Chirped-Pulse Amplification with Flashlamp-Pumped Ti:Sapphire Amplifiers

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ABSTRACT

Ti:Sapphire (Ti:Al_2O_3) amplifier stages are typically pumped with Q-switched Nd:YAG lasers doubled to 532 nm because of good spectral overlap, short temporal width, high repetition rate (i.e., 10 Hz to > 5 kHz) and the problems associated with flashlamp pumping a material with a relatively short upper state lifetime. Limitations to this pumping method arise due to the 1 to 1.5 joule/pulse ceiling found in most commercial high rep rate Nd:YAG lasers. The availability of high quality, large aperture Ti:Sapphire rods has made the flashlamp-pumping scheme an attractive option. The excellent thermal properties of Ti:Sapphire also allows an amplifier to be operated at high repetition rates.

The front end of our laser relies on Chirped Pulse Amplification (CPA) in laser pumped Ti:Sapphire to generate 55 mJ, 90 fsec pulses at a 10 Hz rate. We report the use of a flashlamp pumped Ti:Sapphire head to further amplify the output of our system, producing 90 fsec, 250 mJ pulses at 5 Hz. The excellent output spatial profile yields a near diffraction-limited 5 μm spot size and peak irradiance in excess of 5×10^{18} W/cm^2.

1. INTRODUCTION

We have investigated the performance of a flashlamp-pumped titanium sapphire laser amplifier (Cynosure model CRD-4) in a CPA[1] system. Test data includes amplification of 400 psec, 800 nm (10 nm FWHM) chirped laser pulses with near gaussian spectral, spatial beam and temporal profiles. Optical input energies to this amplifier range from 2 mJ to near 150 mJ per pulse. Two separate laser rods were evaluated along with two methods of converting flashlamp-pump energies into the absorption band of the Ti:Sapphire lasing medium.

0-8194-1409-3/94/$6.00

2. EXPERIMENTAL SETUP

Our system, described in detail by White *et al.* [2] and depicted in figure 1, is similar to many of the CPA systems[3, 4, 5] based on laser pumped Ti:Sapphire that are currently in use or commercial production. A commercial mode-locked Ti:Sapphire oscillator pumped by an Argon-ion laser (9 W, all lines) produces an 82 MHz train of 80-100 fsec pulses centered at 800 nm (10 nm FWHM gaussian spectral profile). These 10-15 nJ pulses are temporally stretched to about 400 psec in a single diffraction-grating pulse stretcher[6, 7]. The stretcher consists of a 1800-line/mm gold coated, holographic diffraction grating, a 60 cm focal-length achromatic lens and a flat high reflecting aluminum mirror. Positive group velocity dispersion as well as loss of signal is realized during the eight passes of this stretcher. The resulting output pulses are 4-5 nJ and are used to seed the regenerative amplifier.

The TEM_{00} oscillator of the regenerative amplifier consists of a pair of dielectric mirrors with a convex 5-m radius-of-curvature and a concave 4-m radius-of-curvature separated by about 2-m. The S-polarized seed pulses are injected into the regenerative amplifier from the face of the Brewster-cut Ti:Sapphire crystal. This rod has a 6.35 mm diameter with a 2 cm optical path and 0.15% titanium doping. An Nd:YAG laser and doubling crystal producing 532 nm radiation provides longitudinal pumping at 10 Hz with 7 nsec (FWHM), ≈50 mJ pulses.

The single Pockels-cell in the cavity is electronically pulsed once to half-wave retardation (3 nsec FWHM), rotating the seed pulse to P-polarization. The P-polarized optical pulse is trapped within the cavity for approximately 10 round trips when the Pockels-cell is again pulsed to half-wave voltage. The intracavity thin-film-polarizer (TFP) is used to eject the amplified 1.2 mm ($1/e^2$) diameter S-polarized optical pulses. Typical gains from this regenerative amplifier are 1.5 x 10^6 producing nominally 7 mJ/pulse.

A Galilean beam expander just outside the regenerative amplifier serves to expand and collimate the beam to 3.3 mm. The next Pockels-cell/polarizer combination serves to improve the contrast ratio of the ejected amplified pulse to leakage from previous roundtrips through the cavity, as well as to attenuate feedback from subsequent amplification stages.

The cleaned pulse is propagated along a V-path to double pass a 9.5 mm diameter, 2 cm long Ti:Sapphire rod. This rod is longitudinally pumped with 660 mJ of 532 nm radiation at the 10 Hz rate. The double pass gain of this configuration is approximately 20, bringing the per pulse energy to ≈140 mJ. The spatial profile is then expanded to 9.5 mm ($1/e^2$) diameter. The last Pockels cell serves to further improve the extinction ratio of this beam path as well as to reduce the repetition rate as necessary. The rod in the flashlamp-pumped system is slightly overfilled due to the wings of the gaussian beam profile. This results in a slightly truncated gaussian beam profile containing a small amount of diffraction.

