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Optical parametric chirped pulse amplification of Cr:forsterite laser pulses in periodically poled stoichiometric $LiTaO_3$ at 1 kHz

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ABSTRACT We report the first demonstration of a non-degenerate optical parametric chirped pulse amplification at 1 kHz, utilizing a Cr:forsterite laser as the seed source. Using periodically poled stoichiometric $LiTaO_3$ as the gain medium, signal and idler pulses at the μJ-energy level could be generated near 935 nm and 1235 nm in a single-pass operation, respectively. The spectral bandwidth of 9 nm obtained near 1235 nm and a compressed pulse duration as short as 360 fs in a compact scheme suggest a possible alternative to 1 kHz femtosecond Cr:forsterite regenerative amplifiers.

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1 Introduction

Ultrashort pulses are widely used in various applications such as ultrafast spectroscopy, imaging and material processing. Recently, optical parametric chirped pulse amplification, demonstrated for the first time by Dubietis et al. [1], turned out to be an efficient method to amplify ultrashort pulses. With this technique, energies of intensive nanosecond or sub-nanosecond pump pulses can be efficiently transferred to spatially and temporally synchronized stretched low-energy seed pulses in a suitable nonlinear crystal. As previously reviewed in [2], recent activities in the development of optical parametric amplifiers (OPCPA's) were mainly concentrated with the realization of exceptionally high peak power systems at low repetition rates, delivering powers up to the TW-level. Such high-energy OPCPA's were mostly seeded near 1 μm in degenerate schemes, whereas nonlinear crystals such as β-BaB_2O_4 (BBO), LiB_3O_5 (LBO) and KH_2PO_4 (KDP) were used for amplification in multiple stages [3–5]. Compared to low repetition rate high-energy systems, recent development of compact OPCPA operating at kHz repetition rates was limited due to the availability of powerful pump sources with comparable pulse widths to that of stretched seed pulses. Up to now, OPCPA's operating near 1.55 μm in the kHz regime were demonstrated for generation of sub-ps or fs pulses with μJ-energies [6–9]. Most recently, few-cycle pulses at 1 kHz could be generated near 2.1 μm with a carrier-envelop phase stabilization technique [10]. Quasi phase matching (QPM) in periodically poled (PP) ferroelectric crystals such as PP $LiNbO_3$ (PPLN), PP $KTiOPO_4$ (PPKTP), PP $LiTaO_3$ (PPLT) and PP stoichiometric $LiTaO_3$ (PPSLT) was used for efficient amplification at kHz repetition rates.

In this work, we demonstrate a non-degenerate Cr:forsterite OPCPA in a compact single-pass scheme, which we believe to be the first demonstration at kHz repetition rates. It delivers μJ-pulses both at the signal and idler wavelengths. Subsequently, the amplified idler pulses near 1235 nm were recompressed. Recently, a complex multi-cascade Cr:forsterite OPCPA was demonstrated at a low repetition rate of 2 Hz with slightly different pump and seed wavelengths to generate high-energy ultrashort pulses, whereas the compression of the signal pulses near 910 nm was performed [11, 12].

2 Experimental

The compact non-degenerate OPCPA system presented in this work is schematically depicted in Fig. 1. As the pump source, a kHz-tunable diode-pumped frequency-doubled Nd:YVO_4 Q-switched laser (DS20H-532, Photonics Industries) was used. The pump laser operating at 532 nm delivers 10-ns pulses with the maximum single pulse energy of 1.5-mJ at 1 kHz. A home-made Cr:forsterite seed oscillator operating near 1235 nm delivers 70-fs output pulses at 83 MHz with a spectral bandwidth $\Delta\nu_{FWHM}$ of 32 nm. The seed pulses from the oscillator were sent to an all-reflective single grating stretcher. For efficient energy transfer from the 10 ns pump to the seed pulses, the stretcher was designed to expand the seed pulses up to the ns range after four-fold diffraction on the grating. The appropriate stretching factor was chosen by taking into account the obtainable output pulse energy from the stretcher and the overall jitter (< 1.5 ns) including contributions from the synchronization unit and the pump laser. The com-

