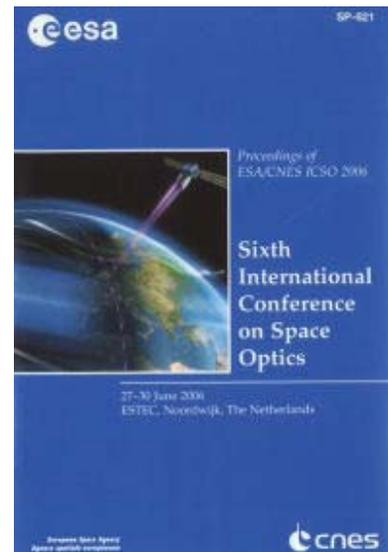


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Neutral atom optical frequency standards at PTB

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NEUTRAL ATOM OPTICAL FREQUENCY STANDARDS AT PTB

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ABSTRACT

Due to their orders-of-magnitude higher frequencies, optical frequency standards are beginning to outperform the best microwave standards with respect to their stability and accuracy and, hence, offer very promising prospects for novel space-based applications. We report on recent results for optical standards in PTB based on neutral atoms and discuss the suitability of the different approaches for space applications.

Key words: Optical clocks; optical frequency standards; narrow linewidth laser; super stable optical resonators.

1. INTRODUCTION

Optical frequency standards basically comprise of a narrow linewidth laser with its frequency being stabilised to a suitable optical transition in atoms, ions or molecules (Ref. 1, 2, 3). Since the invention of the femtosecond frequency comb (Ref. 4) optical frequencies can be related to the microwave domain much more easily than previously (Ref. 5) and can be used to set up optical clocks. Given the same linewidth $\Delta\nu$, the five orders of magnitude higher frequencies ν of optical clocks as compared to microwave clocks allow for five orders of magnitude higher Q factors $Q = \Delta\nu/\nu$. Hence, in the most advanced optical clocks (Ref. 6, 7, 8) the achieved stability and accuracy compete favourably with the best caesium fountain clocks (Ref. 9). Consequently the committees of the metre convention now investigate some of the most advanced optical frequency standards (Ref. 10) as secondary representations of the second that eventually may form the basis for a new definition of the second. Currently two different routes are followed to develop the best future optical clocks. The first route relies on optical transitions in a single ion trapped in the field-free region of a radio-frequency electromagnetic trap whereas the second route is based on optical transitions in an ensemble of large numbers of

neutral atoms. Even though ion trap standards currently achieve the lowest uncertainties, due to the large number of atoms that can be interrogated in parallel, neutral atom optical frequency standards and clocks allow for unprecedented high short-term stability as compared to single ion standards. In this contribution we therefore restrict ourselves to the latter ones. Neutral atom optical frequency standards can be grouped into two classes: The first one uses a laser-cooled atomic cloud trapped in a magneto-optical trap which is switched off for the interrogation. The freely moving atoms follow ballistical trajectories under the action of gravity and hence allow only for a limited interrogation time. Since these limitations are reduced in microgravitation we will discuss the Ca standard of PTB in section 2. To achieve longer interaction times, Katori (Ref. 11) has devised a scheme where atoms are trapped in an optical lattice whose "magic wavelength" is chosen such that the ac Stark shifts are the same for both levels connected by the clock transition and, thus, the clock transition frequency does not suffer from a light shift. An optical frequency standard based on Sr atoms trapped in an optical lattice operated at the magic wavelength is currently being set up at PTB (see section 3). In section 4 we present new developments that might extend the capabilities of optical clock to space-based applications.

2. OPTICAL STANDARD BASED ON ULTRACOLD BALLISTICAL CA ATOMS

Each optical clock requires a narrow transition. Examples include the $^1S_0 - ^3P_1$ transition e.g. in calcium which is highly forbidden for electrical dipole radiation due to the intercombination rule, quadrupole or octupole transitions, or even $^1S_0 - ^3P_0$ transitions that are allowed only due to the hyperfine interaction (Sr, (Ref. 11)) or magnetic admixture (Yb, (Ref. 12)).

