Self-compression of millijoule pulses from a 1.5 μm OPCPA

'O. D. Mücke[*,1], S. Ališauskas[*,†], A. J. Verhoef[*], A. Pugžlys[*], A. Baltuška[*,2], V. Smilgevičius[†], J. Pocius[$], L. Giniūnas[$], and R. Danielius[$]

[*]Photonics Institute, Vienna University of Technology, Gusshausstrasse 27-387, A-1040, Vienna, Austria
[†]Laser Research Center, Vilnius University, Saulėtekio av. 10, LT-10223 Vilnius, Lithuania
[$]Light Conversion Ltd., P/O Box 1485, Saulėtekio av. 10, LT-10223 Vilnius, Lithuania

Abstract

We demonstrate a four-stage optical parametric chirped-pulse amplification (OPCPA) system delivering carrier-envelope phase (CEP)-stable ~1.5-μm pulses with energies up to 12.5 mJ before recompression. The system is based on a fusion of femtosecond DPSS Yb technology and a picosecond 100-mJ Nd:YAG pump laser. Pulses with 62-nm bandwidth are recompressed to a 74.4-fs duration close to the transform limit. To show the way toward a terawatt-peak-power single-cycle IR source, we demonstate self-compression of 2.2-mJ pulses down to 19.8 fs duration in a single filament in argon with a 1.5-mJ output energy and 66% energy throughput.

Recently, OPCPA has attracted a lot of attention as a promising path toward intensity scaling of few-cycle laser pulses. Intense CEP-stable few-cycle laser pulses have numerous intriguing applications in attosecond science and strong-field physics [1]. In particular, few-cycle high-power IR sources featuring high ponderomotive energy $U_\text{p} \propto \lambda^2 I$ [2, 3, 4] also open the door to experimental studies of the λ-scaling laws of strong-field physics [5], and high-harmonic generation driven by intense few-cycle IR pulses [4, 6] represents a promising route toward bright coherent X-ray sources with several keV photon energies.

Parametric amplification of CEP-stable two-cycle IR seed pulses obtained from difference-frequency generation (DFG) to the energy level close to 1 mJ has been demonstrated [2, 3]. However, the inherently low DFG seed energy causes a sizeable superfluorescence background [2] that prevents further energy upscaling. By narrowing the bandwidth of an optical parametric amplifier (OPA), one can optimize the spectral brightness of the seed at the expense of the seed energy, achieve a more uniform saturation across the pulse spectrum, and minimize energy back-conversion into the pump. In saturation, however, the parametrically amplified spectra exhibit steep slopes that lead to a poor fidelity of the compressed pulses in the time domain.

Recently, Hauri *et al.* [7] demonstrated that filamentation of ~55-fs OPA pulses at 2 μm in a xenon cell allows the generation of self-compressed spectrally broadened 17-fs 0.27-mJ pulses. The limited pulse energy available in that experiment implied the use of xenon as a noble gas with the highest nonlinearity. Detailed numerical investigations of self-compression of 2-μm laser filaments in gases with a moderate ionization potential ($I_\text{p} < 20$ eV) by Bergé [8] predicted a number of highly attractive features of femtosecond filamentation at longer wavelength including higher filament energies, broader supercontinua with a flatter spectral phase, and the feasibility to reach single-cycle pulse durations as compared to 2-3 cycle durations in the visible.

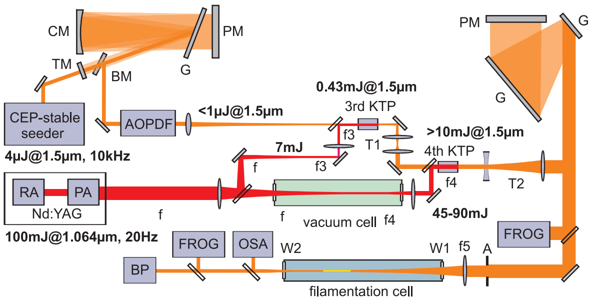

Fig. 1. Scheme of the OPCPA power-amplification stages 3 and 4: AOPDF, acousto-optic programmable dispersive filter; RA, regenerative amplifier; PA, double-pass post amplifier; A, aperture; W1/W2, input/output windows; BP, beam profiler.

These fascinating numerical findings motivated us to explore the filamentation aproach with the pulses from a multimillijoule IR OPCPA. The experimental scheme of our four-stage IR OPCPA is depicted in Fig. 1. The front-end of the OPCPA is based on a femtosecond Yb:KGW DPSS MOPA (Pharos, Light Conversion, Ltd.) and two stages of CEP-stable parametric preamplifiers [9]. Adding two OPCPA booster stages 3 and 4 allows us to reach pulse energies above 10 mJ. Amplification stages 2-4 employ type-II KTP crystals ($\theta = 45.5°$, $\phi = 0°$) which exhibit a relatively broad bandwidth

[1]E-mail: oliver.muecke@tuwien.ac.at
[2]E-mail: baltuska@tuwien.ac.at

around 1.5 μm [9, 10].