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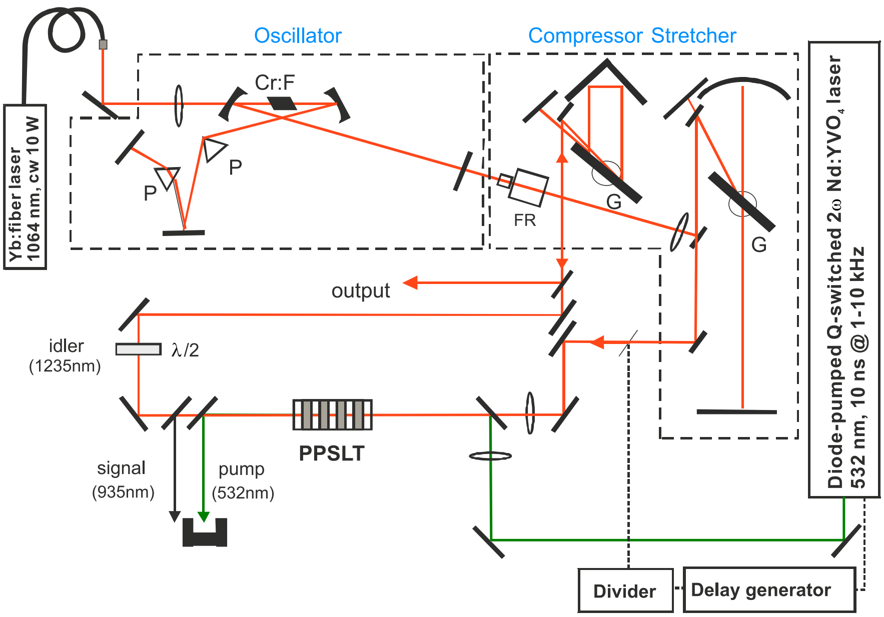

FIGURE 1 Experimental setup of the 1 kHz non-degenerate Cr:forsterite OPCPA in PPSLT

bination of a grating (1400 l/mm blazed for 1250 μm, Spectrogon) and protected gold mirrors including a parabolic mirror with $f = 91.4$ cm enabled stretching of the input pulses up to 1.2 ns.

The spectral bandwidth of the seed pulse behind the stretcher was reduced down to 20 nm due to spectral clipping in the parabolic mirror as well as in the retroreflector. This reduced bandwidth, however, plays no role in the present parametric amplification since the nonlinear crystal used possesses a narrower gain bandwidth. Time synchronization between the 1 kHz pump and the free running seed pulses was realized by using a pulse train divider and a digital delay generator. The average seed power measured in front of the gain medium amounted to 25 mW, which corresponds a the single pulse energy of ∼ 300 pJ. The beam sizes of the pump and the seed pulses were controlled with separate focusing lenses for optimum spatial overlap. After the single-pass amplification with seeding at the idler wavelength, the amplified idler and the concurrently generated signal pulses were separated by using dichroic mirrors.

The PPSLT used for efficient amplification was grown by the double-crucible Czochralski method with 1 mol % Mg-doping. Compared to LN and KTP, a much lower coercive field is required for polarization reversal in SLT [13]. This enables fabrication of thick uniform QPM samples for high-power applications. As previously reported [14, 15], the nonlinear coefficient d_{33} of SLT is larger than that of congruent $LiTaO_3$ (CLT) and KTP. Additionally, SLT exhibits a higher damage threshold and a smaller photorefractivity. We prepared a photoresist pattern of 8 μm period and deposited a plane metal electrode on the pattern. Initial micro-domains induced by pyroelectric effects were eliminated by the electric field before periodical poling. Electric pulses of 1.4 kV/mm were applied at room temperature for polarization reversal. Electric charge for each pulse was monitored to determine the end point of the poling. The quality of the domain structure was checked with an optical microscope after surface etching in HF acid. The uncoated 20 mm long and 0.5 mm thick PPSLT sample with a grating period of 8.0 μm used in the experiment was mounted in an oven and heated for a better QPM. The temperature dependence of the QPM period for 532 nm pumping, shown in Fig. 2, was calculated with the temperature-dependent Sellmeier dispersion relation from [16]. The suitable temperature for the QPM period of 8.0 μm was experimentally found to be ∼ 100 °C by monitoring the maximum parametric gain and the evolution of the phase-matched spectra at the idler and signal wavelengths. It turned out that the determined QPM temperature agreed very well with the theoretical calculation.