In the optical frequency standard of PTB (Ref. 13, 14, 15) about 10^7 Ca atoms are cooled in a magneto-optical trap (MOT) to about 3 mK in a first cooling

stage on the strong $^1S_0 - ^1P_1$ transition (see Fig. 1). A second cooling stage is implemented by using the

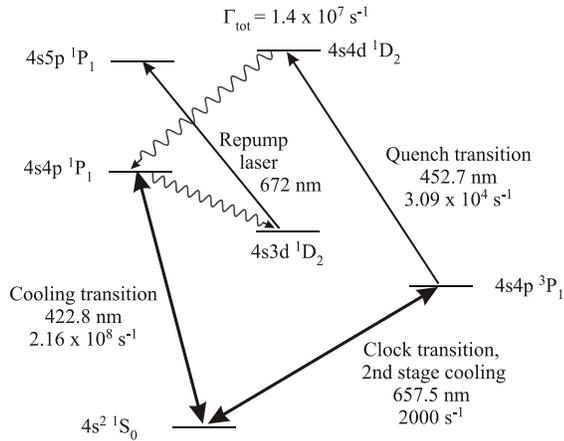


Figure 1. Energy level diagram of ^{40}Ca with the laser transitions relevant for the optical frequency standard.

clock transition at 456 THz, broadened by a quench laser that deexcites atoms from the 3P_1 level to the ground level via the 1D_2 level (Ref. 16). This results in an ultra-cold ensemble of 10^7 atoms at a temperature of $12 \mu\text{K}$, corresponding to an rms-velocity of 10 cm/s. After the cooling sequence all fields are turned off and the intercombination line $^1S_0 - ^3P_1$ at 657 nm is probed with a 4-pulse Ramsey-Bordé excitation (Ref. 17), where two counterpropagating pairs of pulses are used to excite the atoms. After the excitation an electron-shelving detection scheme is used to detect the atoms in the ground state and as well in the excited state with high efficiency. Thus atom number fluctuations were largely suppressed in the determination of the excitation probability and a fractional frequency instability (fractional Allan standard deviation) of $\sigma_y = 2 \times 10^{-14}$ in one second has been obtained which currently is limited by the Dick effect due to the pulsed interrogation (Ref. 18, 15). With the cycle time reduced to 15 ms (but using a smaller number of atoms) in the Ca standard at NIST a fractional frequency instability corresponding to $\sigma_y(10 \text{ s}) = 3 \times 10^{-15}$ has been observed (Ref. 14).

The frequency of the calcium standard has been measured over about a decade first with a phase-coherent multiplication chain (Ref. 5) later with a femtosecond comb (Ref. 19) (see Fig. 2). The transition frequency as determined in PTB's latest and most accurate measurement was $\nu_{\text{Ca}} = (455\,986\,240\,494\,144 \pm 5.3) \text{ Hz}$. This value is slightly higher but within the combined uncertainties compared to the value derived recently at NIST, Boulder (Ref. 20). The uncertainty of PTB's measurement has been investigated extensively (Ref. 15) and was mainly limited by the uncertainty of the contribution of the ac Stark shift that arises when calcium atoms interact with

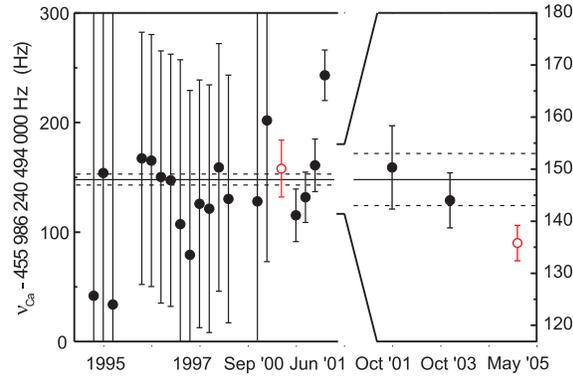


Figure 2. Summary of all frequency measurements performed at PTB. Until September 2000 a frequency chain was used. From June 2001 on a frequency comb generator was used. Open symbols represent the measurements of the Ca standard at NIST, Boulder (Ref. 20). The line depicts the weighted mean of all values with its uncertainty (dashed lines).

