SESAMs for high-power femtosecond modelocking: power scaling of an Yb:$LuScO_3$ thin disk laser to 23 W and 235 fs

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Abstract: We report on power scaling of a modelocked thin disk laser based on the broadband mixed sesquioxide material Yb:$LuScO_3$. One of the key elements to achieve this result was an improved SESAM design with reduced two-photon-absorption (TPA) and high damage threshold. In a first experiment, using a standard antiresonant SESAM with no topcoating, we could demonstrate record short pulse durations of 195 fs at a moderate average power of 9.5 W. Furthermore, we were able to power scale our thin disk laser while keeping the pulses short reaching 23 W at a pulse duration of 235 fs. This was made possible by designing a new SESAM with multiple quantum wells (QW) and a suitable dielectric topcoating. We will present SESAM optimization guidelines for short pulse generation from high-power modelocked oscillators.

OCIS codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers.

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1. Introduction

SESAM modelocked thin disk lasers, which were first demonstrated in the year 2000 [1,2], are currently the technology that enables the highest average powers and energies directly from any modelocked oscillator. Recently, pulse energies > 30 µJ were demonstrated in 1-ps pulses using the well-established gain material Yb:YAG [3], whereas 141 W of average power in 738-fs pulses were demonstrated with the sesquioxide material Yb:Lu_2O_3 [4]. Achieving shorter pulse durations from such sources has important impact for a wide range of applications that benefit from table-top high peak power systems operating in the MHz regime [5,6]. Some examples are high-field science applications based on high harmonic generation [7–10], or industrial applications such as high-speed micromachining. High peak power MHz systems with short pulse durations (< 200 fs) currently rely on external pulse compression schemes such as passive spectral broadening using self-phase modulation (SPM) without any additional gain [11], active spectral broadening in fiber amplifiers [12,13], compression in gas-filled hollow core fibers and capillaries [14–16], and OPCPA techniques [17]. Although impressive performance has been reached with these systems, they usually suffer from a reduced temporal quality of the pulses and a rather high complexity. SESAM modelocked thin disk lasers operate in the soliton modelocked regime [18], allowing for transform-limited $sech^2$-shaped pulses directly from an oscillator with a footprint similar to that of a low-power oscillator.

Finding broadband materials suitable for high power levels and short pulse generation is challenging and currently a topic of extensive research [19,20]. Usually, broadband materials exhibit a disordered lattice structure that in turn limits its thermal properties. Nevertheless, the thin disk geometry with its excellent heat removal capabilities is potentially suitable to overcome these limitations, and extend the high power operation to the sub-100-fs regime [20].

Many Yb-doped gain materials have been modelocked in the thin disk geometry in the past years (Fig. 1 and table in the Appendix). Using Yb:YCOB, 270 fs pulses were achieved in modelocked operation at an average power of 2 W [21]. In this case, the quality and necessary thickness of the available low-doping level crystals limited the average power in modelocked operation. The monoclinic double tungstate materials are interesting candidates: 440 fs pulses with an average power of 21.3 W were demonstrated with Yb:KLuW [22], whereas 22 W were demonstrated in 240 fs pulses using Yb:KYW [23]. In this last case, a prism and a knife-edge had to be inserted into the cavity in order to tune off the emission maximum. Despite these impressive first results, the strong anisotropy in the thermal properties of these materials has limited further power scaling [24,25].

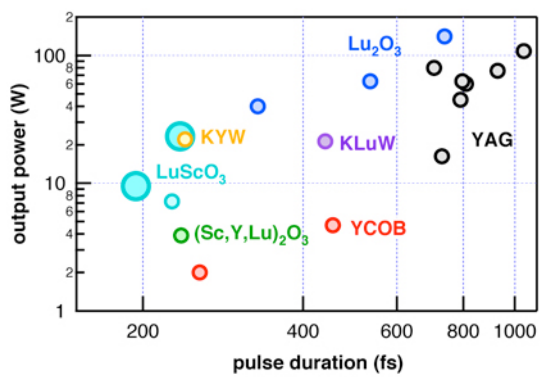

Fig. 1. Overview of average power versus pulse duration of modelocked thin disk lasers. The large dots are the laser results presented in this paper. Data taken from Refs [2–4,21–23,30,34,35,49–53] and summarized in the table in the Appendix.

