Extension of femtosecond Cr: LiSAF systems to the 100 TW level

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ABSTRACT

The availability of ultrashort (100 fs or shorter) high intensity lasers capable of producing focused intensities in excess of 10^{18} W/cm^2 provides many new opportunities in studying the interaction of radiation with matter. In this paper we describe and compare three methods for generating these high intensity pulses into the 100 TW power range. In addition, we describe in detail the use of Cr:LiSAF as an amplifying medium for this type of laser system. This work also includes descriptions of the factors that affect the performance of short pulse laser systems, especially with regard to Cr: LiSAF. Techniques of how to overcome the obstacles created by these factors are also discussed together with experimental data regarding the bandwidth limits of an existing regenerative amplifier.

1. INTRODUCTION

There are many applications and experiments which can benefit from the development of lasers whose powers approach the Petawatt range. These include laser fusion, particle acceleration, coherent x-ray generation, and the behavior of matter under extremely high electric and magnetic fields. The generation of PW powers is being approached through three different solid state laser technologies. Each of these will provide a unique set of irradiation conditions that will open many fresh horizons to physics research.

The most advanced approach incorporates the use of ultrashort pulse Ti:Sapphire oscillators operating at 1053 nm in conjunction with large aperture flashlamp pumped Nd:glass amplifiers. The latter have undergone sustained development over the past 20 years, largely in response to the drive to demonstrate inertially confined fusion. As of this meeting, already powers of ~ 100 TW have been generated[1], and plans are in place to assemble a system capable of PW powers. The use of Nd:glass as an amplifying medium in this approach constrains the minimum laser pulse to that contained within the spectral gain bandwidth of the Nd:glass. This is typically ~ 400 fs, although the use of composite amplifiers may allow somewhat shorter pulses. Thus, PW powers will only be achieved with laser pulse energies of many hundreds of joules, through large scale amplifier optics with output apertures > 30 cm diameter. Such a system will only run in the single-shot mode at shot rates of ~ 1 shot/hr. However, this capability, most probably restricted to the confines of large national laboratories, will have a major impact on the exploration of important concepts for laser fusion, such as plasma channeling and fusion ignition. These PW systems will also have many applications to experiments where the laser pulse energy, or number of photons is an important factor, such as for the generation of x-rays in a laser plasma for plasma or fusion pellet backlighting experiments.

Another approach to high power laser pulse generation, currently under intense investigation involves the use of the enormous spectral bandwidth of the Ti:Sapphire laser. This allows extremely short (< 10 fs) pulse to be generated. In principle, if these pulses could be amplified to only modest energy levels, several joules, then power levels approaching the PW level could be achieved. This modest system energy should allow fairly high repetition rates. Since all high intensity laser pulse systems using solid-state media incorporate chirped pulse amplification, this requires that throughout the amplification of process of these extremely short laser pulses, the integrity of the laser pulseshape, its spatial distribution, spectrum and temporal dispersion, be rigidly controlled. Impressive progress has been made, and already powers of ~ 10 TW has been reported, with pulse durations of ~ 20 fs.[2] The extension of this approach to still higher powers, although possible through the amplification of yet shorter pulses, is more dependent on the availability, cost and complexity of coherent visible laser pump sources. The short fluorescence decay time of Ti:Sapphire (3 μsec), excludes the effective use of simple flashlamp excitation. Given these coherent pump sources, however, this approach will lead to the provision of exciting laser capabilities for many fields of research. With modest laser energies, a few joules, the final output aperture can be < 5 cm, allowing the construction of a compact laboratory-scale system. The preservation of high beam quality will lead to the generation of unprecedented focal spot intensities. The implications of the latter for studies in high field physics are enormous. However in considering a possible path for Ti:Sapphire systems toward the PW level, its reliance on high power visible laser pump radiation significantly increases the overall system cost and complexity. Pump energies in the range of ~ 100 J will require a single-shot solid state laser system comprising many amplifiers in a sophisticated beam line, making such it into a major facility.