The first significant advantage of using the femtosecond Yb front-end is the ease of optical synchronization since both Yb and Nd regenerative amplifiers (RA) at 1030 and 1064 nm, respectively, are simultaneously seeded from a single Yb master oscillator that emits 30-nm FWHM bandwidth pulses. To seed the Nd:YAG RA, we pick up unused 1064-nm light behind a transmission grating in the pulse stretcher of the Yb MOPA. The repetition rate of the Yb:KGW MOPA, tunable in the range of 1-100 kHz, was set at 10 kHz, i.e., at the 500$^{\text{th}}$ harmonic of the 20-Hz flash-lamp-pumped 100-mJ Nd:YAG amplifier (Ekspla Ltd.). In the Nd:YAG RA, an intracavity etalon is used to narrow the pulse bandwidth and keep the pulse duration safe for post amplification.

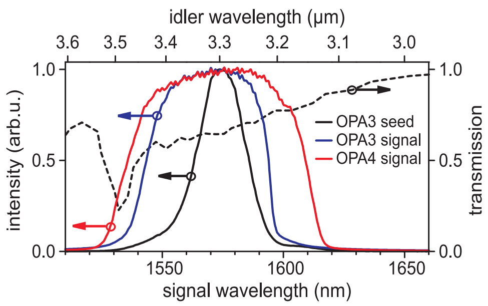

Fig. 2. Spectral properties of the power-amplification stages: spectrum of the third stage seed, amplified signal spectra after stages 3 and 4. The amount of ASE is immeasurable in absence of the WL seed in OPA stage 1. The dashed curve indicates the idler transmission through 10 mm of KTP.

The CEP-stable 1.5-μm pulses from the front-end are temporally stretched to $\sim$40 ps using a grating-based stretcher and an IR high-resolution acousto-optic programmable dispersive filter (DAZZLER by Fastlite) [9] in order to optimize energy extraction from the 60-ps-long Nd:YAG pump pulses. To guarantee a homogeneous pump profile free of "hot spots", we relay-image the 10-mm-diameter crystal rod in the Nd:YAG power amplifier onto the 10-mm-thick KTP crystals in stages 3 and 4. From the measured surface damage threshold of KTP for our pump pulses (21 GW/cm^2), we obtain a pump diameter of 2 mm for stage 3 and 3.1 mm for stage 4. Relay-imaging is achieved with three lenses with focal lengths of f=75 cm, f3=10 cm, and f4=35 cm. Because of the larger pump intensities in the fourth stage, the focus needs to be placed inside a vacuum cell to avoid a break-through in air. The 1.5-μm (seed) pulses are focused onto the third-stage KTP crystal with a 750-mm lens and imaged onto the fourth-stage KTP crystal with telescope T1. The (external) walk-off compensation angle between pump and seed beam is 2.1°. With this pumping geometry and 45-90 mJ pump pulses, we have achieved up to 12.5 mJ signal pulses centered at 1.57 μm and pump-signal conversion efficiency of $\sim$22 % in the final OPCPA stage.

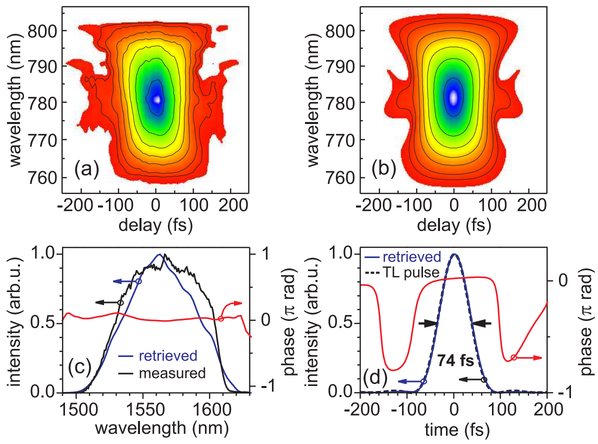

Fig. 3. SHG-FROG characterization of the 20-Hz output from the four-stage IR OPCPA: (a) Measured and (b) retrieved FROG traces. (c) Measured spectrum, retrieved spectral intensity and phase. (d) Retrieved temporal intensity and phase profiles exhibiting a 74.4-fs duration. The TL intensity profile (dashed) corresponds to a 72.6-fs duration.

The spectra of the seed and amplified signal pulses of the power-amplification stages are shown in Fig. 2. In principle, saturating the OPCPA stages permits amplification of pulses with nearly 80 nm bandwidth and $\sim$65-fs Fourier limit. As idler absorption increases above 3.4 μm in KTP, we can achieve higher output powers when tuning the signal center wavelength above 1.55 μm. The SHG-FROG characterization data of 3.5-mJ 1.57-μm pulses with 62-nm bandwidth from the 20-Hz four-stage IR OPCPA (Fig. 3) indicate a FWHM 74.4-fs pulse duration, close to the transform limit (TL) of 72.6 fs. Ultimately, with further optimization sub-70-fs pulse durations seem in reach by recompressing pulses with bandwidths approaching 80 nm.

