Terawatt diode-pumped $Yb:CaF_2$ laser

Mathias Siebold,[1,2,*] Marco Hornung,[1] Ragnar Boedefeld,[1] Sebastian Podleska,[1] Sandro Klingebiel,[2] Christoph Wandt,[2] Ferenc Krausz,[2] Stefan Karsch,[2] Reinhard Uecker,[3] Axel Jochmann,[4] Joachim Hein,[1] and Malte Christoph Kaluza[1]

[1]*Institute of Optics and Quantum Electronics, FSU Jena, Max-Wien-Platz 1, 07743 Jena, Germany*
[2]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Straße 1, 85748 Garching, Germany*
[3]*Institute for Crystal Growth, Max-Born-Straße 2, 12489 Berlin, Germany*
[4]*Forschungszentrum Dresden-Rossendorf, Bautzner Landstraße 128, 01328 Dresden, Germany*
**Corresponding author: mathias.siebold@gmx.de*

Received July 16, 2008; revised October 4, 2008; accepted October 15, 2008;
posted October 21, 2008 (Doc. ID 98893); published November 20, 2008

We present what we believe to be the first terawatt diode-pumped laser employing single-crystalline $Yb:CaF_2$ as the amplifying medium. A maximum pulse energy of 420 mJ at a repetition rate of 1 Hz was achieved by seeding with a stretched femtosecond pulse 2 ns in duration, preamplified to 40 mJ. After recompression, a pulse energy of 197 mJ and a duration of 192 fs were obtained, corresponding to a peak power of 1 TW. Furthermore, nanosecond pulses containing an energy of up to 905 mJ were generated without optical damage. © 2008 Optical Society of America

OCIS codes: 140.7090, 140.3280, 140.3615, 140.3480.

Over the past few decades we have witnessed tremendous progress in the field of high-intensity laser-plasma physics. Experiments at peak intensities in excess of 10^{21} W/cm^2 have only been possible owing to the rapid development of chirped-pulse laser amplifier systems (CPA) [1], delivering pulses with peak powers in the range of several tens of terawatts up to 1 PW. Nowadays, either high-energy Nd:glass [2] or short-pulse Ti:sapphire laser systems [3], both based on technically mature flash-lamp technology, are available for such experiments. Alternatively, compact diode-pumped solid-state laser systems are envisioned to be an efficient approach for the direct generation of ultrahigh peak laser intensities at a high average power [4]. Moreover, the next generation of peak-power lasers based on the optical parametric chirped-pulse amplification technique [5] also demands efficient high-energy pump lasers, which compact diode-pumped lasers are suitable for. At present, several high-energy class diode-pumped solid-state lasers (HEC-DPSSLs) are being constructed worldwide with expected energies of 100 J or more [6–8].

Owing to their low quantum defect and a comparably long fluorescence lifetime, ytterbium-doped gain media are preferably utilized for high-power, diode-pumped systems and laser amplifiers with high optical-to-optical conversion efficiency. Recently, ytterbium-doped alkaline-earth fluorides ($Yb:CaF_2$, $Yb:SrF_2$, $Yb:BaF_2$) have attracted considerable interest for use in diode-pumped, femtosecond lasers and amplifiers [9,10]. It was additionally shown that single-crystalline $Yb:CaF_2$ can be grown up to a diameter of 200 mm, which is superior for high-energy short-pulse lasers with centimeter-sized apertures (crystals provided by Korth GmbH, Germany).

In this Letter, we report the first (to our knowledge) use of $Yb:CaF_2$ to amplify femtosecond laser pulses to the terawatt level. Cylindrical $Yb:CaF_2$ crystals with a diameter of 28 mm and a length of 20 mm were used, which were provided by the Institute for Crystal Growth, Berlin, Germany, and the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. The samples, which were doped with a Yb^{3+}-concentration of 2.0–2.2 mol%, were antireflection (AR) coated for the pump and lasing wavelengths.

Figure 1 illustrates the experimental setup. The front end and the compressor of the POLARIS laser system were used for seeding the multipass amplifier and recompression of the amplified pulses [8]. The seed pulses with a duration of 85 fs (FWHM) were generated in a commercial Ti:sapphire oscillator (Mira 900, Coherent Inc., USA). Pulses that passed

