

Highly Efficient Tabletop Optical Parametric Chirped Pulse Amplifier at 1 μm

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*Highly efficient tabletop optical parametric chirped pulse amplifier at 1 μm

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ABSTRACT

Optical parametric chirped pulse amplification (OPCPA) is a scalable technology for ultrashort pulse amplification. Its major advantages include design simplicity, broad bandwidth, tunability, low B-integral, high contrast, and high beam quality. OPCPA is suitable both for scaling to high peak power as well as high average power.

We describe the amplification of stretched 100 fs oscillator pulses in a three-stage OPCPA system pumped by a commercial, single-longitudinal-mode, Q-switched Nd:YAG laser. The stretched pulses were centered around 1054 nm with a FWHM bandwidth of 16.5 nm and had an energy of 0.5 nJ. Using our OPCPA system, we obtained an amplified pulse energy of up to 31 mJ at a 10 Hz repetition rate. The overall conversion efficiency from pump to signal is 6%, which is the highest efficiency obtained with a commercial tabletop pump laser to date. The overall conversion efficiency is limited due to the finite temporal overlap of the seed (3 ns) with respect to the duration of the pump (8.5 ns). Within the temporal window of the seed pulse the pump to signal conversion efficiency exceeds 20%. Recompression of the amplified signal was demonstrated to 310 fs, limited by the aberrations initially present in the low energy seed imparted by the pulse stretcher. The maximum gain in our OPCPA system is 6×10^7 , obtained through single passing of 40 mm of beta-barium borate. We present data on the beam quality obtained from our system ($M^2=1.1$).

This relatively simple system replaces a significantly more complex Ti:sapphire regenerative amplifier based CPA system used in the front end of a high energy short pulse laser. Future improvement will include obtaining shorter amplified pulses and higher average power.

1. INTRODUCTION

Generation and amplification of ultrashort (femtosecond) laser pulses is important for a myriad of scientific and commercial applications. Scientific applications of high peak power short-pulse lasers include high-harmonic and x-ray generation, generation and acceleration of electron and proton beams, and fast ignition for inertial confinement fusion. On the commercial side, high average power short-pulse laser materials processing¹ and biomedical applications such as laser surgery² are becoming more present as the femtosecond sources become cheaper, more robust and reliable. Chirped pulse amplification (CPA)³ is the state-of-the-art technology that allows laser amplification of ultrashort pulses to high pulse energies, while avoiding damage in the laser amplifiers induced by high intensity associated with ultrashort pulses. Ti:sapphire is an ubiquitous laser gain material used for ultrashort pulse amplification, which is the result of its extremely broad spectral bandwidth and favorable mechanical properties. To obtain energetic femtosecond pulses at 1 μm , hybrid systems have been used previously, such as a combination of a Ti:sapphire front end a high-energy Nd:glass laser.⁴ By producing most of the laser gain in the broadband Ti:sapphire front end, sufficient bandwidth exists in Nd:glass to produce high-energy pulses as short as several hundred femtoseconds. One problem with the 1 μm front end based on Ti:sapphire is the relatively large number of passes necessary to produce sufficient gain, since the gain of Ti:sapphire is relatively small near 1 μm . As an example, the number of passes in a 1 mJ Ti:sapphire regenerative amplifier is often greater than 100.⁵ As a result, relatively large dispersion and B-integral occurs in the system. Additionally, regenerative laser cavity produces prepulses, which are spaced at an integer multiple of the cavity round-trip time prior to the main

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pulse. Prepulses are usually amplified in the subsequent amplifiers, and they experience amplification which is often greater than the amplification of the main pulse. The resulting prepulses can become energetic enough to perturb the target and produce unfavorable experimental conditions.

An alternative convenient approach exists to obtain broad bandwidth amplification at 1 μm and avoid complicated regenerative amplification schemes. Optical parametric amplifiers (OPAs)⁶ can be used in CPA as an alternative to laser amplifiers. The technique was demonstrated in 1992,⁷ and termed parametric chirped pulse amplification (PCPA)⁷ and, more recently, optical parametric chirped pulse amplification (OPCPA).⁸ As opposed to laser amplification, OPCPA is an instantaneous nonlinear process, in which the energy is transferred from the high-frequency pump to lower frequency signal and idler waves. The signal wave is used in subsequent amplification in a laser system, if desired, while the idler wave at the difference frequency is discarded.

