Dual-crystal Yb:CALGO high power laser and regenerative amplifier

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Abstract: This paper reports on a high-power dual-crystal Yb:CALGO laser head with greatly reduced sensitivity to thermal lensing in the gain medium. In continuous-wave operation 23 W of power were extracted from 2% doped crystals, and tunablity between 1018 nm and 1060 nm was demonstrated. This is the highest output power reported from a bulk Yb:CALGO laser to date, as well as the demonstration of the broadest tuning range. 4 mJ pulses at 1040 nm were achieved in cavity-dumped operation with quasi-CW pumping at 1 kHz repetition rate with nearly diffraction-limited beam quality. When seeded at 1030 nm with stretched femtosecond pulses, 3 mJ were achieved.

OCIS codes: (140.3615) Lasers, ytterbium; (140.3460) Lasers; (140.7090) Ultrafast lasers; (140.3540) Lasers, Q-switched.

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1. Introduction

Multi-mJ pulses with 100-500 fs pulse duration are ideal for pumping of optical parametric amplifiers [1]. When designing a kHz repetition rate system, the lifetime of the gain material has to be considered. Longer lifetimes give the advantage of increased energy storage, allowing high extraction efficiencies under pulsed pumping. This requirement limits the usability of many Yb-doped materials, like tungstates.

The first femtosecond laser operation of Yb:$CaAlGdO_4$ (Yb:CALGO) was reported in 2006 [2] and bulk [3–7] as well as thin-disk lasers [8,9] have been operated. Recently, tunability over 80 nm with more than 20 W of output power was achieved from a thin-disk setup [10]. In a single-crystal cavity, 12.5 W with sub-100 fs pulse duration were obtained in [3]. This promising material has thus successfully demonstrated its ability to reach high power as well as ultra-short pulses.

This paper presents a novel design for a multi-mJ, sub-500 fs, kHz repetition rate regenerative amplifier based on Yb:CALGO. 500 fs long pulses correspond to a Fourier-limited bandwidth of 2.2 nm at FWHM. To reach multi-mJ energy levels a gain of 60 dB is necessary, which leads to strong gain narrowing. To minimize gain narrowing, CALGO was chosen as gain material, since it shows the largest bandwidth for Yb-doped lasers. The undoped host CALGO has a thermal conductivity of 9.5 W/m/K [11]. The lifetime of the ytterbium ions in this host is 420 µs [3], about half the value of YAG at room temperature. Both properties make Yb:CALGO, in principle, better qualified for an amplifier crystal than Yb:KYW (3.6 W/m/K and 300 µs). Also, the pump wavelength at 979 nm reduces the quantum defect to 5%, resulting in a reduced heat load. Recent measurements showed a decrease of thermal conductivity with increasing doping concentration [11]. Taking this into consideration, a thermal conductivity of 6.3 W/m/K for a 2% doped crystal and 5 W/m/K for a 5% is expected. This is still close to half the thermal conductivity of Yb:YAG. For operation at 1030 nm, an emission cross-section of 0.8×10^{-20} cm^2 has been measured for polarization along the c-axis [2].

This paper reports on cw-operation of a Yb:CALGO laser at 1030 nm with greater than 15 W of output power between 1030 nm and 1057 nm and a maximum output power of 23 W at 1042 nm. When operated as seeded regenerative amplifier at 1030 nm, in the absence of a seeder at 1042 nm, pulse energies up to 3 mJ have been extracted at 1 kHz repetition rate limited by the reduced gain of the material, at this wavelength, to two-third of its maximal value.

2. Experimental set-up

A bulk crystal regenerative amplifier was implemented, using a cavity design similar to the one shown in [12]. The dual crystal approach was chosen in order to distribute the thermal load and to accommodate the thermal lensing in the gain medium when compared to a single-crystal.

The layout of the resonator, shown in Fig. 1, was based on a segmented design, separating the easy to align short resonator containing the gain modules from the extended resonator containing the Pockels cell. The short resonator comprised mirrors M1, M2, both dichroic mirrors (DC) and the output couplers OC1 and OC2. This cavity was extended with the mirrors M3 to M6 to include Pockels cell and thin-film polarizer. The short cavity was symmetric around the symmetry point S, between the crystals, each half building a stable resonator with identical beam parameters, used to characterize the crystals independently.

