Contrast enhancement in a Ti:sapphire chirped-pulse amplification laser system with a noncollinear femtosecond optical-parametric amplifier

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We experimentally demonstrated the contrast enhancement in a Ti:sapphire chirped-pulse amplification (CPA) laser with a noncollinear femtosecond optical-parametric amplifier. A total gain of 3.4×10^4 and pulse energy of 26 μJ were achieved. With the clean high-energy seeding pulse, the contrast ratio of the main amplified laser pulse to the amplified spontaneous emission in the Ti: sapphire CPA laser system was improved to around 10^{10} within the time scale of hundreds of picoseconds. © 2010 Optical Society of America

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The remarkable progress of chirped-pulse amplification (CPA) technology [1] provides great opportunities for study of laser–matter interactions in the relativistic regimes with on-target intensity exceeding 10^{22} W/cm^2 in recent years [2]. For laser–matter interaction experiments at such an intense level, one of the most important factors is the temporal contrast (referred to as *contrast* henceforth) of the pulses. The contrast, defined as the ratio of the intensity of peak pulses to that of prepulses or background in different temporal ranges, is required as high as 10^{10} to prevent preplasma dynamics [3].

High-peak-power laser systems suffer mainly from three kinds of prepulse: nanosecond amplified spontaneous emission (ASE), prepulses introduced by the incomplete compensation of higher-order dispersion, and limited extinction ratio of polarized elements in a regenerative amplifier [4]. The time scale of the prepulses introduced by the residual dispersion is generally in the range of tens of picoseconds prior to the onset of the main pulse, so that it does not sufficiently affect the laser–matter interaction dynamics. Nanosecond prepulses can be removed by external techniques, such as utilization of Pockels cells. To suppress the ASE, several pulse-cleaning techniques have been reported. For example, in 1998, Itatani *et al.* increased the ASE contrast by 2 orders from 10^5 to 10^7 with saturable absorbers [5]. In particular, contrasts as high as 10^{10} to 10^{11} have been achieved by using cross-polarized wave generation [6,7], nonlinear polarization rotation [8,9], and double CPA [9]. In addition, the contrast can be further increased by about 2 orders by setting a plasma mirror after the final compressor [10].

Compared with the amplification in laser media, optical-parametric chirped-pulse amplification (OPCPA) [11] exhibits many attractive properties, such as high single-pass gain, no ASE accumulation, lower thermal load on nonlinear crystals, and ultrabroad-gain bandwidth. In principle, it supports an even higher contrast. However, because of the parametric superfluorescence within the time window defined by a pump laser on hundreds of picoseconds time scale [12,13], the contrast of the conventional OPCPA systems can be significantly degraded. To improve the contrast in the tens of picoseconds region, the pump laser should be as short as possible. Although some OPA schemes [14,15] have been successfully realized and high contrast has been demonstrated for Nd:glass laser systems at a 1053 nm central wavelength, it may be not applicable for Ti:sapphire-based CPA systems because of the limited bandwidth. Therefore, noncollinear OPA (NOPA) [16], in which the signal generated directly from the oscillator is pumped by a nonchirped pulse with femtosecond duration could be a more attractive solution for contrast enhancement in Ti:sapphire CPA systems.

In this Letter, we report a novel near-degenerative NOPA technique for contrast enhancement in a Ti:sapphire CPA laser system. Because the signal and pump pulses are derived from the same pulse, they can be synchronized with minimal timing jitter. Although environmental fluctuation may lead to a timing jitter between the pump and signal pulses, the jitter will be less than a few femtoseconds. By using two stages of NOPAs, the extracted signal pulse energy is 26 μJ. After further amplification by the second CPA setup, we measured that the ASE contrast was enhanced to around 10^{10} within time scale of hundreds of picoseconds. The spectral width (FWHM) after subsequent amplification is 41 nm, which may support pulse duration of shorter than 30 fs. This method could also be used in combination with other pulse-cleaning methods, and higher contrast could be expected.

