CALCIUM OPTICAL FREQUENCY STANDARD RESEARCH AT PTB

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ABSTRACT

At PTB we have developed an optical frequency standard based on laser cooled calcium atoms. A laser is frequency-stabilized to the intercombination transition at a wavelength of 657 nm by means of time-domain atom interferences. The dependence of its frequency on various parameters was investigated by using different excitation schemes corresponding to phase sensitive and frequency sensitive atom interferometers. At present the total relative uncertainty of the measured frequency amounts to $2 \cdot 10^{-14}$. As a result the Ca stabilized laser is among the optical frequency standards of lowest uncertainties. Further improvements using ultracold atoms are demonstrated.

INTRODUCTION

The recent progress in the field of laser manipulation of atomic absorbers and optical femtosecond laser frequency measurements [1-3] allows the realization of optical clocks that compare favorably to current microwave standards [4]. Optical clocks employing single trapped ions or neutral atomic clouds have different properties and are complementary in many aspects. The optical frequency standard based on the intercombination transition at $\lambda \approx 657$ nm (Fig. 1) of laser cooled ^{40}Ca atoms belongs to the most accurate standards of the latter group [5,6]. A sample of laser cooled neutral Ca atoms can give high signal-to-noise ratio leading to a small frequency instability of the standard combined with very high accuracy. On the other hand, it has been shown that the movement of the ballistic atoms and the associated frequency shifts currently limit the achievable accuracy of the optical Ca frequency standard. The limitation results from the residual velocities of the atoms and the gravitational acceleration leading to phase shifts during the interrogation by non-planar wave fields. We have therefore addressed this problem first by developing means and techniques to identify and to eliminate spurious phase shifts [7]. Still the biggest contribution to the uncertainty budget is due to the residual Doppler effect because of the thermal motion of approximately 1 m/s (T = 1 mK) that is achieved by Doppler cooling on the resonance line of calcium. A novel method based on broad-band cooling on the narrow intercombination transition [8] enabled us to reduce the velocity of the Ca atoms in three dimensions equivalent to a temperature below 7 µK (v = 5 cm/s).

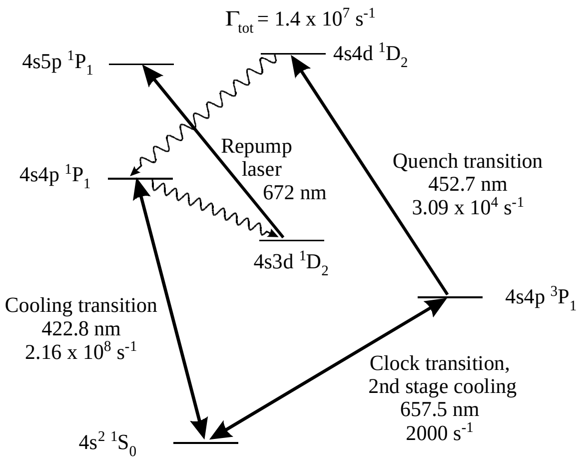

Fig 1. Energy diagram of ^{40}Ca with wavelengths and Einstein coefficients relevant to the clock and the cooling scheme

EXPERIMENTAL SETUP

Ca atoms effusing from an oven ($T \approx 900$ K) are directly injected into a Magneto-Optical Trap (MOT) where the slowest atoms of the thermal velocity distribution are trapped (Fig. 2 a). The radiation at $\lambda \approx 423$ nm for cooling and trapping (Fig. 1) is generated by frequency doubling the radiation of a diode laser. Additionally, we use a diode laser for repumping at 672 nm to close the leak to the 4s3d $^1D_2$ level, which would limit the lifetime of the trap. Up to 10^7 atoms are trapped at a temperature $T \approx 3$ mK at a trap lifetime of typically 300 ms.

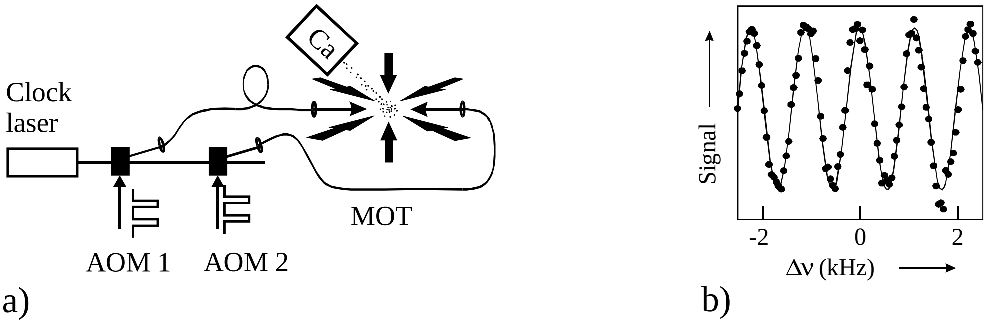

Fig. 2. a): Experimental setup. Ca atoms are trapped in a Magneto-Optical Trap (MOT). Their clock transition is interrogated by pulses cut from a cw clock laser beam by two Acousto-Optical Modulators (AOM).
b): High-resolution optical Ramsey resonances observed by pulsed excitation