The first demonstration of OPCPA featured modest stretching ratios (~ 18) and μJ -level amplified pulse energies.⁷ Subsequently, arguments were made for scaling OPCPA to high peak power by using large-aperture KDP crystals.⁸ More recent experimental development produced TW-level pulses using OPCPA pumped by a large glass laser.⁹ While high conversion efficiency of 20% in an OPCPA system based on a quasi-phase-matched OPA pumped by a fiber laser has been reported,¹⁰ experiments that use commercial tabletop Q-switched Nd:YAG lasers for pumping OPAs were relatively inefficient, with maximum energies reported of 0.6 mJ and conversion efficiencies of 0.6%.^{11,12} This was a result of both the pump laser characteristics and the particular OPCPA design. Here we report, to our knowledge, the most efficient 1 μm OPCPA system pumped directly by a simple Q-switched Nd:YAG pump laser, which is normally used to pump Ti:sapphire. Our OPA exhibited efficiency of 6%, which is a ten-fold improvement over previous results. In the subsequent chapters, we will describe the advantages of using OPCPA compared to regenerative CPA. We describe our numerical model for OPCPA and our system design, followed by the results of our experiments and conclusion.

2. CHARACTERISTICS OF OPCPA

OPCPA has numerous advantages compared to conventional regenerative amplification systems. Most of those advantages are related to the shortness of amplification path and the single-pass architecture. Design simplicity is the inherent characteristic of OPCPA. Some of important characteristics of OPA design include precise timing between signal and pump, and relay imaging of the desired pump profile onto OPA crystals. Relay imaging of the near-field pump profile is important because, in many cases, near field of the pump laser is a flat top beam, which facilitates transversely uniform amplification. Additionally, pump uniformity reduces the risk of crystal damage. Relay imaging often requires vacuum telescopes to prevent air breakdown in the beam focus. This can be sometimes avoided by using a large f-number focusing, at the expense of the increasing size of the system.

One of the most important advantages of OPCPA is the elimination of electro-optic modulators. This includes the modulators inside the regenerative laser cavity, and the pulse slicer that is normally used after the pulse stretcher. It is unnecessary to select a single pulse from the oscillator pulse train, because only the pulse that is temporally overlapped with the pump will be amplified. Pulse contrast in such OPCPA system that does not employ pulse selection prior to amplification is essentially determined by the total signal gain in the system. Some parametric fluorescence can be also produced, which is temporally coincident with the amplified pulse. Since amplification cavities are not used, no cavity-related prepulses exist in OPA such as in regenerative amplifiers.

The amplification length in OPA is typically very short – even when nanosecond pulses are used, typical length is on the order of a few cm. Short amplification length results in negligible accumulated nonlinear phase (B-integral). This allows pulse recompression without additional compensation for B-integral. Typical amplification bandwidth is broad, on the order 100 nm·cm, which allows amplification of ultrashort pulses. OPCPA is more flexible than laser CPA with respect to the selection of center wavelength for amplification. Broad bandwidth is naturally achieved in a degenerate or a nearly degenerate OPA that operates in a collinear geometry. Broad bandwidth around other center wavelengths can be also achieved in nondegenerate geometry using noncollinear geometry. Additional flexibility of center wavelength can be achieved by using quasi-phase matching and alternative pump wavelengths.

Good beam quality can be obtained from OPA, which is a characteristic of a process which has relatively narrow angular tolerance. In effect, OPA acts like a spatial filter and can produce very good beam quality. For high average power applications, it is important that OPA does not exhibit significant intrinsic heat load. The absence of quantum defect allows all the energy that enters the nonlinear crystal to leave it in the form of optical field, except for minimal material absorption. This positions OPCPA as a technology with a potential to produce ultrashort pulses with average powers in

excess of 1 kW.

The most problematic feature with OPCPA is the performance limit when tabletop commercial pump lasers are used for pumping OPCPA. In the first approximation, the conversion efficiency in OPCPA is determined by the temporal overlap of signal and pump. Since the pump pulse width in simple tabletop pump lasers is often relatively long compared to the stretched signal pulse width, relatively poor conversion efficiency results.

