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$Yb:CaGdAlO_4$ Thin-Disk Laser

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We present the first demonstration of an Yb:CALGO thin-disk laser. In a slightly multimode configuration we obtained up to 30 W of average power at a slope efficiency of 40% and an optical-to-optical efficiency of 32%. With a single-mode cavity, an average power of 25 W was achieved. A tuning range from 1018 to 1052nm could be demonstrated by inserting a prism into the cavity. In Q-switched regime, we obtained 1 mJ of pulse energy at a repetition rate of 100 Hz. © 2011 Optical Society of America

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Ultrafast thin-disk oscillators permit the generation of pulsed radiation with high average power, high efficiency and good beam quality [1,2]. Indeed, the concept of using a very thin crystal cooled on its back side leads to efficient cooling and a reduced thermal lens. Furthermore, the commonly used recycling multipass pump configuration enables efficient absorption of the pump light despite the low thickness of the crystal. And finally, the power can be easily scaled by increasing the pump spot diameter while keeping the pump power density constant.

The thin-disk configuration is well mastered with Yb:YAG, which was first selected because of its easy growth, mechanical robustness and high peak emission cross section compared to other Yb-doped laser materials. Very high average power mode-locked oscillators with energetic pulses (up to 30.7 µJ at 3.5 MHz and 108 W of average power) have been demonstrated with Yb:YAG [3]. Moreover, other interesting results have been published with Yb-doped sesquioxide crystals. Up to 141 W of average power have been obtained with $Yb:Lu_2O_3$ [4]. Likewise, the shortest pulses reported from a thin-disk laser have been achieved with $Yb:LuScO_3$; the pulse duration was 227 fs at an average power of 7.2 W [5]. There is an ongoing search for new materials with larger emission bandwidth and still good thermal properties, enabling the generation of even shorter pulses [6]; Yb:CALGO seems to be an interesting candidate.

In fact, this crystal combines remarkable spectroscopic and thermal properties. Firstly, it shows an exceptionally broad and flat emission bandwidth due to two surroundings for one crystallographic site for both Ca^{2+} and Gd^{3+} cations [7], exhibiting different and atypically compensating emission spectra. Secondly, its thermal conductivity of $6.5\ W{\cdot}K^{-1}{\cdot}m^{-1}$ (measured for a 2 %-doped Yb:CALGO) allows high-power pumping. These properties have been positively used to demonstrate very short pulses at different levels of power and energy in bulk laser geometries [7-9]. Furthermore, the fluorescence lifetime of Yb:CALGO with 2 % doping is 0.42 ms [10]. This small value is in good agreement with the relatively high emission cross-section value. The main limiting factor for this crystal is the difficulty to restrict scattering losses and to obtain high optical quality crystal. Indeed experimental gain measurements show values lower than expected considering the absorption and emission cross sections. These scattering losses strongly depend on the growing process and can severely degrade the laser performance if this process is not well mastered. Nevertheless, the potential for realizing efficient high-power short pulse laser oscillators and amplifiers with Yb:CALGO is considerable. In this letter, we present what to the best of our knowledge is the first demonstration of an Yb:CALGO thin-disk laser in cw and Q-switch regime.

The experiment is performed with a 2%-doped, 350-µm-thick Yb-CALGO crystal, grown by the Czochralski method. It has a highly reflective coating for both pump and laser wavelength on the side that is contacted onto a water-cooled copper-mount heatsink. The other side of the disk has an antireflective coating for the same spectral range. A fiber-coupled diode laser emitting up to 95 W at 980 nm is used for pumping. The pump module allows 24 passes of the pump light through the crystal. The pump spot diameter on the disk is 1.9 mm adapted to a TEM_{00} laser beam waist of 0.6 mm. With a slightly multimode cavity ($M^2 = 1.8$), we obtained up to 30 W of average power, a slope efficiency of 40 %, and an optical-to-optical efficiency of 32 %.

The cavity used for single-mode operation ($M^2 = 1.2$) is shown fig. 1. Figure 2 presents the output power versus the pump power obtained with this cavity with different output coupler (OC) transmissions. With an OC transmission of 5 %, the Yb:CALGO thin-disk laser delivers 25 W of output power, a slope efficiency of 37 %, and an optical-to-optical efficiency of 26 %. The maximum measured round-trip gain is 1.15.