Before compression, the beam is expanded to a e^{-2} diameter of 3 cm to prevent damage to the compressor gratings. The parallel grating pulse compressor consists of the same diffraction grating type used in the pulse stretcher. Negative group velocity dispersion renders 80-100 fsec pulses from the 400 psec amplified chirped pulses. Each grating bounce results in an 87% first order reflection and the resulting compressor output pulse energy is down to 57% at best. An off-axis paraboloidal mirror is then used to focus each optical pulse to a diameter of 5 μm, resulting in peak irradiances in excess of 5×10^{18} W/cm^2. In order to avoid non-linear beam degradation by propagation of the compressed beam through air or a chamber window, the pulse compressor is entirely contained in a vacuum chamber allowing the compressed pulse to be focused on target with no transmissive optics after compression.

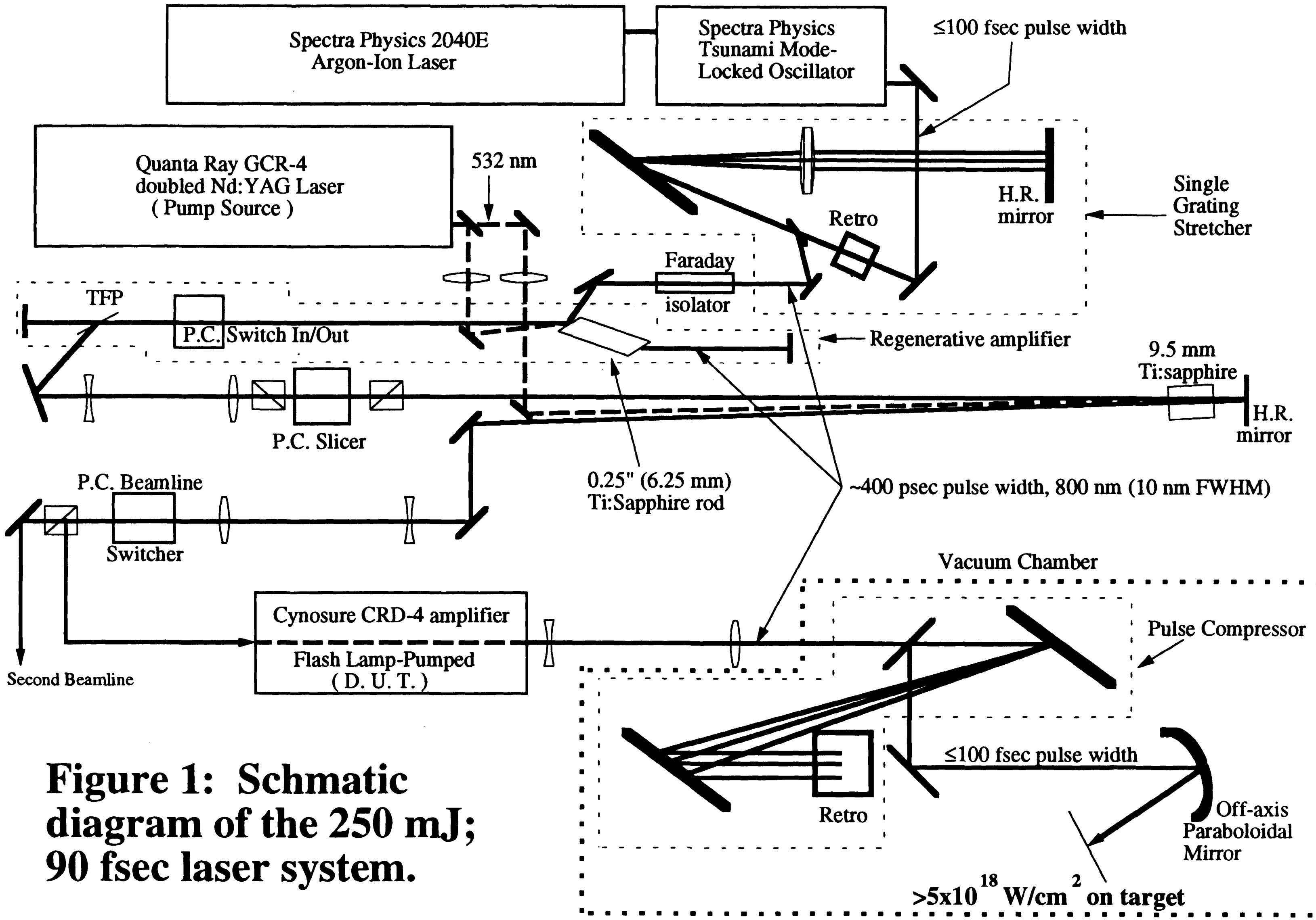


Figure 1: Schmatic diagram of the 250 mJ; 90 fsec laser system.