Relatively high beam quality is required from the pump laser in OPCPA that uses critical angular phase matching due to narrow angular tolerance.¹³ The desired transverse and temporal profile of the OPCPA pump laser is a top-hat. A uniform pump beam produces uniform amplification in space and in time (spectrum) of the chirped signal beam in the small-signal regime. When depletion of the pump beam occurs, it is also desirable that the spatial and temporal profile of the signal is a top-hat, which maximizes efficiency. This can be approximately achieved by using an OPA preamplifier in which some back-conversion occurs. Alternatively, gaussian temporal profile can also be used, in a combination with a double-hump-shaped seed, which can produce a gaussian beam with high conversion efficiency.

OPCPA has to operate in the regime of high pump depletion to achieve high stability,¹⁴ which is not an inherent characteristic of a nonlinear process in the small-signal regime.

3. NUMERICAL MODEL

We developed a numerical model of OPCPA and used to optimize the performance of our preamplifier and the power amplifier. We base our numerical model on the system of coupled differential equations that govern difference frequency generation:

$$\frac{dA_1}{dz} = i \frac{2\omega_1}{n_1 c} d_{eff} A_2^* A_3 \exp(i\Delta kz), \quad (1)$$

$$\frac{dA_2}{dz} = i \frac{2\omega_2}{n_2 c} d_{eff} A_1^* A_3 \exp(i\Delta kz), \quad (2)$$

$$\frac{dA_3}{dz} = i \frac{2\omega_3}{n_3 c} d_{eff} A_1 A_2 \exp(-i\Delta kz). \quad (3)$$

We denote by A_1 , A_2 , and A_3 the amplitude of the electric field of the signal, idler, and pump, respectively; d_{eff} is the effective nonlinearity, and Δk is the wave vector mismatch. Eqs. (1)-(3) describe the propagation of traveling monochromatic set of waves with negligible group velocity dispersion (GVD). This approximation is allowed, since we are modeling nanosecond pulses. Small dephasing introduced by GVD is negligible over the length of nonlinear crystal. We do not include diffraction explicitly, assuming that the beam quality of the pump and seed is relatively good and well inside the angular acceptance of OPA. In nanosecond OPAs, beam focusing is relatively weak and the resulting dephasing is small. Similarly, apart from depletion effect, pump profile can be assumed constant along the amplification length.

An important feature of our experiments is the spatial and temporal nonuniformity of pump and signal pulses. This implies that the coupled differential equations Eq. (1)-(3) cannot be used directly, but have to be solved on a spatio-temporal grid that captures the characteristics of pump and seed pulses. In addition, birefringent walk-off and optional noncollinearity reduce the effective amplification length and introduce a more complicated spatial coupling of pump, signal, and idler. This is very important when the beam diameter is comparable to total transverse walk-off over the crystal length.

Intensity distribution at a point (x, y, t) is related to the amplitude of electric field:

$$I_i(x, y, t) = 2n_i \sqrt{\frac{\epsilon_0}{\mu_0}} |A_i(x, y, t)|^2, \quad i = 1, 2, 3, \quad (4)$$

which can be normalized as following:

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_i(x, y, t) dx dy dt = E_i, \quad i = 1, 2, 3, \quad (5)$$

where E is the integrated pulse energy. The effect of beam walk-off and noncollinearity is modeled as following:

$$x_1' = x_1 + \Omega_{1x}z, \quad y_1' = y_1 + \Omega_{1y}z, \quad (6)$$

$$x_2' = x_2 + \Omega_{2x}z, \quad y_2' = y_2 + \Omega_{2y}z, \quad (7)$$

$$x_3' = x_3 + \rho z, \quad (8)$$

where ρ is the walk-off angle, (Ω_x, Ω_y) are the noncollinear angles, and $(x'(z), y'(z))$ are the coordinates corrected for walk-off and noncollinearity at the axial distance z . Wave vector mismatch can be modeled for a point in time t in collinear geometry as

$$\Delta k_z(t) \approx 2\pi \left(\frac{n_3}{\lambda_3} - \frac{n_1(t)}{\lambda_1(t)} - \frac{n_2(t)}{\lambda_2(t)} \right) \quad (8)$$

