

Demonstration of a Transportable 1 Hz-Linewidth Laser

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We present the setup and test of a transportable clock laser at 698 nm for a strontium lattice clock. A master-slave diode laser system is stabilized to a rigidly mounted optical reference cavity. The setup was transported by truck over 400 km from Braunschweig to Düsseldorf, where the cavity-stabilized laser was compared to a stationary clock laser for the interrogation of ytterbium (578 nm). Only minor realignments were necessary after the transport. The lasers were compared by a Ti:Sapphire frequency comb used as a transfer oscillator. The thus generated virtual beat showed a combined linewidth below 1 Hz. © 2010 Optical Society of America

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Optical clocks based on trapped cold atoms are now outperforming the best microwave clocks, thus enabling new studies and applications. Operated in space and on the ground at different locations, they could enable relativistic geodesy and improved fundamental physics tests [1, 2]. Reliable and rugged optical clocks with high stability and accuracy are therefore an important need. So far, high-performance cold atom optical clocks are still bulky laboratory setups that cannot easily be transported. Therefore developments towards transportable optical clocks are required and have been initiated [3, 4].

One of the most critical parts concerning transportability is the optical reference cavity that is used as a flywheel to ensure a high short-term frequency stability of the interrogation laser between the atom interrogation cycles. To achieve an optical linewidth of the clock laser in the range of one Hertz, the cavity has to be isolated from all external disturbances. Usually, the cavity is mounted very loosely [5] to avoid excessive forces that would lead to deformations of the cavity and fluctuations of the optical path length and therefore its resonance frequency. However, this prevents the cavity from being easily transported, because the resonator will move and might be damaged during transportation.

In this letter, we describe a prototype clock laser for a transportable neutral atom lattice clock. As a first realistic test for future transportable clock setups it was transported from Braunschweig to Düsseldorf.

The design of the laser system is constrained by requirements for its transportability in a car or truck and its spectral purity, for which typically a linewidth of 1 Hz and a fractional stability of 10^{-15} on timescales of a few seconds is needed.

The transportable clock laser setup consists of three separate parts: the laser breadboard (60 cm × 90 cm) made with standard optical components, a rolling table with the reference cavity on a vibration isolation table inside a box for acoustic noise isolation (outer dimen-

sions including the table 150 cm × 88 cm × 195 cm) and an electronics rack (60 cm × 60 cm × 180 cm). No effort was made to compactify the electronics. The light from the laser was provided to the cavity via a 2 m long fiber. The volume of the system without the electronics rack was less than 3.0 m³. The temperature of an aluminum tube enclosing the vacuum system was stabilized to 24 °C using a heating foil as control element. The sensitivity of the resonator frequency to changes in the temperature stabilization is approximately 20 kHz/mK. During the transport, an uninterruptible power supply unit was used to keep the the vacuum pumps and the temperature stabilization of the cavity running. Both,

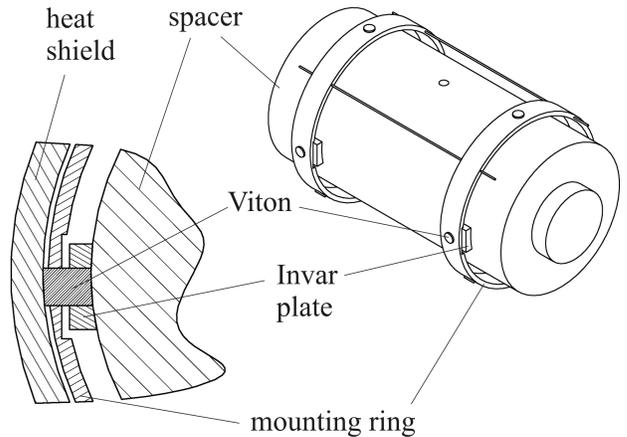


Fig. 1. Sketch of the semi-rigid mounting of the transportable reference resonator.

the cylindrical cavity spacer and the mirrors, are made of ULE (ultra-low expansion glass). The spacer has a diameter of 50 mm and is 100 mm long. The finesse of the cavity is 330 000. To ensure transportability the mounting of the reference resonator was designed to be much more rigid than for other ultra-narrow linewidth lasers [5, 6]. Small Viton cylinders are tightly pressed into

holed Invar plates glued onto the cavity spacer (Fig. 1, details given in [7]). The cylinders (and thus the cavity) are held in mounting rings that fix the resonator position in all three directions. Side-way movement is inhibited because the Viton pieces penetrate the mounting rings and touch the inner side of the heat shield. The suspension positions of the mounting points were optimized by finite element (FEM) calculations. In previous measurements large frequency changes of the resonator mode were observed under accelerations. It was assumed that mechanical contact of the spacer to the housing was the source of this effect. A refined layout resulted only in a marginally lower sensitivity to vertical vibrations.