To explore a possible route toward a terawatt-peak-power single-cycle IR source, we demonstrate spectral broadening of the 74.4-fs 1.57-μm pulses by filamentation in noble gases. As shown in Fig. 1, the pulses were focused using a 50-cm lens placed 4 cm in front of the AR-coated input window W1 of a 138-cm-long gas cell filled with argon (I_{p}=15.76 eV) at the absolute pressure of 5 bar. In the filamentation regime without plasma-induced pulse self-recompression, we generated high spatial quality ∼3-mJ 600-nm-wide IR supercontinua (not shown) supporting 8-fs pulse durations, i.e., less than two optical cycles at 1.5 μm. Careful SHG-FROG characterization of such spectrally broadened pulses has revealed a complex temporal structure consisting of a 200-fs FWHM main split pulse and additional low-intensity satellites. By lowering the input pulse energy and tuning the gas pressure in the cell, we achieved the regime of pulse self-compression, in which CEP-stable 2.2-mJ 74.4-fs 1.57-μm input pulses are compressed in a single filament in argon down to a 19.8 fs duration. The output energy was 1.5-mJ, corresponding to the energy throuput of 66%, including the 8% reflection losses on the uncoated 1-mm-thick BK7 output window W2.

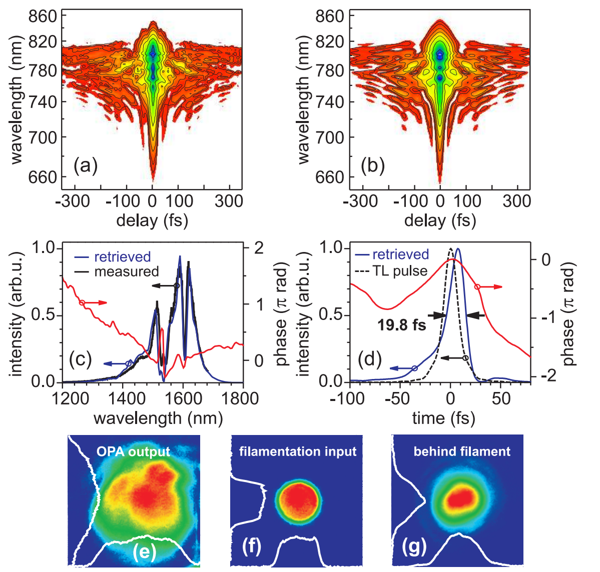

Fig. 4. Self-compression of 1.5-mJ pulses in argon at 5 bar: (a)-(d) as in Fig. 3, 19.8-fs pulse duration, TL 15.9 fs. We emphasize that the FROG characterization was performed without aperturing the filamentation output beam. (e)-(g) Far-field spatial beam profiles measured with the pyroelectric 2D array: (e) after OPCPA grating compressor; (f) apertured filamentation input measured behind the iris aperture A; (g) total beam profile behind the filamentation cell. Image size is 12.4 mm×12.4 mm.

The self-compression results are summarized in Fig. 4. For these experimental conditions, a supercontinuum with a 130-nm FWHM bandwidth originated from a 12-15 cm-long filament visible with the naked eye. The measured duration of the self-compressed pulse was 19.8-fs, corresponding to 4 cycles at 1.5 μm. This represents a temporal compression of the input pulses by a factor of ∼4. Importantly, for self-compression of 2-μm pulses, Bergé [8] pointed out that, as the result of nonlinear propagation, the shortest achievable pulse duration survives only over a shorter distance of ∼15-20 cm in the gas as compared to the 800-nm case. Therefore, careful optimization of the propagation distance in the pressurized Ar cell behind the filament might lead to the observation of even shorter pulse durations. In addition, the spectral phase was shown to be remarkably reproducible on a daily basis which holds potential for further recompression using fixed-dispersion chirped mirrors.

In conclusion, we have demonstrated CEP-stable parametric amplification at 1.5 μm with pulse energies up to 12.5 mJ based on a fusion of a DPSS femtosecond Yb-MOPA system and picosecond Nd:YAG solid-state technology. Furthermore, we demonstrated self-compression of CEP-stable 2.2-mJ 74.4-fs 1.57-μm input pulses down to 19.8 fs duration in a single filament in argon with 1.5-mJ output energy and a 66% energy throughput. The output energy was scaled up by 5.6 times over earlier results [7]. The output energy and energy throughput can be further increased by replacing window W2 with an AR coated window and by systematically optimizing the experimental conditions (input pulse energy and beam diameter, focusing lens and position, gas type and pressure, cell length etc.). Ultimately, with our 1.6-μm pulses we expect to surpass the present energy limitation (4-5 mJ at 0.8 μm [11]) for gas broadening schemes [8].

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