# Multimillijoule chirped parametric amplification of few-cycle pulses

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The concept of optical parametric chirped-pulse amplification is applied to attain pulses with energies up to 8 mJ and a bandwidth of more than 100 THz. Stretched broadband seed pulses from a Ti:sapphire oscillator are amplified in a multistage noncollinear type I phase-matched $\beta$-barium borate parametric amplifier by use of an independent picosecond laser with lock-to-clock repetition rate synchronization. Partial compression of amplified pulses is demonstrated down to a 10-fs duration with a down-chirped pulse stretcher and a nearly lossless compressor comprising bulk material and positive-dispersion chirped mirrors. 

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Typical processes in laser-driven strong-field physics[1] are confined to one or a few optical oscillations and therefore require appropriately short laser pulses of the highest possible peak power. The proven way to obtain intense few-cycle laser fields relies on external bandwidth broadening of amplified pulses in gas-filled capillaries[2,3]—a method that involves heavy energy losses and is not easily scalable in the multimillijoule regime. In contrast with laser media, the gain bandwidth of some noncollinearly phase-matched nonlinear optical crystals, especially $\beta$-barium borate (BBO),[4] is directly suitable for amplification of two-cycle visible pulses without subsequent spectral broadening.[5–7] Since the nonlinear optical crystal does not provide inversion storage, efficient broadband amplification with a narrowband pump pulse becomes possible only if the seed pulse is stretched to match the pump duration. Such optical parametric chirped-pulse amplification (OPCPA) was originally proposed and demonstrated by Dubietis *et al.*[8] and has since found broad recognition as a promising scheme for designing ultrahigh-peak-power laser systems.[9–11] To date, high-energy subpicosecond parametric systems[12–15] and few-cycle 100-$\mu$J-level OPCPA[16,17] have been reported. In this Letter we demonstrate a terawatt-class 10-fs scheme that, in our opinion, presents a feasible alternative to a similar-level amplifier based on a Ti:sapphire laser.

The schematic of our OPCPA setup is presented in Fig. 1(a). Similarly to Refs. 16 and 17, the employed seed source is a nanojoule broadband Ti:sapphire seed oscillator. The repetition rates of the femtosecond seed laser and an actively mode-locked 60-ps $Nd:YVO_4$ oscillator are synchronized with an external rf clock. The pulses from the picosecond oscillator are amplified to 100 mJ at a 20-Hz repetition rate in a Nd:YAG amplifier (EKSPA Ltd.) and frequency doubled to produce a 50-mJ, 532-nm pump for OPCPA.

Our parametric amplifier consists of two 4-mm-thick antireflection-coated type I BBO crystals. The internal noncollinearity angle between the pump and the seed beams is set at approximately 2.3° to provide the broadest gain bandwidth. Although we can achieve a factor of $10^6$ gain in a single-stage parametric amplifier, the multistage, multipass arrangement shown in

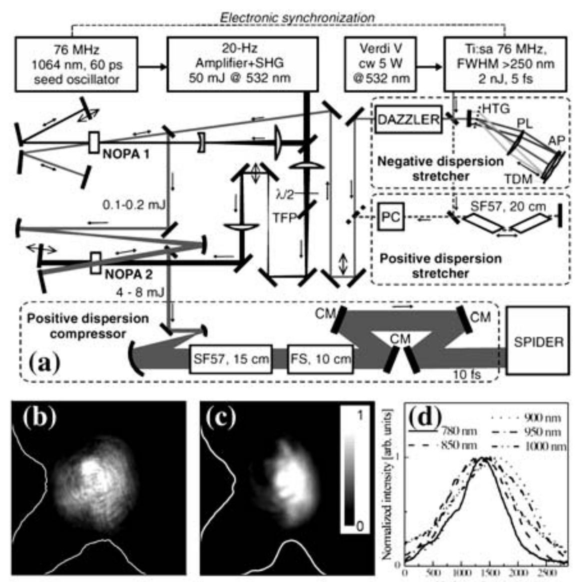


Fig. 1. Two-stage, four-pass chirped-pulse parametric amplifier: (a) layout of the optical setup, (b) relay-imaged pump beam profile at the second-stage crystal, (c) beam profile of the signal beam amplified to 5 mJ, (d) horizontal cross section of the signal beam at several wavelengths. HTG, holographic transmission diffraction grating; PL, parabolic lens; AP, micromachined aspheric plate; TDM, thermally activated mirror; PC, Pockels cell; $\lambda/2$, 532-nm half-wave plate; TFP, thin-film polarizer; SF57, block of Schott SF57 glass; FS, block of synthetic fused silica; CM, positive-dispersion chirped mirror; SHG, second-harmonic generation; Ti:sa, Ti:sapphire laser. SPIDER, spectral phase interferometry for direct electric field reconstruction.

