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PARAMETRIC TECHNIQUES FOR EXTREME-CONTRAST, HIGH-ENERGY PETAWATT PULSES

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Abstract

Prepulses are of great concern in high-power lasers: if their intensity is sufficiently high, they can heat and/or destroy a target before the arrival of the main pulse. For ultrahigh peak power lasers, for which focused intensity can exceed 10^{21} W/cm^2, a contrast of at least 10^8 is the minimum requirement to avoid preionization of solid targets. Conventional preamplification stages do not meet this requirement, primarily due to prepulse originating from regenerative amplification. Optical parametric amplification (OPA) is well-known to generate pulses with a prepulse contrast equal to the gain of the amplifier, but it does not remove pre-existing prepulses. In this paper we describe a novel technique for contrast enhancement in cascaded optical parametric amplifiers (COPA). Based on cascaded idler utilization, COPA represents a versatile technique with a potentially infinite prepulse contrast enhancement. We have experimentally demonstrated COPA, producing a prepulse contrast of 10^8, limited by the sensitivity of measurement. A simple modification of the front end of a petawatt-type laser that utilizes optical parametric chirped pulse amplification (OPCPA) can yield unprecedented levels of prepulse contrast.

I. INTRODUCTION

The advent of chirped pulse amplification (CPA)[1] has enabled construction of petawatt-scale lasers[2] with important applications in high-density laser-matter interactions, such as fast ignition[3] via energetic electrons or protons. High-field science experiments are driven by the exceptional focused irradiance that is possible using high-energy, short-pulse lasers.

Prepulses are of great concern in high-power laser chains: if their intensity is high enough they can heat and/or destroy a target before the arrival of the main pulse. In this way, the laser-matter coupling can then be dramatically reduced. For high-energy petawatt lasers (HEPW), for which intensity can be above 10^{21} W/cm^2, a contrast of at least 10^8 is the minimum requirement to avoid preionization of solid targets. Even the effect of nonionizing prepulses may be intolerable for some experiments, as the prepulse intensities as low as 10^8-10^9 W/cm^2 can significantly influence laser-solid interactions.[4]

The origin of imperfect pulse contrast in CPA can be traced to three sources. First, amplified spontaneous emission in lasers, or parametric fluorescence in parametric generators and amplifiers results in a pulse pedestal. The characteristic pulse width of the pedestal is on the order of fluorescence lifetime in lasers, or pump pulse width in parametric devices. Second, any spectral clipping, spectral pulse shaping, or accumulation of spectral phase that occurs in the CPA system may lead to prepulse ringing. This is the consequence of the pulse shape being the Fourier transform of the pulse spectrum.

The third and usually the most limiting source of imperfect prepulse contrast in CPA is the leakage prepulse from regenerative amplification. High-gain regenerative amplifier stages usually used in CPA systems utilize electro-optic modulators (Pockels cells) and polarizers to switch the pulses in and out of their cavity via polarization rotation. Since the extinction of the Pockels cell – polarizer pair is typically on the order 10^3, this results in prepulses being ejected out of the cavity with a characteristic separation of one cavity round-trip time. This problem becomes more pronounced when ultrashort pulses are used, since the polarization rotation employed in Pockels cells is frequency-dependant. Prepulses emited from the regenerative amplifier propagate through the remaining stages of the laser system, get compressed and impinge on the target nanoseconds before the arrival of the main pulse. Regenerative amplifier prepulses can also experience higher gain than the main pulse if the laser system is operating in saturation.

II. CONVENTIONAL METHODS FOR CONTRAST IMPROVEMENT

The requirement for high prepulse contrast of $>10^8$ cannot be met by conventional preamplification stages. The common method for prepulse contrast improvement has been cascading Pockels cells, with an improvement of pulse contrast on the order of 10^3 per stage. While this method is straightforward, it is expensive and its performance is limited when broad bandwidth pulses are used. Additionally, it requires a complicated timing system and a number of high-voltage pulsed drivers. Finally, it leads to linear and nonlinear (B-integral) phase accumulation in the system and is difficult to implement at higher energies.