3. ABOUT THE CRD-4 AMPLIFIER UNIT

This amplifier unit is a spin-off of Cynosure Inc. Ti:Sapphire lasers. It features a 17.8 cm gain length double ellipse cavity that accommodates two linear xenon flashlamps. The power supply and pulse forming network (PFN) produces 300 joule, 6 μsec (FWHM) electrical pulses that are applied to the two flashlamps that are electrically connected in series. Pyrex flow tubes surround the flashlamps and deionized water flow keeps them cool. The amplifier was first tested with a KC-331 glass flow tube surrounding the rod. Laser dye solution flowed through both the cavity and the rod flow tube. After testing this configuration, Cynosure provided us with a KTF-2 fluorescing glass modification allowing use of both 12 mm and 14 mm diameter laser rods without the hazards associated with using laser dyes. Both laser rod flow tubes are products of Kigre Inc. Our present amplifier is limited to 5 Hz by the power supply but higher repetition rates would be possible.

4. ABOUT THE TWO LASER RODS

We tested this amplifier with two laser rods grown and fabricated by Union Carbide Inc.: The first rod tested has a 12 mm diameter with a 190 mm optical length. The second rod is 14 mm in diameter and is 210 mm long. Both were cut from boules with a titanium doping level of 0.15%.

For both rods, the polarization of the propagating beam was carefully aligned along the C-axis and the transmission was measured using ≈4 mJ pulses from the regenerative amplifier. The beam was apertured down so that there was no clipping on the edges of the laser rods. The transmission for the 12 mm and 14 mm rods showed 77% and 71% respectively. A quick reflectivity check of the AR coatings revealed that most of the signal loss appears to be absorption in the rods themselves.

5. TEST AND MEASUREMENTS RESULTS

5.1 Original head configuration with 12 mm rod and KC-331 rod flow tube:

Initial small signal gain measurements were performed using pulses directly from the stretcher. We then used energies derived from operating the regenerative amplifier but did not allow the 9.5 mm stage to be pumped. These ≈2 mJ level pulses provided measurements with an acceptable signal to noise ratio. Initially only methanol was used in the amplifier circulating system that flows through the rod flow tube and the cavity. Figure 2 shows how the small signal gain behaves as a function of PFN voltage.

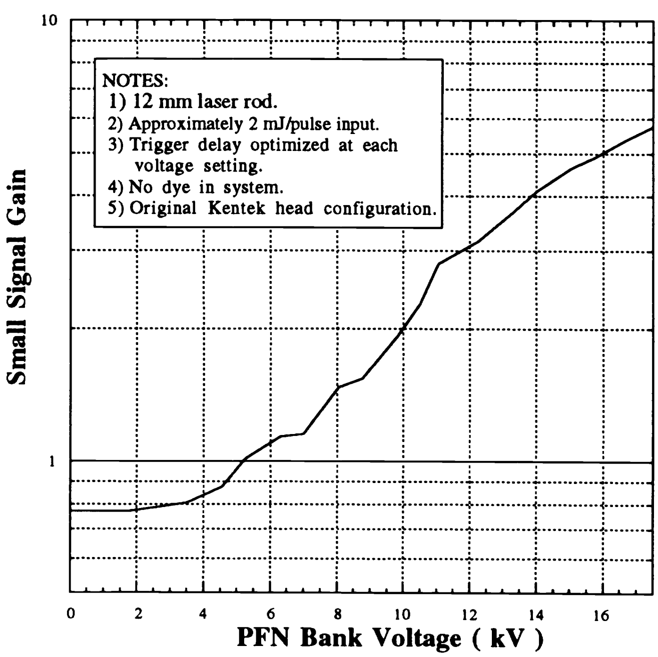


Fig. 2. Small signal gain of the CRD-4 amplifier as a function of PFN voltage.

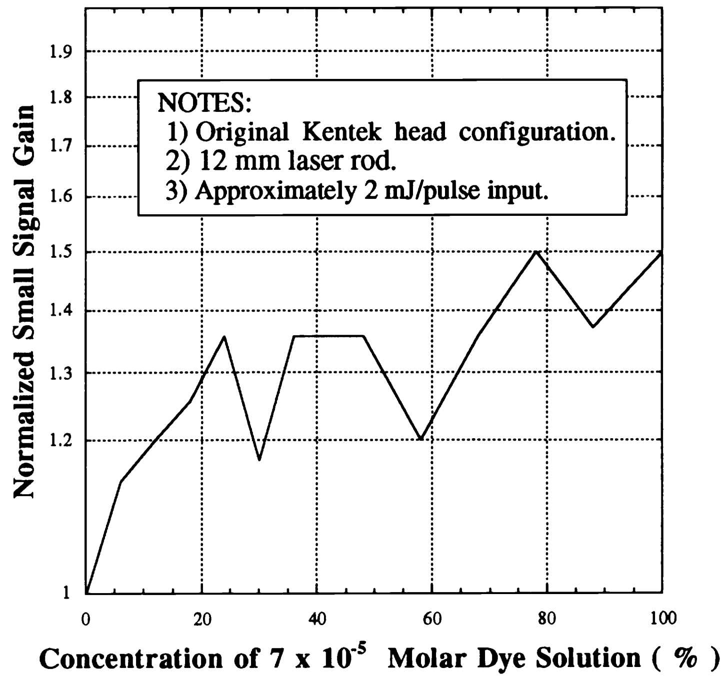


Fig. 3. Relative small signal change as LD-489 laser dye concentration increases.

