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Double-passed, high-energy quasi-phase-matched optical parametric chirped-pulse amplifier

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1 Introduction

Quasi-phase-matched (QPM) optical parametric chirped-pulse amplification (OPCPA) in periodically poled materials such as periodically poled $LiNbO_3$ (PPLN) and periodically poled $KTiOPO_4$ (PPKTP) has been shown to exhibit advantages over the OPCPA in bulk nonlinear crystals. [GHH98, RPN02] The use of the maximum material nonlinear coefficient results in ultra-high gain with low pump peak power. Furthermore, propagation of signal, pump, and idler beams along one of the crystal principal axes eliminates the birefringent walk-off, reduces angular sensitivity, and improves beam quality. Relatively high level of parasitic parametric fluorescence (PF) in QPM OPCPA represents an impediment for simple, single-stage, high-gain amplification of optical pulses from nJ to mJ energies. PF in QPM is increased when compared to PF in critical phase matching in bulk crystals as a result of broader angular acceptance of the nonlinear conversion process. PF reduces prepulse contrast and conversion efficiency by competition with the signal pulse for pump pulse energy. Previous experiments with QPM OPCPA have thus resulted in pulse energies limited to tens of μJ. [JSE03] Optical parametric amplification of a narrowband signal pulse in PPKTP utilizing two pump beams has been demonstrated at a mJ-level, [FPK03] but the conversion efficiency has been limited by low energy extraction of pump pulse in the first pass of amplification. Additionally, narrow spectral bandwidth was the result of operation far from signal-idler degeneracy.

Here we present a novel double-pass, broad-bandwidth QPM OPCPA. 1.2 mJ of amplified signal energy is produced in a single PPKTP crystal utilizing a single 24-mJ pump pulse from a commercial pump laser. [JFE05] To our knowledge, this is the highest energy demonstrated in QPM OPCPA. Double-passed QPM OPCPA exhibits high gain ($> 3 \times 10^6$), high prepulse contrast ($> 3 \times 10^7$), high energy stability (3% rms), and excellent beam quality. We additionally present a simple extension of QPM OPCPA to cascaded-optical parametric amplification (COPA), [WJB02] resulting in, in principle, infinite prepulse contrast. This amplifier is highly suitable for a high-gain section of a high-energy OPCPA system which has previously employed two or more crystals and higher pump energies, or a stand-alone, high-contrast preamplifier for a petawatt-class Nd:glass short-pulse laser. OPCPA front end systems for petawatt-class lasers are now used or planned at numerous laser facilities [OPC05] and may benefit from utilization of this type of system.

2 Experimental Setup

Fig. 1 depicts our experimental setup. The seed pulse centered at 1053 nm and with 6-nm FWHM bandwidth is generated by a mode-locked Yb:glass oscillator (High Q Laser IC-1053-200) operating at 77 MHz. The oscillator produces 200-fs pulses which are subsequently stretched to 1.2-ns FWHM with conventional anti parallel grating pulse stretcher. The stretched pulse energy is 800 pJ. Pump pulses are generated by a commercial, injection-seeded Nd:YAG laser (Continuum Powerlite Plus), producing 532-nm pulses with 5.7-ns FWHM pulse duration in the pulse center with a spatiotemporal shape characteristic for an unstable resonator. The repetition rate of the pump laser is 10 Hz and its pulses are synchronized with the oscillator pulses with a characteristic pulse-to-pulse jitter of 0.5 ns rms. Only a small amount (24 mJ) of the available pump energy from the pump laser is split from the pump laser and a circular aperture of $\sim$7.5 mm diameter is inserted in the beam. The aperture is relay imaged using a 5:1 beam relay telescope onto a 1.5x5x7.5 mm^3 PPKTP crystal (Raicol). The PPKTP crystal is periodically poled for a first-order, type-0 1053 nm+1075 nm=532 nm process and both its input and output surfaces are antireflection coated for 532 nm/1053 nm/1075 nm. A 3° wedge is used on the crystal back surface to prevent parasitic oscillation.

