HTML ABSTRACT • LINKS

High-gain multipass noncollinear optical parametric chirped pulse amplifier

Yuriy Stepanenko[a)]
Institute of Physical Chemistry, Polish Academy of Sciences and Laser Centre, Kasprzaka 44/52, 01-224 Warsaw, Poland

Czesław Radzewicz
Institute of Physical Chemistry, Polish Academy of Sciences and Laser Centre, Kasprzaka 44/52, 01-224 Warsaw, Poland and Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland

(Received 19 January 2005; accepted 20 April 2005; published online 20 May 2005)

We demonstrate a multipass noncollinear optical parametric chirped pulse amplifier seeded by pulses from a femtosecond Ti:sapphire oscillator and pumped by a commercial Q-switched, frequency doubled Nd:yttrium–aluminum–garnet laser. Amplification higher than 10^6 and pulse energy exceeding 1.7 mJ are achieved with four passes through a single β-barium borate crystal. Good beam quality and high gain, together with broad amplification bandwidth, make it an attractive alternative to Ti:sapphire chirped pulse amplifier systems. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1940132]

Optical parametric chirped pulse amplifiers (OPCPAs)[1,2] have been identified as attractive sources of ultrashort high power laser pulses. Most of the work done so far in this field has been devoted to the development of extremely high power (multi-TW) infrared systems in which broadband operation of the parametric amplifier is secured by operating it at or close to the degeneracy point.[3–5] The broadband operation of an optical parametric amplifier can also be achieved away from the degeneracy point with noncollinear geometry.[6,7] Noncollinear geometry is well understood and is extensively used in femtosecond pulse pumped noncollinear optical parametric amplifiers (NOPA) capable of delivering sub-10 fs pulses in the visible.[8,9] However, an attempt at scaling the NOPA to higher output energies is hampered by limited pulse energy available from femtosecond Ti:sapphire systems. This can be overcome with application of high energy nanosecond pulses from commercial solid state lasers such as Nd:yttrium–aluminum–garnet(YAG). The advantages of noncollinear geometry in a nanosecond pumped ultrafast optical parametric amplifier were, demonstrated by Yang *et al.*[10] They showed experimentally a moderate parametric gain of 55 in a type-I β-barium borate (BBO) crystal amplifier seeded by temporally stretched pulses at 800 nm and pumped by nanosecond pulses at 532 nm.

As has been pointed out,[11] the upper limit of the gain available in the nanosecond pulse pumped OPCPA systems is imposed by the material damage by pump pulses ($\sim$1 GW/cm^2 for BBO at 532 nm). One should also bear in mind that, unlike a conventional laser amplifier, the parametric amplifier cannot store energy and thus the amplified and the pump pulses should be of comparable duration. This can be achieved by either using a stretcher with extremely large diffraction gratings or by tailoring the pump pulse. Neither of the two methods is very easy. For a typical system, the stretched seed pulse duration is below 1 ns while the pump pulse is 6–10 ns long. It has been proposed[12] that high gain and high conversion efficiency can be achieved with several nonlinear crystals separated by adjustable time delays so the shorter seed pulse overlaps with different temporal parts of the longer pump pulse in different crystals. However, one can easily achieve higher gain by using several passes through the amplifier during the time window defined by the pump pulse. In this letter we demonstrate experimentally a noncollinear nanosecond pulse pumped OPCPA system that exploits this idea.

The scheme of our multipass noncollinear optical parametric chirped pulse amplifier (NOPCPA) is shown in Fig. 1(a). A set of flat mirrors was used to steer the seed beam in such a way that it made four passes through the pumped region of the BBO crystal. To keep the pump-seed angle the same for all four passes, the amplified beams are aligned on a cone around the pump beam direction [see Fig. 1(b)] The seed pulses were obtained from a train of pulses (800 nm, 26 nm spectral width) generated by a Ti:sapphire oscillator (MiraSeed, Coherent) operating at 76 MHz. The pulses were stretched in a grating stretcher to about 300 ps and single pulses were selected at 10 Hz repetition rate by a Pockels cell (MEDOX Inc.). After the Pockels cell, the beam propagated 10 m in the air and then was collimated by the 3:1 lens