 

Fig. 1(a) is used for its pulse contrast and bandwidth. In this scheme, by using a weaker pump, we reduce the gain in a single stage below $10^4$. On the one hand, this measure suppresses the competition between the external seed and the internal parametric superfluorescence generated in the presence of a strong pump, and, on the other hand, it prevents amplification of the seed replica that is caused by a small double retroreflection from the crystal surfaces.

The BBO length was chosen as a compromise between the gain bandwidth and the amplification factor. In the first noncollinear optical parametric amplifier [NOPA 1; Fig. 1(a)] the collimated pump and signal beams are retroreflected onto the nonlinear optical crystal by flat mirrors located ~25 cm behind the crystal that filters, to some degree, the parametric superfluorescence acquired in the first pass. In contrast with NOPA 1, the reflectors in NOPA 2 are located only 7 cm behind the crystal and are slightly tilted horizontally to change both the phase matching and the noncollinearity angles for the second pass. This angular detuning in NOPA 2, in combination with an independent alignment of NOPA 1, allows us to reshape the gain bandwidth[18,19] and reduce the cumulative bandwidth narrowing through the amplifier. Another important aspect of an optical parametric amplifier is the potential angular chirp of a broadband signal wave whereby a thick noncollinearly phase-matched crystal plays the role of a dispersive monochromator.[20] To characterize this distortion, we monitored the beam profile of the signal amplified to 5 mJ [Fig. 1(c)] and frequency resolved the beam profile behind NOPA 2. As can be seen from the frequency-dependent cross sections in the pump–signal intersection plane, the high-gain amplification causes significant modulation of the output beam but does not lead to a clearly observable mode displacement characteristic of angular chirp. This result ascertains the usability of the chosen crystal length for a broadband noncollinear amplification under the condition of seed collimation, which overrides the selection of output direction imposed by phase matching.

The pump-to-signal energy conversion efficiency of NOPA 1 and NOPA 2, both optimized for the broadest bandwidth, is summarized in Fig. 2. Theoretically, the most efficient performance of OPCPA requires the pump pulse to have roughly top-hat spatial and temporal profiles. Nonetheless, even without adequate temporal (a nearly Gaussian pump pulse intensity profile) and spatial [Fig. 1(b)] shaping, the peak pump-to-signal conversion efficiency in NOPA 2 reaches 27% [Fig. 2(b)]. As can be seen in Figs. 2(a) and 2(b), the pump spot sizes were chosen to permit gain saturation and to improve signal pulse stability. However, deep saturation, observed for the pump energy around 30 mJ, was found to be detrimental because it dramatically enhances the uncompressible background of the signal pulse consisting of amplified superfluorescence. The safe operating conditions in terms of superfluorescence suppression and pulse stability correspond to approximately 5 mJ in the signal pulse, at which the rms intensity fluctuation of the signal pulse is approximately 2.9%, whereas the pump rms fluctuation is nearly 1.5%.

To match the pump pulse duration, the seed pulse was chirped with two alternative stretchers: positive-dispersion bulk material and a negative-dispersion $4f$ dispersion line, both presented in Fig. 1(a). Amplification results obtained with bulk chirping are summarized in Fig. 3. The advantages of this stretching technique are its simplicity, excellent transmitted beam quality, and high throughput for the entire bandwidth of the seed. The solid curve in Fig. 3 shows the spectrum of the signal wave amplified to 8 mJ, which compares well with the overlap between the seed spectrum (dotted curve) and the theoretically calculated gain bandwidth (dashed curve).

