Atomic clocks of the future: using the ultrafast and ultrastable*

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Abstract. The application of ultrafast mode-locked lasers and nonlinear optics to optical frequency metrology is revolutionizing the field ofatomic clocks. The basic concepts and applications are reviewed using our recent results with two optical atomic frequency standards based on laser cooled and trapped atoms.

1. Introduction

In contrast to today's atomic clocks that are based on electronic oscillators locked to microwave transitions in atoms, the next generation of atomic clocks will most likely employ lasers and optical transitions in laser-cooled atoms and ions. Optical atomic frequency standards use frequency-stabilized CW lasers with good short-term stability that are stabilized to narrow atomic resonances using feedback control systems. At NIST we are developing two optical frequency standards, one based on laser cooled and trapped calcium atoms and the other on a single laser cooled trapped Hg+ ion. Similar research is being done at labs around the world.

Moving from microwave frequencies, where one cycle corresponds to 100 ps, to optical frequencies where one cycle is a femtosecond long, allows us to divide time into smaller intervals and hence gain frequency stability and timing precision. Steady progress over the past 30 years has improved the performance of optical frequency standards to the point that they are now competitive with, and even moving beyond, their microwave counterparts.[1-3] A major impediment to the development of optical clocks was that it was extremely difficult to count optical frequencies and to make the coherent connection between laser oscillators and countable microwave sources. To reconfigure an optical frequency standard into an atomic clock we need to provide a mechanism to count and accumulate the optical cycles of the atomically stabilized laser.

2. Femtosecond laser-based optical frequency combs

A breakthrough occurred when Udem et al. proved in 1999 that femtosecond mode-locked lasers could be used to count large optical frequencies intervals (tens of THz) with high accuracy.[2] The method is straightforward and was first clearly described by Hänsch in the '70s, but it was not rigorously tested until recently. Those ideas, along with new techniques from the Hall and Hänsch groups, now provide femtosecond laser-based systems that can phase-coherently connect stable lasers in the visible with frequencies that are accessible to electronics.

Optical frequency combs spanning the entire visible are now readily generated using Ti:Sapphire lasers and nonlinear microstructure fibers. For example, a 1 GHz repetition rate Ti:sapphire laser can be spectrally broadened in a microstructure fiber to produce discrete modes separated by 1 GHz throughout the broadened spectrum from ≈ 500 to 1100 nm. These modes can connect to, and measure, essentially any optical frequency. The frequency of any mode of the comb can be written as $f_N = Nf_{rep}+f_0$, where Nf_{rep} is a large integer N times the pulse repetition rate f_{rep}, and f_0 is the offset of the entire comb extrapolated back to zero frequency. The origin of the offset frequency has a clear physical interpretation in terms of the difference between the group and phase velocities for the pulse in the laser cavity. The "self-referencing" method [1-3] is used to measure the offset frequency by frequency doubling the IR end of the comb and subtracting the existing blue end of the comb from the second harmonic signal, obtaining $2(Nf_{rep}+f_0) - (2Nf_{rep}+f_0) = f_0$. The basic clockwork is shown in Fig. 1.

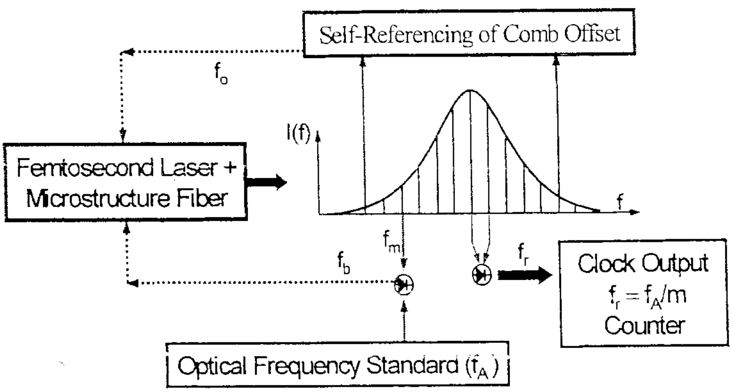

Fig. 1. A simplified diagram of the optical comb shows the counting mechanism used for optical clocks. The beatnote f_b between the optical frequency standard and one tooth of the comb is used to phase-lock that comb tooth to the atomic frequency f_A. This can be done using a PZT on the cavity of the mode-locked laser. The "self-referencing" method generates the offset frequency f_0, which can be controlled by changing the pump power to the femtosecond laser. When the two servos are locked the frequency of all the modes of comb are stabilized relative to the narrow optical atomic reference. The optical clock output then appears at the repetition rate of the modelocked laser. For an appropriate choice of locking parameters the output frequency at the repetition rate is an integer sub harmonic of the optical atomic frequency f_A[3]

