Multi-mJ, 200-fs, cw-pumped, cryogenically cooled, Yb,Na:CaF_2 amplifier

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Received March 20, 2009; revised May 15, 2009; accepted May 15, 2009;
posted June 4, 2009 (Doc. ID 109037); published June 30, 2009

Using a novel (to our knowledge) broadband Yb-doped $Yb^{3+},Na^{+}:CaF_2$ crystal cooled in a closed loop to 130 K we demonstrate a chirped pulse regenerative laser amplifier delivering the energy of up to 3 mJ at a repetition rate of 1 kHz and an average output power of 6 W at 20 kHz. The gain narrowing in the laser crystal is compensated by shaping the amplitude of the seed pulse spectrum. As the result, at the highest amplified pulse energy we obtain a 12 nm FWHM bandwidth supporting a 130 fs pulse duration, assuming ideal compression. Amplified pulses were recompressed from 250 ps to 195 fs with a 1700 lines/mm transmission grating compressor. © 2009 Optical Society of America

OCIS codes: 140.7090, 140.3615.

A wide variety of high-field applications and the rapidly developing technology of chirped-pulse parametric amplification motivate the development of economic, directly diode-pumped, broadband, solid-state laser systems that are scalable in output energy and average power. Among broadband Yb^{3+}-doped materials, CaF_2 is the focus of attention for developing high-peak and average-power tunable femtosecond oscillators and amplifiers [1–4] because of a low quantum defect, high damage threshold, low linear and nonlinear refractive indices, and suitability for direct pumping with laser diodes. In this work we utilize the known advantages of low-temperature crystal cooling [5] by applying it to a recently developed codoped host, $Yb^{3+},Na^{+}:CaF_2$ [6]. Cooled to cryogenic temperatures the crystal exhibits a significant increase of absorption cross section and a disappearance of ground state absorption (GSA) beyond 1000 nm [7]. The decreased GSA and increased emission cross section lead to a considerably higher gain cross-section at cryogenic temperatures. A marked advantage of $Yb^{3+},Na^{+}:CaF_2$ over other broadband Yb crystalline hosts, including the singly doped $Yb^{3+}:CaF_2$, is that the codoping with Na^{+} results in a substantial broadening in the blue wing of the zero phonon line, with this broadening preserved even at cryogenic temperatures [7]. Consequently, $Yb^{3+},Na^{+}:CaF_2$ is well suited for pumping with conventional ~980 nm diode stacks without the need for the emission wavelength stabilization with Bragg gratings.

Previously, Kawanaka and coworkers reported multi-mJ femtosecond pulses from a 20 Hz LN2-cooled $Yb^{3+}:YLF$ regenerative amplifier (RA) using a pulsed diode pump [8,9] which permits significantly higher gain and output pulse energies in comparison with cw-pumped Yb amplifiers [10]. Ripin and coworkers have developed a 300 W cw-pumped cryogenically cooled Yb:YAG laser [11]; however a RA based on this technology has not been reported yet (to our knowledge).

In this Letter we present what we believe to be the first multi-mJ-class, cw-pumped, femtosecond Yb amplifier. We explain the design and characterize the performance of a Yb-fiber-laser seeded, closed-loop cryogenically cooled, kHz-repetition-rate $Yb^{3+},Na^{+}:CaF_2$ regenerative amplifier (CRA) that produces few-mJ, sub-200 fs pulses at a kHz repetition rate.

