# A 7: Präzisionsmessungen und Metrologie 3

Time: Monday 16:30–19:00 Location: V7.03

A 7.1 Mon 16:30 V7.03

**Precision spectroscopy of the $2S_{1/2} - 4P_{1/2}$ transition in atomic hydrogen** — •Axel Beyer[1], Arthur Matveev[1], Christian G. Pathey[1], Janis Alnis[1], Randolf Pohl[1], Nikolai Kolachevsky[1], Thomas Udem[1], and Theodor W. Hänsch[1,2] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching — [2]Ludwig-Maximilians-Universität, 80799 München

The comparison between measured and calculated transition frequencies in atomic hydrogen can provide stringent tests of bound state QED. For the last decade, this comparison has been limited by the proton charge radius determined by electron-proton scattering. Recently, laser spectroscopy of muonic hydrogen provided a value, which is ten times more accurate than any previous measurement (Pohl *et al.*, Nature **466**(7303), 2010). But this value differs from the CODATA 2010 value, obtained by a global adjustment of fundamental constants using data from electron-proton scattering and hydrogen experiments for the proton charge radius, by seven standard deviations. The muonic hydrogen result led to a comprehensive search for the cause of this discrepancy, but no convincing argument could be found so far. Because the current CODATA value is mainly based on observations in atomic hydrogen, transition frequency measurements with improved accuracy can help to solve this puzzle or at least to rule out hydrogen experiments as a possible source for the discrepancy. Here we report on the setup which has been developed for the measurement of the one-photon $2S_{1/2}$-$4P_{1/2}$ transition frequency in atomic hydrogen along with the results and conclusions of our first measurement runs.

A 7.2 Mon 16:45 V7.03

**A sub-40 mHz linewidth laser based on a single-crystal silicon optical cavity** — •Christian Hagemann[1], Thomas Kessler[1], Thomas Legero[1], Uwe Sterr[1], Fritz Riehle[1], Michael J. Martin[2], Lisheng Chen[2], and Jun Ye[2] — [1]Physikalisch-Technische Bundesanstalt (PTB) and Centre for Quantum Engineering and Space-Time Research (QUEST), Bundesallee 100, 38116 Braunschweig, Germany — [2]JILA, NIST and University of Colorado, 440 UCB, Boulder, CO 80309-0440, USA

State-of-the-art ultra-stable lasers achieve fractional frequency stabilities of a few times $10^{-16}$, limited by the thermal noise of the high-finesse optical cavities used as reference.

We present a novel optical cavity machined from single-crystal silicon with the potential to push this limitation by one order of magnitude. Various key advantages of silicon as resonator material compared to conventionally used ultra-low expansion (ULE) glass will be discussed. To minimize the impact of thermal instabilities we operate the cavity at its minimum of thermal expansion at a temperature of 124 K in a low-vibration cryostat with nitrogen gas as coolant. In a three-cornered hat frequency comparison with two ULE glass reference cavities we show that the laser frequency-stabilized to the silicon cavity reaches a world-record instability of $10^{-16}$ and a linewidth of below 40 mHz, the lowest linewidth observed for any laser systems.

We give an outlook on possible applications enabled by dissemination and frequency transfer of this ultra-stable laser light via fiber networks and optical frequency combs.

A 7.3 Mon 17:00 V7.03

**Optical Frequency Transfer via 920 km Fiber Link with $10^{-19}$ Relative Accuracy** — •Stefan Droste[1], Katharina Predehl[1,2], Janis Alnis[1], Theodor W. Hänsch[1], Thomas Udem[1], Ronald Holzwarth[1], Sebastian M. F. Raupach[2], Osama Terra[2], Thomas Legero[2], Harald Schnatz[2], and Gesine Grosche[2] — [1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Since optical clocks have surpassed the performance of the best microwave clocks they are considered for a possible redefinition of the second. One prerequisite for a future redefinition is the ability to com-pare optical frequencies at a high level of stability and accuracy. Optical fiber links have been investigated and considered to serve this purpose. We established a fiber connection between the two institutes Max-Planck-Institute of Quantum Optics (MPQ) in Garching and the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. We measured the stability of the frequency transfer to 3.8 x $10^{-14}$ at 1 s reaching 4 x $10^{-18}$ after $10^3$ s of integration time. We further calculated the deviation of the expected value and the statistical uncertainty to (0.7 ± 3.6) x $10^{-19}$. We can therefore constrain any possible frequency deviation between the local and the far end of the fiber link to be smaller than 3.6 x $10^{-19}$. The demonstrated frequency transfer over an optical fiber link exceeds the requirements for a comparison of todays most accurate clocks by more than one order of magnitude.