Using those definitions, the system of differential equations can be written as

$$\begin{aligned} \frac{dA_1(x_1', y_1', t)}{dz} &= i \frac{2\omega_1(t)}{n_1(t)c} d_{\text{eff}} A_2^*(x_2', y_2', t) A_3(x_3', y, t) \exp(i\Delta k(t)z), \\ \frac{dA_2(x_2', y_2', t)}{dz} &= i \frac{2\omega_2(t)}{n_2(t)c} d_{\text{eff}} A_1^*(x_1', y_1', t) A_3(x_3', y, t) \exp(i\Delta k(t)z), \\ \frac{dA_3(x_3', y, t)}{dz} &= i \frac{2\omega_3(t)}{n_3(t)c} d_{\text{eff}} A_1(x_1', y_1', t) A_2(x_2', y_2', t) \exp(-i\Delta k(t)z). \end{aligned} \quad (9)$$

In the next step, electric field discretization is performed using (DX, DY, DT) points in a spatial and temporal window size (WX, WY, WT) , with the following normalization condition:

$$2n_i \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{WX}{DX} \frac{WY}{DY} \frac{WT}{DT} \sum_{j=1}^{DX} \sum_{k=1}^{DY} \sum_{l=1}^{DT} |A_i(j, k, l)|^2 = E_i, \quad i=1,2,3. \quad (10)$$

We solve system (9) using numerical integration to arrive with the expected energy, transverse beam profile and temporal/spectral profile of the amplified pulse.

4. SYSTEM DESIGN AND RESULTS

We used our numerical model to optimize the performance of our OPCPA system. Initially, we measured the spatio-temporal evolution of the pump pulse. Our pump laser was a Spectra-Physics GCR 270-10 Q-switched tabletop pump laser, operating in a single longitudinal mode. Operation of the pump laser in single longitudinal mode is important, because the temporal modulation of pump pulse is imprinted on the amplified pulse spectrum. Additionally, since OPCPA crystals are often driven close to their damage threshold, strong temporal modulation can lead to instantaneous intensity beyond the material damage threshold. The pulse evolution measurement was performed using a scanning pinhole and a fast silicon diode in the image plane of the second harmonic of the pump. The numerical fit to the data in radial and temporal dimensions is shown in Fig. 1.

The most prominent feature of the measured pump pulse is that the pulse build-up starts preferentially in the center of the laser cavity. At the back of the pulse, radially more distant parts of the pulse achieve appreciable intensity, while the intensity in the center drops due to the depletion of the laser gain medium. In effect, the pulse exhibits different transverse spatial profile at different points in time. In order to model the performance of OPCPA as an instantaneous process, it is important to include this particular pulse shape in the numerical model.

We present our OPCPA system design in Fig. 2. We used a mode-locked Ti:sapphire oscillator to generate the seed pulses. The oscillator was a Spectra-Physics Tsunami, operating at a center wavelength of 1054 nm, with 16.5 nm FWHM bandwidth, producing 100-fs pulses. In this experiment, a pulse selector was used to select a single oscillator pulse at a repetition rate of 10 Hz. While there is no fundamental reason to select a single pulse in an OPCPA system because the selection is performed by OPA, we still used a pulse slicer in order to obtain more reliable low-background measurement of the amplified pulse spectrum and profile. The pulse is introduced into the stretcher, which is based on a single grating and a plano-convex lens. A stripe-mirror design of the stretcher grating allows the pulse to be expanded to 3 ns in a relatively compact setup. The plano-convex lens introduces chromatic and spherical aberrations, eventually limiting the recompressed pulse width to several hundred fs.

The OPA is a quasi two-stage amplifier, consisting of a high-gain preamplifier and a power amplifier. A novel design is introduced in the high-gain preamplifier, with two closely spaced beta-barium borate (BBO) crystals arranged in a walk-off compensating scheme. Independent angular tuning is realized for both crystals. The small air gap (~2 mm) between

the crystals provides for several advantages of this design. First, a very small dephasing in air allows high gain. Only single relay imaging of the pump beam is necessary for both crystals, and the pump beam is re-used after the first crystal, where it is essentially undepleted. Finally perfect timing of pump and seed can be achieved in both crystals by timing the pump and the seed on the first crystal only. The idler is propagated from the first into the second crystal, since the required bandwidth does not necessitate idler separation after propagating through the first crystal. Both preamplifier crystals were 15 mm long, and cut at 22.8° to facilitate type I angular phase matching. All the crystals were cut with a 2° wedge on the output surface to reduce the effect of parasitic oscillation.

