Phase-stabilization of the carrier-envelope-offset frequency of a SESAM modelocked thin disk laser

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Abstract: We phase-stabilized the carrier-envelope-offset (CEO) frequency of a SESAM modelocked Yb:CaGdAlO$_4$ (CALGO) thin disk laser (TDL) generating 90-fs pulses at a center wavelength of 1051.6 nm and a repetition rate of 65 MHz. By launching only 2% of its output power into a photonic crystal fiber, we generated a coherent octave-spanning supercontinuum spectrum. Using a standard *f*-to-2*f* interferometer for CEO detection, we measured CEO beats with 33 dB signal-to-noise ratio in 100 kHz resolution bandwidth. We achieved a tight lock of the CEO frequency at 26.18 MHz by active feedback to the pump current. The residual in-loop integrated phase noise is 120 mrad (1 Hz-1 MHz). This is, to our knowledge, the first CEO-stabilized SESAM modelocked TDL. Our results show that a reliable lock of the CEO frequency can be achieved using standard techniques in spite of the strongly spatially multimode pumping scheme of TDLs. This opens the door towards fully-stabilized low-noise frequency combs with hundreds of watts of average power from table-top SESAM modelocked thin disk oscillators.

OCIS codes: (320.0320) Ultrafast optics; (140.4050) Mode-locked lasers; (320.6629) Supercontinuum generation.

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#194747 - $15.00 USD Received 29 Jul 2013; revised 24 Sep 2013; accepted 30 Sep 2013; published 9 Oct 2013

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#194747 - $15.00 USD Received 29 Jul 2013; revised 24 Sep 2013; accepted 30 Sep 2013; published 9 Oct 2013

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1. Introduction

The generation of carrier-envelope-offset (CEO) frequency stabilized pulses with multi-megahertz repetition rates and hundreds of watts average power is highly attractive for numerous applications in science and industry. Such performance would result in frequency combs with extremely high power per comb line, substantially improving signal-to-noise ratio (SNR) for many measurements. Moreover, carrier-envelope-phase (CEP) stable pulses with high average power are essential for high-harmonic generation (HHG) at multi-megahertz repetition rate, an area with an extremely high scientific potential [1–4]. Today, most commonly used high power CEP-stabilized laser systems are either based on Ti:sapphire amplifiers that are usually limited to the kHz regime, or on multi-stage fiber amplifier systems, which can reach MHz repetition-rates and high average powers [5] but their low Q-factor cavities and strong nonlinearities make the noise reduction more challenging, thus require careful design schemes for low noise operation [6]. In both cases, a CEO-stabilized femtosecond oscillator seeding one or several preamplifer and power amplifier stages are required to reach the targeted high average power level, making the overall systems relatively complex. The seed oscillators are typically pumped with low-noise single transverse-mode pump lasers, which limits their achievable output power in addition to other factors such as the maximum tolerable intracavity nonlinearities and thermal distortions.

Recently, frequency combs from diode-pumped solid-state lasers (DPSSL) have achieved excellent stability [7]. Among DPSSL technologies, ultrafast thin disk lasers (TDLs) are the most promising technology to generate powerful CEO-stable frequency combs directly from modelocked oscillators. TDLs benefit from the low intrinsic noise level of high-Q diode-pumped solid-state lasers and can reach record-high power levels at multi-megahertz repetition rates with a footprint comparable to a low power oscillator. They are based on a very thin disk-shaped gain medium (typical disk thicknesses are of some hundred micrometers) that allows for excellent heat removal and low nonlinearities, supporting straightforward power scalability [8, 9]. Reliable high-power modelocked operation is achieved using semiconductor saturable absorber mirrors (SESAMs) [10], which are designed for high intracavity fluences [11] and benefit from similar power-scaling capabilities as the thin gain medium. Since the first demonstration of an ultrafast TDL in 2000 [12], they have achieved higher average powers and pulse energies than any other laser oscillator technology [13, 14]. Currently, 275-W average power in 580-fs pulses [15] and >40-µJ pulse energy in 1.1-ps pulses [16] are achieved.