To avoid light shifts and Zeeman shifts of the atomic reference frequency, the trapping fields (laser fields and magnetic quadrupole field) are switched off before the clock transition is probed. Consequently, trapping of Ca atoms, probing of the clock transition, and its detection are performed in sequence: First, the trapping fields are switched on for approximately 15 ms and the Ca atoms are trapped. After the trapping fields are switched off and allowed to decay, the clock transition is probed. The number of excited atoms versus frequency is detected either by their fluorescence (Fig. 2 b) using a photomultiplier when they decay from the excited $^3P_1$ state into the ground state.

UNCERTAINTY OF THE STANDARD

To explore and to reduce the relative uncertainty of this optical frequency standard to a few parts in 10^{14} the dependence of its frequency on various parameters was investigated. It has been shown earlier [5] that the largest contributions to the uncertainty budget result from residual first-order Doppler shifts. They result e.g. from non-ideal wavefronts or from tilts with respect to the equipotential surface of the gravitational potential. To measure the associated spurious phase shifts and to reduce their influence a method is now routinely applied that makes use of a combination of excitation sequences [7] of the laser beam. These sequences consist of either three laser pulses from one direction (deflected by AOM 1; Fig. 2 a), or three pulses from the laser beam of the opposite direction (AOM 2), or from a four-pulse sequence (AOM 1 and AOM 2). In the latter case two pulses from one side and two pulses from the second side are successively applied. It has been shown that such excitation schemes lead to time-domain atom interferometers [7,9] where an interference signal shows up in the number of excited atoms. It varies with the phase of one of the laser pulses in the three pulse scheme or with the frequency of the laser pulses in the four-pulse scheme (Fig. 2 b). The latter scheme is often referred to as the optical Ramsey method or Bordé interferometry. It allows one to stabilize the laser frequency to a particular maximum or minimum of the interference structure.

We conclude that the consequent application of this method now allows to reduce the influence of the residual first-order Doppler effect to below 10^{-14}. The next largest contributions to the uncertainty that have been identified earlier [5] are the influence of cold collisions (1.8 Hz) and the black-body shift (4.3 Hz). In total, the relative uncertainty of the Ca optical frequency standard that is operated at PTB is estimated [10] to be $2 \cdot 10^{-14}$.

The first phase-coherent frequency measurements of the Ca optical frequency standard have been performed as early as 1995 [11]. Over the years, several measurements of the frequency of the standard have been performed (Fig. 3). The weighted mean of all frequency measurements performed at PTB is (455 986 240 494 151 ± 9) Hz which is in excellent agreement with measurements obtained at NIST [6].

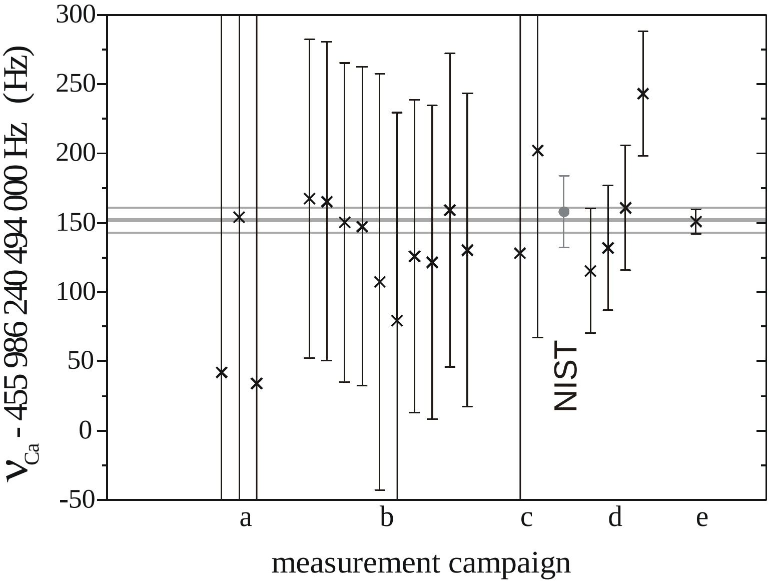

Fig. 3. Frequencies of PTB's Ca optical frequency. The campaigns a) 1995 and b) 1996/97 were performed with the conventional chain and the campaigns c) 2000, d) June 2001 and e) October 2001 were performed using a femtosecond frequency comb [12]. The point labeled NIST denotes the measurement of fall 2000 [6]. The line represents the weighted mean of all measurements at PTB.

