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SESAM mode-locked Yb:CaGdAlO$_4$ thin disk laser with 62 fs pulse generation

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We present a semiconductor saturable absorber mirror (SESAM) mode-locked thin disk laser (TDL) based on Yb:CaGdAlO$_4$ (Yb:CALGO) generating 62 fs pulses, which is the shortest pulse duration achieved from mode-locked TDLs to date. The oscillator operates at a repetition rate of 65 MHz and delivers 5.1 W of average output power. The short pulse duration of our TDL in combination with the high intracavity peak power of 44 MW makes this oscillator attractive for intracavity table-top extreme nonlinear optics applications such as high harmonic generation and vacuum ultraviolet frequency comb generation. The current average power was limited by the quality of the Yb:CALGO disk. However, power scaling of Yb:CALGO TDLs to the multi-10-W range with short pulse durations (<100 fs) appears feasible in the near future by using thinner disks of better quality and further optimized SESAMs.

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High average power ultrafast laser systems find numerous applications both in science and industry. The leading laser technologies that have successfully pushed the average power into the >100 W regime are based on thin disk, fiber, or Innoslab laser systems [3]. In the case of thin disk lasers (TDLs) [4], no additional amplifiers are used and they are mode locked with semiconductor saturable absorber mirrors (SESAMs) [5], which have been optimized for high damage thresholds [6]. To date, pulse energies of >40 μJ in 1.1 ps pulses [7] and 275 W of average power at a pulse duration of 583 fs [1] have been demonstrated directly from ultrafast TDL oscillators based on Yb:YAG.

One interesting aspect of TDLs is the high intracavity peak power which can be realized because the output coupler typically has values in the order of 10%. This intracavity peak power should allow for extreme nonlinear frequency conversion such as high harmonic generation (HHG). Realizing those experiments at a high repetition rate in the MHz regime, typically obtained with ultrafast TDLs, is highly desirable for an improved signal-to-noise ratio and to reduce acquisition times in high field laser physics. However, for efficient operation, HHG typically requires peak intensities of $>10^{13}$ W/cm^2 (i.e., peak powers of >30 MW for a spot diameter of 25 μm) in combination with short pulse durations <100 fs [8–10] [Fig. 1(c)]. State of the art mode-locked TDLs are typically based on the well-established gain material Yb:YAG, which has only reached the 200-fs-regime so far with a Kerr lens mode-locked TDL setup [11].

Therefore, there is a strong research effort in extending the record performance of mode-locked TDLs to the sub-100-fs regime [Fig. 1(a)], and overcoming the trade-off between pulse duration and average output power [Fig. 1(b)] with novel broadband thin disk gain materials that meet the spectroscopic and thermomechanical requirements [12,13]. In the past years, many Yb-doped gain materials have been investigated toward this goal. In particular, cubic sesquioxides have demonstrated their

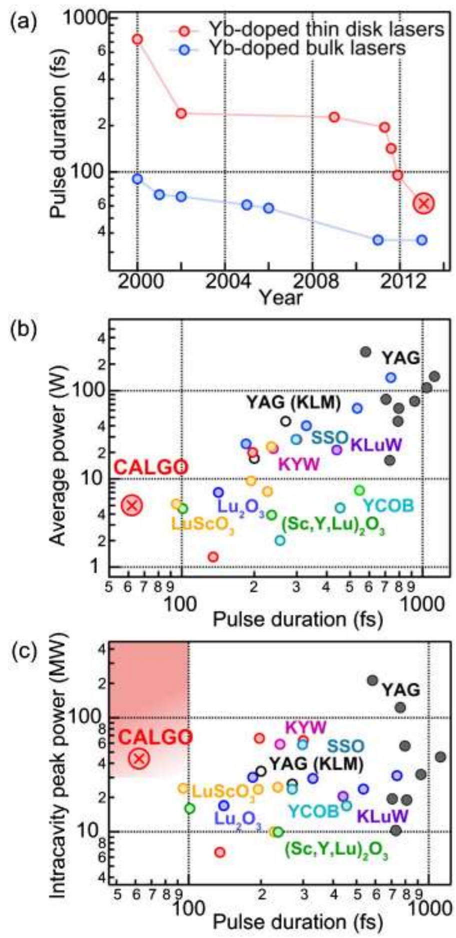

Fig. 1. (a) Minimum pulse duration of ultrafast bulk and TDLs based on Yb-doped gain materials over the years. The result presented here is marked with a crossed circle. (b) Overview of average power versus pulse duration of mode-locked TDLs demonstrated to date and (c) the corresponding intracavity peak power versus pulse duration. The references for all the data points presented in (b) and (c) can be found in [13].

potential [14]. To date, the shortest pulses from a mode-locked TDL were obtained with the broadband mixed sesquioxide material $Yb:LuScO_3$ [~20 nm full width at half-maximum (FWHM) of the gain cross section at inversion levels of around 10%]. In this result, 96 fs pulses were demonstrated at an average power of 5 W [15], corresponding to an intracavity peak power of 23 MW.