A 7.4 Mon 17:15 V7.03

**Precision phase measurement of an optical resonator with a high FSR squeezer** — •Timo Denker, Maximilian Wimmer, Dirk Schütte, and Michèle Heurs — Albert-Einstein Institut Hannover: Max-Planck-Institut für Gravitationsphysik, 30167 Hannover

For many applications using optical resonators (e.g. cavity spectroscopy) good frequency stability is required. To achieve this it is necessary to measure the phase shift of the optical resonator with high accuracy. The quality of this measurement depends on the Signal-to-noise-ratio (SNR). For the shot-noise-limited case the SNR can be increased either by increasing the signal or reducing the noise. We present an experimental scheme that makes use of the output of an optical parametric oscillator, a so-called squeezer. The cavity enhanced squeezed signal of a high free spectral range (FSR) squeezer provides a reduced noise-floor for a precision phase measurement of an optical resonator with high finesse. The phase quadrature variance is measured directly at the homodyne detector and yields a suitable error signal for frequency stabilisation.

A 7.5 Mon 17:30 V7.03

**An Ultra-Stable Iodine-Based Frequency Reference for Space Applications** — •Anja Keetman[1], Thilo Schuldt[1], Klaus Döringshoff[2], Matthias Reggentin[2], Evgeny V. Kovalchuk[2], Moritz Nagel[2], Achim Peters[2], and Claus Braxmaier[1] — [1]University of Applied Sciences Konstanz, Germany — [2]Humboldt-University Berlin, Germany

We present the further development of an iodine-based optical frequency reference on elegant breadboard (EBB) level for future application in space. A frequency-doubled Nd:YAG laser is stabilized to a transition in molecular iodine using modulation transfer spectroscopy near 532 nm. For improving the frequency stability (by a higher pointing stability of the two counter-propagating laser beams in the iodine cell), and also for its future application in space, the optical setup for spectroscopy is realized on a thermally and mechanically ultra-stable baseplate made of a specific glass ceramics (Clearceram by OHARA). The optical components are fixed to the baseplate using adhesive bonding technology, which was already successfully demonstrated in the realization of a highly stable heterodyne interferometer, developed as a prototype demonstrator in the context of the LISA space mission. With the EBB setup, we aim for a frequency stability of $3 * 10^{-15}$ at an integration time of 1000 s, comparable to state-of-the-art iodine-based frequency references realized on laboratory level, e.g. at the Humboldt-University Berlin. This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50 QT 1102.

A 7.6 Mon 17:45 V7.03

**Interferometry-Based CTE Measurement Facility with Demonstrated 10 ppb/K Accuracy** — •Ruven Spannagel[1], Martin Gohlke[2,3], Thilo Schuldt[1], Ulrich Johann[2], Dennis Weise[2], and Claus Braxmaier[1] — [1]University of Applied Sciences Konstanz, Germany — [2]Astrium GmbH, Friedrichshafen, Germany — [3]Humboldt-University, Berlin, Germany

Structural materials with extremely low coefficient of thermal expansion (CTE) are crucial to enable ultimate accuracy in terrestrial as well as in space-based optical metrology due to minimized temperature dependency. Typical materials, in particular in the context of space-based instrumentation are carbon-fiber reinforced plastics (CFRP), C/SiC, and glass ceramics, e.g. Zerodur, ULE or Clearceram. To determine the CTE of various samples with high accuracy we utilize a highly symmetric heterodyne interferometer with a noise level below 2 pm/$\sqrt{\text{Hz}}$ at frequencies above 0.1 Hz in our measurement facility. A sample tube made out of the material under investigation is vertically mounted in an ultra-stable support made of Zerodur. Measurement and reference mirrors of the interferometer are supported inside the tube using thermally compensated mounts made of Invar36. For determination of the CTE, a sinusoidal temperature variation is radiatively applied to the tube. One of the essential systematic limitations is a tilt of the entire tube as a result of temperature variation. Using a Zerodur tube as a reference, it is shown that this effect can be reduced in post processing to achieve a minimum CTE measurement sensitivity $< 10$ ppb/K.

A 7.7 Mon 18:00 V7.03

**A rigidly mounted and vibration insensitive optical reference cavity** — •Sebastian Häfner, Stefan Vogt, Stephan Falke, Christian Lisdat, and Uwe Sterr — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

We report on the development of a sub-Hertz laser system for a transportable optical clock based on an ultra-narrow transition in strontium at 698 nm. A challenge is that its optical reference cavity should withstand transportation shocks. This clock will enable direct comparisons with stationary set-ups and is a predecessor to optical clocks for space missions. This talk will focus on the crucial element of the laser system, namely the reference cavity whose mechanical stability is transferred to frequency stability through Pound-Drever-Hall lock. The spacer of the cavity is made from Ultra-Low-Expansion-glass (ULE), with optical contacted, high finesse fused silica mirrors. It shows a finesse of 460 000 and a theoretical thermal noise floor of $\Delta\nu/\nu = 2.3 \cdot 10^{-16}$.