Figure 3 demonstrates the effect of adding LD-489 laser dye to the amplifier head. As shown, the addition of the UV converting dye in the pump chamber improves the peak small signal gain by 50%.

The next step was to pump the 9.5 mm Ti:Sapphire amplifier stage to graduated levels, producing a range of input energies for the flashlamp-pumped amplifier. (Fig. 4). It was at this point that the beam was directed into the pulse compressor for further analysis.

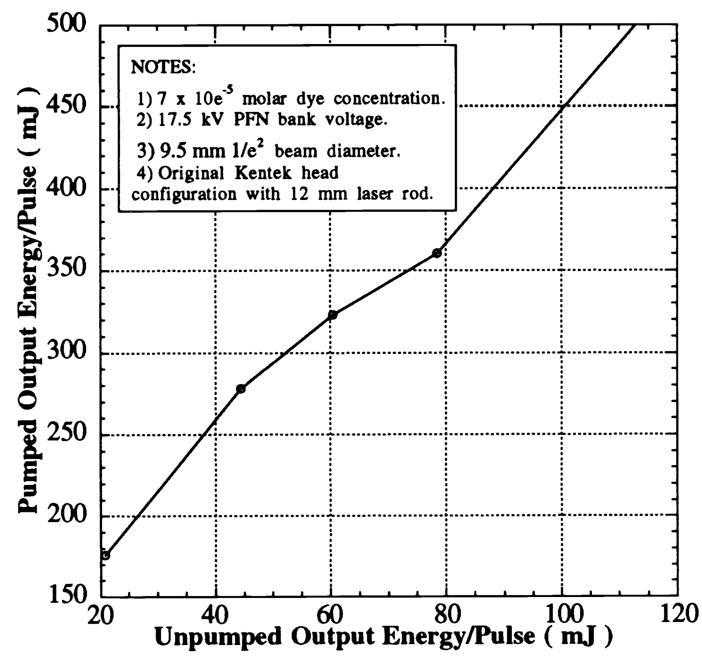


Fig. 4. Tramsmitted energies through the amplifier with and without pumping.

The complete system was operated at maximum gain, producing near 250 mJ level pulses, while a spectrum was gathered, an autocorrelation was performed and an image was gathered of a split-off portion of the beam focused onto an aluminum target 1 µm thick. Spectral content of these intense pulses experienced negligible distortion as can be observed in figure 5.

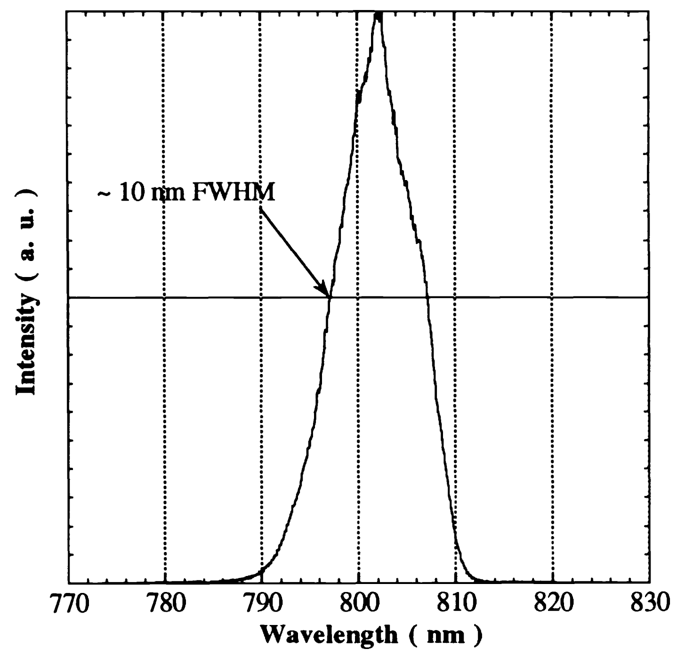


Fig. 5. Spectrum of the 250 mJ, 90 fsec compressed pulse.

