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High-Stability High-Energy Picosecond Optical Parametric Chirped Pulse Amplifier as a Preamplifier in Nd:Glass Petawatt System for Contrast Enhancement *

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We demonstrate a novel picosecond optical parametric preamplification to generate high-stability, high-energy and high-contrast seed pulses. The 5 ps seed pulse is amplified from 60 pJ to 300 μJ with an 8.6 ps/ 3 mJ pump laser in a signal stage of short pulse non-collinear optical parametric chirped pulse amplification. The total gain is more than 10^6 and the rms energy stability is under 1.35%. The contrast ratio is higher than 10^8 within a scale of 20 ps before the main pulse. Consequently, the improvement factor of the signal contrast is approximately equal to the gain 10^6 outside the pump window.

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The ultra-short and ultra-intense laser system generates an intensity at the focus as high as 10^{21} W/cm^2, which meets the requirement of preplasma formation for target modification.[1,2] Temporal contrast of pulse, a main bottleneck for high-intensity laser-matter interaction, should be as high as 10 orders of magnitude in tens of picoseconds to restrict destructive pre-plasma dynamics.[3] Optical parametric chirped pulse amplification (OPCPA) which combines the advantages of chirped pulse amplification (CPA) and optical parametric amplification (OPA) has high single pass gain, low ASE noise and slight thermal deposition on crystals. Then OPCPA is an attractive technique which helps to improve the temporal contrast and to reduce the noise of a petawatt system by shackling parametric fluorescence (PF) in picosecond duration.[4−6] The high-contrast optical-parametric amplifier serving as a front end of a high-power laser system has been proposed by Dorrer, University of Rochester. A gain larger than 10^5 and measurement-limited contrast than 10^{11} has been obtained by this method, which means that it is a good choice for the seed source for high-power laser systems.[7] The Orion and Vulcan Petawatt laser facility in the UK has constructed a single stage of picosecond OPCPA amplification before the main stretcher. The gain of nanosecond OPCPA is reduced by operating only two of the three stages to provide a small-signal gain of 10^3, rather than the usual 10^8. This method has demonstrated a nanosecond ASE contrast improvement by more than 2 orders of magnitude.[8,9] Meanwhile, the Texas Petawatt laser system is also to eliminate the fluorescence pedestal with a short pulse OPCPA before the stretcher for contrast enhancement. The design of a short pulse OPCPA with 10^5 gain reduces PF by 10^5 outside the 10 ps pump window to clean 10 ps–4 ns range noise.[10] The proposal of the front-end of the Appollon laser system, a 10 petawatt class high-repetition-rate laser system, also provides a design of high gain OPCPA pre-amplification in the picoseconds regime to improve the contrast ratio by the gain factor and low gain OPCPA main amplification in the nanosecond regime.[11] In general, high-contrast and high-energy picosecond OPCPA as a preamplifier in the high-power laser system is a promising tendency of enhancing the contrast ratio.

In this Letter, we demonstrate a novel picosecond optical parametric preamplifier to generate high-contrast and high-energy seed pulses for the SGⅡ Nd:glass petawatt system based on a high-intensity picosecond pump laser system we reported before.[12] Compared with the current petawatt system, as higher energy pulses are generated at the front end when using our picosecond optical parametric preamplifier, one of the three nanosecond amplifiers in the next stage of the petawatt system can be removed and these nanosecond amplifiers can work in lower gain mode to reduce ASE noise. In addition, the contrast can be improved from 10^6 to 10^8, which will be helpful for restricting PF noise in picosecond duration. The output parameters of parametric amplified pulse are as follows: the pulse energy is more than 300 μJ, the gain is 10^6, the contrast within the scales of 20 ps is 10^8, 87% of the far-field beam is cumulated in 1 mrad, and the Strehl ratio is 0.8. Thus this highest level system can meet the needs of engineering requirements as a preamplifier in the Nd:glass petawatt system for contrast enhancement.