We attribute this effect to squeezing forces that change under acceleration and were not considered in the FEM analysis. For a force of 1 N we calculated a change of the cavity length $\Delta L/L \approx 1 \times 10^{-8}$.

Meticulous elimination of vibration incoupling on the vibration isolation platform led to acceptable laser performance. We also used the virtual beat with an ultra-stable laser at 657 nm [6] to optimize our laser setup. A width of the beat signal of about 1 Hz was achieved. Calculating the Allan deviation from the counted beat note we observed a flicker floor at about 2×10^{-15} fractional stability. The laser is regularly used to record spectra of the Sr $^1S_0 - ^3P_0$ transition with a Fourier-limited linewidth of 9 Hz and close to 90% excitation probability.

The clock laser for the Düsseldorf ytterbium lattice clock is based on a 1156 nm diode laser [8] with an external Littrow configuration cavity and containing a homemade intracavity electro-optic phase modulator for fast frequency corrections. The free-running linewidth is less than 100 kHz.

The output radiation (approx. 20 mW) is focused into a 20 mm PPLN waveguide for frequency doubling. A maximum output of 0.5 mW at 578 nm was produced. This wave is stabilized to an all-ULE cavity with a standard Pound-Drever-Hall scheme. The finesse of the cavity exceeds 300 000. It is of the cut-out type [5], with 100 mm length, 50 mm diameter, a 30 mm deep cut-out starting 4 mm below the mid-plane. The cavity is housed in a gold-plated copper box and both are contained in a compact (11 cm \times 11 cm \times 18 cm) aluminum vacuum chamber. Both the vacuum chamber and the copper housing are actively temperature stabilized by thermoelectric cooling devices.

All the optics hardware fits on a 90 cm \times 90 cm breadboard that is supported by an active vibration isolation system, providing isolation along the three spatial directions. Except for lock electronics, the system is enclosed by a wooden box for acoustic protection. This clock laser had previously been characterized by comparison with a second, independent ULE cavity. A beat with an instability of less than 2.5×10^{-15} for 1 s – 10 s was obtained (after subtraction of the differential cavity drift of approx. 0.1 Hz/s).

The 5 hour transport of the 698 nm laser system was performed using a small transport truck. The Sr laser

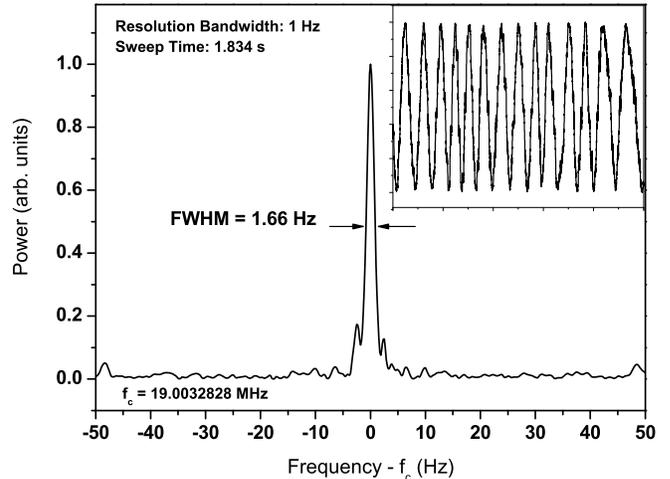


Fig. 2. Virtual beat monitored with a spectrum analyzer. The inset shows 2.5 seconds of the digitized virtual beat signal mixed down to a few Hertz. The two measurements were taken at slightly different times.

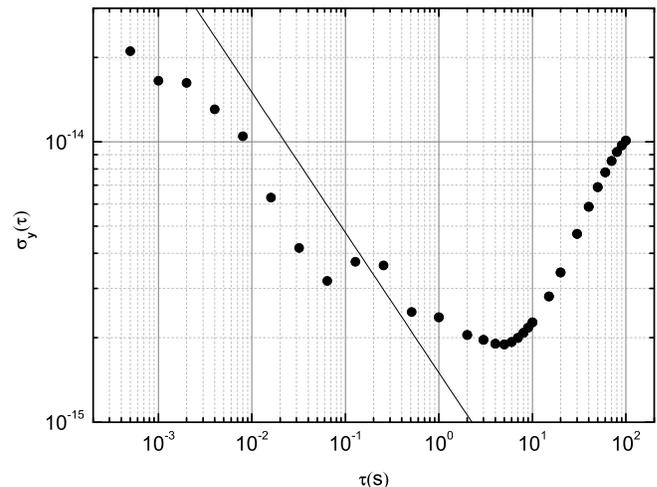


Fig. 3. Fractional Allan deviation of the virtual beat between the two clock lasers during a quiet period. For times shorter than one second the values were derived using the Hilbert transform of the mixed down beat signal (see also text). For longer times we used a frequency counter. Linear and quadratic cavity drifts were removed in both cases. The straight line corresponds to the stability of a virtual beat at 1156 nm with white frequency noise and 1 Hz width.

was locked to its ULE cavity in Düsseldorf within one day after start of loading in Braunschweig. For the characterization of the Sr clock laser the two lasers were operated in the frequency comb laboratory room in Düsseldorf. Both laser beams were transported via fibers to the frequency comb, the fiber noises were actively canceled.

