

Carrier-envelope offset frequency stabilization of a thin-disk laser oscillator operating in the strongly self-phase modulation broadened regime

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Abstract: We demonstrate the carrier-envelope offset (CEO) frequency stabilization of a Kerr lens mode-locked Yb:Lu₂O₃ thin-disk laser oscillator operating in the strongly self-phase modulation (SPM) broadened regime. This novel approach allows overcoming the intrinsic gain bandwidth limit and is suited to support frequency combs from sub-100-fs pulse trains with very high output power. In this work, strong intra-oscillator SPM in the Kerr medium enables the optical spectrum of the oscillating pulse to exceed the bandwidth of the gain material Yb:Lu₂O₃ by a factor of two. This results in the direct generation of 50-fs pulses without the need for external pulse compression. The oscillator delivers an average power of 4.4 W at a repetition rate of 61 MHz. We investigated the cavity dynamics in this regime by characterizing the transfer function of the laser output power for pump power modulation, both in continuous-wave and mode-locked operations. The cavity dynamics in mode-locked operation limit the CEO modulation bandwidth to ~10 kHz. This value is sufficient to achieve a tight phase-lock of the CEO beat via active feedback to the pump current and yields a residual in-loop integrated CEO phase noise of 197 mrad integrated from 1 Hz to 1 MHz.

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1. Introduction

Optical frequency combs (OFCs) based on mode-locked lasers are a key tool for numerous scientific and industrial applications [1–4]. Most commonly, they are either based on Ti:sapphire lasers that are pumped by complex frequency-doubled solid-state lasers [1,2], or more recently diode-pumped sources [5] or based on diode-pumped fiber-lasers which require several stages for amplification and pulse compression [6].

Yb-doped diode-pumped solid-state laser (Yb-DPSSL) oscillators are an alternative technology providing reliable and low noise operation [7,8]. These sources have also a high potential for power-scaling, which is especially attractive for nonlinear frequency conversion to the mid-infrared spectral region by parametric nonlinear processes [3,9] and to the extreme ultraviolet by high harmonic generation [9–11].

However, only a few Yb-DPSSL oscillators have been reported with a stabilization of the carrier envelope offset (CEO) frequency (f_{CEO}) operating at a watt-level average power and sub-100-fs pulses generated directly from the oscillator, i.e. without the need for external amplification or pulse compression. So far, the direct f_{CEO} stabilization of sub-100-fs Yb-DPSSL oscillators relied exclusively on broadband gain materials (Fig. 1). In the bulk geometry, f_{CEO} -stabilized Yb:CALGO oscillators delivered pulses as short as 64 fs at an average power level of 2 W [12,13]. A shorter pulse duration of 57 fs has been achieved from

a f_{CEO} -stabilized Yb:CYA oscillator but at a lower average power of 250 mW [14]. In the thin-disk geometry, f_{CEO} -stabilization has been realized with an Yb:CALGO thin-disk laser (TDL) oscillator delivering 77 fs pulses at 2.1 W average power [15,16]. The highest reported average power of an f_{CEO} -stabilized Yb-DPSSL oscillator was recently generated by an Yb:YAG TDL operating at 105 W with 190-fs pulses, but a compression stage was required before coherent supercontinuum generation [17].

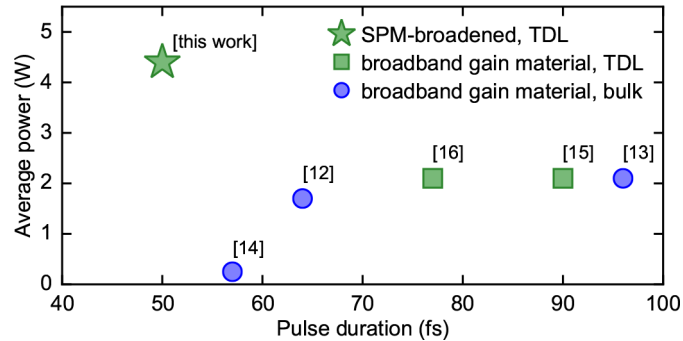


Fig. 1. Overview of f_{CEO} -stabilized Yb-DPSSL oscillators delivering sub-100-fs pulses without external pulse compression. So far, they have relied exclusively on broadband gain materials (bulk [12–14], thin-disk laser (TDL) [15,16]). Our Yb:Lu₂O₃ TDL oscillator operates in the strongly self-phase modulation (SPM) broadened regime and is highlighted with a green star symbol.