3 Results and discussion

The surface damage of the PPSLT was first verified with 10 ns pump pulses at 532 nm near the edge of the used sample. At pump intensities of about 200 MW/ cm^2, dam-

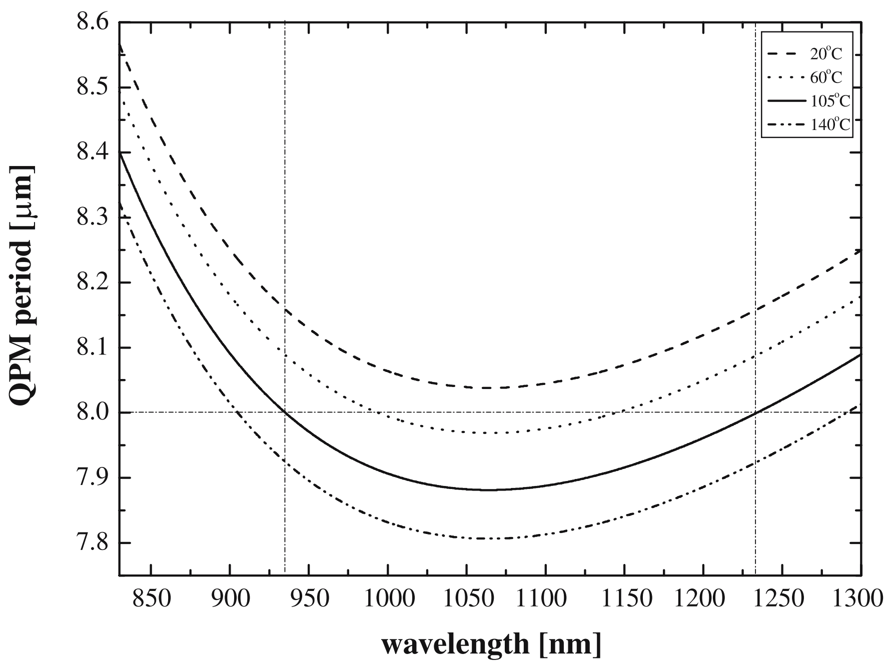

FIGURE 2 Temperature dependent QPM-period of PPSLT for 532 nm pumping

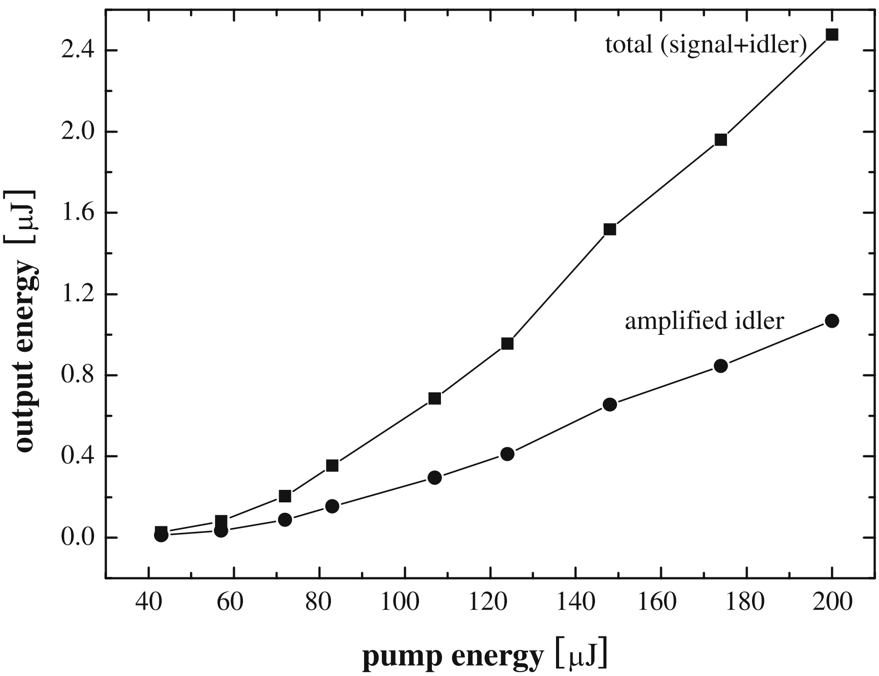

FIGURE 3 Amplified idler and total (signal + idler) energies obtained with the single-pass OPCPA at 1 kHz. The QPM period of the PPSLT used was 8.0 μm