The layout of the CRA cavity is presented in Fig. 1. An antireflection (AR)-coated $2\%Yb^{3+},3\%Na^{+}:CaF_2$ slab with a length of ~4 mm and a height of 1.2 mm is sandwiched using optical contact between two plates of artificial diamond (Diamond Materials GmbH) which are In-soldered onto a copper heat sink. The crystal assembly is mounted inside a cryogenic chamber and cooled to a temperature of 130 K with a closed-loop refrigerator (CryoTiger). The isotropic crystal is pumped in a double-pass configuration (bottom of Fig. 1) with circularly polarized light from two 60 W diode laser bars (Jenoptik Laserdiode GmbH) coupled to a set of micro-optics (Light Conversion, Ltd.). A thin-film polarizer in front of each diode bar is used to block the unabsorbed pump light, the polarization of which is rotated by 90° in two passes through a quarter-wave plate. Because the overall quantum defect of our system is about 5%, the crystal temperature increases only very modestly to ~140 K under the full combined pump power of both diodes. The photoinduced thermal lens in the $Yb^{3+},Na^{+}:CaF_2$ crystal as estimated from a compari-

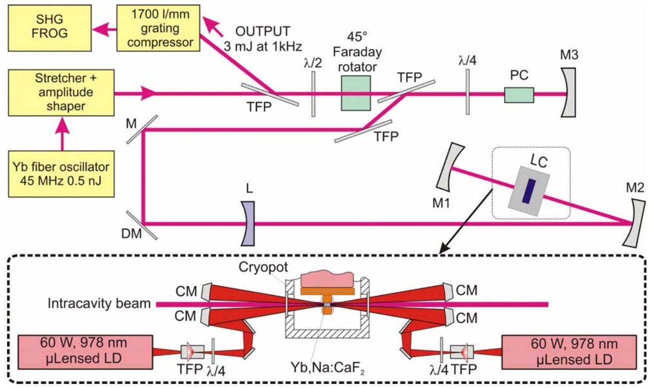

Fig. 1. (Color online) Schematics of cryogenically cooled $Yb^{3+}, Na^{+}:CaF_2$ RA. M1, M2, M3, curved mirrors with ROC −300 mm, −500 mm, and −2500 mm, respectively; LC, cryogenically cooled laser crystal chamber; L, negative lens, $f=-400$ mm; DM, dichroic mirror; M, folding mirror; TFP, thin film polarizers; PC, Pockels cell; λ/2 and λ/4, half- and quarter-wave plates; LD, laser diode bars. The roundtrip time of the RA cavity is 13.3 ns. Bottom panel, schematic of the double-pass pumping.

son of numerical intracavity beam tracing, performed using the ABCD matrix formalism and beam profile measurements at various positions in the cavity, corresponds to $f=-500$ mm under the lasing conditions at 50 W of pump power. The dichroic mirror DM in the cavity (Fig. 1) suppresses parasitic lasing at ~1000 nm.

The output of the CRA exhibits an excellent spatial profile and a comparatively high slope efficiency. As shown in Fig. 2, the beam profile is virtually ideally Gaussian in both vertical and horizontal cross-sections with an M^2 of ~1.05. In cw mode, the 2-m-long CRA cavity delivers more than 14 W output at an incident pump level of ~60 W, corresponding to a 25% slope efficiency. At a 1 kHz repetition rate, 3 mJ 12-ns-long pulses are generated in the Q-switched regime, whereas in ps operation mode the seed pulses are amplified to 2 mJ (Fig. 3). The incident pump power on the crystal was 60 W and 36 W, respectively. Further amplification in the case of the 1 kHz repetition rate is forestalled by optical damage of the AR coatings of the crystal. The laser mode size on the $Yb:CaF_2$ crystal was ∅300 μm at the $1/e^2$ level.

At 20 kHz repetition rate, the ps pulses are amplified to 300 μJ, corresponding to an average extracted power of 6 W. It is important to note that the average

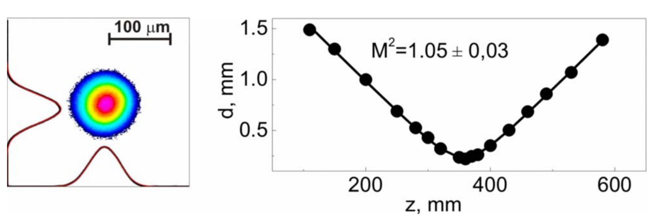

Fig. 2. (Color online) Left, profile of the 1 mJ 1 kHz output beam in the focus of a lens ($f=300$ mm); curves, vertical and horizontal beam profile cross sections. Right, M^2 measurement; dots, experimental data; solid curve, a fit corresponding to an M^2 of 1.05.