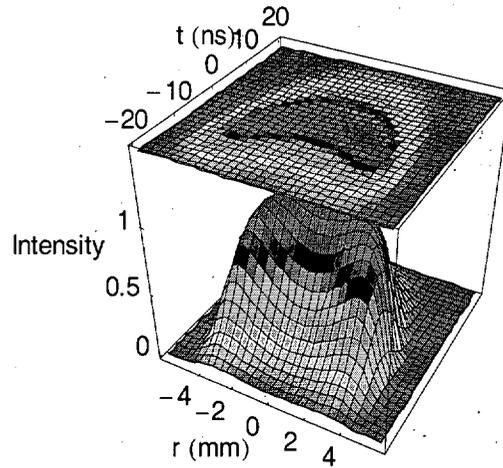


Fig Shown is the numerical fit to the data taken on our pump laser.

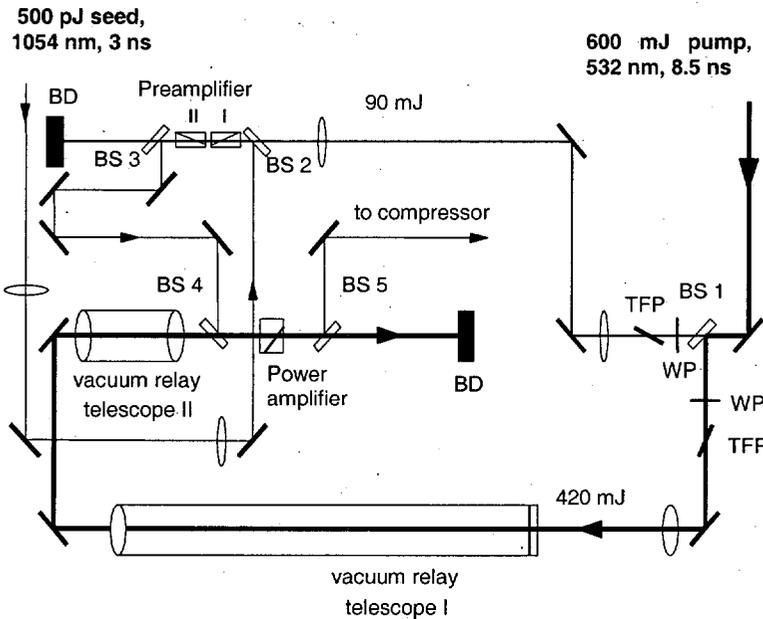


Figure 2. OPCPA setup. BS-beamsplitter, TFP-thin film polarizer, WP-waveplate, BD-beam dump

The 500-pJ stretched seed pulses are introduced into the preamplifier by reflection from a dichroic beamsplitter, at a 0.5° external noncollinear angle with respect to the pump beam. The preamplifier is pumped by 85 mJ of pump energy, producing a peak intensity of 450 MW/cm^2 . The intensity we used allowed us to run our repetitive system with a minimal risk of crystal damage. The obtained maximum amplified pulse energy from the preamplifier was 1.5 mJ, for a gain of 3×10^6 . The idler is angularly separated and discarded after amplification in the preamplifier, while the signal is appropriately delayed and introduced into the final amplifier crystal. While the aperture of the preamplifier crystals is 4 mm^2 , the power amplifier is a 10 mm-long BBO crystal of sufficient aperture (10 mm^2) to handle high pulse energy available from our pump laser. The power amplifier was seeding by 420 mJ of energy from the pump laser, with the maximum intensity of 420 MW/cm^2 . The maximum amplified signal energy was 31 mJ, which is 20% of the calculated pump energy in the temporal window defined by the pump pulse. With the overall efficiency of 6%, this system represents the most efficient OPCPA system pump by a tabletop Q-switched pump laser. We measured the output from the power amplifier and compared the results with our numerical model described above. With several different energies used to seed the power amplifier from the preamplifier, a good agreement was obtained between the calculations and the experiment (Fig. 3).

