Femtosecond Chirped Pulse Amplification in Cryogenically Cooled Yb,Na:CaF_2

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Abstract

By seeding stretched pulses from a femtosecond Yb fiber oscillator into a cryogenically cooled DPSS regenerative amplifier based on a novel Na^+-co-doped Yb^{3+}:CaF_2 laser crystal, we obtain >3-mJ pulses at a 1-kHz repetition rate with a spectral bandwidth exceeding 12 nm. The pulses are compressed with a single grating compressor to 173 fs as verified by SHG FROG. Shaping of the spectral amplitude of the seed and active control of the higher order phase is shown to be crucial for obtaining sub-200-fs pulses at multi-mJ energies.

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 the output energy and average power. Among broadband Yb^{3+}-doped materials, CaF_2 is in 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 co-doped 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 the 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 (Fig.1).

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 co-doping with Na^+ results in a substantial broadening in the blue wing of the zero phonon line (ZPL), with this broadening preserved even at cryogenic temperatures (Fig.1).

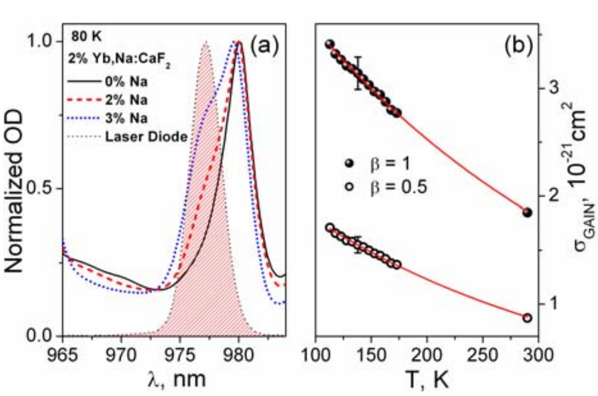

Fig.1. (a) Absorption spectra of Yb,Na:CaF_2 at 80 K at different Na concentrations (indicated in the panel) and typical laser diode spectrum (filled area). (b) temperature dependence of gain cross-section at two fractions of the excited state population.

In this contribution we present the first to our knowledge multi-mJ-class cw-pumped femtosecond regenerative amplifier (CRA) that produces few-mJ sub-200-fs pulses at kHz repetition rate. Previously, K. Yamakawa 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]. T.-Y. Fan and coworkers have developed a 300-W cw-pumped cryogenically cooled Yb:YAG laser

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[11], however a RA based on this technology has not been reported yet.

The layout of the CRA cavity is presented in Fig. 2. An AR-coated 2%Yb^{3+},3%Na^{+}:CaF_2 slab with the length of ~4 mm and the height of 1.2 mm is sandwiched using an optical contact between two plates of artificial diamond (Diamond Materials GmbH) which are In-soldered onto a copper heatsink. The crystal assembly is mounted inside a cryogenic chamber and cooled to the temperature of 110 K with a close-loop refrigerator (CryoTiger). The isotropic crystal is pumped in a double-pass configuration (bottom of the Fig. 2) with circularly polarized light from two 60-W diode laser bars (Jenoptik Laserdiode GmbH) coupled to a set of microoptics (Light Conversion, Ltd.). A thin film polarizer in front of each diode bar is used to block off 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 comparison of a 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. 2) is installed to suppress parasitic lasing at ~1000 nm.

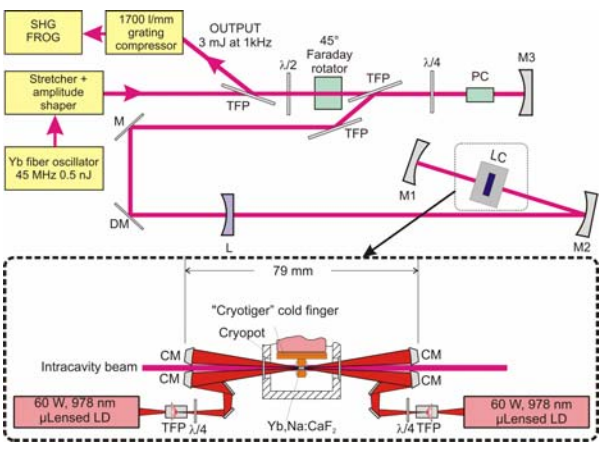

Fig.2. Schematics of cryogenically cooled Yb^{3+},Na^{+}:CaF_2 RA. M1, M2 and M3 are curved mirrors, LC– cryogenically cooled laser crystal chamber, L – negative lens, DM – dichroic mirror, M – folding mirror, TFP – thin film polarizers, PC– Pockels cell, λ/2 and λ/4 – half- and quarter-waveplates, LD –laser diode bars. Bottom panel: schematics for a double-pass pumping.

