227-fs pulses from a mode-locked $Yb:LuScO_3$ thin disk laser

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Abstract: We report on the first mode-locked thin disk laser based on $Yb:LuScO_3$. This new mixed gain material combines the emission peaks of two sesquioxides, leading to a gain bandwidth of more than 20 nm. We achieve 7.2 W average output power in 227-fs pulses, which is shorter than for any previous ultrafast thin disk laser. The output power was limited by a growth defect near the center of the thin disk.

OCIS codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers

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1. Introduction and motivation

The combination of the thin disk laser concept [1,2] with semiconductor saturable absorber mirrors (SESAMs) [3] resulted in compact mode-locked lasers with unprecedented power levels and pulse energies [4]. Ultrafast thin disk lasers reached average powers of up to 80 W [5], which is higher than for any other mode-locked laser source. Pulse energies as high as 11.3 µJ [6] were generated in a cavity geometry using the thin disk as a simple folding mirror and 25.9 µJ were achieved in an active multi-pass cavity with 13 reflections on the disk [7]. These results were obtained with the well established gain material Yb:YAG (Yb:$Y_3Al_5O_{12}$). Unfortunately, its limited gain bandwidth does not support pulse durations shorter than 700 fs in an efficient high-power mode-locked thin disk laser. This pulse duration is too long for many application areas. An important example is high field science, which previously relied on complex amplifier systems operating at low repetition rates. The multi-megahertz repetition rate of ultrafast thin disk lasers can substantially shorten measurement times and increase signal-to-noise ratio [4]. Ultrafast thin disk lasers are promising for driving high-harmonic generation at high average power levels. Such table-top multi-megahertz VUV/XUV sources with high photon flux would have a high impact in fields as diverse as medicine, biology, chemistry, physics and materials science. So far, high field experiments with Yb:YAG thin disk lasers used external pulse compression [8,9]. Achieving shorter pulses directly from a thin disk laser by employing new gain materials with larger bandwidths is a promising alternative. The shortest pulse duration previously demonstrated with an ultrafast

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thin disk laser was realized with the Yb:KYW (Yb:KY(WO_4)$_2$) gain material, which provides an emission bandwidth of about 25 nm but also a strongly curved spectrum at the emission peak [10]. At a pump power of 100 W, the laser generated 22 W average output power in 240 fs pulses. The laser wavelength was tuned off the emission maximum with a prism and a knife edge, which flattened the gain spectrum. Without intra-cavity spectral shaping, the laser generated 400 fs pulses [11]. Despite these promising first results, which were already published in 2002, power scaling with this gain material is not yet demonstrated. Unfortunately, it is challenging to manufacture high quality thin disks because the host material KYW shows a strong anisotropy in terms of thermo-optical and mechanical properties. This is typical for all monoclinic double tungstate crystals and challenges stable fundamental mode operation at high pump power levels [12,13].