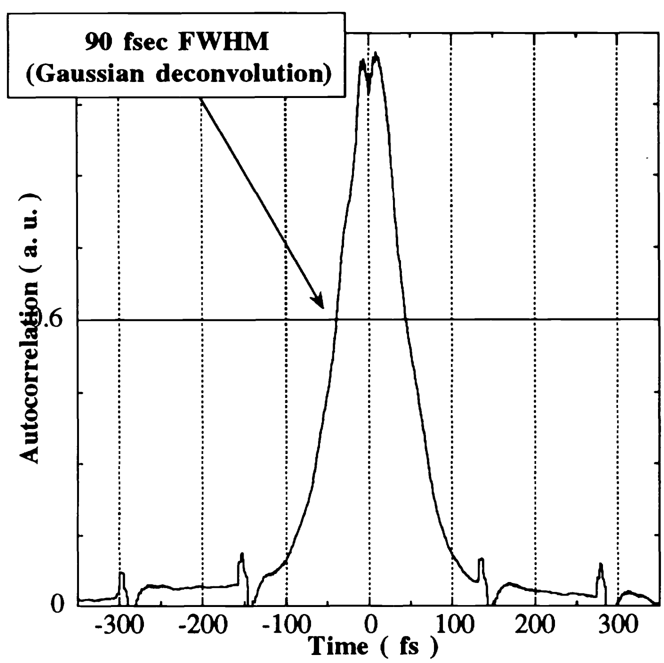


Fig. 6. Second order autocorrelation of the 250 mJ amplified pulse (assuming Gaussian deconvolution).

Figure 6 shows the measured second order autocorrelation of the amplified, compressed 90 fsec (assuming Gaussian deconvolution) pulses. Relay imaging with a magnification near 25x is used to transfer the image of the focused spot on target to a calibrated Cohu CCD camera (Fig. 7). The excellent output spatial profile yields a near diffraction-limited 5 µm spotsize and peak irradiances in excess of 5×10^{18} W/cm^2.