In this work, we followed a new approach to mount the cavity in a way that its length has a small sensitivity to accelerations ($\Delta l/l = 10.7 \cdot 10^{-10}/g$). We used a rigidly and defined mounting that withstands accelerations of up to 50 $g$ (design): the cylindrical cavity is mounted in its symmetry planes by using a wire-bar mounting system. We measured the performance of this clock laser system by a comparison with two independent sub-Hertz laser systems using a frequency comb. We achieve a relative frequency stability of $\Delta\nu/\nu = 6 \cdot 10^{-16}$ at 10 s. This work is supported by the Centre for Quantum Engineering and Space-Time Research (QUEST).

A 7.8 Mon 18:15 V7.03

**Towards Testing General Relativity with a dual species interferometer** — •Jonas Hartwig, Dennis Schlippert, Ulrich Velte, Daniel Tiarks, Sven Ganske, Olga Lysov, Ernst Maria Rasel, and Wolfgang Ertmer — Institut für Quantenoptik, Hannover, Germany

We report on our work directed towards a dual species matter-wave interferometer for performing a differential measurement of the acceleration of free falling $^{87}$Rb and $^{39}$K atoms to test Einstein's equivalence principle (universality of free fall). Based on minimal Standard Model Extension calculations this combination of elements is very sensitive for composition based equivalence principle violating effects.

During free fall, a Mach-Zehnder type interferometry sequence employing stimulated Raman transitions is applied synchronously for both species, achieving high common noise rejection. With an expected single shot resolution of $\sim 5\times10^{-8}g$ the apparatus will allow for studying systematics at a level of few parts in $10^9 g$ after 100 s integration time.

To guarantee well defined starting conditions the two species will be trapped in an optical dipole trap formed by an Fiber Laser of 1960 nm wavelength. The special properties of this dipole trap allow for fast and efficient cooling. Also, use of evaporative and/or sympathetic cooling techniques is possible.

We will show the enviromental noise limited performance of the single species Rubidium gravimeter and the progress in the implementation of the Potassium Interferometer.

A 7.9 Mon 18:30 V7.03

**A hybrid on-chip optonanomechanical transducer for ultrasensitive force measurements** — •Emanuel Gavartin[1], Pierre Verlot[1], and Tobias J. Kippenberg[1,2] — [1]Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Nanomechanical oscillators have been employed as transducers to measure force, mass and charge with high sensitivity. They are also used in opto- or electromechanical experiments with the goal of quantum control and phenomena of mechanical systems. Here, we report the realization and operation of a hybrid monolithically integrated transducer system consisting of a high-$Q$ nanomechanical oscillator with modes in the MHz regime coupled to the near-field of a high-$Q$ optical whispering-gallery-mode microresonator. The transducer system enables a sensitive resolution of the nanomechanical beam's thermal motion with a signal-to-noise of five orders of magnitude and has a force sensitivity of $74\,\mathrm{aN\,Hz}^{-1/2}$ at room temperature. Energy averaging, required to retrieve incoherent signals, converges only very slowly with the fourth root of the averaging time. We propose and explicitly demonstrate by detecting a weak incoherent force that this constraint can be significantly relaxed by use of dissipative feedback. We achieve a more than 30-fold reduction in averaging time with our hybrid transducer and are able to detect an incoherent force having a force spectral density as small as $15\,\mathrm{aN\,Hz}^{-1/2}$ within 35 s of averaging. This corresponds to a signal which is 25 times smaller than the thermal noise and would otherwise remain out of reach.

A 7.10 Mon 18:45 V7.03

**A membrane in a Michelson-Sagnac interferometer with balanced homodyne detection readout** — •Andreas Sawadsky, Henning Kaufer, Ramon Moghadas, Daniel Friedrich, Tobias Westphal, and Roman Schnabel — Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Institut für Gravitationsphysik, Leibniz Universität Hannover, Hannover, Germany.

Using a balanced homodyne detector we measure a broadband shot noise limited displacement of a silicon nitride membrane with a mechanical Q-factor of $6 \cdot 10^5$ in a Michelson-Sagnac interferometer. Thereby we achieved a displacement sensitivity of $2 \cdot 10^{-16}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ above 50 kHz. We showed that, as expected, thermal noise is only present in amplitude quadrature by performing a zero-span measurement exactly at resonance and varying the homodyne readout phase. By implementing a signal recycling mirror in the interferometer output port we could enhance the displacement sensitivity by a factor of 50 at an input power of 1 mW.