#194747 - $15.00 USD Received 29 Jul 2013; revised 24 Sep 2013; accepted 30 Sep 2013; published 9 Oct 2013

However, for more than a decade the pulse duration of ultrafast TDLs was limited to above 200 fs and shorter pulse durations down to 24 fs were only achieved using additional nonlinear fiber compression [14, 17–19]. Durations above 200 fs are usually too long to directly support the generation of a coherent octave-spanning spectrum in a nonlinear fiber [20], which is required for standard CEO frequency detection in an *f*-to-2*f* interferometer [21]. Furthermore, it remained so far unclear whether pump-induced instabilities could potentially increase the noise level of the oscillator such that a stable frequency comb could not be achieved [22].

In 2011, the first CEO frequency detection of a TDL was performed using a SESAM modelocked Yb:Lu_2O_3 TDL that delivered 142-fs pulses and 7 W of average power [23, 24]. Launching the pulses directly into a nonlinear fiber resulted in successful CEO frequency beat detection with >25 dB signal-to-noise in a 3-kHz resolution bandwidth (RBW). However, damage of the only laser crystal available at the time of the experiment prevented further steps towards full stabilization.

More recently, CEO stabilization of a Kerr-lens modelocked Yb:YAG thin disk oscillator was reported [25]. In this case, the 250-fs pulses provided by the laser were externally compressed to <30 fs in a nonlinear fiber and subsequently launched into a photonic crystal fiber (PCF) for generating a coherent octave-spanning spectrum required for CEO detection. Furthermore, an intracavity acousto-optic modulator was used to stabilize the oscillator, which is a challenge for further increase of the average power and pulse energy.

Here we demonstrate the first CEO frequency phase-locking of a SESAM modelocked thin disk oscillator. In our stabilization scheme, we use feedback to the current of the multi-mode pump laser. The laser uses an Yb:CALGO (Yb:$CaGdAlO_4$) thin disk and generates 90-fs pulses at 65-MHz repetition rate and an average power of 2.1 W directly from the oscillator, which is among the shortest pulse durations reported from TDLs to-date [26–28]. Therefore, no external pulse compression stages were required for CEO phase-stabilization. We measured the in-loop phase noise of the locked CEO signal (f_{CEO} = 26.18 MHz) and achieved an integrated residual phase noise of 120 mrad (1 Hz-1 MHz). This work proves that the standard CEO stabilization schemes can also be applied for high-power modelocked laser oscillators which are pumped by inexpensive spatially-multimode pump diodes, opening the door to unamplified high-power self-referenced frequency combs with average powers of hundreds of watts.

2. CEO detection of Yb:CALGO modelocked TDL

2.1 Laser setup

For all the experiments presented here, we used a SESAM modelocked TDL based on the broadband gain material Yb:CALGO (Yb:$CaGdAlO_4$). This material recently attracted significant attention due to its potential for short pulse generation in the thin disk geometry [29]. Very recently, this was confirmed with the demonstration of the shortest pulses from a modelocked thin disk oscillator using this gain material, generating 5 W of average power and pulses as short as 62 fs [28]. For the experiments presented here, the oscillator was operated in a different setting than the one reported in [28] for more parameter flexibility for CEO frequency detection and stabilization.

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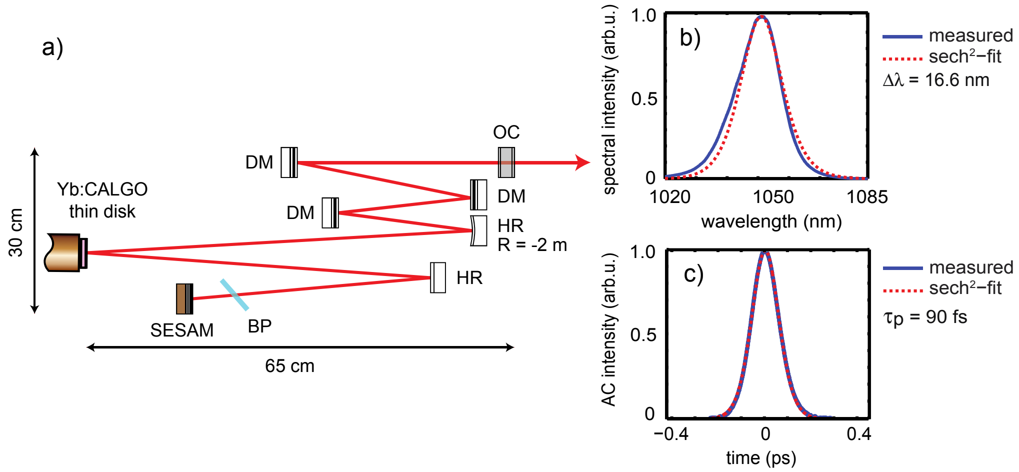

Fig. 1. (a) Experimental setup showing the modelocked Yb:CALGO laser cavity layout. Highly reflective mirrors (HR), output coupler (OC), Brewster plate (BP), dispersive mirror (DM); (b) The measured optical spectrum is 16.6 nm broad (FWHM) and is centred at 1051.6 nm; (c) The intensity autocorrelation trace corresponds to a pulse duration of 90 fs, proving nearly transform-limited pulses.

