A compact femtosecond-laser-based optical clockwork

S. A. Diddams[a†], Th. Udem[a‡], K. R. Vogel[a], C. W. Oates[a], E. A. Curtis[a*], R. S. Windeler[b], A. Bartels[c]
J. C. Bergquist[a], and L. Hollberg[a]

[a]National Institute of Standards and Technology, MS 847, 325 Broadway, Boulder, CO 80305
[b]Bell Laboratories, Lucent Technologies, 700 Mountain Ave, Murray Hill, NJ 07974
[c] GigaOptics GmbH, Louis-Raverat Str. 23, 63165 Mühlheim/Main, Germany

ABSTRACT

We describe in detail an optical clockwork based on a 1 GHz repetition rate femtosecond laser and silica microstructure optical fiber. This system has recently been used for the absolute frequency measurements of the Ca and Hg^+ optical standards at the National Institute of Standards and Technology (NIST). The simplicity of the system makes it an ideal clockwork for dividing down high optical frequencies to the radio frequency domain where they can readily be counted and compared to the existing cesium frequency standard.

Keywords: Optical frequency metrology, femtosecond lasers, frequency standards

1. INTRODUCTION

Emerging optical frequency standards based on laser-cooled atoms and ions promise superior stability and accuracy over existing microwave standards[1,2,3,4]. However, until recently an appropriate clockwork for dividing down the very fast optical oscillations to a countable frequency had been missing. As demonstrated in just the past year, frequency dividers based on mode-locked femtosecond lasers provide a convenient, robust, and accurate means of phase-coherently linking optical frequencies to standards in the microwave domain[5,6,7,8,9,10]. The basic concepts that make this possible are as follows. The spectrum emitted by a mode-locked laser consists of a comb of regular spaced continuous waves that are separated by the pulse repetition rate f_r. The frequency of the n^{th} mode of the comb is given by $f_n = nf_r + f_o$ where f_o is the frequency offset common to all modes that is caused by the difference between the group and the phase velocity inside the laser cavity[11,12,13]. This expression reveals that the easily measured f_r is directly linked to an optical frequency (f_n) provided that f_o is known. If the frequency comb of the laser covers an entire octave, then f_o can be measured by frequency doubling an infrared mode and heterodyning it with an existing mode in the visible portion of the comb[7,9]. The heterodyne signal yields the difference $2(nf_r + f_o) - (2nf_r + f_o) = f_o$. Only with the arrival of novel microstructure silica fibers has the required octave-spanning spectrum been attained with high-repetition-rate, low-power femtosecond lasers[14,15]. This breakthrough has revolutionized optical frequency metrology and opened the door to a new generation of atomic clocks based on optical transitions. In this paper we describe in detail an optical clockwork based on a high repetition rate (1 GHz) femtosecond laser and novel microstructure optical fiber. The described system has recently been used to make absolute frequency measurements of the Ca and Hg^+ optical standards at NIST. A summary of these results is also presented.

2. THE OPTICAL CLOCKWORK

2.1 The femtosecond laser and microstructure fiber

The femtosecond Ti:Sapphire laser, shown schematically in Fig. 1, is based on a commercial system produced by GigaOptics[16,17]. The laser cavity is a simple "bow-tie" design with 3 cm radii of curvature mirrors surrounding the 1.5 mm highly-doped Ti:sapphire crystal, which is optically excited with the 532 nm radiation from a diode-pumped solid-state laser. The two curved mirrors and the flat high reflector all employ special negative dispersion coatings as required for stable soliton-like mode-locked operation of the laser. Coarse adjustment of the repetition rate to near 1 GHz is achieved with a translation stage on which the flat high reflector is mounted, while a piezoelectric transducer (PZT) behind the same mirror provides fine adjustment. In the present setup, the excess heat from the pump laser is removed by a thermoelectric cooler,

[†] email: sdiddams@boulder.nist.gov
[‡] email: thu@mpq.mpg.de. On leave from Max-Planck Institut für Quantenoptik, Hans-Kopfermann Str.1, 85748 Garching, Germany.
[*] Also with the Department of Physics, University of Colorado, Boulder, CO 80309.

which is subsequently water-cooled. At this point, we have not employed active temperature stabilization. All the laser components are mounted on a steel plate (30 x 30 cm^2) that rests on several layers of vibration-isolating rubber, and the entire laser is enclosed in a sealed thick-walled aluminum box to minimize environmental perturbations. The inner walls of this box are further covered with lead-lined foam to damp acoustic resonances.