The schematic experimental setup is shown in Fig. 1. A homemade all-fiber Yb-doped mode-locked

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laser, achieved through nonlinear polarization evolution (NPE) along with spectral filtering, is used as the seeding source for the picosecond OPCPA experiment. Stable 21.5 ps linear chirped pulses, with a central wavelength of 1053 nm and a spectral bandwidth of 6 nm, are generated at a repetition rate of 15.2 MHz, and the corresponding pulse energy is 0.6 nJ. High precision synchronization of picosecond time-domain OPCPA demands the same seed pulse for signal and pump pulses, and the spectral width of the pump must be at least 10 times narrower than that of the signal pulse in OPCPA.

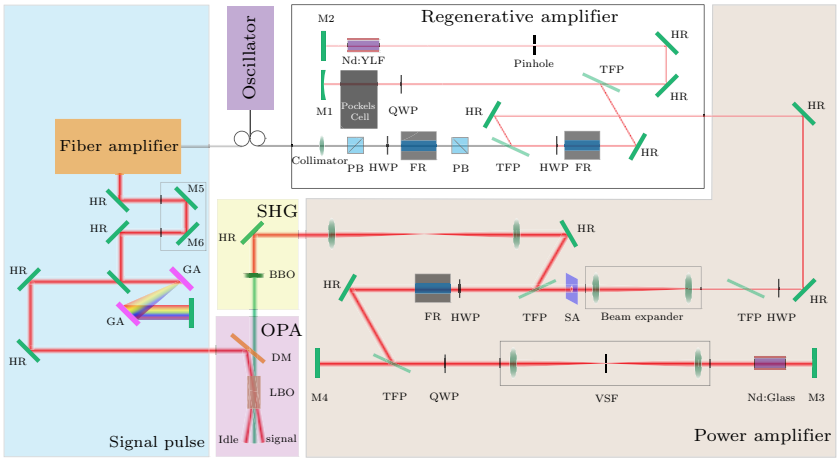

Fig. 1. Schematic experimental setup of picosecond optical parametric chirped pulse amplification. PB: polarizing beam splitter; HWP: half wave plate; TFP: thin film polarizer; QWP: quarter wave plate; FR: Faraday rotator; HR: high reflector; M1–M6: mirror; SA: serrated aperture; GA: grating; and DM: dichroic mirror.

A splitter is used to divide the laser beam into two parts with energies of 60% (360 pJ) and 40% (240 pJ). The beam of 60% energy is served as the seed of the pump for short pulse OPCPA, and the pump pulse system is MOPA, which consists of three major components, i.e., a Nd:YLF regenerative amplifier, a power amplifier and a frequency doubler. The diode pumped Nd:YLF regenerative amplifier (1 Hz, 60 dB gain) is used as the first stage amplifier to generate narrow-band high power laser by taking advantage of the gain narrowing effect. The output bandwidth is 0.3 nm and the pulse duration is 8.6 ps. The energy of 1.5 mJ and fluctuation of 0.8% (rms) are achieved by a stable regenerative amplifier, which employs a three-steel-rod structure to mount the cavity. The beam is spatially shaped to a round top hat by a 3-mm-diameter serrated aperture (SA) for increasing energy conversion efficiency and avoiding the self-focusing effect because of high peak power before the power amplifier. The serrated aperture plane becomes the reference plane. For ensuring the good beam quality, it is relay-imaged onto M3, back to M4, then onto the frequency doubled crystal and finally onto the parametric amplified crystal by another pair of lenses (both $f = 1m$, not shown in Fig. 1). The power amplifier is an LD pumped four-pass Nd:glass amplifier instead of the widely used Nd:YLF amplifier, owing to the fact that the Nd:glass material is more suitable for four-pass amplifying but still obtains a good beam quality. The maximum output energy is 8 mJ with an excellent top flat profile.[13] Finally, the amplified laser pulse is frequency doubled by a 2-mm type-I BBO crystal (Fujian Castech Inc.) to generate a second-harmonic pulse with energy of up to 4.6 mJ for pumping the picosecond short pulse OPCPA. The beam of 40% energy is used as the seed of the signal pulse for the short pulse OPCPA. The fiber amplifiers are used to amplify the signal pulse. As our homemade all-fiber Yb-doped mode-locked laser which generates stable 21.5 ps linear chirped pulses, the pulse should be pre-compressed before optical parametric amplification to match the pump pulse width instead of broadening when using commercial femtosecond lasers. Thus a grating-based pre-compressor is used to compress the pulse duration to 5 ps for matching the pump time window. The signal pulse delay is controlled to match the delay of the pump, mainly by a timing slide (mirrors M5 and M6) and accurately by a variable optical delay line (AFR, Ltd.) with an optical path variation of more than 15 cm (500 ps), which means about 3 ps in a minimal step. The spot sizes of Gaussian-shaped signal beam and flat-top-shaped pump beam are matched to 3 mm in the 25 mm LBO crystal (AR: 1053–527 nm, 3° wedged, X–Y plane used, Fujian Castech Inc.) for type-I phase-matching, and a small 0.4° (internal angle) non-collinear angle is employed, thus the signal and idle beams can be separated. The 300 μJ parametric amplified pulse is achieved with the pump energy of 3 mJ for high output energy stability consideration, representing a conversion efficiency of 10%. The output energy stability is less than 1% (rms) and the total gain of non-collinear OPCPA is more than 10^6. The high gain and high-energy parametric amplified pulses as seed pulses will be injected into the exiting SGⅡ PW nanosecond amplification system. Because the nonlinear process between the signal pulse and the pump pulse occurs on a time scale of tens of picoseconds in the short pulse OPCPA system, the background noise