More advanced nonlinear techniques have been demonstrated for prepulse contrast improvement. Saturable absorbers allow only the high-intensity, main pulse to pass or be reflected in the system, but is applicable only in a limited range of energies. Frequency doubling after amplification also enhances the pulse contrast, but leads to energy loss. A technique that utilizes intensity-dependent polarization rotation has also been demonstrated recently, with a similar limitation on the useful range of energies.[5] Another approach to high-gain broad-band preamplification, optical parametric chirped pulse amplification (OPCPA),[6,7] is well-known to generate pulses with a prepulse contrast equal to the gain of the amplifier. The parametric amplification process occurs only when signal and pump pulses are overlapped in time. However, OPCPA does not remove pre-existing prepulses but only decreases their relative peak intensity by a factor equal to OPCPA gain.

III. CASCADED OPTICAL PARAMETRIC AMPLIFICATION

We present a novel technique that removes all prepulses and is applicable in the energy range from oscillator pulse trains to Joule-level pulses. It is based on the fact that OPCPA generates a chirped idler pulse, which is usually considered unusable. Since this idler is generated only in the parametric process, it carries no prepulses preceding the main signal pulse if they are not contained within the pump temporal window. However, this idler pulse central wavelength is different from the signal central wavelength and its spectral phase dispersion is incompatible with recompression using a matched stretcher-compressor pair.[8] We send this idler pulse into a second optical parametric amplifier (OPA) crystal (Fig. 1) The difference-frequency generation process in the second OPA generates the second idler pulse, which, under ideal conditions, has the exact temporal and spectral characteristics of the original signal pulse, except that all the pre- and post-pulses have been removed. This cascaded-OPA (COPA) technique has potentially infinite contrast enhancement, limited only by parametric fluorescence and how well idler and signal can be separated after each of the two cascaded OPA stages.

Due to the 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 makes the idler pulses not recompressible to Fourier transform-limited pulse durations in conventional CPA chains. However, when this idler is sent into the second OPA, the newly generated idler has only its even orders inverted back to their original value, so that it is potentially compressible

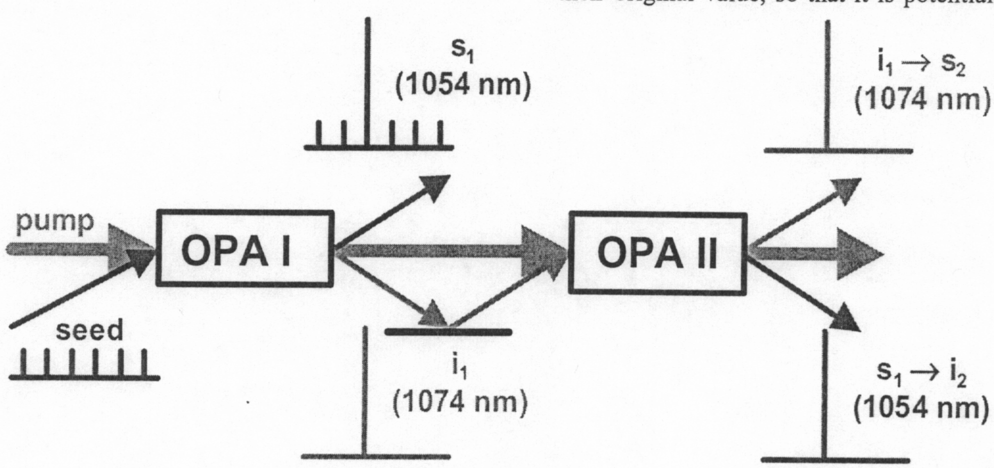

Fig. 1. The principle of cascaded-optical parametric amplification (COPA). The idler i_1 generated in the first amplification stage (OPA I) is amplified in the second amplification stage (OPA II) to generate idler i_2 with the original center wavelength and chirp consistent with compression in CPA. The signal beams s_1 and s_2 amplified in two OPA stages are discarded.

to Fourier transform-limited pulse duration, similar to the original signal pulse. The compressibility limit is determined by the total phase error accumulated from the pump phase aberrations in the first and second OPA, which leads to requirement for single-longitudinal pump mode.

