Low noise frequency comb based on an all-fiber polarization-maintaining figure-8 laser

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Abstract: We present a frequency comb based on an all-fiber polarization-maintaining figure-8 laser. It is locked to an optical reference through an intracavity high-bandwidth electro-optical modulator and has a flat phase noise of -78 dBc/Hz.

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Laser frequency combs have repeatedly proven to be a very valuable tool for precision spectroscopy and optical frequency metrology in laboratories around the world [1, 2]. Early research concentrated mostly on solid-state Ti:Sapphire femtosecond systems, but lately fiber laser combs have matured and have become a valuable alternative. Their performance is comparable to that of Ti:Sapphire combs in terms of frequency stability [3], and fiber and Ti:Sapphire combs were shown to be on par for comparing state-of-the-art optical clocks [4]. Also, like Ti:Sapphire combs, fiber frequency combs can be phase-locked to an optical reference with subradian phase noise, at which point the comb lines exhibit a linewidth limited only by the observation time. In that case, the relevant metric is not the linewidth, but rather the phase noise on each comb line; Ti:Sapphire-, Erbium- and Ytterbium-based combs have all demonstrated similar low residual phase noise.

Fiber combs do have a number of well recognized advantages over Ti:Sapphire combs. These advantages include lower costs, unattended long-term operation [5], and ease of integration into fiber systems and compactness. Mode-locking of fiber lasers, which is required for fiber laser frequency combs, can be achieved by various means such as soliton or stretched-pulse fiber ring lasers, Fabry-Perot lasers with a saturable absorber, or figure-8 lasers; all those approaches result in similar overall functionality of the comb [3]. A drawback of mode-locked fiber lasers is their sensitivity to environmental fluctuations, such as changes in temperature and humidity or vibrations. The vibration sensitivity can be greatly reduced by use of polarization maintaining (PM) instead of standard single-mode fiber (SMF) [6]. Recently, an all-PM-fiber figure-8 laser was demonstrated [7]. To initiate mode-locking of this figure-8 an intracavity electro-optical modulator (EOM) is driven at the cavity's repetition rate of 27 MHz. As opposed to actively harmonic mode-locked fiber lasers with high repetition rates [8], the EOM is switched off once mode-lock is achieved and the figure-8 operates passively. This laser has a number of advantages as an optical frequency comb including robustness to environmental perturbations, automatic initiation of mode-locking, and an intracavity EOM of very high bandwidth to achieve tight phase-locking to an optical reference. Here, we demonstrate a tightly locked frequency comb that incorporates this PM figure-8. This work is a further step towards a robust, fieldable comb to support transportable optical clocks.

The comb setup is shown in Fig. 1. The pump laser diode of the figure-8 PM erbium-doped fiber amplifier (EDFA) was driven at near its maximum drive current and its output was attenuated from 400 mW down to 130 mW in order to reduce pump current induced noise on the figure-8's output [9]. The combination of a high- and a low-bandwidth actuator in form of an EOM and piezoelectric transducer (PZT) in the cavity allows for tight stabilization of the repetition rate over a large dynamic range, as demonstrated by Hudson et al. [10], who placed both actuators in a free-space section of the cavity. In this work, the PZT directly stretches fiber in the cavity, and the PM-EOM is a commercial module designed for integration in 1550 nm fiber links.

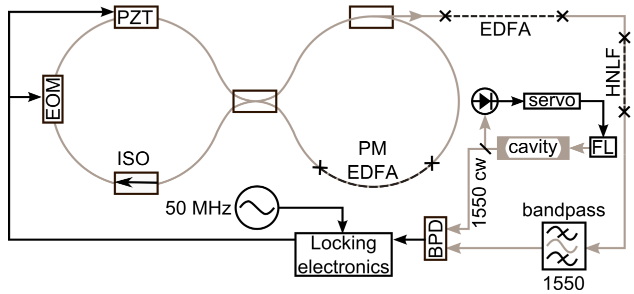

Fig. 1: Schematic comb setup. BPD: balanced photodetector, ISO: optical isolator, FL: fiber laser. Grey lines represent fiber, black lines wire. The figure-8's fiber is PM, the remaining fiber is SMF. The EDFA pumps and CEO feedback are not shown.

