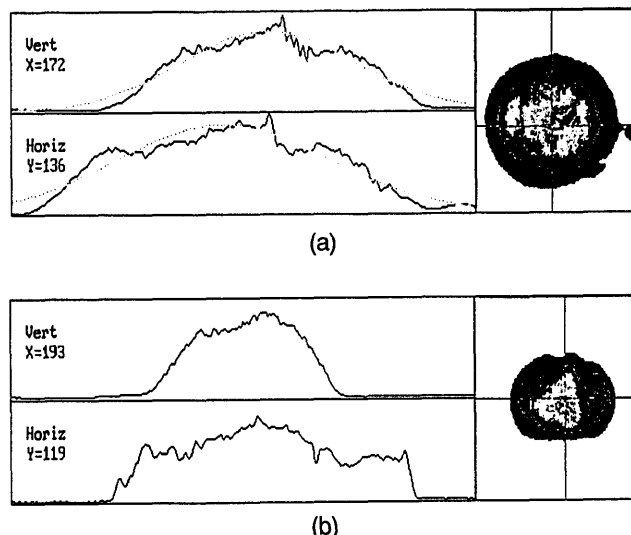


Fig. 3. (a) Beam spatial profile after a single pass through the first 9.5-mm amplifier rod. (b) Beam spatial profile (full system).

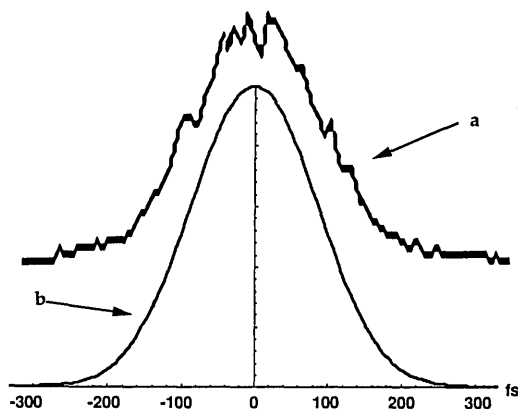


Fig. 4. Autocorrelation measured after recompression (curve a) and calculated for a transform-limited pulse (curve b).

charging the capacitor banks for the first head. This repetition rate can be raised to the 1-Hz level in the future.

Transmission interferograms of these rods indicate that there is significant wave-front distortion. In the worst case, this distortion is approximately one half-wave over the length of the rod. The consequence is beam quality degradation on passage through these amplifier rods. This effect is most severe after the double pass in the first amplifier, because the resulting single-pass distortion increases quadratically with the second pass. This degradation can be seen in the pulse spatial profiles (Fig. 3). Shown here is the distortion of the profile after a single pass through the first rod and the spatial profile through the entire system. This phase-front distortion can cause a severe reduction in the far-field intensity. We are currently modeling this effect in detail. We are taking steps to use only single-pass amplifiers, which should ameliorate some of the distortion effects. The problem will decrease as rods of better optical quality become available.

After the second amplifier, the pulse enters a vacuum spatial filter of  $f$ -number = 36 and  $M = 4$ . The pulse is injected into the grating-pair pulse compressor. Double pass results in recompressed energies of 150 mJ and an autocorrelation FWHM of 210 fs (Fig. 4, curve a). The amplified spectrum exhibits a width of 7.0 nm, narrowed from the input spectrum width of 10 nm by the polarizers in the regenerative amplifier (Fig. 2). A  $\text{sech}^2$  deconvolution of the autocorrelation suggests a pulse FWHM of <140 fs and a resulting time-bandwidth product  $\Delta\nu\Delta\tau = 0.40$ . A numerical Fourier transform of the amplified pulse spectrum indicates a transform limit of 135 fs and a resulting autocorrelation of 205 fs (Fig. 4, curve

b), indicating that the recompressed pulse is nearly transform limited.

In conclusion, we have developed a compact 1-TW laser system based on the laser material Cr:LiSAF. The system produces 150 mJ in a near-transform-limited 140-fs pulse and fires at a 0.5-Hz repetition rate. We observe moderate phase-front distortion on the output-beam profile due to imperfect optical quality of the 9.5 mm  $\times$  115 mm amplifier rods. This problem can be overcome by spatially filtering the output beam, by obtaining better optical quality rods, or by using only single-pass amplifiers after the regenerative amplifier.

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