8-TW 90-fs Cr:LiSAF laser

Paul Beaud, Martin Richardson, Edward J. Miesak, and Bruce H. T. Chai

Center for Research in Electro-Optics and Lasers, University of Central Florida, 12424 Research Parkway, Orlando, Florida 32826

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Ultrashort 90-fs 8-TW Fourier-transform-limited pulses are generated with chirped pulse amplification in a Cr^{3+}:$LiSrAlF_6$ laser system incorporating a regenerative amplifier and three additional double-pass amplifiers with increasing aperture up to 25 mm.

The generation of ultraintense subpicosecond pulses by use of the chirped pulse amplification (CPA) technique[1] has led to peak powers recently of up to 50 TW with a hybrid Ti:sapphire/Nd:glass amplifier system.[2] However, the laser-pulse duration with this approach (~0.5 ps) is considered too long for many high-intensity laser experiments. The amplification of shorter pulses of the order of 100 fs to the terawatt level concentrates currently on Ti:sapphire[3–5] and Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) laser systems.[6–10] In this Letter we report the generation of 90-fs Fourier-transform-limited pulses with a peak power of 8 TW obtained by use of a Cr:LiSAF laser system with a final amplifier aperture of 25 mm.

Whereas Ti:sapphire has the higher gain cross section and better mechanical strength, Cr:LiSAF has the advantages of a nonlinear refractive index ~3 to 4 times lower[11] and efficient flash-lamp pumping,[12] which permit the construction of more-compact, less-complex laser systems of larger aperture. Although flash-lamp pumping of Ti:sapphire (upper-state lifetime of ~3 μs) with pump pulse durations of 8 μs and a dye converter has been demonstrated recently,[13] efficient flash-lamp pumping of Cr:LiSAF (upper-state lifetime of 67 μs) is more straightforward and is easy to achieve with current technology. Up to now, pulse energies of 50–200 mJ have been generated with both laser materials, the output being primarily limited by the aperture size of available high-quality crystals (~1 cm).[4,5,8–10,13] Recently we have concentrated our efforts on the growth of large boules of Cr:LiSAF; from these boules we have fabricated rods with diameters of up to 25 mm,[14] which permit the amplification of femtosecond pulses up to the joule range. We have incorporated these 25-mm laser rods as the final amplifier into a high-intensity femtosecond Cr:LiSAF laser system that has a design based on our investigations of the gain and damage properties of Cr:LiSAF.[11,15] This system has the potential to generate 90-fs pulses of several joules of output energy with its present configuration.

The configuration of the laser system is shown in Fig. 1. The initial femtosecond pulse source is a Kerr-lens mode-locked Ti:sapphire laser that produces pulses of ~85-fs duration with a peak power of ~50 kW at 855 nm. These pulses are expanded 2000 times to 170 ps by four passes through a single-grating pulse stretcher corresponding to a double pass through an antiparallel grating-pair configuration. A single pulse selected by a Pockels-cell gate is then injected into a regenerative amplifier and amplified to the millijoule level at a repetition rate of 6 Hz.[7]

Two pulse slicers are used in series to select a single pulse from the pulse train produced by the regenerative amplifier. These ensure prepulse and postpulse suppression of the pulse train by a factor of ~10^9. The selected pulse is then amplified by two double-pass amplifiers operating at a repetition rate of 1 Hz. These amplifiers have dimensions of 7-mm diameter by 102 mm and 10-mm diameter by 102 mm, successively. The Cr concentration in these rods is 1.4%. Both amplifiers have two flash lamps [arc length of 3.5 in. (89 mm)] in close-coupled laser heads with 300-J maximum pump energy and ~140-μs pump pulse duration. After this stage of amplification, the beam is expanded through a telescope to a beam diameter ($1/e^2$)

