Dual-gain SESAM modelocked thin disk laser based on $Yb:Lu_2O_3$ and $Yb:Sc_2O_3$

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Abstract: We present for the first time a SESAM-modelocked thin-disk laser (TDL) that incorporates two gain materials with different emission spectra in a single TDL resonator. The two gain media used in this experiment are the sesquioxide materials $Yb:Lu_2O_3$ and $Yb:Sc_2O_3$, which have their spectral emission peak displaced by ≈7 nm. We can benefit from a combined gain bandwidth that is wider than the one provided by a single gain material alone and still conserve the excellent thermal properties of each disk. In these first proof-of-principle experiments we demonstrate pulse durations shorter than previously achieved with the single gain material $Yb:Lu_2O_3$. The oscillator generates pulses as short as 103 fs at a repetition rate of 41.7 MHz and a center wavelength of around 1038 nm, with an average output power of 1.4 W. A different cavity layout provides pulses with a duration of 124 fs at an output power of 8.6 W. This dual-gain approach should allow for further power scaling of TDLs and these first results prove this method to be a promising new way to combine the record output-power performance of modelocked TDLs with short pulse durations in the sub-100 fs regime.

OCIS codes: (140.3615) Lasers, ytterbium; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers.

References and links

1. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. **2**(3), 435–453 (1996).
2. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, "Scalable concept for diode-pumped high-power solid-state lasers," Appl. Phys. B **58**(5), 365–372 (1994).
3. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**(2), 94–96 (2010).
4. P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," Opt. Lett. **35**(24), 4169–4171 (2010).
5. J. P. Negel, A. Voss, M. Abdou Ahmed, D. Bauer, D. Sutter, A. Killi, and T. Graf, "1.1 kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses," Opt. Lett. **38**(24), 5442–5445 (2013).
6. C. J. Saraceno, F. Emaury, O. H. Heckl, C. R. E. Baer, M. Hoffmann, C. Schriber, M. Golling, T. Südmeyer, and U. Keller, "275 W average output power from a femtosecond thin disk oscillator operated in a vacuum environment," Opt. Express **20**(21), 23535–23541 (2012).
7. C. J. Saraceno, F. Emaury, C. Schriber, M. Hoffmann, M. Golling, T. Südmeyer, and U. Keller, "Ultrafast thin-disk laser with 80 μJ pulse energy and 242 W of average power," Opt. Lett. **39**(1), 9–12 (2014).
8. T. Südmeyer, S. V. Marchese, S. Hashimoto, C. R. E. Baer, G. Gingras, B. Witzel, and U. Keller, "Femtosecond laser oscillators for high-field science," Nat. Photonics **2**(10), 599–604 (2008).
9. S. R. Leone, C. W. McCurdy, J. Burgdörfer, L. S. Cederbaum, Z. Chang, N. Dudovich, J. Feist, C. H. Greene, M. Ivanov, R. Kienberger, U. Keller, M. F. Kling, Z.-H. Loh, T. Pfeifer, A. N. Pfeiffer, R. Santra, K. Schafer, A.