Sesquioxide materials [26,27] have attracted a lot of attention in the past years due to their excellent properties for efficient continous wave (cw) and modelocked thin disk laser operation. The use of volume Bragg grating (VBG) stabilized diodes [28] for pumping these materials at the narrow zero-phonon line allows for efficient laser operation. In cw multimode operation output powers >250 W with optical-to-optical efficiencies >70% were demonstrated with Yb:Lu_2O_3, Yb:$LuScO_3$ and Yb:Sc_2O_3 [29]. Yb:Lu_2O_3 has already demonstrated its suitability for femtosecond modelocking at high-power levels: 141 W of average output power were demonstrated at a pulse duration of 738 fs with an optical-to-optical efficiency of 40.4% [4], and in a different experiment, 40 W were achieved with 329 fs pulses [30]. However, reaching much shorter pulses with Yb:Lu_2O_3 appears difficult in the thin disk geometry due to the moderate emission bandwidth of this material of approximately 12 nm (FWHM).

A successful technique to tailor gain bandwidth is to combine similar materials with shifted peak emission wavelengths. In particular, the growth of mixed sesquioxides [29,31,32] results in broadband isotropic materials, that still allow for excellent optical-to-optical efficiencies. In this way, the mixture of $Yb:Lu_2O_3$ (emission peak at 1034 nm) and $Yb:Sc_2O_3$ (emission peak at 1042 nm) resulted in the 22-nm-broad emission bandwidth material $Yb:LuScO_3$. The thermal conductivity of this mixed sesquioxide is moderate with 3.5 $Wm^{-1}K^{-1}$ but remains nearly constant when increasing the doping concentration [33]. Using this material, the shortest pulses reported up to date with a modelocked thin disk laser were demonstrated with 227 fs at an average power of 7.2 W [34]. Other mixed sesquioxides are currently being investigated, such as $Yb:(Sc,Y,Lu)_2O_3$ where 3.9 W and 236 fs pulses were demonstrated in initial modelocking experiments [35]. Although these results prove the potential of these materials for short pulse generation, the poor disk quality of the first growth run limited modelocked average power to only a few watts in these preliminary experiments. In this work, we confirm the suitability of $Yb:LuScO_3$ for power scaling and short pulse generation in the thin disk geometry. We were able to achieve 23 W of average power and 235 fs using a crystal from the second growth run of this material. In this case, the crystal quality did not limit our power performance, but most probably an imperfect mounting of the thin disk on the diamond heatsink.

Another important challenge for short pulse generation at high power levels is to design robust SESAMs for operation at high intracavity peak powers. Modelocked thin disk lasers typically operate at large intracavity fluences in the order of several mJ/cm^2 [36]. These demanding conditions require robust SESAMs. In particular in the case of short pulses (< 300fs) the rollover of the SESAM reflectivity due to two-photon absorption (TPA) [37] can already occur at moderate pulse fluences. Although TPA is beneficial for reduced Q-switching instabilities in high-repetition rate lasers [38,39], it can lead to multiple pulsing instabilities at strong saturation parameters [40] and can be one of the main limiting factors in high-power modelocked oscillators. Furthermore, the Q-switched modelocking (QML) threshold [41] can be relatively high due to the large modulation depths (in the order of 1-2%), large saturation fluences (> 50 $\mu J/cm^2$) and large spot sizes on the gain crystals needed to achieve modelocking at high power levels and with short pulses. This makes it difficult to overcome the Q-switching regime without causing damage on the SESAMs. Therefore, special care needs to be taken in designing SESAMs with the appropriate parameters, reduced TPA effects and high damage threshold. In a recent study, it was demonstrated that tailoring these parameters is possible using appropriate dielectric topcoatings on antiresonant structures with multiple QWs as absorbers [36].

In this paper, we present a first experiment where we achieved the shortest pulse duration ever demonstrated from a modelocked thin disk laser with 195 fs at 9.5 W of average power. This was obtained using a standard uncoated SESAM. In this case, we were not limited by the crystal quality, but by SESAM operation close to the rollover in reflectivity due to TPA. We therefore designed an optimized SESAM with reduced TPA and high damage threshold using our guidelines. In a second experiment using this SESAM, we were able to scale the output power of our laser by more than a factor of two while keeping the pulses short, reaching 23 W and 235 fs pulses. We will therefore present guidelines on how to specifically design SESAMs for short pulses from high power oscillators.