The third approach, discussed in detail here, is based on the use of Cr:LiSAF, a laser material not so well developed as Nd:glass or Ti:Sapphire, but having many characteristics making it ideal for the generation of ultrashort laser pulses of extreme intensity . Its laser spectral bandwidth is nearly as large as, and strongly overlaps that of Ti:Sapphire, permitting the construction of hybrid systems. This is sufficient therefore for the generation and amplification of pulses down to the 20 fs level. A second important feature of Cr:LiSAF is its relatively long fluorescence lifetime, 67 μs, long enough for the use of incoherent pump sources. Combined with the strong overlap of its absorption bands with the spectral emission of conventional Xe flashlamps, this gives Cr:LiSAF a strong advantage as a short pulse amplification material. Moreover, it can be fabricated to large dimensions (boules of 50 mm diameter and 120 mm in length have been grown), and of variable Cr doping allowing it to be configured optimally into flashlamp cavities that provide uniform and efficient optical gain. Lastly, although its optical gain is modest, forcing the use of long paths of amplified material for the high gain required in a high power short pulse laser system, its nonlinear optical coefficients are low, and therefore of less impact on B-integral effects on the propagation of the pulse.

Currently, two systems based on this material have been developed to the ~ 10 TW level.[3,4] Both these systems employ ~ 100 fs pulses, the initial generator being a Kerr-lens mode-locked Ti:Sapphire laser. In this paper, we examine the factors that would allow these systems to be developed to higher power levels on a laboratory scale. Specifically we see a path that would lead to the generation of powers at the 100 TW level with existing technology. Lastly, we discuss how this technology might be developed still further to allow the construction of a Cr:LiSAF system capable of powers approaching a Petawatt.

2. CURRENT CAPABILITIES OF Cr:LISAF AMPLIFIED LASER SYSTEMS

Currently, existing Cr:LiSAF systems have produced multi-Terawatt pulses by amplifying pulses of ~ 100fs to the single Joule energy level.[3,4] The experimental configuration of the laser system at CREOL has been described in previous publications.[3,5] The initial femtosecond pulse source is a Kerr lens modelocked Ti:Sapphire laser.[6] 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 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 8W of an Argon-Ion laser (Spectra Physics 2040 Beamlok). The mode-locked laser utilizes a thick one-plate Lyot-filter for wavelength selection and produces 300 - 500 mW, < 100 fs pulses centered at 845 nm. These pulses are expanded ~ 1500 times to 150 ps by four passes through a single grating pulse stretcher[7] before being injected into the regenerative amplifier. Two pulse slicers are used in series to select a single pulse from the pulse train produced by the regenerative amplifier which ensure a pre-pulse suppression ~ 10^9. The selected pulse, of energy of ~ 5 mJ, is then amplified by two 105 mm long, double-pass amplifiers of diameters 7 mm and 10 mm, operating at a repetition rate of 1/2 Hz. The final 25 mm diameter, 200 mm long amplifier has 8 flashlamps and a maximum input energy of 5 kJ.[8] The output of this amplifier is recompressed with two gratings in the standard parallel double pass configuration.[9]

The current configuration of the system allows the generation of peak powers of ~ 10 TW, 1 J in a pulse duration 100 fs. In an initial upgrade of this system, we plan several improvements to the system which will significantly increase its output. Our current pulse stretcher limits the bandwidth to ~ 14 nm, and therefore constrains the pulse duration to ~ 60 fs. We plan shortly to incorporate a reflective stretcher, replacing the current setup which uses a conventional achromat[3], allowing the propagation of up to 20 nm bandwidth pulses. This will also allow us to increased the chirped pulse duration to ~ 300-500 ps, allowing higher energies to be generated in the system at the same power. A cavity dumped regenerative amplifier will be used to generate ~ 10 mJ at the pre-amplifier stage.[4] Anti-reflection coating will be incorporated onto all the amplifiers. A redesign of our final stage amplifier should improve its optical gain and repetition rate. Finally, the compressor will utilize larger more diffraction efficient grating which will be contained within an existing vacuum compressor box which is directly coupled to a large 50 port vacuum target chamber. This will prevent the high intensity compressed pulse from interacting with the air during propagation, thus avoiding the breakdown of air and the pulse distortion associated with that phenomena. The schematic of this system is shown in Fig. 1. These changes should allow output energies of 1-5 J in 50 fs to be generated.

