It's Time for New Clocks

Optical clocks for a better timekeeping

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A precise measurement of time allows everyone to be in time for the start of a lecture. More precise clocks are required for state of the art measurements to detect possible changes in the fundamental physical "constants" or to test the laws of physics, e.g. Einstein's theories of special and general relativity. And even more: also a lot of everyday systems crucially rely on precise time/frequency standards. Cell phones, telecommunication systems and the global positioning system (GPS) are only a few examples. The second is the base unit of time in the SI system and it is also used to define other SI units. The meter for example, is defined as the distance traveled by light in vacuum during 1/299.792.458 of a second, assuming that the speed of light is constant. Lasers with a fixed and known frequency thus can serve as standards for length metrology, e.g. for lithography of semiconductor wavers. All this makes the operation of high-precision time and frequency standards a very important task at metrology institutes worldwide.

Tab. 1 Examples for ion optical clocks (from [1])

Ion	Clock Transition	Clock wavelength in nm	Cooling laser wavelength in nm
Al^+	$^1S_0 - ^3P_0$	267	Symp. cooling Mg^+ at 280 nm or Ca^+ at 397 nm or Be^+ at 313 nm
Ca^+	$^2S_{1/2} - ^2D_{5/2}$	729	397
Sr^+	$^2S_{1/2} - ^2D_{5/2}$	674	422
In^+	$^1S_0 - ^3P_0$	237	231
Yb^+	$^2S_{1/2} - ^2D_{3/2}$, $^2S_{1/2} - ^2F_{7/2}$	436/467	369
Hg^+	$^2S_{1/2} - ^2D_{5/2}$	282	194

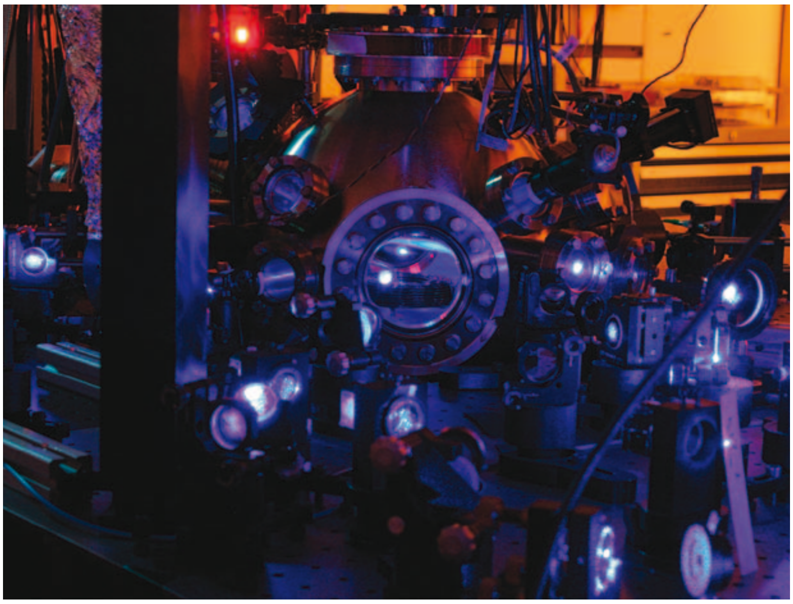

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Fig. 1 Experimental set-up for a clock with Strontium atoms in an optical lattice.

If the period of a certain process is known, stable and constant, it can be used as a time scale to characterize the dynamics of other objects. For example, one second could be defined as a certain fraction of the time the earth needs to revolute around the sun. A more precise value can be obtained from a microwave atomic clock based on cesium. Since 1967, one second is defined as the duration of 9.192.631.770 cycles of the radiation that corresponds to the transition between two hyperfine levels of the ground state of cesium 133. Current cesium-based atomic fountain clocks have uncertainties down to three parts in 10^{16} – which corresponds to roughly 30 ps per day or one second in about 100 million years.

Atoms absorb and emit energy at a frequency ν and within a small spread, the linewidth $\Delta\nu$. The higher the frequency and the narrower the linewidth of the transition, the more precise results can be obtained. For microwave-clocks the frequency is in the GHz-range ($\nu_{Cs} = 9.2$ GHz). The use of optical frequencies with several hundred THz therefore has the potential to increase the clock's stability by 5 orders of magnitude – if transitions with a narrow linewidth and suitable lasers to probe this transition can be found. Only the advent of tunable lasers and the advances in laser-cooling and atom-trapping enabled novel approaches that aim to further improve the time standard with optical atomic clocks.