Another promising candidate for high-power short pulse generation is $Yb:CaGdAlO_4$ (Yb:CALGO) [16]. It exhibits a smooth and very broad gain spectrum (>35 nm FWHM at inversion levels of around 10%) and a good thermal conductivity of 6.3 W/(m × K) along the c axis for a 2 at. % doped crystal [16]. In low-power bulk mode-locked lasers, pulses as short as 47 fs with 38 mW average output power [17] and 40 fs with 15 mW [18] were demonstrated. In both cases, extracavity dispersion management was required to reach the shortest pulses. Furthermore, remarkable performance was achieved in a high-power bulk mode-locked laser, reaching 12.5 W with 94 fs pulses [19]. The suitability of Yb:CALGO for ultrafast high-power operation in the thin disk configuration was also confirmed in recent results where 28 W at 300 fs were reached [20]. However, the potential of this material for short pulse generation (sub-100-fs) in the thin disk geometry had not yet been fully exploited and only 1.3 W with 135 fs pulses could be obtained in the first mode-locking experiments [20].

Here, we demonstrate a SESAM mode-locked Yb:CALGO TDL that delivers 62 fs pulses, which is more than two times shorter than previously achieved with this material in the thin disk configuration. These are, to our knowledge, the shortest pulses ever obtained from a mode-locked TDL. In this first experiment that aimed at exploring the pulse duration limits of this promising broadband material, we restricted ourselves to 5.1 W of average power to avoid damage of the disk, which had limited optical quality. Nonetheless, even at this moderate average output power and pulse energy, the output peak power exceeds 1.1 MW and the intracavity peak power reaches 44 MW [Fig. 1(c)]. In combination with the short pulse duration and the repetition rate in the MHz regime, this opens promising new possibilities for intracavity extreme nonlinear optics experiments with TDL table-top sources.

The commercially available wedged 3.1 at. % Yb:CALGO disk used in our experiments has a thickness of ≈220 μm, and its c-cut accounts for isotropic mechanical and thermal properties in the disk plane. In addition, this allows us to operate the laser in the optical σ polarization, which exhibits a broader and smoother gain cross section than the π polarization, an advantage for short pulse generation. The disk was vacuum soldered using indium at 180°C onto a copper–tungsten heat sink (20% of copper) with a coefficient of thermal expansion (CTE) at room temperature of 8.3×10^{-6} K^{-1}, which is close to the CTE of Yb:CALGO for the a axis (10.1×10^{-6} K^{-1} [16]). The thin disk head was arranged for 24 passes through the disk, enabling a pump absorption of >90%. We used a fiber-coupled volume Bragg grating stabilized pump diode at 979.5 nm, which can deliver up to 400 W of power. The pump spot was set to a diameter of 2.1 mm.

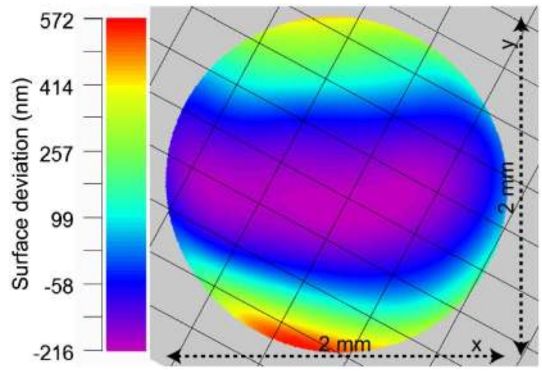

Fig. 2. Surface deviation, compared to a flat surface, of the contacted disk obtained from an interferometric measurement, indicating a strong astigmatism with radii of curvature of −4.8 m in the y direction, and infinity in the x direction.

The disk was first tested in continuous wave (cw) operation in a linear multimode cavity that consisted of a curved (radius of curvature $R = -100$ mm) output coupler (transmission $T = 0.9\%$) and the high reflective side of the disk, separated by ≈7 cm. In this configuration, we obtained up to 45 W of output power with an optical-to-optical efficiency of 45% and a slope efficiency of 54%. From this, we estimated the disk losses of a single pass to be <0.5%. This value is about five times higher than the ones for typical Yb:YAG or $Yb:Lu_2O_3$ disks [21]. We decided not to push the pump intensity beyond 3.0 kW/cm^2 in order to avoid damage due to the low optical quality and the strong astigmatism of the thin disk (Fig. 2). Prior contacting, the disk had an uniform curvature of R = −1.81 m; improvement in the current contacting method, in particular better tailoring the pressure applied on the disk during the contacting, should prevent such an astigmatism in the future. Furthermore, gluing on diamond should also yield better contacting quality as was observed in [20].

