Multi-Terawatt Femtosecond Cr:LiSAF Laser

Paul A. Beaud, Martin Richardson, and Edward J. Miesak

***Abstract*—We discuss the design of a Cr:LiSAF laser system capable of generating ultrashort, 90-fs Fourier-transform limited pulses with a peak power of 8 TW. Using chirped pulse amplification and flashlamp-pumped Cr:LiSAF amplifiers this system incorporates a regenerative amplifier and three additional double-pass amplifiers with increasing aperture up to 25 mm. The temporal performance as well as the spatial beam quality are discussed in detail. We discuss extension of this system to the Petawatt power level.**

I. Introduction

The chirped pulse amplification (CPA) technique [1], [2] has made possible development of table-top solid-state laser systems producing ultrashort pulses with peak powers in the Terawatt range. The first CPA systems were based on Nd:glass amplifiers [3], [4] which generate today peak powers of 10–30 TW [5]–[8]. The minimum pulse duration obtainable with Nd:glass amplifiers is limited to approximately 1 ps limited by the spectral linewidth of Nd:glass. However in a hybrid Nd. system incorporating Ti:sapphire in the low power, high gain section of the amplifier chain, shorter pulses ($\sim$ 400 fs) and higher powers (50 TW) have been generated [9], and powers up to the PW level are planned [10].

The amplification of pulses of 100 fs or less to the Terawatt level has so far concentrated on Alexandrite [11], [12] Ti:sapphire [13]–[16], and recently Cr:LiSAF [17], [18] as the amplifying media. Ti:sapphire based systems, however, require a frequency-doubled Q-switched laser as a pump source that increases the cost and complexity of these systems. Alexandrite can be efficiently flashlamp pumped, but displays large thermal lensing, making difficult the attainment of diffraction-limited beam output from amplifiers [19]. Cr-doped, LiSAF, $LiSrAlF_6(Cr.^{3+})$ is a new laser material [20], [21] which does not suffer these handicaps. It has many versatile characteristics as a laser material for the generation and amplification of ultrashort laser pulses. Its broad spectral bandwidth permits the amplification of pulses of several 10's fs duration. It has a relatively long upper state lifetime (67 μs), and absorption bands convenient for flashlamp pumping. It can now be grown in boules of varying Cr concentration to sizes in excess of 25 mm diameter, having high optical quality, suitable for the assembly of large aperture amplifiers. Its versatility as a laser material has been demonstrated in several ways. Tunable flashlamp pumped operation has been demonstrated [22], and it has been successfully diode pumped [23]–[25]. Pulses as short as 30 fs have been generated with mode-locked [26]–[30] Cr:LiSAF lasers. A CW pumped high repetition rate Cr:LiSAF regenerative amplifier [31] has also been demonstrated. In the past three years considerable progress has been made in the development of high-intensity femtoseond Cr:LiSAF CPA laser systems. Flashlamp pumped Cr:LiSAF regenerative amplifiers [32]–[34] producing $\sim$100 fs pulses at the milli-Joule level have been demonstrated and by combining these with a successive chain of Cr:LSAF amplifiers, peak powers in the multi-Terawatt range have been obtained [17], [18], [35]–[37].

In this paper, we give a detailed description of a Cr:LiSAF laser system that has demonstrated peak powers of 8 TW in 90 fs pulses. This is the highest power so far reported at this pulse duration. Although we have previously published brief communications on various aspects of the operation of this system, this is the first time that a comprehensive description has been made of its design criteria, properties, and potential. The paper is divided into several sections. Section II discusses the optical and physical properties of Cr:LiSAF that are relevant to ultra-high power short pulse laser technology. In Section III we describe the design and performance of the multi TW Cr:LISAF laser. Finally in Section IV we discuss improvements to the performance of this system and the potential this technology has to achievement of PW powers in pulses of $<$ 100 fs.

II. Properties of Cr:LiSAF

Growth of single crystals of Cr:LiSAF is best fabricated by the Czochralski pulling technique. Other crystal growth techniques, such as the horizontal zone-melting technique and the vertical Bridgeman approach have so far not been successful in producing large crystals with high optical quality. Because Cr:LiSAF has a negative thermal expansion coefficient along the c-axis, great care has to be taken with the Czochralski method to produce good crystals. This involves the maintenance of strict control of the thermal gradients in the growth furnace. Cr:LiSAF melts congruently at $\sim$ 750 °C, and very stable pulling conditions must be maintained during the growth process. Careful experimentation has progressively optimized this approach to produce single crystal boules having outside diameters of $\sim$3 cm and overall lengths of 13–14 cm [38]. These improvements have principally been to the reduction of stress induced optical refractive effects, and the elimination of optical scattering sites within the crystal. In addition in the last few years several studies of specific physical characteristics of Cr:LiSAF have been published: its spectroscopic characteristics [20], [21], its crystallographic structure [39], [40], its thermo-mechanical and thermo-optical properties [41], [42], optical damage limits [41] and its opti-

Manuscript received January 20, 1994; revised September 1, 1994. This work was supported by the State of Florida and the National Science Foundation under Grant ECS-9113726.

The authors are with the Center for Research in Electro-Optics and Lasers (CREOL), University of Central Florida, Orlando, FL 32826 USA.

IEEE Log Number 9407797.

TABLE I
LASER PROPERTIES OF LiSAF, Ti:sapphire, Nd:Glass AND Nd:YAG.
[a]: REF. [20], [b]: REF. [49], [c]: REF. [50], [d]: REF. [47].

	Cr:LiSAF	Ti:sapphire [b]	Nd:Glass [b]	Nd:YAG [b]
Peak wavelength (l) [nm]	850 [a]	790	1054	1064
Linewidth (Dl) [nm]	180 [a]	230	20	0.45
Emission cross section [10^{-19} cm^2]	0.5 [a]	4.1	0.42	6.5
Fluorescence lifetime (t) [msec]	67 [a]	3.2	315	230
Refractive Index (n)	1.41 [c]	1.76	1.53	1.82
Scat. loss (a) [cm^{-1}]	0.002 [d]	0	0	0.002

cal gain properties [43]–[46]. Those properties of Cr:LiSAF relevant for the design of high energy amplifiers are shortly summarized in this section.

A comparison of the primary laser parameters of Cr:LiSAF compared with those of Ti:sapphire, Nd:Glass (LHG-8) and Nd:YAG is summarized in Table I [41], [47], [48]. The gain bandwidth of Cr:LiSAF is nearly as large as that of Ti:sapphire which makes this material attractive for the amplification of ultrashort optical pulses. Whereas its gain is approximately one order of magnitude lower than that of Ti:sapphire, Cr:LiSAF has a long enough lifetime of 67 μs to permit flashlamp pumping fairly efficiently [20], [22]. The optical loss of Czochralski grown Cr:LiSAF has continued to improve and material with losses of $\sim$0.002 cm^{-1} is now commercially available [48]. The peak emission wavelength of Cr:LiSAF at 850 nm, overlaps well that of a mode-locked Ti:sapphire laser which at present is the most reliable femtosecond pulse source in this spectral region.