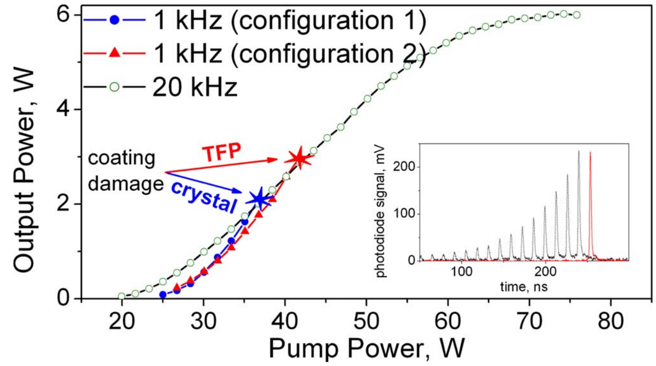

Fig. 3. (Color online) Dependence of the output power on the incident optical pump power in the CPA regime. Solid circles and triangles correspond to two different cavity configurations, described in the text, at the repetition rate of 1 kHz and 90 cavity round trips. Open circles show the performance at 20 kHz. Inset, oscilloscope traces of the intracavity pulse train (dashed curve) and the selected pulse (solid curve) taken at the 3 mJ output energy.

power saturation at 20 kHz is mainly caused by a decreased pump absorption efficiency owing to the redshift of the pump diode wavelength at higher currents. To test the feasibility of pulse amplification to higher pulse energies, an adjustment of the cavity configuration was made to increase the mode size on the crystal. This allowed the generation of 5 mJ nanosecond pulses in the Q-switched regime and amplification of the picosecond pulses to 3 mJ at a 1 kHz repetition rate (Fig. 3). However, the modification also causes a decreased spot size on the thin film polarizers (TFP), leading to optical damage of the TFP coating. It is important to note that neither the pulse train saturation (inset in Fig. 3) nor a bistable behavior of the pulse train are present in the 3 mJ 1 kHz output despite a ~1.7 ms effective storage time of the laser crystal. This reveals a possibility for further scaling of the amplified pulse energy by switching to a Brewster-angle-cut CaF_2 crystal or by improving the quality of the dielectric AR coatings.

In the picosecond regime, the CRA was seeded with a stretched-to-250 ps output of a femtosecond Yb fiber laser. The fiber laser generates a 25 nm FWHM spectrum centered at 1034 nm. A positive dispersion stretcher with a 40% throughput is based on a single transmission grating (1700 l/mm, Wasatch Photonics) and a R=−600 mm spherical mirror. Seeded with an unshaped spectrum, the amplifier supports a ~5 nm bandwidth centered at 1031 nm (dashed curve, Fig. 4). To compensate for spectral gain narrowing in the amplifier, we introduced an amplitude shaper in the Fourier plane of the stretcher. Spectral preshaping of the seed (thick dotted curve, Fig. 4), obtained at an added 60% loss of the seed power, enables the generation of ~12 nm FWHM spectrum of the amplified mJ pulses (solid curve, Fig. 4). The amplified pulse spectrum broadens mostly on the blue side, where the gain is higher.

