FIRST FULLY STABILIZED FREQUENCY COMB FROM A SESAM-MODELOCKED 1.5-µm SOLID-STATE OSCILLATOR

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1) INTRODUCTION

Self-referenced optical frequency combs from femtosecond lasers have enabled impressive progress in numerous research areas such as precision metrology and high resolution 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 carrier envelope offset (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 semiconductor saturable absorber mirror (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, 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 have demonstrated the first self-referencable ultrafast solid-state laser oscillator operating in the telecom 1.5-µm spectral region [5]. Here we present the full stabilization of this frequency comb, i.e. the stabilization of both the CEO frequency and the repetition rate of the laser to the same 10 MHz local reference. 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. Using a standard f-to-$2f$ CEO frequency detection scheme [6], the obtained free-running CEO-beat is 49 dB above the noise floor and its linewidth of 3.6 kHz is more than an order of magnitude lower than typically obtained by free-running ultrafast fiber laser systems [7]. The CEO frequency was stabilized by feedback from a phase-locked loop to the pump diode current, while the repetition rate was stabilized to the same external reference by control of the cavity length via a piezo-electrical transducer, leading to the first fully stabilized frequency comb from a SESAM-modelocked 1.5 µm solid-state oscillator.

2) THE FEMTOSECOND Er:Yb:GLASS OSCILLATOR

The schematic of our passively modelocked Er:Yb:glass oscillator is shown in Fig. 1. The Er:Yb:glass gain plate is pumped by 600 mW from a 980-nm telecom-grade laser diode. The 4-m long resonator is made of 10 dispersive dielectric mirrors with a total negative dispersion of -2000 fs^2 per cavity roundtrip, a SESAM with <0.2% nonsaturable losses and an output coupler with 1.7% transmission. The total roundtrip losses of the cavity are well below 3% which leads to a substantially higher Q-factor and a significantly lower quantum noise limit than typical fiber lasers. The laser achieves stable mode-locking with 170-fs pulses and an average power of 110 mW at a repetition rate of 75 MHz. The pulses are transform-limited and show excellent spectral and temporal agreement with $sech^2$ fitting functions as typically observed for stable soliton modelocking. The duration of the pulses, determined by the amount of negative dispersion and self-phase modulation, can also be adjusted with the pump power. This property will be used to control the CEO frequency as explained later.

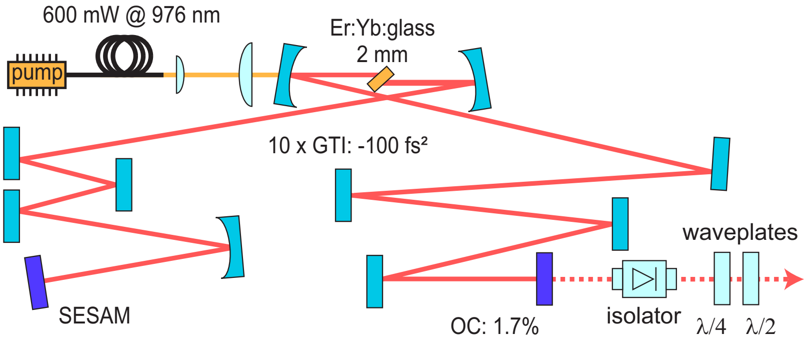

Fig. 1: Design of the ultrafast Er:Yb:glass oscillator. SESAM: semiconductor saturable absorber mirror; GTI: high reflective Gires-Tournois interferometer type mirror, dispersion -100 fs^2; OC: output coupler, transmission 1.7%. The laser output passes through an isolator for protection against back reflections, and waveplates for polarization control.

3) SUPERCONTINUUM GENERATION AND CEO DETECTION

A coherent octave spanning supercontinuum (SC), necessary to implement the *f*-to-2*f* interferometer scheme for CEO frequency detection, 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 1.3-m length of the highly nonlinear fiber 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 within the SC to one octave. The polarized and stable SC has an average power of 50 mW. Numerical simulations of the SC generation process were used to optimize the pump parameters [9].

The CEO-beat frequency was detected with a standard *f*-to-2*f* detection scheme. For this purpose, the SC is spectrally separated by a dichroic beam-splitter and combined again after the long-wavelength signal has been frequency-doubled in a room temperature, 4-mm long periodically poled lithium niobate (PPLN) crystal with a poling period of 31.1 µm. The generated second harmonic signal has a 8-nm bandwidth at 1025 nm. An average frequency-doubled power of up to 0.5 mW, corresponding to a conversion efficiency of 10% of the available SC power in a 16 nm bandwidth at 2050 nm, is achieved, which is essential for a good signal-to-noise ratio of the CEO-beat. This efficiency was mainly achieved thanks to the high peak power from the outermost Raman soliton.