Stolow, U. Thumm, and M. J. J. Vrakking, "What will it take to observe processes in 'real time'?" Nat. Photonics **8**(3), 162–166 (2014).
10. T. Südmeyer, C. Kränkel, C. R. E. Baer, O. H. Heckl, C. J. Saraceno, M. Golling, R. Peters, K. Petermann, G. Huber, and U. Keller, "High-power ultrafast thin disk laser oscillators and their potential for sub-100-femtosecond pulse generation," Appl. Phys. B **97**(2), 281–295 (2009).
11. K. Beil, C. J. Saraceno, C. Schriber, F. Emaury, O. H. Heckl, C. R. E. Baer, M. Golling, T. Südmeyer, U. Keller, C. Kränkel, and G. Huber, "Yb-doped mixed sesquioxides for ultrashort pulse generation in the thin disk laser setup," Appl. Phys. B **113**(1), 13–18 (2013).
12. C. J. Saraceno, O. H. Heckl, C. R. E. Baer, C. Schriber, M. Golling, K. Beil, C. Kränkel, T. Südmeyer, G. Huber, and U. Keller, "Sub-100 femtosecond pulses from a SESAM modelocked thin disk laser," Appl. Phys. B **106**(3), 559–562 (2012).
13. R. Peters, C. Kränkel, S. T. Fredrich-Thornton, K. Beil, O. H. Heckl, C. R. E. Baer, C. J. Saraceno, T. Südmeyer, U. Keller, K. Petermann, and G. Huber, "Thermal analysis and efficient high power continuous-wave and mode-locked thin disk laser operation of Yb-doped sesquioxides," Appl. Phys. B **102**(3), 509–514 (2011).
14. C. J. Saraceno, S. Pekarek, O. H. Heckl, C. R. E. Baer, C. Schriber, M. Golling, K. Beil, C. Kränkel, G. Huber, U. Keller, and T. Südmeyer, "Self-referenceable frequency comb from an ultrafast thin disk laser," Opt. Express **20**(9), 9650–9656 (2012).
15. P. Klopp, V. Petrov, U. Griebner, K. Petermann, V. Peters, and G. Erbert, "Highly efficient mode-locked Yb:Sc_2O_3 laser," Opt. Lett. **29**(4), 391–393 (2004).
16. A. Diebold, F. Emaury, C. J. Saraceno, C. Schriber, M. Golling, T. Südmeyer, and U. Keller, "62-fs pulses from a SESAM modelocked Yb:CALGO thin disk laser," Opt. Lett. **38**, 3842–3845 (2013).
17. S. Ricaud, A. Jaffres, K. Wentsch, A. Suganuma, B. Viana, P. Loiseau, B. Weichelt, M. Abdou-Ahmed, A. Voss, T. Graf, D. Rytz, C. Hönninger, E. Mottay, P. Georges, and F. Druon, "Femtosecond Yb:$CaGdAlO_4$ thin-disk oscillator," Opt. Lett. **37**(19), 3984–3986 (2012).
18. D. E. Spence, P. N. Kean, and W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti:sapphire laser," Opt. Lett. **16**(1), 42–44 (1991).
19. O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M. C. Amann, V. L. Kalashnikov, A. Apolonski, and F. Krausz, "High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator," Opt. Lett. **36**(24), 4746–4748 (2011).
20. F. Salin, J. Squier, and M. Piché, "Modelocking of Ti:AI(2)O(3) lasers and self-focusing: a Gaussian approximation," Opt. Lett. **16**(21), 1674–1676 (1991).
21. M. Tokurakawa, A. Shirakawa, K. Ueda, H. Yagi, M. Noriyuki, T. Yanagitani, and A. A. Kaminskii, "Diode-pumped ultrashort-pulse generation based on Yb^{3+}:Sc_2O_3 and Yb^{3+}:Y_2O_3 ceramic multi-gain-media oscillator," Opt. Express **17**(5), 3353–3361 (2009).
22. S. Han, W. Lu, B. Y. Sheh, L. Yan, M. Wraback, H. Shen, J. Pamulapati, and P. G. Newman, "Generation of sub-40 fs pulses from a mode-locked dual-gain-media Nd:glass laser," Appl. Phys. B **74**(S1), S177–S179 (2002).
23. U. Buenting, H. Sayinc, D. Wandt, U. Morgner, and D. Kracht, "Regenerative thin disk amplifier with combined gain spectra producing 500 µJ sub 200 fs pulses," Opt. Express **17**(10), 8046–8050 (2009).
24. V. Peters, A. Bolz, K. Petermann, and G. Huber, "Growth of high-melting sesquioxides by the heat exchanger method," J. Cryst. Growth **237–239**, 879–883 (2002).
25. R. Paschotta and U. Keller, "Passive mode locking with slow saturable absorbers," Appl. Phys. B **73**(7), 653–662 (2001).
26. M. Haiml, U. Siegner, F. Morier-Genoud, U. Keller, M. Luysberg, R. C. Lutz, P. Specht, and E. R. Weber, "Optical nonlinearity in low-temperature-grown GaAs: Microscopic limitations and optimization strategies," Appl. Phys. Lett. **74**(21), 3134–3136 (1999).

