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# First fully stabilized frequency comb from a SESAM-modelocked 1.5- $\mu\text{m}$ solid-state oscillator

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**Abstract:** A diode-pumped 170-fs, 110-mW Er:Yb:glass-laser generates an octave-spanning supercontinuum without amplification in an optimized PM-HNLF. The CEO frequency is self-referenced and stabilized by feedback on the diode current. Cavity length control stabilizes the repetition rate.

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## 1. Introduction

Self-referenced frequency combs from femtosecond lasers have enabled impressive progress in numerous research areas such as precision metrology and spectroscopy. Frequency combs from Ti:Sapphire lasers are widely employed despite several disadvantages associated with their complexity and high costs. In this regard, the demonstration of CEO-stabilized femtosecond fiber lasers was an important breakthrough [1] although noise suppression with fiber lasers is more challenging than for Ti:Sapphire systems due to the high gain and strong fiber nonlinearities. A promising alternative are SESAM-modelocked diode-pumped solid state lasers (DPSSLs). DPSSLs have low intrinsic noise because of their high-Q cavities with low residual losses and can access higher average power than unamplified femtosecond fiber oscillators. Even 100 GHz repetition rates have already been achieved in fundamental modelocking at 1.1 ps pulse duration [2]. Despite the large number of femtosecond DPSSLs reported, however, carrier envelope offset (CEO) frequency detection has only been demonstrated to date with a Kerr-lens modelocked 865-nm Cr:LiSAF laser oscillator [3] and a fiber-amplified, temporally compressed 1030-nm Yb:KYW laser [4].

Very recently, we demonstrated the first self-referencable ultrafast solid-state laser oscillator operating in the 1.5- $\mu\text{m}$  spectral region [5]. Here we present for the first time the full CEO frequency stabilization and repetition rate stabilization of this laser. Our system is based on a 170-fs Er:Yb:glass laser generating 110 mW output power at <1.5 W electrical power consumption. It generates a coherent octave spanning frequency comb in a polarization maintaining highly nonlinear fiber (PM-HNLF) without any amplification. The fiber length was optimized for a strong CEO frequency signal between the outermost Raman soliton and the spectral peak of the dispersive wave within the supercontinuum (SC). We use a standard f-to-2f CEO frequency detection scheme [6]. Our free-running CEO-beat is 49 dB above the noise floor and its linewidth of 3.6 kHz (Figure 1) is more than an order of magnitude lower than typically obtained by free-running ultrafast fiber laser systems [7]. A stable CEO-beat was observed even with pulse durations above 260 fs. The CEO frequency was stabilized by feedback on the diode current from a phase-locked loop (PLL). The repetition rate was stabilized to the same 10 MHz local reference by control of the cavity length.

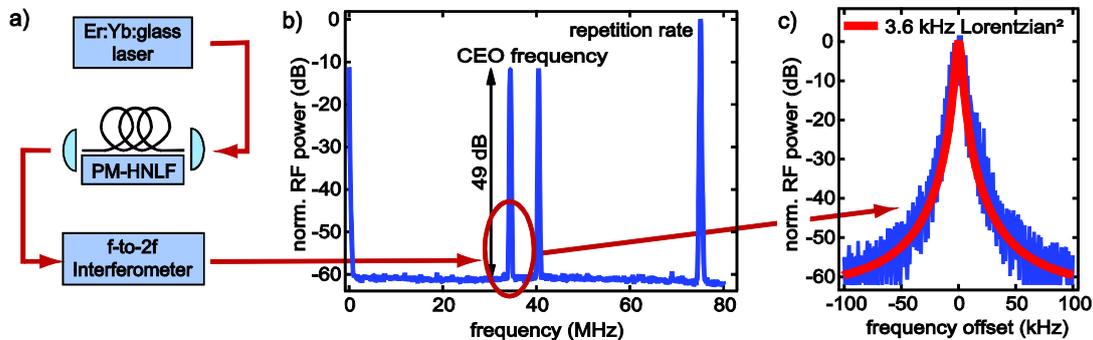


Fig. 1: a) Experimental setup. b) RF spectrum with CEO frequency (RB = 100 kHz). c) Magnified and centered RF spectrum of the left CEO frequency peak with a Lorentzian<sup>2</sup>-fit of 3.6 kHz FWHM (RB = 1 kHz).