the thermal radiation of the oven ($T \approx 873 \text{ K}$) used to produce the thermal beam of Ca atom that are later decelerated and trapped in a magneto-optical trap. The next largest contribution to the uncertainty resulted from the variations of the temporal laser phase of the pulses which interrogate the atoms. Other contributions include spatial phase inhomogeneities in the interrogation beams, the line form asymmetry of the absorption line, quadratic Zeeman and Stark effects, the influence of collisions and the drift of the reference resonator. In particular, the first contribution has now been eliminated by using an additional deflection stage of the cold calcium atoms by laser radiation pressure so that the interrogated atoms are no longer exposed to the thermal radiation of the oven. With this and other modifications a fractional uncertainty of 2×10^{-15} can be expected (Ref. 15) which is close to the uncertainty of the best caesium fountains. It can be expected that the fractional uncertainty could be reduced in a microgravitational environment like on a satellite since there in particular the phase inhomogeneities (that essentially correspond to a residual first-order Doppler effect) would contribute less due to the reduced velocities of the atoms.

3. OPTICAL STANDARDS BASED ON ATOMS CONFINED IN AN OPTICAL LATTICE

Lower uncertainties are expected also on ground if the atoms are confined to the Lamb-Dicke regime where the motion of the atoms interacting with an interrogating radiation field is restricted to dimensions small compared to the wavelength λ of this radiation

which completely eliminates the first-order Doppler effect. This situation can be achieved if the atoms are trapped in an optical lattice created by a suitable light-shift potential (see Fig. 3). At the "magic

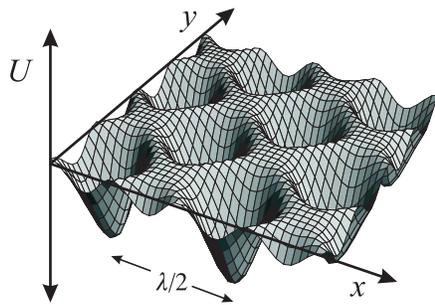


Figure 3. Potential of a two-dimensional optical lattice.

wavelength" the light shift is the same for the two states connected by the clock transition. This can be seen, e.g., from Fig. 4 where the frequency shift due to the ac Stark shift has been measured using the calcium optical frequency standard (Ref. 21) described in section 2. The lowest curve shows a zero

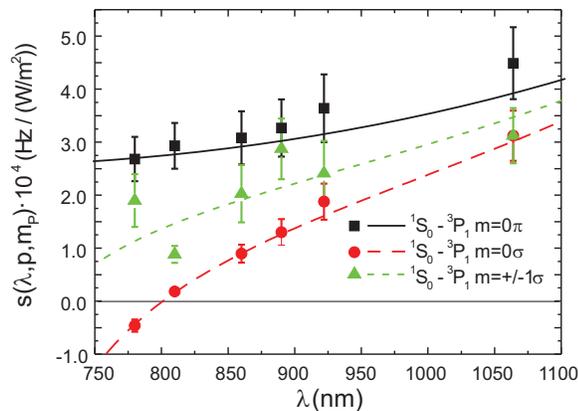


Figure 4. Measured frequency shifts (symbols) and best fits (lines) (Ref. 22).

crossing of the light shift at the "magic wavelength" near 800 nm. In principle, Ca could be used to set up an optical lattice clock on the $^1S_0 - ^3P_0$ transition if the ^{43}Ca isotope would be used where this transition with about 0.35 mHz linewidth occurs as a consequence of the hyperfine interaction (Ref. 23). However, since the isotope ^{43}Ca has a natural abundance of 0.135% it is more appropriate to use Sr or Yb atoms which have similar linewidths but are technically easier to cool and have the relevant isotopes in higher abundance.