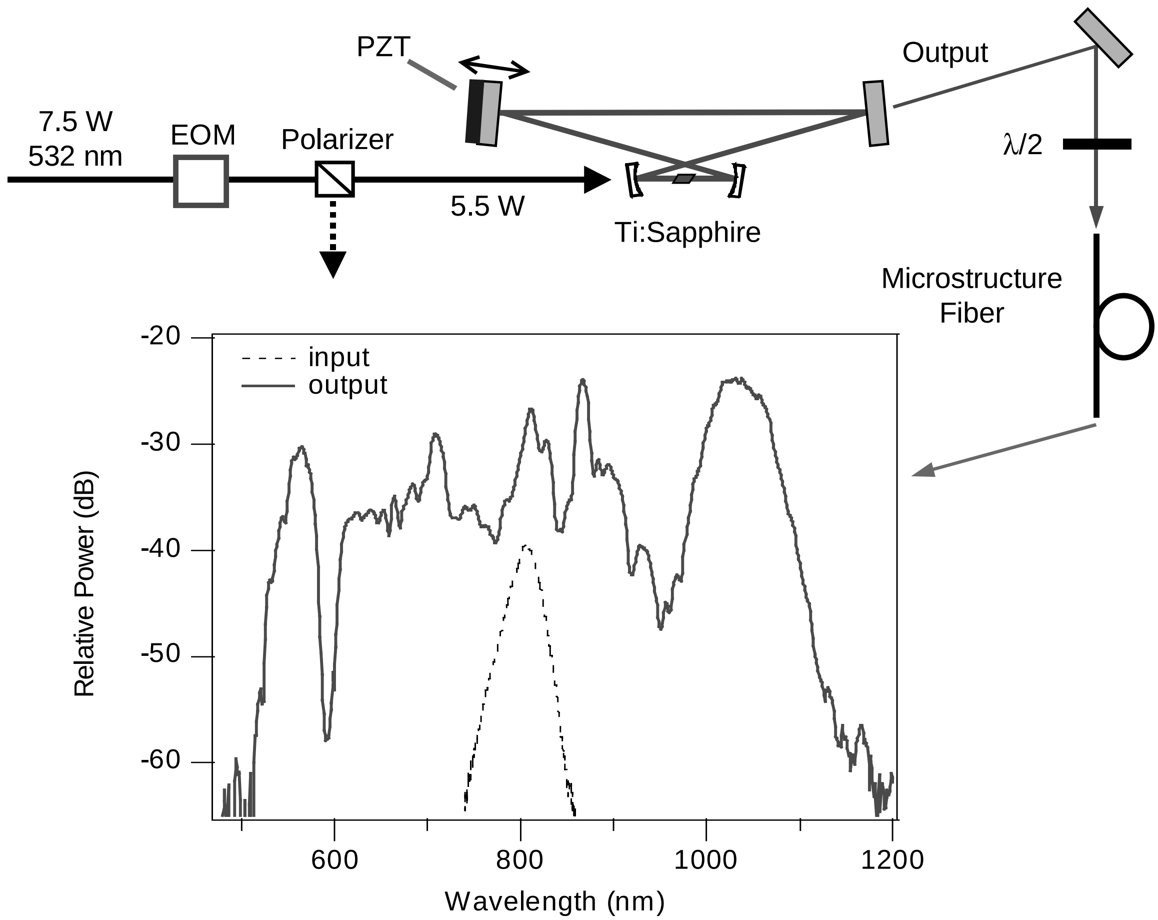

Figure 1: Diagram of the 1 GHz femtosecond laser and the octave-spanning spectrum produced by the microstructure optical fiber. The input spectrum to the fiber is shown as a dashed line for comparison.