age spots were generated on the crystal surface. As expected, the idler-seeded parametric process already began at lower intensities. The threshold of the parametric gain was observed at a peak on-axis pump intensity of 15 MW/cm^2, whereas the unseeded spontaneous parametric fluorescence was generated first at higher intensities above 25 MW/cm^2.

Figure 3 shows output energies obtained with the idler-seeded single-pass amplification in PPSLT. Because the thickness of PPSLT used was limited to 0.5 mm, the pump beam had to be tightly focused. At present, only a part of the total available 1.5 mJ pump energy could be used due to the limited aperture size. At the pump energy of 200 μJ, corresponding to a pump intensity of 100 MW/cm^2, the amplified idler pulses with 1.1 μJ energy were generated. This energy corresponds to a parametric gain of $\sim 5 \times 10^3$ taking into account the Fresnel losses at the front and rear surfaces of the PPSLT. The total (signal + idler) output energy amounted to 2.5 μJ. Higher energies could be obtained with pump energies of > 200 μJ, but unwanted competing parametric processes were dominant and the spectral qualities became poor. In this case, the amplified pulses cannot be recompressed to the bandwidth-limited pulse duration. The solid curves in Fig. 4 show the signal and amplified idler spectra ($\Delta\lambda_s = 4.5$ nm and $\Delta\lambda_i = 9.0$ nm) which are simultaneously recorded with two separate spectrometers. The spectral bandwidths approximately agreed with the calculated values for the signal (4.2 nm) and idler pulses (7.7 nm) near 935 nm and 1235 nm, respectively. In unseeded cases with pump intensities < 100 MW/cm^2, narrower spectra at the signal and idler wavelengths were observed with small side-peaks caused by the off-axially phase-matched parametric fluorescence (dashed curves). At increased pump intensities near to the damage threshold (< 200 MW/cm^2), both signal and idler spectra became much more broader with strong fluctuations and modulations. The unseeded parametric processes could not be further suppressed and controlled by seeding.

As the next step, the repetition rate of the pump laser was tuned up to 2 kHz. At this repetition rate, parametric amplification could also be obtained with pump energies > 60 μJ. The spectral shapes of the amplified idler and signal pulses were similar to those at 1 kHz. Detailed output characteristics at higher repetition rates than 1 kHz will be studied in the near future with improved output energies.

Subsequently, the amplified idler pulses were compressed in a compressor. It mainly consisted of a grating with an analogous dispersive line such as that of the stretcher. The overall transmission through the compressor

