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Optical Atomic Clocks: A Revolution in Performance

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Abstract: Optical atomic clocks using cold atoms, stable lasers and femtosecond laser frequency combs provide high accuracy and stability from RF to the ultraviolet. They have unprecedented performance: ultrahigh stability, sub-fs timing jitter, low-noise microwaves, and several new uses.

OCIS codes: (120.3940) Metrology; (320.7090) Ultrafast lasers; (300.6320) Spectroscopy, high-resolution

1. Introduction

There is considerable excitement about recent progress on optical atomic clocks that results from advances in laser technology and precision atomic spectroscopy. The concept of an Optical Atomic Clock (OAC) has been around for some time. It is based on the idea that the frequency of a stable laser can be locked to a spectrally-sharp atomic resonance to produce a very stable and absolute optical frequency reference. Significant research efforts during the past 40 years have focused on developing the technologies that are necessary to reach that goal.[1] By 2000 the critical technologies were all in place and beginning to working at the levels required for high performance OAC; these include: stable lasers, precision non-linear laser spectroscopy, laser-cooling and –trapping of atoms, and the (then new) Femtosecond Laser optical Frequency Combs (FLFC). The impressive performance achieved has simulated new research programs to further the development of optical frequency standards, clocks and associated technologies. This presentation will provide some historical background, some recent highlights will illustrate the current state of the field, and some new concepts will be used to speculate about the future.

The major advantage gained by increasing the frequency of the clock oscillator from microwaves to optical frequencies is that the scale of "time" is divided into smaller units. Faster clock "ticks" provide better timing resolution and stability. Thus we would like to use an oscillator with the highest frequency that can be precisely controlled and counted. Laser based oscillators at ~ 500 THz produce clock ticks (phase crossings) that have a period of just 2 fs. Basic physics arguments show that N atoms in the quantum-projection-noise limit can provide a fractional frequency instability of $\sigma_y \approx \dfrac{\Delta\nu}{\nu_0\sqrt{N\tau}}$, where $\Delta\nu$ is the transition linewidth, ν_0 is the oscillation frequency, and τ is the averaging time.[2] The advantage of using narrower lines and higher oscillation frequencies is clear. A simplified diagram of an optical atomic clock is shown in figure 1.

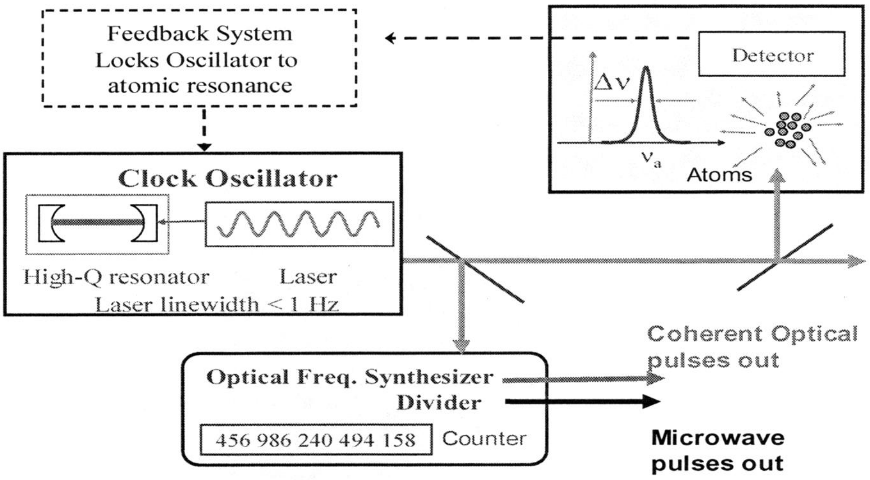

Fig 1. Basic diagram of an optical atomic clock. A cw laser is pre-stabilized on short time scales to a high-Q Fabry-Perot cavity and on longer times scales a feedback control system locks the laser frequency to a narrow atomic resonance. The third component of the optical clock is the optical frequency counter that records the total number of oscillations of the clock oscillator laser and divides the optical frequency down to the microwave range required for interface with electronics.