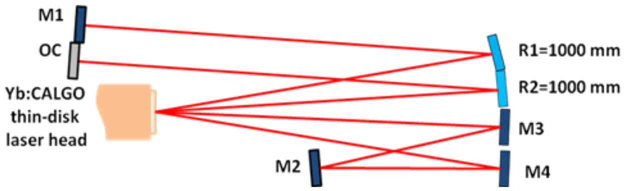

Fig. 1. Experimental setup: M1, M2, M3, and M4, plane HR mirrors; OC: Flat Output coupler. Cavity dimensions: M1-R1 = OC-R2 = 48 cm; R1-TD = TD-M3 = M4-TD = TD-R2 = 41 cm; M3-M4 = 23 cm.

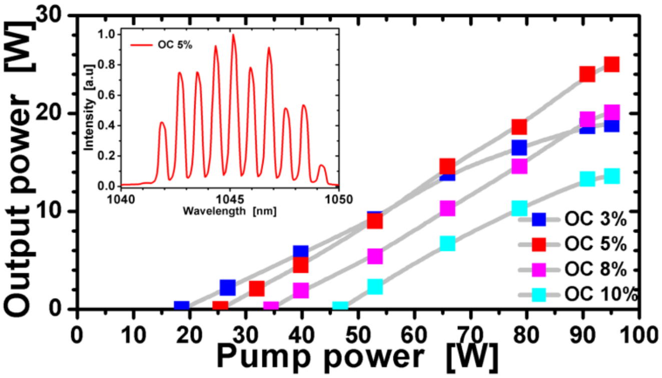

Fig. 2. Output power characteristics with different OC. Inset: Laser spectrum with the optimal OC.

Due to the higher inversion, the central emission wavelength changes from 1048 to 1038 nm when increasing the transmission of the output coupler from 3 to 10 %. The laser emission spectrum obtained with the optimal OC with 5 % transmission is shown in fig. 2. The laser spectrum is structured due to spatial hole-burning [11].

In order to evaluate the potential of the crystal for higher average powers in thin-disk configuration, thermal measurements have also been performed: with an IR camera covering the spectral range of 8-12 µm we measured the thermal cartography of the crystal surface with and without laser operation. The crystal mount temperature is set to 14 °C. Fig. 3 shows the maximum temperature on the crystal for various pump powers. Due to the good thermal properties of the crystal and the efficient cooling, the surface is kept below 90 °C in our configuration. Furthermore, we have noticed a strong difference of crystal temperature with and without laser operation. At full pump power, the maximum temperature varies from 52 °C without to 84 °C with laser operation. This pronounced difference is due to two main effects: reduced pump absorption caused by bleaching of the pump transition at high inversions and a smaller quantum defect under fluorescence operation.

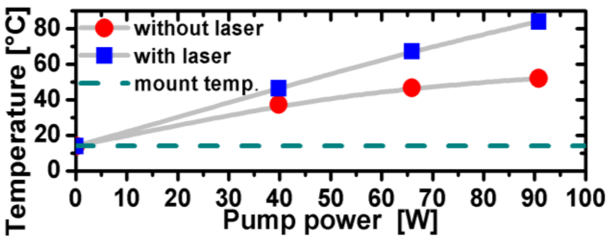

Fig. 3. Evolution of the crystal temperature with the pump power: without (circles) and with (squares) laser operation.

This is confirmed, first, by measuring the remaining pump light after 12 pump passes through the crystal. For 95 W of pump power, 58 W of pump light is absorbed without and 78 W with laser operation, corresponding to an increase of absorption of 35 % with laser operation. The mentioned values are taking into account about 4 W of pump power loss due to 28 reflections at the pump mirrors, having a nominal reflectivity of 99.7 %.

Concerning the thermal load, the laser quantum defect $\eta_Q = 1-\lambda_P/\lambda_L = 6.2\%$ ($\lambda_P = 980$ nm and $\lambda_L = 1045$ nm) is higher than the mean fluorescence quantum defect $\eta_{fluo} = 1-\lambda_P/\lambda_{fluo} = 3.1\%$ ($\lambda_{fluo} = 1011$ nm [8,12]). Thus, a de-excitation by laser emission leads to almost twice the thermal load than by fluorescence emission.

