EFTF 2014 – POST-DEADLINE SESSION

Session Type: Lecture Session
Code: A5L-A
Location: Main Aula
Date & Time: Tuesday, June 24 (6:15 pm to 7:15 pm)
Chair: Stephane Schilt, University of Neuchâtel

Time	paper ID	Name	First name	Title
18:15	7401	Luiten	Andre	Accurate Thermometry with Atoms
18:30	7402	Mejri	Sinda	Ultra-stable Mid-IR Quantum Cascade Laser for high-resolution spectroscopy and metrology
18:45	7403	Zeng	Xi	Optical Beam Size Effects in Spin Polarized Pumping
19:00	7404	Geršl	Jan	Relativistic corrections for time and frequency transfer in optical fibers

Paper ID: 7401
Paper title: Accurate Thermometry with Atoms
Authors: G.-W. Truong[1,2], J. D. Anstie[1,2], E. F. May[3], T. M. Stace[4] and A. N. Luiten[1,2]
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We have developed an atomic spectrometer that delivers ultra-high precision measurements of the shape of an absorption line. This has been motivated out of call by the metrological community to base the SI units on robust physical principles – our measurements can yield a new value for Boltzmann's constant. We will present quantum-limited transmission measurements of a Cs absorption line that have an accuracy of 2 ppm in a 1 second measurement. This extreme precision allows us to directly detect subtle lineshape perturbations that have not been previously observed. Using a new theoretical model of the spectrum we obtain a measurement of Boltzmann's constant with 6ppm precision and a 71ppm uncertainty.

Paper ID: 7402
Paper title: Ultra-stable Mid-IR Quantum Cascade Laser for high-resolution spectroscopy and metrology
Authors: Sinda Mejri[1,2], P.L.T. Sow[1,2], S.K. Tokunaga[1,2], O.Lopez[1,2], A.Goncharov[3], B. Argence[1,2], C. Chardonnet[1,2], A. Amy-Klein[1,2], C. Daussy[2,1], and B. Darquié[1,2]
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We report the coherent phase-locking of a quantum cascade laser (QCL) at 10 µm to the secondary frequency standard of this spectral region, a CO_2 laser stabilized on a saturated absorption line of OsO4. The stability and accuracy of the standard are transferred to the QCL resulting in a line width of the order of 10 Hz, and leading to our knowledge to the narrowest QCL to date. The locked QCL is then used to perform absorption spectroscopy spanning 6 GHz of NH_3 and methyltrioxorhenium, two species of interest for applications in precision measurements.

Paper ID: 7403
Paper title: Optical Beam Size Effects in Spin Polarized Pumping
Authors: Xi Zeng, Christine Y. Wang, and Dmitri L. Boiko
Affiliation : Centre Suisse d'Électronique et de Microtechnique, Jaquet-Droz 1, 2002 Neuchâtel, Switzerland

We present what we believe to be the first study on the effects of optical beam size on the spin polarized pumping of atoms with narrowband optical pump sources. We experimentally measured and theoretically modeled the beam size dependence of ground state hyperfine level net relaxation time, net spin relaxation time, and spin polarization for ^{87}Rb D_1 *transition, and we obtained good agreement between theory and measurement for the two relaxation times. We present parameters such as the achievable spin polarization as a function beam diameter for typical operating conditions of single and dual frequency optical pumping.*

Paper ID: 7404
Paper title: Relativistic corrections for time and frequency transfer in optical fibers
Authors: Jan Geršl[1], Pacôme Delva[2], Peter Wolf[2]
Affiliations:
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In the first part of the paper we derive a relativistic differential equation governing the signal propagation in optical fiber. Solving this equation we obtain formulas for signal propagation times depending on the refractive index, fiber positioning on Earth surface and Earth's gravitational field. All terms larger than 1 ps are included. Next we derive formulas for proper frequency evolution during the signal propagation in the fiber. We derive how the frequency of signal changes depending on the fiber motion, expansion and time evolution of the refractive index. All terms with relative contribution to frequency of 10^{-18} *or larger are included.*