Under continuous wave (CW) operation, the laser is bi-directional. However, with proper cavity alignment, Kerr-lens mode-locking (KLM) can be initiated by tapping on one of the mirror mounts. When mode-locked the laser then runs in either of the clockwise or counter-clockwise directions with near equal probability. If oscillation occurs in the direction that is not desired, mode-locking is stopped and the laser is restarted. If necessary, this stopping and restarting is repeated a few times until the output is in the desired orientation. The typical mode-locked output power is ~650 mW with 5.5 W of pump power. Once it is mode-locked the laser runs almost indefinitely, although over periods of many hours the slow thermal drift of some cavity components may require slight re-adjustment of the optics to maximize the output power. One distinct advantage of the ring geometry is that the laser is largely immune to the back-reflected light that arises, for example, from the tight focusing of the laser beam into an optical fiber.

The –3 dB spectral bandwidth of pulses emitted from the laser is approximately 15 THz, which is sufficient to support pulses of ~25 fs in duration. In order to broaden the optical spectrum to the required octave, the output of the laser is coupled into a 15-20 cm long piece of microstructure optical fiber. An aspheric lens with focal length of 1.45 mm (110x, 0.55 NA) is used for focusing into the fiber, and coupling efficiencies approaching 50% have been obtained (~300 mW of continuum output from the fiber). However, we have observed that the coupling efficiency tends to degrade over a period of about one week—presumably because of optical damage. Efficient and very stable coupling into the ~1.7 µm diameter fiber core are essential to the operation of the optical clockwork. In addition to a high-quality coupling stage, we have found that the fiber must be held very close to its end. Otherwise, the fiber tip may oscillate and bend under the force of the tightly focused light. To prevent such difficulties, after cleaving it we pot the end of the fiber in epoxy, leaving only ~50 microns of the fiber tip exposed.

The unique dispersion properties of the microstructure fiber provide guidance in a single spatial mode (~1.7 μm diameter) with zero group velocity dispersion near 770 nm[14]. Because temporal spreading of the pulse is minimized, peak intensities in the range of hundreds of GW/cm^2 are maintained over a significant propagation length, thus providing enhanced spectral broadening due to self-phase modulation. In fact, the 800 nm output of the laser is in the anomalous dispersion regime of the microstructure fiber such that the up-chirped pulses (due to normal dispersion in the output coupler and focusing lens) should re-compress to minimum duration in the first few centimeters of the fiber. For this reason no attempt is made to re-compress the pulses before launching them into the fiber. The fiber is also birefringent, and the output spectral width and content depend strongly on the polarization of the input light. We therefore use an achromatic half-wave plate prior to coupling so as to optimize the output spectrum. A typical output spectrum containing ~ 250 mW of total power is shown in the lower half of Fig. 1. No complete models of the nonlinear processes that yield this spectrum have been reported; however, the large gaps are likely the result of destructive interference and/or phase mismatch in the four-wave mixing processes that produce the broadening.

Although not resolved in the data of Fig. 1, this spectrum consists of a comb of optical modes spaced by 1 GHz. It is worth pointing out that, in contrast to more typical femtosecond lasers having f_r on the order of 100 MHz each mode of the 1 GHz comb has 10 times more power (assuming the same total average power). Furthermore, it has been observed that broadband amplitude noise (whose physical origin has not been fully described) that appears on the output light of the microstructure fiber is very much reduced with the lower energy pulses from the 1 GHz system. For example, with a 100 MHz femtosecond laser producing only slightly shorter pulses, this broadband noise was observed to increase almost 30 dB when the coupling was increased from only 25 mW to 60 mW. In order to avoid the excessive noise with the lower repetition rate system one is obliged to couple less light (25-30 mW) into the fiber, which again means less power per mode. On the other hand, for the 1 GHz system the same 250 pJ per pulse is obtained with a tenfold increase in the average power. Thus, with the required octave coverage from the microstructure fiber, the typical frequency domain power per mode with the 1 GHz system could be 100 times greater than that attained with a 100 MHz system that delivers similar pulses. In practice, we find this to be qualitatively true.