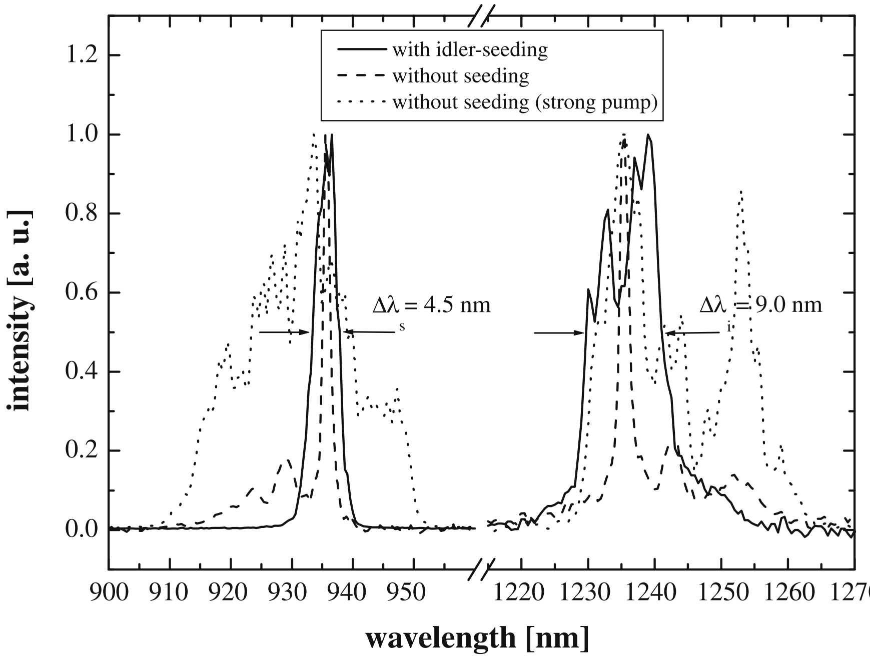

FIGURE 4 Signal and idler spectra obtained with a 20 mm long PPSLT. *Solid curves* show measured spectra with idler-seeding. *Dashed* and *dotted curves* were obtained without seeding at pump intensities of < 100 MW/cm^2 and > 200 MW/cm^2, respectively

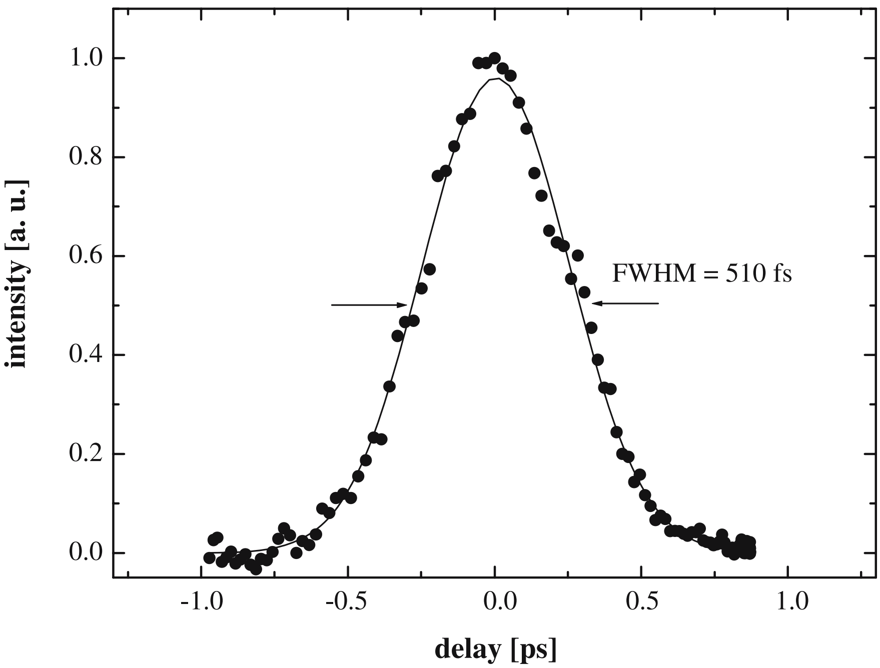

FIGURE 5 Second-harmonic autocorrelation trace of the amplified idler pulses. Deconvolution assuming a Gaussian pulse shape leads to a pulse width of 360 fs

was about 65%. Figure 5 shows the second-harmonic autocorrelation trace measured in 1 mm-thick type-I LBO. It corresponds to a pulse width of 360 fs assuming a Gaussian pulse shape. The exceeded time-bandwidth product of ∼ 0.64 from the Fourier-limitation is mostly attributed to the imperfect recompression of the amplified idler pulses due to the residual parts of the unseeded parametric fluorescence in the idler spectrum. As can be seen in Fig. 4, it caused modulations of the idler spectrum and broader spectral bandwidth as expected.