The gain of Cr:LiSAF is moderate, strongly polarized and affected by excited state absorption (ESA) and upconversion [43]–[46], [51]. ESA reduces the gain for the p-polarization by $\sim$30% and approximately cancels that for s-polarization [43]–[46]. The effective gain cross sections for both polarizations and the unpolarized ESA cross section are shown in Fig. 1. At first sight ESA could simply be overcome by increasing the pump energy. However, with increasing pump power the upconversion process becomes more important due to its square law dependence on the population of the upper laser level [44], [51]. As a result it is nearly impossible to reach exponential gain with Cr:LiSAF. As a rule relatively large pump densities are required to overcome the drawback of ESA, and the effect of upconversion can be reduced with the use of long rods. The strong polarization of the small-signal gain observed for Cr:LiSAF has strong implications for the design of high power oscillator-amplifier systems. In these systems amplifiers are configured to maximize energy extraction, and minimize ASE and the amplification of retro-reflected laser light. Many amplifier system designs take advantage of the gain properties of both polarizations. Cr:LiSAF does not offer this advantage.

Bulk damage thresholds of 160–500 GW/cm^2 for low doped Cr:LiSAF (at 1064 nm with a 47 ps pulse) have been measured [41]. We have also observed optical damage to a regenerative amplifier crystal at an intensity level of $\sim 15\,GW/cm^2$. Although refraction within the cavity may be partially responsible in this case, we believe that the damage

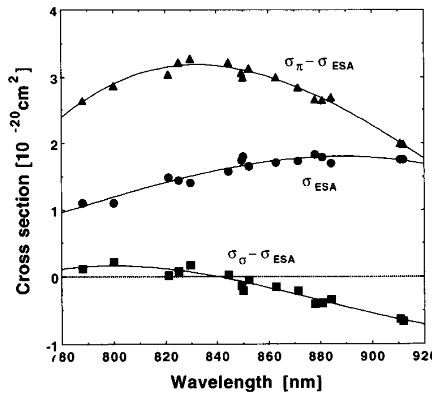


Fig. 1. Wavelength dependence of the ESA cross section (circles) and of the effective gain cross sections for p (triangles) and s polarization (squares) of Cr:LiSAF.

was triggered by scattering centers in the crystal. The nonlinear refractive index of Cr:LiSAF at 1064 nm is 5.5×10^{-17} cm^2/W [41] which is significantly lower than that of fused silica of 3.2×10^{-16} cm^2/W. This is an important advantage for the design of high intensity laser systems since it allows higher energy extraction avoiding the detrimental influence of small-scale self-focusing to the focusability of the output beam.

Measurements of the thermal and mechanical properties of LiSAF have been made to determine the maximum stress the material can sustain under thermal loads [41], [42]. These factors are important in considering LiSAF for high power applications under high repetition-rate flashlamp pumping configurations. The most important parameters are listed in Table II. The mechanical strength of Cr:LiSAF is rather weak compared to Nd:glass and Nd:YAG, and Cr:LiSAF has a negative expansion coefficient along its c-axis, which is usually oriented orthogonal to the rod axis. These characteristics, together with the difficulty of removing residual thermo-mechanical stress in the medium, limit at present the repetition rate of flashlamp-pumped Cr:LiSAF laser systems [52]. The thermal lens in direction perpendicular to the c-axis (which is parallel to the a-axis) is expected to be small since a and dn/dT have opposite signs and tend to cancel each other. Parallel to the c-axis however both a and dn/dT are negative, leading to negative c-axis lensing of Cr:LiSAF amplifiers when operated at high average powers.

III. DESIGN AND PERFORMANCE OF HIGH-INTENSITY Cr:LiSAF LASER

A. Experimental Setup

Based on the parameters summarized above, we have built a high intensity femtosecond Cr:LiSAF laser system capable at present of powers of $\sim$8 TW. The experimental configuration of the laser system is shown in Fig. 2. The initial femtosecond pulse source is a Kerr lens mode-locked Ti:sapphire laser [53]. The output pulses of this laser are expanded in an anti-parallel grating-pair pulse stretcher and injected into a regenerative amplifier. Pulse slicers used before and after the regenerative amplifier select a single pulse out of the pulse train. This single

TABLE II
THERMAL AND MECHANICAL PROPERTIES OF LiSAF, Nd:Glass AND Nd:YAG. [a]: REF. [41], [b]: REF. [41], [c]: REF. [49].

	Cr:LiSAF		Nd:Glass [c]	Nd:YAG [c]
	∥ c-axis	∥ a-axis		
Thermal shock resistance $(R_T)'$ [W/m$^{1/2}$]	-	~0.4 [a]	~0.4	5.2
Fracture strength (s_f) [kg/mm^2]	-	39 [b]	11.4	6.7
Young's modulus (E) [GPa]	108 [b]	109 [a]	50	280
Vickers microhardness (H) [GPa]	-	1.9 [b]	3.1	11.9
Fracture toughness (K_{Ic}) [MPa m$^{1/2}$]	0.33 [b]	0.39 [b]	0.45	1.4
Thermal expansion (a) [10^{-6}/°C]	-9.8 [b]	22 [b]	12.7	7.8
Therm. cond. (k) [Wm^{-1}K^{-1}]	1.68 [b]	1.0 [b]	0.62	13
dn/dT [10^{-6}/°C]	-4.0 [a]	-2.5 [a]	-5.3	7.3

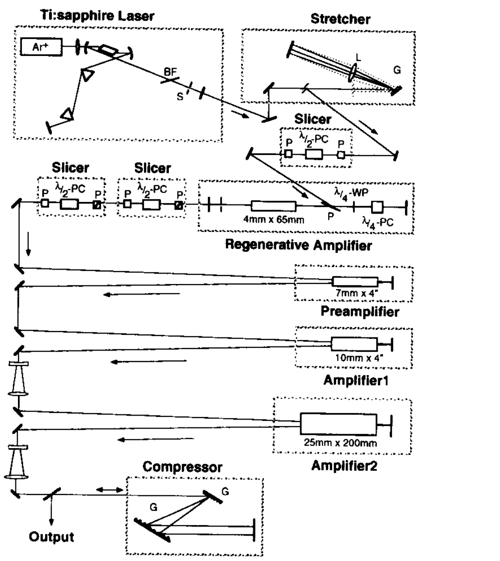


Fig. 2. Experimental set-up: BF: birefringent filter, S: slit, G: grating, L: lens, P: polarizer, PC: Pockels-cell, WP: waveplate.

pulse is then further amplified in three double pass amplifiers with increasing aperture up to 25 mm and finally recompressed in a grating-pair pulse compressor.