2.2 Controlling the femtosecond comb

As shown in Fig. 2, we measure and phase-lock both f_o and f_r to synthesized frequencies derived from a hydrogen maser that has its frequency calibrated by the NIST primary cesium standard. Approximately 5 mW of the output of the microstructure fiber is focused onto a P-I-N photodiode and the photocurrent generated at f_r is filtered, amplified, and mixed with the 1 GHz output of a synthesizer (HP 8662A)[17]. The mixer's output is then further filtered and amplified before being applied to the PZT element behind the flat cavity high reflector (see Fig. 1). Measurements indicate that the phase noise in f_r for a free-running femtosecond laser falls below that of the HP 8662A[17] synthesizer at an offset of approximately 1 kHz from f_r[18]. We therefore employ the minimum phase-lock bandwidth required to suppress the large fluctuations at low frequencies (typical bandwidth $\leq$ 1 kHz). With a larger locking bandwidth, broadband noise from the synthesizer actually degrades the femtosecond laser comb, which only needs to have servo corrections for the acoustic and thermal fluctuations of f_r. It is important to note that we derive the signal for locking f_r from the light that has passed through the fiber so that we can also in principle correct for any slow variations or shifts in f_r due to the thermal heating and expansion of the fiber.

To measure and control f_o the infrared part of the comb from the fiber ($\lambda \approx 1060$ nm) is split off by a dichroic mirror and frequency-doubled into the green portion of the visible spectrum in a 2 mm long angle-tuned $KNbO_3$ crystal. This frequency-doubled light is spatially combined with the green part of the original comb using a polarizing beam splitter. An important detail is a variable optical delay used to match the path lengths of the two arms of the Mach-Zender interferometer at the ~10 μm level. The time-domain interpretation of this requirement is that high-contrast interference will be observed only if the two pulses overlap temporally. Equivalently, in the frequency domain we obtain the greatest signal-to-noise-ratio (S/N) if multiple pairs of modes contribute to the heterodyne signal. This occurs when the phase delay is made equal in the two arms of the interferometer for the greatest number of modes.

After the visible beams from the two arms of the interferometer are recombined, a second rotatable polarizer projects the polarization of the combined beams onto a common axis so that they can interfere on a photodiode. This polarizer is also used to adjust the relative power of the two beams for optimum S/N in the heterodyne signal. A 10 nm wide optical bandpass filter (or alternatively a small grating) prior to the photodiode helps to select only that part of the frequency comb that matches the frequency-doubled light, thereby reducing noise from unwanted comb lines[13]. The generated photocurrent is filtered and a digital phase-lock loop (PLL)[19] is employed for phase-locking f_o to a synthesized frequency derived from the same hydrogen maser used in locking f_r. In the current implementation, f_o is digitally divided by 64 to increase the locking range of the PLL to ±32 π. This division may not be required for phase-locking f_o in all circumstances, but it does improve the robustness of the lock. The error signal generated from the PLL is used to control the 532 nm pump power with an electro-optic modulator (EOM) oriented as a Pockels cell combined with a polarizer (see Fig. 1)[9]. In order to operate in a regime where the pump power varies approximately linearly with voltage applied to the EOM, it is necessary to apply a bias of about 1.2 kV, which results in a loss of approximately 2 W of pump power. (Recently we have demonstrated that a fused silica acousto-optic modulator can perform the same function as the EOM/polarizer combination, but with significantly less loss of pump power.) As expected, changing the pump power also changes the intracavity power of the femtosecond laser. In the simplest picture, this has the effect of modifying the nonlinear Kerr phase shift in addition to shifting the pulse spectrum, which in turn changes the group velocity. As the phase and group velocities of the pulse change by differing amounts, this has the net effect of varying f_o over some limited range (~15 % of f_r). Experimentally, we find a given change in the pump power ΔP yields $|\Delta f_o/\Delta P|$=0.26 MHz/mW, and only very small changes in the pump power are sufficient to phase-lock f_o. As just pointed out, this means of controlling f_o directly affects f_r by changing the group velocity. In this case the tuning coefficient is $|\Delta f_r/\Delta P|$=1 Hz/mW. These can be compared to the tuning coefficients for the PZT element that is used to control f_r, which are $|\Delta f_o/\Delta V|$=83 kHz/V and $|\Delta f_r/\Delta V|$=3 Hz/V, where the PZT translates approximately 0.75 nm per Volt. Although the two control loops are clearly non-orthogonal, this has not proved detrimental to the performance of the system for measuring optical frequencies. As will be shown, the current limit for such measurements is the stability of the hydrogen maser.