Accurate Thermometry with Atoms

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Spectroscopy has an illustrious record in motivating new physics, as well as providing a test-bed for new physical theories. In this talk we will describe our experiments aimed at pushing the precision limits of laser absorption spectroscopy. This has been motivated by a call in the scientific community to develop new techniques to measure Boltzmann's constant, k_B, in preparation for a redefinition of the Kelvin, and other SI units. To this end, we report on a quantum-limited atomic spectrometer that measures the lineshape of the Cs D1 absorption line. Our transmission measurement accuracy is 2ppm in a 1 second measurement, which gives us a unique tool to identify the various contributions to lineshape. For example, our measurements (upper part of Fig. 1) show twin absorption peaks due to the excited state splitting in this transition. Our extreme precision immediately yields a tenfold improvement in the measured accuracy of the D1 hyperfine splitting in Cs [we obtain 1167.716(3)MHz], and reveals the breakdown of the well-known Voigt spectral profile.

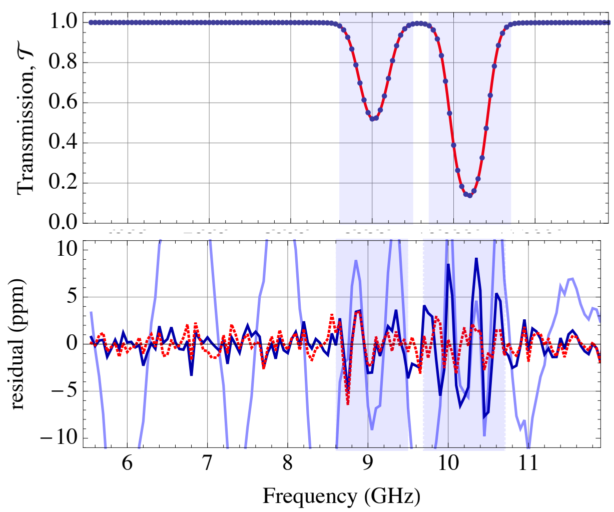

Fig. 1: (top) Plot of the transmission through a Cs absorption cell (data – blue dots, theory – red line); (bottom) residuals after fitting with three different models (light blue – no etalons in model, blue –first order correction to Voigt model, red – second order correction to Voigt model). Residuals for the red curve are consistent with shot-noise.

The observations of deviations from the Voigt profile prompted the development of a theoretical model, which now allows us to make a clean discrimination between the internal atomic state dynamics and their external motional degrees. Using the model we are able to estimate the velocity dispersion of the atoms with a precision (standard error) of 53 ppm during a single line scan, taking just 30 seconds. This precision is perfectly consistent with the sample standard deviation over multiple scans, demonstrating the excellent reproducibility of our system. The measurement precision averages down to 3.7 ppm after 200 scans, which is nearly an order of magnitude improvement over past reports. The quality of the fits is exemplified on the lower part of Fig.1 in which the residuals becomes consistent with shot-noise for the fully corrected theoretical model.

We will describe our new instrument, the careful methods necessary to take such measurements, as well as its potential to generate new values for atomic constants. We use the velocity dispersion of the atoms to generate a value for Boltzmann's constant, $k_B = 1.380\ 560(98) \times 10^{-23}$ J/K, which is consistent with the accepted value of $1.380\ 648\ 8(13) \times 10^{-23}$ J/K. We will also describe a route to measurements with an accuracy of 1ppm.

Ultra-stable Mid-IR Quantum Cascade Laser for high-resolution spectroscopy and metrology

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Quantum cascade lasers (QCL) are a new mature technology well suited for molecular spectroscopy. Several can be combined giving access to the whole mid-IR region. Nevertheless, for high-resolution spectroscopy, it is important to narrow their linewidth. We present different QCL-based mid-IR spectrometers we have developed and first applications to high accuracy molecular spectroscopy and metrology.