A schematic of the modelocked TDL layout is presented in Fig. 1(a). We used a 220-µm thick c-cut 3% doped Yb:CALGO disk mounted on a CuW heatsink as a folding mirror in a single fundamental-mode cavity. The pump laser diode is electrically driven by a standard power supply (SM18-50, Delta Elektronika). It contains two diode stacks that are optically stabilized to a wavelength of 979.5 nm using Volume Bragg Grating (VBG) technology. A maximum pump power of 400 W is available of which only 65 W are used for the present experiment. The pump light is coupled to a multimode fiber with 400-µm diameter and a numerical aperture of 0.22, resulting in an M^2 of about 140. The fiber output power is launched into a standard thin disk head configured for 24 passes over the gain disk.

In order to achieve soliton modelocking, we introduced a set of GTI-type mirrors leading to 300 fs^2 of negative group delay dispersion per cavity round trip. This compensates for the self-phase modulation, mostly provided by a 5.3-mm thick YAG-plate placed at Brewster angle in the laser cavity. For modelocking, we used a SESAM with a saturation fluence of 10 $\mu J/cm^2$, a modulation depth of 1.34% and nonsaturable losses of 0.50% (measured at 1052 nm with 85-fs pulses with the setup presented in [30]). We used an output-coupling mirror with a transmission of 2.5%.

In this configuration, the range of fundamental modelocked operation spans average output powers from 1.5 W to 2.6 W and pulse durations from 100 fs down to 70 fs. This regime of pulse durations is ideal for coherent supercontinuum (SC) generation with the available highly-nonlinear PCFs, as it will be discussed in the next section. The laser operates in single transverse-mode over the whole operational range ($M^2 < 1.1$). For the stabilization of the CEO beat frequency, the laser was set to 2.1-W average output power. The repetition rate of the oscillator is 65 MHz and the resulting output pulse energy and peak power available for the experiment are 32 nJ and 318 kW, respectively. The corresponding optical spectrum spans 16.6 nm (FWHM) and the measured pulse duration is 90 fs (Fig. 1(b), 1(c)). This proves nearly transform-limited pulses with a time-bandwidth product of 0.405 (theoretical limit would be 0.315 for $sech^2$-pulses).

2.2 Generation of a coherent octave-spanning spectrum and f_{CEO} detection

An essential step for the self-referenced stabilization of a frequency comb is the generation of an octave-spanning optical spectrum of high temporal coherence. For typical modelocked lasers with nJ-pulse energies and pulse durations in the range of 100 fs, this is usually achieved by launching the pulses into a PCF of an appropriate length, dispersion profile and sufficient nonlinearity to efficiently broaden the spectrum to the required octave. Generally, a longer fiber provides a broader spectrum, but with a reduced temporal coherence.

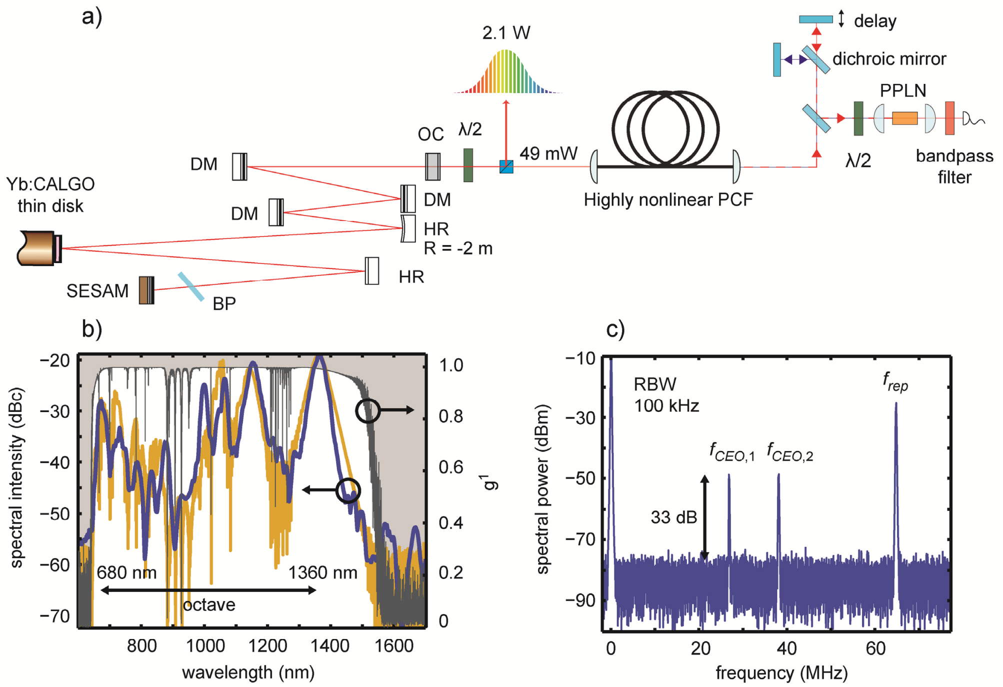

Fig. 2. (a) Experimental setup showing the laser cavity, highly nonlinear photonic crystal fiber (PCF) and f-to-$2f$ interferometer for measuring CEO beat signals. The quasi-common path f-to-$2f$ interferometer uses a Periodically-Poled Lithium Niobate crystal (PPLN) for second harmonic generation to access the CEO frequency; (b) The generated supercontinuum spectrum spans more than an octave (left y-axis; measurement: blue line, simulation: yellow line). For CEO frequency detection the wavelength of 1360 nm was frequency doubled and superimposed with the 680-nm spectral component. The simulated first order coherence is almost 100%, especially for the two wavelengths used for beat detection (right y-axis, grey line); (c) Strong f_{CEO} beat signals of 33 dB SNR are obtained using the f-to-$2f$ interferometer (RBW: 100 kHz).

Furthermore, too long pulse durations greatly reduce the coherence. A proposed simplified metric for a sufficient supercontinuum coherence is a soliton order N not exceeding a value of 10 [20].

In our experiment, we launched only a small fraction (≈2%, i.e., 49 mW) of the total laser power into a 1-m long highly nonlinear PCF (NKT photonics 3.2-945, zero-dispersion wavelength of 945 nm, 3.2-µm core diameter). Assuming a coupling efficiency of 70%, the resulting soliton order was calculated to be $N = 5$, supporting the generation of a coherent octave-spanning supercontinuum (Fig. 2(b)). The measured SC spectrum (blue) is in good agreement with simulations carried out using John M. Dudley's code (yellow) [31]. These simulations further indicate a very high degree of coherence, in particular for the spectral components around 1360 nm and 680 nm, which are used for CEO beat generation. This suggests a SC that is robust against amplitude and pulse duration fluctuations, which is important for stable CEO detection.

This SC was launched into a quasi-common path f-to-$2f$ interferometer, the details of which are presented in [32]. It consists of a Michelson-type interferometer with a dichroic mirror to separate the short and long wavelengths. A temporal delay is introduced in one arm of the interferometer to adjust the temporal overlap between the two different spectral components used for beating. After recombination, the beams are launched into a Periodically-Poled Lithium Niobate crystal for frequency doubling of the 1360-nm spectral components. The beams are subsequently filtered using an optical bandpass filter with 10-nm spectral bandwidth and generate a beat signal on a fast photodiode. The coherence of the broadened spectrum is experimentally proved by the straightforward detection of CEO beat-notes with 33 dB SNR in a 100-kHz resolution bandwidth (Fig. 2(c)). This value is typically sufficient for locking the CEO frequency to an external reference. It is worth noting that the above-mentioned strong CEO beat signal was detected reliably over hours and reproduced over several days, proving the stability and reliability of the modelocked TDL.

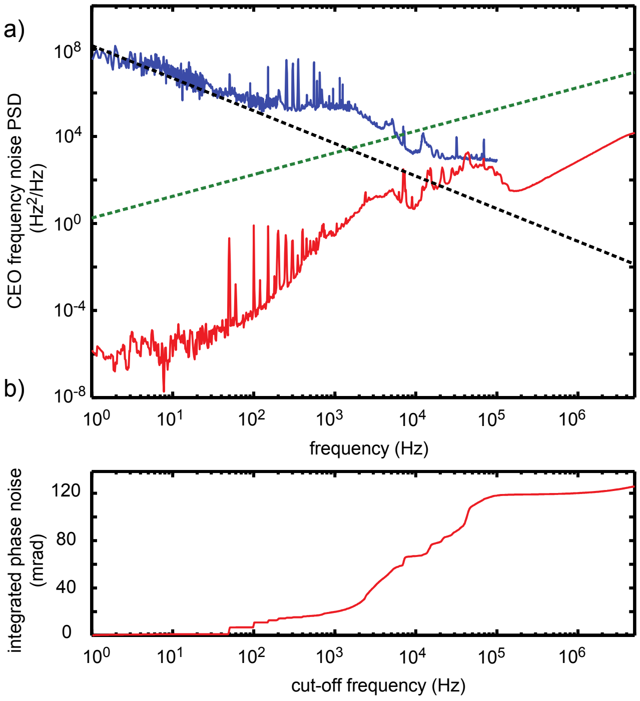

Fig. 3. (a) Frequency noise power spectral density (PSD) of the CEO beat in free-running mode (blue curve, measured using a frequency discriminator) and phase-locked to 26.18 MHz (red curve, measured using a Signal Source Analyzer Agilent, E5052) at a pulse repetition rate of 65 MHz. For frequencies from 1 Hz to 100 Hz, $1/f^{3/2}$ noise dominates the free-running signal as indicated by the black, dashed line. Above ≈200 kHz the frequency noise PSD of the locked CEO beat is limited by the shot noise of the phase noise detection. The β-separation line (green, dashed line) that is relevant for the determination of the linewidth [33] gives an estimate of the required feedback bandwidth of the stabilization loop; (b) The residual in-loop phase noise of the tightly locked f_{CEO} integrated from 1 Hz up to an upper cut-off frequency f_c is 120 mrad (for $f_c = 1$ MHz).

3. Stabilization of the carrier-envelope-offset frequency

3.1 Characterization of the free-running CEO beat

As a first step, we characterized the frequency noise power spectral density (PSD) of the free-running CEO beat (Fig. 3(a), blue trace). We used a frequency discriminator (Miteq FMDM 21.4/2-4) to convert frequency fluctuations of the input signal into voltage fluctuations that were measured using an FFT spectrum analyzer. This measurement shows that below 100 Hz the CEO beat is affected by flicker ($1/f^{\alpha}$) noise (with a slope $\alpha \approx 3/2$

indicated as a black dashed line in Fig. 3(a), but some excess noise is observed in the range 100 Hz – 5 kHz. This excess noise is also visible in the amplitude noise of the laser and is believed to originate from the laser diode current supply. A detailed analysis of the different noise sources in our oscillator is currently under investigation in the context of a more thorough study.

Using the β-separation line introduced by Di Domenico *et al.* [33], a rough estimation of the feedback bandwidth required to achieve a tight lock of the CEO beat can be assessed from its crossing point with the frequency noise PSD. For our TDL, the measurement shows a crossing point located at around 7 kHz (see Fig. 3(a)), indicating that a feedback bandwidth of about 10 kHz should be sufficient for a tight phase-lock according to this simple approach. However, the excess noise observed in the range 100 Hz - 5 kHz will likely demand for a slightly higher bandwidth.

3.2 CEO stabilization

Feedback for CEO stabilization was applied to the pump laser current. This is very convenient as it does not require any additional optical component in the laser cavity and preserves the power scalability of TDLs. The extra degree of freedom of adjusting the resonator length, e.g., acting on the position of the SESAM, is left for future stabilization of the repetition rate. A specific electronic system was designed in-house to modulate the pump current with an amplitude of up to 50 mA peak-to-peak and a bandwidth of approximately 100 kHz, which should be sufficient for CEO stabilization, as mentioned previously.

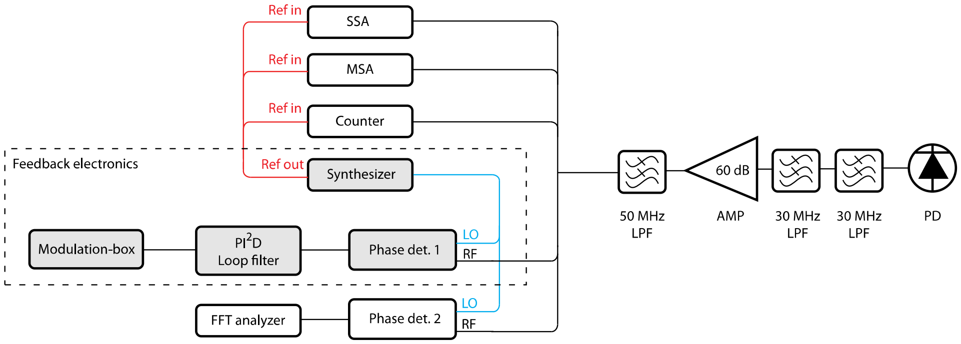

Fig. 4. Schematic of the electronics for CEO frequency detection, locking and characterization: the signal from the fast photodiode (PD) of the f-to-$2f$ interferometer is filtered using two 30-MHz low pass filters (LPF) and amplified in a 60-dB RF-amplifier (AMP) followed by a 50-MHz LPF. The signal is then split in different branches for stabilization and characterization. A microwave spectrum analyzer (MSA) is used for CEO frequency detection and a frequency counter for fractional frequency stability analysis. Both devices are referenced to a synthesizer, which also serves as the local oscillator (LO) for two digital phase detectors. f_{CEO} is locked to the synthesizer using a phase-lock loop made of a phase detector, a Proportional-double-Integral-Derivative (PI^{2}D) controller and an in-house-built modulation box that controls the current of the pump diode. For cross-validation, the frequency noise of the locked CEO is also measured using a second phase detector of the same model and an FFT spectrum analyzer. The electronics used for phase-locking are highlighted and framed. All other devices are used for control and characterization of the stabilization performance.

The layout for the stabilization of the CEO beat and analysis of the phase-lock is depicted in Fig. 4. A phase error signal between the CEO frequency and an external reference synthesizer was generated using an appropriate digital phase detector [34]. This error signal was amplified in a high-bandwidth Proportional-double-Integral-Derivative (PI^{2}D) servo-controller producing the feedback signal that controls the pump current via the home-build modulation box. When the feedback loop was activated, a tight phase lock of the CEO beat to the external reference was achieved, characterized by the full reduction of the in-loop CEO frequency noise PSD below the β-separation line as shown in Fig. 3(a). The external reference used to achieve the CEO tight lock was set to 26.18 MHz. A coherent peak is observed in the RF spectrum of the stabilized CEO beat (Fig. 5(b)) with a linewidth limited by the instrumental spectral resolution of 1 Hz.

The frequency noise of the tightly-locked f_{CEO} was measured using a Signal Source Analyzer (E5052, Agilent). For cross-validation, the CEO frequency noise was furthermore assessed from the phase error signal produced by a second independent digital phase detector referenced to the same 26.18-MHz reference signal and measured using an FFT spectrum analyzer. The two measurements perfectly overlapped each other. An out-of-loop measurement could not be performed since a second f-to-$2f$ interferometer was not available at the time of the experiment.

No significant servo bump appears in the frequency noise spectrum of the locked CEO beat (Fig. 3(a), red line). This indicates that an additional reduction of the residual noise might be possible by further increasing the gain of the feedback loop. This might require a redesign of the modulation-box that controls the current of the pump diode. Comparison of the frequency noise PSD of the free-running and stabilized CEO beats (Fig. 3(a)) shows that the current stabilization bandwidth is 30 – 40 kHz.

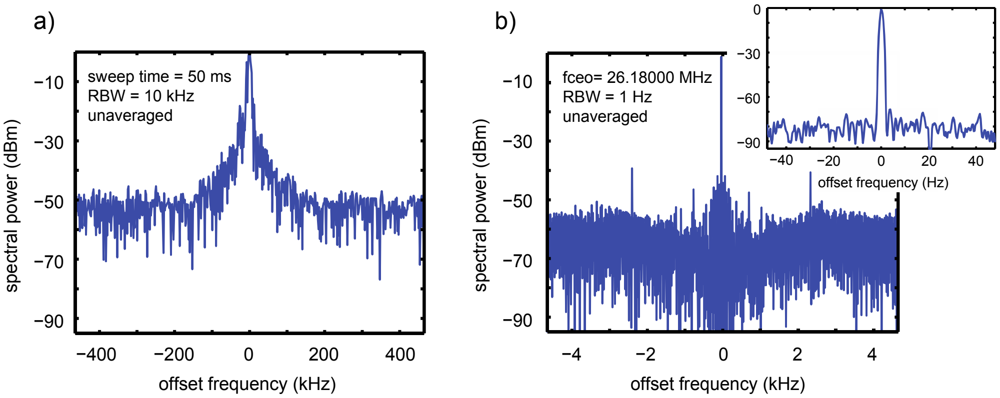

Fig. 5. (a) Free-running CEO beat measured with a sweep time of 50 ms (unaveraged, RBW: 10 kHz) after filtering and amplification to about 0 dBm; (b) CEO beat phase-locked to a reference synthesizer at 26.18 MHz (unaveraged, RBW: 1 Hz). The inset shows the coherent peak with a strong signal-to-noise ratio and a linewidth that is limited by the smallest instrumental resolution bandwidth of 1 Hz.

Integrating the measured phase noise PSD from 1 Hz up to 1 MHz leads to a residual RMS phase noise of 120 mrad for the tight-locked CEO beat at 26.18 MHz (Fig. 3(b)). This low RMS phase noise is comparable to typical out-of-loop values obtained for Ti:sapphire laser oscillators operating at comparable repetition rates [35]. It is worth noting that the RMS amplitude of the feedback current necessary to tightly lock f_{CEO} to our external reference is ≈6.25 mA, which is only 0.05% of the operating current of the diode driver.

3.3 Frequency stability analysis

Once phase-locked to an external frequency reference, the CEO beat of the TDL oscillator remained very stable for more than one hour without the need of any further adjustment. During this time, few punctual unlocking events were observed, which were immediately compensated by the feedback electronics, bringing the CEO frequency back into phase-lock. Figure 6(a) shows the residual fluctuations of the CEO beat frequency recorded over a 17-min timescale using a high-resolution frequency counter (Agilent 53220A) with a gate time of 100 ms. With a few outliers (21, i.e., 0.2% of the total number of data points) removed from the recorded time series, an RMS frequency fluctuation of 8.8 mHz is achieved for the 26.18-MHz CEO frequency. We believe that a reduction of the 50-Hz line noise that is clearly visible in the CEO frequency noise spectrum in Fig. 3(a) and a higher feedback gain will strongly improve the locking reliability.

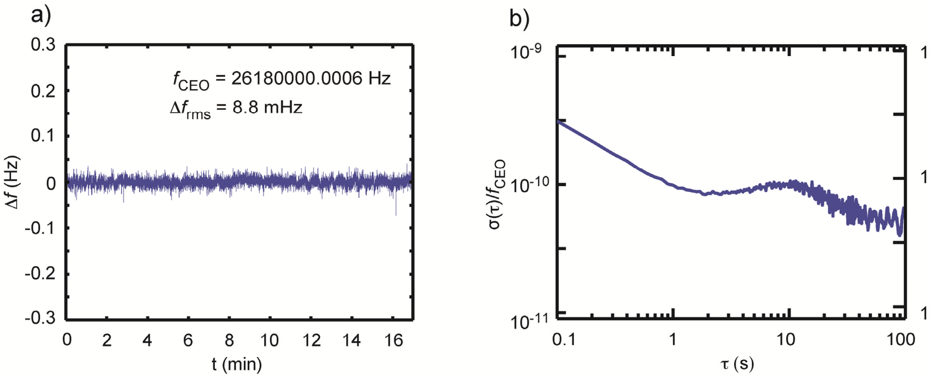

Fig. 6. (a) Time series of the stabilized CEO frequency recorded over 17 min with a Λ-type frequency counter with 100 ms gate time (0.2% outliers are removed from the trace); (b) Fractional frequency stability relative to the CEO frequency f_{CEO} (left y-axis) and to the optical laser frequency ν_{opt} (right y-axis) assessed from the counter measurement. The bump at around 10 s integration time τ indicates the influence from a periodic noise source.

The fractional frequency stability of the CEO beat was assessed by processing the standard Allan deviation [36] of the recorded counter frequency series. The result displayed in Fig. 6(b) shows a characteristic slope of –1/2 of the Allan deviation with respect to the integration time τ at timescales $0.1 \text{ s} < \tau < 1 \text{ s}$ that we attribute to the operation principle of the high-resolution counter used in the CEO evaluation. This device behaves as a Λ-type counter discussed by Dawkins *et al.* [37] and furthermore has a dead time after each measurement that leads to the falsified time dependence of $\tau^{-1/2}$ that is observed in Fig. 6(b). A similar observation was made by Bernhard *et al.* [38] using a different type of high-resolution counter. As the noise in the stabilized CEO beat is expected to be dominated by white phase noise, a τ^{-1} dependence of the Allan deviation should be observed instead. Despite that, the performed stability analysis of our self-referenced TDL oscillator is worthwhile as it shows the presence of a bump at around 10 s integration time, corresponding to a periodic noise source (oscillation) with a period of about 20 s. We believe that this results from a periodic noise source in the laboratory such as originating from the thermal control system of the pump laser cooling. This observation is important for future improvement of the long-term stability of the self-referenced TDL. The exact Allan deviation calculated from the measured CEO frequency noise spectrum amounts to $\sigma(1\text{s})/f_{CEO} \approx 1.1 \cdot 10^{-9}$, when considering the bandwidth of the measured noise spectrum up to 100 kHz. This value is one order of magnitude higher than the Allan deviation assessed from the counter measurement displayed in Fig. 6(b), showing the effect of the Λ-type averaging of the counter. But even this higher CEO instability contributes only below 10^{-16} to the frequency instability of an optical comb line. This small value proves the high frequency stability and low phase noise properties of the locked CEO beat in our TDL.

4. Conclusion

We present the first self-referenced SESAM modelocked TDL. The oscillator is based on the broadband gain material Yb:CALGO that delivers 90-fs pulses at a 65-MHz repetition rate and an average power of 2.1 W. The short pulse duration allows for generating a coherent octave-spanning SC in a standard highly-nonlinear PCF directly from the laser oscillator without additional pulse compression and enables the detection of strong CEO beats (33 dB SNR in a 100-kHz RBW). Simulations indicate that the generated octave-spanning spectrum is robust against amplitude and pulse duration fluctuations.

By feedbacking to the pump current, we obtained a tight phase lock of the CEO beat to an external reference without noticeable increase of the amplitude noise of the laser. This convenient stabilization scheme does not require any additional optical equipment and preserves the power scalability capabilities of TDLs. The locked CEO frequency was carefully characterized showing a coherent peak limited by the instrument resolution (1 Hz) and a frequency noise PSD fully reduced below the β-separation line, which is another proof of a tight lock. Furthermore, we measured a low residual in-loop integrated phase noise of 120 mrad (1 Hz-1 MHz, f_{CEO} = 26.18 MHz), which is comparable to out-of-loop values for Ti:sapphire laser oscillators operating at similar repetition rates and which is sufficiently low for CEP-sensitive strong field experiments.

In the near future, a detailed study about the CEO frequency dynamics will reveal the current limitations of the implemented stabilization scheme and show how the stability can be further improved. One straightforward way to decrease the residual CEO phase noise will be to further increase the gain of the feedback loop. This was not possible at the time of our experiments, because a modification of the modulation-box would have been required. Furthermore, a careful investigation of the noise sources that affect the CEO beat will allow us to improve the long-term stability of the CEO phase-lock. In addition, we will perform a full stabilization of our frequency comb by locking the repetition rate, for example by actuating on a piezo-driven cavity element.

Our measurements show that a reliable tight lock of the CEO beat can be achieved using standard pump-current modulation, in spite of the very strongly spatially multimode pumping scheme of TDLs. This is an important first step towards stabilization of other multimode-pumped ultrafast laser technologies, such as high repetition rate semiconductor and bulk lasers [39–41]. Furthermore our stabilization scheme does not limit the power scalability of the TDL technology and enables stabilized low-noise frequency combs from table-top oscillators with much higher average power in the near future. This opens the venue of intra-cavity highly nonlinear optics such as MHz high-harmonic-generation (HHG) for VUV/XUV spectroscopy from table-top thin disk oscillators.

Acknowledgments

We acknowledge financial support by the Swiss National Science Foundation (SNF). Thomas Südmeyer acknowledges support from AFOSR EOARD (FA8655-12-1-2127) and the European Research Council for the project “Efficient megahertz XUV light source” (ERC Starting Grant 2011 #279545).

#194747 - $15.00 USD Received 29 Jul 2013; revised 24 Sep 2013; accepted 30 Sep 2013; published 9 Oct 2013