In contrast, Yb^{3+}-doped cubic sesquioxides RE_2O_3 (i.e. with RE = Sc and/or Lu) have isotropic thermo-mechanical properties, making these materials well-suited for power scaling. In conventional laser cavity designs, efficient cw operation with a slope efficiency up to 86% [14] and mode-locked operation with a pulse duration of 65 fs [15,16] have been demonstrated. Thin disk lasers with cubic sesquioxides reached slope efficiencies over 80% and total efficiencies up to 73%, which is better than any other thin disk material [14,17]. The first mode-locked sesquioxide thin disk laser employed Yb:Lu_2O_3 as gain material. It generated pulses as short as 370 fs at a central wavelength of 1034 nm with an average output power of 20.5 W. The laser achieved with 43% a higher optical-to-optical efficiency than previous ultrafast thin disk lasers. The output power was only limited by the available pump power [18]. Very recently, we further improved the mode-locked average output power to 63 W [19], confirming the power scaling potential of sesquioxides for mode-locked thin disk lasers. However, the bandwidth of Yb:Lu_2O_3 does not support substantially shorter pulse durations in thin disk operation. One approach to achieve shorter pulses is the combination of different gain media in one resonator as presented with Yb:Y_2O_3 and Yb:Sc_2O_3 in [20], which resulted in pulses as short as 53 fs with an average output power of 1 W. A more established technique and easier to implement for thin disk lasers is the growth of mixed crystals with a disordered lattice structure to tailor the emission properties and enlarge the gain bandwidth of the gain medium [21,22]. Yb:Sc_2O_3 and Yb:Lu_2O_3 are very suitable for this purpose, because their emission peaks are separated by 8 nm. This is due to the larger splitting of the Yb:Sc_2O_3 Stark-sublevels of the lower $^3F_{7/2}$-multiplet compared to Yb:Lu_2O_3. The new stoichiometrically mixed Yb:$LuScO_3$ combines the emission peaks of both materials, leading to a nearly doubled gain bandwidth of more than 20 nm centered around 1039 nm (Fig. 1). Despite its disordered crystal structure, the thermal conductivity is as high as 3.5 W/(m·K) and remains nearly constant with increasing Yb-doping concentration [23]. Thus, the thermo-mechanical properties of a Yb:$LuScO_3$ thin disk laser have supported a cw output power of 33 W with 45 W launched pump power at a high slope efficiency of 81% [24]. In addition, a conventional low-power SESAM mode-locked Yb:$LuScO_3$ laser generated pulses of only 111 fs, which was half the pulse duration of Yb:Sc_2O_3 in the same laser setup [25]. Here we report on the first passively mode-locked Yb:$LuScO_3$ thin disk laser. We obtained 227-fs-pulses with an average output power of 7.2 W without any spectral shaping or external pulse compression. These are the shortest pulses that have ever been obtained from an ultrafast thin disk laser.

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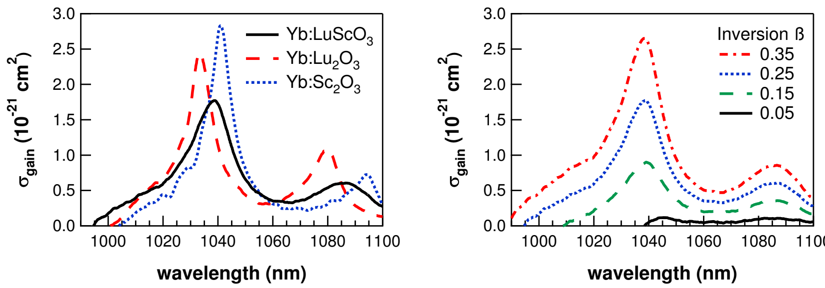

Fig. 1. (color online) Comparison of the gain spectra of $Yb:LuScO_3$ with $Yb:Lu_2O_3$ and $Yb:Sc_2O_3$ for an inversion of $\beta = 0.25$ (left). Gain spectrum of $Yb:LuScO_3$ for different levels of inversion (right).

2. Experimental setup

Our Yb(3%):$LuScO_3$ crystal was grown by the heat exchanger method (HEM) at the Institute of Laser-Physics in Hamburg, Germany [26]. The only available disk has a thickness of 250 µm. It has a highly reflective coating for both pump and laser wavelength on the side which is soldered onto a water-cooled heat sink. The other side of the disk has an antireflective coating for the same spectral range. Additionally, the disk has a wedge of 0.1° in order to reduce the effect of residual reflections into the cavity mode, which can make mode-locked operation unstable. The crystal was pumped with a fiber-coupled diode laser with an emission bandwidth of 3 nm at the center wavelength of 976 nm. Our pump module is set up for 24 passes through the gain medium and a pump spot diameter on the disk of 1.2 mm. The fraction of absorbed pump power in this configuration was estimated to be > 98%. The experimental setup of the laser resonator is shown schematically in Fig. 2.