The schematic experimental setup is shown in Fig. 1. A homemade mode-locked Ti:sapphire oscillator (4 nJ, 80 MHz) pumped by an Nd:YVO_4 intracavity frequency-doubled cw laser (Millennia, Spectra Physics Inc.) is used as the seeding source for the experiment. Stable sub-10 fs laser pulses with a central wavelength of 800 nm are generated at a repetition rate of 80 MHz, corresponding to pulse energy of 4 nJ. A splitter with a bandwidth of about 200 nm is used to divide the laser beam into two parts with energies of 70% ($\sim$3 nJ) and 30% ($\sim$1 nJ), respectively. The 70% is used as the seed for the first CPA

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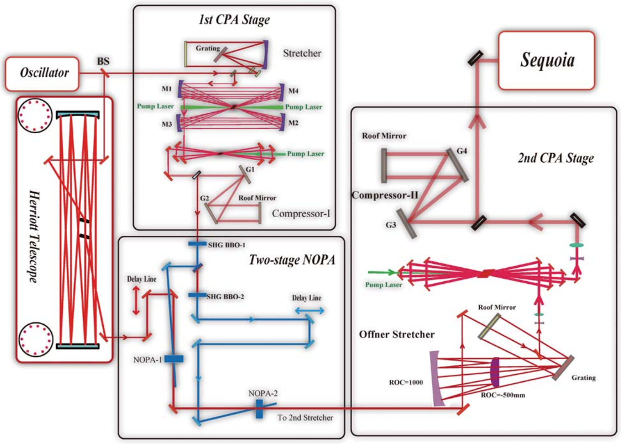

Fig. 1. (Color online) Schematic experimental setup of the femtosecond NOPA.

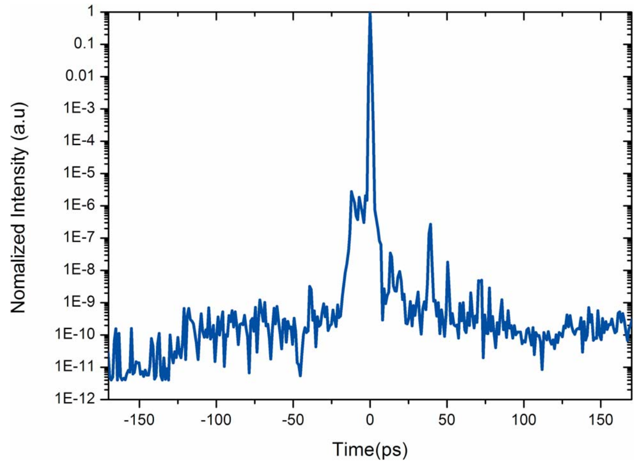

Fig. 2. (Color online) Contrast ratio of the amplified NOPA pulse within time scales from −170 to 170 ps.

stage. The other 30% is used as the signal of two-stage NOPA.

A grating-based stretcher to expand the pulse duration to ∼200 ps first temporally stretches the seeding pulse for the first CPA stage. Then it is amplified to 8 mJ by two multipass amplifiers, which are pumped by a commercial 10 Hz 532 nm Q-switched laser (Quanta-Ray Pro, Spectra Physics Inc.). The first amplifier is designed in ten-pass as the preamplifier, and the second one is designed in four-pass as a boost amplifier. Finally, the amplified laser pulse is compressed to ∼50 fs by a compressor, which consists of two 1480 line/mm diffraction gratings and a retroreflector. The compressed pulse energy is about 4 mJ, corresponding to a transmission efficiency of 50%. Following the first CPA, the 4 mJ laser is frequency doubled by a Type I β-BaB_2O_4 (BBO-1) crystal (Fujian Castech Inc.) to generate a second-harmonic pulse with energy of up to 500 μJ for pumping the first NOPA. The residual fundamental wave from the BBO-1 is further frequency doubled by another Type I β-BaB_2O_4 (BBO-2) crystal to produce another second-harmonic pulse with energy of up to 500 μJ for the next stage pumping. The fundamental central wavelength from the first CPA stage is 810 nm and the second-harmonic generation wavelength is subsequently around 405 nm.

The delay between the signal pulse and the pumping pulse of NOPA is accurately controlled by a Herriott telescope [17], which consists of a plane mirror and a concave mirror with 16 m radius of curvature. The distance between the two mirrors is 1.2 m. To make sure that the input and output beam spot sizes are as similar as possible, the q value of the telescope is set to be constant; therefore, no extra beam collimation is needed. The signal pulse travels 24 times inside the telescope, and the total optical length is about 30 m. Because of the reflection loss, the energy of the signal pulse arriving at the first NOPA crystal is reduced to 750 pJ. To boost the laser energy, a two-stage NOPA system is utilized. Two pieces of $10\ \text{mm} \times 10\ \text{mm} \times 3\ \text{mm}$ BBO crystal cut for Type I phase-matching ($\theta = 28.9°$, $\varphi = 0°$) are utilized in both NOPA stages. The spot sizes of signal and pump are matched to 3 mm in the NOPA crystals, and the internal noncollinear angle is 3.7°. The total gain of the two-stage NOPA is 3.4×10^4 and the amplified signal energy is 26 μJ. Because the nonlinear process between the signal and the pump pulse occurs on a time scale of tens of femtoseconds in our NOPA system, the background noise is far beyond this time range and cannot be amplified. Consequently, the improvement factor of the signal contrast is approximately equal to the gain.