The challenges one has to solve for a good atomic clock are manifold. The atomic motion and the associated Doppler shift, collisions between atoms that lead to frequency shifts and linewidth broadening as well as the sensitivity of the energy levels involved in the clock transition to magnetic and electric fields are only a few examples. A very early suggestion to solve some of these issues was to use slowed down Cs atoms in a laser-cooled atomic fountain

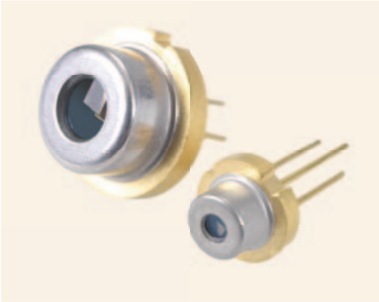

Fig. 2 From laser diode to diode laser (from left to right): laser diodes, ECDL resonator with optical isolator and fiber coupler, external-cavity diode laser „DL pro“

clock. The laser-cooling extends the interaction time between the electromagnetic field in the microwave-range and the atoms. This narrows down the transition linewidth which in turn results in a more precise and more accurate frequency standard.

New approaches to measure time

Novel frequency standards based on molecules, neutral atoms or ions can be created using tunable lasers instead of microwaves. Currently many different types of so-called „optical clocks“ are under research. The various approaches use either a few trapped ions (mostly one single ion) or large numbers of neutral atoms – each approach having its own advantages and drawbacks.

Ion-based clocks use laser-cooled ions (e. g. Al^+, Hg^+, Yb^+, Sr^+, In^+) that are trapped in a rf- or Paul trap. The trap confines the ion near the zero of a time-varying quadrupole electric field. The advantage of this approach is that the atomic resonance frequency is mostly unaffected by the trapping. Another benefit is that the ions are cooled to a motional ground state and thus are strongly confined in the trap, practically removing the linear Doppler effect-induced shifts on the clock transition. Furthermore, trapped ions suffer only minimal collisional perturbation. However, ion-based clocks are limited to a few trapped ions only, which in turn means that it requires a long averaging time to reach a desired precision – but they still exceed the frequency stability of microwave clocks.

Tab. 1 lists several ions that have suitable clock transitions with a narrow linewidth. The ions with alkali-like and quasi-alkali like structure (Al^+, Ca^+, Sr^+, Yb^+ and Hg^+) have ^2D states lying below the lowest ^2P states. These metastable ^2D states decay into the $^2S_{1/2}$ ground state with a transition linewidth of less than a few Hz. The clocks based on ions like Al^+ and In^+ with two valence electrons make use of the strongly forbidden $^1S_0$-$^3P_0$ transition. These transitions have frequencies in the UV-range and often require frequency quadrupled diode lasers to excite this transition.

The stability of a clock measures how quickly statistical uncertainties are reduced. Trapping a larger number of atoms increases the attainable S/N ratio, and thus has the potential to increase the stability of the clock. This idea fuelled the research on neutral optical clocks, where thousands to millions of atoms can be trapped in an optical lattice (**Fig. 1**). In the beginning however, these optical lattice clocks had problems due to systematic errors. The lattice induces differential shifts of the atomic energy levels, so the atoms could not be trapped while probing the clock transition. This is in contrast to a single-ion trap, where the ions suffer only minimal electromagnetic perturbation. The solution was proposed by Katori and first realized on ^{87}Sr [2]. The idea that Katori had was that at a specifically chosen wavelength the light – while still shifting the electronic states of atoms trapped in the optical lattice – induces the same shift on both states of the clock transition. Hence the net effect of the trapping light on the clock transition frequency is minimized. The corresponding wavelength is therefore called the “magic wavelength”. These far-detuned lattice wavelengths are distant from atomic resonances – therefore lasers with high powers are required at these special wavelengths.

Atom species that are currently investigated for optical clocks based on neutral atoms are e.g. Sr, Yb, Hg, Mg, Ca [3]. As clock transitions in fermionic alkaline-earth elements (Be, Mg, Ca, Sr) the hyperfine-induced $^1S_0$-$^3P_0$ or similar transitions in odd isotopes with linewidths down to the order of 1 mHz are employed. Other approaches use bosonic isotopes with the highly forbidden $^1S_0$-$^3P_0$ transition (e.g. ^{174}Yb, ^{88}Sr).