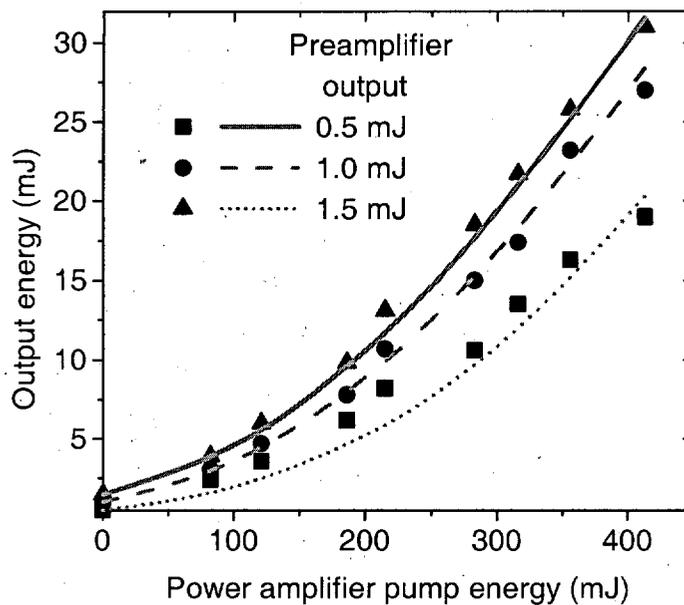


Figure 3. Amplified signal energy in the power amplifier for several inputs from the preamplifier. Indicated by lines are the results obtained from our numerical model.

Seed and amplified pulse spectra were measured, and the results are shown in Fig 4. The hard-clip points in the spectrum are the result of spectral slipping on the stretcher lens. After amplification in preamplifier, which does not operate near saturation, spectrum is slightly narrowed at its FWHM. The clip points in the spectrum remain the same, however, indicating that this spectral narrowing is a temporal CPA effect. After amplification in the saturated power amplifier, the spectrum is modified and resembles a top-hat shape. This is the result of saturated conversion and the onset of back-conversion in the pulse temporal center, while the pulse wings are still converting with relatively high efficiency. This hard spectral shape eventually limits the recompressed pulse contrast. To verify the depletion of the pump beam in the power amplifier, we scattered the residual pump and monitored the power on a fast silicon diode. As shown in Fig. 5, when we maximized our amplified pulse energy from the system by adjusting the seed-pump delay, the point of maximum pump depletion did not occur at the peak power of the pump pulse. This can be understood by considering the spatio-temporal evolution of the pump pulse. Using the data on the pulse evolution in Fig. 1, and by calculating the peak power of the central 70% of the transverse pump size, we were able to determine that the central part of the pulse peaks 2-3 ns earlier compared to the pump pulse integrated across the transverse profile. The result of this calculation is also shown in Fig. 5. Since the beam center is more important for amplification in our system, this effect is consistent with

expectations.

We measured the beam quality from our system, and by optimizing the beam overlap and minimizing the noncollinear angle in the power amplifier, we were able to obtain beam quality which is close to the diffraction limit ($M^2=1.1-1.2$). In Fig. 6 we show the measured beam profiles in the near field and in the far field.