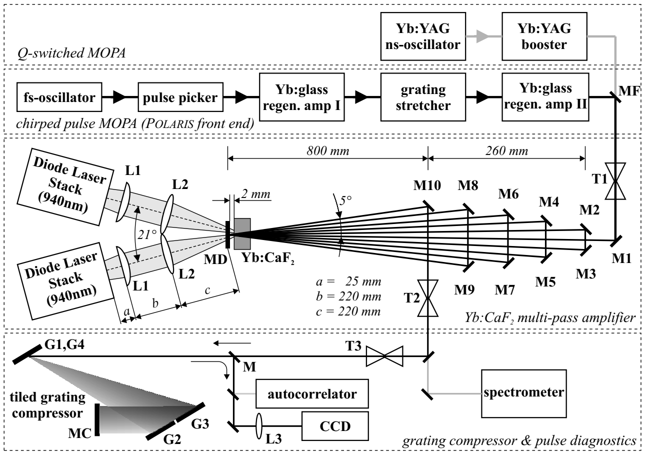

Fig. 1. Experimental setup: multipass CPA based on $Yb:CaF_2$, seeded either by a two-stage chirped-pulse Yb:glass MOPA or a *Q*-switched nanosecond Yb:YAG MOPA. MF, flip mirror; MD, dichroic flat mirror (HR 1020–1060 nm, AR 930–950 nm); M1–M10, dielectric flat mirrors (HR 45° 1010–1060 nm), diameter, 25 mm; angle between incoming and outgoing beam, 5°; T1, spherical lens telescope (magnification: 1) for divergence control; T2, T3, spherical lens telescopes [magnification: 2 (T2) and 6 (T3)], vacuum tubes at the focal regions of T1–T3; L1, cylindrical lens ($f=115$ mm); L2, spherical lens ($f=250$ mm); G1–G4, compressor gold gratings; MC, dielectric compressor end mirror; incoming and outgoing beam are vertically separated on G1, G4 and M; L3, focusing lens ($f=5$ m).

0146-9592/08/232770-3/$15.00 © 2008 Optical Society of America

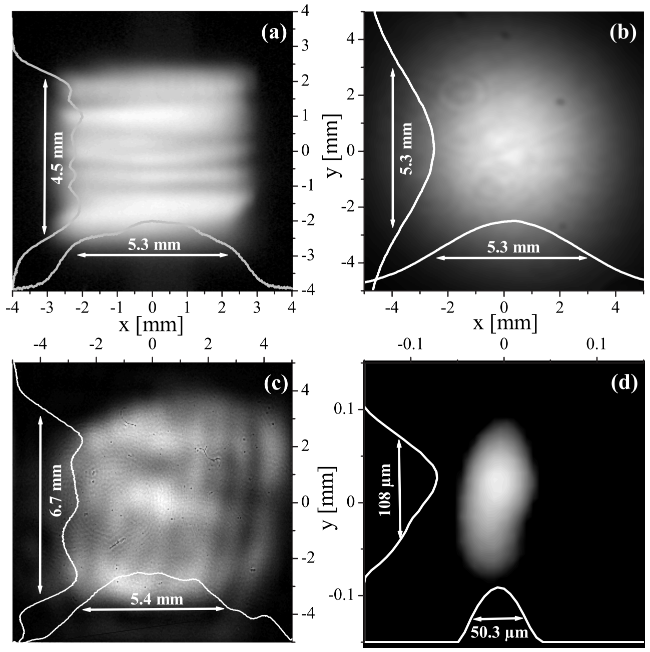

Fig. 2. Beam profiles. Dimensions denote the width of the projection at FWHM: (a) pump profile, (b) input beam profile, (c) near-field pattern after multipass amplification, (d) far-field pattern after recompression.

the 1 Hz pulse picker were preamplified from 1.3 nJ to 20 μJ. These pulses with a bandwidth of 11 nm centered around 1031 nm were then stretched to 2 ns by a four-pass grating stretcher (General Atomics Inc., USA) incorporating a 350-mm-wide gold grating with 1480 lines per mm and a hard-clip bandwidth of 32 nm. After that, the seed pulses were boosted to the 40 mJ level by a second regenerative Yb:glass amplifier.

A diode-pumped Yb:YAG master oscillator power amplifier (MOPA) was used as an alternative source for nanosecond and microsecond pulses, respectively. Pulses as short as 6 ns were generated in a Q-switched oscillator and amplified to an energy of 220 mJ in a four-pass booster [11]. The gain medium of the ten-pass amplifier was pumped by two stacks of 25 fast-axis collimated diode-laser bars (Jenoptik Laserdiode GmbH, Germany). In this case, the single-pass absorption of the Yb:CaF$_2$ crystal at the pump wavelength of 940 nm was 73%. At a maximum operating current of 190 A, peak output powers of 3.5 and 3.9 kW from the two stacks were measured, respectively. A pump duration of 4 ms, which is about twice the fluorescence lifetime of Yb:CaF$_2$, was chosen. Although in this case the fluorescence losses are calculated to be 57%, a minimum pump peak power per output pulse energy is required. To recollimate the pump light along the slow axis and focus it into the gain medium, each diode stack was followed by a cylindrical (L1) and a spherical lens (L2). Figure 2(a) shows the rectangular pump profile at the gain medium. A plane dichroic mirror (MD) directly behind the Yb:CaF$_2$ crystal acted as a wavelength coupler and a reflecting mirror for the ten-pass setup with high-reflection (HR)-coated turning mirrors (M1–M10). After beam expansion by a factor of 12 using two Keplerian refracting telescopes, the chirped pulses were recompressed with a tiled grating compressor [12]. The vacuum compressor incorporates four gold gratings (350 mm × 190 mm) with 1480 lines per millimeter. Originally, the grating compressor with a grating separation of 5.76 m was designed to recompress chirped pulses with a pulse duration of 2 ns and a beam diameter of up to 15 cm at a hard-clip bandwidth of 46 nm.