For loading an optical lattice trap, the temperature of the atoms needs to be reduced to several ten microkelvin. Therefore, the atoms have to be cooled and trapped in a magneto-optical trap first. In some cases a two-step cooling procedure is employed: first laser-cooling of the broad $^1S_0$-$^1P_1$ transition results in temperatures in the millikelvin range. A subsequent second cooling step on a narrower transition ($^1S_0$-$^3P_1$) cools the atoms to the required temperatures.

Tab. 2 Examples for optical lattice clocks

Atom	Magic wavelength in nm	Clock wavelength in nm	First stage cooling in nm	Second stage cooling in nm
^{25}Mg	432	457	285	
^{43}Ca	680	659	423	657
^{87}Sr	813	698	461	689
^{174}Yb	759	578	399	556
^{199}Hg	360	266	254	-
^{201}Hg	360	266	254	

from [1]

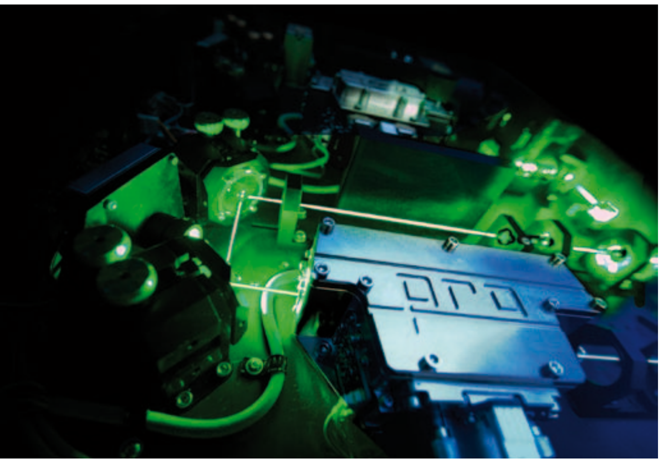

Fig. 3 A look in a FHG unit with two subsequent SHG stages (left) and a frequency doubled diode laser providing 589 nm and a diode laser at 689 nm for second stage cooling of Strontium (right).

Tunable diode lasers for clocks

All these novel optical clock techniques require high-precision lasers that can be tuned precisely to the energy difference of the atomic transition. A broad wavelength regime can be covered directly with diode lasers (**Fig. 2**). Second- or fourth harmonic generation of these diode lasers create many more wavelengths, and allow to cover also the visible and UV-range. For the clock transition of Yb for example, a laser operating at 578 nm is required. This wavelength can be generated by frequency conversion (SHG) of a diode laser at 1156 nm. The clock transition of Hg^+ requires a laser at 282 nm, which can be obtained by two subsequent frequency-doubling steps (FHG). **Fig. 3** shows an example of such a FHG system. The required laser output powers for the preparation are between several milli-Watt and Watt. The output power of an unamplified grating-stabilized diode laser is typically up to 100 mW, depending on the wavelength. Using tapered amplifiers increases these output powers to up to 3 Watt (e.g. at 970 nm).

Another crucial property is the linewidth of the laser: it has to be narrower than the linewidth of the atomic transition in order not to limit the overall performance. Without any additional measures, the linewidth of a diode laser is typically several hundred gigahertz. If the diode is operated together with a frequency-selective device (such as a grating) in an external resonator (external cavity diode laser, ECDL), the linewidth is reduced to less than 100 kHz. This increases the coherence length of the laser by more than 6 orders of magnitude and results in a coherence length of several kilometers. Furthermore, the frequency-selective device allows tuning the wavelength of the laser over a certain range. This way, the frequency of the laser can be matched precisely to the atomic transition.

Optical transitions with linewidths on the order of Hz are ideal candidates for atomic clocks. In order to further reduce the linewidth of an ECDL, it is locked to external references which give an error-signal to the lasers' control electronics (e.g. FALC, DigiLock). Suitable references are for example wavemeters, atomic transitions, resonators or frequency combs. This way, even sub 1 Hz linewidths can be achieved with stabilized diode lasers [4–6].

Atomic clock experiments are very complex setups with several lasers, control electronics and many more instruments as well as plenty of optical and mechanical components. Therefore, even the most complex laser systems should be reliable and very easy to operate. TOPTICAs "pro" technology ensures highest stability and simple operation along with top performance for these fundamental instruments.

No matter which sort of atom or clock design will make it as future time and frequency standard – for sure, lasers at different wavelengths fulfilling the special demands of optical clocks will be required. TOPTICA's tunable diode lasers with broadest wavelength coverage open up a wealth of possibilities. Latest developments in tapered amplifier systems offer for example improved solutions at 689 nm for Sr cooling, 578 nm for the Yb clock transition or 813 nm for Sr optical lattices.

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