is far beyond this time range and thus cannot be amplified. Consequently, the improvement factor of the signal contrast is approximately equal to the gain. In other words, gain of 10^6 reduces fluorescence by 10^6 outside the pump window.

Considering the non-collinear case which helps to separate the pump and the signal laser in calculation, the k-vectors of the signal, the idler and the pump laser have the relations to satisfy energy and momentum conservations,[14]

$$\boldsymbol{k}_{\rm p} = \boldsymbol{k}_{\rm s} + \boldsymbol{k}_{\rm i}, \tag{1}$$

$$\Delta k = k_{\rm p} - k_{\rm s}\cos\alpha_{\rm s} + k_{\rm i}\cos\alpha_{\rm i}, \tag{2}$$

where the subscripts s, i and p refer to the signal, idler and pump waves, respectively, Δk is the phase mismatch per unit length in the pump light direction, and α is the angle between the signal or the idler and the pump light direction. They have a relationship as

$$\alpha_{\rm i} = -\arcsin\left(\frac{n_{\rm s}\lambda_{\rm i}}{n_{\rm i}\lambda_{\rm s}}\sin\alpha_{\rm s}\right). \tag{3}$$

The refractive indexes $n_{\rm po}$ and $n_{\rm pe}$ can be calculated according to the Sellmeier equations and the LBO crystal match angle of type-I matching. The match angle can be calculated by

$$\theta_m = \arcsin\left[\frac{n_{\rm p}^{-2} - n_{\rm po}^{-2}}{n_{\rm pe}^{-2} - n_{\rm po}^{-2}}\right]^{\frac{1}{2}}. \tag{4}$$

When the pump laser transmits inside the crystal, it will suffer from the walk-off effect. The pump walk-off angle can be written as

$$\rho_{\rm p} = \frac{1}{2}n_{\rm po}^2\left(\frac{1}{n_{\rm pe}^2} - \frac{1}{n_{\rm po}^2}\right)\sin(2\theta_m). \tag{5}$$