Lacking an appropriate high-throughput pulse compressor for the bulk stretcher, we designed a matched pair consisting of a down-chirping stretcher and an up-chirping compressor.[21] In our stretcher [Fig. 1(a)] the beam is dispersed by a holographic 900-line/mm transmission grating (Wasatch Photonics) and passed through an $f \approx 80$ mm parabolic quartz lens. In the Fourier plane of this lens we introduced a micromachined quartz plate for higher-order

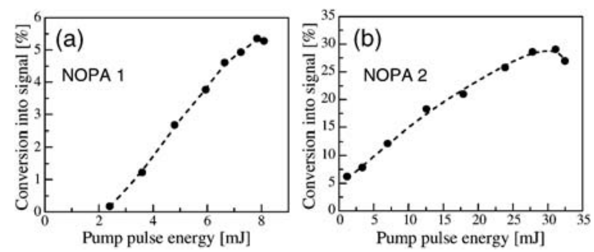


Fig. 2. Energy conversion efficiency into the signal wave. (a) First amplifier stage in a double pass. The pump and the seed beam diameters are ~0.5 and ~0.4 mm FWHM, respectively. (b) Second amplifier stage in a double pass. The pump and the seed beam diameters are ~2.5 and ~3.2 mm FWHM, respectively. Dashed curves are guides to the eye.

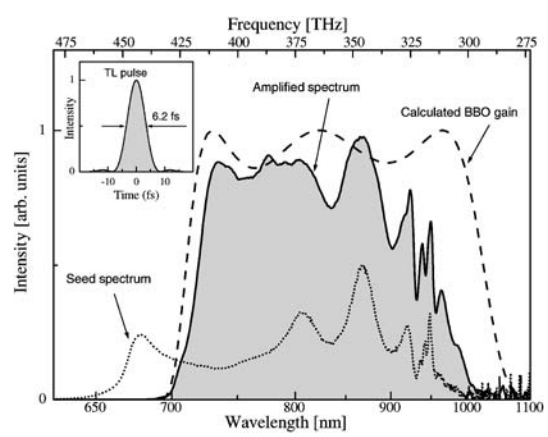


Fig. 3. Parametric amplification of a positively chirped seed pulse. The dotted curve and the shaded contour show the spectra of the seed pulse (2 nJ) and the amplified pulse (8 mJ) spectra, respectively. The dashed curve depicts the calculated gain of a 4-mm type I BBO. The inset shows a pulse profile calculated assuming an ideal compression of the amplified pulse. TL, transform-limited.

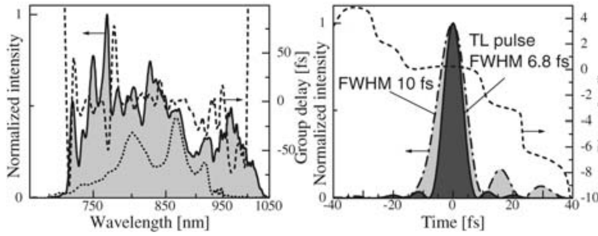


Fig. 4. Results of amplification and recompression of a negatively chirped seed pulse. (a) Seed spectrum behind the grating stretcher (dotted curve), amplified pulse spectrum (shaded contour), and residual group delay (dashed curve). (b) Recompressed 5-mJ pulse (dashed–dotted curve) and temporal phase (dashed curve). The dark contour shows the intensity profile assuming ideal pulse compression.

dispersion correction and a thermally activated deformable mirror (OKO Technologies) for wave-front correction. In total, the beam propagates through the grating four times, which significantly reshapes the transmitted seed spectrum [Fig. 4(a), dotted curve]. To provide the target pulse duration of 50 ps at the NOPAs, the stretcher precompensates the positive dispersion of the programmable acousto-optic filter (DAZZLER, Fastlite) containing a 45-mm-long $TeO_2$ crystal. After amplification, the beam is expanded to a FWHM diameter of ~3 cm and is sent through a compressor consisting of 15 cm of SF57 glass (Schott), followed by 10 cm of Suprasil synthetic quartz (Heraeus) and a set of three custom-made positive-dispersion dielectric chirped mirrors. This stepwise compression is used to reduce pulse self-action inside the bulk material, and the B-integral value for a fully compressed 5-mJ pulse is estimated to be below 1.3. The measured losses in the compressor are below 4%. The amplified bandwidth in the case of the grating-based stretcher [Fig. 4(a), solid curve] is somewhat narrower in comparison with the bulk stretcher and potentially supports ~7-fs pulses. By use of the feedback from a SPIDER measurement of spectral phase, the dispersion of the DAZZLER is tuned to recompress the amplified pulses to ~10 fs [Fig. 4(b)]. We expect to achieve a better pulse compression after upgrading the DAZZLER synchronization and the single-shot SPIDER setup.

In summary, we have designed multistage OPCPA for broadband multimillijoule pulse amplification around 800 nm and employed a unique pulse stretching and compression scheme. Because of the absence of thermal load on the nonlinear optical crystal, the demonstrated concept is scalable both in energy and repetition rate.

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