Both the Q-switched Yb:YAG and the chirped-pulse MOPA provide Gaussian-shaped seed pulses [see Fig. 2(b)]. Owing to both the structure of the pump profile and the crystal abberations such as stress polarization and inhomogeneities of the refractive index profile, the near field at the output of the multipass amplifier is distorted [see Fig. 2(c)]. The far-field intensity profile obtained using a spherical lens ($f = 5$ m) is shown in Fig. 2(d). For this setup, a diffraction limit of 25 μm was calculated.

In the case of CPA operation the seed pulse energy was limited to 40 mJ owing to the damage threshold of the preamplifier, leading to a maximum output pulse energy of 420 mJ (repetition rate: 1 Hz) after the multipass amplifier. Figure 3(a) shows the spectra of the seed (40 mJ) and amplified (420 mJ) laser pulses. The center wavelength of the amplified pulses was redshifted owing to the shape of the gain spectrum at the excitation level achieved (see Fig. 3 given in [10]).

During these experiments, a maximum output pulse energy of 197 mJ was measured after recompression, which was due to losses of 53% in the compressor and the beam transport optics. Assuming Gaussian-shaped pulses, a duration of 191 fs (FWHM) was measured with a single-shot second-harmonic generation autocorrelator [see Fig. 3(b)].

The amplifier dynamics both on a nanosecond and microsecond time scale are shown in Fig. 4. A maximum pulse energy of 905 mJ without optical damage was achieved using nanosecond pulses. Laser induced damage to the AR coating of the Yb:CaF$_2$ crystal was observed at an output pulse energy of 956 mJ. Owing to the quasi-three-level scheme of Yb^{3+}, a minimum pump energy of 5.9 J was required to bleach out the absorption at the laser wavelength. This reduces the extractable energy by 27% at a peak absorbed pump energy of 18 J for nanosecond operation of the amplifier. In general, the damage threshold and the minimum pump energy of Yb-doped gain

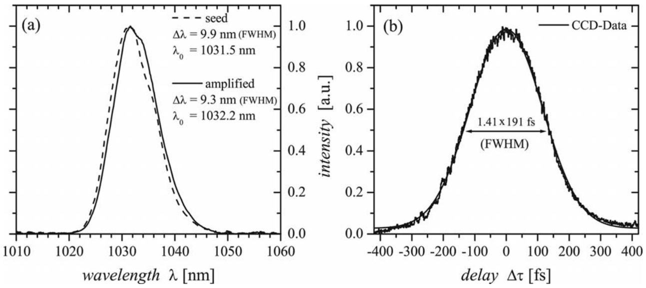

Fig. 3. Chirped pulse amplification: (a) Spectra of seed and amplified laser pulses (total gain, 10.5); (b) corresponding intensity autocorrelation.

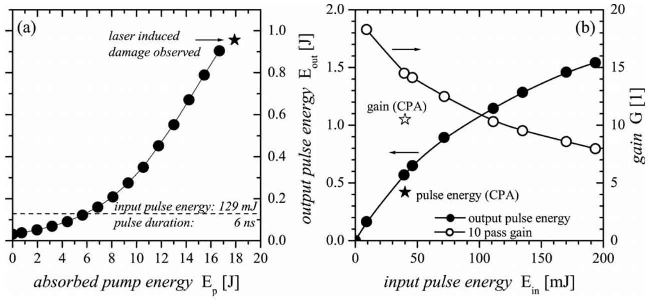

Fig. 4. Dynamic of the multipass amplifier; repetition rate, 1 Hz. (a) Nanosecond pulse amplification: output pulse energy versus absorbed pump pulse energy, input pulse energy of 129 mJ, pulse duration of 6 ns; (b) CPA and amplification of flat-top-shaped 100 μs pulses: output pulse energy and total gain versus input pulse energy at an absorbed pump pulse energy of 21.6 J.

media are limiting factors for the extraction efficiency of short-pulse amplifiers. However, the population of the lower laser level can be significantly reduced at cryogenic temperatures (≈70 K) [13].