When the delay between both interferometer arms is well adjusted, a clear CEO-beat signal is observed 49 dB above the noise floor in a 100-kHz resolution bandwidth (RB) as shown in Fig. 2. This high signal-to-noise ratio is significantly better than typically obtained by fiber oscillators and substantially higher than the typical 30-dB required for standard stabilization electronics. Even more important is the linewidth of the CEO-beat signal which reflects the intrinsic stability of the laser oscillator. The squared-Lorentzian fit of 3.6 kHz FWHM (Fig. 2c) is to our knowledge the narrowest CEO frequency linewidth of a free-running laser in the 1.5-µm region.

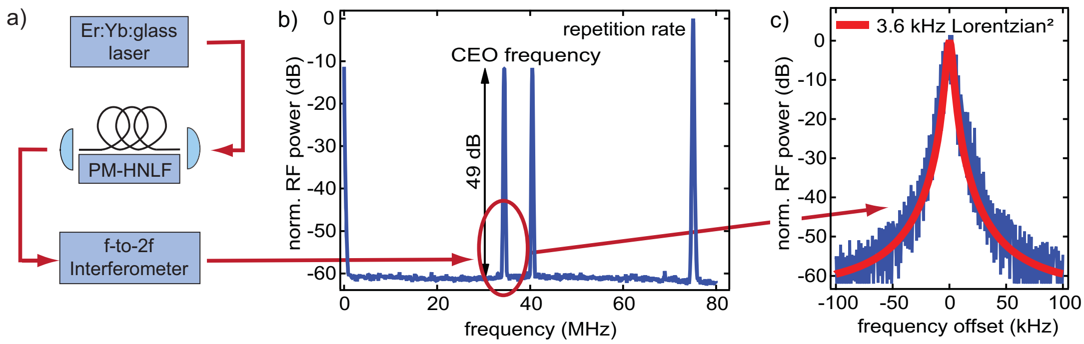

Fig. 2: a) Experimental setup for SC generation and CEO-beat detection. b) Output RF spectrum of the *f*-to-2*f* interferometer with CEO frequency (RB = 100 kHz). c) Magnified and centered RF spectrum of the left CEO frequency peak with a Lorentzian²-fit of 3.6 kHz FWHM (RB = 1 kHz).

4) FULLY STABILIZED FREQUENCY COMB

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 stable reference. The CEO frequency can be continuously shifted with the pump current by more than 40 MHz (see Fig. 3) and a CEO frequency signal can still be observed at reduced pump power, resulting in a decreased intracavity pulse energy and in an increased pulse duration up to 260 fs. A feedback loop was used to phase-lock the CEO frequency to 20 MHz, corresponding to the second harmonic of a 10-MHz external reference as depicted in Fig. 4. The loop is based on a digital phase detector (Menlosystems XPS800-E), which has a larger detection range than a standard analog phase detector and can follow phase deviations up to ±32· 2π. The error signal is forwarded to a PI-controller driving the pump current. A linear variation of the CEO-beat frequency around 20 MHz is achieved with respect to the pump current at a rate of ~200 kHz/mA.

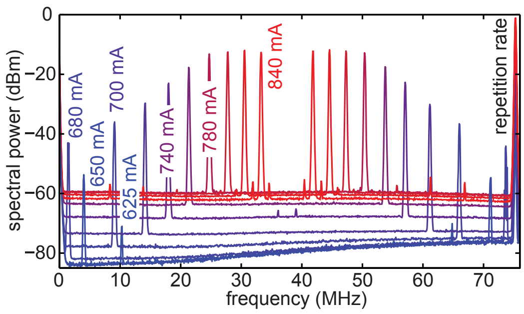

Fig. 3: Dependence of the CEO-beat frequency with respect to the pump current.

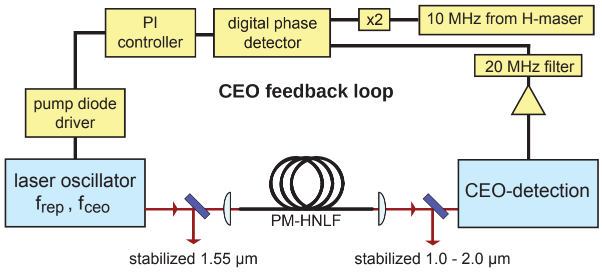

Fig. 4: Scheme of the implemented feedback loop for locking the CEO-beat frequency to an external reference.

