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Optical parametric chirped-pulse amplification (OPCPA) can be used to improve the prepulse contrast in chirped-pulse amplification systems by amplifying the main pulse with a total saturated OPCPA gain, while not affecting the preceding prepulses of the seed oscillator mode-locked pulse train. We show that a simple modification of a multi-stage OPCPA system into a cascaded optical parametric amplifier (COPA) results in an optical switch and extreme contrast enhancement which can completely eliminate the preceding and trailing oscillator pulses. Instrument-limited measurement of prepulse contrast ratio of 1.4×10^{11} is demonstrated from COPA at a 30-mJ level.

OCIS codes: (190.4970) Optical parametric amplifiers and optical parametric oscillators; (320.7090) Ultrafast lasers.

There has been a significant recent interest in utilization of optical parametric chirped-pulse amplification (OPCPA)[1, 2] for generation of ultrashort pulses with high pulse energies. This interest has been motivated by a number of favorable features of OPCPA, particularly when used to replace regenerative amplifiers in Nd:glass short-pulse laser systems.[3-5] The important capability of OPCPA of producing large gain while maintaining broad spectral bandwidth near degeneracy has been the primary driver for replacement of the Ti:sapphire front-end technology in Nd:glass short-pulse lasers. Equally important, the requirement for high prepulse contrast ($>10^8$ for a 10^{21} W/cm^2 – class laser system) is incompatible with simple regenerative preamplification. A small fraction of the regeneratively amplified pulse is rejected on a cavity-dump polarizer on each pass, resulting in a series of prepulses spaced at the regenerative amplifier round-trip time. These prepulses require additional post-amplification contrast enhancement techniques (for example, references[6,7]). OPCPA, on the other hand, enhances the prepulse contrast by a factor equal to the total saturated gain, since the amplification occurs only during the time window defined by the pump pulse. The only requirement for the prepulse enhancement in OPCPA is that the pump pulse duration is sufficiently short so that the pump pulse does not overlap with the preceding pulses from the mode-locked oscillator pulse train. While the use of OPCPA results in significant prepulse enhancement, it does not remove prepulses; it merely reduces their relative peak intensity, typically of order $<10^8$ in a large laser system. Amplified oscillator prepulses could still lead to preionization of solid targets. In this Letter, we describe for the first time a novel, simple, and versatile technique which is capable of selecting and amplifying a single broadband pulse out of a mode-locked pulse train with complete elimination of the remainder of the pulse train.

This technique is implemented by reconfiguration of a two-stage OPCPA into a phase-conjugated, cascaded optical parametric amplifier (COPA). The COPA scheme is applicable to any energy level and to either stretched or compressed pulses, and in principle can act like an ultrafast all-optical switch. Instrument-limited experimental measurement of the prepulse contrast enhancement by $1.4\text{x}10^{11}$ at a 30-mJ level is presented.

The basis of the COPA technique is the utilization of the idler pulse rather than the signal pulse in a multi-stage optical parametric amplifier (OPA) (Fig 1).[8] Since this idler pulse is generated in the parametric mixing process between the pump and the main signal pulse, it carries no prepulses that would occur by mixing of the pump pulse with the seed signal prepulses. However, the idler pulse center frequency is shifted with respect to the original signal center frequency if the process is not ideally degenerate. Moreover, the spectral phase content of the idler pulse is incompatible with recompression using a matched stretcher-compressor pair.[9] In a temporal phase conjugation process, the sign of the even orders of spectral dispersion is inverted from signal to idler, whereas the sign of the odd orders of dispersion is conserved. This prevents recompression of idler pulses to Fourier transform-limited pulse durations using simple, nearly matched stretcher-compressor configurations. However, introduction of this idler pulse into a second OPA results in generation of the second idler pulse. Under ideal conditions of flat spectral gain in the OPA and no pump pulse chirp, the idler pulse generated by the second OPA has the exact temporal and spectral characteristics of the original signal pulse. If the pump pulse duration is less than twice the mode-locked pulse spacing, all the pre- and post-pulses are removed. In the second stage of phase conjugation, the newly generated idler has all of its dispersion orders reverted back to their original sign and magnitude in the seed pulse, so that it is compressible to Fourier transform-limited pulse duration. The compressibility limit is determined by the total phase error accumulated from pump phase aberrations in the first and second OPA, which generally leads to the requirement for an unchirped, unaberrated pump pulse. An even number of phase conjugations is required in the scheme.

