Experimental implementation of optical clockwork without carrier-envelope phase control

O. D. Mücke, O. Kuzucu, F. N. C. Wong, E. P. Ippen, and F. X. Kärtner

Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307

S. M. Foreman, D. J. Jones,* L.-S. Ma,† J. L. Hall, and J. Ye

JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440

Received June 4, 2004

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

OCIS codes: 120.3940, 320.7090, 320.7160.

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_{rep} and carrier-envelope frequency f_0, leads to an optical clockwork that connects optical frequencies $f_n = nf_{\text{rep}} + f_0$ with radio frequency (rf) f_{rep} via an integer $n \sim 10^5$–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[9] (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 frequency standard [e.g., a methane-stabilized He–Ne laser at 3.39 μm (Refs. 12 and 13)] and the long-wavelength portion of a frequency comb yields a SFG comb that can be tuned to overlap spectrally with the short-wavelength portion of the original frequency comb. The resultant heterodyne beat between these two combs of the same origin leads to construction of carrier-envelope-frequency-independent optical clockwork. A similar scheme to eliminate the carrier-envelope frequency was used earlier.[2,14] In this Letter we implement such an optical clockwork based on SFG between a cw 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_{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

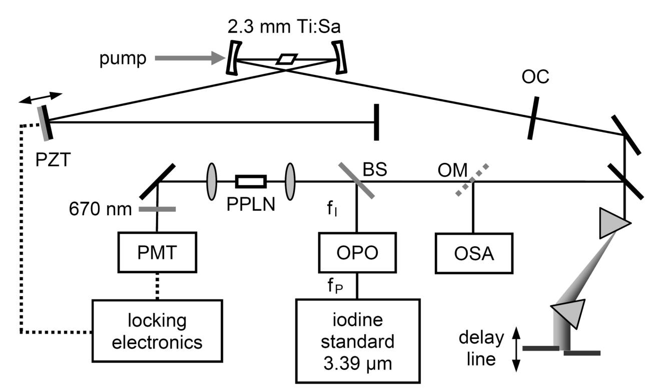

Fig. 1. Setup for a SFG-based optical heterodyne beat for the implementation of an optical clock without carrier-envelope phase control. Note that 3.39 μm + 834 nm → 670 nm. OC, output coupler; OM, optional mirror; BS, beam splitter; PZT, piezoelectric transducer; PMT, photomultiplier tube; OSA, optical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

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 ~60°. 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 ~0.5% in the center of the output coupler at ~800 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 $\lambda_P = 1064$ 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 $\lambda_S = 1550$ nm by varying the PPLN crystal's temperature and using the intracavity etalon of the OPO. The resultant idler wavelength is $\lambda_I = 3390$ 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 μm and is heated to 130 °C. The resultant phase-matching bandwidth is ~0.75 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 ~23 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 $f_I + mf_{rep}$ (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_{rep} and the optical OPO idler frequency f_I. In addition, we have phase locked the OPO pump laser to our iodine-stabilized Nd:YAG laser at 1.064 μm,[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_{rep} under the locked condition arises directly from the frequency fluctuations of

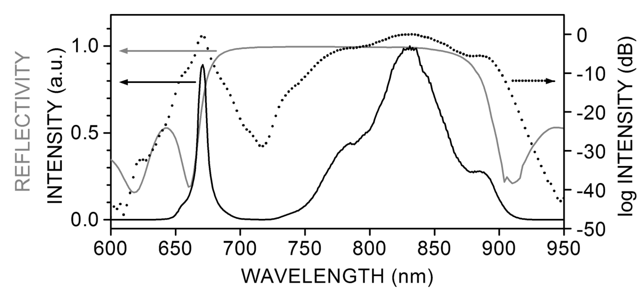

Fig. 2. Ti:sapphire laser spectra on a linear scale (darker solid curve) and on a logarithmic scale (dotted curve) measured after the prism-based delay line (cf. Fig. 1). The lighter solid curve shows the output coupler's reflectivity for comparison. The amplitude of the short-wavelength peak at 670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

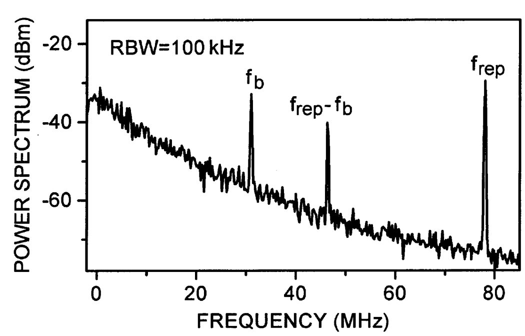

Fig. 3. Heterodyne beat between the SFG comb and the Ti:sapphire comb at 670 nm. The signal-to-noise ratio of the beat signal is ~23 dB measured in a 100-kHz resolution bandwidth.

