Experimental implementation of optical clockwork without carrier-envelope phase control

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We demonstrate optical clockwork without the need for carrier-envelope phase control by use of sum-frequency generation between a continuous-wave optical parametric oscillator at 3.39 μm and a femtosecond mode-locked Ti:sapphire laser with two strong spectral peaks at 834 and 670 nm, a spectral difference matched by the 3.39-μm radiation. © 2004 Optical Society of America

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Femtosecond-laser-based optical frequency combs have recently revolutionized the field of precision optical frequency metrology and facilitated the construction of optical atomic clocks.1,2 Stabilization of the two degrees of freedom of the frequency comb, i.e., repetition frequency $f_{\text{rep}}$ and carrier-envelope frequency $f_0$, leads to an optical clockwork that connects optical frequencies $f_n/f_0$ with radio frequency (rf) $f_{\text{rep}}$ via an integer $n \approx 10^5-10^6$ and a fixed value of $f_0$. Typical setups employ Ti:sapphire lasers that produce 10–30-fs pulses with subsequent spectral broadening in a microstructure fiber to yield octave-spanning spectra that are a prerequisite for f-to-2f self-referencing.3,4 More-recent laser systems that directly produce octave-spanning spectra for frequency-comb stabilization have been demonstrated.5–7 In this Letter we demonstrate an optical clockwork without the need for carrier-envelope phase control, simplifying the implementation of the clockwork and avoiding the need for an octave-spanning spectrum.

Recently Baltuška et al.8 showed that the phase relationship among pump, signal, and idler pulses in a parametric interaction permits the generation of a carrier-envelope-phase-independent idler pulse. Similarly, by use of difference-frequency generation (DFG) between different spectral portions of the same frequency comb, a carrier-envelope-frequency-independent DFG comb in the infrared spectral region can be generated with excellent accuracy and stability.10 Furthermore, a carrier-envelope-frequency-independent DFG comb tuned to 800 nm might also pave the way to an all-optical carrier-envelope phase stabilization scheme by injection locking.11 Equivalently to the DFG approach, sum-frequency generation (SFG) between an infrared optical parametric oscillator (OPO) at 3.39-μm idler wavelength and a custom-tailored mode-locked Ti:sapphire laser with two strong spectral peaks at 834 and 670 nm. In our setup, neither a microstructure fiber nor additional single-frequency lasers that are phase locked to the Ti:sapphire comb are needed. Our experimental setup is depicted in Fig. 1.

The X-folded Ti:sapphire laser operates at a repetition frequency $f_{\text{rep}}$ of 78 MHz and emits an average output power of typically 150 mW. It employs a 2.3-mm-thick Ti:sapphire gain crystal and seven bounces on double-chirped mirrors for dispersion

Fig. 1. Setup for a SFG-based optical heterodyne beat for the implementation of an optical clock without carrier-envelope phase control. Note that 3.39 μm + 834 nm = 670 nm. OC, output coupler; OM, optional mirror; BS, beam splitter; PZT, piezoelectric transducer; PMT, photomultiplier tube; OSA, optical spectrum analyzer. All intracavity mirrors are double-chirped mirrors.

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compensation. The two concave double-chirped mirrors, each with a focal length of 50 mm, produce a beam waist inside the gain crystal, which is oriented at Brewster's angle of \( \sim 60^\circ \). Approximately 6.7 W of 532-nm pump light emitted by a frequency-doubled Nd:YVO\(_4\) laser is focused into the gain crystal by an achromatic doublet lens (76.2-mm effective focal length). The output spectrum (see Fig. 2) is spectrally shaped by a custom-designed narrowband output coupler consisting of five pairs of SiO\(_2\)-TiO\(_2\) layers. The resultant transmission is \( \sim 0.5\% \) in the center of the output coupler at \( \sim 800 \text{ nm} \); it increases strongly to 5\% at the designated wavelengths of 685 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 cw OPO used in our experiment is a commercially available system (OS 4000, Linos Photonics\(^{15}\)) pumped by a Nd:YAG ring laser at \( \lambda_p = 1064 \text{ nm} \). This singly resonant OPO with a resonated pump is based on a periodically poled lithium niobate (PPLN) crystal, and it features a narrow linewidth (<150 kHz) and an output power of more than 20 mW.\(^{16}\) The OPO’s cavity length is locked to the pump laser by the Pound–Drever–Hall stabilization technique. One can conveniently tune the signal wavelength, which is monitored with a wavemeter, to \( \lambda_s = 1550 \text{ nm} \) by varying the PPLN crystal’s temperature and using the intracavity etalon of the OPO. The resultant idler wavelength is \( \lambda_i = 3390 \text{ nm} \).