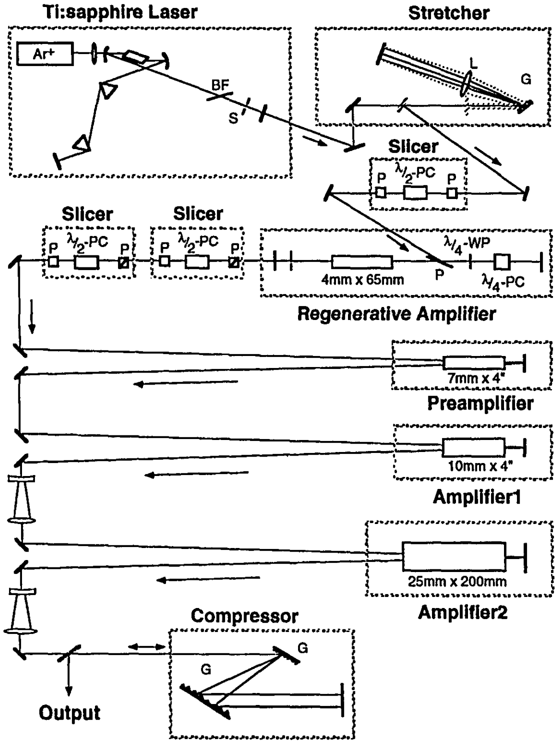

Fig. 1. Experimental setup: BF, birefringent filter; S, slit; G's, gratings; L, lens; P's, polarizers; PC's, Pockels cells; WP, wave plate.

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of 12 mm and double passed through the 25-mm amplifier. After this final amplifier, the beam is magnified to a beam diameter ($1/e^2$) of ~40 mm, and the pulses are recompressed with two gratings having dimensions of 110 mm × 110 mm and 110 mm × 135 mm in the standard parallel double-pass configuration. For future experiments we are planning to place the compressor stage and the output beam in a vacuum environment to avoid spatial and temporal deterioration of the recompressed pulse owing to the nonlinear refractive index of the air. In the present experimental setup a small fraction of the beam is selected close (~30 cm) to the output grating so that a single-shot autocorrelation measurement of the output pulse can be performed by minimization of the contribution of nonlinear pulse propagation in air to the measured pulse duration.

The final 25-mm amplifier is an eight flash lamp, close-coupled laser head with an arc length of 200 mm. The maximum input energy to the flash lamps is 5 kJ in a 300-μs-long pulse. This amplifier requires laser rods of >200 mm length. Since the maximum lengths of the 25-mm Cr:LiSAF rods are 100–115 mm, a glass tube with 26-mm inner diameter is installed into the laser head.[14] This arrangement permits us to insert two Cr:LiSAF rods lying end to end in the glass tube, at the expense of the repetition rate of the amplifier (since the rods are not cooled in this configuration). Currently we are firing this amplifier once every 10 min. The rods are of good optical quality. Each rod has scattering losses of ~0.01 cm^{-1} and a total wave distortion of less than a $\lambda/2$-wave rms measured across the full aperture. The actual chromium concentration is 0.6%, resulting in a uniform gain distribution.[10] With an electrical pump energy of 5 kJ, we measure a net amplification of 2.5 by inserting two rods into the laser head, which permits a double-pass amplification of 6. We emphasize that this laser head is not optimized for the current application. We expect a shortening of the relatively long pump pulse to result in higher gain. In addition, an improved mechanical design for holding and cooling the rods, and better still, the growth of >200-mm Cr:LiSAF rods, permits a higher repetition rate.

The energy of the single pulse selected by the pulse slicers at the output of the regenerative amplifier is 4.5 mJ with a stability of better than ±5%.[7] When directly compressed, it reliably produces 2.5-mJ (sech^2) pulses of 95-fs duration in a diffraction-limited Gaussian beam. The spectral width of the amplified pulse is 8.5 nm, resulting in a time–bandwidth product of 0.33, which is close to 0.315, the Fourier-transform limit. This result was obtained by adjustment of the regenerative amplifier for the highest output powers. Optimization of the regenerative amplifier for generation of the largest spectral width instead resulted in an ~10% wider Gaussian-shaped spectrum (FWHM)[7] but without any noticeable changes to the autocorrelation trace. This autocorrelation trace is shown in Fig. 2 on a logarithmic scale. The dynamic range of 3×10^4 is limited by the scattered second-harmonic signal that is produced by each arm of the autocorrelator rather than by the dynamic range of the photomultiplier tube. Although a shoulder is present in the signal, no satellite pulses are present, and the data points closely fit a sech^2 pulse over two orders of magnitude. These shoulders are typically observed in femtosecond CPA laser systems (see, for example, Ref. 5). In our opinion they represent a dispersive wave originating from higher-order dispersive effects that are not compensated in our CPA system and from small spectral inhomogeneities in the amplified pulse spectrum. These could arise from imperfections of the gratings, from residual self-phase modulation in the amplifiers, or from other effects such as absorption lines in the atmosphere. This interpretation and the determination of the dominant effects, however, need further clarification.