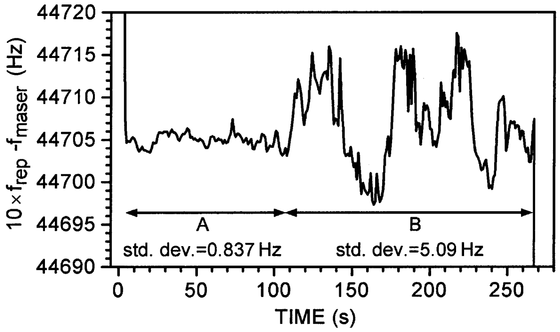

Fig. 4. Comparison of the tenth harmonic of the Ti:sapphire repetition frequency and the hydrogen maser-based rf reference at 780 MHz (at a 1-s gate time). In time interval A, the optical heterodyne beat signal is stabilized and the OPO pump laser is phase locked to the iodine frequency standard, resulting 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.

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 clockwork when the OPO is further stabilized by methods such as use of a 2:1 frequency divider.[19]

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}.[13] 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.[20]

This research for the development of optical clocks has been supported in part by the Multidisciplinary Research Program of the University Research Initiative, administered by the U.S. Office of Naval Research, and by NIST and NASA. O. D. Mücke (odmuecke@mit.edu) gratefully acknowledges support from the Alexander von Humboldt Foundation.

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

*Present address, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada.

†Present addresses, Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres, France, and Department of Physics, East China Normal University, Shanghai 200062, China.

References

1. S. A. Diddams, T. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, and D. J. Wineland, Science **293,** 825 (2001).
2. J. Ye, L. S. Ma, and J. L. Hall, Phys. Rev. Lett. **87,** 270801 (2001).
3. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, Science **288,** 635 (2000).
4. A. Apolonski, A. Poppe, G. Tempea, C. Spielmann, T. Udem, R. Holzwarth, T. W. Hänsch, and F. Krausz, Phys. Rev. Lett. **85,** 740 (2000).
5. R. Ell, U. Morgner, F. X. Kärtner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, and B. Luther-Davies, Opt. Lett. **26,** 373 (2001).
6. T. M. Fortier, D. J. Jones, and S. T. Cundiff, Opt. Lett. **28,** 2198 (2003).
7. L. Matos, D. Kleppner, O. Kuzucu, T. R. Schibli, J. Kim, E. P. Ippen, and F. X. Kaertner, Opt. Lett. **29,** 1683 (2004).
8. A. Baltuška, T. Fuji, and T. Kobayashi, Phys. Rev. Lett. **88,** 133901 (2002).
9. S. M. Foreman, D. J. Jones, and J. Ye, Opt. Lett. **28,** 370 (2003).
10. M. Zimmermann, C. Gohle, R. Holzwarth, T. Udem, and T. W. Hänsch, Opt. Lett. **29,** 310 (2004).
11. T. Fuji, A. Apolonski, and F. Krausz, Opt. Lett. **29,** 632 (2004).
12. M. A. Gubin, D. A. Tyurikov, A. S. Shelkovnikov, E. V. Koval'chuk, G. Kramer, and B. Lipphardt, IEEE J. Quantum Electron. **31,** 2177 (1995).
13. N. G. Basov and M. A. Gubin, IEEE J. Sel. Top. Quantum Electron. **6,** 857 (2000).
14. A. Amy-Klein, A. Goncharov, C. Daussy, C. Grain, O. Lopez, G. Santarelli, and C. Chardonnet, Appl. Phys. B **78,** 25 (2004).
15. Mention of commercial product names is for purposes of identification only.
16. E. V. Kovalchuk, D. Dekorsy, A. I. Lvovsky, C. Braxmaier, J. Mlynek, A. Peters, and S. Schiller, Opt. Lett. **26,** 1430 (2001).
17. All synthesizers and frequency counters used in the experiment were referenced to a local cesium clock.
18. J. Ye, J.-L. Peng, R. J. Jones, K. W. Holman, J. L. Hall, D. J. Jones, S. A. Diddams, J. Kitching, S. Bize, J. C. Bergquist, L. W. Hollberg, L. Robertsson, and L.-S. Ma, J. Opt. Soc. Am. B **20,** 1459 (2003).
19. D. Lee and N. C. Wong, Opt. Lett. **17,** 13 (1992).
20. K. W. Holman, D. J. Jones, D. D. Hudson, and J. Ye, Opt. Lett. **29,** 1554 (2004).