In the last years, Kerr lens mode-locked (KLM) TDL oscillators based on the gain materials Yb:YAG and Yb:Lu₂O₃ [18] operating in the regime of strong self-phase modulation (SPM) have been developed [19,20]. In this regime the optical spectrum of the oscillating pulse strongly exceeds the bandwidth of the gain material. An expansion up to a factor of 3 has been achieved so far. Strong intra-oscillator SPM in the Kerr medium (usually a fused silica, sapphire, or YAG plate with a thickness of several millimeters) generates frequencies beyond the spectral range of the gain. This enables the direct generation of sub-100-fs soliton pulses from bandwidth-limiting gain materials at high average powers. More than 10 W of average power in 88-fs pulses and pulse durations as short as 35 fs at 1.6 W were demonstrated [20]. Therefore, the strongly SPM-broadened regime is promising for the generation of high power OFCs without the need for additional amplification or pulse-compression. Prior to this work, it was uncertain if oscillators operating in this regime could be f_{CEO} -stabilized. Although their output parameters appear suitable, particular cavity and f_{CEO} dynamics could prevent a stabilization [16,21].

Here, we demonstrate for the first time the f_{CEO} stabilization of an Yb-DPSSL oscillator operating in the strongly SPM-broadened regime with 50 fs pulse durations, shorter than the gain bandwidth of the active material would support. We characterize the transfer function of the output power of the oscillator in continuous-wave (cw) and mode-locked operation for a modulation of the pump power and achieve a tight f_{CEO} lock with <200 mrad of integrated phase noise in a phase-locked loop with feedback applied to the pump current.

2. Thin-disk laser oscillator and experimental setup

The experiment has been performed using a KLM Yb:Lu₂O₃ TDL oscillator generating pulses which are among the shortest of any TDL oscillators. The laser is described in detail in [20]. It delivers 4.4 W of average output power in time-bandwidth-limited 50-fs soliton pulses [inset of Fig. 2(a)] at 61 MHz repetition rate. This results in a pulse energy of >60 nJ and a peak power of >1 MW. The optical spectrum of the mode-locked laser is centered at around 1031 nm with a full width at half maximum (FWHM) bandwidth of 24 nm that exceeds the FWHM gain bandwidth of Yb:Lu₂O₃ by a factor of 2 [Fig. 2(a)]. A schematic of the

experimental setup is shown in Fig. 2(b). The oscillator is pumped by a highly transverse-multimode fiber-coupled (600 μm core diameter; 0.22 numerical aperture) volume-Bragg-grating stabilized pump diode with a power of 100 W at a wavelength of 976 nm. The driver of the pump diode operates at a current of ~ 16 A with a compliance voltage of ~ 17 V.

A MHz-bandwidth modulation of the pump current is enabled by an in-house-developed voltage-to-current (V-I) converter that delivers up to ± 1 A of current for ± 10 V of applied voltage modulation. The transfer function of its output current was measured using a lock-in amplifier for a modulation of the input voltage (Fig. 3). The V-I converter induces a -90° phase shift at a frequency around 2 MHz. It was connected to the pump diode in parallel to the diode driver. Cross-talks between both current sources were prevented using a low-pass RC-filter with a cut-off frequency of 7 Hz (0.22 Ω , 0.1 F), which attenuates at the same time the noise of the high current DC source.