The 7-mm preamplifier produces pulse energies of 75 mJ at a repetition rate of 1 Hz, which are then further amplified by the 10-mm amplifier to 280 mJ at the same repetition rate. Two additional passes through the 25-mm final amplifier result in 1.45-J pulse energy in a single-shot mode (1 shot/10 min). After recompression, the pulse energy is 750 mJ. A single-shot autocorrelation of these pulses is shown in Fig. 3. The measured (FWHM) width is 140 fs, which corresponds to a pulse duration of 90 fs, assuming a sech^2 pulse shape.

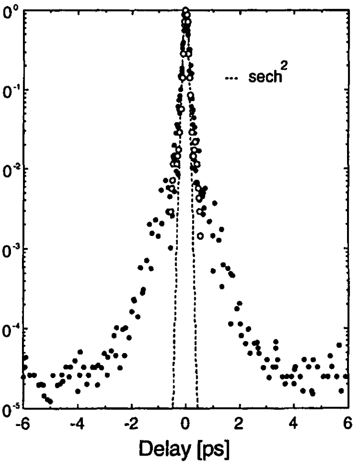

Fig. 2. Autocorrelation of the recompressed regenerative amplifier output pulses measured with a multiple-shot (solid circles) and a single-shot autocorrelator (open circles) on a logarithmic scale.

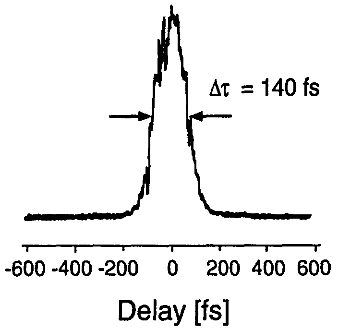

Fig. 3. Single-shot autocorrelation trace of the 750-mJ output pulse after recompression.

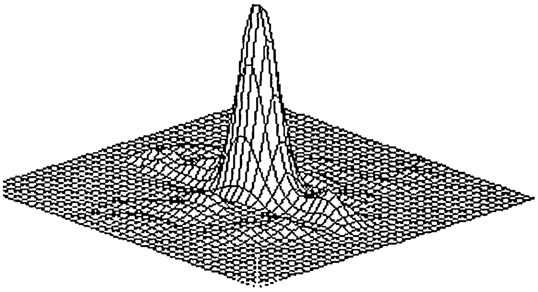

Fig. 4. Far-field distribution measured after the 25-mm amplifier when focused with a 1.5-m lens. The lateral dimensions of the plot are 1300 μm × 1300 μm.

An important requirement of all high-intensity lasers is their focusing capability. We used a CCD camera and a Spiricon LBA-100A beam analyzer to diagnose the near- and far-field profiles at various points in the system to ensure optimum pulse propagation. Figure 4 shows, at the 1-TW level, the far-field distribution of the output from the 25-mm amplifier when it is focused with a 1.5-m lens. The central peak contains >65% of the total energy and has a $1/e^2$ width of 280 μm, corresponding to an ~2 times diffraction-limited beam. This would imply that when the output beam of the system is focused with a 5-cm focal-length focusing element, spot sizes of <5-μm diameter are obtainable, resulting in peak intensities of $\sim 5 \times 10^{19}$ W/cm^2. We believe that part of the energy loss from the far-field central peak is caused by diffraction from within the 25-mm-diameter laser crystals we are currently using. This is manifested as a square grid-like structure in the near-field distribution of the output beam, aligned to the crystal axes. The cause of this effect is under investigation.

We expect to make further improvements to the output performance of this system in the near future. Replacement of some of the amplifier crystals with low-loss Cr:LiSAF will lead to a threefold increase in output power and an improvement in focusing. Both the Lightning Optical Corporation[16] and we at the Center for Research in Electro-Optics and Lasers can now produce Cr:LiSAF rods with negligible scattering losses. In addition, a further increase of a factor of 2 can be gained from antireflection coating all our amplifier rods. We also anticipate further optimizing of the pump conditions for our large-diameter amplifiers.

In summary, we have developed a compact femtosecond multiterawatt CPA laser system that uses flash-lamp-pumped Cr:LiSAF amplifiers with apertures of up to 25 mm. We have demonstrated the generation of Fourier-transform-limited 90-fs pulses with 8-TW peak power. To our knowledge this is the highest power achieved so far for pulses in this time domain. With further improvements this system has the potential of providing focused intensities well in excess of 10^{20} W/cm^2.

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