

Optical phase coherent locking of a 1550-nm mode-locked source to an optical atomic clock's fs comb

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Abstract: We have obtained optical phase coherence between a 1550-nm mode-locked diode laser and a 800-nm femtosecond frequency comb used in an optical atomic clock

Following the demonstration of self-referenced frequency combs spanning 500 nm to 1200 nm that are anchored to either microwave [1] or optical frequency standards [2], a logical next step is to extend this type of spectral coverage into the 1.5 μm wavelength region. Frequency reference grids at these wavelengths could find applications in dense wavelength division multiplexed (DWDM) systems, other areas in telecommunications, and distribution of high precision frequency standards over optical fiber networks. Recently, progress toward realizing a self-referenced comb at 1.5 μm has been reported using external broadening of a mode-locked fiber laser [3]. In this talk we report results from a second approach in which a 1550-nm mode-locked source is phase coherently locked to a Ti:Sapphire (Ti:S)-based femtosecond (fs) frequency comb used as clockwork for optical atomic clocks.

For phase coherent connection to be established between two pulsed lasers, two conditions must be met [4]. The comb spacing of the 1550-nm source ($f_{\text{rep},1550}$) must be locked to the optical clock's fs comb spacing ($f_{\text{rep},\text{ck}}$). Second, the combs' offset frequencies must also be locked together. This latter step requires spectral overlap between the two combs. In the case of the 1550 nm comb, it must be frequency doubled to obtain overlap with the Ti:S comb. A schematic showing these requirements is given in Fig. 1

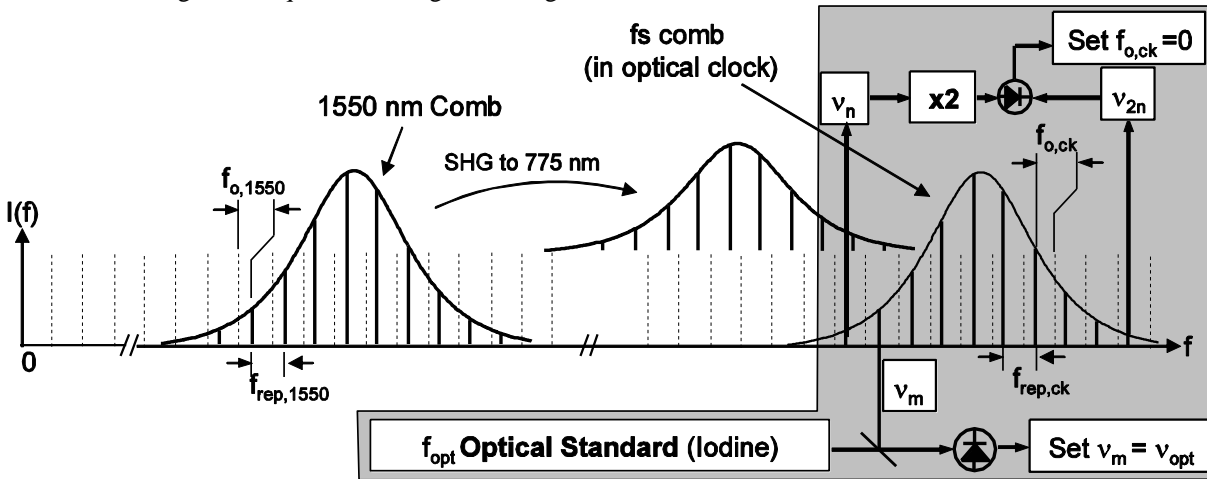


Figure 1. Schematic showing frequency comb locking of a 1550-nm source to an optical clock's fs comb. The optical atomic clock is shown in the gray box.