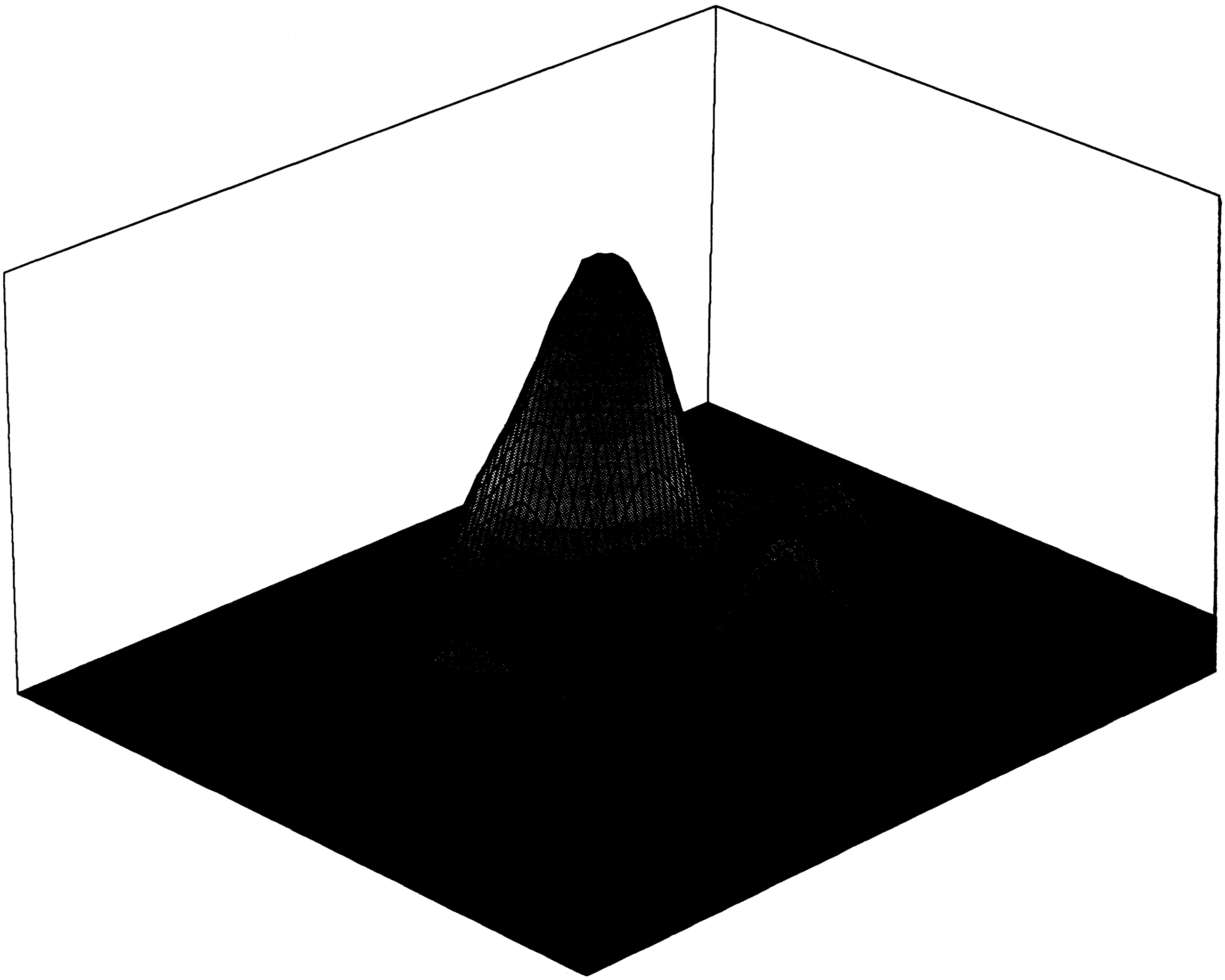


Fig. 7. Three dimensional rendering of the focused laser pulse through the entire system.

5.2 Post-laser head modification using the KTF-2 flow tube without laser dye:

The redesigned cavity end plates allowed for mounting of either laser rod therefore comparative data was collected. Figure 8 shows small signal gain information for both rods with all else being equal.

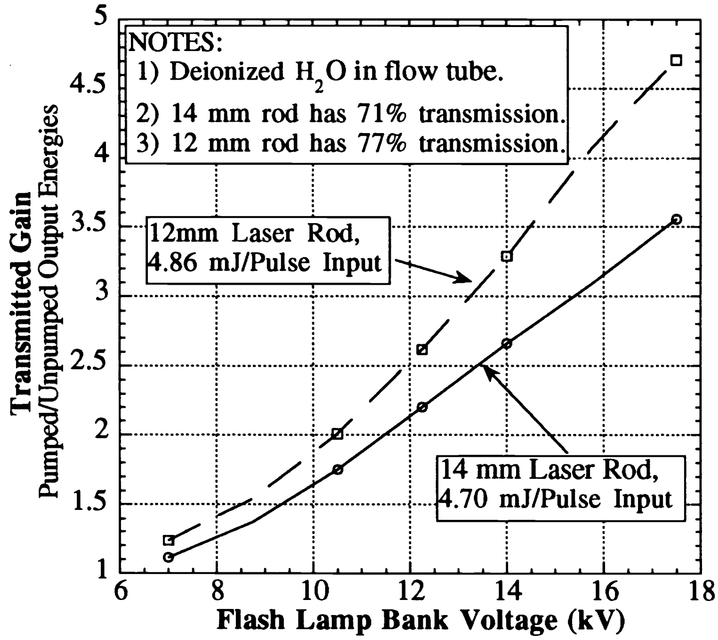
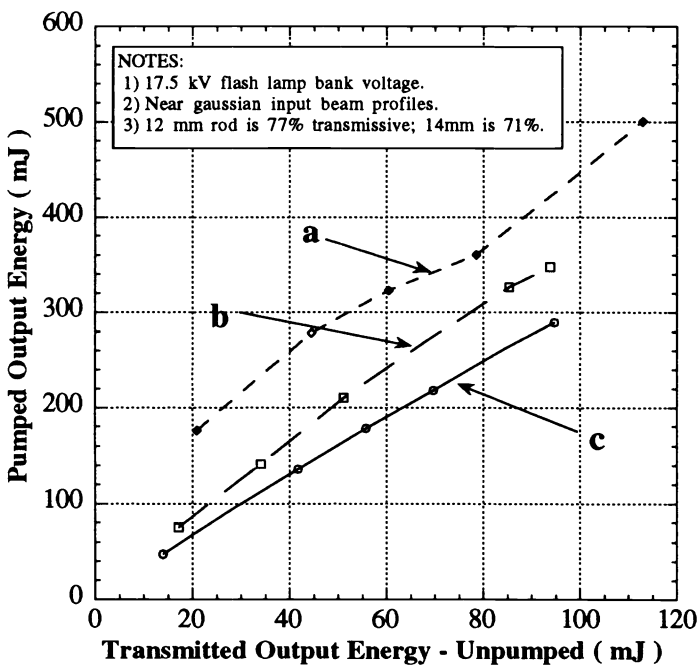


Fig. 8. Pumped/unpumped transmitted small signal gain as a function of the amplifier pulse forming network voltage.



The performance of the two rods demonstrated the same trends at higher transmitted pulse energy levels. (Fig. 9). Here the flashlamps were supplied maximum energy while the signal into the amplifier was increased. Data from the original configuration is included in this plot for comparison of the dye configuration and the KTF-2 flow tube configuration.

Fig. 9. High energy amplification: a) 12 mm rod in original configuration using KC-331 flow tube and LD-489 laser dye; b) 12 mm rod in modified head configuration with KTF-2 flow tube; c) 14 mm rod in modified head.