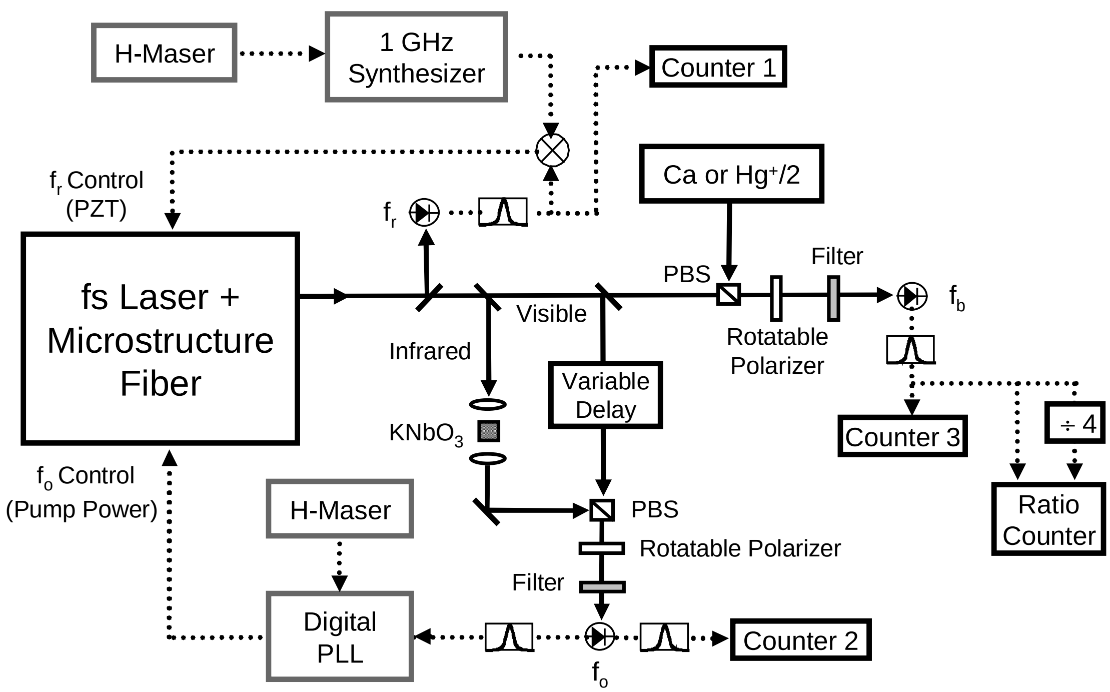

Figure 2: The self-referenced optical frequency synthesizer used for absolute measurements of the Hg^+ and Ca optical frequency standards. The entire optical apparatus sits on a transportable optical breadboard with dimensions of 120 cm by 60 cm. PBS: polarizing beam splitter. H-Maser: hydrogen maser.

3. MEASURING OPTICAL FREQUENCIES

When both f_o and f_r are phase-locked, the frequency of every mode in the comb is known with the same precision as the hydrogen maser. At NIST, the maser has its average frequency calibrated with an uncertainty of approximately $2\cdot10^{-15}$ by comparison with the local cesium fountain clock. In the frequency comb one then has available hundreds of thousands of precision optical oscillators across the entire visible and near-infrared spectrum. As illustrated in Fig. 2, the appropriate portion of the comb can be spatially overlapped with the light of unknown frequency from an optical standard. Again, as already described, it is convenient to combine the two fields in orthogonal polarizations and then use a rotatable polarizer and optical bandpass filter to optimize the S/N. The heterodyne beat f_b between a single element of the comb and an unknown standard yields the optical frequency $f_{opt} = f_o + mf_r + f_b$, where m is a large integer, that can be determined from a lower-resolution measurement (a laboratory wavemeter, for example).