However, the walk-off angle of the pump beam is calculated to be 0.42°, the match angle is about 12.2°, and the angle between the signal beam and the pump beam is set as $\alpha_{\rm s} = 0.42°$, which aims to decrease the influence of the walk-off effect. The coupled wave equations for OPA can be written as

$$\frac{\partial E_{\rm s}}{\partial z} + \tan\rho_{\rm s}\frac{\partial E_{\rm s}}{\partial y} + \frac{1}{\cos\alpha_{\rm s}}\frac{1}{v_{gs}}\frac{\partial E_{\rm s}}{\partial t} + a_{\rm s}E_{\rm s} = \frac{-i\omega_{\rm s}d_{\rm eff}}{n_{\rm s}c\cos\alpha_{\rm s}}E_{\rm p}E_{\rm i}^{*}e^{-i\Delta kz}, \tag{6}$$

$$\frac{\partial E_{\rm i}}{\partial z} + \tan\rho_{\rm i}\frac{\partial E_{\rm i}}{\partial y} + \frac{1}{\cos\alpha_{\rm i}}\frac{1}{v_{gi}}\frac{\partial E_{\rm i}}{\partial t} + a_{\rm i}E_{\rm i} = \frac{-i\omega_{\rm i}d_{\rm eff}}{n_{\rm i}c\cos\alpha_{\rm i}}E_{\rm p}E_{\rm s}^{*}e^{-i\Delta kz}, \tag{7}$$

$$\frac{\partial E_{\rm p}}{\partial z} + \tan\rho_{\rm p}\frac{\partial E_{\rm p}}{\partial y} + \frac{1}{\cos\alpha_{\rm p}}\frac{1}{v_{\rm gp}}\frac{\partial E_{\rm p}}{\partial t} + a_{\rm p}E_{\rm p} = \frac{-i\omega_{\rm p}d_{\rm eff}}{n_{\rm p}c}E_{\rm s}E_{\rm i}e^{i\Delta kz}, \tag{8}$$

where E is the electric field, $d_{\rm eff}$ the effective mixing coefficient, c the velocity of light in vacuum, ρ the walk-off angle, $v_{\rm g}$ the group velocity, and a the linear loss in the crystal. The second terms of these equations are induced by the walk-off effect and the fourth terms are induced by absorbing loss in the crystal. Transferring the second, third and fourth terms into spatial frequency domain, we can simplify the equations and use the fourth-order Runge–Kutta method to solve the coupled wave equation numerically.

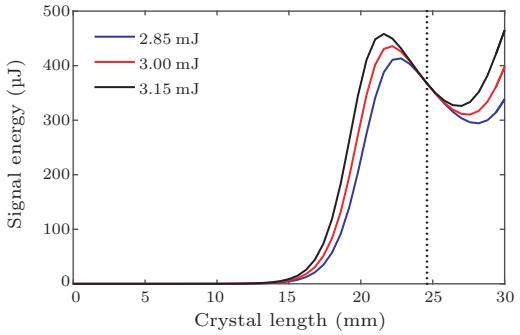

Fig. 2. The calculated output signal beam energy versus the crystal length. When changing the input pump energy for 5%, the different curves obtain a convergence point that indicates the appropriate crystal length choice.

In the simulation, the super-Gaussian model is used to simulate the spatial and temporal profiles. For the pump beam, the spatial profile is a 10-order Gaussian distribution and the temporal one is a 1-order Gaussian distribution. For the signal beam, the 1-order Gaussian model is used for both. The energy, pulse widths and beam sizes of the pump and signal beam are determined according to the experimental data. The pump beam is monochromatic and the signal beam becomes an initial chirp parameter to form a 6-nm spectral width numerically.

Figure 2 shows the calculated signal energy along the crystal length. By intersecting the curves of signal laser energy changed with the crystal length when the pump laser energy fluctuates for 5%, we can determine the appropriate crystal length, and we finally choose a 25-mm length near the stability region for OPA. At the end of the crystal length, the signal laser amplifier is slightly supersaturated and the gain is about 10^6.

Figure 3 plots the temporal and spectra profiles of the pump pulse and the amplified signal pulse. Simulation shows that the conversion of signal laser and pump laser is reversed in the pulse center, which also shows that 25 mm length is the slightly over-saturated point for the crystal. After OPA, the full width at half maximum (FWHM) of the amplified signal laser spectrum is about 6 nm.