3. FACTORS AFFECTING HIGHER POWER OPERATION

Although we plan a significant improvement in this first upgrade of a our TW system, it is useful to examine the primary factors that limit the peak power capabilities of high intensity CPA systems with a view to determining the ultimate limits to which Cr:LiSAF could be extended in output power capability. Three primary factors are involved. Firstly, the spectral bandwidth capacity of the system acts a limit on the duration of the pulsewidth. Although extremely short pulses (< 10 fs) can be generated at the Cr:LiSAF wavelength, it is imperative in a CPA system that the spectral integrity of the ultrashort be preserved throughout the stretching, amplification and compression stages of the system. The gain

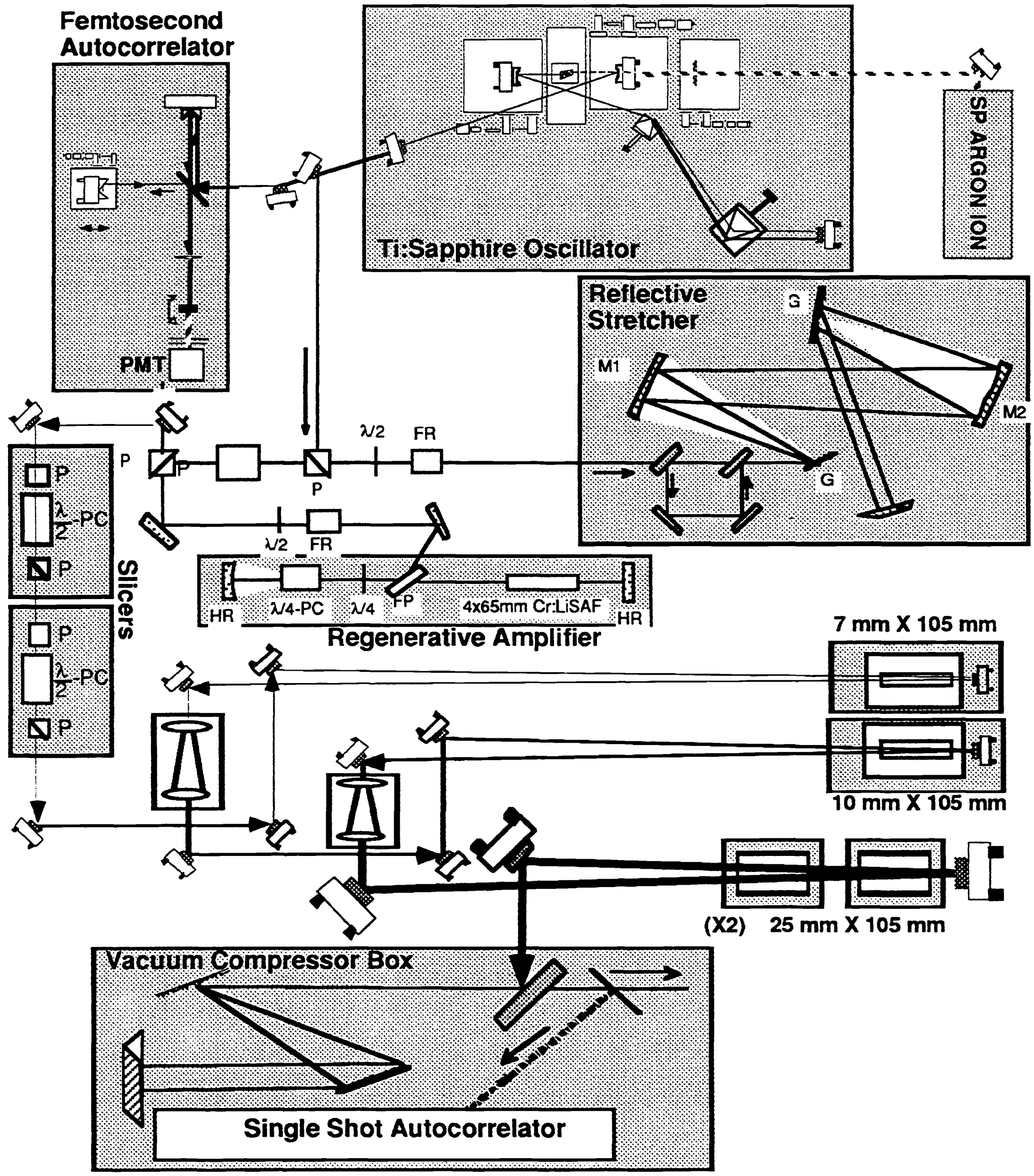

Figure 1: Setup of Upgraded Cr:LiSAF Multi-Terawatt Laser.