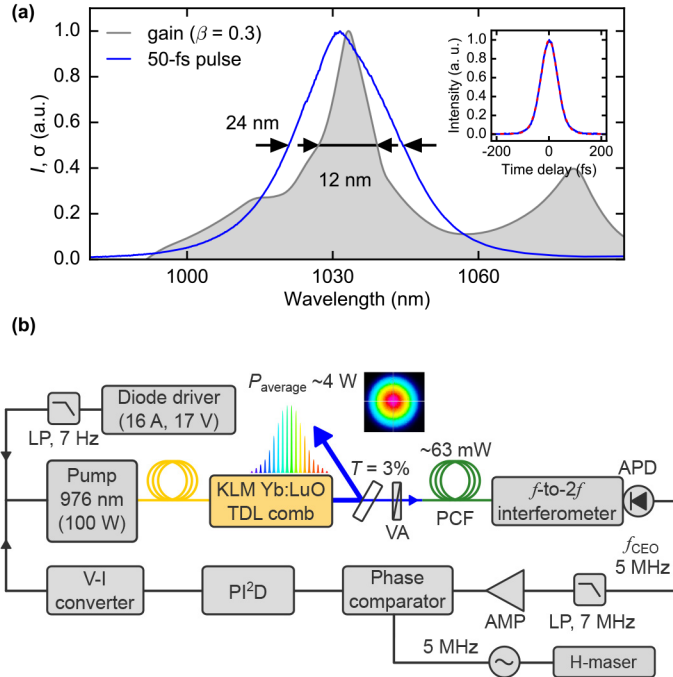


Fig. 2. (a) Optical spectrum of the mode-locked laser operating in the strongly self-phase modulation broadened regime and gain spectrum of Yb:Lu₂O₃ for an inversion level of $\beta = 0.3$ (data taken from [22]); inset: auto-correlation trace of the 50-fs pulses with a sech^2 fit for soliton pulses (dashed red line). (b) Schematic of the experimental setup for f_{CEO} detection and stabilization. The beam profile is shown in mode-locked operation. Electrical connections are indicated by black lines. AMP: amplifier; APD: avalanche photodiode; LP: low-pass filter; P_{average} : average power; PCF: photonic crystal fiber; T : transmission; VA, variable attenuator; V-I converter: voltage-to-current converter; PI^2D : proportional-double-integral-derivative servo controller; \sim : signal generator.

3. Transfer functions

The transfer function of the pump power was measured at a typical operating point of the pump diode of 16 A, corresponding to an emitted power of 100 W. Around this point, the pump current was modulated by the V-I converter with a peak-to-peak amplitude of 20 mA, corresponding to a relative pump power modulation of $\pm 0.06\%$. The transfer function shows a nearly constant amplitude response up to about 10 kHz, followed by a slight decrease resulting in a 3-dB bandwidth of around 100 kHz (Fig. 3). The -90° phase shift in the phase response is reached at around 1.5 MHz.

In the subsequent step, we investigated the transfer function of the laser output power for the same cavity and the same modulation applied to the input voltage of the V-I converter, first in cw and then in mode-locked operation. In cw operation, the laser emitted only 2.3 W at a pump power of 100 W. Its efficiency was reduced, due to the increased losses caused by the hard aperture required for the Kerr lens mode-locking scheme. The peak in the relative amplitude of the transfer function at around 15 kHz [Fig. 3(a)] is attributed to the relaxation oscillation that is typical for oscillators in cw operation. This value is in good agreement with the expected theoretical value of 18 kHz (assuming an upper state lifetime of 850 μ s, experimentally estimated total cavity losses of 10% and a normalized pump rate of 1.9) [23]. The large phase change associated with the relaxation oscillations limits the modulation bandwidth to \sim 20 kHz in cw operation [Fig. 3(b)].