Then we measure the parameters of the output signal pulse. Figure 4(a) is the spectrum after the picosecond OPCPA. It shows that the FWHM of the spectrum is 6 nm, measured with a spectrum analyzer (Ocean Optics) with a resolution of 0.15 nm. After enough transmission distance, the separated parametric amplified is compressed by a pair of gratings. The transform limited pulse width should be about 300 fs and the measured compressed one is 414 fs, as shown

in Fig. 4(b). The contrast is measured by a third-order scanning cross correlator (Sequoia, Amplitude Technologies) with a dynamic range of approximately 10^{11} when the input pulse is with a pulse duration of 30 fs and a pulse energy of 200 μJ. Therefore, when our parametric amplified pulse energy is 180 μJ and its pulse duration is 414 fs, the measured dynamic range is only 10^8. Figure 5 shows that our contrast ratio is higher than 10^8 within the scales of 20 ps before the main pulse, which is limited by the measure dynamic range. The PF should be limited in the duration of pump pulse of short pulse OPCPA, which is less than 10 ps. The peaks at −50 ps, −80 ps, etc. have the intensity of about 10^7 to 10^6, which are due to the multi-reflection of the thin glass plate as reference pulse and will be improved after pulse cleaning.[15] The decreased contrast ratio around −10 ps is due to the imperfect dispersion compensation of compressed gratings.

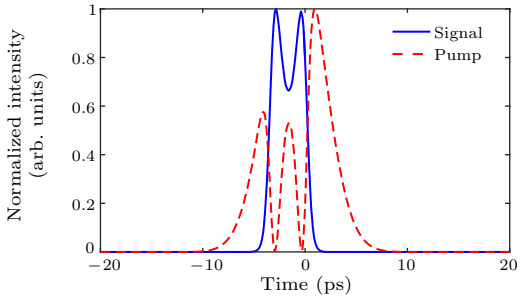

Fig. 3. Temporal profiles of the pump pulse (red line) and amplified signal pulse (blue line). The depression in the peak of the signal pulse shows a slight super-saturation.

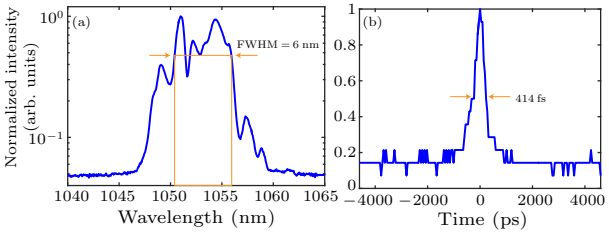

Fig. 4. (a) Parametric amplified pulse spectrum. (b) The compressed pulse duration with the method in Ref. [16].

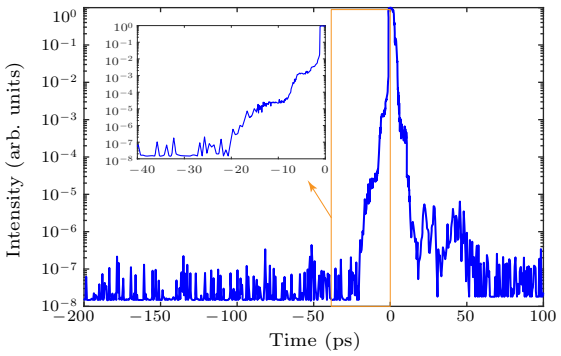

Fig. 5. Contrast ratio of the compressed parametric amplified short pulse OPCPA within timescales from −200 ps to 100 ps. The curve in the red box is plotted on the top left to show the data detail between −40 ps and −20 ps before the main pulse. The contrast ratio is at the level of 10^8 within this timescale of 20 ps.