The fractional frequency uncertainty achieved with optical atomic frequency standards over the past 30 years is shown in figure 2. Clearly, a dramatic change started occurring in 1999 and resulted in improvements in the accuracy of optical frequency standards by three orders of magnitude in just 5 years.

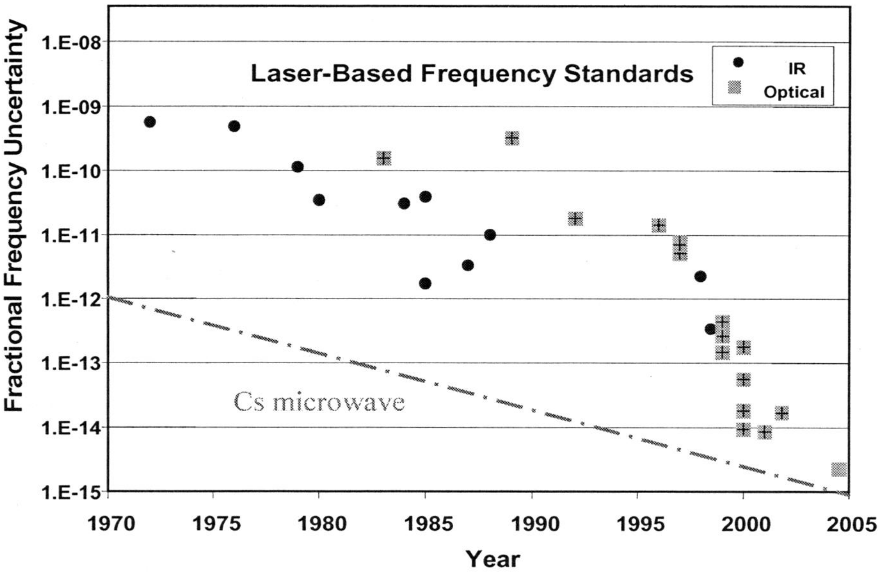

Fig. 2 Fractional frequency uncertainty of optical frequency standards verses time. The relative "accuracy" of optical standards can be compared to the dot-dash line representing the performance of state-of-the-art Cs primary frequency standards at corresponding dates.

2. Precision Atomic spectroscopy with stable lasers

At the present time it is not clear which atoms will give the best performance as optical frequency standards and clocks but several promising candidates are being studied, including: single trapped ions of Ca^+ Sr^+, Yb^+, Hg^+, In^+ and Ba^+ and the neutrals H, Mg, Ca, Sr, Yb, and Ag. To achieve very narrow linewidths and reduce troublesome velocity-dependent frequency shifts all of the advanced frequency standards now use very cold atoms. Laser cooling and trapping has been the enabling technology and well-developed techniques produce clouds of millions of cold neutral atoms at microKelvin temperatures (velocities a few cm/s), or can provide laser-cooled single trapped-ions confined in RF traps to a spatial extent less then the wavelength of the clock radiation (the Lamb-Dicke limit) in which case Doppler shifts are negligible.

Optical frequency standards also require highly stabilized cw lasers to probe the narrow weakly allowed atomic clock transitions. Using high stability Fabry-Perot reference cavities combined with fast and accurate frequency control systems it is possible to achieve laser linewidths < 1 Hz.for time scales of tens of seconds.[3]

Careful attention must be paid to a few small effects that can perturb the atomic energy levels (E and B fields, blackbody radiation, and collisions) and cause frequency shifts. Often more significant are experimental issues such as technical noise and time-dependent phase shifts that cause apparent shifts in the detected atomic transition. Presently the best claimed accuracy of optical atomic frequency standards is a fractional frequency uncertainty of $\sim 3\times10^{-15}$ with several other systems operating at $\sim 1\times10^{-14}$.[4] These results need to be compared to the best accuracy reported for microwave Cs fountain clocks, now as low as 7×10^{-16}.[5] Optics standards are catching up, but today the microwave standards still have the highest accuracy. Conversely, in terms of frequency stability (a measure of the fractional frequency fluctuations on short time scales) optical standards are the clear winners, with demonstrated short-term instabilities of $\sim 3\times10^{-15}$ at one second, and some averaging down to $\sim 1\times10^{-16}$ at a few thousand seconds. This stability is one or two orders of magnitude better than the performance achieved with microwave frequency standards, and allows faster precise measurements of phase, timing and frequency.