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A careful choice of the distances ensured that the spot size in the crystals and on the output couplers were insensitive with respect to thermal lensing in the crystals over a large region of focal length covering 280 mm to more than 800 mm, while at the symmetry point the waist size was able to vary freely with a changing thermal lens. As shown in [13], this is the case when the distance between the symmetry point and the crystal is equal to the Rayleigh length of the waist. This insensitivity is particularly advantageous to have a laser head operating over a large range of pump powers, through continuous-wave (CW) or quasi-CW (QCW) pumping regimes, while ensuring a good stability of the beam parameters. The cavity could be operated both at full CW pump power and at reduced duty-cycle quasi-CW pump power in the cavity-dumped and regenerative amplifier mode. The strength of the thermal lens could be estimated by measuring the waist at the symmetry point S.

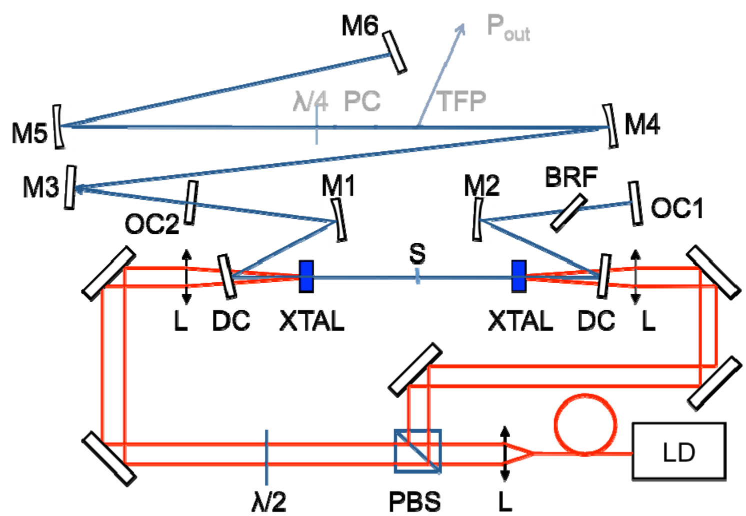

Fig. 1. Layout of the dual-crystal cavity. The abbreviations of the components are L for lenses, DC dichroic mirror, PBS polarization beam splitter, LD laser diode, λ/2 and λ/4 half- and quarter-waveplate, XTAL1 and XTAL2 both Yb:CALGO crystals, PC Pockels cell, TFP thin film polarizer and BRF birefringent filter. M1 to M6 are high reflectors, M1 and M2 curved mirrors with 500 mm radius of curvature, while M4 and M5 have 1000 mm radius of curvature, and OC1-2 are output couplers. S denotes the symmetry point of the short cavity, defined between OC1 and OC2. A high reflector was inserted at S to build the stable single-crystal resonator with OC1. OC2 was removed to operate the long cavity, from OC1 to M6. For cavity-dumped operation, OC1 was replaced by a high reflector and the switching elements were inserted.

The commercially available a-cut CALGO crystals were pumped with a fiber-coupled laser diode (N-Light: model P2-120-0982-2-TKS-C). The temperature of the laser diode was controlled for pumping at the peak absorption wavelength of CALGO of 979 nm. The 4 nm spectral bandwidth of the diode was well matched to the 8 nm absorption bandwidth of the laser medium. The CALGO crystals were pumped polarized along the a-axis because of the higher absorption cross-section of 2.7×10^{-20} cm^2 in comparison with a polarization along the c-axis with absorption cross-section of 1.1×10^{-20} cm^2. The maximum pump power was 120 W; the numerical aperture of 0.22 and the mode field diameter of 200 µm enabled a good mode matching to the laser mode in the crystal. A demagnification of 3:1 fully matched the cavity mode over the length of the crystal. The 3 m long delivery fiber ensured nearly complete depolarization and homogenization of the pump beam, which was collimated before being split in two beams by a polarizing beam splitter working as a polarization analyzer. To match the crystals a-axis, the polarization was turned in one arm with a half-waveplate. An additional pair of lenses focused the beams into the crystals.

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The short cavity was designed for a spot size of about 300 µm in each crystal. By choosing this spot size, the non-linearities in the regenerative amplifier were minimized while keeping enough gain to allow efficient amplification. For cavity-dumped operation, OC1 was replaced with a high reflector, whereas OC2 was removed for operation with the long resonator.

Two doping concentrations were tested: 2% and 5% in the melting pot. Considering the segregation coefficient of 0.49% of ytterbium in the CALGO host, the effective concentrations were around 1% and 2.5%; the later nomenclature will be used in the following. The advantage of low-doped crystals lies in the lower absorption at the entrance surface, thus diminishing its thermal bulging and the total thermal lensing. Due to the high absorption of the 2.5%-doped crystal, shorter crystals could be used, decreasing the non-linearities when operating as a regenerative amplifier. The crystal lengths were 1.5 mm for the 2.5% doped crystal and 2 mm for the 1%-doped one.

