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Kerr lens mode-locked Yb:CALGO thin-disk laser

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We demonstrate the first Kerr lens mode-locked $Yb:CaGdAlO_4$ (Yb:CALGO) thin-disk laser oscillator. It generates pulses with a duration of 30 fs at a central wavelength of 1048 nm and a repetition rate of 124 MHz. The laser emits the shortest pulses generated by a thin-disk laser oscillator, equal to the shortest pulse duration obtained by Yb-doped bulk oscillators. The average output power is currently limited to 150 mW by the low gain and limited disk quality. We expect that more suitable Yb:CALGO disks will enable substantially higher power levels with similar pulse durations.

OCIS codes: (140.4050) Mode-locked lasers; (140.3538) Lasers, pulsed; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium.

High-harmonic generation based on Yb-doped ultrafast thin-disk laser (TDL) oscillators is a simple amplification-free approach to produce coherent extreme ultraviolet (XUV) light at megahertz repetition rates [1,2]. In the current systems, the long pulses produced by the oscillator (250–900 fs duration) either require external pulse compression or severely limit the XUV photon flux and photon energies. This motivates extending the record performance of mode-locked TDLs to the sub-100-fs regime as well as reaching new pulse duration limits.

The TDL geometry [3] enabled ultrafast oscillators to generate record-high average output powers of 275 W [4]. Mounting the thin-disk crystal onto a backside-cooled heat sink allows for an efficient heat removal. High nonlinearities and thermal effects in the gain crystal are efficiently reduced thanks to its thin thickness of 100–300 μm used with millimeter- to centimeter-size beam diameters. The total intracavity nonlinearity can thus be adjusted independently from the gain crystal. However, TDL oscillators demonstrated longer pulses than in the bulk configuration (Fig. 1). Yb-doped bulk oscillators already generated pulses as short as 30 fs, but only at average output powers <100 mW [5,6]. Thermal effects and excessive nonlinearities in the gain crystal are severe challenges for a significant average power increase.

Initially, mode-locked TDLs relied on semiconductor saturable absorber mirrors (SESAMs, [13]). The availability of TDL crystals with broader gain emission bandwidths [14] allowed reducing the pulse duration of TDLs from initially 680 fs [4] to 49 fs, which has been delivered at 2 W average output power [9]. On the other hand, Kerr lens mode-locking is advantageous for generating short pulses because it provides an instantaneous response and a high modulation depth [15]. However, the Kerr lens mode-locked (KLM) resonator design is challenging because it typically requires operation close to a stability edge for continuous-wave (cw) operation. Prior to this work, stable pulsed operation of KLM TDLs has only been demonstrated for the gain materials Yb:YAG [10] and $Yb:Lu_2O_3$ (Yb:LuO) [16]. Despite the limited gain bandwidth of Yb:YAG, 49-fs pulses have been demonstrated at 3.5 W output power [11]. Yb:LuO features a 30% broader gain bandwidth (Fig. 2), which enabled the recent demonstration 35-fs pulses at 1.6 W from a KLM TDL [12]. Combining broadband Yb-based gain materials with the Kerr lens mode-locking scheme is therefore a promising approach towards TDLs generating even shorter pulse durations.

Yb:CALGO offers a nearly flat and broad gain profile due to its disordered crystalline structure. Its full width at half-maximum (FWHM) bandwidth in the σ-polarization exceeds 60 nm at 30% inversion level, being eight times larger than that of Yb:YAG (Fig. 2). The thermal conductivity of Yb:CALGO

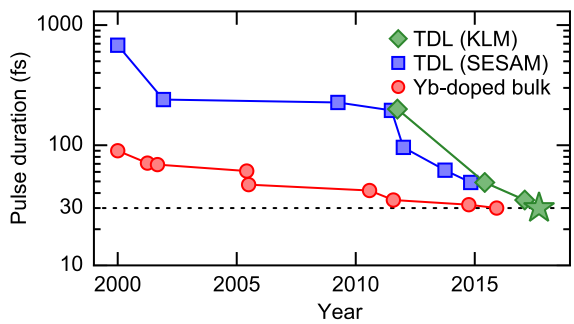

Fig. 1. Evolution of the shortest pulse duration generated by ultrafast Yb-doped bulk and thin-disk laser oscillators [4–12]. The presented result is highlighted with a green star symbol.

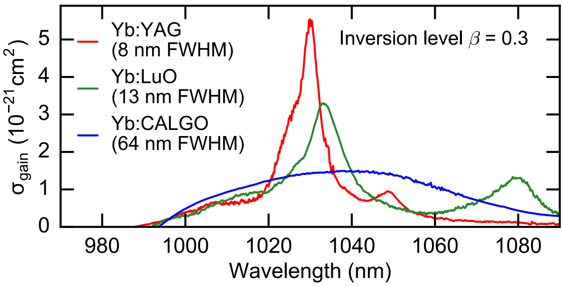

Fig. 2. Calculated gain cross sections (inversion level $\beta = 0.3$) of the Yb-doped laser crystals YAG, LuO, and CALGO (σ-polarization). The corresponding FWHM gain bandwidths are given in parentheses. Data taken from Refs. [17,18].

Table 1. Overview of the State-of-the-Art Performance of Ultrafast Yb:CALGO Bulk and Thin-Disk Laser (TDL) Oscillators[a]

Geometry	ML	τ	P_{out}	Reference
Bulk	SESAM	94 fs	12.5 W	[20]
Bulk	KLM	37 fs	1.5 W	[6]
Bulk	KLM	32 fs	90 mW	[6]
TDL	SESAM	300 fs	28 W	[21]
TDL	SESAM	49 fs	2 W	[9]
TDL	KLM	30 fs	150 mW	This work

[a]ML, mode-locking scheme; τ, pulse duration; P_{out}, average output power.

of 6.3 $Wm^{-1}K^{-1}$ is comparably good with respect to other broadband gain materials [19]. An overview of the state-of-the-art performance of ultrafast Yb:CALGO oscillators in the bulk and thin-disk geometry is given in Table 1. A previous attempt of Kerr lens mode-locking an Yb:CALGO TDL has been reported, but stable pulse operation was not demonstrated [22]. In this Letter, we present, to the best of our knowledge, the first Kerr lens mode-locked Yb:CALGO TDL. The laser achieves 30-fs pulses, which are the shortest pulses generated by ultrafast TDLs and equal to the shortest pulses demonstrated by Yb-doped bulk oscillators.

The laser is based on a wedged, 150-μm-thick Yb(∼3.8 at. %):CALGO disk with a *c*-cut crystal orientation (FEE GmbH). The disk has a diameter of 9.3 mm and a concave radius of curvature of 2 m. It is contacted on a diamond heat sink (Trumpf GmbH) and pumped at 979 nm by a fiber-coupled narrow-bandwidth (<1 nm FWHM) diode-laser system. The pump light passes 36 times through the disk to achieve high pump absorption. The pump spot was set to a diameter of 2 mm. Initial tests in transverse multi-mode (MM) and fundamental-mode (FM) cw operation have been performed in a simple V-cavity [Figs. 3(a) and 3(b)].

The overlap ratio between the FM size on the disk and the pump spot size has been set to 0.4 for highly MM behavior. The extracted power depended strongly on the position on the disk, which indicates inhomogeneities in the crystalline structure. An average output power of 60 W was emitted with 30% optical-to-optical and 37% slope efficiency at 0.8% output coupler transmission (Fig. 4). Increasing the output coupler transmission to 2.7% decreased the optical-to-optical efficiency, which dropped to 6.1% with a slope efficiency of

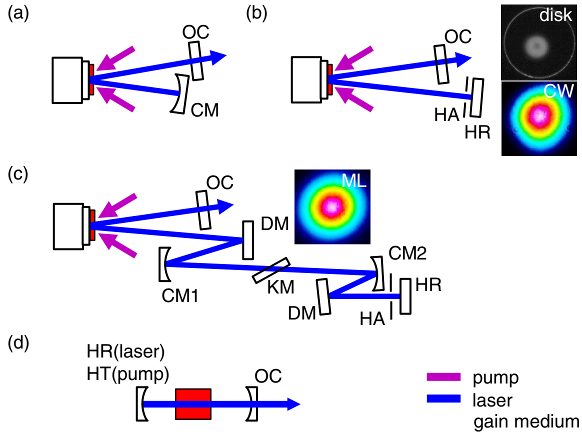

Fig. 3. Schematics of the Yb:CALGO thin-disk laser (TDL) in (a) continuous-wave (cw) transverse multi-mode and (b) fundamental-mode (FM) operation. Inset: pictures of the disk with pump spot (top) and corresponding output beam profile (bottom) in FM operation. The darker area in the center of the pump spot is depleted by the laser. (c) Yb:CALGO TDL cavity with inset of the beam profile in mode-locked (ML) operation. (d) Schematic of a standard end-pumping configuration of bulk oscillators. CM, curved mirror; DM, dispersive mirror; HA, hard aperture; HR, highly reflective; HT, highly transmissive; KM, Kerr medium; OC, output coupler.

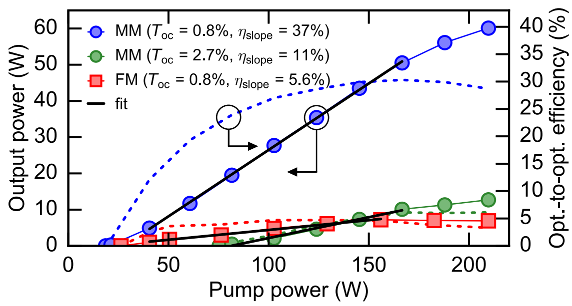

Fig. 4. Continuous-wave performance. Average output power (markers) and corresponding optical-to-optical efficiency (dashed line) of the disk in multi-mode (MM) and fundamental-mode (FM) operation for different output coupler transmissions (T_{OC}). Black solid lines are the linear fits for the calculation of the slope efficiencies (η_{slope}).

11%. This indicates a strong limitation of the tolerable total cavity losses for efficient laser operation, which results from the combination of low doping concentration and thin disk thickness.

Increasing the overlap ratio between the fundamental laser mode and the pump spot to ≥80% did not lead to FM operation as it is usually expected for TDLs. Transverse FM operation (M^2 <1.05) was only achieved when inserting a hard aperture in the cavity to suppress the onset of higher-order modes. Only a small area of the pump spot gets efficiently extracted, as shown in Fig. 3(b). For an overlap ratio of 60% and a 1.8-mm hard-aperture diameter, the laser delivered up to 7 W average power with 4.6% optical-to-optical efficiency and 5.6% slope efficiency at an output coupler transmission of 0.8%. The cw performance of this particular disk is comparably poor in terms of average output power [22,23], efficiency [24], and gain [25]. The decrease of the optical-to-optical efficiency and clamping of the average output power for pump powers higher than 150 W indicates thermal effects of the disk, which was pumped up to a power density of 6.5 kW/cm^2. The strong drop of the laser performance from MM to FM cw operation can therefore be attributed to a low disk quality. The losses from the hard aperture and the small overlap ratio contribute largely to the low efficiency observed in FM operation. Due to the difficulties to operate the laser in the FM, multiple bounces on the disk were not considered.

For mode-locking experiments, the FM cavity was extended with two curved mirrors (CM1 and CM2) with a concave radius of curvature of 250 mm [Fig. 3(c)]. A 4 mm-thick undoped YAG plate placed under Brewster's angle between CM1 and CM2 serves as Kerr medium (KM) for the mode-locking mechanism. The beam radii inside the KM are estimated to be 80 μm × 140 μm in the tangential and sagittal planes, respectively, during cw operation. The plate induces self-phase modulation (SPM) and forces the laser to operate in linear polarization. A water-cooled intracavity pinhole with an aperture diameter of 1.6 mm placed in front of an end mirror serves as hard aperture for Kerr lens mode-locking, while the second end mirror is an output coupler with a transmission of 0.3%. Two dispersive mirrors introduce a group delay dispersion (GDD) of −900 fs^2 per round trip. The corresponding spectral profile is shown in Fig. 5(a). They have been designed to support a broad spectral bandwidth and were grown using our ion-beam-sputtering coating machine. Mode-locking is initiated by shifting the position of CM2. Then, the pump power is adjusted to suppress parasitic cw lasing. The oscillator footprint is 90 cm × 30 cm.

The laser generates pulses with a temporal width of 30 fs FWHM as shown by the autocorrelation trace in Fig. 5(b). We introduced −440 fs^2 of GDD in front of the autocorrelator (obtained by two dispersive mirrors and a 3-mm-thick fused silica plate). Single pulse operation is proven by a 180-ps scan in the autocorrelator and by observing the pulse train with an 18.5-ps-rise-time photodetector on a 40-GHz sampling oscilloscope [Fig. 5(c)]. The small fluctuations appearing at 0.5 ns are an artifact from the detection electronics. An average output power of 150 mW is achieved with an optical-to-optical efficiency of 0.1% and an excellent beam quality [M^2 <1.05, Fig. 5(e)]. The laser optical spectrum shown in Fig. 5(a) has a central wavelength of 1048 nm and a bandwidth of 45 nm FWHM, which leads to a time-bandwidth product of 0.37 (1.17 times the ideal value for sech^2 pulses). The observed chirp can be attributed to uncompensated higher-order dispersion originating from the non-flat profile introduced by the dispersive mirrors [26]. Improved dispersion management should result in transform-limited pulses as demonstrated in a SESAM mode-locked Yb:CALGO TDL [9]. The peaks around 950 nm and 1150 nm are associated with dispersive waves as already observed in various oscillators, e.g., [5,6,12]. While the disk coating supports the entire laser optical spectrum, the transmission of the output coupler increases from 0.3% at the central wavelength to ∼2% at the wings. Additionally, the dispersive mirrors operate at the limit of their spectral bandwidth. The radio-frequency spectrum at the repetition rate of 124 MHz shows no side peaks and the modulation-free higher harmonics confirm a clean mode-locking [Fig. 5(d)]. While the laser operates over hours, the short-term stability is confirmed by the amplitude and phase noise measurement [Figs. 5(f) and 5(g)]. We measured a root-mean-square (rms) amplitude noise of <0.2% (integrated from 1 Hz to 1 MHz), which is lower compared to previous ultrafast TDLs [1,2,27]. The rms timing jitter is <2 ps (from 100 Hz to 1 MHz, corresponding to an integrated phase noise of 1.49 mrad) and <150 fs (from 1 kHz to 1 MHz, integrated phase noise of 116.7 μrad). The phase noise in the lower Fourier frequency range is comparably high