In general, the contrast ratio of laser pulses generated from the oscillator is about 10^{6-7} [18]; thus, we can infer that the contrast ratio of the amplified pulse from NOPAs would be 10^{10-11}. To demonstrate the enhancement ability of the NOPA experiment, we further amplify the laser pulse by using the second CPA stage to characterize the pulse contrast, where the clean high-energy pulse is expanded by an Öffner-triplet stretcher and then amplified to ∼10 mJ by a multipass amplifier. After compression by the second grating pair compressor, the contrast is measured by a third-order scanning cross correlator (Sequoia, Amplitude Technologies) with a dynamic range of approximately 10^{11}. Figure 2 shows the typical result; the contrast ratio is around 10^{10} within the time scale of 100 ps. They are still higher than 10^9 and 10^7, within the scales of 30 and 15 ps, respectively. The degradation of the contrast ratio around −15 ps is due to the ASE, similar to the phenomena in [11]. The decreased contrast ratio compared with that of the oscillator is due to ASE generation in the subsequent multipass amplification, which has a gain factor of $\sim 10^3$. Figure 3(a) is the spectrum after the subsequent amplification. It shows that the FWHM spectral width is 41 nm, which supports a recompressed pulse of shorter than 30 fs, as shown in Fig. 3(b). The beam profile was measured with a commercial beam

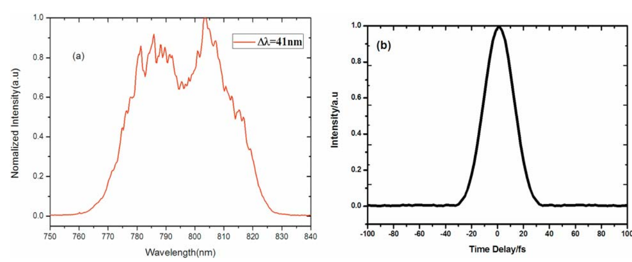

Fig. 3. (Color online) (a) NOPA spectrum after subsequent amplification and (b) the corresponding pulse duration.

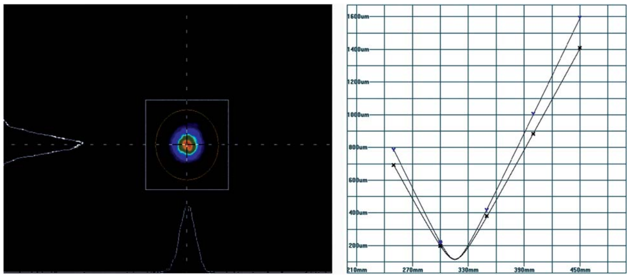

Fig. 4. (Color online) Far-field beam profile and M^2 factor of the NOPA signal after subsequent multipass amplification in the second CPA stage as measured by a commercial beam analyzer (Spiricon M^2, 200 s).

analyzer (Spiricon M^2, 200 s). Figure 4 shows the far-field beam profile and M^2 factor of the NOPA signal after subsequent multipass amplification in the second CPA stage. The calculated M^2 factor is ${M_x}^2 = 1.128$, ${M_y}^2 = 1.105$, which is good for subsequent amplification in a terawatt laser system.

In conclusion, we have experimentally demonstrated a novel contrast enhancement technique based on using a femtosecond NOPA as seeding source. Gained by a factor of 3.4×10^4 with two NOPA stages, the boosted signal energy was $\sim$26 μJ. By further amplification of the second CPA stage, measurement shows that the ASE contrast ratio is enhanced to around 10^{10} within the time scale of hundreds of picoseconds. Such a contrast ratio value is sufficient for the high-field experiments of plasma physics at a peak intensity of 10^{21} W/cm^2. In addition, this NOPA scheme well overcomes the gain-narrowing effect, and a broad bandwidth of up to 41 nm (FWHM) is obtained with recompressed pulse duration shorter than 30 fs. We believe that the novel NOPA design can be employed as a high-energy and high-contrast front end for a high-intensity Ti:sapphire- or Nd:glass-based CPA system.

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