For the mode-locking experiments, we built a cavity (Fig. 3) supporting single fundamental mode operation ($M^2 < 1.1$). With an output coupler transmission of 3.0%, we achieved a cw average power of up to 14 W at an optical-to-optical efficiency of 19%. The output power was not pushed further to avoid damage of our crystal at pump power densities of >3 kW/cm^2.

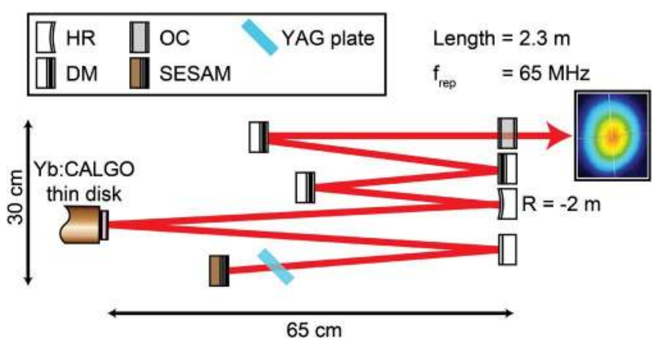

Fig. 3. Schematic (not to scale) of the single fundamental mode laser cavity used for the mode-locking experiment. The inset on the right shows the output beam profile for 62 fs pulses. HR, high-reflectivity mirror; OC, output coupler; DM, dispersive GTI-type mirror.

We inserted a 5.3-mm-thick-undoped YAG plate at Brewster's angle into the cavity to ensure a linear polarization and to introduce the self-phase modulation (SPM) required for soliton mode locking [22]. The addition of three Gires–Tournois interferometer (GTI) type mirrors led to an estimated total group delay dispersion (GDD) per roundtrip of $-300\ \text{fs}^2$, which balanced the total SPM phase shift of 600 mrad at our maximum intracavity peak power.

For starting and stabilizing the mode-locking mechanism, we inserted a SESAM as one end mirror into the fundamental mode cavity. It consisted of a single quantum-well absorber and no dielectric top coating. The SESAM was indium soldered onto a water-cooled copper substrate. We measured the saturation parameters of this SESAM using a high-precision nonlinear reflectivity setup described in detail in [23]. For this characterization, we used our Yb:CALGO mode-locked TDL, operated at a pulse duration of 85 fs and a center wavelength of 1051 nm. This allowed us to extract the correct saturation parameters and to evaluate the influence of two-photon absorption (TPA) on the nonlinear reflectivity of the SESAM for sub-100-fs operation. As was studied in detail in [6,24], TPA causes a rollover in the reflectivity of the sample at high fluences, which can be the main cause of damage and mode-locking instabilities in high-power TDLs. For the sample used in this experiment, at a temperature of 20°C we measured a saturation fluence $F_{\text{sat}} = 10\ \mu\text{J/cm}^2$, a modulation depth $\Delta R = 1.34\%$, nonsaturable losses $\Delta R_{\text{ns}} = 0.50\%$, and an induced absorption coefficient $F_2 = 275\ \text{mJ/cm}^2$ (Fig. 4).

With an output coupler transmission of 2.5%, stable mode locking was obtained from 1.1 to 5.1 W of average power in single fundamental mode operation ($M^2 < 1.1$). The optical-to-optical efficiency at the maximum output power was moderate (≈7%) due to the low optical quality of the mounted laser crystal. At the maximum average power, we achieved a pulse duration of 62 fs [Fig. 5(a)]. The repetition rate of our oscillator was 65 MHz [Figs. 5(c) and 5(d)], corresponding to a maximum pulse energy of 80 nJ, an extracavity peak power of 1.1 MW, and an intracavity peak power of 44 MW. The output spectrum [Fig. 5(b)] had a FWHM of 23 nm, supporting 52 fs pulses. At an estimated inversion level of ≈10%, this corresponds to ≈66% of the available gain FWHM, demonstrating the potential of this material for the generation of short pulses in the thin disk geometry. The time–bandwidth product of 0.38 was within 20% of the transform limit of the spectrum. The observed chirp was most likely due to uncompensated higher-order dispersion in our laser cavity. In particular, the dispersive GTI-type mirrors were not designed for flat GDD at our center wavelength of 1051 nm. Stable soliton mode locking is illustrated by the clean microwave frequency spectra of Figs. 5(c) and 5(d), where no side peaks or modulation of the harmonics of the fundamental frequency are observed.