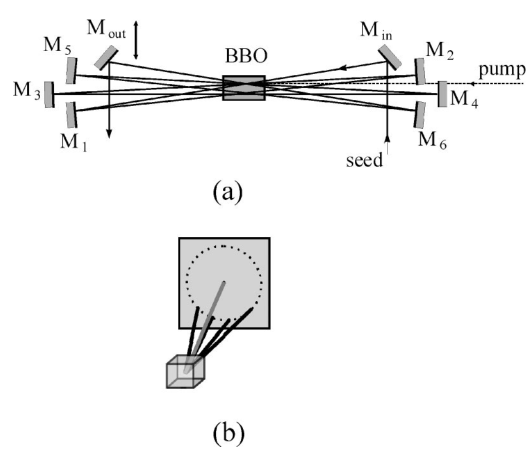

FIG. 1. (a) Scheme of the multipass noncollinear optical parametric chirped pulse amplifier (NOPCPA), M_1-M_6, M_{in}, and M_{out} are flat mirrors highly reflective @ 800 nm, the distance between mirrors M_3 and M_4 is 190 mm, (b) amplified beam alignment with respect to the pump beam.

[a)]Author to whom correspondence should be addressed; electronic mail: stepanenko@ichf.edu.pl

 © 2005 American Institute of Physics
Downloaded 22 Jun 2007 to 193.0.81.226. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

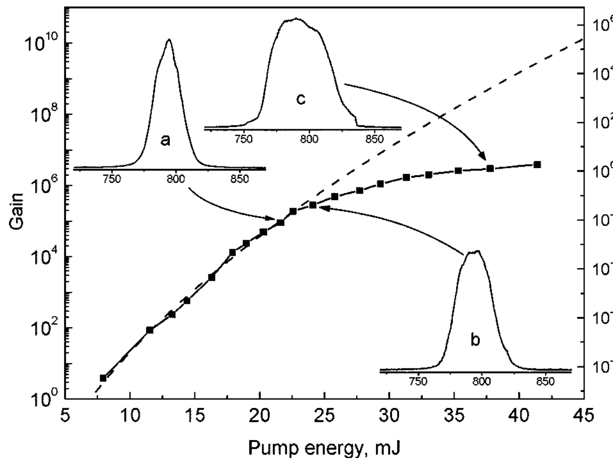

FIG. 2. Experimental gain (left axis) and output energy (right axis) of the amplifier vs pump pulse energy (solid squares). The gain of an unsaturated amplifier fitted to the experimental data is shown by a dashed curve. Insets in the figure show spectra of the output pulse measured at energies (a) 100 μJ, (b) 400 μJ, (c) 1500 μJ.

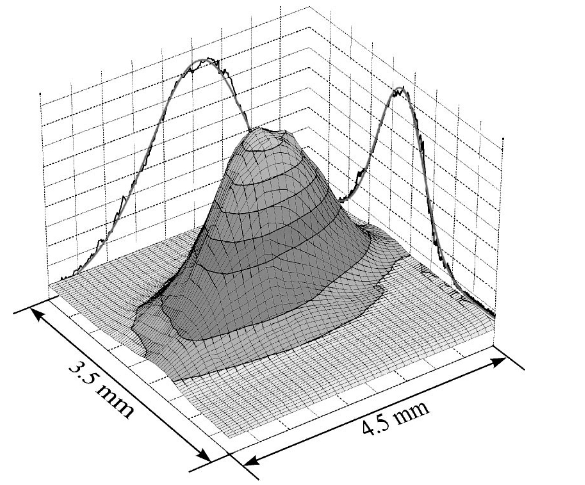

FIG. 3. Output beam profile. Curves on sidewalls show beam crosssections fitted with Gaussian functions.

telescope. The beam radius after the telescope was 600 μm and the corresponding Rayleigh range was approximately 1.5 m—a value roughly equal to the distance the amplified beam traveled in the amplifier. The energy of the pulse injected into the amplifier was 0.3 nJ.

The amplifier was pumped by a Q-switched frequency doubled Nd:YAG laser (Continuum Powerlite 8010) operating in a single longitudinal mode. A combination of a half-waveplate and a polarizing beamsplitter was used for precise control of the pump pulse energy. The pump beam was collimated by 4:1 telescope to the radius of 1000 μm. The pulse duration of the pump and energy fluctuations were 8 ns and 1.5% (rms), respectively. Proper timing between the Pockels cell and the pump laser was provided by a delay generator (DG535, Stanford Research) resulting in the pump-seed jitter ±1 ns.

Our NOPCPA used a 16-mm-long, 5×7 mm aperture, uncoated BBO crystal (θ=30°, 1° wedge) cut for type I ($e\rightarrow o+o$) phase matching. This particular crystal was selected because of its availability. The pump beam was overlapped with the 800 nm beam inside the crystal at the angle of 2.4° (about 4° in the air) corresponding to the broadest amplification band.[10] In our parametric chirped pulse amplifier the highest amplification also corresponds to the broadest amplification bandwidth and we used energy amplification as the sole criterion while aligning the amplifier.

