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Optical clockwork without carrier-envelope phase control

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Abstract: We demonstrate optical clockwork without carrier-envelope phase control using sum-frequency generation between a cw optical parametric oscillator at 3.39 \( \mu \text{m} \) and a mode-locked Ti:sapphire laser with dominant spectral peaks at 834 nm and 670 nm.

The use of phase-stabilized, wide-bandwidth optical frequency combs has revolutionized the field of precision optical frequency metrology and enabled the construction of optical atomic clocks [1,2]. Typical setups employ Ti:sapphire lasers producing 10-30-fs pulses and spectral broadening in microstructure fiber to achieve octave-spanning spectra which is required for f-to-2f self-referencing [3]. More recent laser systems can directly produce sufficient spectral bandwidth for stabilization of the comb's two degrees of freedom [4]. Our work here demonstrates optical clockwork without the need for carrier-envelope phase control, simplifying the implementation of the clockwork and avoiding the necessity of an octave-spanning spectrum or a microstructure fiber.

Recently, A. Baltuska et al. [5] have shown that the idler frequency comb generated by a pulsed optical parametric oscillator (OPO) can eliminate identical carrier-envelope frequency shifts in the signal and pump. This has been further investigated using difference-frequency generation [6]. Here, we implement an optical clockwork without the need for carrier-envelope phase control. Our scheme is based on sum-frequency generation (SFG) between a cw OPO at 3.39 \( \mu \text{m} \) and a custom-designed mode-locked Ti:sapphire laser with two dominant spectral peaks near 834 nm and 670 nm. Our experimental setup is shown in Fig. 1.

The Ti:sapphire laser spectrum (see Fig. 2) is spectrally shaped by means of a narrowband output coupler consisting of 5 pairs of SiO\(_2\)/TiO\(_2\) layers. The resulting transmission is about 0.5% in the center of the output coupler at about 800 nm, it increases strongly to 5% at the designated wavelengths of 685 nm and 866 nm. This enhances the peak at 670 nm and gives rise to a shoulder in the spectrum at 880 nm (Fig. 2). The Ti:sapphire laser runs at a repetition rate of 78 MHz with an average output power of typically 150 mW. The cw OPO used in our experiment is a singly resonant OPO with a resonated pump featuring a linewidth <150 kHz. The OPO cavity length is locked to the Nd:YAG pump laser at \( \lambda_p=1.064 \ \mu \text{m} \) by using the Pound–Drever–Hall stabilization technique. In addition, we have phase-locked the OPO pump laser to our iodine-stabilized Nd:YAG laser at 1.064 \( \mu \text{m} \) [2], which was delivered to our setup via optical fiber. Using a 40 mm focal length calcium fluoride lens, the 28 mW of output power of the Ti:sapphire laser near 834 nm and the 16 mW OPO idler output at \( \lambda_i=3.39 \ \mu \text{m} \) are focused into a 5-mm long periodically-poled Lithium Niobate (PPLN) crystal heated to 130°C with a quasi-phase matching period of 16.2 \( \mu \text{m} \). The corresponding phase matching bandwidth of this PPLN crystal is around 1 THz.

Fig. 1: Setup for SFG-based optical heterodyne beat for the implementation of an optical clock without carrier-envelope phase control. Note 3.39 \( \mu \text{m} \) + 834 nm → 670 nm. Output coupler OC, optional mirror OM, beam splitter BS, OPO idler frequency \( f_i \), OPO pump laser frequency \( f_p \), piezoelectric transducer PZT, photomultiplier tube PMT. All intracavity mirrors are double-chirped mirrors.
The resultant SFG comb and the original Ti:sapphire comb at 670 nm are temporally and spatially overlapped with the aid of the prism-based delay line (Fig. 1). A heterodyne beat signal between the two combs is detected by a photomultiplier with a signal-to-noise ratio of ~ 23 dB in a 100 kHz resolution bandwidth (not shown). Note that the final beat signal results from the coherent superposition of many corresponding comb pairs. Importantly, this beat signal only depends on the repetition frequency of the comb but not on the carrier-envelope frequency. By phase locking this beat signal to a radio-frequency reference, we establish a direct phase-coherent link between the rf repetition frequency $f_{\text{rep}}$ and the optical OPO idler frequency $f_i$.

In order to evaluate the stability of our optical clockwork, we have performed a comparison of the tenth harmonic of the Ti:sapphire repetition frequency $f_{\text{rep}}$ against a stable rf signal $f_{\text{maser}}$ derived from the NIST ST-22 hydrogen maser (instability of $\sim 2.4 \times 10^{-14}$ at 1-s counter gate time). The measured frequency counting data depicted in Fig. 3 present convincing evidence that the instability of $f_{\text{rep}}$ (standard deviation of 0.837 Hz at 1-s counter gate time) under tightly locked conditions arises directly from the frequency fluctuations of the OPO idler. Although the OPO cavity length, measured at 1.064 µm, is stabilized to that of the OPO pump laser, which is in turn stabilized to the iodine transition, the intracavity etalon used to tune the OPO idler wavelength causes cavity length instabilities at 3.39 µm, hence limiting the stability of the idler frequency and subsequently the repetition frequency $f_{\text{rep}}$ of the Ti:sapphire laser.

In the near future, we intend to build an optical clock based on a transportable methane-stabilized Helium Neon laser [7]. Such a system would represent a compact, robust, and relatively inexpensive optical clock featuring both high accuracy and high stability.

References