2. Shortest pulses from an $Yb:LuScO_3$ thin disk laser

The 150-µm-thick $Yb(3\%):LuScO_3$ crystal used in these experiments was grown by the heat exchanger method (HEM) at the Institute of Laser-Physics in Hamburg, Germany [42]. The disk was glued on a 1.4-mm-thick diamond heatsink with epoxy glue using the method described in [43]. It had a highly reflective coating for both the pump and laser wavelength on the backside and an antireflective coating for the same spectral range on the front side. Additionally, the disk had a wedge of 0.1° in order to avoid residual reflections which can destabilize modelocked operation. This crystal was pumped with a volume Bragg grating (VBG) stabilized fiber-coupled diode that emits up to 400 W at 976 nm with a narrow FWHM bandwidth of 0.5 nm [28]. The pump module was arranged for 24 passes through the disk and

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a pump spot diameter of 2.6 mm. The thickness and doping concentration of the disk allow for a pump absorption >95% with this pump arrangement. The unpumped disk was characterized with a polarized Michelson interferometer and the mean radius of curvature of this disk was measured to be R_m = 1.95 m, with no significant astigmatism.

The first tests on this disk were performed in cw operation. In a linear multimode cavity that consisted of a 1.2% transmission curved mirror with a radius of curvature of 100 mm and the HR-backside of the disk, we measured output powers of more than 100 W with an optical-to-optical efficiency of 63% and a slope efficiency of 84% (Fig. 2a). The pump power density at this output power level was 1.0 kW/cm^2.

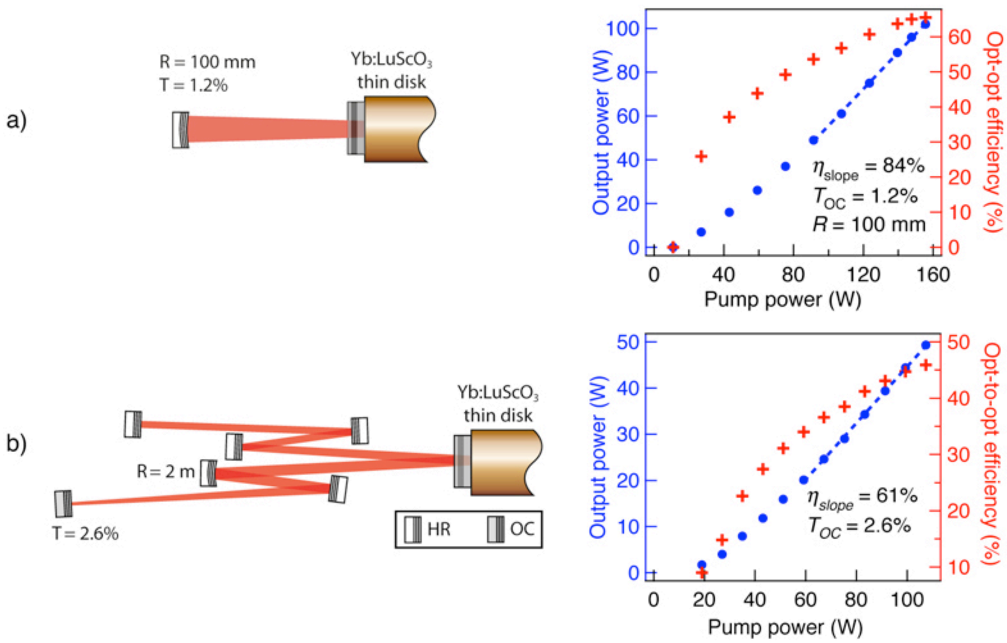

Fig. 2. Experimental results for two different cw Yb:$LuScO_3$ thin disk laser cavity designs: a) Simple linear multimode laser cavity (not to scale) and corresponding output power slope. b) Folded single-mode laser cavity (not to scale) and corresponding output power slope. HR: highly reflective mirror, OC: output coupler.

In a cw single-mode folded cavity with an output coupler transmission of 2.6% we could achieve 50 W of output power with an optical-to-optical efficiency of 45% and a slope efficiency of 61% (Fig. 2b). At this output power, we measured an M^2 < 1.3, suitable for modelocking experiments. The pump power density on the disk at this maximum power level was 1.1 kW/cm^2. Although the single-mode cavity design allows for compensating for small changes of the thermal lens [4], significant changes were not required to achieve single-mode operation up to the demonstrated 50 W.

At the maximum output power levels presented, we did not observe a decrease in the optical-to-optical efficiency. Therefore we could have, in principle, pushed for higher power levels in both cases. However, we did not further increase the pump power to avoid damage of the crystal before the modelocking experiments.