6. FLASHLAMP PUMPING CONSIDERATIONS

Output energies from high power xenon flash lamp systems typically occur over a period much longer than the near 3 µsec (FWHM) excited state lifetime of Ti:Sapphire.[8] Because of this, a faster PFN and higher voltage power supplies are required than those used in Nd:YAG or Cr:LiSAF amplifiers.

In this case, the PFN operates at 17.5 kV, storing 300 J in a 2 µF capacitor. The PFN is thyratron discharged producing a 6 µsec (FWHM) electrical pulse and a 8µs (FWHM) light pulse from the two lamps. Driving the flashlamps at these short pulse durations also tends to shift the lamp spectrum towards the ultraviolet, and away from the Ti:Sapphire absorption peak.

Spectral conversion and matching of the flashlamp energies is necessary because of the relatively narrow absorption band of the Ti:Sapphire[8] and the high UV content of the flashlamps. The risk of laser rod solarization also exists with prolonged exposure to intense UV radiation. The original configuration of the flash lamp amplifier discussed here utilized a KC-331 flow tube that blocks UV below about 347 nm and a LD-489 laser dye in methanol that has an absorption peak at 392 nm. The fluorescence spectrum of LD-489 laser dye with flashlamp pumping is in the 482-509 nm region with a lifetime on the order of nanoseconds.

The second (modified) configuration utilized a KTF-2 glass laser rod flow tube that blocks wavelengths below about 400 nm and converts some of the UV flash lamp energy, via fluorescence, into the 455 nm spectral region. (Fig. 10)[9]. The fluorescence lifetime is estimated by the manufacturer to be >10 µsec although it has not been measured. We suspect LD-489 laser dye is not effective inside this flow tube due to heavy UV filtering. The absorption band for Ti:Sapphire also shown in figure 11 for comparison.[8]

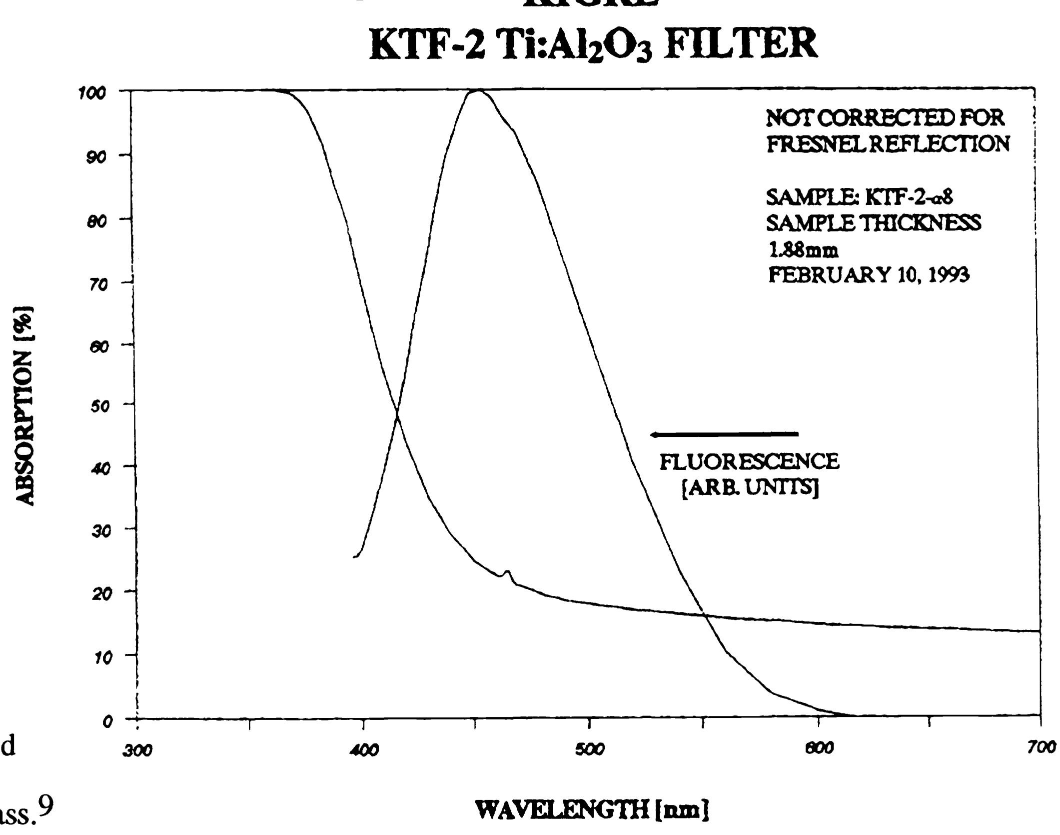


Fig. 10. Absosorption and fluorescence of Kigre KTF-2 glass.[9]