3) The optical synthesizer/counter

Optical clocks also require a totalizing counter that can count at optical frequencies (~500 THz), and do so phase-coherently and with high fidelity. The ability to conveniently measure optical frequencies had been a major stumbling block until the optical counter problem was solved using ideas from T. Hänsch and demonstrated by his group in 1999, and extended by many thereafter.[6] As predicted, the frequencies of the discrete modes of a mode-locked femtosecond laser can be described by a simple formula for an optical frequency comb, $f_N = Nf_{rep} + f_{offset}$.

Several experiments have now proven that (at least in the time average for $\tau >$ about 100 ms) this equation is valid to a very high degree.[7] All the modes under the broad spectrum of the optical comb can be controlled with just two radio frequency sources, for example the repetition rate f_{rep} and the offset frequency f_{offset}. However, the more interesting and powerful approach is to lock a single mode of the comb to a stable optical frequency reference and then use the "self-referencing" method to stabilize the offset frequency (see figure 3).

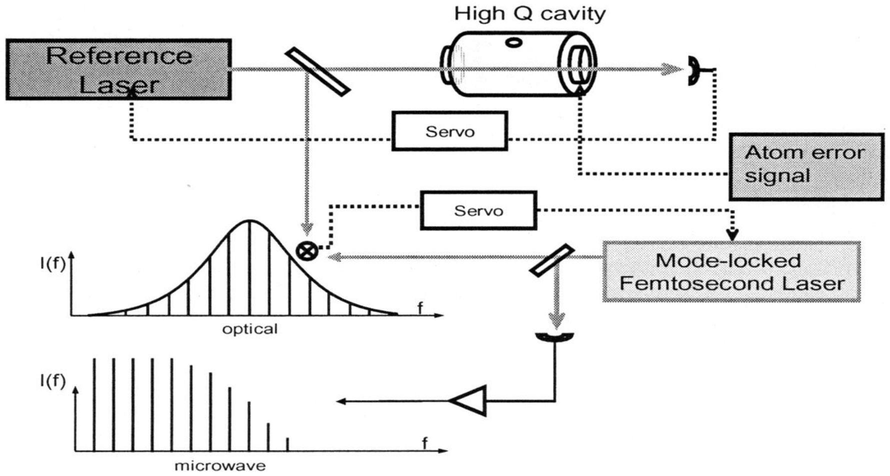

Fig. 3. A simplified diagram of a modern optical clock using a stable atomic resonance, a high-Q reference cavity for short-term stability and a self-referenced optical frequency comb as the frequency divider.

In this configuration the whole system is locked-up as an optical clock, with all frequencies are coherently referenced to the optical atomic transition and then transferred across the optical range by the comb and divided down to provide a microwave frequency output.

4. Summary

Optical atomic clocks are not yet ready to replace microwave based frequency standards for the primary clocks and time keeping purposes. However they improving very rapidly and are still far from their fundamental performance limits. In the meantime they are already making an impact on some scientific and technical fields. High accuracy comparisons of optical atomic frequencies references relative to each other, and to the Cs frequency that defines the SI "second", are now providing some of the most stringent laboratory tests for any possible time variation of the fundamental "constants" (such as combinations of the fine structure constant α, the proton to electron mass ratio m_p/m_e, and gyromagnetic ratios). Femtosecond laser frequency combs stabilized to high quality optical references are also producing microwave frequency combs that have higher stability and lower phase noise than has been achieved with any other sources. Similarly, optically stabilized FLFC provide exquisite timing resolution and ultra-low timing jitter (sub femtosecond). These and other achievements result from the synergistic combination of ultrastable cw lasers, precision atomic physics, and ultrafast laser technologies.

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