The near-field profile and wavefront of the parametric amplified pulse were measured with a wavefront sensor (PHYSICS, SID4), as shown in Figs. 6(a) and 6(b). The profile seems to be in low resolution as the spot aperture is small to be 3 mm in diameter. The wavefront is below 0.25λ, indicating a good far field. The beam far-field energy can be calculated from the near-field data. Figure 6(c) shows the energy concentration rate curve of the focal spot, and 87% beam energy is cumulated in 1 mrad, and the Strehl ratio is 0.8, which is good for subsequent amplification in a petawatt laser system.

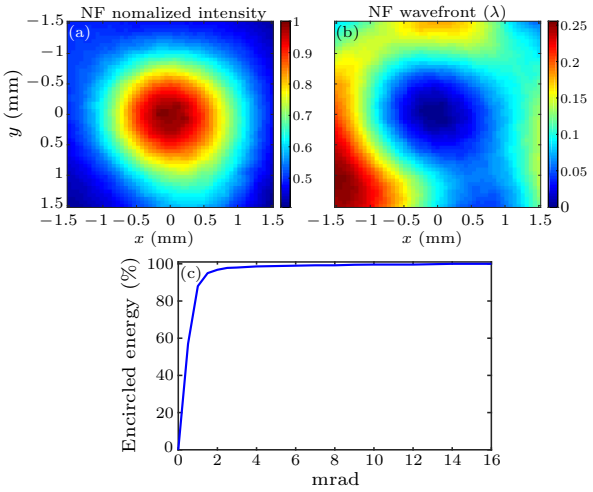

Fig. 6. (a) Near-field beam profile of parametric amplified pulse. (b) Wavefront of parametric amplified pulse. (c) Far-field beam encircled energy of parametric amplified pulse.

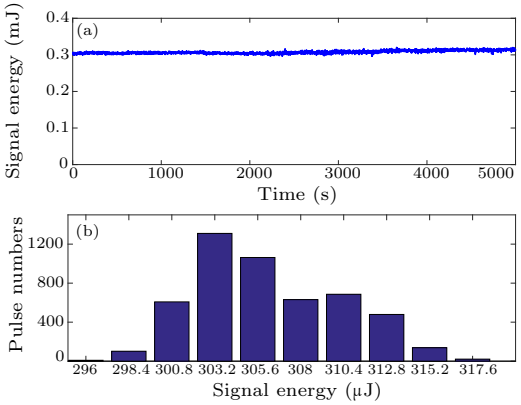

Fig. 7. Signal pulse energy in 5000 shots: (a) the laser system works under 1 Hz repeat frequency and gives an output signal laser with energy of about 307 μJ, and (b) the histogram of pulse numbers shows that more than 90% of the pulses are distributed from 300 μJ to 315 μJ.

The mean value of the output signal energy is 307 μJ, which is below the simulated energy, maybe due to the energy loss and the angle deviation in the experiment. To test the stability of the output signal pulse, after separating it out by two dichroic mirrors and about a 2-meter distance transmission, we measured the energy of 5000 sequent pulses (one pulse per second) using a pyroelectric energy sensor (THORLABS, ES111C) and show the results in Fig. 7.

Though the curve has a slightly rising tendency, the standard deviation is μJ, about 1.35% of its mean value, which means that the OPCPA system has a good energy stability for series of pulses in a temporary time.

In conclusion, a novel high stability and high-energy picosecond optical parametric chirped pulse amplification is demonstrated. Common seed for signal and pump pulses ensures the high precision optical synchronization. The pump pulse of 3 mJ and 8.6 ps with 3 mm diameter round top hat supports the high gain of 10^6 for the short pulse OPCPA. The 5 ps seed pulse is amplified from 60 pJ to 300 μJ in a signal stage of short pulse non-collinear OPCPA. The output spectral width is 6 nm and the compressed pulse width is 414 fs, close to the Fourier transformation limitation. The energy stability of amplified pulse is less than 1.35% of its mean value. The contrast ratio is higher than 10^8 within the scales of −20 ps. The contrast can be significantly improved by providing 10^6 gain of the un-stretched pulse with about 10 ps pump pulse.

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