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Generation of Femtosecond Laser Pulse at 1053 nm with Contrast of 10^{-11} by Optical-Parametric Amplification *

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A high contrast 1053 nm femtosecond laser pulse with free background is demonstrated based on non-collinear optical-parametric amplification (NOPA). By permuting the signal and idler in two stages of NOPAs, 48.2 fs, 62 µJ laser pulse at 1053 nm with contrast ratio of 2.3×10^{-11} is obtained within the time scale of sub-5 ps. The beam quality factors M^2 for tangential and sagittal directions are 1.59 and 1.30, respectively. This work not only proves a feasible way to generate a clean femtosecond laser pulse but can also be employed as an ideal frontend for ultrashort ultrahigh intensity Nd:glass-based laser systems.

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Following the remarkable recent progress of chirped-pulse amplification (CPA) technology,[1] laser peak power has exceeded petawatt (PW) scale[2−4] and the on-target intensity of ultrashort intense laser has reached 10^{22} W/cm.^{2} [5] At these relativistic intensities, one of the major challenges is the capability of achieving very clean pulses with an extremely high contrast ratio. The pulse contrast, which is defined by the ratio between the intensity of the pre-pulse or pedestal and that of the main pulse, is therefore one of the most important parameters of a high-intensity laser system. In particular, the high contrast ultrashort laser pulse at 1053 nm is attracting wide interest because it can seed the high energy Nd:glass laser facility for driving inertial confinement fusion.[6,7]

Up to now, several pulse-cleaning techniques have been proposed in order to improve the contrast, including saturable absorber,[8] nonlinear polarization rotation,[9] cross-polarized wave generation (XPW),[10] Double-CPA,[11] optical-parametric chirped-pulse amplification (OPCPA),[12] etc. The OPCPA technique offers significant advantages over other schemes, such as broad gain bandwidth, high single-pass gain, no ASE accumulation, low thermal effect. Conventionally, laser pulses with pulse durations of nanosecond to tens of picosecond are utilized to pump the temporal stretched seed pulse in OPCPA, so that the main amplified pulse will still be accompanied by the parametric superfluorescence extending over the temporal window that is defined by the pump laser, and the contrast will significantly degrade in that time scale.[13] For example, although a contrast ratio of 10^{-11} is achieved in these experiments, it quickly drops to 10^{-6} level in the time scale of less than 50 ps before the main pulse. Recently, an OPA pumped by ultrashort femtosecond pulse has been used to enhance the contrast in the region of tens of picosecond.[14,15] Especially, under undepleted pump and small-signal gain approximation the idler exhibits higher contrast than the amplified signal, and the contrast can be enhanced from R to R^3 by combining second-harmonic generation and OPA.[16,17]

In this Letter, we demonstrate a method to generate high contrast 1053 nm ultrashort laser with a free background based on non-collinear optical-parametric amplification. The pump laser is the second harmonic pulse of a CPA Ti:sapphire laser, and the initial signal is generated from white-light continuum (WLC). By permuting the signal and idler in two stages of NOPAs, a 48.2 fs laser pulse at 1053 nm with contrast ratio of 2.3×10^{-11} is obtained, extending within less than 5 ps before the peak of the pulse.

The NOPAs system for high contrast 1053 nm femtosecond laser generation is schematically shown in Fig. 1. A homemade Ti:sapphire regenerative amplifier was employed in the experiment, providing 2.3 mJ/40 fs/1 kHz pulses at 800 nm. A piece of 1-mm-thick β-BaB2O4 (BBO) crystal (Fujian Castech Inc.), cut at $\theta = 28.9°$ for type-I phase matching, was used to generate second harmonic pulses at 400 nm. The conversion efficiency of SHG was about 30%. After the frequency was doubled, a dichroic mirror BS1 was used to transmit 400 nm laser and reflect 800 nm laser. A beam splitter BS2 was utilized to divide the 700 µJ at 400 nm laser beam into two parts with energies of 30% (∼210 µJ) and 70% (∼490 µJ), which were used as the pump laser of two stages of NOPAs, respectively. On the other hand, the reflected resid-

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ual 800 nm laser pulse, whose energy was changed by a combination of a half-wave plate and a Glan prism, was focused into a 2-mm undoped YAG plate to generate the stable WLC.[18] Then, the WLC was collimated by a lens L2. After that, three mirrors with high-reflective coating at 1053 nm were used to extract the initial signal from WLC.