media as well as the optical components in the system must allow for a broad spectral band throughput. In addition, the dispersion of the optics must also be considered. The bandwidth of Cr:LiSAF is broad enough to carry pulses of duration less than 50 fs.[10] Secondly, it is important to keep the peak power within the chirped pulse amplifier chain as low as possible. Longer chirped pulse lengths will avoid optical damage within the system as well as reduce the overall B-integral for the amplifier chain. Large bandwidths like that of Cr:LiSAF help to stretch along with the addition of totally reflective stretchers which eliminate chromatic aberrations and are now commonly used with Ti:Sapphire lasers.[11-13] Finally, because of damage and B-integral issues, large beam apertures are advantageous with systems of these type. In principle our amplifiers can carry energies as high as ~ 10J due to their large (25 mm) aperture. Multi-beam configurations and/or large aperture amplifiers with spatially multiplexed laser crystals like those originally developed for large scale-energy harmonic conversion crystals, could extend the energy output to 100J.

3.1 Propagation of shorter pulses

There are several issues to consider when broadband, high peak powered pulses are propagated through any optical system. These include the non-linear pulse distortions due to the B-integral, as well as issues associated with broad bandwidth such as dispersion and the preservation of the bandwidth through the gain media and the optics of the entire system. In addition, the optical quality of the gain media and its physical characteristics have a significant impact on beam quality and energy extraction. Here we consider these issues with respect to current and future ultrashort pulse multi-Terawatt Cr:LiSAF laser systems.

3.1.1 Preservation of Spectral bandwidth

The propagation of shorter pulses through amplifier systems of the type described above place a premium on the preservation of the spectral integrity of the chirped laser pulse. In our current system the ~ 9 nm bandwidth of the 100 fs pulse is maintained through the amplifier chain. However to achieve higher peak powers, we wish to shorten the laser pulse. To this end we end we have studied the propagation of chirped 14 nm pulses through a regenerative amplifier, having a total small signal gain of ~ 10^6. The experimental setup used is shown in Fig. 2. A Kerr-lens modelocked Ti:Sapphire oscillator was used to generate ~ 55 fs bandwidth limited pulses ($\Delta\lambda$ ~ 14 nm). These pulses were then stretched using the folded Martinez compressor mentioned in section 2, single pulses were then sliced and injected into the regenerative amplifier with a Pockels Cell slicer. Output pulse energies were on the order of 2/mJ. Fig. 3 shows both the injected and amplified spectrum. The 'dip' seen in the amplified spectrum was also seen in unamplified spectrum propagated through the amplifier setup and is assumed to be due to a dip in reflectivity of an optic within the system.

The spectral output of the regenerative amplifier shown in Fig. 3 is approximately 13.5 nm wide and corresponds to a bandwidth limited pulse duration limit of ~ 60 fs. Attempts to compress the output of the system using the compressor mentioned in section 2 resulted in compression of the pulses to ~ 85 fs. This result is thought to be due to two problems. Firstly, a standard achromat was used in the stretcher of the system. This provided inadequate correction for chromatic aberration in the range of the center of the output spectrum at 845 nm. Secondly, we did not employ adequate compensation for third order dispersion in the compressor. These results show that Cr:LiSAF can be used to amplify bandwidth-limited pusles of 60 fs to the Joule level. We are confident that these pulses can be properly compressed when a chromatically neutral stretcher is used and optimum third order compensation is used. In addition, the current setup is limited by the