With appropriate feedback parameters, the linewidth of the CEO-beat is virtually reduced to zero (it was measured to be instrument-limited to < 4 mHz) and residual phase noise contributes only to the sidebands observed ~6 kHz away on both sides of the carrier in the RF spectrum (see Fig. 5). The feedback loop strongly reduces low-frequency noise as shown by the measured frequency noise power spectral density of the free-running and locked CEO-beat in Fig. 6, but is inefficient in the kHz range due to the limited bandwidth of the laser (limited by the lifetime of the excited energy level of the Er ions in the gain medium). It should be stated that the measured frequency noise of the locked CEO-beat is limited at low Fourier frequency by the noise floor of our measurement system at a level of ~0.4 Hz^2/Hz, while it is expected to continue to drop at low frequency due to the increasing gain of the CEO servo-loop. The relative stability of the 20-MHz CEO reaches 10^{-8} at 1-s when stabilized to an H-maser (see Fig. 7) and a stable locked operation of more than 11 hours was achieved in a preliminary long-term evaluation.

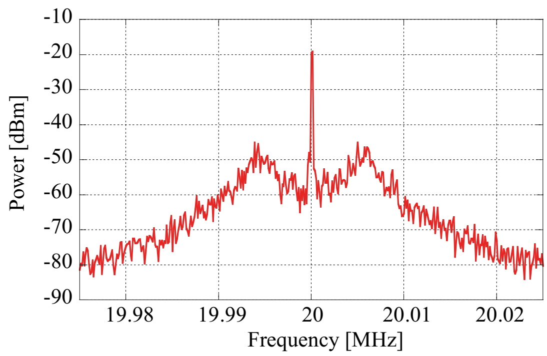

Fig. 5: The locked RF spectrum of the CEO-beat (30-Hz resolution bandwidth). The width of the central peak is limited by the resolution of the RF-analyzer.

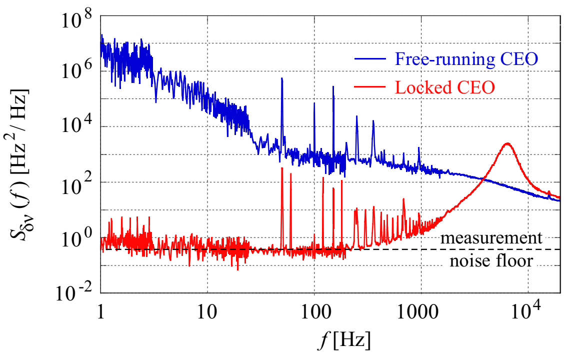

Fig. 6: Frequency noise power spectral density of the free-running and locked CEO-beat measured with a frequency discriminator.

A similar feedback loop was used for the stabilization of the repetition rate to the same 10-MHz local reference. In this case, the digital phase detector operates at the 28^{th} harmonic of the repetition frequency at 2.1 GHz. The control of the cavity length is implemented with a stepper-motor for coarse tuning and a piezo transducer for fine adjustment, both devices acting on the position of the SESAM in the resonator.

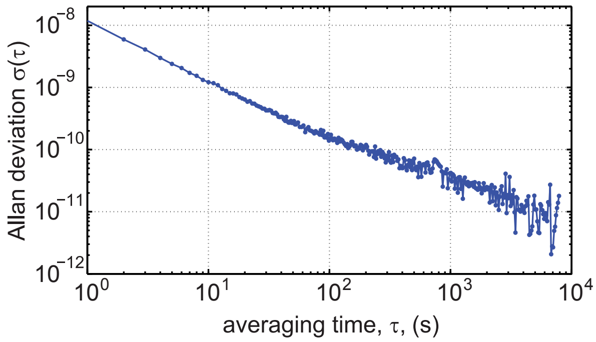

Fig. 7: Allan deviation of the 20-MHz CEO-beat phase-locked to an H-maser.

5) 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. 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 are stabilized to the same 10-MHz external reference over hours. The Allan deviation of the 20-MHz CEO reaches 10^{-8} at 1-s with an H-maser as an external reference and a stable locked operation of more than 11 hours was achieved in a preliminary long-term evaluation. A CEO-beat signal can still be observed at a large reduction of the pump power, resulting in a reduced intracavity pulse energy and in an increased pulse duration up to 260 fs. We expect that this result will have a significant impact for the future development of more compact stable frequency combs as the relatively long pulse duration relaxes the requirements on the modelocked laser. This will become even more important for gigahertz pulse repetition rates.

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