We report on the linewidth narrowing of a room-temperature mid-infrared quantum cascade laser by phase-locking to the secondary frequency standard of this spectral region (around 10 µm), a CO_2 laser stabilized to a saturated absorption line of OsO_4. The laser linewidth is narrowed by more than four orders of magnitude below 10 Hz leading to our knowledge to the narrowest QCL to date [1]. Spectra of both NH_3 and methyltrioxorhenium (MTO) have been recorded in linear (Fig1) and saturated absorption, there by demonstrating the potential of such a phase-locked QCL for two of our main projects respectively dedicated to the determination of the Boltzmann constant [2] and to the observation of parity violation in chiral molecules [3] by high resolution molecular spectroscopy. Thanks to the high precision achieved with our QCL based spectrometer we measured the absolute frequency of three transitions of ammonia by saturated absorption spectroscopy. These measurements in agreement with HITRAN (High-resolution TRANsmission) molecular absorption database, lead to an uncertainty improved by almost three orders of magnitude.

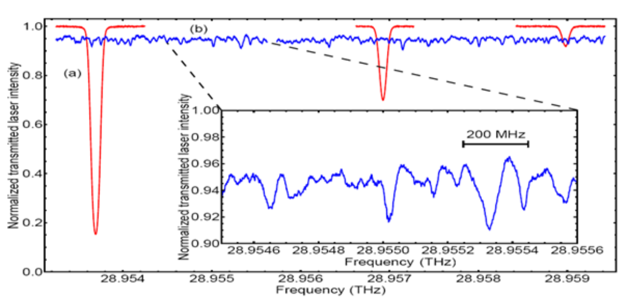

Fig. 1: Linear absorption spectra of NH_3 (curve (a)) and MTO (curve (b)) recorded over more than 6 GHz with a ~10 Hz line width QCL phase-locked to a frequency-stabilized CO_2 laser.

[1] P.L.T. Sow *et al*, accepted Appl. Phys. Lett. (2014), arXiv: 1404.1162

[2] C. Lemarchand *et al.*, Metrologia 50 623 (2013).

[3] S. K. Tokunaga *et al.*, Molecular Physics 111, Issue 14-15, 2363–2373 (2013)

Optical Beam Size Effects in Spin Polarized Pumping

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Spin-exchange optical pumping of alkali-metal atoms and noble gasses has wide range of applications, from use in fundamental physics studies to realizing miniature atomic gyroscopes[1]. Following miniaturization trends, it is highly advantageous to use narrowband optical pumping sources (e.g., VCSEL) as they are vastly smaller and less power consuming than their broadband counterparts. Here, we present what we believe to be the first study on the effects of optical beam size on the spin polarized pumping of atoms with narrowband optical pump sources.

We have experimentally and theoretically investigated the effects of optical pump beam size on ground state hyperfine level net relaxation time τ_g, net spin relaxation time T_s, and spin polarization P_{Rb} for ^{87}Rb D_1 transition. Our analysis and expressions for transit effects through the optical pump beam and contribution from wall relaxation are different from the typically used approaches[2], and there is good agreement between our model and experimental measurements for τ_g and T_s as shown in Fig. 1(a) for a cylindrical cell with 4 mm diameter. The experimentally acquired τ_g were measured from single frequency (SF) π-pumping under optical saturation, while T_s was measured from SF σ+ pumping.

Under SF σ+ pumping, the maximum spin polarization achievable at high (saturating) optical power increases with the pump beam diameter as shown in Fig. 1(b), and this is due to decreasing ratio τ_g/T_s . We find that under SF σ+ pumping, the asymptotically highest spin polarization P_{Rb} is less than 47% (24%) for hyperfine ground state F_g=2 (F_g=1) due to beam transit effects and wall collisions conditioning the net ground state relaxation rate τ_g. Under dual frequency (DF) σ+ pumping, the maximum possible P_{Rb} approaches 100% for asymptotically high optical intensities. In Fig. 1(c), we plot P_{Rb} as a function of beam diameter for the finite optical intensity of 50 mW/cm^2. We find that using larger beam sizes is favorable in obtaining high P_{Rb}.