The Ti:sapphire laser is pumped with 8 W of an Argon-Ion laser (Laser Ionics, Model 1400 15 A). This laser is configured in an X-type cavity, uses a 7.5 mm long Ti:sapphire crystal and contains two SF10 prisms for group velocity dispersion compensation, a thick one-plate Lyot-filter for wavelength tuning and a variable slit acting as a saturable absorber. With the mid-range mirror set the Ti:sapphire laser produces 300–500 mW, < 100 fs pulses tunable from 780 to 900 nm. These pulses are expanded $\sim$ 2000 times to 170 ps by four passes through a single grating pulse stretcher corresponding to a double pass through an anti-parallel grating-pair configuration [54]. The gratings are 1800 grooves/mm, gold coated holographic diffraction gratings. The achromatic telescope lens with a focal lens of 40 cm is placed at a distance of 20 cm from the grating resulting in an effective grating separation of 40 cm. The incident and diffracted angles are 60 ° and 41.6 °, respectively, and the diffraction efficiency is $\sim$90%.

A single stretched pulse is selected by a double quarter-wave Pockels-cell optical gate and injected into the regenerative amplifier having an energy at this point of $\sim$1 nJ. The regenerative amplifier is configured in a linear cavity using a flat 60% output coupler and a 5 m radius high reflective end mirror and contains a thin film broad-bandwidth polarizer, a zero order quarter-wave plate and a quarter-wave Pockels-cell. The 4 mm dia. × 65 mm rod is pumped at 6 Hz in a dual flashlamp laser head (a modified Continuum, SF 606-04) with an effective pump length of 56 mm and with a maximum (electrical) pump energy of 50 J. The flashlamp pulse duration is 130 ms, sufficiently short to pump the Cr:LiSAF crystal efficiently. A shorter flashlamp pulse duration would limit flashlamp lifetime. The dopant concentration of the Cr:LiSAF rod is 2% (CrF_3 replacing AlF_3). An iris pinhole of $\sim$2 mm near the output coupler is used as an intra-cavity aperture. The single chirped input pulse is injected into the regenerative amplifier through the thin film polarizer. A digital logic circuit combined with a photodiode which detects the output pulse train of the Ti:sapphire laser is used to synchronize both the optical gate and the Q-switch with the Ti:sapphire oscillator.

Two pulse slicers are used in series to select a single pulse from the pulse train produced by the regenerative amplifier. These ensure pre-pulse suppression of the pulse train by approximately a factor of 10^9. The selected pulse is then amplified by two double-pass amplifiers (Laser Modules Inc.) operating at a repetition rate of 1 Hz. The amplifier rods have dimensions of 7 mm dia. × 105 mm and 10 mm dia. × 105 mm, successively. The Cr-concentration in these rods is 1.4%. Both amplifiers (Laser Modules Inc.) have two flashlamps (arc length of 3.5 in) in close coupled laser heads with 300 J maximum pump energy and $\sim$140 ms pump pulse duration. After this stage of amplification the beam is expanded through a telescope to a beam diameter $(1/e^2)$ of 12 mm and double passed through the 25 mm amplifier. This final 25 mm amplifier is an 8 flashlamps, close coupled laser head with an arc length of 200 mm. The maximum input energy to the flashlamps is 5 kJ in a 300 ms long pulse. This amplifier (Continuum, SF 320-25) requires laser rods of $>$ 200 mm length. Since the maximum length of the 25 mm Cr:LiSAF rods is 120 mm, a glass tube with 26 mm inner diameter is installed into the laser head [55]. This arrangement allows 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 we are currently firing this amplifier once every 10 min. The rods are of good optical quality. Each rod has scattering losses of $\sim$0.01 cm^{-1} and a total wave distortion of less than a 1/2 wave rms measured across the full aperture. The Chromium concentration is set at 0.6% to provide a uniform gain distribution.

After this final amplifier the beam is magnified to a beam diameter $(1/e^2)$ of $\sim$ 40 mm and the pulses are recompressed with two gratings in the standard parallel double pass configuration [56]. These grating are identical to those used in the pulse stretcher and have a size of 110 × 110 mm and 110 × 135 mm, respectively. The transmission efficiency of the grating compressor is approximately 55%. For future experiments we are planning to place the compressor

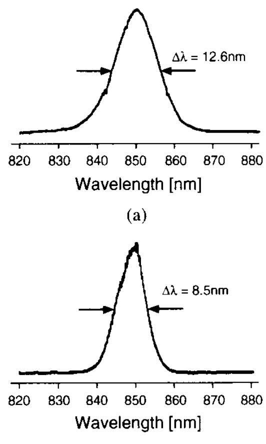


Fig. 3. Spectrum of (a) the 80 fs pulses of the KLM Ti:sapphire laser (a) and spectrum of the regenerative amplifier output pulse (b).

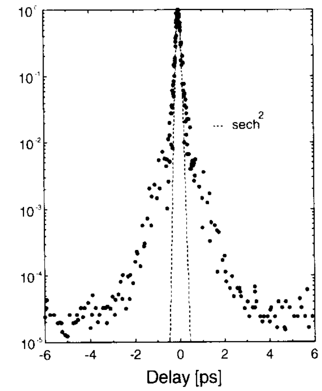


Fig. 4. Multiple shot autocorrelation trace of the recompressed regenerative amplifier output pulses shown in logarithmic scale.

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 and of the entrance window to the target chamber. In the present experimental setup a fraction of the beam is selected close ($\sim$ 30 cm) to the output grating to perform a single shot autocorrelation measurement of the output pulse by minimizing the contribution of nonlinear pulse propagation in air to the measured pulse duration.

B. Regenerative Amplifier and Temporal Performance

The Ti:sapphire laser produces nearly Fourier-transform sech^2 pulses when operated at pulse durations of 100 fs or longer. Increasing the amount of prism material in the laser cavity leads to somewhat shorter pulses, but significantly increases the time-bandwidth product due to the rather large third order dispersion when using SF10 prisms in a Kerr lens mode locked Ti:sapphire laser [57]. Shorter pulses as short as 10 to 20 fs can be—if necessary—obtained by replacing our prisms by prisms made of Quartz or LaK121 [57]–[60]. However, we typically operate the Ti:sapphire laser at a pulse duration of $\sim$ 80fs. The pulse spectrum has a width of 12.6 nm (see Fig. 3(a)) resulting in a time bandwidth product of 0.42. The pulse wavelength is matched to the center wavelength of the spectrum of the Q-switched regenerative amplifier which typically lies around 850–855 nm (slightly depending on the output coupler used). The free running spectrum of the regenerative amplifier has a width of $\sim$ 15 nm.