1. Introduction

Semiconductor saturable absorber mirror (SESAM) modelocked thin-disk lasers (TDLs) [1, 2] outperform any other ultrafast laser oscillator in terms of average power and pulse energy. Progress achieved over the last decade has allowed for a performance level that approaches the level of the latest high average power but more complex amplifier systems operating in the MHz pulse repetition-rate regime [3–5]. The most typical gain material for TDLs is Yb-doped YAG. SESAM modelocked Yb:YAG thin-disk oscillators currently hold both the average output-power record of 275 W [6] and the pulse energy record of 80 µJ [7] [Fig. 1(a)]. The 275-W average power record generates a pulse duration of 583 fs and a repetition rate of 16.3 MHz resulting in a pulse energy of 16.9 µJ. The 80-µJ pulse energy record delivers an average output power of 242 W with a pulse duration of 1.07 ps at a repetition rate of 3.03 MHz. The demonstrated performance is promising for many important applications both in industry and science. One promising science application is in strong laser field physics, particularly for high-harmonic generation and attosecond pulse generation at high repetition rates [8, 9]. State-of-the-art ultrafast TDLs will be able to drive these experiments directly with a modelocked oscillator operating in the megahertz pulse repetition-rate regime to reduce acquisition time and to improve signal-to-noise ratio in measurements. Although the peak powers achieved with ultrafast TDLs are already sufficient for many applications, significantly shorter pulse durations (< 100 fs) are required to obtain acceptable efficiencies in high harmonic generation.

Therefore a strong research efforts is dedicated towards the ultimate goal to generate both high average power and sub-100 fs pulses from the oscillator [10, 11]. The key challenge is to achieve sufficiently broad gain bandwidth in the TDL oscillator together with good power scaling capabilities. One approach is to increase the gain bandwidth by choosing Yb-ions in a host material with a disordered lattice structure or the growth of mixed materials, which combine the shifted emission spectra of the constituting components. This enabled new performance milestones of ultrafast TDLs in the short pulse duration regime: the first demonstration of sub-100 fs operation with a SESAM-modelocked TDL was achieved in 2012 using the promising broadband sesquioxide material Yb:$LuScO_3$ (Yb:LuScO), that delivered 96-fs pulses at an output power of 5.1 W [12]. Yb:LuScO is a stoichiometric mixture of the two sesquioxides Yb:Lu_2O_3 (Yb:LuO) with a center gain wavelength at 1034 nm and an emission bandwidth of 13 nm, and Yb:Sc_2O_3 (Yb:ScO) with a center gain wavelength at 1041 nm and an emission bandwidth of 12 nm [13]. As it combines the emission peaks of both crystals its emission spectrum is nearly doubled, centered around 1039 nm [11]. However, the broadband nature of these mixed Yb-doped laser crystals often comes at the expense of a low thermal conductivity [Fig. 1(b)], which hinders average power scaling in the thin-disk geometry. Using Yb:LuO alone, pulses as short as 142 fs with 7 W of average power were demonstrated [14]. To the best of our knowledge no ultrafast TDL based on a single Yb:ScO crystal has been demonstrated so far, but a standard SESAM-modelocked Yb:ScO laser delivered 230-fs pulses [15].