This was the first experiment using a sesquioxide thin disk mounted on a diamond heatsink. The higher thermal conductivity of diamond should lead to better heat removal compared to indium-tin soldered disks, and therefore higher efficiencies and damage thresholds. We believe this contributed to achieve the cw performance presented here. However, during the modelocking experiments, we observed damage of the crystal at low pump intensity below 2 kW/cm^2. Note that a thicker, 200-µm disk from the first growth run of

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this material presented in [29] soldered with indium-tin on a copper heat sink delivered a comparable multimode performance (140 W) under the same conditions and could withstand intensities up to 3.8 kW/cm^2 with high efficiencies. This seems to suggest an imperfect mounting on the diamond heatsink. Further improvement of this technique should allow reaching the 100-W regime in single mode operation.

In the first modelocking experiment, we used an uncoated antiresonant SESAM as an end mirror in the single-mode cavity (Fig. 2b) to start and stabilize the modelocking process. The absorber section of this SESAM consisted of a single 10-nm quantum well (QW) embedded in GaAs. The full characterization of this SESAM using a high-precision nonlinear reflectivity setup [44,45] will be presented in the next section. These measurements yielded a saturation fluence of 64 μJ/cm^2, a modulation depth of 1.9% and nonsaturable losses of 0.3%. In order to achieve soliton modelocking [18], two GTI mirrors in the cavity accounted for a total dispersion of –2200 fs^2 per roundtrip and a 6-mm thick Brewster plate introduced most of the required SPM and further ensured a linearly polarized output. We used a 2.6% transmission output coupler. In this way, we could achieve stable modelocking from 5.3 W up to 9.5 W of average power at a repetition rate of 70 MHz. At the maximum output power, the pulse duration was measured to be 195 fs (Fig. 3a). At higher pump powers, multiple pulsing instabilities limited stable modelocking. The pulses were nearly transform-limited with a time bandwidth product $\Delta\tau\Delta\nu = 0.32$ (ideal sech^2 0.315). These are, to the best of our knowledge, the shortest pulses obtained with a modelocked thin disk laser up to date. The optical-to-optical efficiency at this power level was 13% corresponding to a pump power of 73 W. The drop in efficiency compared to the single-mode cw result is due to losses from the different elements introduced to achieve soliton modelocking. These include losses from the uncoated Brewster plate, small losses introduced by the dispersive mirrors, nonsaturable losses and two-photon absorption of the SESAM.

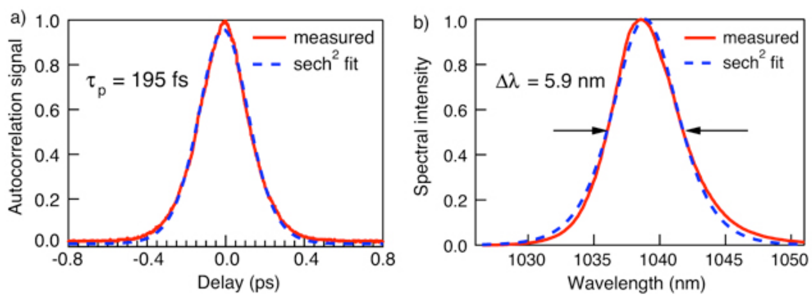

Fig. 3. First experimental results for SESAM modelocked Yb:$LuScO_3$ thin disk laser which was limited in average power to 9.5 W due to SESAM operation close to the rollover and damage. a) Measured autocorrelation trace at 9.5 W average power and corresponding fit assuming a sech^2 pulse shape. b) Measured optical spectrum of the pulses, and corresponding sech^2 fit showing a 5.9 nm wide spectrum (FWHM).

We believe shorter pulses are feasible using different cavity elements. Lower outcoupling rates, and therefore a lower inversion level of the gain medium, would reduce the pulse duration according to Ref [46]. In this experiment we focused on achieving higher average powers, and therefore did not explore lower outcoupling rates, which would have in this case reduced the optical-to-optical efficiency. Furthermore, at the time of the experiment, the minimum amount of negative dispersion available from one GTI mirror was –550 fs^2. Two GTI mirrors were the minimum amount where stable modelocking was observed, and for this it was necessary to use the thickest Brewster plate that was available (6 mm). Using a finer control for the intracavity dispersion and a thinner Brewster plate would have been helpful to achieve the correct balance of SPM and GDD required for stable soliton modelocking with shorter pulses.

