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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 $834\ \text{nm}$ and $670\ \text{nm}$.

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. Baltuška *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 $834\ \text{nm}$ and $670\ \text{nm}$. Our experimental setup is shown in Fig. 1.

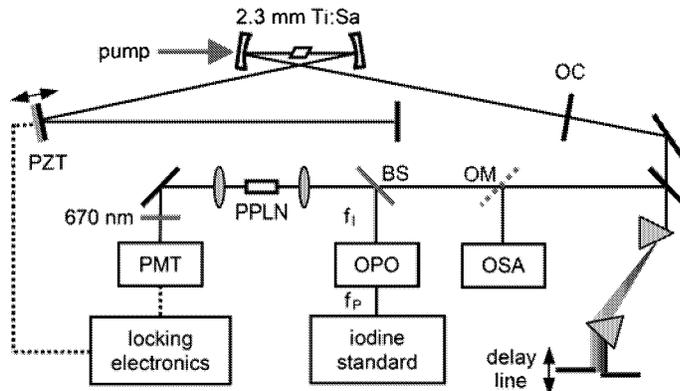


Fig. 1: Setup for SFG-based optical heterodyne beat for the implementation of an optical clock without carrier-envelope phase control. Note $3.39\ \mu\text{m} + 834\ \text{nm} \rightarrow 670\ \text{nm}$. Output coupler OC, optional mirror OM, beam splitter BS, OPO idler frequency f_i , OPO pump laser frequency f_p , piezoelectric transducer PZT, photomultiplier tube PMT. All intracavity mirrors are double-chirped mirrors.

The Ti:sapphire laser spectrum (see Fig. 2) is spectrally shaped by means of a narrowband output coupler consisting of 5 pairs of $\text{SiO}_2/\text{TiO}_2$ layers. The resulting transmission is about 0.5% in the center of the output coupler at about $800\ \text{nm}$, it increases strongly to 5% at the designated wavelengths of $685\ \text{nm}$ and $866\ \text{nm}$. This enhances the peak at $670\ \text{nm}$ and gives rise to a shoulder in the spectrum at $880\ \text{nm}$ (Fig. 2). The Ti:sapphire laser runs at a repetition rate of $78\ \text{MHz}$ with an average output power of typically $150\ \text{mW}$. The cw OPO used in our experiment is a singly resonant OPO with a resonated pump featuring a linewidth $<150\ \text{kHz}$. 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 $40\ \text{mm}$ focal length calcium fluoride lens, the $28\ \text{mW}$ of output power of the Ti:sapphire laser near $834\ \text{nm}$ and the $16\ \text{mW}$ 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 $1\ \text{THz}$.

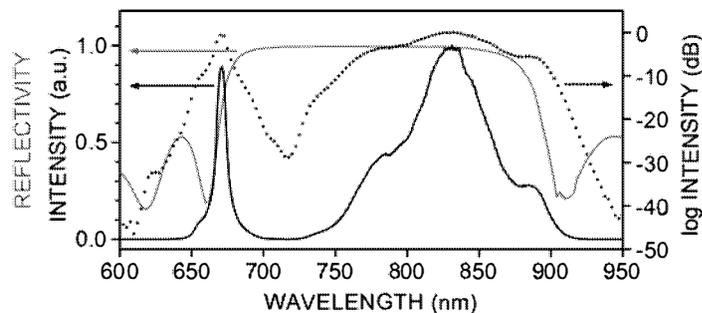


Fig. 2: Ti:sapphire laser spectrum on a linear scale (black curve) and on a logarithmic scale (dotted curve) as measured after the prism-based delay line (compare Fig. 1). The grey curve shows the output coupler reflectivity for comparison. The amplitude of the short-wavelength peak at 670 nm is strongly enhanced due to the roll-off of the output coupler, and it is very sensitive to intracavity dispersion.

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_{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_{rep} against a stable rf signal f_{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_{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 $1.064 \mu\text{m}$, 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 $3.39 \mu\text{m}$, hence limiting the stability of the idler frequency and subsequently the repetition frequency f_{rep} of the Ti:sapphire laser.

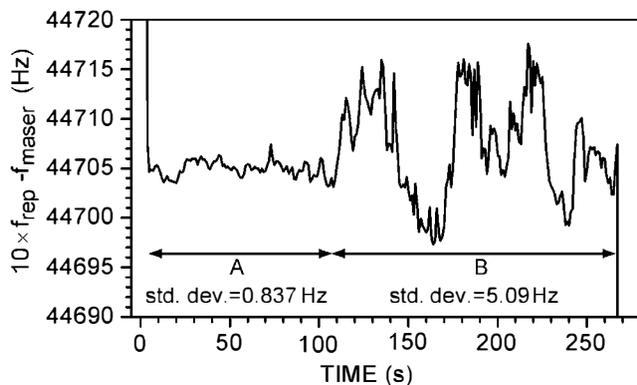


Fig. 3: Comparison of the tenth harmonic of the Ti:sapphire repetition frequency against the NIST ST-22 hydrogen maser-based rf reference at 780 MHz (at 1-s gate time). In the time interval A, the optical heterodyne beat signal is stabilized while the OPO pump laser is phase-locked to the iodine frequency standard, resulting in a standard deviation of 0.837 Hz at 1-s gate time. At 108 s, the optical beat signal remains stabilized, but we deliberately unlock the OPO pump laser. In the subsequent time interval B, the standard deviation is correspondingly increased to 5.09 Hz.

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

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