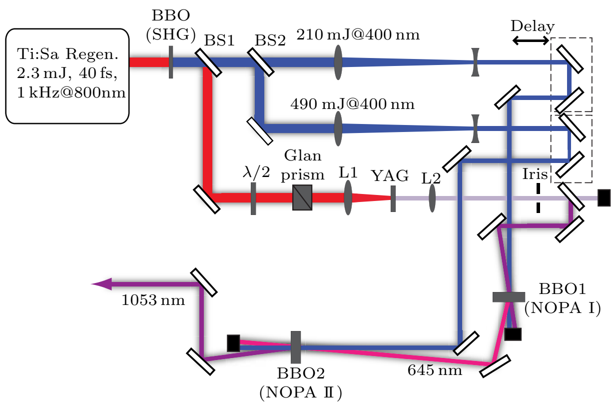

Fig. 1. (Color online) The schematic layout of the NOPAs system.

Two pieces of 7 mm × 7 mm×3 mm BBO crystals (Fujian Castech Inc.) cut for type-I phasematching ($\theta = 28.2°$, $\phi = 0°$) were used in two stages of NOPA. The spot sizes of signal and pump were matched to 2 mm in the crystals. A slight noncollinear angle of $\sim$1° was set between the signal and pump pulses, which allowed separation of the signal and idler, and which also meant that the sufficiently small angular dispersion could be neglected. After fine alignment, the 1053 nm initial signal was amplified, accompanied by the generation of the idler pulse with central wavelength of 645 nm. The idler pulse carrying the remainder of the pump photon energy was only generated within the pump pulse duration. Consequently, the idler pulse will not have a background leading to superior temporal contrast. The energy of the 645 nm idler pulse was 11 µJ under the pump energy of 210 µJ. To increase the energy we sent the idler pulse into the second OPA stage. The idler pulse of the first stage, which was background-free, was now the seed pulse of the second stage and was amplified by another pump beam. Therefore, the idler generated in the second OPA stage was shifted back to 1053 nm, and its prepulses outside the time window defined by the main pulse had been removed. Pumped with energy of 490 μJ at 400 nm, the 1053 nm idler pulse with free background was boosted to 62 µJ, which corresponds to the conversion efficiency of 12.7%.

In order to demonstrate the high contrast property of idler pulse, contrast measurements were carried out by a scanning third-order cross correlator (Sequoia, Amplitude Technologies). Figure 2 presents the compared contrast ratios. The contrast of the regenerative amplifier (red dashed curve) is only 10^6, and it is worse in several picoseconds before the main pulse. This happens because of the amplified spontaneous emission (ASE) in the CPA system. By permuting the signal and idler in two-stage NOPAs, the contrast of the 1053 nm idler pulse (black solid curve) in the second OPA stage reaches 2.3×10^{-11} over a temporal range from −35 ps to 35 ps. No pedestals are observed, even though the time scale is extended to several picoseconds before the main pulse. The prepulses in 27 ps before the main pulse are due to multiple reflections in the cross correlator and are of no practical concern. The contrast of idler pulse here is still limited by the dynamic range of the Sequoia (typ.10^{10}). It may reach a much higher level without the limitation of the measuring device.

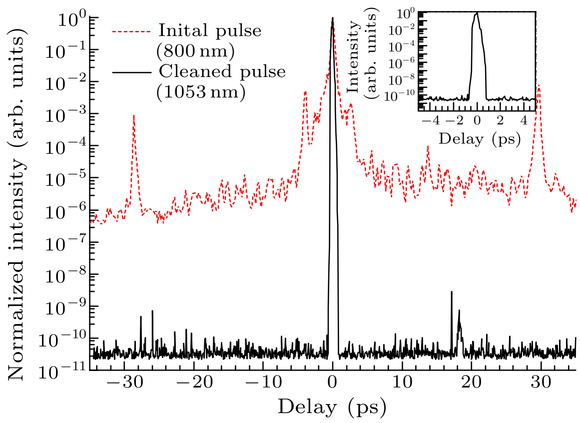

Fig. 2. (Color online) Third-order correlation traces of the initial 800 nm pulse (red dashed curve) and the cleaned 1053 nm idler pulse (black solid curve) within the time scale from −35 ps to 35 ps. The inset expands the 1053 nm idler pulse to the time scale of 5 ps before the main pulse.

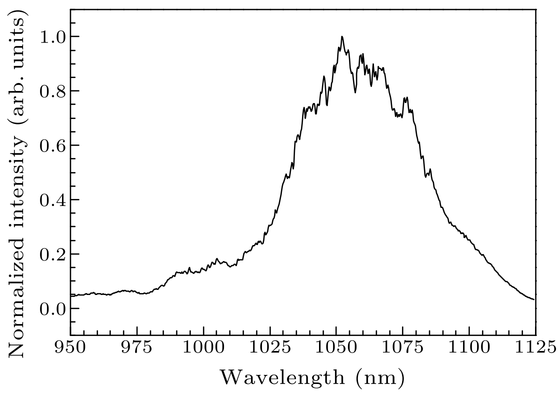

Fig. 3. Spectrum of the 1053 nm idler pulse.