Very recently a TDL based on the gain material Yb:CALGO demonstrated pulses as short as 62 fs at an average power of 5.1 W [16]. Using this gain material, higher power was achieved but only at longer pulse durations (28 W with 300-fs pulses) [17]. First experiments using Kerr Lens Modelocking (KLM) [18] enabled the demonstration of a TDL based on Yb:YAG delivering 17 W of average power at a pulse duration of 200 fs [19]. This result has allowed to exploit a large fraction of the gain bandwidth available from Yb:YAG. However, in contrast to SESAM modelocking the saturable absorber action for KLM is defined with the laser cavity design and typically operated close to the cavity stability limit [20].

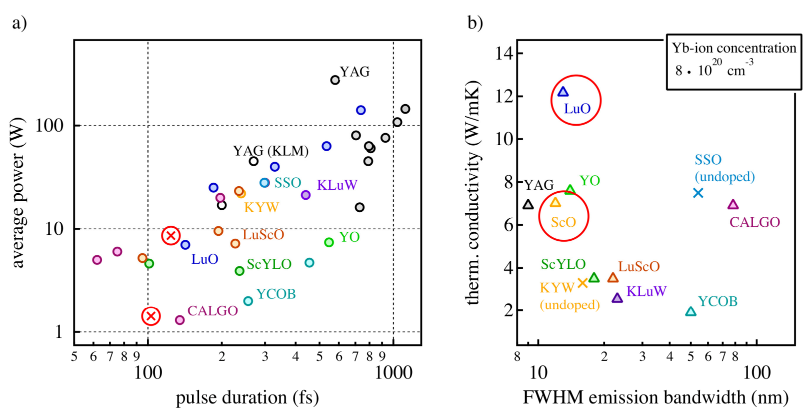

Fig. 1. (a) Average output power of ultrafast thin disk lasers as a function of the achieved pulse duration. The two results presented here are highlighted with red crosses and are based on combining two different gain materials in the thin disk geometry within one laser resonator. (b) Thermal conductivity as function of FWHM emission bandwidth. The advantage of Yb:LuO and Yb:ScO (red circles) compared to their stoichiometric mixture Yb:LuScO is a better thermal conductivity, here given for a doping concentration of $8 \cdot 10^{20}$ cm^{-3}.

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An interesting alternative approach that extends laser performances to shorter pulse durations is to combine two spatially separated gain media with displaced emission spectra within one resonator. In modelocked operation, the two independent gain materials support a single pulse with a broad gain spectrum. Therefore, this combination allows for working with gain materials that exhibit moderate emission bandwidths but high thermal conductivities while reaching out for shorter pulse durations. To date this concept has been successfully implemented in oscillator and amplifier systems: A laser oscillator based on bulk ceramic Yb:ScO and Yb:Y_2O_3 (Yb:YO) gain media delivered 53 fs pulses with an output power of 1 W [21] and the modelocking of a dual-gain Nd:glass laser yielded 38-fs pulses at 40 mW of output power [22]. The combined gain spectra of a regenerative thin disk amplifier generated sub-200 fs pulses with an energy of 500 µJ [23].

Here we present the successful implementation of this method to the modelocked TDL geometry by demonstrating a dual-gain SESAM-modelocked TDL that combines the gain of two sesquioxide materials (Yb:LuO and Yb:ScO) with high thermal conductivity in the same resonator. In this first proof-of-principle experiment, we obtained 8.6 W of average power with a pulse duration of 124 fs and a repetition rate of 41.7 MHz, resulting in a pulse energy of 200 nJ. The modelocked spectrum has a FWHM of 10.1 nm with a center wavelength of 1038.5 nm. At the same repetition rate but in a different laser layout, pulses as short as 103 fs centered at 1037.7 nm could also be achieved at an average output power of 1.4 W. The obtained pulse duration in both cases is shorter than previously achieved with a single Yb:LuO-disk [14] confirming the potential of this approach. The power was limited by the poor quality of the Yb:ScO-disk available for the experiment [Fig. 2(a)], resulting in a significant beam degradation at higher powers. We believe current progress in the growth of sesquioxide materials combined with contacting on diamond heatsinks would result in significantly higher average powers. In addition, adding other gain materials with a larger shift in emission cross section (e.g. Yb:YO and Yb:ScO with a displacement of their emission peaks of 10 nm) could be an additional option to obtain even shorter pulses.