The regenerative amplifier needs 37 roundtrips to reach gain saturation producing a pulse train approximately 70 ns long from which a single pulse is selected at its peak. The output pulse spectrum (Fig. 3(b)) of the regenerative amplifier is $\sim$8.5 nm which is significantly narrower than the injected spectrum. We believe that the bandwidth of the regenerative amplifier is limited by the output coupler (which has a single stack coating) rather than by gain narrowing. Due to the narrower pulse spectrum the duration of the uncompressed pulse leaving the regenerative amplifier is estimated to be $\sim$115 ps when including the material dispersion of the amplifier. The energy of the single pulse selected by the pulse slicers at the output of the regenerative amplifier is 5 mJ with a stability of better than $\pm$ 5%. When directly recompressed the pulse energy is 2.7 mJ. The pulse width is measured with a single shot autocorrelator using a 300 mm thin KDP crystal [61]. After first alignment of the pulse compressor the autocorrelation typically shows extended pulse wings and satellites and has a width of typically longer than 200 fs. These satellites are due to residual higher order dispersion introduced in the stretcher/compressor as soon dispersive elements are placed between the stretcher and compressor even if the gratings are perfectly aligned. However, tweaking of the gratings and mirrors of the pulse stretcher and the gratings of the compressor results in pulse durations of typically 90 to 100 fs corresponding to a time-bandwidth product of 0.32 to 0.35 which is close to 0.315, the Fourier-transform limit of a sech^2 pulse. A multishot autocorrelation trace is shown in Fig. 4 in logarithmic scale. The dynamic range of 3×10^4 is limited by 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 to a sech^2 pulse over nearly two orders of magnitudes. These shoulders are due to residual third order dispersion not compensated in our CPA system.

Since the amplification of shorter pulses is the most straight forward way to increase the output power of high intensity laser systems, where larger pulse energies are only difficult or at great cost to achieve, a more systematic way to optimize the output pulse duration becomes necessary. Several methods to minimize third, fourth and even quintic order dispersion have recently been proposed [61], [63]. We have tested one of these methods to minimize third order dispersion. We have performed calculation of the dispersion of the overall system including the gratings and accounting for the material dispersion in the amplifiers. The dispersion of Cr:LiSAF has been calculated using the Sellmeier equation given in [50]. Choosing identical angles in pulse stretcher and compressor we calculate a residual third order dispersion of 6.8×10^5 fs^3 and fourth order dispersion of -2.2×10^5 fs^4 when the second

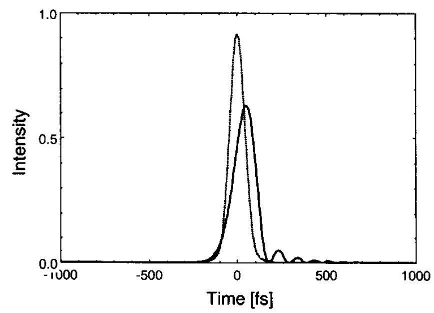


Fig. 5. Calculated temporal pulses shapes for incident angles to the first compressor grating identical to that of the pulse stretcher of 60° (solid line) and when tuned to 62.6° (dashed line). The intensities are normalized to the peak of the input pulse.

order dispersion is minimum. The resulting temporal pulse shape is shown in Fig. 5 (solid curve) and has a width of 140 fs. The oscillatory structure at the trailing edge of the pulse is due to third order dispersion. In this simulation we used an initial pulse duration of 88 fs which is the Fourier transform limit of a pulse with a bandwidth of 8.5 nm. It was shown in [62] that third order dispersion can be minimized by detuning the incident angle to the grating-compressor. Our calculation indicates that zero third order dispersion can be obtained at an input angle of 62.6°. The corresponding temporal pulse shape is shown in Fig. 5 (dashed curve). The fourth order dispersion term has increased to $+4.9 \times 10^6$ fs^4 and is responsible for a slight increase of the pulse width to 95 fs.

In the experiment, we first align the pulse stretcher and compressor as accurate as possible and adjust the compressor grating separation for minimum pulse width without any additional tweaking of the stretcher and compressor. In this case the autocorrelation trace shows considerably large wings (see Fig. 6(a)). Assuming a $sech^2$ pulse shape the pulse width is 145 fs. The grating separation is 41 cm close to the calculated value of 41.1 cm. By changing the angle of the compressor gratings while at the same time keeping them parallel, and by readjusting their separation the pulse duration can be adjusted to a minimum and the wings suppressed. The incident angle to the first compressor grating giving the shortest pulse was 54° which significantly deviates from the calculated value of 62.6°. This discrepancy may be due to i) imperfect alignment of the pulse stretcher and ii) other sources of dispersion not taken into account in the calculations such as beam size and divergence effects [64], as well as the effects of coatings and the phase-matching fluid in the Pockels-cell. The autocorrelation trace of the optimized compressor (shown in Fig. 6(b)) has no wings and has a width of 145 fs which corresponds to a nearly Fourier-transform limited pulse duration of 95 fs. According to [62] the fourth order dispersion can be adjusted by changing the separation of the telescope lenses in the pulse stretcher, which in a single grating pulse stretcher can easily be done by moving the mirror placed in the focus of the stretcher lens. However, since the effect of fourth order dispersion is rather small for 100 fs pulses, this method had little effect on the pulse duration within the accuracy of the measurements (± 5 fs).

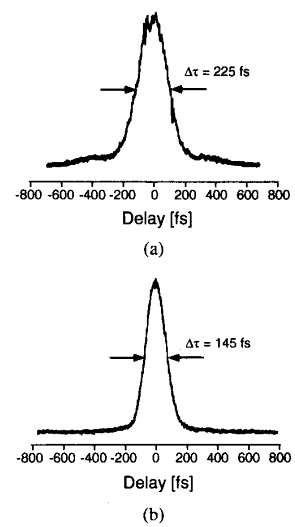


Fig. 6. Measured single shot autocorrelation traces for an incident angle to the first compressor grating of 60° (a) and 54° (b).