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3. Discussion on SESAM limitations

Although 50 W were demonstrated in cw single-mode operation, modelocked power was limited at these short pulse durations. We believe this mainly originates in the strongly saturated uncoated SESAM and the early onset of the rollover in its reflectivity. We observed in our experiment that using this SESAM, higher powers could only be achieved at the expense of longer pulse durations (for example 16 W and 350 fs were achieved using a thinner Brewster plate). This suggests that the rollover is the main cause of the observed power limitation, since for longer pulse durations, the onset of this rollover occurs at a higher power level. In order to confirm this assumption, we measured the nonlinear reflectivity of this uncoated SESAM using the setup described in [45] and a high-power Yb:YAG thin disk laser. This enabled measurements up to a maximum fluence of approximately 80 mJ/cm^2, enough to characterize nonlinear reflectivity (saturation fluence F_{sat}, modulation depth ΔR, nonsaturable losses ΔR_{ns}), rollover strength (characterized by the TPA coefficient F_2), and damage threshold (F_d) of our samples. More details on these measurements can be found in [36]. The results are presented in Fig. 4. All measurements were performed at a pulse duration of 1 ps. Ideally the SESAM should be characterized at the laser pulse duration, however we did not have a table-top laser system with this pulse duration available for these measurements. It is nevertheless possible to estimate the behavior of a SESAM at a different pulse duration using the TPA formula that predicts a linear dependence of the F_2 coefficient with respect to the pulse duration [37,39]:

$$F_2 = \frac{\tau_p}{0.585\int \beta_{TPA}(z) n^2(z) |E(z)|^4} \tag{1}$$

where τ_p is the pulse duration, β_{TPA} is the TPA coefficient in cm/GW of the different materials in the structure, n their refractive index and E the normalized electric field in the structure. This formula gives a good approximation of the observed reflectivity rollover for pulse durations < 1 ps [39]. Therefore we characterized our samples at a longer pulse duration of 1 ps and numerically estimated the behavior of our SESAM according to Eq. (1) at a pulse duration of 200 fs in order to understand the power limitation observed in our experiment (Fig. 4a).

We also used a standard pump-probe measurement setup to evaluate the recovery time of this SESAM using a low-power Yb:YAG bulk laser at 1 ps pulse duration. Although this pulse duration is not sufficiently short to characterize in detail the fast component of the recovery time, the measurements give a good indication of the speed of the SESAM. The results of this measurement are shown in Fig. 4b.

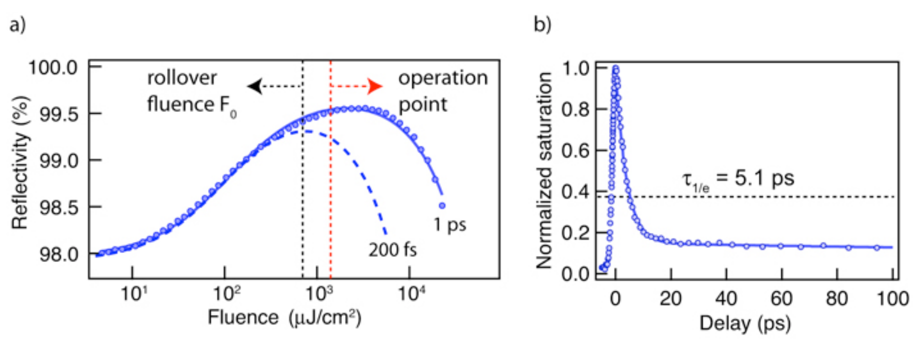

Fig. 4. Characterization of the SESAM used for the first thin disk laser experiment described in this paper, in which a limited output power of 9.5 W was obtained: a) Nonlinear reflectivity (dots for the measurement and full line for the corresponding fit) and estimation of the behavior of this SESAM using 200 fs pulses (dashed line). The vertical dashed line in black indicates the rollover fluence position and the red dashed line the intracavity fluence on the

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SESAM in the laser. We can see that the sample is strongly oversaturated. b) Recovery time of this SESAM. The measurement was performed with a pump probe setup using 1-ps pulses. The recovery time at 1/e was measured to be 5.1 ps.

The spot size used on the SESAM in this cavity is approximately 390 µm. This results in an intracavity fluence on the SESAM for this experiment of approximately 1.09 mJ/cm^2. We can clearly see in Fig. 4a that we are limited by the early rollover in the reflectivity of the uncoated SESAM. Operating this SESAM at 200 fs results in extra losses due to TPA of approximately 0.5% compared to a pulse duration of 1 ps, which results in a reduced optical-to-optical efficiency. Furthermore, the QW absorber layer in this SESAM was grown at low temperature (LT) (T = 280°C) and annealed for 60 s at 550°C to achieve fast recovery times, which results in nonsaturable losses of 0.3% as previously observed for LT grown GaAs SESAMs [47]. These added effects result in losses of approximately 0.8% at the operation fluence of our laser.