3. Results

3.1 Continuous-wave operation

The crystals were first tested in the short, single-crystal cavity. The distance between the crystal and the symmetry point S was set to 157 mm for the 1%-doped crystal. With 2.5% output coupling and 52 W incident pump power (40% absorbed), 11.9 W were extracted at a wavelength of 1045 nm with a beam quality parameter, M^2, better than 1.2. The spatial properties of the beam were measured with a commercial device (Metrolux M^2 Monitor ISO) according to the 4-sigma algorithm.

To compensate for the stronger thermal lens of the 2.5%-doped crystal, the distance between the crystal and point S was adjusted to 107 mm. 11 W were extracted from the 2.5%-doped crystals with 60 W incident pump power, thereof 80% absorbed, and with 5% output coupling. The slope efficiency, measured with respect to the incident and absorbed pump power, was 23% and 32%, respectively. The free-running wavelength decreased from 1056.7 nm to 1047.8 nm whilst the output coupling was increased from 2.5% to 7.5%.

The free-running wavelength of the laserhead with the 1%-doped crystal is closer to the one of the seeder, whose setup is detailed below, than the one with the 2.5%-doped crystal, indicating a higher achievable gain. Also the bigger spot sizes in the 1%-doped crystals than in the 2.5%-doped ones, due to the change of the distance of the crystal to the symmetry point, allow a reduction of the non-linear phase shift in the regenerative amplifier operation. For those two reasons, the experiment was continued exclusively with the 1%-doped crystal cavity.

In the short two crystal cavity, the optimum output coupling to achieve maximum output power was first determined. For this purpose the output coupler was varied while adjusting the pump power to keep the beam quality parameter, M^2, between 1.1 and 1.2. For high output couplers, the limitation was due to the available pump power. The optimum output coupling was determined to be 7.5%, as shown on Fig. 2, corresponding to 305 W intra-cavity power. For output couplers below 6%, the intracavity power is nearly constant, reaching 350 W. It decreased to 138 W for a 12.5% output coupler.

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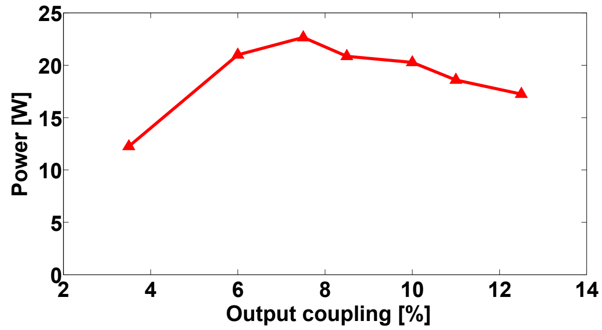

Fig. 2. Variation of output coupling at fixed beam quality parameter, M2 < 1.2.

The cavity was further characterized with the 7.5% output coupler. Figure 3(a) shows the output power versus incident pump power of the short, two-crystal cavity, with the beam profile in the focus as inset. The beam quality parameter, M^2, was better than 1.2 on both axes. During these measurements, the free-running wavelength of the laser was around 1042 nm. Changing from the short to the long cavity, without the switching elements, no noticeable change of power was observed and the free-running wavelength was still around 1042 nm. The maximum output power obtained was as high as 23 W for an input pump power of 112 W. The slope efficiency was measured to be 37% and the threshold reached 54 W pump power. The focal length of the thermal lens was determined experimentally to be 320 mm at nearly full pump power, which lied well in the estimated range for the cavity design.

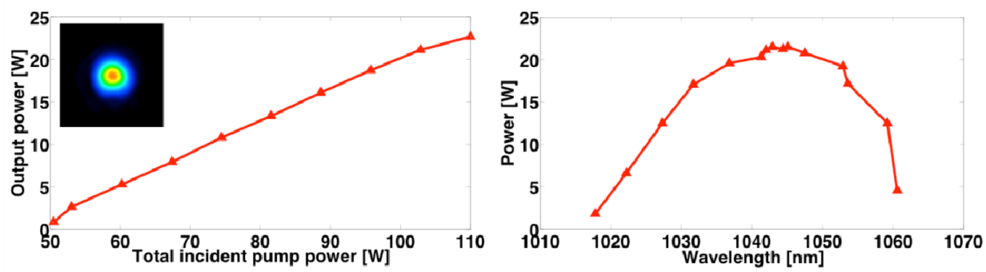

Fig. 3. Characterization of the CW-operation of the dual 1%-doped crystal cavity. (a) Power characterization of the laser head in CW regime, with the beam profile in the focus as inset, and (b) measured tuning curve. The measurement was taken with the 7.5% output coupler and the cavity aligned to ensure a beam quality better than 1.2 at the maximal output power of 23 W.