2. Experimental setup and results

The layout of the oscillator used for the dual-gain modelocking experiments is shown in Fig. 2. Both sesquioxide crystals used in the modelocked oscillator were grown by the heat exchanger method (HEM) at the Institut für Laser-Physik in the Universität Hamburg [24]. They are wedged (0.1 deg) in order to avoid parasitic reflections that could result in modelocking instabilities and were indium-soldered on copper heatsinks.

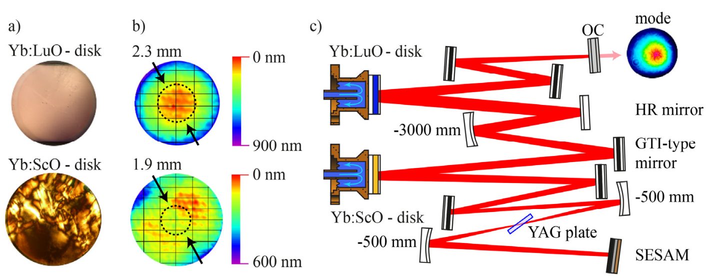

Fig. 2. (a) Microscope photo of the Yb:LuO-disk (top) and the Yb:ScO-disk (bottom). The high-quality Yb:LuO crystal does not show any visible grain boundaries, which is in contrast to the Yb:ScO crystal. (b) Interferometric measurement of the surface flatness deviation of the two disks. The measurement is performed at 1 bar of water pressure at the backside of the disk. The Yb:LuO-disk (top) has a perfect spherical surface whereas the Yb:ScO-disk shows slight astigmatism. The pump spot on the corresponding disk is marked with a dotted black circle. (c) Cavity design of the dual-gain resonator supporting fundamental transverse mode operation up to 10 W cw. The two disks are separated by a distance of ≈1.15 m. The SESAM and the output coupler are the two end mirrors of the linear cavity. We measured for all experiments an $M^2 < 1.2$.

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The Yb:LuO-disk, with a doping concentration of 2 at. %, has a thickness of 250 μm and a diameter of 5.2 mm. The 2.4 at. % doped Yb:ScO-disk is 300 μm in thickness and 6 mm in diameter. Two separate fiber-coupled volume Bragg grating (VBG) stabilized diodes, emitting at the maximum absorption wavelength of 976 nm of the crystals, are used to optically pump the gain materials. At the pump wavelength the absorption cross-section for Yb:LuO is $3.1\cdot10^{-20}$ cm^2 and $4.4\cdot10^{-20}$ cm^2 for Yb:ScO. The two multimode pump-fibers have an NA of 0.22 and a core diameter of 600 μm. The pump modules are both arranged for 24 pump passes on the corresponding disk.

Single-transverse-mode operation is crucial for modelocking experiments and in such a dual-gain cavity two unknown thermal lensing elements can make the fundamental resonator design very challenging. Therefore, we carefully characterized the quality of the contacted disks by inspecting them with a microscope [Fig. 2(a)] and by measuring the deformation of the disks under optical pumping with a Michelson interferometer [Fig. 2(b)]. The Yb:LuO-disk exhibits a good surface quality without any visible grain boundaries. We measured the radius of curvature (ROC) of the cold disk and the deformation of the disk under pumping levels used in the experiment. The cold disk shows a spherical curvature with an average ROC of $r_m = -2.5$ m. When the disk is water-cooled at a water pressure of about 1 bar, we observed a small change of the average ROC to $r_m = -2.6$ m. During continuous wave (cw) single-mode operation, with a pump power of 44 W on a pump spot diameter of 2.3 mm, no additional changes in the average ROC were observed.