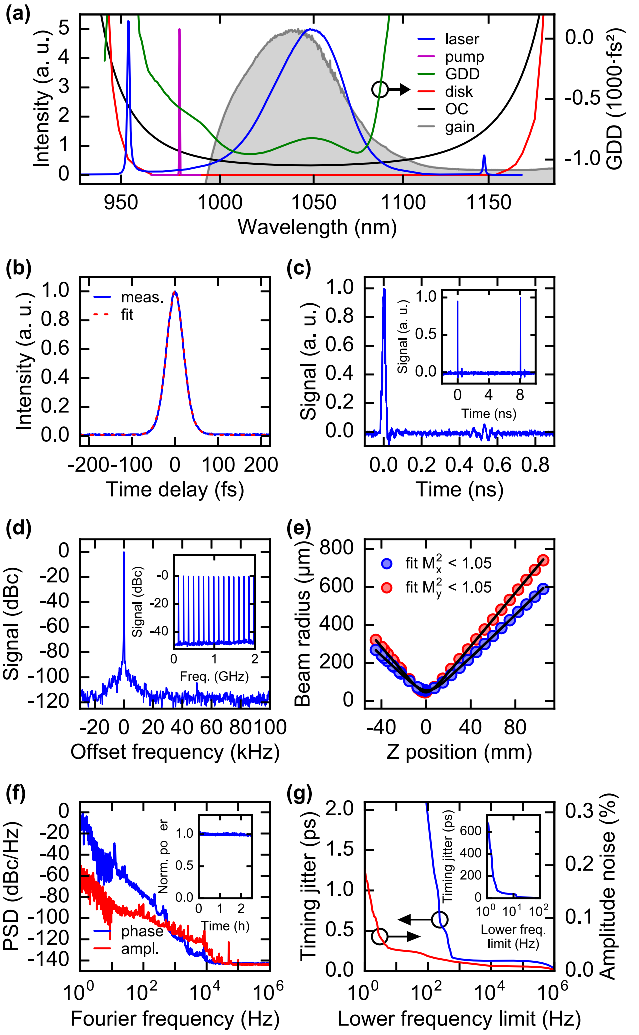

Fig. 5. Characterization of the KLM Yb:CALGO TDL. (a) Normalized optical spectrum of the pump and laser output, gain cross section for an inversion level of $\beta = 0.3$ chosen for reference, transmission (left y-axis, 5.0 ≙ 5.0%) of the highly reflective disk coating and of the output coupler (OC), introduced group delay dispersion (GDD) of the dispersive mirrors per cavity round trip (right y-axis); (b) autocorrelation trace of the 30-fs pulses and sech^2 fit; (c) 1-ns and (inset) 10-ns sampling oscilloscope trace; (d) radio-frequency (RF) spectrum of the laser fundamental repetition-rate frequency measured with a 300-Hz resolution bandwidth (RBW); inset: RF spectrum of the higher harmonics with a 100-kHz RBW; (e) beam quality factor M^2; (f) phase and amplitude noise power spectral densities measured at the fundamental repetition frequency of 124 MHz; inset: normalized average output power logged over 2.5 h; (g) rms timing jitter and rms amplitude noise integrated up to 1 MHz as a function of the lower cut-off frequency; inset: rms timing jitter in different scales.

for a TDL, which operates at an order of magnitude higher repetition rate. Moreover, it is directly mounted onto a laser without mechanically stable laser housing and not actively stabilized. We expect that the rather high phase noise at Fourier frequencies <1 kHz can be strongly reduced by active stabilization of the repetition rate.

The optical spectrum extends to shorter wavelengths below the pump wavelength [Fig. 5(a)]. The short-wavelength part of the spectrum is generated via SPM in the KM and not amplified by the gain medium. However, reabsorption in the gain medium causes additional losses that decrease the optical-to-optical efficiency. This broad spectral width is enabled by the TDL pumping geometry [Figs. 3(a)–3(c)], where the pump delivery and the laser cavity share no optics except of the disk. The spectral properties of intracavity components can be optimized for shorter pulses independently from the pumping wavelength. In contrast, standard end-pumped bulk oscillators [Fig. 3(d)] use intracavity dichroic mirrors with high transmission for the pump wavelength and high reflectivity for the laser wavelength, which would prevent such a mode of operation. Although similar broad spectra have been obtained in bulk configuration, the lasers operated at longer central wavelengths of ∼1060 nm [5,6].

In conclusion, we presented the first KLM Yb:CALGO TDL. It generates the shortest pulses of any TDL, being equal to the shortest pulses demonstrated by Yb-doped bulk oscillators. Our work confirms the benefits of the thin-disk pumping scheme for the generation of ultrashort pulses. KLM TDLs already produced pulses with an optical spectrum three times larger than the gain bandwidth [11,12]. The presented 30-fs laser does not fully exploit the ultra-broad bandwidth of Yb:CALGO. Therefore, we believe that further decrease of the pulse duration towards the direct generation of few-cycle pulses from Yb-based diode-pumped solid-state lasers is feasible. Next steps require the optimization of the disk parameters (doping concentration, thickness, crystal quality) as well as the optimization of the optical properties of all intracavity components for a broad reflectivity and flat dispersion profile. This should also enable substantially higher power levels with better optical-to-optical efficiencies at similar pulse durations.

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