The wavelength was tuned by inserting a birefringent filter in the cavity [14], as shown on Fig. 3(b) for the 7.5% output coupler and at 112 W pump power. The cavity was easily tunable over a bandwidth as wide as 42 nm, beginning at 1017.8 nm with 1.8 W and ending at 1060.6 nm with 4.5 W output power. More than 20 W were extracted between 1040 nm and 1047 nm. The output power dropped off at long wavelengths due to the reduced emission cross-section of CALGO, and for short wavelength due to the reabsorption losses in the ytterbium ions.

3.2 Cavity-dumping and regenerative amplifier operation

In order to demonstrate cavity dumped and regenerative amplifier operation, the well-known scheme presented in [15] was implemented. A thin-film polarizer, a quarter waveplate and a Pockels cell were inserted in the cavity, where the waveplate and Pockels cell were used in

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combination to turn the polarization of the intracavity pulse either by 90° to capture and eject a pulse or by 180° to amplify the captured pulse.

The repetition rate aimed at was 1 kHz, corresponding to a 1 ms period, which was long compared to the upper state lifetime of the gain material, around 420 µs. To store the maximum possible energy, a pump duration corresponding to one to two upper state lifetimes is necessary. Increased pump duration leads to higher heat dissipation in the crystal, and thus to enhanced thermal effects. To avoid this, a well-known solution lies in quasi-CW operation of the pump diode. As the cavity was designed to be insensitive to the thermal lens and as the product of lifetime and repetition rate was close to 1/2, both pumping schemes, CW and QCW, were implemented.

A Stanford Research pulse-delay generator DG645 was used to synchronize the Pockels-cell, the pulsed power supply of the laser diode and the seed laser.

During the alignment, one of the crystals broke and had to be replaced; however, the new crystal limited the output power to 16.5 W for 105 W of input power. This loss of power was attributed to either a higher concentration of color centers or to impurities in the new crystal, as the control of the crystal growth was still not fully reproducible. These additional losses could not be compensated. The additional intracavity loss of 2% due to the switching elements further reduced the maximum output power in CW-operation at the free-running wavelength of 1045 nm to 10.9 W.

Under both pumping conditions, CW and QCW, 4 mJ-pulses at a repetition rate of 1 kHz were extracted. The similarity of the output-power suggests that the CALGO crystals are not limited by thermal gain quenching. Due to the insensitivity of our cavity, the beam quality was similar for both pumping schemes, even so the thermal load was reduced during the non-lasing time. The extraction time amounted to 3.72 µs for CW-pumping and 3.79 µs in QCW-pumping with pump duration of 650 µs. The amplification duration corresponded to 186 and 187 round trips, respectively.

For the seeded operation, a commercial Yb:KYW bulk oscillator running at a central wavelength of 1030 nm and delivering 16 nJ, 210 fs pulses at 42.5 MHz repetition rate was used. The 6.5 nm spectral bandwidth of the seeder could sustain 170 fs long pulses. To reduce nonlinear effects, the seed pulses were chirped [16] before injection into the regenerative amplifier. They were stretched to the stretching ratio necessary for the amplification stages located after the regenerative amplifier. The stretcher consisted of four chirped fiber Bragg gratings and fiber circulators. The 210 fs compressed oscillator pulse had to be attenuated before coupling in the fiber, to avoid non-linearities. Two ytterbium doped fiber amplifiers were inserted in the stretcher to compensate for the low input energy and for the losses of the stretcher, such that the pulse energy was 1 nJ at the stretcher output. The output pulses were 3 ns long and their bandwidth was limited to 4.5 nm by the combination of the bandwidth of the CFBGs and the fiber amplifiers. Moreover, the CFBGs were designed to compensate for the higher order dispersion of a grating compressor, thus enabling a theoretical recompression to Fourier-limited pulse duration. The central wavelength was matching the one of a following Yb:YAG based amplifier.