The output of the CRA exhibits an excellent spatial profile and a comparatively high slope efficiency. The beam profile is virtually ideally Gaussian in both vertical and horizontal cross-sections with the M^2 of ~ 1.05 measured in the picosecond operation regime. In the cw mode, the 2-m-long CRA cavity delivers a more than 14 W output at the incident pump level of ~60 W, corresponding to a 25% slope efficiency. At a 1-kHz repetition rate 5-mJ 12-ns-long pulses are generated in the Q-switched regime, whereas in the ps operation mode the seed pulses are amplified to a 3-mJ level (Fig. 3). Further amplification in the case of the 1-kHz repetition rate is prevented by optical damage of the AR coatings either of the crystal or of TFP (in dependence of CRA cavity configuration). At a 20-kHz repetition rate, the ps pulses are amplified to a 300-μJ level, corresponding to an average extracted power of 6 W. It is important to note that the average power saturation at 20 kHz is mainly caused by a decreased pump absorption efficiency caused by the red shift of the pump diode wavelength at higher currents. It is important to notice that neither the pulse train saturation (inset in the figure 3) nor a bi-stable behavior of the pulse train are present in the 3-mJ 1-kHz output despite an ~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.

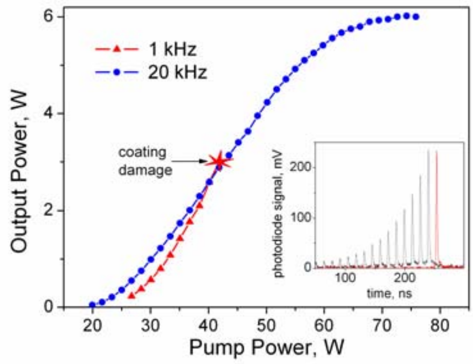

Fig.3. Dependence of the output power on the incident optical pump power in the CPA regime at the repetition rate of 1 kHz (triangles) and 20 kHz (circles). The inset shows the oscilloscope traces of the intracavity pulse train (black) and the selected pulse (red) taken at the output pulse energy of 3 mJ.

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 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 an ~5-nm bandwidth centered at 1031 nm (dashed green curve, Fig. 4). To compensate spectral gain narrowing in the amplifier, we introduced an amplitude shaper in the stretcher. Spectral pre-shaping of the seed (red dotted curve, Fig. 4), obtained at an added 60% loss of the seed power, enables the generation of a ×2.5 broader, 12 nm FWHM, spectrum of the amplified mJ pulses (solid blue curve, Fig. 4).

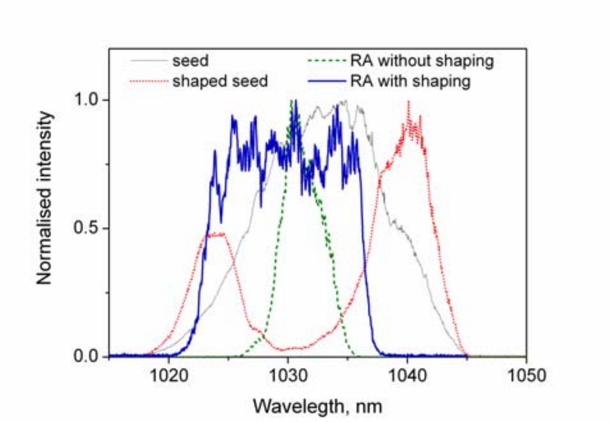

Fig.4. Spectra of the seed laser before (thin black line) and after (red dotted line) shaping, and resulting spectra of the RA output without (green dashed line) and with (blue solid line) the shaper installed.

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 duration inferred from FROG (Fig.5.) is 173 fs, which is close to the calculated spectrum-limited pulse duration of 165 fs.

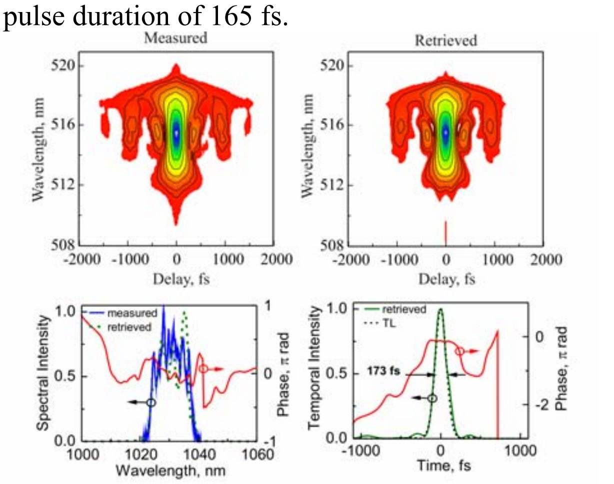

Fig.5. Recompressed pulse measurement with SHG FROG for the output energy of 1 mJ. TL represents the transform limited pulse.

Such a high level of the compression is achieved with the help of a piezoelectric deformable mirror (Flexible Optical B.V.), installed in the stretcher, which allows careful higher-order dispersion control. 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. As evidenced by the SHG FROG measurements at different levels of amplification (up to 2.5 mJ of the output energy) for a fixed number of cavity roundtrips, the pulse compressibility is not noticeably affected at high output energies, implying that the nonlinear phase is well under control.

In conclusion, the novel Yb host, CaF_2 codoped with Na^+ crystal, despite being a low gain cross-section material, presents a considerable interest for cw-pumped CRA of multi-mJ femtosecond pulses with repetition rates around 1 kHz. By seeding the cryogenically cooled DPSS 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 173 fs as confirmed with SHG FROG. Shaping of the spectral amplitude of the seed and active control of the higher order phase appear to be crucial for obtaining close to transform limited sub-200 fs pulses. Further scaling of 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.

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