Our experimental setup for COPA is based on a simple reconfiguration of a previously described double-stage OPCPA system.[10] The idler pulse is generated by difference frequency mixing of the 1053-nm stretched seed pulse train with a 532-nm pump pulse in the preamplifier, resulting in ~1-mJ pulses at a center wavelength of 1075 nm. No electro-optic pulse selection is performed on the oscillator pulse train prior to injection into the OPA. The idler is separated from the signal pulse and amplified to ~50-mJ level in the power amplifier. The idler pulse produced by the power amplifier (second OPA) is the output of the COPA system and is characterized.

The amplified spectrum of the COPA output is shown in Fig. 2 and is identical to the amplified spectrum of the OPCPA system under same pump conditions. This is expected since the COPA system still evolves with the identical set of laws and initial conditions as the OPCPA system. Spectral gain broadening is observed as a result of operation with high pump depletion and has been previously reported.[3]

We have performed recompression of pulses generated by the same system operating in both the OPCPA and the COPA mode. The recompressed pulse duration was measured using a second-order, dispersion-balanced intensity autocorrelator. The results are shown in Fig. 3 and indicate a small increase in recompressed pulse duration of the COPA pulse. In the OPCPA mode, the recompressed pulse autocorrelation width was 420 fs, which is ~1.7x longer than the transform-limited autocorrelation width calculated from the amplified pulse spectrum. The calculated transform-limited pulse duration based on the measured pulse spectrum is 190 fs. Imperfect pulse compression has been noted previously in this system and is attributed to chromatic and spherical aberrations in the pulse stretcher.[10] When operating in the COPA mode, recompressed pulse autocorrelation width increased to 460 fs, which represents a 10% increase over the OPCPA result. The increase of pulse duration is attributed to the accumulation of phase aberration from the pump pulse in two stages of phase conjugation in COPA. In both cases the pulse duration is significantly shorter than the gain-narrowed output of high-energy, short-pulse Nd:glass lasers (PW-class systems).

Demonstration of a large prepulse contrast requires a high dynamic range prepulse measurement technique. We have chosen a relatively simple setup using a photodetector and a cascade of Pockels cells. To detect any existent prepulses, the photodetector must have a high responsitivity in the required spectral range, a small dark current, a low noise level and a sufficient fast rise- and falltime. We used an InGaAs PIN photodetector (ET-3000) from EOT. To protect the photodiode from damage by the main pulse we installed a cascade of two fast Pockels cells, each with a set of two thin-film polarizers before and after the cell. The Pockels cells had a rise time of approximately 1 ns and were thus triggered 2-3 ns before the main pulse arrives allowing the transmission of prepulses and suppression of the main pulse. The attenuation of the main pulse was 1.1×10^5, equivalent to an extinction ratio of 1:334 per Pockels cell. The attenuation was sufficient to protect the diode from damage by the main pulse and to have a good signal to noise ratio for the prepulses in case of the OPCPA measurement. Fig. 4 shows the setup of our contrast measurement.

We first determined the contrast ratio for the OPCPA system. With the Pockels cells turned on we measured the amplitude of the prepulse. Calibrated neutral density filters were then inserted to protect the photodetector from damage by the main pulse and the Pockels cells were turned off. Filters were chosen such that the amplitude of the signals was nearly identical throughout the measurement to avoid errors due to small photodetector response nonlinearities. We have also averaged each signal over 100 pulses to determine signal fluctuations introduced by the laser itself, Pockels cell drivers, beam pointing or other sources. The prepulse contrast was 1.4×10^{8} which is approximately equivalent to the gain of the system.

We reconfigured the OPCPA setup to the COPA configuration as described before. We first recorded the maximum amplitude of the pulse with the Pockels cell turned off and using neutral density filters to attenuate the intensity on the photodetector sufficiently. In the next step we turned the Pockels cell on and removed the filters. As expected, we could not detect any prepulses. The baseline was measured with and without COPA turned on to correct for the noise level. We found the noise level to be at $6.2 \pm 0.05 \times 10^{-3}$ on the normalized scale of Fig. 5. The main source for noise derives from the digitizer and crosstalk effects in the oscilloscope; the dark current of the photodetector is specified $<3 \times 10^{-6}$ and thus well below our common noise level. We determined the contrast ratio by comparing the pulse amplitude with the leading baseline ahead after subtracting the noise level and obtained an instrument-limited contrast ratio of $1.4\mathrm{x}10^{11}$. Fig. 5 shows the comparison between OPCPA and COPA contrast measurement. The measurement dynamics were limited by the maximum available energy determining the signal to noise ratio.

In conclusion, we have demonstrated a novel technique for prepulse contrast enhancement/prepulse cleaning based on the use of cascaded OPAs with temporal phase conjugation and demonstrated an instrument-limited prepulse contrast enhancement of $1.4\mathrm{x}10^{11}$ at a 30-mJ level. The COPA technique has, in principle, infinite contrast enhancement capability outside of the time window defined by the pump pulse and is limited only by the angular separation of signal and idler pulses after each OPA. In the shorter temporal window, on the time scale of the pump pulse duration, the COPA contrast is limited by usual parametric fluorescence. Simple modification of a multi-stage OPCPA system results in its operation in a COPA mode, particularly for systems operating near degeneracy. In the case of nondegenerate OPCPA, angular dispersion of the idler beam requires careful relay imaging through each pair of phase-conjugation stages, but results in a collimated beam if the ratio of the noncollinear angle to the idler angular dispersion is preserved in two OPAs. Since the COPA technique does not rely on the nonlinear effects on the pulse itself, it is extraordinarily versatile. COPA can be operated at any energy level, with either stretched or compressed pulses. It can be used as a preamplification stage or as a high-contrast, large-bandwidth pulse selector.

A particularly attractive implementation of the scheme is in conjunction with quasi-phase-matched OPA,[11] where a simple low-energy contrast enhancement can be accomplished utilizing a single OPA crystal. The accumulation of the spectral phase present on the main pulse also presents an opportunity for spectral phase shaping and/or phase compensation by use of a chirped pump pulse. The temporal sensitivity of such spectral phase control technique could be alleviated by utilizing a common source for seed and pump pulses.

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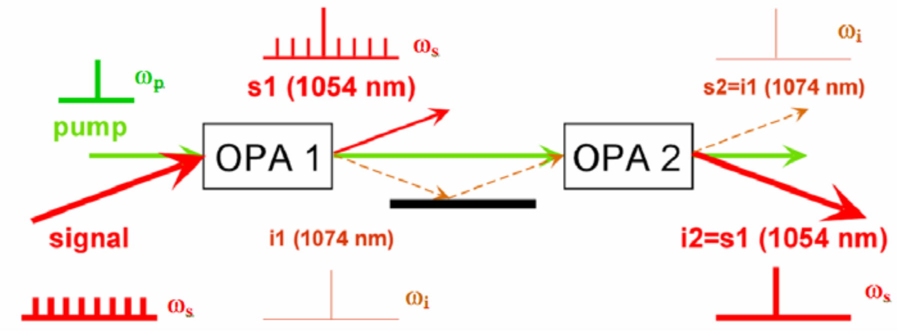

Figure 1. The COPA principle. A signal pulse from the incident pulse train at a frequency ω_s is amplified in OPA 1 using a pump pulse at a frequency ω_p. An isolated idler pulse at a frequency $\omega_{i=}\omega_p$-ω_s is generated in OPA 1 and subsequently introduced into OPA 2 pumped by an identical pump pulse. The idler generated in OPA 2 is shifted back to the original frequency ω_s and its prepulses outside the time window of defined by the main pulse have been removed.

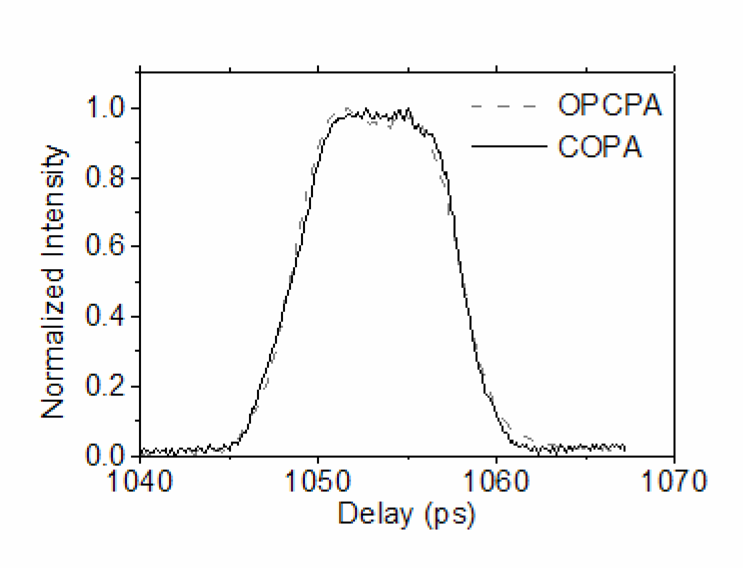

Figure 2. Amplified pulse spectra in OPCPA (dashed line) and COPA (solid line). High pump depletion results in spectral broadening.

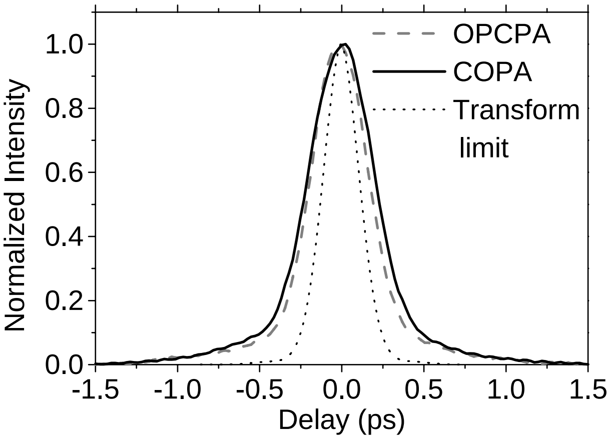

Figure 3. Autocorrelations of OPCPA and COPA. Also shown is the calculated autocorrelation of the transform limited pulse based on the measured OPCPA spectrum.

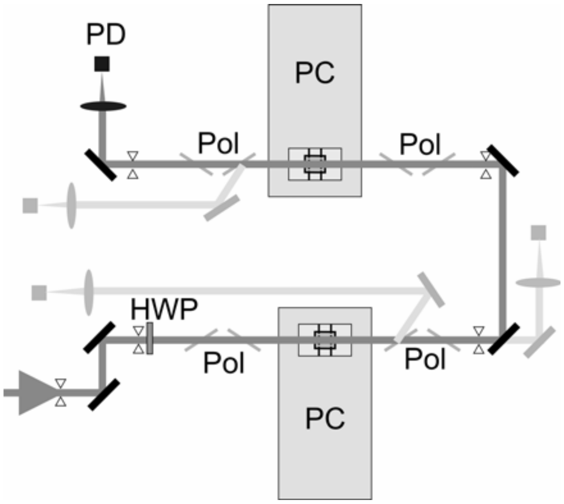

Figure 4. Schematic of optical setup for contrast measurement. The pulse is passing a set of two Pockels cells. Shaded beam paths are used only for calibration and timing purposes. Abbreviations: PC – Pockels cell, Pol – thin film polarizer, HWP – half wave plate, PD – photodetector.

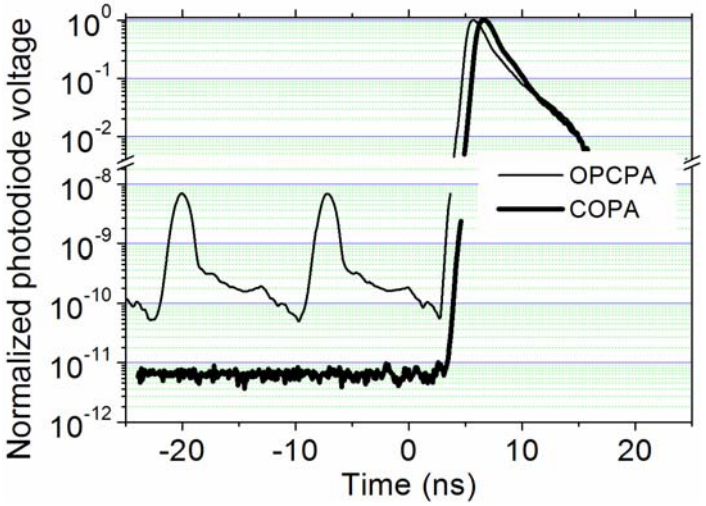

Figure 5. (thin line) OPCPA amplifies an isolated oscillator pulse, but does not remove prepulses; (thick line) COPA removes all oscillator prepulses. COPA pulse is shifted by 1 ns for better distinction.

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