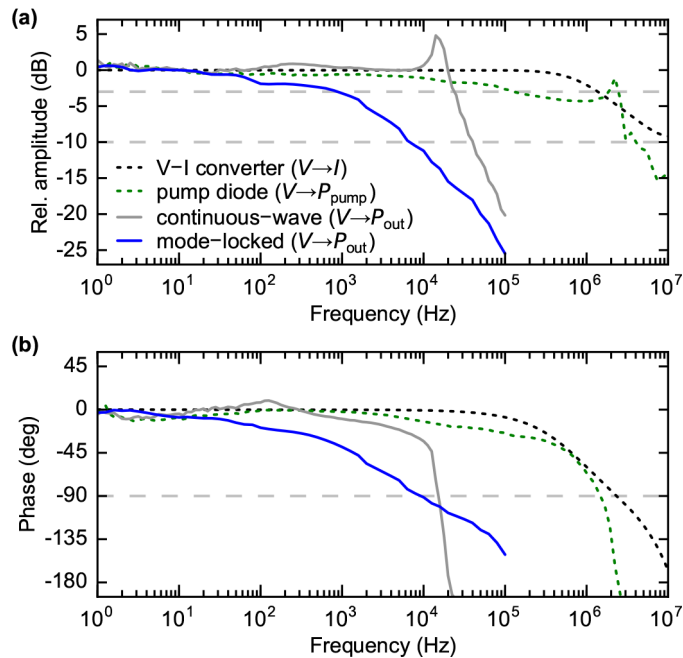


Fig. 3. Transfer functions for the modulation of the input voltage (V) of the voltage-to-current (V - I) converter. (a) Relative amplitude and (b) phase are shown in dotted lines for the resulting modulation of the pump current (I) and diode pump power (P_{pump}), and in solid lines for the output power (P_{out}) in continuous-wave and mode-locked operation. Gray dashed lines highlight a 3-dB and 10-dB drop in the relative amplitude and a -90° phase shift.

The transfer function of the laser output power in the strongly SPM-broadened regime was similarly measured at an operation current of 16 A. It is to be noted that in this case, the pump current can be varied in a range of \sim 400 mA equivalent to a change of 4 W in pump power without destabilizing the mode-locking. In this condition, the laser operated stably for hours. A 3-dB drop in the relative amplitude is reached at a frequency of around 1 kHz, while the -90° phase shift occurs near 10 kHz (Fig. 3). The amplitude response drops by an order of magnitude up to this point. The transfer function corresponds roughly to a second-order low-pass filter, which is characteristic of a laser operating in a strongly damped regime [24,25]. The frequency response and modulation bandwidth are comparable to TDL oscillators that have been successfully f_{CEO} -stabilized via pump power modulation [16,26]. Based on previous studies of Yb-DPSSL bulk [13] and TDL [16] oscillators, a similar behavior can be considered for the transfer function of the f_{CEO} . Therefore, the cavity dynamics of our KLM TDL limit the pump-current-to- f_{CEO} modulation bandwidth for CEO beat stabilization to about 10 kHz.

4. CEO beat detection and stabilization

An octave-spanning supercontinuum spectrum was generated in a photonic crystal fiber (PCF) using a small fraction of 3% of the laser output power directly from the oscillator and without the need of an additional pulse compression stage [Fig. 2(b)]. The major part of the laser output power remained accessible for applications. A variable attenuator enabled fine adjustment of the average power launched into the 2-m-long collapse-cleaved PCF (NKT Photonics, SC-3.7-975). The fiber has a core diameter of 3.7 μm , a cut-off wavelength of 975 nm and a nonlinear coefficient of $\gamma \approx 18 \text{ W}^{-1} \cdot \text{km}^{-1}$ (at 1060 nm). The coupling efficiency into the PCF was approximately 67%. From around 63 mW of launched average power, an octave-spanning supercontinuum spectrum was generated, ranging from 680 nm to 1360 nm. It was then launched into a standard quasi-common-path f -to- $2f$ interferometer for CEO-beat detection [27]. An MgO-doped periodically-poled lithium niobate (MgO:PPLN, 14.00- μm poling period, 3.0-mm length) crystal was used for second harmonic generation of the Raman soliton. The CEO beat was detected at 5 MHz with a signal-to-noise ratio >25 dB at a resolution bandwidth of 10 kHz using a fiber-coupled avalanche photodiode [Fig. 4(a)]. The free-running CEO beat fluctuated in a range of around 200 kHz in a timescale in the order of a few seconds [Fig. 4(b)]. We attribute this fluctuation to power fluctuations of the free-running pump laser. The noise of the pump power has generally the dominant contribution to the CEO frequency noise in TDLs, being pumped by highly transverse-multimode fiber coupled diode modules with power levels of several hundreds of watts [16]. This pump noise also has a significant contribution to the amplitude noise of the oscillator [16]. Therefore, the active stabilization of f_{CEO} by modulation of the pump current results in the simultaneous decrease of the amplitude noise of the oscillator up to a frequency of 10 kHz [Fig. 4(d)]. The increase in amplitude noise observed at higher frequencies of around 20 kHz is attributed to the servo bump of the CEO stabilization loop. A similar correlation between the CEO frequency noise and the amplitude noise of the mode-locked laser was also observed in other types of frequency combs based on diode-pumped solid-state lasers [12] or fiber lasers [28].

The detected CEO beat signal was low-pass filtered, amplified and phase-locked to an external waveform generator that was itself referenced to a hydrogen maser for long-term stable operation [Fig. 2(b)]. The phase error signal was generated using a digital phase detector and was subsequently amplified in a proportional-double-integral-derivative (PI^2D) servo-controller. The feedback signal was applied to the V-I converter to modulate the pump current. The frequency noise power spectral density (FN-PSD) of the free-running and stabilized CEO beat was directly measured from the photodiode signal with a phase-noise analyzer (Rohde-Schwarz FSWP26) [Fig. 4(e)]. From the crossing-point of the FN-PSD of the free-running CEO beat with the β -separation line [29], a feedback bandwidth in the order of 3 kHz is estimated to be necessary to achieve a tight phase lock of the f_{CEO} . When the f_{CEO} -stabilization loop was activated, the noise was reduced up to a frequency of ~ 10 kHz, which is in good agreement with the -90° phase-shift bandwidth retrieved from the transfer function in mode-locked operation [Fig. 3(b)]. The servo bump appears at around 20 kHz. The residual in-loop integrated phase noise was 197 mrad (integrated from 1 Hz to 1 MHz) and is comparable to previously reported TDL oscillator results [15,26,30]. Residual spikes at 50 Hz and its harmonics as well as at 6-8 kHz and at around 20 kHz are attributed to the noise of the pump diode [16]. A tight phase-lock of the CEO beat was achieved as shown by the coherent peak with a signal-to-noise ratio of >30 dB in the radio-frequency spectrum, measured with a resolution bandwidth of 1 Hz [Fig. 4(c)]. An out-of-loop measurement of the CEO noise has not been performed since no second f -to- $2f$ interferometer was available at the time of the experiments.