Seed and pump pulses are combined and injected into a PPKTP crystal with a small noncollinear angle of $< 0.5°$. Seed pulses overfill the crystal aperture, so that $\sim$50% of the available seed energy is introduced into the crystal. After the first pass of amplification, the pump is separated from the signal and idler using a dichroic beamsplitter and is fully relay imaged onto a roof mirror retro reflector. The roof mirror retro reflector displaces the pump beam laterally by 2 mm on the second (reverse) pass through the PPKTP crystal. Signal and idler pulses propagate freely without relay imaging to the second flat-mirror retro reflector. Idler pulses are separated from signal pulses using a knife edge (K).

Double-pass amplification scheme has a significant advantage over the single-pass amplification scheme due to the reduction of PF through propagation of

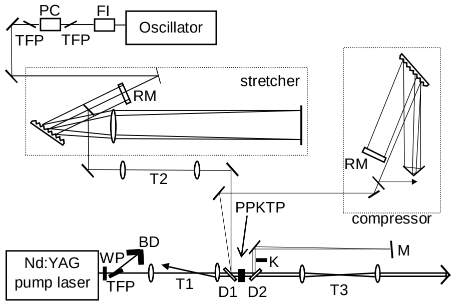

Fig. 1. Schematic for millijoule OPCPA/COPA in PPKTP. FI-Faraday isolator, PC-Pockels cell, TFP-thin film polarizer, RM-roof mirror, T-telescope, WP-waveplate, D-dichroic beamsplitter, BD-beam dump, K-knife edge. Selection between OPCPA and COPA is accomplished by tilting the mirror M to direct the signal or idler pulse, respectively, into the second amplification pass.

the signal/idler pulse over extended distances, thus allowing angularly divergent PF to be separated from the main signal/idler pulse prior to second-pass amplification. This property allows high-energy, high-gain amplification with a fluorescence level orders-of-magnitude lower than previously. The removed fraction of PF can be increased by spatial filtering of the signal between two amplification passes.

3 Results

We have obtained 1.2 mJ of amplified signal energy using 24 mJ of pump energy and a peak on-axis pump intensity of 170 MW/cm^2. Amplified spectrum exhibits spectral broadening to 12 nm FWHM (Fig. 2), which has been previously observed in saturated OPCPA. In Fig. 3 we show amplified signal free propagation after 1 m and far field beam profiles. The amplified signal pulse has been recompressed and its intensity autocorrelation is shown in Fig. 4. The calculated transform-limited autocorrelation width is 280 fs FWHM, resulting in transform-limited pulse width of 147 fs FWHM. Nonidealities in the existing stretcher (spherical and chromatic aberrations) impose a $\sim$200-fs aberration limit of the expansion-compression system. Pulse compression of QPM OPCPA-amplified pulse has been achieved at this aberration limit.

Prepulses in CPA systems can arise from preexisting oscillator pulse train or cavity- and etalon-produced pulses. We have measured the prepulse and fluorescence contrast of the amplified signal pulse after recompression and determined to be $> 3 \times 10^7$, limited by the experimental sensitivity of our measurement. The measured energy stability is 3% rms and is greatly enhanced when local pump depletion occurs.

When the idler pulse is removed in the signal/idler return line with the knife edge, the system operates in the normal optical parametric amplifier mode.

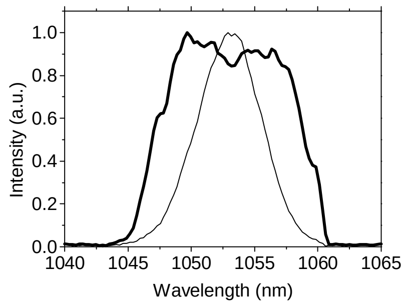

Fig. 2. Oscillator (6 nm FWHM, thin line) and amplified signal spectra (12 nm FWHM, thick line). Spectral broadening is evident when OPCPA operates with high pump conversion efficiency.