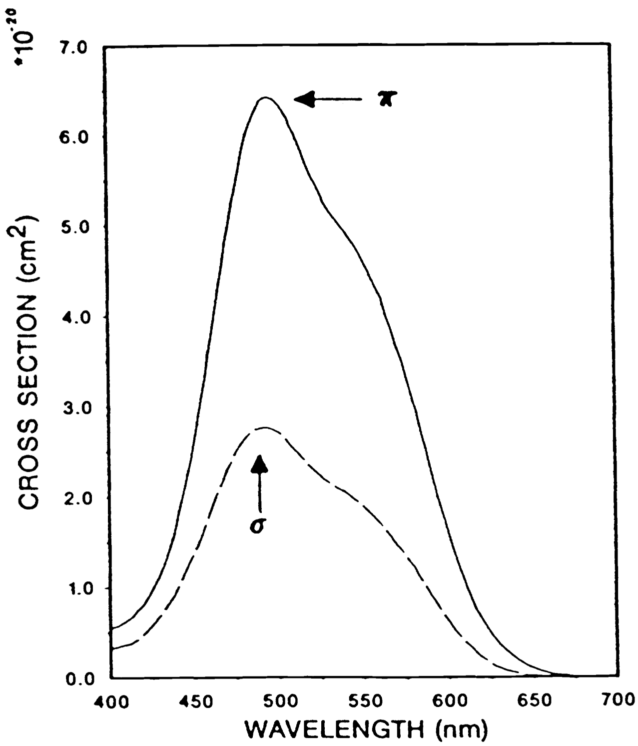


Fig. 11. Polarized absorption cross sections for the $^2T_2 \longrightarrow {}^2E$ transition in Ti:Al_2O_3. Baseline was arbitrarily set to zero for both polarizations at 700 nm.[8]

The 14 mm rod was then rotated inside the head of the CRD-4 so that the C-axis was vertically oriented. Vertically polarized optical pulses in the 4 mJ range were then propagated through the rod and small signal gain measurements were again made. There was no noticeable change in the measured small signal gain due to this 90° rotation. Perhaps with this head design and the relatively broad pump pulse, the rod is uniformally pumped.

7. CONCLUSIONS

We have demonstrated amplification of chirped 400 psec laser pulses to the 500 mJ level at a reasonably high repetition rate i.e., 5 Hz. Subsequent compression back to 90 fsec results in pulses with 250 mJ energies. The availability of high quality Ti:Sapphire rods for this type of amplifier allows amplification with no significant spatial beam degradation. The excellent output spatial profile yields a near diffraction-limited 5 µm spotsize and peak irradiance in excess of 5×10^{18} W/cm^2.

The most energetic laser pulses were observed when testing the amplifier in the original configuration. Although pump chambers using KTF-2 glass have been reported to provide similar performance to those using LD-489 dye when incorporated into long pulse laser cavities, we suspect the longer florescence lifetime of the KTF-2 glass prevents the performance from matching that of the dye in this configuration. We intend on testing a sample of the KTF-2 glass to determine the florescence lifetime. Then the amplifier head will be modified again so the cavity can be flooded with a LD-489 dye solution both inside and out of the KTF-2 glass flow tube. We plan to characterize the effectivness of the combination of dye and KTF-2 glass for spectral conversion and pumping.

8. ACKNOWLEDGMENTS

The author gratefully acknowledges L. Van Woerkom and J. Hunter for their early work with the amplifier, P. Crowley for many technical discussions, T. Donnelly for technical assistance of the small signal dye measurements and D. Perressini of Union Carbide for technical discussions on Ti:Sapphire.

This work was performed for the U.S. Department of Energy under the auspices of contract W-7405-Eng-48.

9. REFERENCES

1. D. Strickland and G. Mourou, Opt. Comm., **56**, 219 (1985):
2. W. E. White, J. R. Hunter, L. Van Woerkom, T. Ditmire and M. D. Perry, Opt. Lett. **17**, 1069, (1992).
3. J. D. Kmetec, J. J. Macklin, and J. F. Young, Opt. Lett., **16**, 1001 (1991).
4. A. Sullivan, H. Hamster, H. C. Kapteyn, S. Gordon, W. E. White, H. Nathel, R. J. Blair, and R. W. Falcone, Opt. Lett.,**16**, 1406 (1991).
5. B. E. Lemoff, and C. P. J. Barty, Opt. Lett. **18**, 57 (1993).
6. O. E. Martinez, IEEE J. Quan. Elec., QE-23, 59 (1987).
7. W. E. White, F. G. Patterson, R. L. Combs, D. F. Price and R. L. Shepherd, Opt. Lett.,**18**,1343,(1993).
8. P. F. Moulton, J. Opt. Soc. Am. B, Vol. **3**, No. 1, 125 (1986).
9. M. J. Myers, D. H. Garrett, Kigre, Inc.