Efficient All-Diode-Pumped Double Stage Femtosecond Optical Parametric Chirped Pulse Amplification at 1-kHz with Periodically Poled KTIOPO$_4$

Valentin Petrov, Frank Noack, Fabian Rotermund$^{1,*}$, Valdas Pasiskevicius$^2$, Anna Fragemann$^2$, Fredrik Laurell$^2$, Holger Hundertmark$^3$, Peter Adel$^3$ and Carsten Fallnich$^3$

Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Str., D-12489 Berlin, Germany
$^1$Department of Molecular Science & Technology, Ajou University, 5 Wonchan-dong, Paldal-gu, 442-749 Suwon, Korea
$^2$Department of Physics, Royal Institute of Technology, 10044 Stockholm, Sweden
$^3$Laser Zentrum Hannover e. V., Hollerithalle 8, D-30419 Hannover, Germany

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A practical efficient optical parametric chirped pulse amplification is demonstrated with periodically poled KTIOPO$_4$. It provides a compact solution to amplify stretched pulses to the 100µJ level (signal + idler) at 1kHz. The amplified signal pulses near 1.57µm are recompressed to 270fs. [DOI: 10.1143/JJAP.42.L1327]

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In recent years optical parametric chirped pulse amplification (OPCPA) turned out to be a practical method for efficient energy transfer from powerful nano- or picosecond pulses to stretched femtosecond pulses. This technique, in which ultrashort pulses are temporally stretched, parametrically amplified in a nonlinear crystal in the field of a powerful pump pulse, and subsequently recompressed, was originally demonstrated with picosecond pump and seed pulse, but it is clear from the limits of the achievable stretching factors that it should be most effective with pump pulse lengths of the order of 1 ns (0.5–5 ns). OPCPA offers a compact and simpler alternative to wide spreaded regenerative/multipass femtosecond laser amplifiers with a number of additional advantages: larger gain bandwidth, high gain achievable without the use of gated electro-optic modulators and multipass amplification, lack of cumulative spectral narrowing and nonlinear phase distortion during the amplification, high contrast ratio, and low heat deposition. Due to the variety of high-quality nonlinear crystals available at present one can expect a larger freedom in the choice of the wavelengths for an OPCPA scheme in comparison to a broadband femtosecond laser amplifier. However, in practice the limitations come from the availability of the femtosecond seed source and also of the temporally synchronized pump source since the above given pump pulse durations in the range of 1 ns are too short for conventional active Q-switching techniques, especially in the kHz repetition rate regime. Motivated by the potential to obtain exceptionally high peak powers and focussed intensities with crystals like β-BaB$_2$O$_4$ (BBO), LiB$_3$O$_5$ (LBO) and KH$_2$PO$_4$ (KDP) used in a degenerate pump-signal-idler configuration, most of the reported experimental activities were focussed on the 1 µm spectral range operating at relatively low (< 10 Hz) repetition rates, up to now. We are aware of the highest peak power experimentally achieved amounts to 16.7 TW with three LBO stages in a single shot regime. The potential to develop simpler, compact and all-diode-pumped femtosecond sources at kHz repetition rates based on OPCPA seems not to have been exploited sufficiently, yet. The two such OPCPA configurations were previously demonstrated with periodically poled LiNbO$_3$ (PPLN), using a lamp-pumped alexandrite amplifier and an Yb-fiber amplifier as pump sources. Pulse durations of 680 fs and 1.6 ps, respectively, were obtained after recompression near 1560 nm. The use of periodically poled ferroelectric crystals for quasi-phase-matching (QPM) permits to achieve substantial improvement of the parametric gain as compared to conventional birefringent crystals due to their higher effective nonlinearities. Operation in the near-IR is expected to profit from the reduced damage susceptibility for such materials and the availability of different pump and seed sources. Recently, we demonstrated 1-kHz OPCPA with a single stage scheme based on periodically poled KTIOPO$_4$ (PPKTP) achieving 20 µJ for the amplified signal pulse energy and 320 fs pulse duration after recompression. Here we describe a double stage PPKTP OPCPA scheme which delivered > 4-fold increasement of output energy and improvement of the temporal/spatial characteristics in terms of the compressed pulse duration and time-bandwidth product.

The experimental setup of the double stage OPCPA system is shown in Fig. 1. The home made Er$^{3+}$-all-fiber oscillator was pumped by a 200-nW, 980-nm telecommunication diode and mode-locked by nonlinear polarization rotation. It produced 55-fs long output pulses near 1.58 µm that were nearly Fourier-limited. The pulses from the fiber oscillator were expanded in an all-reflective one grating stretcher where aperture effects introduced a spectral clip reducing the bandwidth to about 50 nm. The spherical mirror (diameter = 15.24 cm) with a radius of curvature of 152.4 cm acts as a reflective (free of chromatic aberrations) one-to-one telescope between two reflections on the grating to change the sign of the group dispersion from negative to positive. The same Au-coated holographic gratings with 600 grooves/mm (Spectrogon) were used both in the stretcher and the compressor. The effective distance about 88 cm between two diffractions on the grating was sufficient to stretch the pulses up to 250 ps in two passes. The pump source of the OPCPA was a diode-pumped 1-ns, 1-nJ Nd:YAG regenerative amplifier (High Q-Laser, IC-119) operating at 1064 nm. It was seeded by an actively Q-switched 1-ns, 8-µJ Nd:YVO$_4$ microlaser (ECR Corp., PML1000-10) through a total reflecting end mirror, which, in fact, transmits a tiny part of the seed beam at 1064 nm. For coupling out the amplified