Considering 90W of absorbed pump power (5W lost due to reflections) for 24 passes of pump signal, we obtained 25W of laser signal and 65W of fluorescence emission, which leads to an optical-to-optical efficiency of 28 % relative to the absorbed power. The average quantum defect at this efficiency (taking into account fluorescence and laser photons) is then of 3.6 %. When including the variation of absorption due to saturation, the variation of temperature can be fully explained. Finite element simulations using LASCAD corroborate the temperature rises with and without laser operation assuming a quantum efficiency of 97 %.

By inserting a prism into the cavity, we investigated the tuning range of the laser emission. As can be seen in fig.4, with a 2% OC, we obtain a broad tunability from 1018 to 1052 nm, which is in the same range as the tunability obtained with bulk crystals, permitting to generate sub-100 fs pulses.

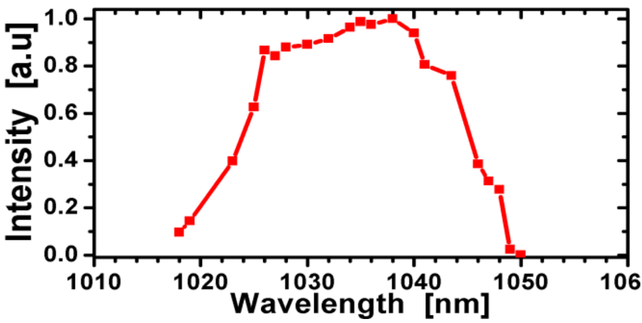

Fig. 4. Experimental laser tunability.

By adding a thin-film polarizer and a Pockels cell to the cavity, we obtained a Q-switched laser regime. This regime permits to estimate the potential of this laser in terms of average power, energy and pulse duration in a regenerative amplifier configuration. We obtained the spectrum shown in fig. 5, which is centered at 1040 nm and has a bandwidth of around 15 nm FWHM, confirming the potential to amplify pulses with about 100-fs duration.

In Fig. 6, output energy and average power are plotted versus the repetition rate. At low repetition rates (< 1 kHz typically, in good agreement with the short fluorescence lifetime of 0.42 ms), we measured 1 mJ of pulse energy. At higher repetition rates the average power increases up to 4.5 W, remaining smaller than in continuous wave because of the high sensibility to losses of our cavity.

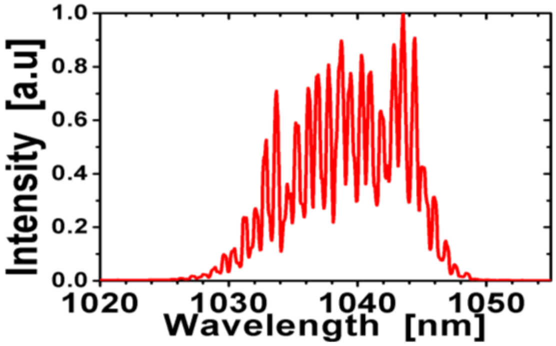

Fig. 5. Laser spectrum in Q-switched regime

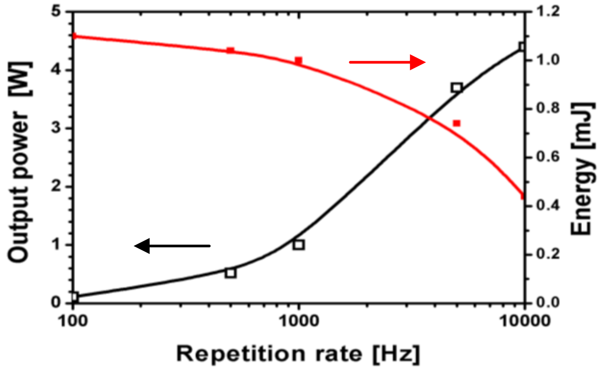

Fig. 6. Evolution of output pulse energy and average power versus repetition rate.

In conclusion, we have demonstrated an Yb:CALGO thin-disk laser operating in continuous-wave and Q-switched regime. We obtained up to 30 W of output power in cw regime, corresponding to an optical-to-optical efficiency of 32 %. In Q-switched regime, we achieved generating pulses with 15 nm FWHM spectral width and an energy at the millijoule level. These promising results demonstrate the actual relevance of Yb:CALGO crystals in thin-disk configuration and the potential to generate sub-100 fs pulses with high average power in oscillator as well as in amplifier configuration with them. Finally, the good thermal behavior of this crystal should permit to pump this crystal with powers in the kW-range.

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