In making high-precision measurements of the Ca and Hg^+ optical standards it is critical to avoid errors due to cycle-slips in the phase-locks and the counting of f_b. We detect cycle slips in both of the phase-locks by monitoring f_r and f_o with additional counters (Counters 1 and 2 in Fig. 2)[20]. We selectively discard any measurement of f_{opt} for which the measured f_r or f_o deviate from the expected value by more than $1/\tau_{gate}$, where τ_{gate} is the counter gate time in seconds. We avoid miscounts of f_b by using an auxiliary counter to record the ratio r between f_b and $f_b/4$, where the division by 4 is implemented digitally. Any measurements of f_b where the auxiliary counter gives a result that does not satisfy $(r\text{-}4)\cdot f_b < 10/\tau_{gate}$ are discarded. We rely on the assumption that the two counters recording f_b and r, if in disagreement, do not make the *same* mistake. This increased threshold is required because the ratio counting yields a resolution much lower than that of the direct counting of f_r and f_o. Nonetheless, this corresponds to an acceptable measurement window for the optical frequency of $\sim 2\cdot 10^{-14}/\tau_{gate}$. For each data point the three additional counters (f_r, f_o, and r) are started before the counting of f_b and operated with 50 ms longer gate times to ensure temporal overlap.

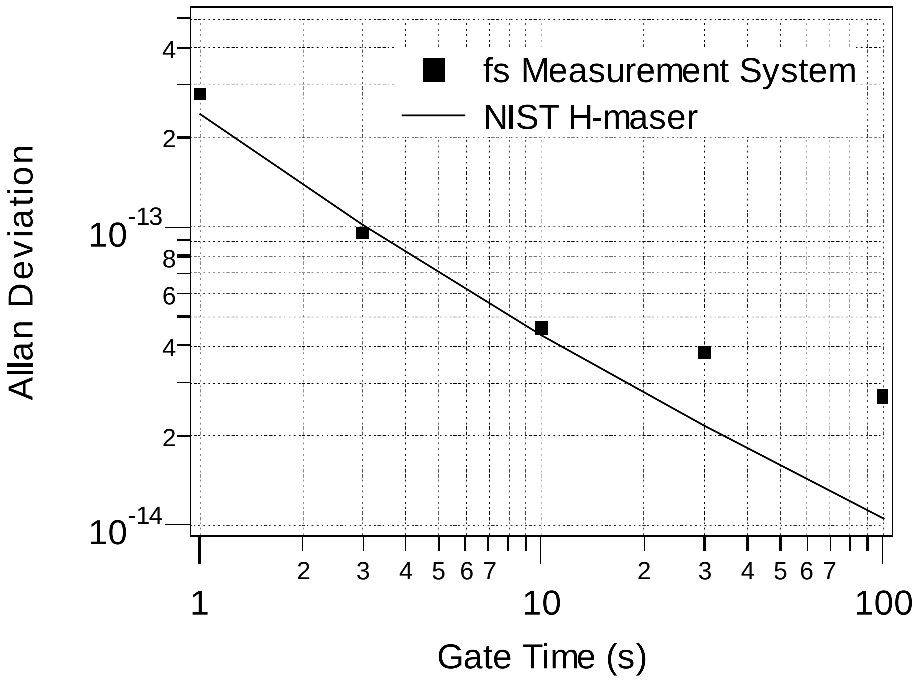

Figure 3: Stability of the femtosecond-laser-based measurement system as determined in a measurement of the Ca optical frequency standard. The squares are the measured Allan Deviation of the heterodyne between the Ca standard and one element of the femtosecond comb. The line is the stability of the hydrogen maser to which the femtosecond system is phase-locked.