C. Amplifier Performance

The 7 mm preamplifier has a small signal gain of ~6.3 at an electrical pump energy of 300 J. This amplifier uses somewhat older Cr:LiSAF material grown at CREOL and exhibits scattering losses of $\sim 0.04\,cm^{-1}$. Since the rod is also not antireflection coated the effective double pass gain is reduced to 15 and the 5 mJ pulse leaving the regenerative amplifier is amplified after a double pass through the 7 mm amplifier to a pulse energy of 75 mJ. (Note that a lower gain was reported in [37] from this amplifier. We have meanwhile exchanged the transformer in the pulse forming network resulting a reduction of the pump pulse from 180 to 140 ms and to a ~20% higher gain.) The single pass gain of the 10 mm amplifier is 2.7 at a pump energy of 300 J. The scattering loss of this rod is $\sim 0.015\,cm^{-1}$ resulting in a double pass gain of 5.3. The Cr-concentration of both the 7 mm and 10 mm diameter rods is 1.4% that results in somewhat higher gain at the rod edges. The gain distribution for both amplifiers is shown in Fig. 7(a) and (b). We expect a homogeneous gain profile with a Cr-concentration of ~1.2% for the 7 mm, and 0.8% for the 10 mm amplifier, respectively. After double passing this amplifier we measure a pulse energy of 280 mJ—corresponding to an effective gain of only 3.7—which is less amplification than expected from our gain measurements. We believe that the discrepancy is due to the fact that part of the energy is scattered from the beam because of the relatively poor optical quality of this rod. The final 25 mm amplifier has a single pass gain of 3.8 at an electrical pump energy of 5 kJ when inserting two rods into the laser head (Fig. 7(c)). The scattering loss of both rods is $\sim 0.01\,cm^{-1}$ and both rods are not AR coated resulting in a net double pass amplification of ~6. Two passes through the 25 mm final amplifier results in 1.45 J pulse energy in a single shot mode (1 shot/10 min). We expect to further increase the output performance of this system in the near future. Replacement of the amplifier crystals with low-loss Cr:LiSAF and by AR coating all the amplifier

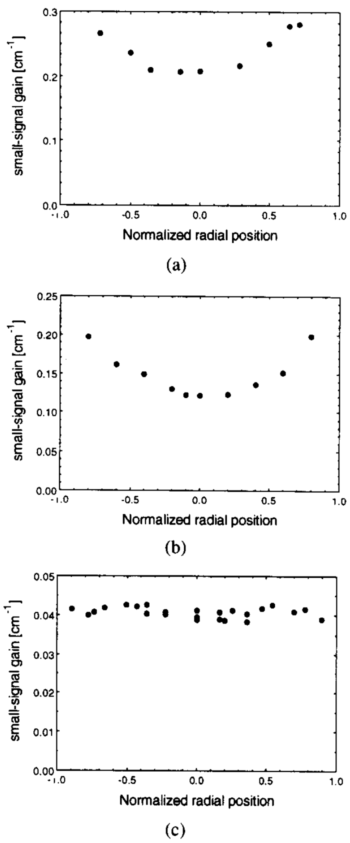


Fig. 7. Radial gain distribution of (a) the 7 mm preamplifier at an electrical pump energy of 300 J, (b) the 10 mm amplifier (300 J), and (c) the final 25 mm amplifier (2.25 kJ).

rods will increase the available gain by a factor of 7. We also anticipate optimizing further the pump conditions for 25 mm diameter amplifiers by shortening the relatively long pump pulse which is currently 300 ms.

The energy density at the first compressor grating is approximately 120 mJ/cm^2. No optical damage to the grating has been observed at this intensity. After recompression the pulse energy is 750 mJ. We have measured the pulse duration when operating the amplifier system at full energy. A single shot autocorrelation of these pulses is shown in Fig. 8. The measured (FWHM) width is 140 fs which corresponds to a pulse duration of 90 fs assuming a sech^2 pulse shape.

D. Spatial Beam Quality

An important requirement of all high intensity lasers is their focusing capability. We have 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. We determined B-integral [65] values of 0.2, 0.3, and 1.7 for the 7, 10, and 25 mm amplifiers. Although the B-integral of the final amplifier is rather high, the overall B-integral of the amplifier chain of 2.2 is still smaller than 3, the limit for stable beam propagation [65]. Furthermore

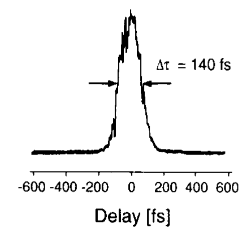


Fig. 8. Single shot autocorrelation trace of the 750 mJ output pulse after recompression.

we do not observe any intensity dependent changes of the beam profile.

Fig. 9 shows the diffraction limited ($M^2 = 1 \pm 0.1$) near field profile of the regenerative amplifier output beam. A diffraction limited beam is also maintained in the 7 mm preamplifier. Since the optical quality of the 10 mm amplifier is rather poor we amplified the output beam of the 7 mm preamplifier directly with the 25 mm amplifier in order to measure its optical quality. The output beam of the preamplifier was magnified with a telescope to a $1/e^2$ diameter of 12 mm and transmitted in a double pass through the final amplifier. The uncompressed pulse energy was in this case 390 mJ. Fig. 10(a) shows the far field measurement of the input beam to the 25 mm amplifier when focused with a 1.5 m lens. The $1/e^2$ beam diameter at focus is 136 mm which corresponds to that expected for a diffraction limited Gaussian beam. The focused output from the 25 mm amplifier when focused with a 1.5 m lens is shown in Fig. 9(b) (note that the lateral scale in Fig. 10(b) is twice of that in Fig. 10(a)). The beam waist has a width of 280 mm (FW $1/e^2$M) corresponding to that of a ~2 times diffraction limited beam. The central peak contains >65% of the total energy. We believe that part of the energy loss from the far field central peak is due to 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 parallel to the crystal axes. The beam leaving the final amplifier has a slightly cylindrical divergence. The divergence is larger in the horizontal plane (parallel to the c-axis) which makes it difficult to magnify the beam and pass it through the compressor gratings. The cause of this diffraction within the crystal is under investigation. We do not believe that the increased divergence in the plane of the c-axis is due to thermal lensing since the pump absorption is as shown above homogeneous within the aperture of the rod and we operate this amplifier at a very low repetition rate. A slight improvement in focusing is expected when correcting for the cylindrical divergence.

We expect to make further improvements to the output beam focusability in the near future. Replacement of some of the amplifier crystals with low-loss Cr:LiSAF will lead to an improvement in focusability and an output beam less than 2× diffraction limited should be achievable operating this system at the 1 Joule level (10 TW). 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 mm diameter are obtainable, resulting in peak intensities of $>5 \times 10^{19}\ \mathrm{W/cm^2}$.

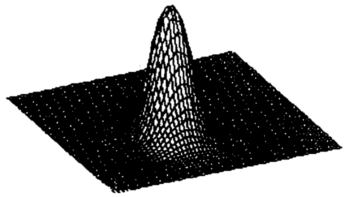
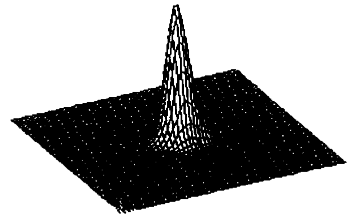
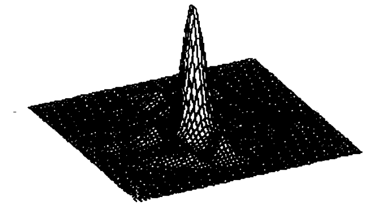


Fig. 9. Near field measurement of the regenerative amplifier output beam. The lateral dimensions of the plot are 5664 × 5664 mm.