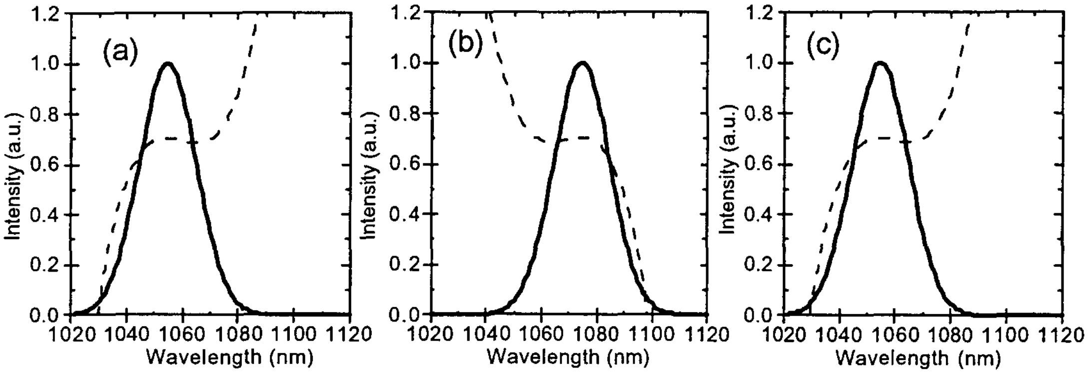

Fig. 2. Schematic of spectral phase dispersion in COPA with simulated input spectrum and exaggerated spectral phases. Due to the phase conjugation process, the sign of even orders of the spectral dispersion is inverted from the signal 1 (a) to the idler 1 (b), whereas the sign of dispersion of the odd orders is conserved. This makes the idler pulses not recompressible to Fourier transform-limited pulse durations. However, when this idler 1 is sent into a second OPA, the generated idler 2 (c) has only its even orders inverted back, so that it is potentially compressible to Fourier transform-limited pulse duration, just like the original signal pulse. The compressibility limit is determined by the phase accumulated from the pump phase aberrations in the two OPAs.

IV. EXPERIMENTAL RESULTS

In order to evaluate the contrast enhancement, we measured the intensity on a photodiode at the output of our stretcher and at the output of COPA. Starting from the 1:1 contrast of the oscillator pulse train, we measured a contrast enhancement of 77 dB with an OPA gain of 65 dB. (Fig. 3 (a)) Our measurements were limited by the signal-to-noise (S/N) ratio on the measurement of the oscillator pulse train. Furthermore, we studied a time-FFT transform of the oscilloscope traces (Fig. 3(b)) and obtained the ratio of the COPA-generated signal component to the component at 80 MHz (the repetition rate of the oscillator) to be 33 dB. We have a developed a scheme which will enable us to measure contrast enhancement from COPA up to 80 dB.

We measured the amplified spectrum of our COPA system when the OPA is driven into the high-conversion-efficiency regime, with output energies on the order of 3