The amplified pulses were recompressed with a 50% throughput grating compressor based on a single transmission grating (1700 l/mm, Wasatch Photonics, grating separation ~200 mm). The pulse

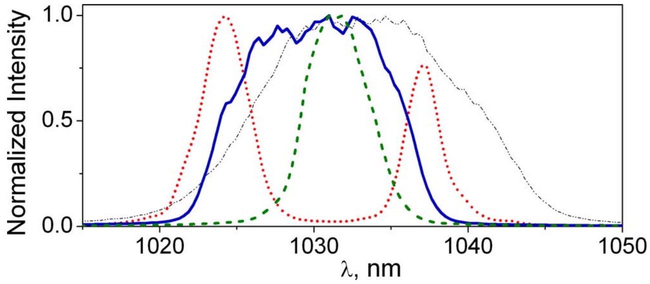

Fig. 4. (Color online) Spectra of the seed laser before (thin dotted curve) and after (thick dotted curve) shaping; resulting spectra of the RA output without (dashed curve) and with (solid curve) shaper installed.

duration inferred from frequency-resolved optical gating (FROG) (Fig. 5) is 195 fs, whereas the calculated spectrum-limited pulse duration is ~130 fs. This suggests that a more careful higher-order dispersion control is required to handle the rather broad bandwidth obtained from the Yb^{3+},Na^{+}:CaF_2 amplifier.

Note that special care was taken to maximize the intracavity beam size at highly nonlinear CRA elements to keep the level of the overall B-integral of the system low. Specifically, the measured mode size at the 30-mm-long β-barium borate optical (BBO) Pockels cell was 1.2 mm at the $1/e^2$ level. As evidenced by the second-harmonic generation (SHG) FROG measurements at different levels of amplification (up to 2.5 mJ of the output energy) for a fixed number of cavity round trips, the pulse compressibility is not noticeably affected at high output energies, implying that the nonlinear phase is well under control.

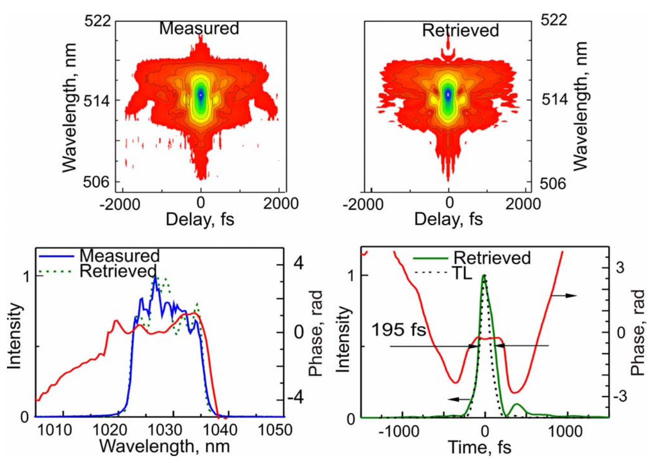

Fig. 5. (Color online) Recompressed pulse measurement with SHG FROG for the output energy of 1 mJ. TL represents the transform-limited pulse.

In conclusion, the Yb host, CaF_2 codoped with Na^{+} crystal, despite being a low-gain-cross-section material, presents considerable interest for cw-pumped CRA of multi-mJ ~100-fs pulses with repetition rates around 1 kHz. By seeding the cryogenically cooled diode-pumped solid-state Yb^{3+},Na^{+}:CaF_2 CRA with the pulses from an Yb fiber oscillator we have generated 3 mJ pulses with a spectral bandwidth of 12 nm. The pulses are compressed with a single grating compressor to 195 fs as confirmed with SHG FROG. Amplification beyond 3 mJ is feasible by improving the the quality of AR coatings, as well as by optimizing the CRA cavity. Spectral shaping of the seed is crucial for amplification of broad spectra and shows potential for attaining ~100 fs pulses. Further scaling of the energy to the level of tens of mJ at a kHz repetition rate can be achieved by designing a diode-laser-pumped, cryogenically cooled Yb^{3+},Na^{+}:CaF_2 multipass amplifier.

This work has been supported by the Austrian Science Fund (FWF), grants U33-N16 and F1619-N08, and the Austrian Research Promotion Agency (FFG), project 819292.

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