(a)



(b)

Fig. 10. Far field measurements of (a) the input and (b) of the output beam of the 25 mm amplifier when focused with a 1.5 m lens. Note that the scale of (b) is twice of that of (a). The lateral dimensions of the plots are 708 × 708 mm (a) and 1416 × 1416 mm (b).

IV. Higher Powers

The technology that we have employed in the development of this laser has much potential for the achievement of much higher power levels. In principle this technology can make possible the construction of a laboratory-size femtosecond pulse laser operating at the Petawatt level. Such a laser might be expected to have a focused spot intensity of $>10^{21}$ W/cm^2. The demonstration of focused intensities of this order in a laboratory environment would have a major impact on several fields, particularly those involving high field physics. In this section we describe the measures we are currently taking to extend the output of this system up to the 100 TW level, and discuss the technology involved and the improvements that would necessary to upgrade this system to the 1 Petawatt level.

We are currently modifying our Ti:sapphire laser to produce pulses of less than 20 fs duration at a center wavelength of 850 nm [59], [60]. Reflective telescope optics will be used in the pulse stretcher. The design of the regenerative amplifier will be based on a cavity-dumped system. Cavity dumping of the regenerative amplifier becomes necessary to reduce the number of round-trip passes in the resonator in order to preserve the larger spectral bandwidth of the 20 fs pulses. Whereas the number of cavity passes in the present cavity is 37, the use of a cavity-dumped system will permit the number to be reduced to ~16. Modifications to the current amplifier chain will both increase the gain per unit length in the amplifier units and reduce the optical path length in the LiSAF rods, thereby significantly decreasing the B-integral value since the full aperture of the rods can be used. A single pass gain of 10 from a 10 mm Cr:LiSAF rod pumped with 600 J electrical input energy from 4 flashlamps has been demonstrated by Ditmire and Perry [36]. An amplifier head designed for our 25 mm Cr:LiSAF rods should allow a single pass gain of approximately 5. The use of lower-loss AR coated Cr:LiSAF rods in these amplifiers will allow the generation of compressed pulse energies of ~2 J.

To achieve recompression of 20 fs pulses it will be necessary to compensate for dispersion up to the fifth order. Although this can be achieved by careful design of the system, an exact knowledge and very precise alignment of all the optical elements in the pulse stretcher and compressor will be required without any possibility to fine tune third and higher order dispersion if once the system design is set. For this reason we are currently investigating the possibility of using additional elements which may allow simultaneous fine alignment of both second and third order dispersion. Such an element might consist in an additional prism pair inside the regenerative amplifier cavity. Simultaneously changing the amount of prism material and the separation of the compressor gratings would allow one to tune the third order dispersion.

The assumption that energies in the range 1–5 J can be extracted from rod amplifiers of 25 mm diameter, places a practical power limit of ~200 TW for the current system architecture. To achieve significantly higher peak powers on the assumptions of rod technology and the current limits of crystal growth would imply the use of multiple beamlines. To achieve higher powers in a single beam requires development of alternative amplifier approaches to increase the beam aperture beyond 25 mm. We are currently working on these approaches.

V. Summary

We have described the development of a new approach to ultrashort ultrahigh power laser pulse generation that is dependent on a new solid state laser material, Cr:LiSAF. This material possesses unique properties ideally suited to the deployment of convention oscillator-amplifier technology in a high intensity system. After making a detailed study of this material's optical and physical properties, we have successfully incorporated it in a ~8 TW, 90 fs high power laser system. This system incorporates chirped pulse and regenerative amplification techniques, but otherwise uses pumping and laser technologies that have been in use for many years. Already the current femtosecond laser capability provides many new opportunities for fundamental research in several exciting fields, including high field physics, x-ray lasers, x-ray generation and particle acceleration. However, it is our view that the approach to ultrashort high power pulse generation that we have described can sustain considerably more development. We believe it can provide a path toward the demonstration of laboratory-size laser systems capable of providing ultrashort pulses eventually with powers in the Petawatt range, and repetition-rates high enough to allow productive research.

ACKNOWLEDGMENT

The authors are grateful to B. Chai (CREOL) for the Cr:LiSAF material used in these experiments. The authors also acknowledge the help of Lightning Optical Corp., Spiricon Inc., Laser Modules Inc., Quantum Tech. Inc., and Schwartz E.-O. Inc. We also want to thank G. Woodfin (Los Alamos National Laboratory) for interferometric measurements of the 25 mm Cr:LiSAF rods and acknowledge the technical assistance of C. Bogusch, J. Darnell, P. Reese, and J. Eichenholz.

REFERENCES

[1] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.*, vol. 56, pp. 219–221, 1985.

[2] M. Pessot, P. Maine, and G. Mourou, "1000 times expansion/compression of optical pulses for chirped pulse amplification," *Opt. Commun.*, vol. 62, pp. 419–421, 1987.

[3] P. Maine and G. Mourou, "Amplification of 1-nsec pulses in Nd:glass followed by compression to 1 psec," *Opt. Lett.*, vol. 13, pp. 467–469, 1988.

[4] P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, "Generation of ultrahigh peak power pulses by chirped pulse amplification," *IEEE J. Quantum Electron.*, vol. 24, pp. 398–402, 1988.

[5] C. Sauteret, D. Husson, G. Thiell, S. Gary, A. Migus, and G. Mourou, "Generation of 20-TW pulses of picosecond duration using chirped-pulse amplification in a Nd:glass power chain," *Opt. Lett.*, vol. 16, pp. 238–240, 1991.

[6] Y.-H. Chuang, D. D. Meyerhofer, S. Augst, H. Chen, J. Peatross, and S. Uchida, "Suppression of the pedestal in a chirped-pulse-amplification laser," *J. Opt. Soc. Am.*, vol. B8, pp. 1226–1235, 1991.

[7] K. Yamakawa, H. Shiraga, Y. Kato, and C.P.J. Barty, "Prepulse-free 30-TW, 1-ps Nd:glass laser," *Opt. Lett.*, vol. 16, pp. 1593–1595, 1991.

[8] F. G. Patterson and M. D. Perry, "Design and performance of a multiterawatt, subpicosecond neodymium:glasss laser," *J. Opt. Soc. Am.*, vol. B8, pp. 2384–2391, 1991.

[9] C. Rouyer, É. Mazataud, J. Allais, A. Pierre, S. Seznec, and C. Sauteret, "Generation of 50-TW femtosecond pulses in a Ti:sapphire/Nd:glass chain," *Opt. Lett.*, vol. 18, pp. 214–216, 1993.

[10] B. C. Stuart, S. Herman, and M. D. Perry, "Amplification in Ti:Sapphire beyond 1mm," in *Proc CLEO '94*, Publ by OSA, 1994, pp. 405–406, (Paper JFA3).