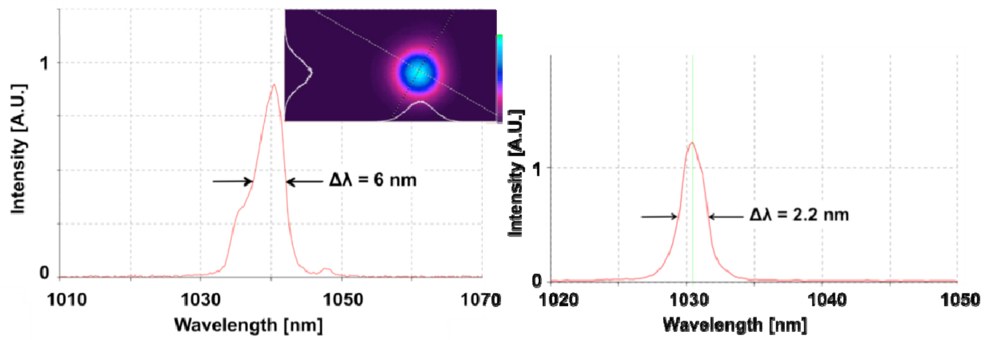

Fig. 4. (a) Spectrum and beam profile at the waist as inset of the cavity dumped pulse; and (b) spectrum for seeded operation. Both cases are for 1 kHz repetition rate, and 118 W of total incident pump power.

Figure 4 shows the spectra in both cavity-dumped and seeded operation for CW pumping. For the cavity-dumped case also the beam profile is shown in Fig. 4(a). The M^2 parameter was in both cases 1.2. In the first case, the spectrum was centered at 1040 nm and was 6 nm wide at FWHM. This corresponded to the maximum gain of the laser, however it did not overlap well with the seeding spectrum, centered at 1029.5 nm. Seeded, as much as 3 mJ were extracted with a 2.2 nm wide spectrum, while the central wavelength shifted to 1031 nm. Both behaviors, gain narrowing and spectral shift, were consistent with the observed tuning curve, which reflects the available gain at each wavelength. As shown in Fig. 3, the gain reached a maximum for wavelengths between 1040 nm and 1047 nm, whereas it reached only two-thirds of that value at 1030 nm, with a decreasing slope towards shorter wavelengths, thus shifting the pulse to longer wavelength during regenerative amplification. The optimal amplification occurred for 2.53 µs extraction time, corresponding to 125 round trips and a single-pass gain G_0 per crystal of 1.03. The high amount of round-trips, due to the low single-pass gain, compensated for the intracavity losses, among others the ones of the Pockels cell, and the reduced amplification off the gain peak of the material. The transform-limited pulse duration would be 500 fs. Due to the strong wavelength shift, the energy comprised in 1 nm around 1029.5 nm represented only a small fraction (20%) of the total pulse energy. This would prevent efficient seeding of follow-on YAG-based amplifiers.

The energy in cavity-dumped operation at 1 kHz was consistent with the lifetime of the material (420 µs) and the CW power. The energy extracted by the seed pulse was also consistent with the gain available around 1030 nm.

Even though Yb:CALGO has a broad emission bandwidth, the spectral shape of the gain is responsible for gain-narrowing, especially for seed spectra not centered on the maximum gain of the material. The measurement of the tuning curve in Fig. 3, reflecting the spectral profile of the gain, shows a maximum gain between 1040 nm and 1047 nm. A short seed-pulse would have to be centered in this wavelength range to be amplified while minimizing gain-narrowing and taking advantage of the broad emission of the material.

4. Conclusion

In the reported experiment, 1% and 2.5% doped Yb:CALGO bulk crystals were used in a high power CW laser and further in cavity dumped and seeded operations. In the single crystal cavity, 11.1 W at a free-running wavelength of 1051 nm was extracted from the 2.5%-doped crystal, as well as above 10 W for a wavelength tuned between 1048 nm and 1057 nm. The CW output power from the dual, 1%-doped crystal was as high as 23 W at a wavelength of 1042 nm; the laser presented a smooth tuning behavior between 1017.8 nm and 1060.6 nm. In cavity dumped operation, pulses with an energy of 4 mJ and a spectrum centered on 1040 nm were extracted out of the cavity at a repetition rate of 1 kHz, in good agreement with the wavelength of the highest gain of the material. When the laser head was used as a regenerative amplifier at the same repetition rate, the 1 nJ seed pulses, centered at 1030 nm, were amplified to 3 mJ. This is the first report on Yb:CALGO used in a cavity dumped laser head and in a regenerative amplifier achieving both the broadest tunability as well as highest CW output power from this material. Seeded between 1040 nm to 1047 nm and considering the CW output power of 23 W and the lifetime of the ytterbium ions in the CALGO host, potentially 10-mJ pulses at 1 kHz repetition rate can be extracted using low loss switching elements. Even though not yet fully mature, the good thermal properties of Yb:CALGO make it a very promising material for a high energy, ultrashort pulses, regenerative amplifier.

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