In PTB we are presently setting up a standard based on Sr atoms that are cooled in two stages to about 4 μK (see Fig. 5). These atoms will be transferred into a lattice at the magic wavelength and interrogated on the narrow transition with a natural

linewidth close to 1 mHz.

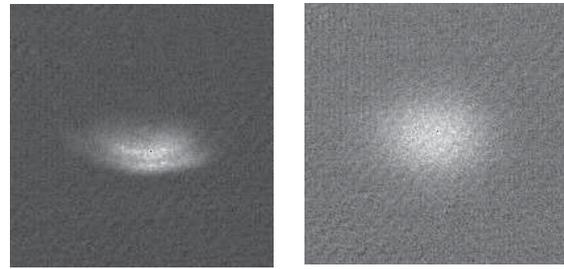


Figure 5. Absorption picture of about 10^6 ultracold strontium atoms in a MOT (left) and after 9 ms expansion (right). The size corresponds to 1.5 mm \times 1.5 mm.

4. NOVEL TECHNOLOGIES

To utilise the full potential of this lattice clock it would be beneficial if the local (laser) oscillator for interrogation would have a similar linewidth. To reduce the laser linewidth accordingly novel approaches and technologies have to be applied, some of which will be discussed in the following.

4.1. Tuneable narrow linewidth diode laser

The highly coherent radiation required to interrogate the atoms is generated from diode laser systems whose frequencies are stabilized to a non-tunable reference Fabry-Perot resonator by means of the Pound-Drever-Hall technique (Ref. 24). This technique applied to diode laser systems based on anti-reflection coated commercial laser diodes in an extended cavity design leads to cost- and energy-effective highly coherent sources of tuneable radiation with linewidths as low as 1 Hz as was inferred from the comparison of two independent systems (Ref. 25). Due to their compact design and low energy consumption such lasers have the potential to be used in space applications if certain provisions for improved ruggedness will be made.

4.2. Vibration insensitive optical reference cavity

Analysis of the contributions to the linewidth showed that they mainly arise from low-frequency sidebands induced by length variations of the optical reference resonator as a consequence of acoustic and seismic perturbations. To increase the immunity to external perturbations we have developed a novel type of reference cavity (Ref. 26) where the cavity axis is oriented horizontally and the cavity is supported in the

horizontal symmetry plane on four support points. The positions of the points were optimized by finite element analysis. Measurements of the sensitivity to external perturbations show a considerably reduced sensitivity to external forces (see Fig. 6). A sen-

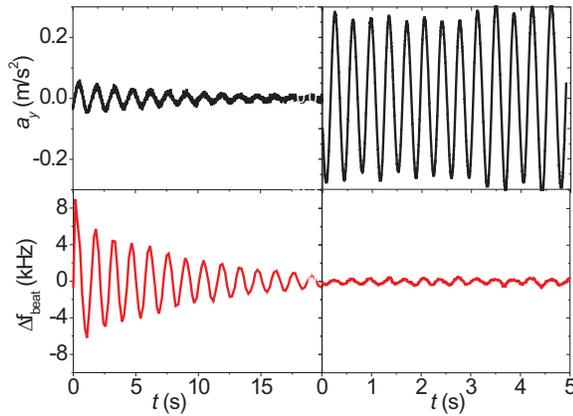


Figure 6. Comparison of the sensitivity of the laser frequency Δf_{beat} to vertical accelerations a_y for the asymmetrical (left) and the symmetrical (right) mounting configuration.