[11] M. Pessot, J. Squier, P. Bado, G. Mourou, and D. J. Harter, "Chirped pulse amplification of 300 fs pulses in an Alexandrite regenerative amplifier," *IEEE J. Quantum Electron.*, vol. 25, pp. 61–66, 1989.

[12] M. Pessot, J. Squier, G. Mourou, and D. J. Harter, "Chirped-pulse amplification of 100-fs pulses," *Opt. Lett.*, vol. 14, pp. 797–799, 1989.

[13] H. C. Kapteyn, A. Sullivan, H. Hamster, and R. W. Falcone, "Multiterawatt femtosecond laser based on Ti:sapphire," *SPIE*, vol. 1229, pp. 75–81, 1990.

[14] J. Squier, F. Salin, and G. Mourou, "100-fs pulse generation and amplification in Ti:Al_2O_3," *Opt. Lett.*, vol. 16, pp. 324–326, 1991.

[15] J. D. Kmetec, J. J. Macklin, and J. F. Young, "0.5-TW, 125-fs Ti:sapphire laser," *Opt. Lett.*, vol. 16, pp. 1001–1003, 1991.

[16] A. Sullivan, H. Hamster, H. C. Kapteyn, S. Gordon, W. White, H. Nathel, R. J. Blair, and R. W. Falcone, "Multiterawatt, 100-fs laser," *Opt. Lett.*, vol. 16, pp. 1406–1408, 1991.

[17] P. Beaud, M. Richardson, E. J. Miesak, and B. Chai, "8-TW, 90-fs, Cr:LiSAF laser," *Opt. Lett.*, vol. 18, pp. 1550–1552, 1993.

[18] T. Ditmore, N. Ngyuyen, and M. D. Perry, "Design of multi-terawatt Cr:LiSAF laser," *J. Opt. Soc. Am.*, vol. B, no. 11, p. 580, 1994.

[19] J. D. Walling, D. F. Heller, H. Samelson, D. J. Harter, J. A. Pete, and R. C. Morris, "Tunable Alexandrite lasers: Development and performance," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1568–1580, 1985.

[20] S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway, and H. W. Newkirk, "Laser performance of Cr:LiSAF," *J. Appl. Phys.*, vol. 66, pp. 1051–1054, 1989.

[21] S. A. Payne, L. L. Chase, and G. D. Wilke, "Optical spectroscopy of the new laser materials, Cr:LiSAF and Cr:LiCAF," *J. Luminescence*, vol. 44, pp. 167–176, 1989.

[22] M. Stalder, B. H. T. Chai, and M. Bass, "The flashlamp-pumped Cr:LiSrAlF6 laser," *Appl. Phys. Lett.*, vol. 58, pp. 216–218, 1991.

[23] R. Scheps, J. F. Myers, H. Serreze, A. Rosenberg, R. C. Morris, and M. Long, "Diode pumped Cr:$LiSrAlF_6$ laser," *Opt. Lett.*, vol. 16, pp. 820–822, 1991.

[24] Q. Zhang, G. J. Dixon, B. H. T. Chai, and P. N. Kean, "Electronically tuned diode-laser-pumped Cr:$LiSrAlF_6$ laser," *Opt. Lett.*, vol. 17, pp. 43–45, 1992.

[25] R. Scheps, "Cr-doped solid state lasers pumped by visible laser diodes," *Optical Materials*, vol. 1, pp. 1–9, 1992.

[26] A. Miller, P. LiKamWa, B. Chai, and E. W. van Stryland, "Generation of 150-fs tunable pulses in Cr:$LiSrAlF_6$," *Opt. Lett.*, vol. 17, pp. 195–197, 1992.

[27] N. H. Rizvi, P. M. W. French, and J. R. Taylor, "50-fs pulse generation from a self-starting cw passively mode-locked Cr:$LiSrAlF_6$ laser," *Opt. Lett.*, vol. 17, pp. 877–879, 1992.

[28] J. M. Evans, D. E. Spence, W. Sibbet, B. Chai, and A. Miller, "50-fs pulse generation from a self-mode-locked Cr:LiSrAlF6 laser," *Opt. Lett.*, vol. 17, pp. 1447–1449, 1992.

[29] N. H. Rizvi, P. M. W. French, and J. R. Taylor, "Generation of 33-fs pulses from a passively mode-locked Cr:LiSrAlF6 laser," *Opt. Lett.*, vol. 17, pp. 1605–1607, 1992.

[30] N. H. Rizvi, P. M. W. French, J. R. Taylor, P. J. Delfyett, and L. T. Lopez, "Generation of pulses as short as 93 fs from self-starting femtosecond Cr:LiSrAlF6 lasers by exploiting multiple-quantum-well absorbers," *Opt. Lett.*, vol. 18, pp. 983–985, 1993.

[31] F. Balembois, P. Georges, F. Salin, and A. Brun, "High-repetition-rate cw-pumped Cr3+:LiSrAlF6 femtosecond regenerative amplifier," *Opt. Lett.*, vol. 18, pp. 1250–1252, 1993.

[32] P. Beaud, E. Miesak, Y-F. Chen, B. Chai, and M. Richardson, "A flashlamp pumped Cr:LiSAF regenerative amplifier," in *OSA Proc. Advanced Solid State Lasers*, L. L. Chase and A. A. Pinto, Optical Society of America, Washington DC, vol. 13, 1992, pp. 109–112.

[33] M. D. Perry, D. Strickland, T. Ditmire, and F. G. Patterson, "Cr:$LiSrAlF_6$ regenerative amplifier," *Opt. Lett.*, vol. 17, pp. 604–606, 1992.

[34] P. Beaud, E. Miesak, Y.-F. Chen, B. H. T. Chai, and M. C. Richardson, "110 fs Fourier-transform limited Gaussian pulses from a Cr:LiSAF regenerative amplifier," *Opt. Commun.*, vol. 95, pp. 46–50, 1993.

[35] W. E. White, J. R. Hunter, L. Van Woerkom, T. Ditmire, and M. D. Perry, "120-fs terawatt $TiAl_2O_3$/Cr:$LiSrAlF_6$ laser system," *Opt. Lett.*, vol. 17, pp. 1067–1069, 1992.

[36] T. Ditmire and M. D. Perry, "Terawatt Cr:$LiSrAlF_6$ laser," *Opt. Lett* vol. 18, pp. 426–428, 1993.

[37] P. Beaud, M. C. Richardson, E. Miesak, and B. H. T. Chai, "Large aperture 95 fs Terawatt Cr:LiSAF laser," in *OSA Proc. Short Wavelength V: Physics with Intense Laser Pulses*, P. B. Corkum and M. D. Perry, Eds., to be published.

[38] B. H. T. Chai (CREOL, University of C. Florida, Orlando, FL) and V. Castillo (Lightning Optical Corp, Tarpon Springs, FL), private communication.