When operating with microsecond pulses [see Fig. 4(b)] the extractable energy can be determined without the danger of laser-induced damage. In this case, an output pulse energy of 1.54 J (15.4 kW peak output power) was obtained. From the near-field beam profiles a peak output fluence of 4.9 J cm^{-2} at microsecond or 3.1 J cm^{-2} at nanosecond pulses was calculated.

With regard to the number of laser diodes invested, a minimum pump power of 7.4 kW per terawatt peak power or 7.7 kW per joule pulse energy of the directly diode-pumped amplifier was required. An optical-to-optical conversion efficiency of 3.9% for nanosecond or 1.4% for chirped-pulse amplification was obtained, which are of the same order of magnitude achieved with similar HEC-DPSSL systems mentioned above.

In this work we demonstrated for the first time (to our knowledge) chirped-pulse amplification to the terawatt level in a fully diode-pumped scheme employing Yb:CaF_2 as an amplification medium. We also presented the amplification of nanosecond pulses to the joule level using Yb:CaF_2, showing the potential of this promising new laser material for diode-pumped large-scale high-energy nanosecond lasers. Although the efficiency of the CPA described is a few percent, there is a large potential for further optimization and scaling of this current terawatt diode-pumped prototype laser. In summary, we believe that with further improvement of its optical quality, Yb:CaF_2 will be a promising gain medium for future ultrahigh-peak-power diode-pumped laser systems.

We thank M. Rabe, R. Bertram, N. Jovanov, M. Hellwing, R. Kind, and K. Rühle. This work has been supported by the German Federal Ministry of Education and Research (BMBF) under contract 03ZIK052 (ultra optics).

References

1. D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
2. E. W.Gaul, M. Martinez, T. Ditmire, S. Douglas, W. Henderson, J. Blakeney, J. Caird, A. Erlandson, I. Iovanovic, C. Ebbers, and B. Molander, in *Advanced Solid-State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper WD2.
3. M. Aoyama, K. Yamakawa, Y. Akahane, J. Ma, N. Inoue, H. Ueda, and H. Kiriyama, Opt. Lett. **28**, 1594 (2003).
4. H. Liu, S. Biswal, J. Paye, J. Nees, G. Mourou, C. Hönninger, and U. Keller, Opt. Lett. **24**, 917 (1999).
5. I. Ross, P. Matousek, M. Towrie, A. Langley, and J. Collier, Opt. Commun. **144**, 125 (1997).
6. R. Yasuhara, T. Kawashima, T. Sekine, T. Kurita, T. Ikegawa, O. Matsumoto, M. Miyamoto, H. Kan, H. Yoshida, J. Kawanaka, M. Nakatsuka, N. Miyanaga, Y. Izawa, and T. Kanabe, Opt. Lett. **33**, 1711 (2008).
7. A. Bayramian, P. Armstrong, E. Ault, R. Beach, C. Bibeau, J. Caird, R. Campbell, B. Chai, J. Dawson, C. Ebbers, A. Erlandson, Y. Fei, B. Freitas, R. Kent, Z. Liao, T. Ladran, J. Menapace, B. Molander, S. Payne, N. Peterson, M. Randles, K. Schaffers, S. Sutton, J. Tassano, S. Telford, and E. Utterback, Fusion Sci. Technol. **52**, 383 (2007).
8. J. Hein, M. Kaluza, R. Bödefeld, M. Siebold, S. Podleska, and R. Sauerbrey, Lect. Notes Phys. **694**, 47 (2006).
9. A. Lucca, G. Debourg, M. Jacquemet, F. Druon, F. Balembois, P. Georges, P. Camy, J. Doualan, and R. Moncorgé, Opt. Lett. **29**, 2767 (2004).
10. P. Camy, J. Doualan, A. Benayad, M. von Edlinger, V. Ménard, and R. Moncorgé, Appl. Phys. B **89**, 539 (2007).
11. C. Wandt, S. Klingebiel, M. Siebold, Z. Major, J. Hein, F. Krausz, and S. Karsch, Opt. Lett. **33**, 1111 (2008).
12. M. Hornung, R. Bödefeld, M. Siebold, M. Schnepp, J. Hein, and M. Kaluza, Appl. Opt. **46**, 7432 (2007).
13. A. Pugžlys, D. Sidorov, A. Ali, A. Baltuška, L. Su, J. Xu, R. Li, L. Giniūnas, and R. Danielis, in *Advanced Solid-State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2008), paper MF4.