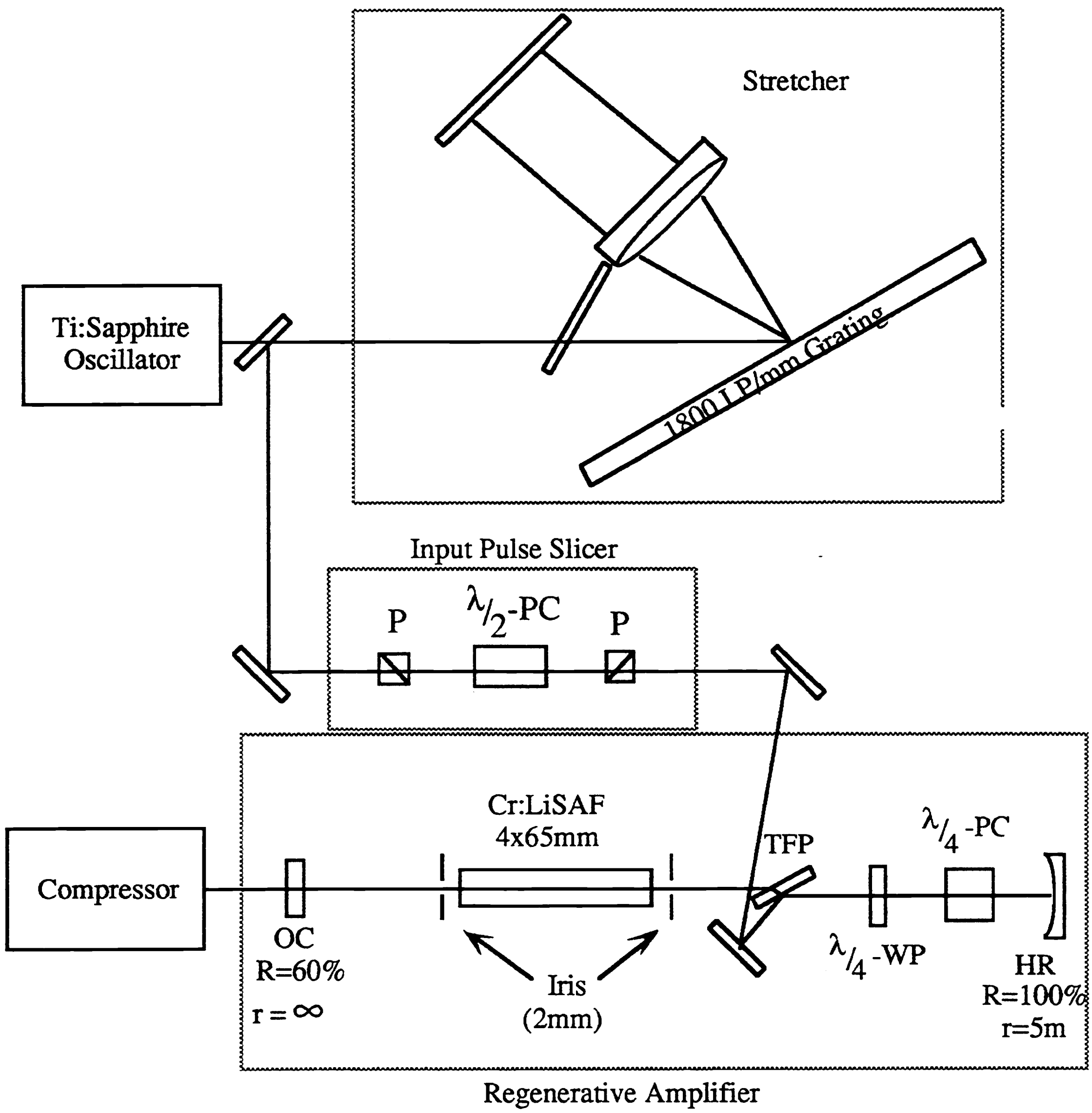

Figure 2: Experimental Setup Used to for Broadband Amplification Experiments.

bandwidth throughput limit of small aperture stretcher, the limiting element was the 2.5" diameter achromat which clipped outgoing diffracted light that was outside a 14.7 nm window. Finally, the use of a cavity dumped regenerative amplifier[4] will reduce the number of passes required, allowing for the propagation of still shorter pulses.