The cold Yb:ScO-disk shows a slight astigmatism and several grain boundaries. Therefore, we confined the diameter of the pump spot to 1.9 mm and centered the spot on the disk in order to work on an area that shows only small astigmatism. In pumped operation without any lasing at 1 bar of water pressure and 6 W of pump power the average ROC is measured to be −12 m. The quality of this disk is clearly a limitation in our experiment. However, it was the only disk available at the time of the experiment.

We first tested the disks separately in cw operation. In a linear resonator consisting of the Yb:LuO crystal and a 100 mm ROC mirror with 1.2% transmission, we could achieve up to 50 W in multimode operation with an optical-to-optical efficiency higher than 60% and slope efficiency of 72%. With the Yb:ScO crystal we obtain optical-to-optical efficiencies higher than 50% in cw multimode operation.

The dual-gain linear cavity [Fig. 2(c)] has a length of ≈3.6 m and separates the two disks by a distance of ≈1.2 m. The cavity is designed to be at the center of the stability zone and exhibits a small sensitivity to the thermal lenses of both disks but with a stronger consideration of the lower quality of the Yb:ScO disk. This cavity then supports single fundamental-transverse mode operation up to 10 W in cw.

We inserted a wedged undoped YAG plate at Brewster's angle into the cavity. This ensures a linearly polarized output and provides the required self phase modulation (SPM) for soliton modelocking [25]. In order to produce enough SPM we placed the YAG plate close to the focus with a spot radius of ≈150 μm between the two curved mirrors with a ROC of 500 mm. The SESAM inserted as one end mirror is the only loss modulator inside the cavity and starts and stabilizes the soliton modelocking.

All experiments were done with an antiresonant SESAM grown at a low temperature of 270 °C resulting in fast recovery time ($\tau_{1/e}$) of 3 ps [26]. The absorber section consists of two InGaAs quantum wells (QWs) with a thickness of 7 nm, placed in two consecutive antinodes of the electric field. Increasing the temperature of the SESAM decreases the band gap energy, which leads to a red shift of the corresponding absorption properties. For the SESAM used in our experiments we measured this red shift to be 0.38 nm/°C. During modelocking, we controlled the temperature of the SESAM using a Peltier element. This additional degree of freedom allowed us to find the best SESAM parameters for modelocked operation of the dual-gain configuration with short pulse durations. The temperature-dependent SESAM

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parameters are shown in Fig. 3(a) measured at a center wavelength of 1030 nm with 1-ps pulses over a temperature range of −20 °C up to 60 °C. It is clearly visible that with increasing temperature the modulation depth (ΔR) is increased whereas the saturation fluence (F_{sat}) is initially reduced and then approximately constant as expected from the red shift of the SESAM absorption edge. The nonsaturable losses (ΔR_{ns}) remain approximately constant and become much smaller than the modulation depth at higher temperatures. In addition we did not observe any change of the recovery time.

During our modelocking experiments we confirmed that a small ΔR of the SESAM at room temperature (20 °C) is not strong enough to fully lock the two gain materials, resulting in two cw instabilities at 1034 nm and 1041 nm [Fig. 3(b) top]. At an increased temperature of 30 °C, the modulation depth at the center gain wavelength of Yb:LuO (1034 nm) increases, but remains low for the peak-gain wavelength of Yb:ScO (1041 nm) [Fig. 3(b) middle]. Therefore, cw breakthrough originating from the gain of the Yb:ScO disk is still observed. The SESAM parameters at a temperature of 40 °C allow to achieve a stable and smooth sech^2–shaped optical spectrum with a broad bandwidth that supports short pulse durations [Fig. 3(b) bottom]. At 40 °C, the SESAM parameters at the center wavelength of 1038 nm are approximately as follows: $\Delta R \approx 2.9\%$, $F_{sat} \approx 39\ \mu J / cm^2$, and $\Delta R_{ns} \approx 0.8\%$.