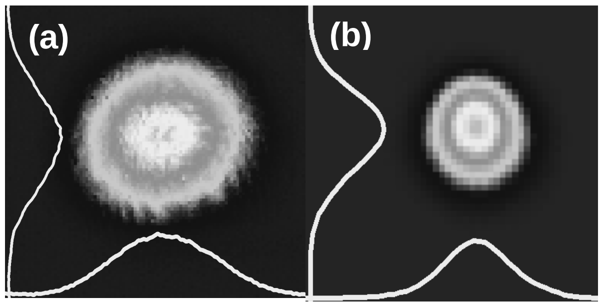

Fig. 3. Amplified signal beam profiles: (a) free propagation for 1 m; (b) far field

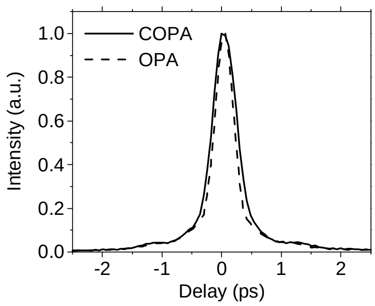

Fig. 4. Experimental autocorrelation trace of the OPCPA recompressed pulse (dashed line; 350 fs FWHM) and COPA recompressed pulse (solid line; 422 fs FWHM)

When the signal pulse is removed instead of the idler pulse in the signal/idler return line, the system can operate in the cascaded-optical parametric amplifier (COPA) [WJB02] mode. In this mode, the signal pulse is regenerated by difference frequency generation of the pump and idler in the second pass, resulting in extreme prepulse contrast enhancement (Fig. 5). Operation in the COPA mode takes advantage of two subsequent chirp reversals through double difference frequency generation in the nonlinear crystal and allows a complete removal of all other pulses from the mode-locked pulse train or optical background propagating on the signal axis outside of the temporal window defined by the pump pulse. COPA contrast is limited only by PF of the parametric process.
COPA-amplified pulse has been recompressed without any adjustments made to the pulse compressor used for OPCPA compression. The resulting autocorrelation trace is also shown in Fig. 4 and is compatible with the set of requirements for a front end of a petawatt-type Nd:glass laser system which is typically limited to ~400-fs pulses.

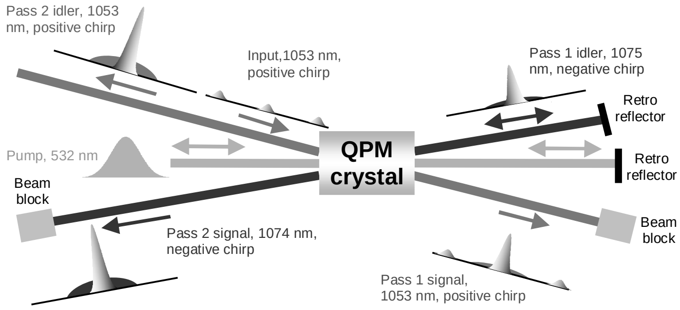

Fig. 5. COPA in double-pass QPM OPCPA. In COPA, the unamplified oscillator pulse train is completely removed and the contrast is limited only by PF.

4 Conclusion

In conclusion, we have demonstrated for the first time multi-pass QPM OPCPA and QPM COPA in PPKTP pumped by a commercial pump laser that produced record pulse energies of 1.2 mJ, spectrally broadened from 6 nm to 12 nm and subsequently compressed to ~200 fs (aberration limit of the system). Recompression to shorter pulse durations should be possible with higher precision expansion and compression components. Simple modification of the demonstrated scheme allows time-multiplexing for higher energy extraction in situations when pump pulse is much longer than the signal pulse. We have not observed any crystal degradation in ~48 hours of continuous operation at full energy, but additional work is required to identify the preferred nonlinear material with greatest resistance to photorefraction and other possible damage and/or degradation processes.

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[OPC05] OPCPA front end systems for petawatt-class lasers are used or under development at the Rutherford Appleton Laboratory, Osaka University, University of Rochester, École Polytechnique, Sandia National Laboratory, Lawrence Livermore National Laboratory, and other institutions.