A straightforward approach to limit oversaturation at high average powers is to modify the cavity to enlarge the spot size used on the SESAM. However, this would result in increased sensitivities to both alignment and possible small thermal lensing of the SESAM [48]. Furthermore, as we mentioned in the introduction, overcoming the QML threshold can also become a critical issue in high-power oscillators with short pulses [41]. During the Q-switching regime, peak powers can easily be larger than the damage threshold of standard samples. Therefore, SESAMs with reduced TPA effects and high-damage thresholds are crucial for comfortable cavity conditions and reduced possible damage during the QML regime.

4. Optimization of the SESAM design

We demonstrated in a recent study that the damage threshold of QW SESAMs for high-power oscillators is strongly related to TPA [36]. It is therefore straightforward to design SESAMs with high damage thresholds by using multiple QWs and appropriate dielectric topcoatings. In this way, the electric field intensity in the GaAs layers of the structure that are mainly responsible for TPA is reduced, shifting the rollover to higher fluences and increasing the damage threshold [36].

Following these guidelines, we designed a SESAM suitable for our application. We grew an antiresonant SESAM that consists of a 30-pair GaAs/AlAs distributed Bragg reflector (DBR) and 4 InGaAs QW absorbers. The absorbers were placed two by two in consecutive antinodes of the electric field and were grown at a low temperature of approximately 250°C to achieve fast recovery times. All samples were grown by Molecular Beam Epitaxy (MBE) in the FIRST cleanroom facilities at ETH Zurich. The details of the grown structure are presented in Fig. 5a. A two pair SiO_2/Si_3N_4 dielectric topcoating was applied on the structure using Plasma Enhanced Chemical Vapor Deposition (PECVD). The topcoating reduces the field in the absorber section therefore increasing its saturation fluence. Since $\Delta R \cdot F_{sat}$ remains constant, the modulation depth of the sample is reduced by the same factor. The measurements of nonlinear reflectivity and recovery time of the non topcoated 4 QW sample and the same sample with dielectric topcoating are presented in Fig. 5 b,c and the relevant fit parameters are presented in Table 1.

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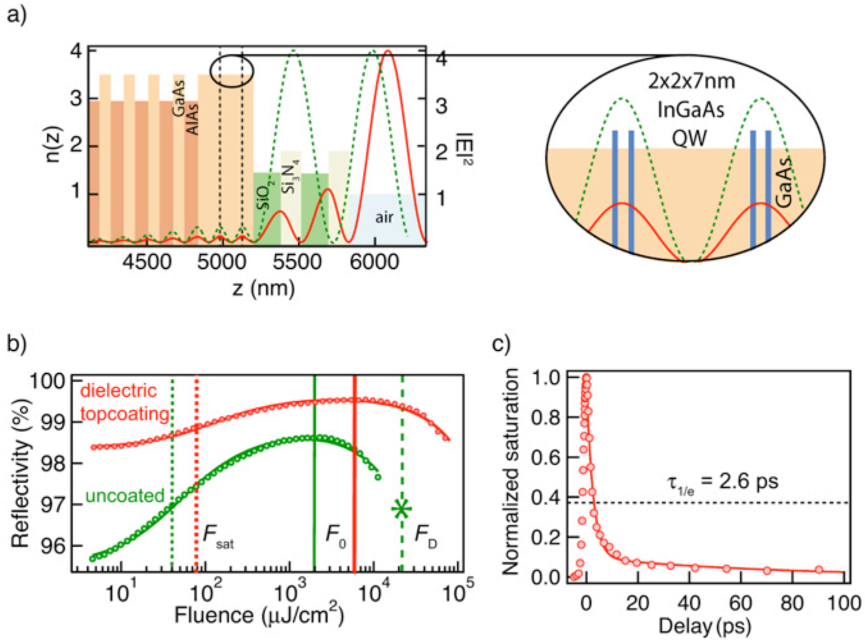

Fig. 5. Optimized SESAM a) Structure of the SESAM with 2-pair SiO_2/Si_3N_4 dielectric topcoating and field enhancement before (green) and after topcoating (red). Zoom on absorber section: 4 InGaAs QW, distributed in two consecutive antinodes of the electric field b) Nonlinear reflectivity and damage measurements performed at 1 ps for both uncoated (green) and coated (red) sample, where one can see the increase in F_{sat}, the corresponding decrease in ΔR, the shift in the rollover fluence F_0 and the increased damage threshold F_{d}. This damage threshold of the topcoated sample could not be measured at the maximum available fluence in the setup of 80 mJ/cm^2. c) Recovery time of the sample with the dielectric topcoating. The measurement was performed with a pump probe setup using 1-ps pulses. The recovery time at 1/e obtained was 2.6 ps.