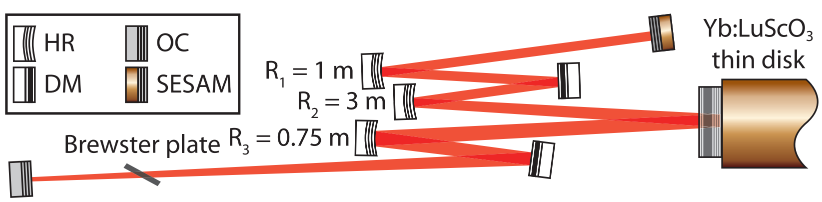

Fig. 2. (color online) Experimental setup of the $Yb:LuScO_3$ thin disk (TD) laser cavity (not to scale). Two dispersive mirrors introduce a negative GDD of ≈-2200 fs^2 per roundtrip. The Brewster plate has a thickness of 5 mm. Cavity dimensions: SESAM-R_1 = 34.9 cm, R_1-R_2 = 42.6 cm, R_2-TD = 47.7 cm, TD-R_3 = 50.1 cm, R_3-OC = 49.4 cm. HR: curved highly reflective mirror, DM: dispersive mirror, OC: output coupler, SESAM: semiconductor saturable absorber mirror.

The $Yb:LuScO_3$ laser head was used as a folding mirror inside a standing-wave cavity. We placed a SESAM as the cavity end mirror to start and stabilize passive modelocking. It consisted of a 30-pair GaAs/AlAs Bragg mirror with two InGaAs quantum well absorber layers placed in the antinodes of the antiresonant standing-wave pattern. Additionally, the cavity contained two dispersive mirrors introducing a total of ≈-2200 fs^2 of negative group delay dispersion (GDD) per cavity roundtrip. A 5-mm thick fused silica plate inserted at Brewster's angle ensured linear polarization of the laser output and was accountable for the self-phase modulation (SPM) required in soliton mode-locked lasers [27]. In order to optimize the pulse duration, the amount of nonlinearity could be controlled by moving this Brewster plate near the output coupler along the axis of the diverging beam. The amount of SPM scales inversely proportional to the cross section of the laser beam in the Brewster plate. The total length of the resonator was 2.25 m, corresponding to a repetition rate of 66.5 MHz. We used a SESAM with a saturation fluence of 61 µJ/cm^2, a modulation depth of 1.47% and non-saturable losses of ~0.2% measured at 1030 nm [28].

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3. Experimental results

We obtained self-starting modelocking with a pulse duration as short as 227 fs using a 4.2% output coupler. The autocorrelation trace and optical spectrum of these pulses are shown in Fig. 3. The spectral bandwidth of 5.2 nm centered near 1041 nm indicates nearly transform limited *sech*^{2}-pulses with a time-bandwidth product of 0.329 (ideal: 0.315). The maximum

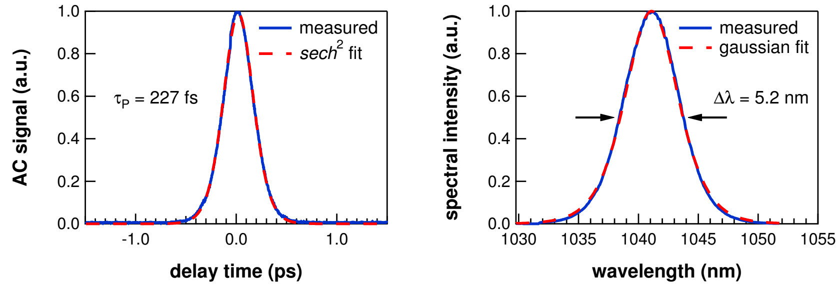

Fig. 3. (color online) Normalized autocorrelation (left) and optical spectrum (right) of the measured output beam (solid blue lines) with fit curves assuming ideal *sech*^{2} pulses (dashed red lines). The shortest pulses have a duration of 227 fs and a spectral bandwidth of 5.2 nm centered near 1041 nm.

output power was 7.2 W with 34 W of pump power, resulting in an optical-to-optical efficiency η_{opt} of 21%. The energy per pulse was 0.11 µJ and the peak power 0.42 MW. The M^2-value was measured to be 1.4. We verified single-pulse operation with a long-range autocorrelation of more than 60 ps and a sampling oscilloscope with a temporal resolution of < 20 ps. This is important because stable modelocking can also be achieved with multiple pulses simultaneously oscillating in the cavity. This mode of operation is often difficult to detect using only short-range autocorrelation, optical and RF-spectrum [29].