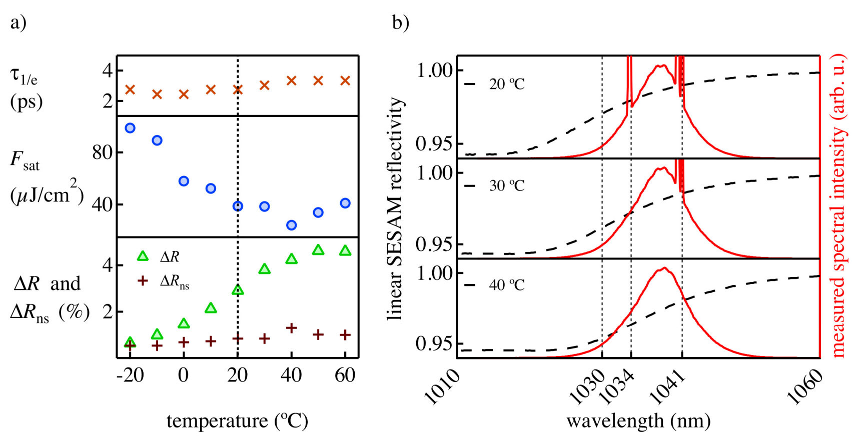

Fig. 3. (a) SESAM parameters: recovery time ($\tau_{1/e}$), saturation fluence (F_{sat}), modulation depth (ΔR) and nonsaturable losses (ΔR_{ns}) measured with a pulse duration of 1 ps at a center wavelength of 1030 nm. Taking into account the red shift of the SESAM, the values measured at 20 °C are a good approximation of the parameters of our experiment operating the SESAM at a temperature of 40 °C and a center wavelength of ≈1038 nm. (b) Left axis: Linear reflectivity spectra of the SESAM measured for different temperatures. The reflectivity exhibits a broad wavelength dependence as expected from low-temperature MBE growth and clearly shows the red shift of the quantum well bandgap with 0.38 nm / °C. Right axis: Modelocked spectrum using the SESAM at three different temperatures. At 20 °C and 30 °C the two separate gain materials at maximum emission wavelength of 1034 nm (Yb:LuO) and 1041 nm (Yb:ScO) are not fully locked because the SESAM does not provide a large enough modulation depth. We therefore observe cw instabilities at 1034 nm and 1041 nm (top and middle). For a fully modelocked spectrum the modulation strength of SESAM had to be increased with the higher temperature of 40 °C (bottom).

In a first experiment we worked with a large amount of SPM in order to find shortest pulse durations of the dual-gain cavity configuration. We introduced a 6 mm thick YAG plate in the cavity focus and balanced it with a total amount of negative group delay dispersion (GDD) of −1170 fs^2 per roundtrip, taking into account the positive dispersion of the Brewster plate. A low output coupling rate of 4.4% yields a spectrum centered at a wavelength of 1037.7 nm with a full width half maximum (FWHM) of 12.8 nm and a pulse duration of 103 fs corresponding to a time-bandwidth product (TBP) of 0.367. The output power of 1.4 W, repetition rate of 41.7 MHz and spot radius of 580 μm on the SESAM result in a

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saturation parameter of $S \approx 2$. The nonlinear phase shift per roundtrip is $\gamma \approx 52$ mrad / MW. To confirm fundamental modelocked operation, we increased the autocorrelator time delay up to 70 ps and used a sampling oscilloscope with a fast photodiode (45 GHz). A good beam quality was confirmed by measuring an $M^2 < 1.2$.

In a second experiment we increased the average output power and replaced the Brewster plate by a thinner 4 mm YAG plate. Using an output coupling rate of 7.8%, we could achieve modelocked operation at 8.6 W of output power and a pulse duration of 124 fs at a center wavelength of 1038.5 nm [Fig. 4]. This result was achieved with a pump power of 82 W on the Yb:LuO crystal and a pump power of 55 W on the Yb:ScO crystal. The nonlinear phase shift of $\gamma \approx 25$ mrad / MW is balanced by a total negative GDD of -2320 fs^2 per roundtrip. The saturation parameter of the SESAM was $S \approx 7$. The pulse spectrum has a FWHM of 10.1 nm which results in nearly transform-limited pulses with a TBP of 0.348, which is ≈1.1-times the time-bandwidth limit of 0.315 of a sech^2-shaped pulse. We confirmed again single-pulse modelocking and measured a good beam quality with an $M^2 < 1.2$.