Operation with a single pulse circulating in the cavity was confirmed with a fast photodiode (45 GHz) and a sampling oscilloscope [Fig. 5(e)]. The SESAM's moderate saturation fluence and strong rollover of the reflectivity led to a tendency to multiple pulsing when trying to obtain higher power levels and shorter pulses (Fig. 4). We believe that optimized dispersive mirrors in combination with either larger beam diameters on the SESAM or high saturation fluence SESAMs will allow for reaching the sub-50-fs range with transform-limited pulses.

Power scaling to substantially higher power levels should be straightforward by using increased mode areas on disks of better quality contacted on diamond heat sinks. In particular, higher doping levels should allow for efficient operation with thinner disks. Recently, a

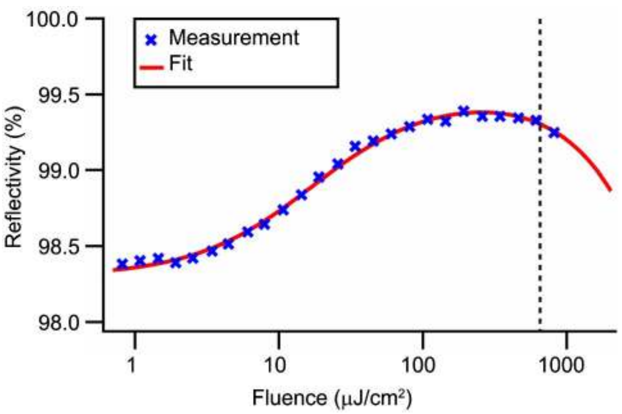

Fig. 4. Nonlinear reflectivity measurement of the SESAM used in our laser, as determined with 85 fs pulses at a center wavelength of 1051 nm, and a temperature of 20°C. The red graph shows the least squares fit, the dashed line marks 640 μJ/cm², the SESAM intracavity fluence for our 62 fs pulses.

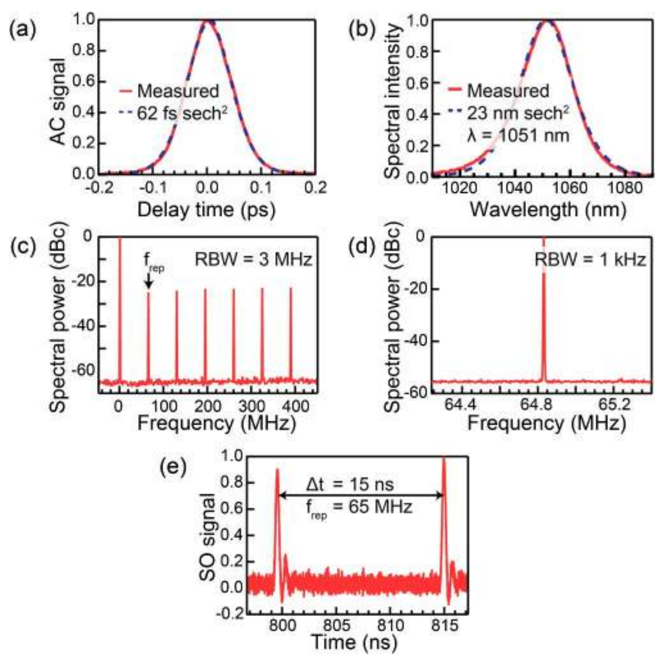

Fig. 5. (a) Normalized intensity autocorrelation (AC) trace and (b) optical spectrum with the fit curves assuming ideal sech² pulses. The pulse duration is 62 fs and the spectral bandwidth is 23 nm, centered at 1051 nm. (c) Microwave spectrum analyzer (MSA) trace at a resolution bandwidth (RBW) of 3 MHz and a 500 MHz span, showing the fundamental repetition rate and its harmonics and (d) MSA trace at a RBW of 1 kHz and a 1.2 MHz span. (e) Sampling oscilloscope measurement showing a temporal pulse separation of 15 ns, corresponding to the roundtrip time of our single-mode oscillator.

significant improvement in the growth of high-quality 5.4 at. % Yb:CALGO crystals was realized and a slope efficiency of 70% was achieved in multimode operation [21].

In summary, we present a Yb:CALGO TDL with 62 fs pulse duration, which are the shortest pulses obtained from a mode-locked TDL to date. Even shorter pulses should be feasible by optimizing the dispersion management in the laser cavity and further improving the SESAM design. We achieved a moderate output power of 5.1 W, limited by the optical quality of our thin disk. Using better quality disks contacted on diamond heat sinks should enable significantly higher power levels while keeping the pulse duration <100 fs. The high intracavity peak power of 44 MW in combination with the pulse duration in the sub-100-fs range should allow for intracavity extreme nonlinear optics experiments with a table-top TDL source.

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