After the Ti:sapphire output and the OPO idler are combined on a beam splitter, the 28-mW Ti:sapphire output near 834 nm and the 16 mW of OPO idler are focused into a PPLN crystal by a 40-mm focal-length calcium fluoride lens. This 5-mm-long PPLN crystal has a quasi-phase-matching period of 16.2 \( \mu \text{m} \) and is heated to 130 °C. The resultant phase-matching bandwidth is \( \sim 0.75 \text{ THz} \). The output light is collimated with a 38-mm calcium fluoride lens. The resultant SFG comb and the (adequately attenuated) Ti:sapphire comb at 670 nm are temporally and spatially overlapped by a prism-based delay line (two SF10 prisms with an apex-to-apex separation of 33 cm; see Fig. 1), prefiltered by a narrowband interference filter at 670 nm, and detected by a photomultiplier (Hamamatsu R7400U-20). In the experiment we observed SFG powers of the order of 870 pW. The signal-to-noise ratio of the heterodyne beat \( f_b \) between the two combs is \( \sim 23 \text{ dB} \) in a 100-kHz resolution bandwidth (Fig. 3). Note that the final beat signal results from the coherent superposition of many corresponding comb lines. Importantly, the beat signal at frequency \( f_1 + m f_{\text{rep}} \) (with integer \( m \)) does not depend on carrier-envelope frequency \( f_0 \). Because of its finite signal-to-noise ratio, we regenerated the beat signal with a rf tracking oscillator, which consists of a voltage-controlled oscillator and a digital phase-locked loop. By phase locking this beat signal to a rf reference\(^{17}\) we establish a direct phase-coherent link between rf repetition frequency \( f_{\text{rep}} \) and the optical OPO idler frequency \( f_1 \). 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 a polarization-maintaining optical fiber.

To evaluate the stability of our optical clockwork we made a comparison of the tenth harmonic of the Ti:sapphire repetition frequency and a rf reference signal that was derived from a low-phase-noise rf synthesizer referenced to the National Institute of Standards and Technology (NIST) ST-22 hydrogen maser (instability of \( \sim 2.4 \times 10^{-14} \) at a 1-s counter gate time) and transferred from the NIST to JILA via the Boulder Research and Administrative Network single-mode fiber.\(^{18}\) Measured frequency-counting data are depicted in Fig. 4. Under unlocked conditions, we typically observe standard deviations of 240 Hz (of a total of 780 MHz) at a 1-s gate time. In time interval A in Fig. 4, the optical heterodyne beat signal is phase locked to the rf reference, while the OPO pump laser is phase locked to the cw laser used in the iodine optical frequency standard. The data reveal a standard deviation of 0.837 Hz at a 1-s gate time. At 108 s, we deliberately unlock the OPO pump laser; however, the heterodyne beat signal remains phase locked. In subsequent time interval B, the standard deviation is correspondingly increased to 5.09 Hz. These data present convincing evidence that the instability of \( f_{\text{rep}} \) under the locked condition arises directly from the frequency fluctuations of

![Fig. 2. Ti:sapphire laser spectra on a linear scale (darker solid curve) and on a logarithmic scale (dotted curve) measured after the prism-based delay line (cf. Fig. 1). The lighter solid curve shows the output coupler’s reflectivity for comparison. The amplitude of the short-wavelength peak at 670 nm is strongly enhanced by roll-off of the output coupler, and it is highly sensitive to intracavity dispersion.](image)

![Fig. 3. Heterodyne beat between the SFG comb and the Ti:sapphire comb at 670 nm. The signal-to-noise ratio of the beat signal is \( \sim 23 \text{ dB} \) measured in a 100-kHz resolution bandwidth.](image)
the OPO idler. Although the OPO cavity length, measured at 1.064 μm, is stabilized to that of the 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 of the mode-locked laser. With the in-loop error signal indicating a tight phase lock between the optical beat signal and the rf reference we will be able to reveal the full potential of this carrier-envelope-frequency-independent optical clockwork.

We are currently building an optical clock based on a transportable methane-stabilized He–Ne laser similar to that described in Ref. 12. When they were stabilized on the methane F_2^{(2)} line at 3.39 μm, He–Ne lasers exhibited a relative frequency instability of 10^{-14} to 10^{-15} for 1–1000-s measurement times and a frequency reproducibility of 10^{-13} to 10^{-14}. Such a system would therefore represent a compact, robust, and relatively inexpensive optical clock featuring both high accuracy and high stability. We note that this SFG/DFG scheme is widely applicable. For example, an absolutely referenced frequency comb can be generated in the 1.5-μm spectral window that is important for telecommunication applications.

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Note added in Proof: Recently, we completed the above-mentioned He–Ne/CH_4 optical clock employing this carrier-envelope-frequency-independent optical clockwork.

References

15. Mention of commercial product names is for purposes of identification only.
17. All synthesizers and frequency counters used in the experiment were referenced to a local cesium clock.

Fig. 4. Comparison of the tenth harmonic of the Ti:sapphire repetition frequency and the hydrogen maser-based rf reference at 780 MHz at a 1-s gate time. In time interval A, the optical heterodyne beat signal is stabilized and the OPO pump laser is phase locked to the iodine frequency standard, resulting in a standard deviation of 0.837 Hz at a 1-s gate time. At 108 s, the optical beat signal remains stabilized, but we deliberately unlock the OPO pump laser. In subsequent time interval B, the standard deviation is correspondingly increased to 5.09 Hz.