$^*$E-mail address: rotermun@ajou.ac.kr
pulses from the regenerative amplifier a common method with a thin film polarizer and a Pockels cell was used. The ns regenerative amplifier delivers stable pulses with a $M^2$-parameter of $<1.2$ at 1 kHz. Finally, the amplifier was synchronized to the fiber oscillator at 1 kHz by using a pulse train divider and a digital delay/pulse generator. Its intrinsic jitter to the microlaser amounts to $<300$ ps. The average power used for seeding the preamplifier amounted to 3.4 mW, which corresponds to a single pulse energy of 60 pJ.

Compared to PPLN, PPKTP exhibits higher damage threshold and weaker photorefractive effect, and the lower electric fields required for poling allow the fabrication of thicker samples. For the present experiment several 9–10-mm long (along X), 5-mm wide (along Y), and 1-mm thick (along Z) flux-grown KTP crystals were poled with domain-inversion periods of $\Lambda = 36 \mu m$ and $\Lambda = 35.6 \mu m$ and QPM-lengths of 5 and 7 mm by the standard room-temperature technique described previously. The front and end surfaces of the crystals were polished with a wedge of $\sim 5^\circ$, antiparallel to each other, to avoid back-reflection effects. Additionally, the crystals were antireflection coated for the pump and signal wavelengths. In order to better match the PPKTP signal gain to the maximum of the seed spectrum the $\Lambda = 36-\mu m$ PPKTP sample (QPM-length = 5 mm) used in the preamplifier stage was mounted in an oven and heated to $\sim 85^\circ C$. A PPKTP sample with $\Lambda = 35.6 \mu m$ and QPM-length = 7 mm was used at room temperature in the power-amplifier stage.

At a peak on-axis pump intensity of 280 MW/cm$^2$ the preamplifier stage produced now a signal pulse energy of 3 $\mu J$ at 1.57 $\mu m$ with full width at half-maximum (FWHM) of 28 nm and an idler pulse energy of $\approx 1.5 \mu J$ near 3.3 $\mu m$. Between the two stages the remaining pump, the amplified signal and the generated idler pulses were separated and recombined by suitable trichroic mirrors whereas the temporal overlap was adjusted by separate delay lines (Fig. 1). Each beam size of the pump, the idler and the signal pulses are optimized with separated focusing lenses to achieve optimal spatial overlap for efficient parametric amplification. We tried seeding of the power-amplifier either with the idler or with the signal pulses but the latter turned out to be more efficient. The use of both seemed not to improve the overall performance. The power-amplifier was pumped at a peak on-axis intensity of 770 MW/cm$^2$. At this intensity level no damage of the crystal could be observed, since the bulk damage threshold expected for KTP should exceed 1 GW/cm$^2$. The amplified signal pulses at 1.574 $\mu m$ had an energy of 85 $\mu J$ after the second stage, which corresponds to a total gain of $1.4 \times 10^6$ (> 60 dB). The amplified signal spectrum measured is shown in Fig. 2.

It should be noted that in addition to the signal pulses, idler pulses as high as $\approx 40 \mu J$ are simultaneously generated near 3.3 $\mu m$ in this non-degenerated OPCPA and the total energy behind the power-amplifier (signal+idler) amounts to about 125 $\mu J$. This corresponds to an overall conversion efficiency of 12.5% with respect to the pump and to 20% in the power-amplifier only.

The amplified signal pulses were then recompressed using a grating compressor. The measured energy transmission through the compressor was 65%. In this experiment we generated the shortest pulse duration produced by kHz-
OPCPA until now. Deconvolution of the autocorrelation trace in Fig. 3 yields a pulse duration of 270 fs, which leads to a time-bandwidth product exceeding only $C^2_1 \times 5$ times the Fourier limit, assuming Gaussian pulse shapes.

The deviation from the ideal time-bandwidth product are mainly affected by the change of the spectral profiles through the gain narrowing in the non-degenerate scheme and the imperfect recompression of the amplified pulses due to the small contribution of the non-seeded competing spontaneous parametric fluorescence, which could not be fully suppressed, during the amplification.

In conclusion, a compact efficient two stage femtosecond OPCPA with PPKTP permitted more than 4-fold increase of the conversion efficiency as compared to a single stage scheme with the same effective crystal length.\(^7\) The relatively narrow (2.1 THz in the preamplifier and 2.3 THz in the power-amplifier) parametric gain bandwidth far from degeneracy is the main reason for the longer output pulses as compared to the seed pulses from the fiber oscillator. Non-degenerate operation, however, offers the attractive feature of providing simultaneously amplified idler pulses in the mid-IR. Improvement of the parametric gain bandwidth can be accomplished by noncollinear interaction or by using periodically poled materials possessing higher nonlinearity (e.g. KNbO\(_3\)) in which case the samples could be shorter.

The whole concept is scalable to higher energies.

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