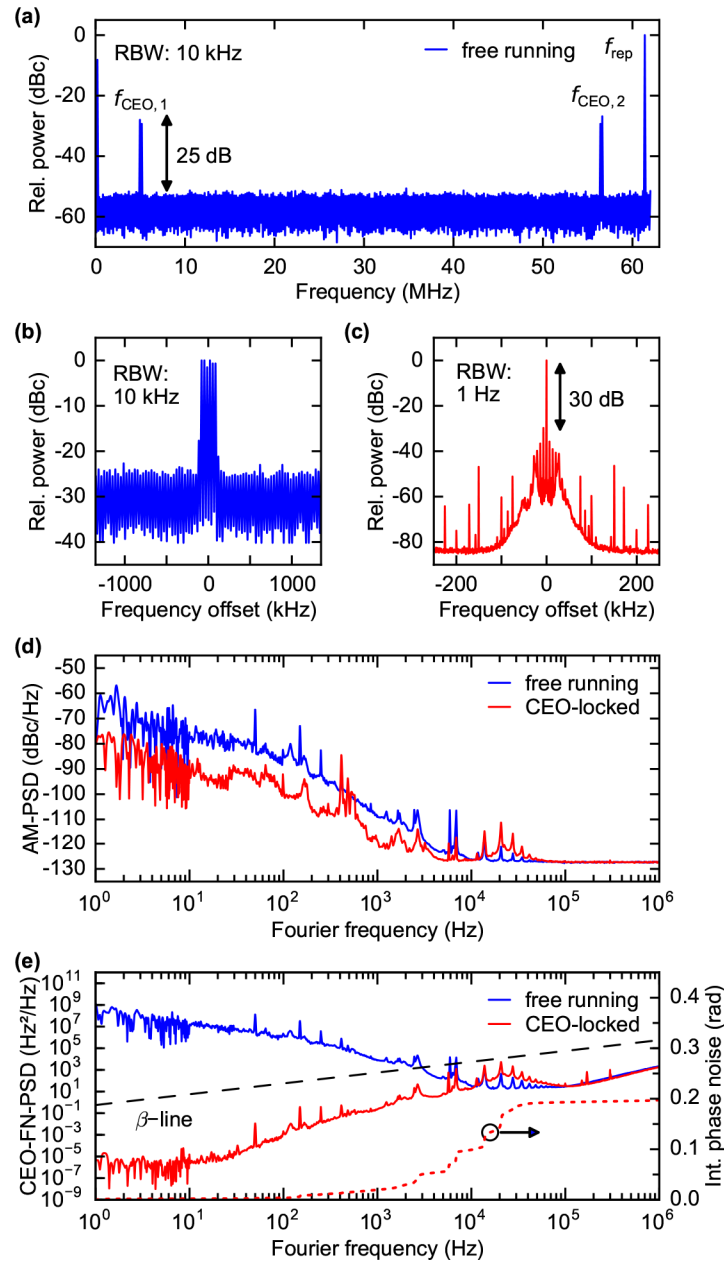


Fig. 4. (a) Radio-frequency spectrum of the free-running carrier-envelope offset (CEO) beat frequency (f_{CEO}). (b) Frequency jitter of the free-running CEO beat in a time scale of seconds and (c) coherent peak of the CEO beat spectrum when phase-locked at a central frequency of 5 MHz. (d) Relative amplitude modulation power spectral density (AM-PSD) of the laser output measured at the fundamental harmonic of the repetition frequency in free-running (blue) and CEO-locked (red) operation. (e) CEO frequency noise power spectral density (CEO-FN-PSD) of the free-running (blue) and locked (red) CEO beat (left axis, solid lines) and integrated phase noise as a function of the upper cut-off frequency (right axis, dotted line). f_{rep} : repetition rate frequency; RBW: resolution bandwidth.

5. Conclusion and outlook

In conclusion, we demonstrated the first f_{CEO} stabilization of an Yb-DPSSL oscillator operating in the strongly SPM-broadened regime. This is also the first time that a f_{CEO}

stabilization is demonstrated for the gain material Yb:Lu₂O₃. The KLM Yb:Lu₂O₃ TDL oscillator generates 50-fs pulses at an average power of 4.4 W. This is to the best of our knowledge the shortest pulse duration and the highest average power that has been CEO-stabilized from an Yb-DPSSL oscillator without the need for additional amplification or pulse compression. We investigated the transfer functions of the laser output power by modulating the pump power in cw and mode-locked operation. The cavity dynamics in mode-locked operation limit the CEO modulation bandwidth to ~10 kHz. A tight phase-lock of the CEO beat has been achieved with a residual in-loop integrated phase noise of 197 mrad (integrated from 1 Hz to 1 MHz). As a next step, we will investigate the long-term stability of the CEO lock and simultaneously stabilize the repetition rate frequency for a fully-stabilized OFC. Additionally, we will investigate other f_{CEO} -stabilization techniques to increase the locking bandwidth, e.g., by implementing an optical-to-optical modulator inside the oscillator [31].

We believe that Yb-DPSSL frequency combs will benefit from the power scalability of KLM TDL oscillators [32]. The strongly SPM-broadened regime will soon enable OFCs based on Yb-DPSSL oscillators to operate directly with several tens of watts and sub-100-fs pulse durations [20]. Such systems are highly attractive as compact sources for the generation of extreme ultraviolet OFCs via high harmonics generation in gases directly driven by the oscillator [33–35].

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