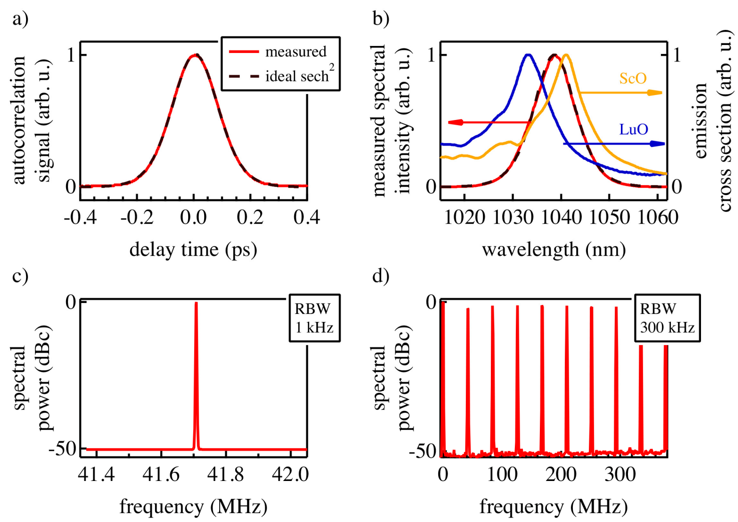

Fig. 4. (a) Noncollinear autocorrelation measured for the highest average output power of 8.6 W reveals a pulse duration of 124 fs. (b) The corresponding spectral bandwidth of 10.1 nm FWHM is centered at 1038.5 nm (red-black striped) in between the two emission cross-section maxima of Yb:LuO (blue) and Yb:ScO (yellow). This clearly demonstrates that both gain materials contribute to the spectral shape of the pulses. (c) Microwave spectrum analyzer shows a pulse repetition frequency of 41.7 MHz with a resolution bandwidth (RBW) of 1 kHz and in (d) with a RBW of 300 kHz over a larger frequency scan with no unusual features in the pulse train.

At this point, the limitation in average power was related to the quality of the available Yb:ScO-disk [Fig. 2(a)]. In addition, both disks were soldered with indium on copper heatsinks which results in stronger thermal lenses. This makes it also more challenging to find a stable fundamental-mode cavity design in a dual-gain configuration. Therefore, future power scaling experiments will require appropriate SESAM parameters and good-quality disks preferably mounted on diamond heatsink.

3. Conclusion and outlook

We present, to our knowledge for the first time, a modelocked TDL based on two different gain materials in a resonator. This dual-gain approach combines the shifted gain spectra of host materials with moderate emission bandwidth but excellent thermal conductivity to an overall broad gain spectrum in order to obtain pulse durations much shorter than supported by a single gain-crystal.

We show in first proof-of principle experiments the successful modelocking of a broad spectrum supported by the two separate sesquioxide gain materials Yb:LuO (centered at 1034 nm) and Yb:ScO (centered at 1041 nm). We demonstrate pulses as short as 103 fs with 1.4 W of average power and achieve 124-fs pulses at a higher output power of 8.6 W. The obtained pulse durations are shorter than previously demonstrated using the Yb:LuO gain material alone. We are limited to moderate output powers for TDLs because of the poor surface quality and thermal lensing of the Yb:ScO-disk. We believe that ongoing progress in the quality of these crystals, the use of gain materials with larger shifts in their gain peaks and accordingly adapted SESAMs parameters will allow to exploit the full potential of this dual-gain concept supporting higher power levels in the sub-100 fs regime.

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