## 2. Experimental Setup

The Er:Yb:glass oscillator used is pumped by 600 mW from a 980-nm telecom-grade laser diode. We achieve stable mode-locking with 170-fs pulses, 110 mW average power, and a repetition rate of 75 MHz. The pulses are transform-limited and show excellent spectral and temporal agreement with  $\text{sech}^2$  fitting functions. A coherent octave spanning supercontinuum (SC) is generated by launching the pulses directly into a dispersion-flattened, polarization-maintaining, highly nonlinear fiber (OFS Fitel Denmark, [8]). The fiber has 10.4 mm beat length and a nonlinear coefficient of 10.5 /W/km. The length of the PM-HNLF was optimized for maximum CEO frequency signal by adjusting the spectral separation between the outer Raman soliton and the spectral peak of the dispersive wave to one octave. The polarized and stable SC had an average power of 50 mW. Numerical simulations of the SC generation process were used to optimize the pump parameters [9]. We detect the CEO frequency with a standard f-to-2f detection scheme. We can shift the CEO frequency continuously with the pump current by more than 50 MHz at a rate of  $\sim 260$  kHz/mA. A CEO frequency signal can still be observed at a large reduction of pump power, which reduces the intracavity pulse energy and increases the pulse duration up to 260 fs. In order to set the lines of the optical frequency comb to known and fixed absolute values, both the repetition rate and the CEO frequency must be locked to a known reference. The CEO frequency is detected as explained above and controlled by the pump current. We phase locked the CEO frequency to an external reference using the feedback loop in Figure 2. The loop is based on a digital phase detector (Menlosystems XPS800-E), which has a larger detection range than a standard analogue phase detector and can follow phase deviations up to  $32 \cdot 2\pi$ . The error signal is forwarded to a PI-controller modulating the pump current. With appropriate feedback parameters a substantial reduction of the CEO linewidth to less than 1 Hz is achieved (Figure 3). We use a similar phase locked loop for the stabilization of the repetition rate, which is locked to the same 10 MHz local reference. The control of the cavity length is implemented with stepper-motor and a piezo transducer acting on the position of the SESAM.

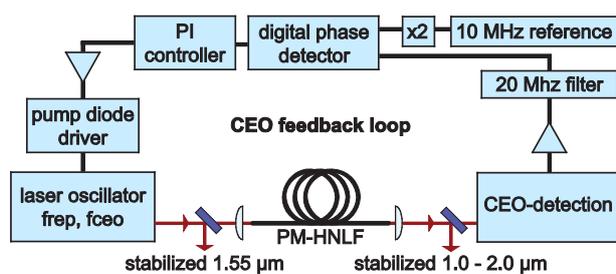


Figure 2: Scheme of the implemented feedback loop for locking the CEO beat frequency to an external reference.

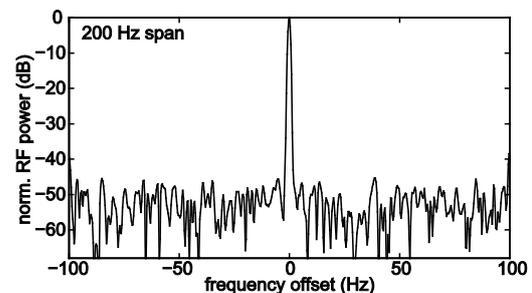


Figure 3: The locked RF-frequency spectrum of the CEO frequency. Its width is below the resolution of the RF-analyzer (RB = 1 Hz). The absolute frequency is 20 MHz.

## 3. Conclusion and Outlook

In conclusion we have demonstrated the first fully stabilized frequency comb generated by an ultrafast Er:Yb:glass laser. The SESAM-modelocked, diode-pumped laser uses a high-Q cavity which results in low-noise operation. A coherent, octave-spanning SC is generated by nonlinear spectral broadening in a polarization maintaining highly-nonlinear fiber (PM-HNLF). We observe a more than 10-times improvement in the free-running CEO frequency linewidth compared to free-running femtosecond fiber laser systems operating in this spectral region [7]. The CEO frequency and the repetition rate could be stabilized to an external reference over hours without losing the lock. We expect that this result will have a significant impact for the future development of more compact stable frequency combs because the relatively long pulse durations of up to 260 fs strongly relax the requirements on the modelocked lasers. This will become even more important for gigahertz pulse repetition rates.

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