4 Conclusion

In conclusion, we were successful in demonstrating, for the first time, a compact non-degenerate 1 kHz OPCPA with a Cr:forsterite seed laser. Due to the high effective nonlinearity of PPSLT, pulses with μJ-energies were generated near 935 nm and 1235 nm in a compact single-pass operation. Significant improvements of the parametric amplification and output energies require a larger aperture size of the PPSLT and two amplifier stages. A shorter pulse duration can be obtained with shorter PPSLT, or two PPSLT devices with slightly different QPM-periods for the amplifier stages. Extension of OPCPA to a double-stage configuration with thicker PPSLT samples is in progress. The Cr:forsterite OPCPA using PPSLT in the compact performance with improved output energies and reduced pulse width can be considered as an alternative to Cr:forsterite regenerative amplifiers at 1 kHz in which there are always thermal problems to be solved.

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REFERENCES

1 A. Dubietis, G. Jonusauskas, A. Piskarskas, Opt. Commun. **88**, 437 (1992)
2 R. Butkus, R. Danielius, A. Dubietis, A. Piskarskas, A. Stabinis, Appl. Phys. B **79**, 693 (2004)
3 I.N. Ross, P. Matousek, M. Towrie, A.J. Langley, J.L. Collier, Opt. Commun. **144**, 125 (1997)
4 X. Yang, Z. Xu, Y. Leng, H. Lu, L. Lin, Z. Zhang, R. Li, W. Zhang, D. Yin, B. Tang, Opt. Lett. **27**, 1135 (2002)
5 I. Jovanovic, C.A. Ebbers, C.P.J. Barty, Opt. Lett. **27**, 1622 (2002)
6 A. Galvanauskas, A. Hariharan, D. Harter, M.A. Arbore, M.M. Fejer, Opt. Lett. **23**, 210 (1998)
7 F. Rotermund, V. Petrov, F. Noack, V. Pasiskevicius, J. Hellstrom, F. Laurell, H. Hundertmark, P. Adel, C. Fallnich, Electron. Lett. **38**, 561 (2002)
8 V. Petrov, F. Noack, F. Rotermund, V. Pasiskevicius, A. Fragemann, F. Laurell, H. Hundertmark, P. Adel, C. Fallnich, Jpn. J. Appl. Phys. **42**, L1327 (2003)
9 F. Rotermund, C.J. Yoon, V. Petrov, F. Noack, S. Kurimura, N.-E. Yu, K. Kurimura, Opt. Express **12**, 6421 (2004)
10 T. Fuji, N. Ishii, C.Y. Teisset, X. Gu, T. Metzger, A. Batuska, N. Forget, D. Kaplan, A. Galvanauskas, F. Krausz, Opt. Lett. **31**, 1103 (2006)
11 V.V. Lozhkarev, S.G. Garanin, R.R. Gerke, V.N. Ginzburg, E.V. Katin, E.A. Khazanov, A.V. Kirsanov, G.A. Luchinin, A.N. Mal'shakov, M.A. Martyanov, O.V. Palashov, A.K. Poteomkin, N.N. Rukavishnikov, A.M. Sergeev, S.A. Sukharev, E.A. Khazanov, G.I. Freidman, A.V. Charukhchev, A.A. Shaykin, I.V. Yakovlev, JETP Lett. **82**, 178 (2005)
12 V.V. Lozhkarev, G.I. Freidman, V.N. Ginzburg, E.V. Katin, E.A. Khazanov, A.V. Kirsanov, G.A. Luchinin, A.N. Mal'shakov, M.A. Martyanov, O.V. Palashov, A.K. Poteomkin, A.M. Sergeev, A.A. Shaykin, I.V. Yakovlev, S.G. Garanin, S.A. Sukharev, N.N. Rukavishnikov, A.V. Charukhchev, R.R. Gerke, V.E. Yashin, Opt. Express **14**, 446 (2006)
13 T. Hatanaka, K. Nakamura, T. Taniuchi, H. Ito, Y. Furukawa, K. Kitamura, Opt. Lett. **25**, 651 (2000)
14 I. Shoji, T. Kondo, A. Kitamoto, M. Shirane, R. Ito, J. Opt. Soc. Am. B **14**, 2268 (1997)
15 J. Hellström, V. Pasiskevicius, H. Karlsson, F. Laurell, Opt. Lett. **25**, 174 (2000)
16 A. Bruner, D. Eger, M.B. Oron, P. Blau, M. Katz, S. Ruschin, Opt. Lett. **28**, 194 (2003)