The spectrum of the 1053 nm idler pulse is presented in Fig. 3, which has a bandwidth of 50 nm (FWHM). The pulse duration, shown in Fig. 4, is 48.2 fs (FWHM) assuming a sech^2 temporal profile measured by a commercial single shot autocorrelator (China Daheng Group, Inc.). The authors of Ref. [19] have shown that the sign of the even orders of spectral dispersion of the idler pulse is inverted from the signal, and the idler pulse can be compensated by passing through an identical positive dispersive material. In our experiment, the negative chirped 645 nm idler pulse in the first NOPA stage is partly compensated for by the material dispersion of the BBO crystal, which causes a relatively small positive chirp of the 1053 nm idler pulse in the second NOPA stage. Therefore, the 1053 nm idler pulse can maintain a relatively short pulse duration without extra dispersion compensation.

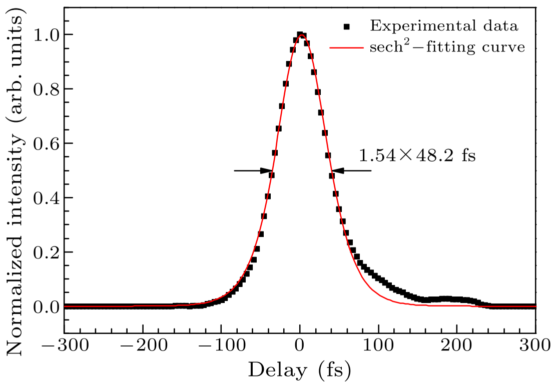

Fig. 4. (Color online) Single shot autocorrelation trace of the 1053 nm idler pulse.

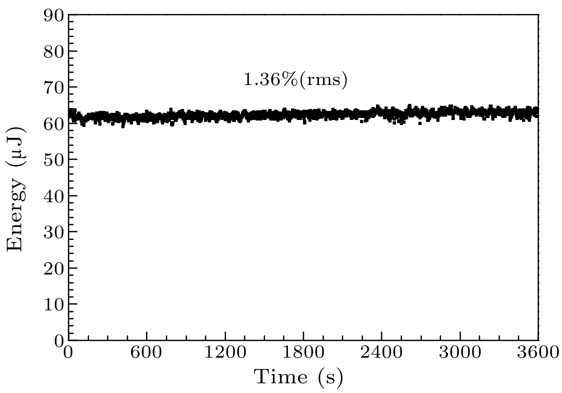

Fig. 5. Energy stability of the 1053 nm idler pulse within one hour.

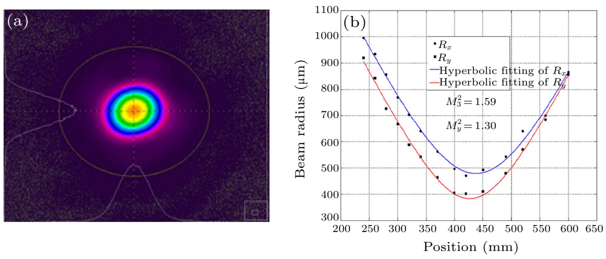

Fig. 6. (Color online) Near-field beam profile and M^2 factor of the 1053 nm idler pulse.

As a seed for a high-power Nd:glass laser system, the energy stability and beam quality are essential features. We measured the energy stability and beam quality of the 1053 nm idler pulse. The energy stability is shown in Fig. 5, which exhibits the energy fluctuation of 1.36% (rms) in one hour. Figure 6 presents the near-field beam profile and M^2 factor of the idler pulse, which is measured by a commercial beam analyzer (M^2-200 s, Ophir-Spiricon Inc.). The calculated beam quality factor M^2 is 1.59 and 1.30 for tangential and sagittal directions, respectively.

In conclusion, we have experimentally demonstrated a high contrast 1053 nm femtosecond laser generation based on a noncollinear optical-parametric amplification. With a 1053 nm laser pulse from WLC as the initial signal, a 1053 nm idler laser pulse with bandwidth of 50 nm and a pulse duration of 48.2 fs is obtained by permuting the signal and idler in two stages of NOPAs. Under a total pump energy of 700 μJ at 400 nm, the output 1053 nm idler pulse is up to 62 μJ with fluctuation of 1.36% (rms). The contrast of the 1053 nm idler pulse reaches a measurement-limited level of 2.3×10^{-11} within the time scale of sub-5 ps. We anticipate that this novel NOPA can be employed as a high-contrast frontend for ultrashort high-power Nd:glass-based CPA systems.

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