Since the amplifier gain and bandwidth are very sensitive to the pump-seed angle,[10] this angle together with the beam overlap and the phase-matching angle were optimized during the alignment of the amplifier to get the highest amplification on each pass through the crystal. During the initial alignment, the mirror M_{out} mounted on a translational stage was used to intercept the amplified beam after a given pass and the gain for this pass was carefully maximized. Day-to-day alignment of the entire amplifier is simple and requires only minor adjustments of a mirror pair that injects the seed beam into the amplifier.

The amplifier gain versus pump pulse energy is shown in Fig. 2. In our setup the pump pulse energy was limited by the damage of the mirror steering the 532 nm beam into the amplifier. We estimate that the maximum pump pulse energy used corresponded to approximately 50% of the damage threshold for the BBO crystal. An unsaturated gain fit of the data assuming $G\propto\exp(\sqrt{E_p})$, where G is gain and E_p is the pump pulse energy, is also shown (dashed line). At high pump powers the output pulse energy saturates and pulse energy fluctuations decrease (7%–8% rms). We attribute the fluctuations predominantly to the timing jitter and MiraSeed beam pointing fluctuations over a long (10 m) distance between the femtosecond oscillator and the amplifier. The amplification of the first three passes was about 10^2 per pass for the highest pump energy used (42 mJ). The fourth pass had an amplification between 4 and 5 due to saturation. The saturation also led to pulse spectrum broadening as shown in insets in Fig. 2.

Figure 3 shows the output beam profile recorded with a charge coupled device (CCD) camera at a distance of about 1 m from the amplifier. The beam is smooth and can be well approximated by an elliptical Gaussian profile. The slight ellipticity of the beam is due to the same property of the seed beam.

The amplifier can be easily scaled up by using seed and pump beams with larger diameters. We estimate that the geometry of our experimental setup allows for the collimated seed beam diameter to be three times larger than the one we used. Therefore, with a suitable increase in the pump power, one could expect a tenfold increase in output energy.

In conclusion, we have demonstrated a multipass noncollinear optical parametric amplifier for femtosecond pulses at 800 nm pumped by a Q-switched frequency doubled Nd:YAG laser with an overall gain of 5×10^6. Pulses from the amplifier have energy of 1.7 mJ, less than 10% pulse to pulse energy fluctuations and good beam quality.

[1] A. Dubietis, G. Jonusauskas, and A. Piskarskas, Opt. Commun. **88**, 437 (1992).
[2] I. N. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, Opt. Commun. **144**, 125 (1997).
[3] X. Jang, Z. Xu, Y. Leng, H. Lu, L. Lin, Z. Zhang, R. Li, W. Zhang, D. Yin, and B. Tang, Opt. Lett. **27**, 1135 (2002).
[4] H. Yoshida, E. Ishii, R. Kodama, H. Fujita, Y. Kitagawa, Y. Izawa, and T. Yamanaka, Opt. Lett. **28**, 257 (2003).
[5] L. J. Waxer, V. Bagnoud, I. A. Begishev, M. J. Guardalben, J. Puth, and J. D. Zuegel, Opt. Lett. **28**, 1245 (2003).
[6] T. J. Driscoll, G. M. Gale, and F. Hache, Opt. Commun. **110**, 638 (1994).
[7] G. M. Gale, M. Cavallari, T. J. Driscoll, and F. Hache, Opt. Lett. **20**, 1562 (1995).

Downloaded 22 Jun 2007 to 193.0.81.226. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

[8]E. Riedle, M. Beutter, S. Lochbrunner, J. Piel, S. Schenkl, S. Spörlien, and W. Zinth, Appl. Phys. B: Lasers Opt. **71**, 457 (2000).
[9]A. Shirakawa, I. Sakane, M. Takasaka, and T. Kobayashi, Appl. Phys. Lett. **74**, 2268 (1999).
[10]X. Yang, Z. Xu, Z. Zhang, Y. Leng, J. Peng, J. Wang, S. Jin, W. Zhang, and R. Li, Appl. Phys. B: Lasers Opt. **73**, 219 (2001).
[11]G. Cerullo and S. De Silvestri, Rev. Sci. Instrum. **74**, 1 (2003).
[12]T. Harimoto and K. Yamakawa, Opt. Express **11**, 939 (2003).

Downloaded 22 Jun 2007 to 193.0.81.226. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp