Self-referenceable frequency comb from an ultrafast thin disk laser

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Abstract: We present the first measurement of the carrier envelope offset (CEO) frequency of an ultrafast thin disk laser (TDL). The TDL used for this proof-of-principle experiment was based on the gain material Yb:Lu_2O_3 and delivered 7 W of average power in 142-fs pulses, which is more than two times shorter than previously realized with this material. Using only 65 mW of the output of the laser, we generated a coherent octave-spanning supercontinuum (SC) in a highly nonlinear photonic crystal fiber (PCF). We detected the CEO beat signal using a standard *f*-to-2*f* interferometer, achieving a signal-to-noise ratio of >25 dB (3 kHz resolution bandwidth). The CEO frequency was tunable with the pump current with a slope of 33 kHz/mA. This result opens the door towards high-power frequency combs from unamplified oscillators. Furthermore, it confirms the suitability of these sources for future intralaser extreme nonlinear optics experiments such as high harmonic generation and VUV frequency comb generation from compact sources.

OCIS codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers; (320.6629) Supercontinuum generation.

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#163286 - $15.00 USD Received 21 Feb 2012; revised 10 Apr 2012; accepted 10 Apr 2012; published 12 Apr 2012

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1. Introduction

Ultrafast thin disk lasers (TDLs), passively modelocked with semiconductor saturable absorber mirrors (SESAMs) [1,2], currently achieve higher pulse energies and average powers than any other modelocked oscillator technology. The thin gain medium of only few 100 µm allows for efficient heat removal and reduced thermal distortions. Using the well-established gain material Yb:YAG in a multi-pass geometry, a pulse energy >40 µJ has been demonstrated with 1.1 ps pulses at an average power of 145 W [3,4]. A comparable average output power level of 141 W with a pulse duration of 738 fs has been demonstrated with one single pass over a disk based on the sesquioxide material Yb:Lu_2O_3 [5].

In principle, the output power of TDLs can be simply scaled up by proportionally increasing the beam diameters on the thin disk gain medium and the SESAM, without excessive increase of nonlinear effects. Therefore, they are excellent candidates for driving experiments requiring high intensities at megahertz repetition rates in systems with the footprint of a low power oscillator [6]. In particular, the high average power levels achievable appear promising to boost the average photon flux in high harmonic generation (HHG) [7,8] and therefore generate a table-top source of vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) radiation. Recently, a record-high average power of 200 µW in the UV was achieved using a passive enhancement cavity seeded by a multi-stage Yb-doped fiber amplifier source operating at MHz repetiton rates [9]. Efficiently driving such highly nonlinear processes requires short pulses durations (<100 fs). Modelocked TDLs were typically limited to pulse durations >200 fs [10] and required pulse compression schemes to reach the sub-100 fs regime [11–13]. Most recently, we have demonstrated for the first time sub-100 fs pulses directly from a modelocked TDL using the mixed sesquioxide material Yb:$LuScO_3$ [14].

Considering these very recent results that confirm that TDLs can directly access the sub-100 fs regime [14] and the carrier envelope offset (CEO) frequency stabilization discussed in this paper, making use of the high intracavity intensity levels inside a TDL to drive extreme nonlinear optics experiments appears very promising. In this approach, which has not yet been demonstrated, one benefits from the high intracavity intensity levels achievable in TDLs to drive for example HHG. Typically, modelocked TDLs operating with one pass over the thin gain medium require low outcoupling coefficients (< 10%). Therefore, they operate at intracavity average powers in the kW regime, pulse energies in the 100 µJ range and peak powers of several tens of MW. For example, the above mentioned femtosecond Yb:Lu_2O_3 TDL with 141 W average output power operated at 1.56 kW intracavity average power and with an intracavity peak power of 31 MW [5], while the high-energy Yb:YAG TDL in [15] already achieved 791 fs pulses with an intracavity energy of 113 µJ at a peak power of 125 MW. Even the recently demonstrated sub-100 fs low-power TDL [14] achieves an intracavity peak power >25 MW and an average power of >200 W, which is already an interesting starting point for first proof-of-principle experiments.

An important range of applications such as VUV/XUV precision spectroscopy on He^+ [16] or even exploring nuclear transitions [17] would benefit from these table-top sources. Very recently, the first demonstration of direct XUV frequency comb spectroscopy was reported [18] at MHz repetition rate using a UV frequency comb driven by a high power fiber based system coupled to a passive enhancement cavity.

In contrast to passive enhancement cavities [19–22] where the circulating pulse has to match the driving pulses, both pulse formation and laser amplification would be achieved inside the TDL cavity, where the nonlinear process takes place. In addition, there is no need for coherent coupling of the driving pulses, which is a challenging point in passive enhancement cavities. Furthermore, when driving HHG inside a TDL, the circulating pulse can simply adapt to the present nonlinearity. Therefore, bi-stability issues observed in high-finesse passive enhancement cavities due to plasma formation are minimized [23]. Another potential advantage is that different transverse mode profiles can be achieved, for example TEM01, for efficient output coupling of the high harmonics via a hole in a cavity mirror [24]. This is not the case in passive enhancement cavities, where efficient extraction of the UV radiation from these very high finesse cavities is challenging [25,26].

The frequency stability of ultrafast TDLs has not been studied before, which is a key aspect for experiments in the area of high field science and spectroscopy. High power levels are very attractive, because an increase in the average power of frequency combs results in a higher power per mode. So far, stabilized multi-stage fiber chirped pulse amplifier (CPA) systems have reached up to 80 W average power [27]. TDLs can reach similar or higher power levels directly from the oscillator. Prior to the work presented here it was not clear whether pump-induced instabilities could potentially increase the noise level such that a stable frequency comb cannot be realized [28]. TDLs are pumped by high power diodes, which operate in a multimode transverse beam (the fiber-delivered pump beam typically has $M^2 > 100$). Furthermore, they require current drivers operating at several tens of amperes.

Here we investigate for the first time the carrier envelope phase properties of a modelocked TDL. For this task, we realized an Yb:Lu_2O_3 TDL achieving a pulse duration of only 142 fs, which is more than twice shorter than previous TDLs based on this material [29]. These record short pulses enabled the generation of a coherent octave-spanning SC launching less than 1% of the available output power of our TDL directly into a highly nonlinear PCF. The SC was then used in a standard *f*-to-2*f* interferometer [30], enabling us to measure for the first time the CEO frequency beat signal of a modelocked TDL.

2. Yb Lu_2O_3 thin disk laser with short pulse duration

The laser setup used for this experiment is shown in Fig. 1a. The thin disk, used as a folding mirror in the single-mode cavity, consisted of a 150-µm thick, 3%-doped Yb:Lu_2O_3 disk mounted on a 1.4-mm thick diamond heatsink, soldered on a back-cooled copper mount. It had a highly reflective coating for both the pump and laser wavelength on the backside and an antireflective coating for the same spectral range on the front side. Additionally, the disk had a wedge of 0.1° in order to avoid residual reflections which can destabilize modelocked operation. In order to efficiently pump Yb:Lu_2O_3 at its narrow zero-phonon line, we used a volume Bragg grating (VBG) stabilized pump diode [31] emitting at 976 nm in a narrow linewidth $\Delta\lambda < 0.5$ nm. The thin disk module was arranged for 24 passes through the disk enabling an absorption >95% of the pump radiation. Throughout the experiment, we used a pump spot diameter of 1.9 mm.

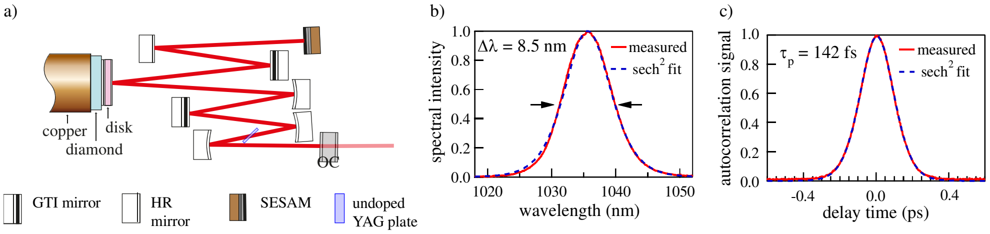

Fig. 1: a) Schematic of the cavity b) Optical spectrum of the pulses at an average power of 7W c) Autocorrelation trace of the corresponding pulses.

#163286 - $15.00 USD Received 21 Feb 2012; revised 10 Apr 2012; accepted 10 Apr 2012; published 12 Apr 2012

In order to achieve soliton modelocking [32,33], we used two Gires Tournois interferometer (GTI) type mirrors that accounted for 2200 fs^2 of negative dispersion per roundtrip. A 1.5-mm thick uncoated YAG plate, introduced at a focus of ≈200 μm radius accounted for the necessary self-phase modulation (SPM) to balance the negative dispersion in the cavity. Furthermore, it ensures a linearly polarized output. The outcoupling coefficient was 4%. The SESAM used for this experiment was characterized at 1030 nm with 1-ps long pulses. The measurement yielded a saturation fluence F_{sat} = 35 μJ/cm^2, a high modulation depth ΔR = 3.4%, nonsaturable losses ΔR_{ns} = 0.8% and a fast recovery time of $\tau_{1/\text{e}}$ = 1.9 ps.

We obtained stable modelocking up to an average power of 7 W. At this average power, pulses as short as 142 fs were obtained with an optical-to-optical efficiency of 15%. This corresponds to a pump power of 47 W. The laser operated at a repetition rate of 64 MHz. The pulses were close to the transform-limit of the spectrum with a time-bandwidth product of 0.34 (Figs. 1 b and c). The corresponding intracavity average power level was 175 W, and the intracavity pulse energy 2.7 μJ. This corresponds to a peak power circulating in the cavity of 17 MW. It is worth noticing that the achieved modelocked optical spectrum (8.5 nm full-width half maximum (FWHM)) is >70% of the available FWHM emission bandwidth of $Yb:Lu_2O_3$, confirming the large potential of this material also in terms of short pulse generation in the thin disk geometry.

In this experiment, small spot sizes on the disk and the SESAM were used to operate in a relaxed cavity configuration [34,35] and to minimize Q-switching instabilities [36] in the goal of investigating the pulse duration limits of this material. Higher average powers will be reached at these short pulse durations in the near future by using larger disks and laser mode sizes both on the disk and the SESAM.

The SESAM used in this experiment proved crucial for pushing the pulse duration to the limits of the emission bandwidth of this material. In particular, the high modulation depth and fast recovery time have an impact on the stabilization of these short pulses, confirming theoretical predictions of soliton modelocking [32,33]. In this proof-of-principle experiment, we focused on obtaining short pulses and achieved the crucial SESAM parameters in samples with moderate saturation fluence. Future designs will combine these crucial parameters (large modulation depths, fast recovery times) with larger saturation fluences and damage thresholds by using dielectric topcoatings [37], allowing to reach higher power levels.

3. CEO beat detection

We generated a coherent SC in a 1-m long, highly nonlinear PCF using only 65 mW out of the available 7 W of our $Yb:Lu_2O_3$ TDL. The fiber used is a commercially available highly nonlinear PCF (NKT Photonics A/S, product NL-3.2-945) with a nonlinear parameter γ = 23 $W^{-1}km^{-1}$, and a zero dispersion wavelength of 945 nm. At the laser wavelength of 1034 nm, the fiber exhibits anomalous dispersion of approximately −15.1 ps^2km^{-1}. Considering an estimated coupling efficiency of 50%, the corresponding soliton order launched into the nonlinear fiber is N = 5. According to numerical simulations [38], and recent experiments [39] a soliton order N < 10 is required for the generation of the coherent supercontinuum in this fiber. The short pulses of our TDL enabled the generation of this coherent SC without the need for external pulse compression or amplification. The SC (Fig. 2b) after the PCF covered more than an octave and was launched into a standard *f*-to-2*f* interferometer [30] for CEO beat detection. The technical details of the components in the *f*-to2*f* interferometer are described in detail in [39]. The CEO beats had a signal-to-noise ratio (SNR) of >25 dB in a resolution bandwidth (RBW) of 3 kHz (Fig. 4c of [39]) and >30 dB in a RBW of 1 kHz. We believe that the achieved SNR ratio is large enough for initial locking tests of the CEO beat, in particular given the high stability of the observed beats. During the time of the experiment (approximately one hour) we did not observe significant frequency excursion or amplitude fluctuations of the CEO beats. Furthermore, significantly better SNR can be achieved by optimizing the laser for low noise performance. It is important to notice that the TDL used for

#163286 - $15.00 USD Received 21 Feb 2012; revised 10 Apr 2012; accepted 10 Apr 2012; published 12 Apr 2012

this proof-of-principle experiment was built with standard optomechanics, and was not isolated in terms of external vibrations. Furthermore, the pump laser was operated at only 15% of its maximum operation current. Therefore, we believe better performance is achievable by improving the mounting technique, boxing, and pump operation point. Furthermore, optimizing the CEO-beat detection scheme (fiber length, input power level, fiber design, temperature stabilization of the fiber [40], etc...) should also result in an improved SNR.