[39] W. Viebahn, "Untersuchungen an quaternären Fluoriden LiMe"Me"'F_6. Die Struktur von $LiCaAlF_6$." *Z. anorg. allg. Chem.*, vol. 896, pp. 335–339, 1971.

[40] K. I. Schaffers and D. A. Keszler, "Structure of $LiSrAlF_6$." *Acta Cryst.*, vol. C47, pp. 18–20, 1991.

[41] M. Richardson, M. J. Soileau, P. Beaud, Y.-F. Chen, R. DeSalvo, S. Garnov, D. J. Hagan, S. Klimentov, M. Sheik-Bahae, A. A. Said, E. Van Stryland, and B. Chai, "Self-focusing and optical damage in Cr:LiSAF and Cr:LiCAF," *SPIE*, vol. 1848, pp. 392–402, 1993.

[42] L. DeLoach, S. A. Payne, L. K. Smith, J. B. Tassano, W. L. Kway, and W. F. Krupke, "Properties of the Cr:LiSAF laser crystal," in *Proc. Annu. Mtg. Opt. Soc. Am.*, 1992, p. 32.

[43] Y.-F. Chen, P. Beaud, B. Chai, and M. Richardson, "Small signal gain measurements in Cr-doped LiSAF and LiCAF," in *OSA Proc. Advanced Solid State Lasers*, L. L. Chase and A. A. Pinto, Optical Society of America, Washington, DC, vol. 13, 1992, pp. 10–13.

[44] W. R. Rapoport, "Excited-state absorption and upconversion in Cr:LiSAF," in *OSA Proc. Advanced Solid State Lasers*, L. L. Chase and A. A. Pinto, Optical Society of America, Washington, DC, vol. 13, 1992, pp. 21–27.

[45] P. Beaud, Y.-F. Chen, B. H. T. Chai, and M. C. Richardson, "Gain properties of $LiSrAlF_6$:Cr^{3+}," *Opt. Lett.*, vol. 17, pp. 1064–1066, 1992.

[46] P. Beaud, M. Richardson, Y.-F. Chen, and B. H. T. Chai, "Optical amplification characteristics of Cr:LiSAF and Cr:LiCAF under flashlamp-pumping," *IEEE J. Quantum Electron.*, to be published.

[47] M. Richardson, V. Castillo, P. Beaud, M. Bass, B. Chai, G. Quarles, and W. Ignatuk, "LiSAF: The next wave in tunability," *Photonics Spectra*, pp. 86–92, Oct. 1993.

[48] M. D. Perry, S. A. Payne, T. Ditmire, R. Beach, G. Quarles, W. Ignatuk, R. Olson, and J. Weston, "Better materials trigger Cr:LiSAF laser development," *Laser Focus*, pp. 85–92, Sept. 1993.

[49] W. Koechner, *Solid-State Laser Engineering*, 3rd ed. Berlin: Springer-

Verlag, 1992.

[50] S. A. Payne, W. F. Krupke, L. K. Smith, W. K. Kway, L. D. DeLoach, and J. B. Tassano, "752nm wing-pumped Cr:LiSAF laser," *IEEE J. Quantum Electron.*, vol. 28, pp. 1188–1196, 1992.

[51] M. A. Noginov, V. G. Ostroumov, I. A. Shcherbakov, V. A. Smirnov, and D. A. Zubenko, "Interaction of excited Cr3+ ions in laser crystals," in *OSA Proc. Advanced Solid State Lasers*, H. P. Jensen and G. Dube, Eds., Optical Society of America, Washington, DC, vol. 10, 1991, pp. 21–24.

[52] F. Hanson, C. Bendall, and P. Poirier, "Gain measurements and average power capabilities of Cr^{3+}:$LiSrAlF_6$," *Opt. Lett.*, vol. 18, pp. 1423–1425, 1993.

[53] D. E. Spence, P. N. Kean, and W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti:sapphire laser," *Opt. Lett.*, vol. 16, pp. 42–44, 1991.

[54] O. E. Martinez, "3000 times grating compressor with positive group velocity dispersion: Application to fiber compensation in 1.3–1.6 mm region," *IEEE J. Quantum. Electron.*, vol. QE-23, pp. 59–64, 1987.

[55] V. Yanovski, B. Chai, and M. Richardson, "High energy 1-in. aperture Cr:LiSAF laser," in *Proc. Annu. Mtg. Opt. Soc. Am.*, 1992, p. 54.

[56] E. B. Tracey," Optical pulse compression with diffraction gratings," *IEEE J. Quantum Electron.*, vol. QE-5, pp. 454–458, 1969.

[57] F . Krausz, M. E. Fermann, T. Brabec, P. F. Curley, M. Hofer, M. H. Ober, C. Spielmann, E. Wintner, and A. J. Schmidt, "Femtosecond solid-state lasers," *IEEE J. Quantum Electron.*, vol. 28, pp. 2097–2121, 1992.

[58] P. F. Curley, C. Spielmann, T. Brabec, F. Krausz, E. Wintner, and A. J. Schmidt, "Operation of a femtosecond Ti:sapphire solitary laser in the vicinity of zero group-delay dispersion," *Opt. Lett.*, vol. 18, pp. 54–56, 1993.

[59] M. T. Asaki, C. P. Huang, D. Garvey, J. Zhou, H. C. Kapteyn, and M. M. Murnane, "Generation of 11 femtosecond pulses from a modelocked Ti:sapphire laser," *Opt. Lett.*, vol. 18, pp. 977–979, 1993.

[60] C. P. Huang, M. Asaki, S. Backus, H. Nathel, H. C. Kapteyn, and M. M. Murnane, "17 femtosecond pulses from a self-modelocked Ti:sapphire laser," *Opt. Lett.*, vol. 17, pp. 1289–1291, 1992.

[61] F. Salin, P. Georges, G. Roger, and A. Brun, "Single shot measurement of a 52-fs pulse," *Appl. Opt.*, vol. 26, pp. 4528–4531, 1987.

[62] B. E. Lemoff and C. P. J. Barty, "Quintic-phase-limited, spatially uniform expansion and recompression of ultrashort optical pulses," *Opt. Lett.*, to be published.

[63] W. E. White, F. G. Patterson, R. L. Combx, D. F. Price, and R. L. Shepherd, "Compensation of higher order frequency-dependent phase terms in chirped-pulse amplification systems," *Opt. Lett.*, vol. 18, pp. 1343–1345, 1993.

[64] O. E. Martinez, "Grating and prism compressors in the case of finite beam size," *J. Opt. Soc. Am. B*, pp. 929–934, 1986.

[65] J. F. Holzrichter, "High-power pulsed lasers," LLNL report, UCRL-52868, 1980.

Paul A. Beaud, photograph and biography not available at the time of publication.

Martin Richardson, photograph and biography not available at the time of publication.

Edward J. Miesak, photograph and biography not available at the time of publication.