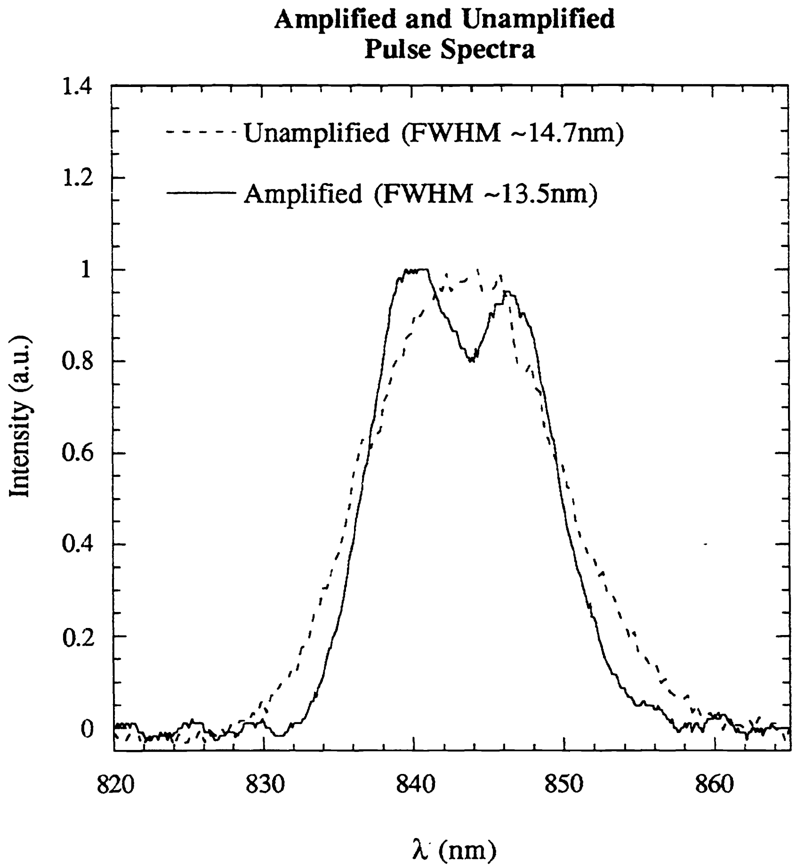

Figure 3: Amplified and Unamplified Pulse Spectrum
Propagated Through the Regenerative Amplifier

3.1.2 Non linear refraction effects - B-integral

The effects of higher order refraction effects can be disastrous to the propagation of a broadband ultrashort laser pulses in an amplifier system. These effects can be assessed with an appreciation of the B integral of a light beam passing a medium, defined as:

$$B = 2\frac{2\pi}{\lambda}\int_0^L n_2 I dz \qquad (1)$$

where n_2 is the second order refractive index of the medium and I is the light intensity. Thus B quantifies the total nonlinearity induced on the beam. A typical acceptable propagation limit for proper pulse compression is B ~ 1 for pulse durations less than 100 fs.[14] For LiSAF $n_2 \sim 8.9\mathrm{x}10^{-17}$ cm²/W, which is low relative to most other materials[15]. It is interesting to consider the impact this has on system architecture for both femtosecond Ti:Sapphire and LiSAF systems. The stimulated emission cross-section of Ti:Sapphire is quite large, $\sigma_{se} \sim 3.0 \times 10^{-19}$ cm², as compared to Cr:LiSAF which is $\sigma_{se} \sim 4.9 \times 10^{-20}$ cm². However, the value of n_2 for Ti:Sapphire is ~ $8.0\mathrm{x}10^{-16}$ cm²/W. Thus to achieve a given overall small signal gain with LiSAF requires a larger active gain-length than one would require with Ti:Sapphire, this can be incorporated into the system without incurring any additional penalty in B -integral effects.

Our current system with a chirped pulse duration of about 150 ps has B-integral values of ~ 0.4, 0.3, 0.7, and 1.6 for the regenerative amplifier, 7 mm, 10 mm and 25 mm amplifiers respectively. This leads to a total B-integral of ~ 3.0. The system upgrade will include the use of stretched pulses of durations on the order of 500ps, This allows for smaller B-integrals than with the existing system. Pulse durations of this order provide B-integral values of approximately 0.13, 0.1, 0.2, and 0.48 for the aforementioned components leading to a total B-integral of ~ .92.