In Fig. 6 and Table 1 we compare the parameters of the new SESAM design (red) with the one used for the first experiment described in section 2 (blue), with which we were limited in our laser to an average power of 9.5 W. As can be seen, the dielectric topcoated SESAM has saturation parameters suitable for short pulses from modelocked TDLs (ΔR = 1.3%, F_{sat} = 70 µJ/cm^2, ΔR_{ns} = 0.4%, see section 2) but most importantly has a reduced TPA (larger F_2) and higher damage threshold compared to the sample used in the first experiment. The damage threshold of the topcoated sample could not be measured at the maximum available fluence in the setup of 80 mJ/cm^2.

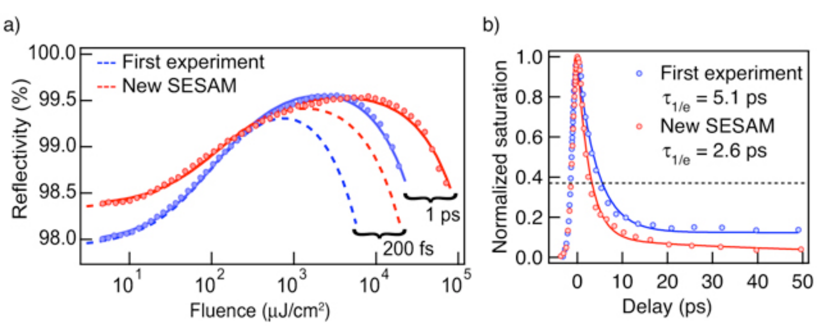

Fig. 6. Comparison of the two SESAMs used in the two different experiments a) Saturation parameters: the old uncoated SESAM (blue) has similar saturation parameters as the new dielectric topcoated sample (red) but one can clearly see the shift in the rollover fluence b)

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Recovery time of the two SESAMs. The new dielectric topcoated SESAM has a faster recovery time with 2.6 ps.

Table 1. Extracted Parameters of Different SESAMs

	Uncoated (First experiment)	**Before Topcoating (New design)**	**Dielectric Topcoating (New design)**
Structure	Single QW no topcoating	4 QW no topcoating	4 QW + 2-pair SiO_2/Si_3N_4
$\boldsymbol{F_{sat}}$ **(μJ/cm²)**	64	31	70
$\boldsymbol{\Delta R}$ **(%)**	1.9	3.3	1.3
$\boldsymbol{\Delta R_{ns}}$ **(%)**	0.3	1.7	0.4
$\boldsymbol{F_2}$ **(mJ/cm²)**	1950	3100	7300
$\boldsymbol{\tau_{1/e}}$ **(ps)**	5.1	2.6	2.6
$\boldsymbol{F_d}$ **(mJ/cm²)**	26	22	> 80

5. Power scaling of Yb:LuScO$_3$ thin disk laser

In a second experiment aiming for higher power levels, we tested the newly designed SESAM with a dielectric topcoating in the single-mode cavity described in section 2. In this experiment, we used a higher outcoupling rate of T = 5% and a thinner Brewster plate with a thickness of 3 mm. We observed stable modelocking starting at 17.5 W up to 23 W of average power. Before the modelocking regime, strong QML was observed, but with no damage of the SESAM. At the highest modelocked average power level, the pulses were 235 fs long (Fig. 7a) and were nearly transform-limited with a time bandwidth product of 0.32 (ideal sech^2 0.315). The optical-to-optical efficiency was 21%, corresponding to a pump power of 109 W. The repetition rate of the pulses was 70 MHz. Notice that compared to previous results using Yb:KYW in which similar performance was obtained [23], no dispersive intracavity elements were necessary to flatten the emission spectrum, showing the potential of Yb:LuScO$_3$ for even shorter pulses.