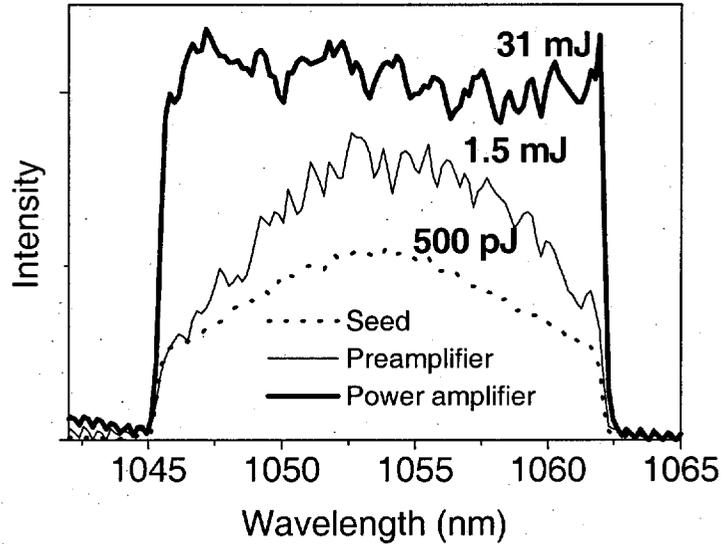


Figure 4. Seed and amplified signal spectra in OPCPA

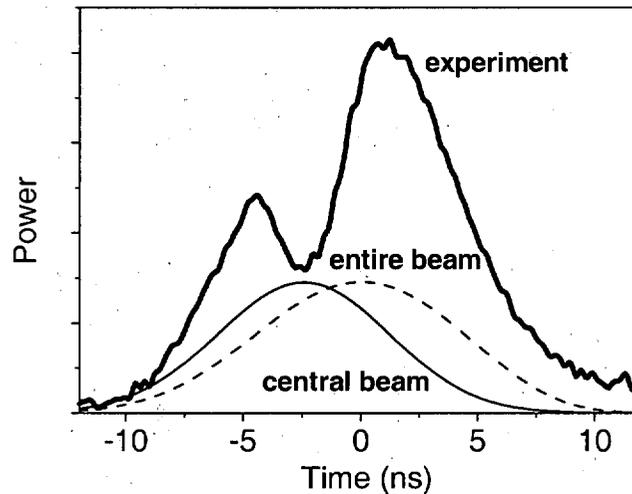


Figure 5. Maximum energy extraction occurs at the temporal peak of the central 70% of the pump pulse

We recompressed the amplified pulses in a single-grating compressor, with 50% efficiency. The obtained 15-mJ pulses were characterized using intensity autocorrelation. We initially recompressed the seed pulses prior to amplification to 280 fs (Fig. 7 (a)). After amplification, the recompressed pulse width was 310 fs (Fig. 7 (b)). This small inconsistency may be the result of spectral modification in the amplification process, and a possible small uncertainty between the two autocorrelation devices used in the measurement (a scanning autocorrelator was used in Fig. 7 (a), while a single-shot autocorrelator was used in Fig. 7 (b)). As mentioned previously, we attribute the recompression results which are 3 times worse than the transform limit to uncompensated aberrations that arise in the pulse stretcher. Since the exact nature and impact of aberrations if unknown, a conservative gaussian deconvolution factor was used when calculating the pulse width from the measured autocorrelation traces.

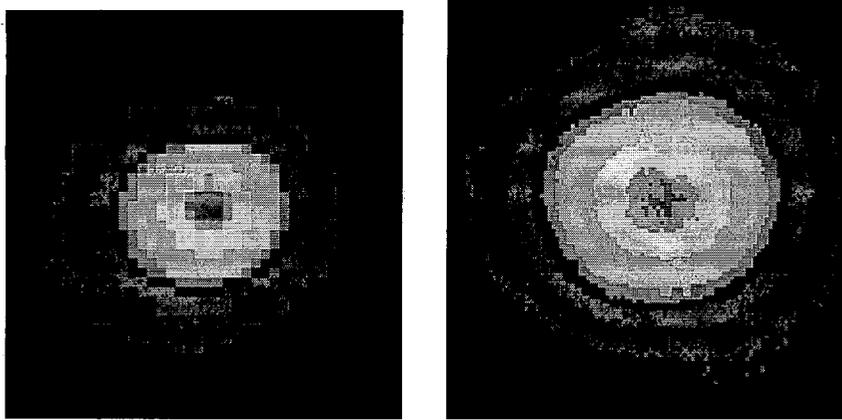


Figure 6. Amplified pulse at full energy, in (a) near field and (b) far-field

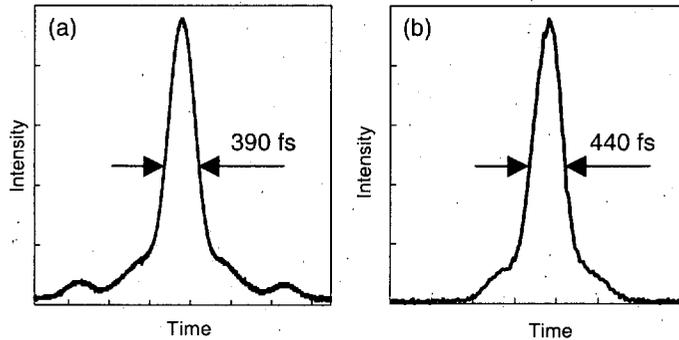


Figure 7. Recompressed pulse intensity autocorrelation, (a) before amplification and (b) after amplification. Deconvolved pulse width is (a) 280 fs, and (b) 310 fs.