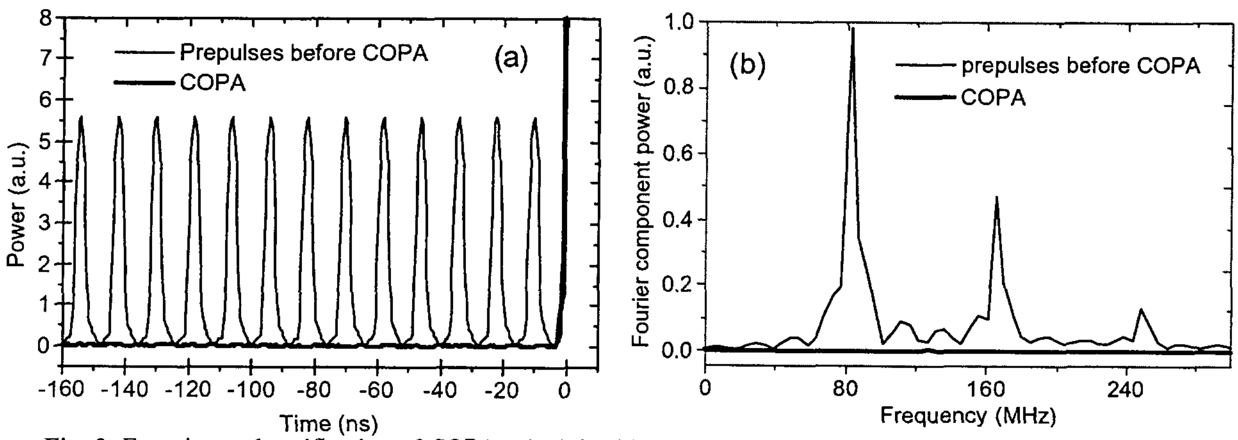

Fig. 3. Experimental verification of COPA principle. (a) Direct measurement of prepulses before and after COPA. (b) A FFT of the oscilloscope traces shows that the ratio of the signal amplitudes at ~80 MHz (the repetition rate of the oscillator) to background noise is at least 33 dB. From the measured dynamic range of the instrumentation and the gain of the COPA device, it is possible to estimate that prepulse contrast enhancement is greater than 6×10^{8}, in this first demonstration.

mJ. We observed spectral broadening (Fig. 4), consistent with our previous experimental observations.[9] Thus, in addition to contrast improvement and pulse amplification, COPA also broadens the pulse spectrum, which is beneficial for injection into subsequent gain-narrowing laser amplifier stages.

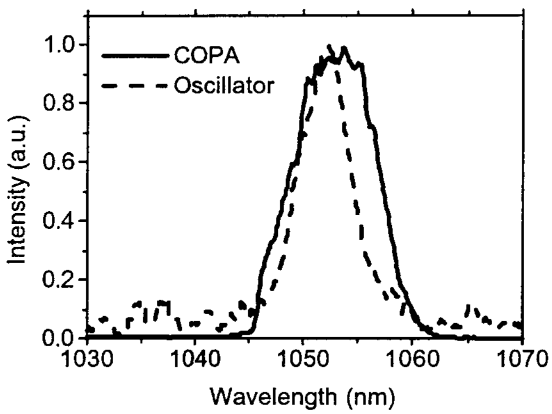

Fig. 4. Pulses produced by COPA operating in the high-conversion-efficiency regime are spectrally broadened

V. CONCLUSION

Numerous techniques have been pursued previously for enhancement of the prepulse contrast. They are usually limited by the contrast enhancement they provide. In most cases, they apply only to specific laser regimes: beam size, energy, pulse duration, and peak intensity. For example, Pockels cells, the most commonly used techniques to filter prepulses, are limited by the size and damage threshold of the crystal they use and have a limited spectral bandwidth. Moreover, most techniques utilize nonlinear effects which require high intensities and cannot be applied at low energy, such as just after the oscillator.

In conclusion, we developed and experimentally tested a new technique to remove all prepulses, enhancing the prepulse contrast by 77 dB without utilization of any electro-optic modulators. The major attraction of this technique is its versatility: since it does not rely on non-linear effects of the pulse itself, it can be operated at any energy level and with either stretched or compressed pulses. In the latter case, it could be used to remove ASE at the end of a laser chain. Finally, it can be used as a preamplification stage or as a high-contrast, large-bandwidth pulse selector when setting its overall gain to unity.

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