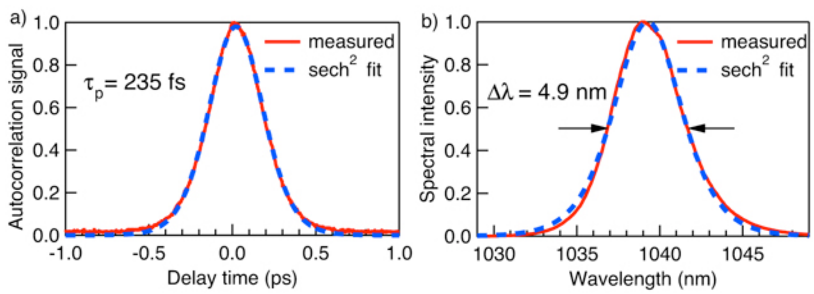

Fig. 7. Experimental results for SESAM modelocked Yb:LuScO3 thin disk laser using the optimized SESAM described above: a) measured autocorrelation trace at 23 W average power and corresponding fit assuming a sech^2 pulse shape. b) measured optical spectrum of the pulses, and corresponding sech^2 fit showing a 4.9 nm wide spectrum (FWHM).

The increase of outcoupling rate from 2.6% to 5% was tested in the cw single-mode cavity described in the previous section. The slope efficiency was slightly reduced to 55% (instead of 61%), and the optical-to-optical efficiency at the pump power where we achieved modelocking was 36% (instead of 43%). The lower outcoupling rate was chosen to reduce the intracavity power and therefore relax the fluence level on the SESAM in order to reach higher average powers at the expense of a small loss in optical-to-optical efficiency.

The modelocked output power obtained was more than double that of the previous experiment. The newly designed SESAM was a key element to achieve this result. The laser mode size on the SESAM in this cavity was similar to the previous experiment with a radius of 390 μm. This results in an intracavity fluence on the SESAM of 1.4 mJ/cm^2, which is approximately 28% higher than in the previous experiment. Further increase in the average power of the laser resulted in damage of the disk. This was probably due to a defect in the

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gluing onto the diamond heatsink. However, we believe that sub-200-fs pulses could have been achieved at these high average powers by using a lower outcoupling rate and using a SESAM with a slightly higher modulation depth as in the first experiment.

7. Conclusion and outlook

We have confirmed the potential of the broadband material Yb:$LuScO_3$ for the generation of short pulses at high power levels from modelocked TDLs. In a first experiment, we could achieve for the first time sub-200 fs pulses at an average power of 9.5 W directly from a modelocked laser oscillator. By designing an optimized SESAM with reduced TPA and increased damage threshold, we were able to scale the output power to 23 W while keeping the pulses short (235 fs). Further increase of the output power resulted in damage of the disk at a low pump intensity of approximately 1.6 kW/cm^2. However, we believe that with the newly designed SESAMs and an improved gluing technique on diamond, reaching average powers in the 50-W range at sub-200 fs should be possible in the near future.

We experimentally confirmed the effect of the SESAM rollover on power scaling at these short pulse durations, and showed the benefit of designing SESAMs with reduced TPA. Furthermore, we verified that our high-damage threshold SESAMs are crucial to overcome the strong QML regime typically observed with these broadband materials. We have shown that SESAMs represent a powerful tool for power scaling of modelocked thin disk lasers with short pulse durations. Further improvement of the SESAM parameters, for instance a larger number of QWs and a suitable dielectric topcoating, should lead to even lower TPA and higher damage thresholds and allow for a further increase of the average power and pulse energy of our laser sources in simple cavities. Therefore, we believe SESAMs are currently not the limiting factor towards higher average powers and shorter pulses from modelocked oscillators.

Appendix

Table 2. Summarized Performance of Results Presented in Fig. 1

Material	Average Output Power (W)	Pulse Duration (fs)	Pulse Energy (μJ)	Peak Power (MW)	Repetition Rate (MHz)	Reference
Yb:YAG	108	1040	30.7	26.0	3.5	[3]
	80	705	1.4	1.8	57	[49]
	76	928	25.7	24.3	2.9	[50]
	63	796	5.1	5.7	12.3	[51]
	60	810	1.7	1.9	34.3	[52]
	45	791	11.3	12.5	4	[53]
	16.2	730	0.5	0.6	34.6	[2]
Yb: Lu2O3	141	738	2.4	2.8	60	[4]
	63	535	0.8	1.3	81	[30]
	40	329	0.5	1.3	81	[30]
Yb:KLuW	21.3	440	0.6	1.2	34.7	[22]
Yb:YCOB	2	270	0.1	0.3	19.7	[21]
	4.7	455	0.2	0.4	24.4	[21]
Yb:$(Sc,Y,Lu)_2O_3$	3.9	236	0.1	0.4	36.5	[35]
Yb:KYW	22	240	0.9	3.2	25	[23]
Yb:$LuScO_3$	7.2	227	0.1	0.4	66.5	[34]
	23	235	0.3	1.2	70	presented here
	9.5	195	0.1	0.6	70	presented here

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