In a slightly different configuration and with a higher output coupling of 5.2% we obtained an output power of up to 10.1 W with 39 W of pump power. The pulse duration was 321 fs and the pulse energy 0.15 µJ. The spectral bandwidth of 3.9 nm corresponds to a nearly transform-limited time-bandwidth product of 0.342. The longer pulses are expected with a higher output coupling because the soliton phase shift decreases [27,30]. The optical-to-optical efficiency of 26% is similar to other high power mode-locked laser systems with potassium tungstates as active media [11,31,32], but clearly below the η_{opt} of 43% obtained with Yb:Lu_2O_3 [18]. From Fig. 4 we can determine a slope efficiency of 39% for the mode-locked Yb:$LuScO_3$ laser. Thus, at higher pump power we will observe a significant increase of the overall optical-to-optical efficiency in our setup.

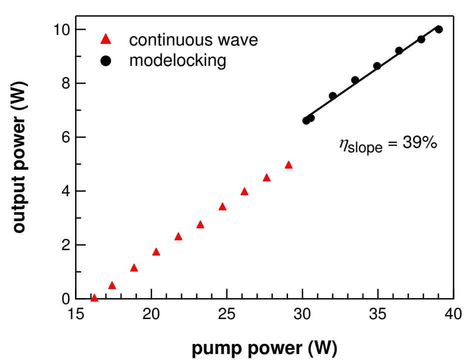

Fig. 4. (color online) Output power versus incident pump power using an outcoupling mirror with T = 5.2% for the laser wavelength. Stable soliton modelocking is obtained at 30 W pump power with a slope efficiency (η_{slope}) of 39%.

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The average output power in mode-locked operation was most likely limited by growth defects in the pumped area of the disk. While at medium pump powers the transverse output beam was nearly diffraction limited, at higher pump powers the mode deformed and the M^2-value increased. Modelocking became unstable at 40 W of pump power. This can be explained by the onset of higher order transverse modes, which destabilize the pulse formation. Nomarski interference microscopy revealed several grain boundaries (Fig. 5) in the pumped area of the only available disk, which is marked with the white circle.

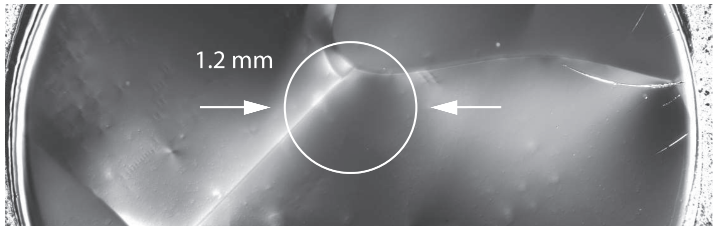

Fig. 5. Nomarski interference microscope photography of the Yb:$LuScO_3$ disk used in the experiments. The white circle corresponds to the pump spot with a diameter of 1.2 mm. The grain boundaries are invisible under a normal microscope.

Unfortunately, the pump module does not allow to shift the location of the pump spot on the disk. This disk was made out of the first boule ever grown of this material and we expect that disks of better quality can be fabricated from boules grown under optimized conditions in the future. Even with this disk the current limitation in output power could have been prevented by soldering the crystal at a slightly different position onto the heat sink. However, as the grain boundaries were invisible under normal light, we were not aware of this issue. Attempts to shift the disk by re-melting the solder were not successful. We believe that the melting point was increased considerably because the metal coating of the disk's back-side partially alloyed with the indium-tin-solder.

4. Conclusion and outlook

We presented the first mode-locked Yb:$LuScO_3$ thin disk laser. It delivered the shortest pulses obtained from a mode-locked thin disk laser so far. The nearly transform limited pulses had a duration of 227 fs at 7.2 W of average output power. In a modified configuration we achieved an output power of up to 10.1 W and pulses with a duration of 321 fs. The average output power was limited by growth defects in the only available disk. We expect that further improvements of the growth process will result in better quality disks. Nevertheless the current result clearly demonstrates the potential of Yb:$LuScO_3$ thin disk lasers for efficient high average power operation and pulse durations in the 200-fs-regime.

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