5. CONCLUSION

In conclusion, we demonstrated, to our knowledge, the most efficient OPCPA system to date pumped by a tabletop, commercial Q-switched, pump laser. In a single pass through only 40 mm of gain medium, a gain of 6×10^7 was realized. The conversion efficiency of 6% is limited by the spatio-temporal evolution of the pump pulse and the mismatch in the pulse duration between the signal and the pump pulse. This indicates that the future development of shorter-pulse pump lasers suitable for OPCPA is desirable to improve the efficiency of the technique.

While our system did not demonstrate the transform-limited pulses, the obtained system is nevertheless applicable as a front end for a large glass-based petawatt-scale laser system, or as a stand-alone system usable for such applications as materials processing. OPCPA proved as a valuable technique with sufficient potential to substitute for regenerative amplification in Ti:sapphire at $1 \mu\text{m}$, and allow such simplifications as the elimination of electro-optic switching. Further developments of high average power pump lasers suitable for pumping OPCPA may lead to future record-setting average power in ultrashort pulses.

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REFERENCES

1. B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, "Optical ablation by high-power short-pulse lasers," *J. Opt. Soc. Am. B* **13**, pp. 459-468, 1996.
2. Las surg
3. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.* **56**, pp. 219-221, 1985.
4. M. D. Perry, D. Pennington, B. C. Stuart, G. Tiethohl, J. A. Britten, C. Brown, S. Herman, B. Golick, M. Kartz, J. Miller, H. T. Powell, M. Vergino, and V. Yanovsky, "Petawatt laser pulses," *Opt. Lett.* **24**, pp. 160-162, 1999.
5. B. C. Stuart, S. Herman, and M. D. Perry, "Chirped-pulse amplification in Ti:sapphire beyond 1 μm ," *IEEE J. Quantum Electron.* **31**, pp. 528-538, 1995.
6. R. A. Baumgartner and R. L. Byer, "Optical Parametric Amplification," *IEEE J. Quantum Electron.* **15**, pp. 432-444, 1979.
7. A. Dubietis, G. Jonusauskas, and A. Piskarskas, "Powerful femtosecond pulse generation by chirped and stretched pulse parametric amplification in BBO crystal," *Opt. Commun.* **88**, pp.437-440, 1992.
8. I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, "The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers," *Opt. Commun.* **144**, pp. 125-133, 1997.
9. I. N. Ross, J. L. Collier, P. Matousek, C. N. Danson, D. Neely, R. M. Allott, D. A. Pepler, C. Hernandez-Gomez, and K. Osvay, "Generation of terawatt pulses by use of optical parametric chirped pulse amplification." *Appl. Opt.* **39**, pp. 2422-2427, 2000.
10. A. Galvanauskas, A. Hariharan, D. Harter, M. A. Arbore, and M. M. Fejer, "High-energy femtosecond pulse amplification in a quasi-phase-matched parametric amplifier," *Opt. Lett.* **23**, pp. 210-212, 1998.
11. J. Collier, C. Hernandez-Gomez, I. N. Ross, P. Matousek, C. N. Danson, and J. Walczak, "Evaluation of an ultrabroadband high-gain amplification technique for chirped pulse amplification facilities," *Appl. Opt.*, **38**, pp. 7486-7493, 1999.
12. S. K. Zhang, M. Fujita, H. Yoshida, R. Kodama, H. Fujita, M. Nakatsuka, Y. Izawa, and C. Yamanaka, "Study on High Gain Broadband Optical Parametric Chirped Pulse Amplification," *Proc. SPIE*, K. Mima, G. L. Kulcinski, and W. Hogan, editors, **3886**, pp. 588-595, 2000.
13. I. Jovanovic, B. J. Comaskey, and D. M. Pennington, "Angular effects and beam quality in optical parametric amplification," *J. Appl. Phys.* **90**, pp. 4328-4337, 2001.
14. S. K. Zhang, M. Fujita, M. Yamanaka, M. Nakatsuka, Y. Izawa, C. Yamanaka, "Study of the stability of optical parametric amplification," *Opt. Commun.* **184**, pp. 451-455, 2000.