3.1.3 Dispersion

As the duration of an ultrashort pulse becomes less than 100 femtoseconds, the bandwidth becomes large enough that the higher order terms of dispersion play a significant role in determining the final pulse length. Our current laser system employs a path-length of < 5 m of Cr:LiSAF. As shown in Table 1, Cr:LiSAF is a low dispersion material which has over five times less second order and approximately one-half the third order dispersion as Ti:Sapphire. It is interesting to note that when 5 m of Cr:LiSAF material is compared to 50 cm of Ti:Sapphire, the second order dispersion (GVD) and fourth order dispersion (FOD) are of the same order of magnitude. In addition, Cr:LiSAF has an advantage in that as the wavelength approaches the maximum gain at 850 nm the fourth order dispersion approaches zero. Cr:LiSAF also has less third order dispersion per millimeter than Ti:Sapphire. However, after propagating through 5 m of active media the third order dispersion is large.

Laser Media	Wavelength (nm)	GVD (fs^2/mm)	GDD (fs^3/mm)	FOD (fs^4/mm)
Ti:Sapphire	780	60.5526	41.2248	-13.0938
Ti:Sapphire	850	52.0334	44.7047	-22.6799
Cr:LiSAF	780	15.4281	29.6961	12.4413
Cr:LiSAF	850	9.6763	28.5591	-1.2411

50 cm of Ti:Sapphire @ 780 nm	30276.3	20612.4	-6546.9
500 cm of Cr:LiSAF @850 nm	48381.5	142795.5	-6205.5

Table 1

We have found experimentally that even with a B-Integral value less than 1, and the bandwidth necessary to support ~ 60 fs pulses, it is difficult to compress the pulse to a duration < ~ 85 fs. We attribute this to the excess 3rd order dispersion introduced by the regenerative amplifier. Our current stretcher/compressor system does not allow for separate adjustment of second and third order dispersion. The use of additional refractive elements in the stretcher beam path to separately compensate for second, third, and fourth order dispersion would correct this inadequacy.[16] However, this technique has the disadvantage of imposing bandwidth limitations. A stretcher which is all reflective would eliminate the problems of chromatic aberration and bandwidth limitations introduced by the lens in our current system.

3.3 Larger aperture amplifiers

The assumption that energies in the range 1-5 J can be extracted from rod amplifiers of 25 mm diameter places a practical limit of ~ 200 TW for the current system architecture. To achieve significantly higher peak powers on the assumption of rod technology and the current limits in crystal growth would imply the use of multiple beamlines. To achieve higher powers in a single beamline will require an amplifier technology that allows for larger active beam apertures. With larger beam diameter amplifiers , flashlamp-pumping in rod geometry becomes less efficient and leads to large radial non-uniformities in optical gain. This can best be circumvented with the use of disc amplifier technology in which the amplifier is face-pumped. Given the limits of current LiSAF crystal fabrication techniques, the use of disc amplifier technology to increase the effective aperture necessarily involves some type of spatially multiplexed crystal amplifiers. We have previously discussed two forms of such amplifiers[17], each of which has been developed as Nd:glass amplifiers for inertial fusion lasers. The first several of these discs are assembled to be face-pumped by conventional linear flashlamps. This approach is now the pump architecture of choice for large inertial fusion lasers.[18] The second approach would involve the so-called, "active mirror" slab amplifier approach originally developed at General Electric[19] ,also developed for ICF lasers.[20] For a LiSAF amplifier, both of these approaches would involve the use of large aperture discs fabricated as a spatial matrix separate of LiSAF crystals. Although spatially multiplexed crystals have been issued in high power laser systems before, notably for frequency upconversion[21], this approach has yet to be used with amplifier crystals. Each crystal element of the array would require precision fabrication. The active mirror approach has some advantages for a LiSAF amplifier because the Cr doping and the thickness of the amplifier can be adjusted for uniform single-pass pumping, avoiding the use of dichroic coatings on the output face of the amplifier. The close flashlamp coupling also leads to greater coupling efficiency in this geometry.

4.0 SUMMARY

Cr:LiSAF provides a unique path to the development of compact laboratory-scale, multi-TW laser systems. Currently these have been developed to the 10 TW level. The studies reported here provide the basis for upgrading our Cr:LiSAF 100 TW level. With further developments in amplifier technology, powers approaching the Petawatt level may be achievable. This technology will have a major impact on the interaction of ultrahigh intensity laser radiation with matter.

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