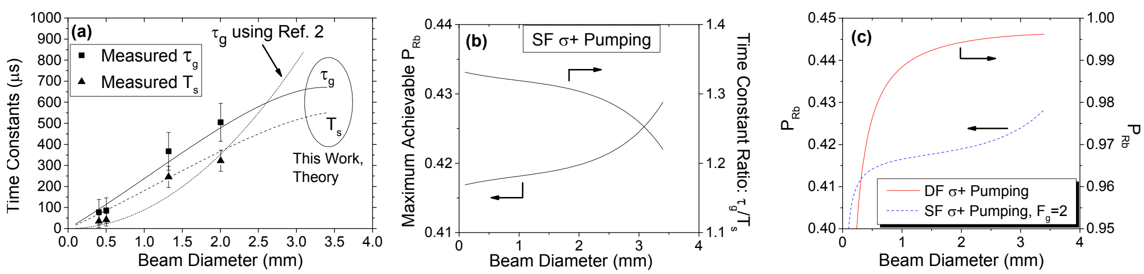

Fig. 1. (a) τ_g and T_s vs. optical beam diameter under SF pumping with both theory (curve) and measurement (points) for a ^{87}Rb cell with 75 torr (Ar:N_2 at 0.58:0.42) at 66 °C. (b) Predicted *maximum possible* P_{Rb} vs. beam diameter under SF σ+ pumping for F_g=2, defined by the ratio of τ_g and T_s. (c) Optical intensity at 50 mW/cm^2, P_{Rb} vs. beam diameter under SF and DF σ+ pumping.

[1] M. Larsen and M. Bulatowicz, "Nuclear Magnetic Resonance Gyroscope For DARPA's Micro-Technology for Positioning, Navigation and Timing Program", 2012 IEEE International Frequency Control Symposium (FCS), p. 1-5, 2012.

[2] W. Happer, "Optical Pumping," Rev. Mod. Phys., vol. 44, pp. 169–249, 1972.

Relativistic corrections for time and frequency transfer in optical fibers

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Optical fibers are or can be used for time and frequency transfer in various applications including metrology, fundamental science or geodesy.[1,2] With increasing accuracy of frequency of the transmitted signal provided by optical clocks also requirements for accurate evaluation of effects appearing during the signal propagation are growing. Besides others relativistic corrections have to be evaluated and applied with the corresponding accuracy required by the optical clocks which nowadays can reach relative frequency uncertainty of several parts in 10^{18}.

Systematic relativistic theory of time and frequency transfer have been worked out e.g. for a case of satellite transfer so far.[3,4] In our work we present a systematic relativistic description of propagation of signal in optical fibers. We show how fiber positioning on the Earth's surface and its motions influence the time and frequency transfer. We derive a general equation governing the signal propagation and we investigate its solution up to terms of order c^{-3} with c being the velocity of light in vacuum. This leads to error in relativistic corrections for time transfer not larger than 1 ps and for frequency transfer not larger than 10^{-18}. The corrections for time transfer include the Sagnac effect and effect of gravitational potential which are related to specific fiber path and the formulas for frequency transfer include a kind of Doppler shift related to changes of fiber path with time. We derive formulas for both one way and two way time and frequency transfer.

The work have been done within EMRP project International Time Scales with Optical Clocks and can be used for any applications of optical fibers in time and frequency transfer.

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[1] K. Predehl et al., "A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place", Science, vol. 336, p. 441, 2012.

[2] S. Droste et al., "Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link", Phys. Rev. Lett., vol. 111, p. 110801, 2013.

[3] P. Wolf, G. Petit, "Relativistic theory for clock syntonization and the realization of geocentric coordinate times ", Astron. Astrophys., vol. 304, p. 653-661, 1995.

[4] L. Blanchet et al., "Relativistic theory for time and frequency transfer to order c^{-3}", Astron. Astrophys., vol. 370, p. 320-329, 2001.