The output of the figure-8 is amplified from 5 mW to about 50 mW by use of a 65 cm long backward-pumped EDFA. The pulses are then compressed by use of ~15 cm of SMF down to a FWHM of 53 fs, as shown in the autocorrelation trace on the left panel of Fig. 2. After passing through ~40 cm of highly nonlinear fiber (HNLF), which generates an octave-spanning continuum, the light is focused on a periodically poled LiNbO3 crystal that creates doubled light at a wavelength of 1017 nm. Afterwards, the light is split into a 1017 nm branch to lock the carrier envelope offset (CEO) frequency beat f_{CEO} to an RF oscillator, and a 1550 nm branch to lock a comb tooth near 1550 nm to a cavity-stabilized cw laser as shown in Fig. 1. The RF beat signal related to f_{CEO} is divided by 8 before locking its phase to an oscillator at 15.0475 MHz through modulation of the figure-8's pump laser current, whereas the RF beat of f_{1550} is directly locked to a 50 MHz oscillator through feedback to both the EOM and PZT.

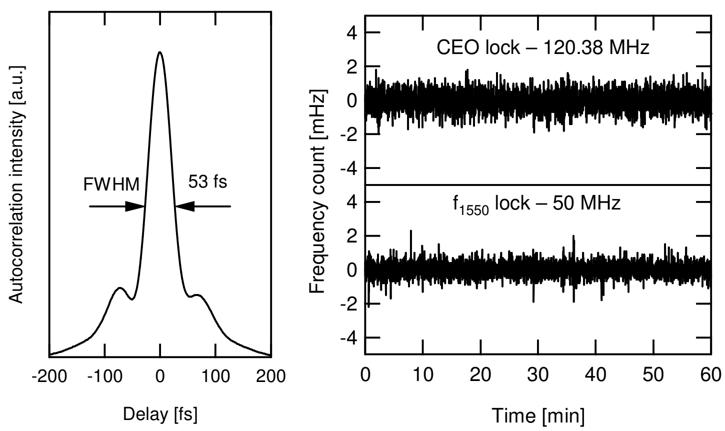

Fig. 2: Left: autocorrelation of the pulse at the start of the HNLF; right: lock count.

The right panel of Fig. 2 shows the frequency counter output of the CEO and optical lock with a gating time of 1 s. No glitches occurred for more than an hour; the standard deviation of the counted values for both are counter-limited at ~0.5 mHz .

Fig. 3 shows the measured phase noise (PN) along with the spectra of the locked CEO and optical beats. The "servo bumps" occur respectively at 40 kHz for PN_{CEO} and 350 kHz for PN_{1550}. The flat PN_{1550} of -78 dBc/Hz at frequencies below 100 kHz is consistent with the corresponding rf signal, which also shows a flat spectrum between the carrier and the "servo bumps". (The increase of the PN_{1550} below 20 Hz is dominated by the measurement system's phase-noise floor.) The integrated PN_{1550} is 40 mrad up to 100 kHz and 450 mrad up to the Nyquist frequency of 13.5 MHz.

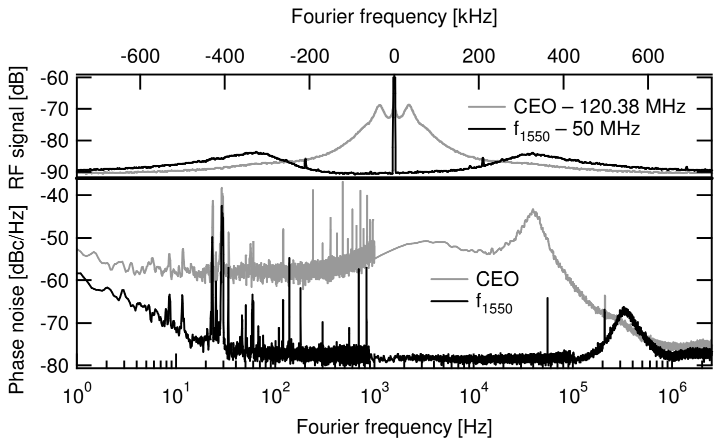

Fig. 3: CEO and optical beat of the locked comb. Top: rf power spectrum with the frequency offset removed measured with a resolution bandwidth of 3 kHz. The peak amplitude at 0 Hz is cut off in order to clarify the pedestals; bottom: phase noise.

In conclusion, we have demonstrated a fiber comb based on a passively modelocked all-PM-fiber figure-8 laser. The combination of a slow PZT and a fast EOM actuator in the cavity of the figure-8 allowed for a high bandwidth feedback to the cavity length and a very tight lock to a stabilized optical reference. The current phase-noise floor of -78 dBc/Hz is limited by the signal-to-noise ratio of the optical beat. Potential applications that could benefit from the low PN lie in heterodyne spectroscopy and range measurements based on frequency combs. Combined with the combs robustness obtained by the use of PM fiber, this comb is a further step to a vibration-resistant portable, compact, fiber-comb system.

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