The stability of the femtosecond-laser-based measurement system, which is phase-locked to the hydrogen maser as just described, can be evaluated in a frequency measurement of either the Ca or Hg^+ standard. The result for the case of the Ca measurement is shown in Fig. 3. For short gate times, the measurement stability mirrors that of the hydrogen maser; however, for gate times ≥30 s, we begin to see a departure of the measurement from the maser stability. Since the optical standards have stabilities well below $1\cdot 10^{-14}\tau^{-1/2}$ (τ measured in seconds), their contribution to the Allan Deviation is negligible. It is believed that the source of instability at longer gate times is the synthesizer that is used to multiply the 5 MHz maser signal up to 1 GHz. Recently, we have measured the temperature-dependent fractional frequency shift of the HP 8662A[17] used in these experiments to be $\sim 2\cdot 10^{-14}$ /(K·hr), which is consistent with the order of magnitude of the deviation seen in Fig. 3. Once the absolute frequency of the hydrogen maser has been calibrated with the cesium fountain clock, the same measurement that produces Fig. 3 also yields the frequencies of the Hg^+ and Ca optical standards. The complete details are reported elsewhere[21], so here we provide just the final measured values, which are f_{Hg} = 1 064 721 609 899 143(10) Hz and f_{Ca} = 455 986 240 494 158(26) Hz. For the Hg^+ measurement, the statistical uncertainty is only 2.4 Hz, but we state a 10

Hz overall uncertainty in the absence of a full evaluation of the standard. These values now represent two of the most precise optical frequency measurements ever made and demonstrate the utility of the femtosecond-laser-based clockwork in the evaluation of optical standards of the highest performance.

ACKNOWLEDGEMENTS

The authors thank Fred Walls, Eugene Ivanov, Tom Parker, Ronald Holzwarth and John Hall for valuable discussions regarding this work. This work is the contribution of the National Institute of Standards and Technology, and is therefore not subject to United States copyright.