The development of convenient optical frequency measuring systems and clockworks based on femtosecond lasers has sparked renewed interest in optical frequency standards and optical atomic clocks. While the comb technology is a powerful and enabling simplification, the optical clocks also rely heavily on advances in laser cooling and trapping of atoms, and the development of highly stabilized cw lasers. Optical frequency combs have been used to measure the frequencies of our two optical standards [f(Ca) = 455 986 240 494 158 +/-26 Hz, and f(Hg+) =1 064 721 609 899 143 +/-10 Hz] relative to the Cs atomic fountain NIST-F1 that realizes the definition of the second.[3]

The performance of optical standards raises obvious questions about the precision, stability, reproducibility, and accuracy of optical frequency metrology based on femtosecond lasers and microstructure fibers. To test for possible errors or limitations of the combs we have been making intercomparisons between two femtosecond combs combined with the two optical standards and a microwave reference derived from a high-stability hydrogen maser. The results show that the combs perform exceptionally well in terms of short-term stability between optical frequencies ($< 6.3\times10^{-16}$ at one second), and in frequency reproducibility across the entire visible spectrum ($< 4\times10^{-17}$), see Fig. 2.[4] Though more than adequate for now, the combs will require improvement to reach the accuracy and stability anticipated for the next generation of optical frequency standards. They are presently at $\approx 7\times10^{-15}$ at 1 second, but the projected instabilities and inaccuracies should approach $\approx 1\times10^{-18}$.[3]

Some technical challenges that we face with femotsecond laser-based frequency combs are instabilities in coupling into the small core of the microstructure fibers, excess broadband noise in the output of the fiber, and extraction of the microwave signals at the repetition rate with high fidelity. Transferring the exceptional short-term stability of the optical frequency standards to the microwave signal from the pulses has proven particularly challenging. In converting the stable optical comb

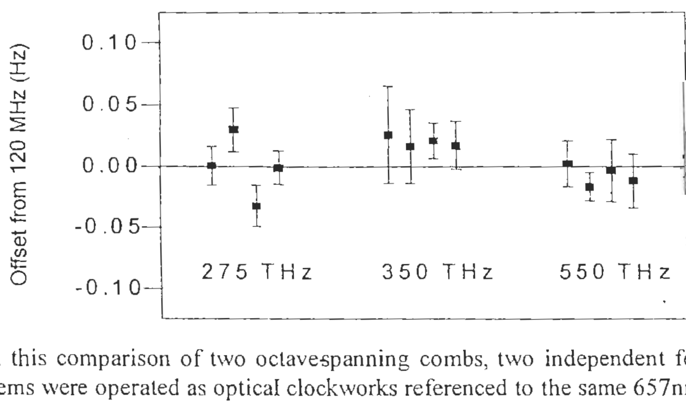

Fig. 2. In this comparison of two octave-spanning combs, two independent femtosecond laser systems were operated as optical clockworks referenced to the same 657nm frequency standard. The repetition rates were set equal but theyhad offset frequencies that differed by 120 MHz. Using different bandpass filters and photodetectors we examined the integrity of the comb in three different wavelength regions as indicated. Within the measurement uncertainty we found no systematic differences between the two combs [5].