A detailed experimental setup is shown in Fig. 2. The 1550-nm source is a hybridly mode-locked laser diode (MLLD). The comb spacing of the 1550-nm source is first synchronized to $f_{\text{rep},\text{ck}}$ by modulating the saturable absorber with a microwave signal that is extracted from the iodine-based optical atomic clock. Further synchronization (leading to lower residual timing jitter) is obtained by implementing a high-speed (multi-MHz) servo loop. Details of this feedback loop are reported elsewhere [5]. The fundamental repetition rate of the MLLD is 6.00 GHz, which is the 8th harmonic of the optical clock's fs comb. Here we report realization of the second step, where the offset frequency of the MLLD is stabilized. Towards this end, the output of the MLLD is first amplified by two stages of erbium-doped fiber amplifiers (EDFA). The amplified signal (average power of 20 mW) is then lightly focused into a 2 cm long piece of periodically-poled Lithium-Niobate (PPLN) for efficient second harmonic generation, producing 35 μW centered at 775 nm. The frequency-doubled signal from the MLLD is then co-linearly

combined with the Ti:S fs comb to generate a heterodyne beat ($=2 f_{o,1550} - f_{o,ck}$). To obtain temporal overlap between the doubled MLLD and Ti:sapphire pulse trains, an RF phase shifter is included in the microwave injection signal path.

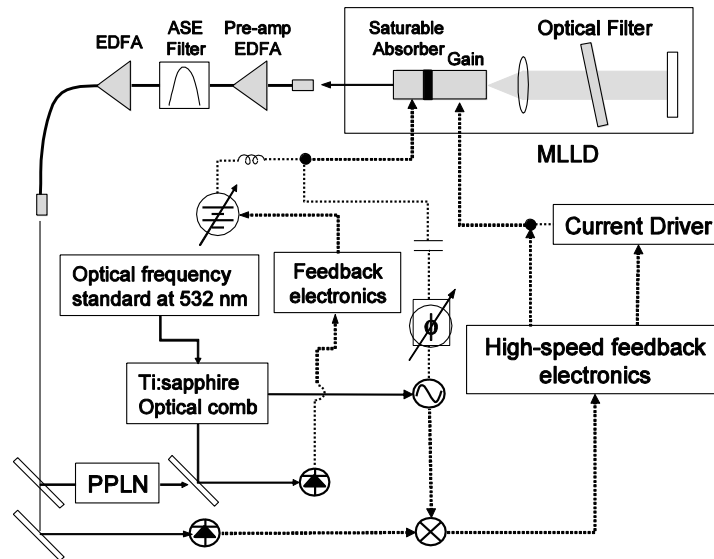


Figure 2. Experimental setup showing the coherent locking of the mode-locked laser diode.

Using a silicon photo-diode as the detector, we observe the heterodyne beat (representing the offset frequency of the MLLD) with a signal to noise ratio of 38 dB in a 100 kHz resolution bandwidth. Subsequently, a digital phase detector and other servo electronics (loop filter with second order integrator and adjustable corners) are employed to lock the beat and enforce phase coherence between the MLLD and the fs Ti:sapphire laser. The actuator utilized in the feedback loop is the bias voltage of the saturable absorber in the MLLD. In this first demonstration, the servo bandwidth is 100 kHz. Figure 3 shows the heterodyne beat between the Ti:S and MLLD offset frequencies (counted with a 1-s gate time) when it is unlocked (rms fluctuations, σ_{rms} of 3.2 MHz) and locked ($\sigma_{rms} = 1.5$ mHz). By monitoring the error signal produced by the digital phase detector we insure that no cycles have slipped over this measurement period.

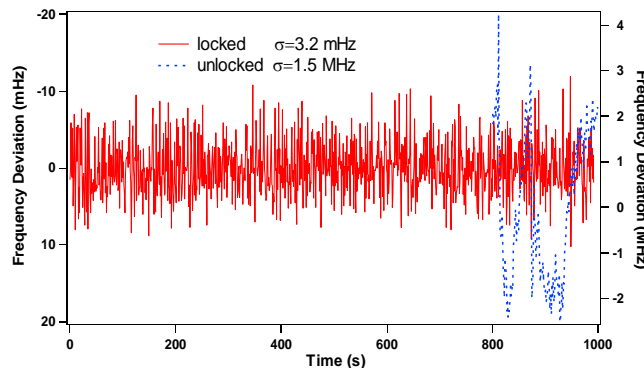


Figure 3. Time record of the heterodyne beat between the MLLD and Ti:S combs, locked (solid, left axis) and unlocked (dashed, right axis).

References:

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