REFERENCES

1. R. J. Rafac, B. C. Young, J. A. Beall, W. M. Itano, D. J. Wineland, and J. C. Bergquist, "Sub-dekahertz Ultraviolet Spectroscopy of $^{199}Hg^{+}$," *Phys. Rev. Lett.*, **85**, pp. 2462-2465, 2000; B. C. Young, F. C. Cruz, W. M. Itano, and J. C. Bergquist, "Visible Lasers with Subhertz Linewidths," *Phys. Rev. Lett.*, **82**, pp. 3799-3802 (1999).
2. H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner, "First Phase-Coherent Frequency Measurement of Visible Radiation," *Phys. Rev. Lett*. **76**, pp. 18–21, 1996; C. W. Oates, E. A. Curtis, and L. Hollberg, "Improved short-term stability of optical frequency standards: approaching 1 Hz in 1s with the Ca standard at 657 nm," *Opt. Lett.*, **25**, pp. 1603-1605, 2000.
3. J. E. Bernard, A. A. Madej, L. Marmet, B. G. Whitford, K. J. Siemsen, and S. Cundy, *Phys. Rev. Lett.*, **82**, pp. 3228-3231, 1999.
4 J. von Zanthier, Th. Becker, M. Eichenseer, A. Yu. Nevsky, Ch. Schwedes, E. Peik, H. Walther, R. Holzwarth, J. Reichert, Th. Udem, T. W. Hänsch, P. V. Pokasov, M. N. Skvortsov, and S. N. Bagayev, "Absolute frequency measurement of the In^{+} clock transition with a mode-locked laser," *Opt. Lett.*, **25**, pp. 1729-1731, 2000.
5. Th. Udem, J. Reichert, R. Holzwarth, and T. W. Hänsch, "Absolute Optical Frequency Measurement of the Cesium D_1 Line with a Mode-Locked Laser," *Phys. Rev. Lett*., **82**, pp. 3568-3571, 1999.
6. M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, Th. Udem, M. Weitz, T. W. Hänsch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon, and A. Clairon, "Measurement of the Hydrogen 1S-2S Transition Frequency by Phase Coherent Comparison with a Microwave Cesium Fountain Clock," *Phys. Rev. Lett.*, **84**, pp. 5496-5499, 2000.
7. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase contol of femtosecond mode-locked lasers and direct optical frequency synthesis," Science, 288, pp. 635-639, 2000.
8. S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, Th. Udem, and T. W. Hänsch, "Direct Link between Microwave and Optical Frequencies with a 300 THz Femtosecond Laser Comb," Phys. Rev. Lett. **84**, 5102-5105, 2000.
9. R. Holzwarth, Th. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. St. J. Russell, "Optical Frequency Synthesizer for Precision Spectroscopy," *Phys. Rev. Lett*., **85**, pp. 2264-2267, 2000.
10. J. Stenger, T. Binnewies, G. Wilpers, F. Riehle, H. R. Telle, J K Ranka, R. S. Windeler, and A. J. Stentz, "Phase-coherent frequency measurement of the Ca intercombination line at 657 nm with a Kerr-lens mode-locked femtosecond laser," *Phys. Rev. A*, **63**, 021802(R), 2001.
11. A. I. Ferguson, J. N. Eckstein, and T. W. Hänsch, "Polarization spectroscopy with ultrashort light pulses ," *Appl. Phys.*, **18**, pp. 257-260, 1979.
12. D. J. Wineland, J. C. Bergquist, W. M. Itano, F. Diedrich, and C. S. Weimer, "Frequency Standards in the Optical Spectrum," in *The Hydrogen Atom*, G. F. Bassani, M. Inguscio and T.W. Hänsch, eds., pp 123-133, Springer-Verlag, Heidelberg, 1989.
13. J. Reichert, R. Holzwarth, Th. Udem, and T. W. Hänsch, "Measuring the frequency of light with mode-locked lasers," *Opt. Comm.*, **172**, pp. 59-68, 1999.
14. J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Efficient visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Conference on Lasers and Electro-optics, Postdeadline paper CPD8-1, 1999; J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," *Opt. Lett*, **25**, pp. 25-27, 2000; J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Optical properties of high-delta air-silica microstructure optical fibers," *Opt. Lett*, **25**, pp. 796-798, 2000.
15. W. J. Wadsworth, J. C Knight, A. Ortigosa-Blanch, J. Arriaga, E. Silvestre, and P. St. J. Russell, "Soliton effects in photonic crystal fibers at 850 nm," *Electron. Lett.*, **36**, pp. 53-54, 2000.
16. A. Bartels, T. Dekorsky, and H. Kurz, "Femtosecond Ti:sapphire ring laser with a 2-GHz repetition rate and its application in time-resolved spectroscopy," *Opt. Lett.*, **24**, pp. 996-998, 1999.

17. The use of specific trade names is for scientific completeness only, and does not constitute an endorsement by the National Institute of Standards and Technology. Products from other manufacturers may be equally suitable for the experiments presented here.

18. E. Ivanov, S. A. Diddams, and L. Hollberg, "Experimental study of the noise properties of a Ti:sapphire femtosecond laser," submitted to *IEEE-FCS*, 2001. Also see the contribution of F. L. Walls in these Proceedings.

19. L. D'Evelyn, L. Hollberg and Z. B. Popovic, "A CPW Phase-Locked Loop for Diode-Laser Stabilization," *IEEE MTT-S Symposium Digest*, 1994.

20. Th. Udem, J. Reichert, T. W. Hänsch, M. Kourogi "Accuracy of optical frequency comb generators and optical frequency interval divider chains," *Opt. Lett*., **23**, pp. 1387-1389, 1998.

21. Th. Udem, S. A. Diddams, K. R. Vogel, C. W. Oates, E. A. Curtis, W. D. Lee, W. M. Itano, R. E. Drullinger, J. C. Bergquist, and L. Hollberg, "Absolute Frequency Measurements of the Hg+ and Ca Optical Clock Transitions with a Femtosecond Laser," submitted to *Phys. Rev. Lett.*, 2001.