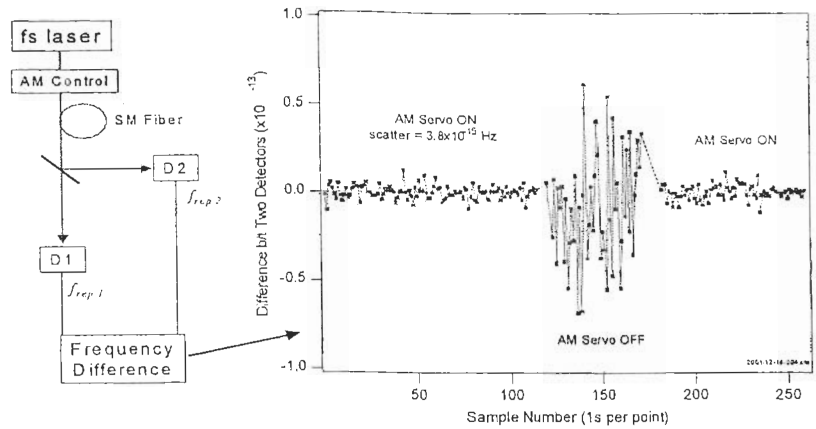

Fig. 3. Two photodetectors measure a stable 1 GHz train of pulses from a stabilized mode-locked laser. The fluctuations on the frequency difference between the two detectors results from phase-noise in the detection process due to time varying differential time delays in the detectors and amplifiers. Removing the fluctuations in pointing, power, and polarization of the input beam using a single mode fiber and a power control servoreduces this noise. With the power control activated the apparent fractional fluctuations in the repetition rate are $\approx 4\times10^{-15}$ in one second, whereas the apparent fluctuations can be $>3\times10^{-14}$ without the AM control, as seen in the central region of the trace.

to electrical pulses, and hence a microwave comb, we find that significant phase-noise is added by the photodetectors and electronics. These effects are illustrated in Fig. 3, which shows the apparent difference in frequency measured by two photodiodes detecting the same femtosecond pulse train at 1GHz.

3. Applications and Discussion

As optical frequency standards and systems develop, we are beginning to access regimes of measurement that were not previously possible. In addition to better clocks, we anticipate improved tests of the symmetries of space-time as understood by relativity, new searches for time variation of fundamental "constants", and even applications to advanced communication and navigation systems. One such application is to use the superior stability of the optical atomic clocks to realize a secure communication link. The idea is simply that one can encode information on the laser frequency (say by a small frequency modulation, or by the absolute optical frequency itself) that would be impossible to detect without a frequency reference with comparable stability and accuracy. For example, adding square-wave FM at 1 Hz with a frequency excursion of 25 Hz on the stable optical clock laser at 10^{15} Hz could not be detected using the world's best quartz oscillators or even a hydrogen maser. This capability is demonstrated in Fig 4.

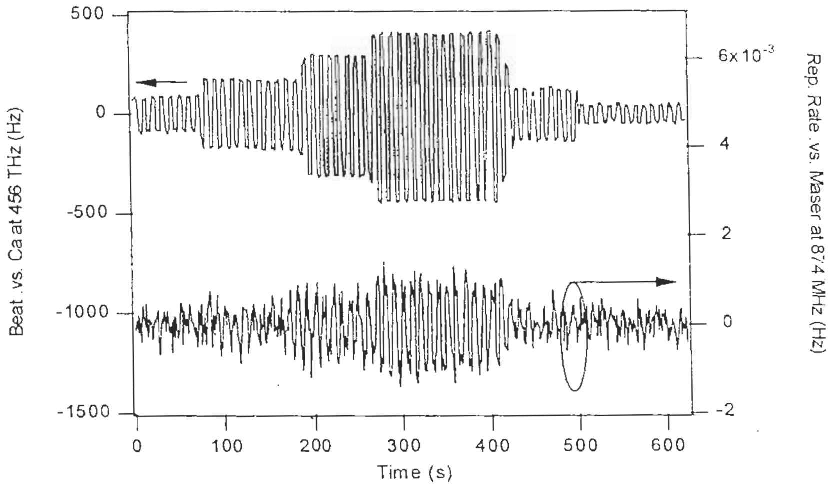

Fig. 4. A small square-wave FM signal with a period of 10 s and varying amplitude was applied to the Hg+ stabilized laser (563 nm, 532 THz) and was easily detected against the Ca stabilized laser (657 nm, 456 THz) once the gap between them is spanned by a self-referenced optical frequency comb locked to the Hg + optical standards. The amplitude of FM detected at 456 THz ranged from +/- 420 to +/- 42 Hz. The lower trace is data taken simultaneously against a hydrogen maser referenced synthesizer at 874 MHz. By locking the fs-comb to the modulated 532 THz laser the repetition rate has the same fractional modulation. Thus, when the modulation is $\lesssim$ 200 Hz at 456 THz the H-maser instability dominates and the FM signal (0.4 mHz at 874 MHz) is not visible against the maser.

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