IMPROVEMENTS USING ULTRACOLD ATOMS

The influence of residual first-order Doppler shift in today's Ca frequency standards results from the high temperature in the millikelvin range which is limited to the Doppler-limit due to the lack of a ground-state splitting. A further decrease of the temperature by means of second-stage cooling on the intercombination transition met with difficulties since the scattering rate on this transition is that low that the resulting force is of the order of the gravitational force. To overcome this problem we have increased the scattering rate by pumping the atoms with the help of a 'quenching' laser ($\lambda \approx 453$ nm) [8] back into the ground state via intermediate levels (see Fig. 1). The velocity distribution of the atomic ensemble with and without the second-stage cooling was obtained by measuring the Doppler broadening of the intercombination transition (Fig. 4). Comparing the areas of the two curves in Fig. 4 we calculate a transfer efficiency of $\eta \approx 12\%$.

These ultracold atoms were utilized to obtain atom interferences with near optimum visibility and significantly reduced residual first-order Doppler effect. The ultracold atoms also allow to apply a novel detection method with a potential to observe quantum projection–noise limited signals, leading to relative instabilities of below 10^{-16} in one second.

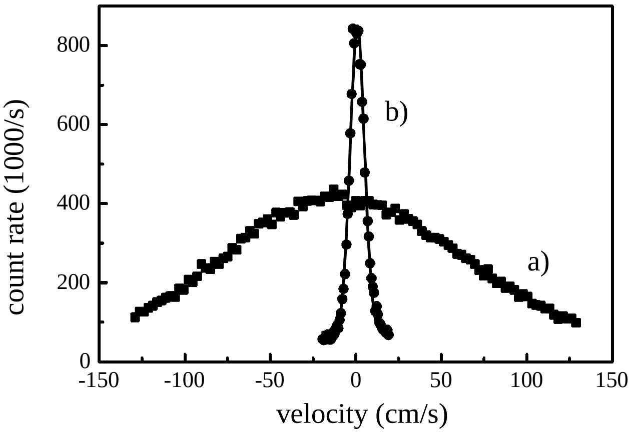

Fig. 4.Velocity distribution before (a) and after 25 ms of narrow-line cooling (b).

CONCLUSIONS

The present uncertainty of the Ca stabilized optical frequency standard has been reviewed and it has been shown that the largest influence resulting from curved wave fronts of the interrogating lasers and the residual velocity of the atoms can be reduced to below 10^{-14}. The frequency of the standard has been measured over several years with both, a conventional frequency measurement chain and a femtosecond laser. As a result, the Ca stabilized laser is among the optical frequency standards of lowest uncertainties. The application of a novel cooling technique leading to temperatures in the microkelvin regime will allow to reduce the contribution of the residual first-order Doppler shift into the 10^{-15} regime.

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REFERENCES

[1] J. Reichert, R. Holzwarth, Th. Udem, and T. W. Hänsch, "Measuring the frequency of light with mode-locked lasers, " *Opt. Comm.* vol. 172, pp. 59-68, 1999.

[2] S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, and J. L. Hall, "Direct Link between Microwave and Optical Frequencies with a 300 THz Femtosecond Laser Comb," *Phys. Rev. Lett.* vol. 84, pp 5102-5105, 2000.

[3] J. Stenger, C. Tamm, N. Haverkamp, S. Weyers, and H. R. Telle, "Absolute frequency measurement of the 435.5 nm $^{171}Yb^+$ clock transition with a Kerr-lens mode-locked femtosecond laser," *Opt. Lett.* vol. 26, pp 1589 - 1591, 2001.

[4] S. A. Diddams, Th. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, and D. J. Wineland, "An Optical Clock Based on a Single Trapped $^{199}Hg^+$ Ion," *Science*, vol. 293, pp. 825-828, 2001.

[5] F. Riehle, H. Schnatz, B. Lipphardt, G. Zinner, T. Trebst, T. Binnewies, G. Wilpers, and J. Helmcke, "The Optical Ca Frequency Standard," *Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium*, pp. 700-705, 1999.

[6] 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 Measurement of the Hg+ and Ca Optical Clock Transitions with a Femtosecond Laser," *Phys. Rev. Lett.* vol. 86, pp. 4996 - 4999, 2001.

[7] T. Trebst, T. Binnewies, J. Helmcke, F. Riehle, "Suppression of spurious phase shifts in precision atom-light interferometry", *IEEE Trans. Instrum. Meas.*, vol. IM 50, pp 535-538, 2001.

[8] T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helmcke, T. E. Mehlstäubler, E. M. Rasel, and W. Ertmer, "Doppler cooling and trapping on forbidden transitions, " *Phys. Rev. Lett.* vol. 87, pp. 123002, 2001.

[9] Ch. J. Bordé, "Atomic Interferometry and Laser Spectroscopy", *Laser Spectroscopy*, ed. M. Ducloy, E. Giacobino, and G. Camy, pp. 239-245, World Scientific, Singapore, 1992.

[10] G. Wilpers, thesis, in preparation, 2002.

[11] H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle and G. Zinner, "First Phase-Coherent Frequency Measurement of Visible Radiation," *Phys. Rev. Lett.* vol. 76, pp. 18-21, 1996.

[12] 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 laser", *Phys. Rev.* vol. A 63, pp, 021802(R), 2001.