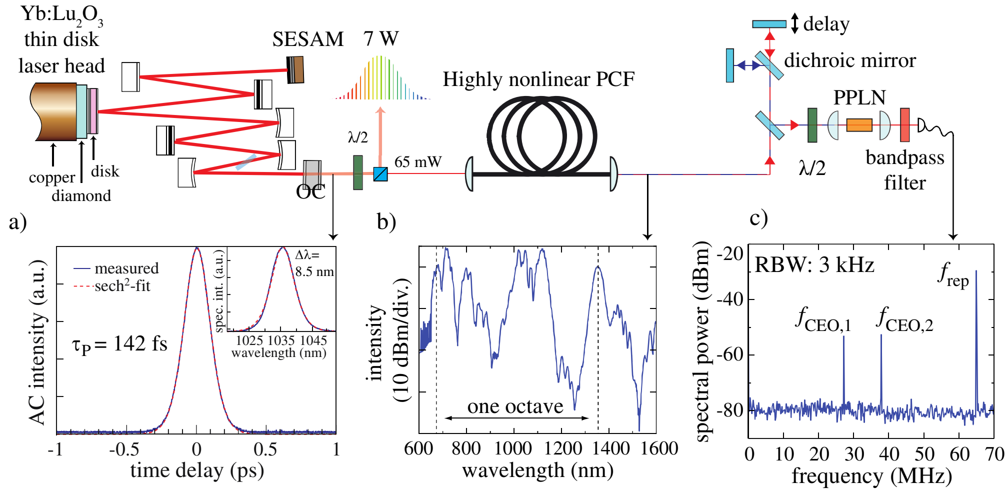

Fig. 2: CEO frequency measurement using a standard f-to-2f interferometer [30]: a) Schematic of the Yb:Lu_2O_3 modelocked TDL b) A small fraction of the output power of this laser is enough to generate a coherent SC from a 1-m long highly nonlinear PCF c) The generated SC is launched into a standard f-to-2f interferometer for CEO beat detection.

To investigate the influence of the pulse duration on the detected CEO beats, we increased the pulse duration to 172 fs according to the soliton formula [32] by lowering the pump power and operating at 5.1 W output power. We could still clearly detect the CEO beats at this longer pulse duration, at the expense of a lower SNR (16 dB in 3 kHz RBW). According to numerical simulations [38], recently confirmed experimentally [39] the generation of a coherent SC in a given nonlinear fiber sets a lower limit in terms of pulse duration of the source. For our system, this limit was calculated to be at a pulse duration of approximately 180 fs, which seems to be in accordance with our experiment. Further investigations will target to confirm this limit in pulse duration experimentally. In our experiment, further lengthening of the pulse duration was not possible without breaking into the Q-switched modelocking regime.

The CEO beat frequency was tunable by the pump current, with a slope of approximately 33 kHz/mA. This mechanism can be used for electronic stabilization of the CEO frequency to an external reference. It is worth emphasizing that CEO detection was possible in spite of the strongly multimode pumping scheme of TDLs, usually associated with a high noise level. This seems to indicate that systems such as the one presented in [5] with an external passive pulse compression stage to reach the necessary short pulse duration for CEO detection would already be suitable to achieve >100-W-level stabilized frequency combs.

4. Conclusion and outlook

Our experimental results represent the first confirmation of the potential of modelocked TDLs as high-power stabilized frequency combs. Pulses as short as 142 fs were obtained with the sesquioxide material Yb:Lu_2O_3, which has already demonstrated its suitability for high power operation in the thin disk geometry [5]. This proves the potential of this material also in terms of high power short pulse generation. Higher output powers will be achieved in the near future at these short pulse durations by using larger disks, increased mode areas and by designing SESAMs with high modulation depths and fast recovery times such as the one used in this experiment, but higher saturation fluences, lower two-photon absorption effects and higher damage thresholds [37]. We expect to reach more than 100 W output power and kW intracavity levels from such a source with sub-100 fs pulse duration in the near future.

The demonstrated Yb:Lu_2O_3 TDL with 142-fs pulses enabled the first CEO frequency beat measurement of a modelocked TDL, which was performed without any external amplification or pulse compression using a standard *f*-to-*2f* interferometer [30]. This measurement established a sufficiently large SNR for future stabilization of the laser system with the pump current. Therefore, high-power stabilized frequency combs in the 100 W range from unamplified laser oscillators appear feasible in the near future. These results further increase our confidence that TDLs are ideal candidates for megahertz intracavity nonlinear optics experiments, such as high harmonic generation for future compact XUV/VUV sources.

Acknowledgments

We acknowledge financial support by the Swiss National Science Foundation (SNF) and support from the FIRST cleanroom facilities of ETH Zurich for the SESAM fabrication. Christian Kränkel and Kolja Beil acknowledge financial support by the Joachim Herz Stiftung. Thomas Südmeyer acknowledges support from the European Research Council for the project "Efficient megahertz XUV light source" (ERC Starting Grant 2011 #279545).

#163286 - $15.00 USD Received 21 Feb 2012; revised 10 Apr 2012; accepted 10 Apr 2012; published 12 Apr 2012