Optical clock based on a fully stabilized microcomb

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We present an optical clock based on all-optical stabilization of a microcomb to rubidium (Rb) optical transitions, and on frequency division to the microwave regime. The clock's output is the 33 GHz comb line spacing, which is a phase-coherent integer sub-division of the Rb references. The absolute stability of our clock is better than the Rb references by a factor of 108, which correspond to the number of comb modes used for sub-division.

A comb with a bandwidth of 25 THz (fig. 1b, bottom trace) is generated with a 2 mm diameter silica disk resonator[1] and highly nonlinear fiber (fig. 1a). For excitation an intensity-modulated CW laser is used, which implements our parametric seeding technique[2] and enables the generation of an equidistant microcomb spectrum as well as mode spacing control.

To run an atomic clock, we stabilize the broadened microcomb spectrum to Rb optical transitions separated by 3.5 GHz. The Rb references are based on semiconductor distributed feedback lasers (DFB), which are frequency doubled and locked to the Rb transitions. For the microcomb stabilization heterodyne beats are obtained with these DFB lasers. The central line of the comb is locked to the 1560 nm laser, and the 108th line from the center is locked to the 1590 nm laser achieved by feedback applied to the comb line spacing. The clock's output is the ~33 GHz line spacing and corresponds to the frequency difference of the DFB lasers divided by 108. Figure 1c illustrates a >12 hour long record of the clock's output.

Furthermore, we will report on progress toward self-referencing combs with 10's of GHz repetition rates by use of spectral broadening in fiber with <200 fs optical waveforms.

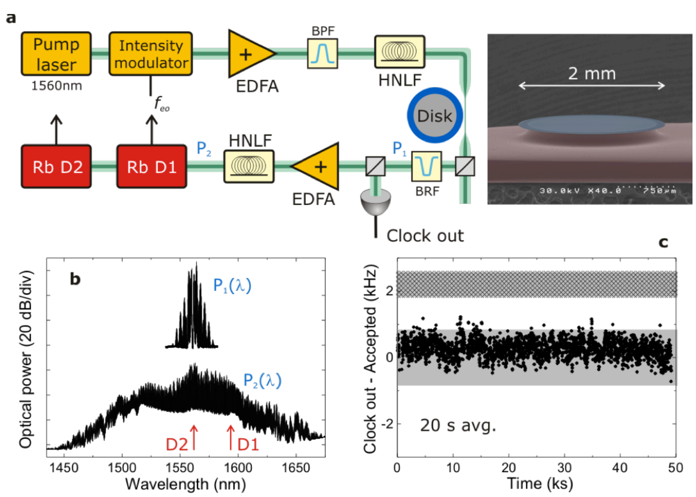

Fig. 1: (a) Schematic of microcomb optical clock. An intensity-modulated pump laser is amplified and coupled into the silica microresonator (micrograph at right). The generated 33 GHz spacing comb is amplified and broadened in highly nonlinear fiber (HNLF), and stabilized to Rb optical transitions. The optical clock's output is recorded by photodetection. (b) Optical spectrum before (top) and after (bottom) the HNLF. (c) Clock output over a time period of >12 hours. Published Rb data[3] on $\mathbf{\Delta}_{Rb}$ divided by 108 has been subtracted.

[1]H. Lee et al., "Chemically etched ultrahigh-Q wedge-resonator on a silicon chip," Nat. Photon. **6,** 369 (2012).
[2]S. B. Papp et al., "Parametric seeding of a microresonator optical frequency comb," Opt. Express **21,** 17615 (2013).
[3]A. Marian et al., "United Time-Frequency Spectroscopy for Dynamics and Global Structure," Science **306,** 2063 (2004).