sitivity to accelerations of $1.5 \text{ kHz}/(\text{m s}^{-2})$ in the vertical and $14 \text{ kHz}/(\text{m s}^{-2})$ in the horizontal direction was measured which is a reduction in the vertical sensitivity by two orders of magnitude compared to the usual support from below. With the reduced sensitivity and a passive vibration isolation system, vibrations present in our laboratory would only contribute 30 mHz to the linewidth of the laser. In contrast to earlier solutions to this problem (Ref. 27) this mounting with horizontal optical axis is more easily applicable to longer cavities than the configuration with vertical optical axis where the relative change of distance scales linear with the length. This can be an advantage in terms of reducing of the thermal noise (Ref. 28) because the influence of the thermal noise of the cavity spacer on the spectral power density of frequency fluctuations $S_\nu(f)$ scales with the cavity length L as $S_\nu(f) \propto 1/L$ while keeping the cross-section the same. The contribution from the mirror substrates and coatings even scale as $S_\nu(f) \propto 1/L^2$. Thus with this novel mount a laser linewidth in the millihertz region seems reachable.

4.3. Fibre laser combs

Soon after the invention of the Kerr-lens mode-locked Ti:Sa femtosecond comb it has been shown that this device is capable of measuring optical frequency ratios with fractional uncertainties below 10^{-18} (Ref. 29). On the other hand, femtosecond combs based on fibre lasers seem to offer better long-term stability in conjunction with cost- and energy-

effective devices also suitable for space applications (Ref. 30, 31). In PTB therefore experiments are underway to investigate to which end fibre laser frequency combs can fulfil the promises. As an example consider Fig. 7 where two independent fibre combs were used to measure the frequency of the Yb^+ optical frequency standard of PTB with respect to the frequency of the Cs atomic fountain clock.

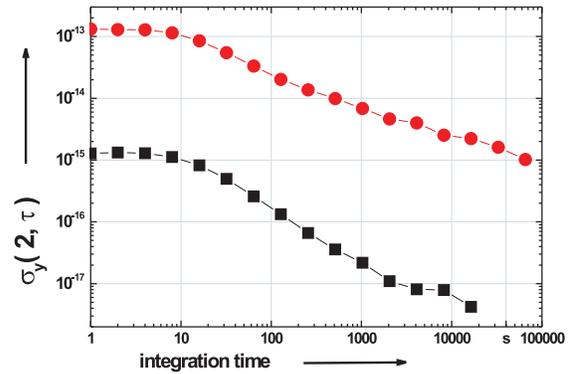


Figure 7. Measured Allan standard deviation of a frequency measurement of the Yb^+ optical frequency standard of PTB and the Cs atomic fountain clock (dots) which is essentially limited by the instability of the Cs clock. The squares represent the instability of the measurement without the contributions of the two standards (see text) (Ref. 32).

The Allan standard deviation of this measurement is limited by the short-term stability of the Cs fountain clock. In a second experiment two independent combs were used to compare simultaneously the frequency ν_{Yb^+} of the Yb^+ standard to the frequency ν_{ir} of an infrared laser. The Allan standard deviation of the ratio $(\nu_{\text{Yb}^+}/\nu_{\text{ir}})_I/(\nu_{\text{Yb}^+}/\nu_{\text{ir}})_{II}$ showed a much smaller instability down to the 10^{-18} range. The measurements also showed that fibre-based femtosecond combs can be operated over long times without any operator handling. This indicates that they fulfil all the requirements needed to serve as clockworks for future optical clocks.

5. CONCLUSIONS

Neutral atom optical frequency standards have the advantage of delivering a very high short-term stability which can be below 10^{-15} at one second measuring time even for discontinuously interrogated standards as the described Ca standard. In microgravitational environment even the fundamental quantum projection noise limit could be reached which, for the achieved parameters, would be an order of magnitude lower. If the atoms are stored in an optical lattice at the magic wavelength this limit could be achieved

also in the presence of Earth's gravity.

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