The frequency comb is based on a Ti:Sapphire laser and a Menlo Systems comb kit, modified in-house. The 698 nm and 1156 nm waves (frequencies ν_{698}, ν_{1156}) are

individually superposed with the comb on two beat lines by coupling the waves out from their fibers, overlapping the beams with the corresponding modes from the comb and sending the beat notes onto two photodetectors. Appropriate band-pass filters block the unnecessary comb modes before the overlap. The beat notes with frequencies Δ_{698} , Δ_{1156} between each laser wave and the nearest comb mode were filtered and amplified with two tracking oscillators. The frequency comb's repetition rate and carrier envelope frequency f_{CEO} were locked to a hydrogen maser, itself steered to GPS on long time scales. Counting Δ_{1156} and Δ_{698} enabled absolute frequency measurement of the two clock lasers to be performed simultaneously.

The virtual beat technique [9] consists in generating by electronic means an r.f. signal oscillating at the frequency $\Delta_{vb} = (f_{CEO} - \Delta_{1156}) - (m_1/m_2)(f_{CEO} - \Delta_{698})$, that shows the properties of a beat note between two lasers at 1156 nm, since $\Delta_{vb} = \nu_{1156} - (m_1/m_2)\nu_{698}$. Here m_1 (m_2) is the mode number of the nearest comb line to the 1156 nm (698 nm) clock laser radiation. This beat note is sent to a spectrum analyzer, counted with a dead-time-free counter and, after mixing it down to a few Hertz, sampled by an analog-digital converter. A record of the spectrum analyzer is shown in Fig. 2 together with a short sample of the digitalized beat (inset).

The fractional Allan deviation shown in Fig. 3 was calculated using two different methods. For time values larger than 1 s we used the counter signal, while the shorter values were derived from the signal of the analog-digital converter. For this purpose we used a Hilbert transform to add an imaginary part to the real signal to obtain an analytic signal [10]. From this signal the phase and the instantaneous frequency were extracted. After removing linear and quadratic drifts the Allan deviation for time intervals as short as 0.5 ms was calculated. For short times the trend is consistent with the linewidth observed in Fig. 2. From 1 s to 10 s a noise floor of 2×10^{-15} is reached. Beyond 10 s, the residual of the differential cavity drift dominates the stability. We conclude from Allan deviation and virtual beat spectrum that both lasers have a linewidth close to 1 Hz.

We have monitored the resonance frequency of the transportable cavity over more than 200 days including the transport. A shift of about 2 MHz measured after arrival in Düsseldorf (hatched area in Fig. 4) was probably due to the laboratory temperature temporarily exceeding the range of the cavity's unidirectional temperature control. This interpretation is supported by observation of a very large drift rate of 5.3 Hz/s during the first day of measurement, when the cavity was cooling down to its set temperature. Back in Braunschweig, the original resonance frequency of the cavity was nearly recovered. However, we observed a reduced drift rate and a small remaining frequency offset, which we attribute to relaxation of stress in the cavity mounting during the transport.

In summary, we have demonstrated, for the first time,

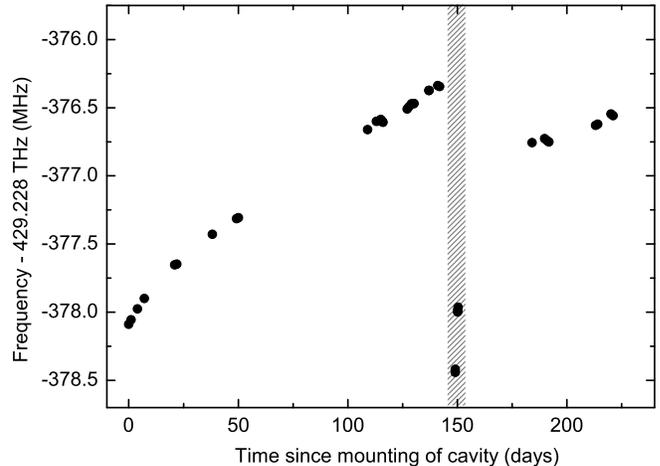


Fig. 4. Frequency of one cavity mode plotted over 8 months. The hatched area shows the measurements during the one week stay in Düsseldorf.

that a high-performance clock laser can be transported without difficulty and set up in a short time for enabling precision metrology applications. In the near future, the transportable clock laser could be combined with a transportable fiber-based frequency comb for even higher flexibility.

Acknowledgment

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References

1. S. Schiller et al., *Experimental Astronomy* **23**, 573–610 (2009).
2. P. Wolf et al., *Experimental Astronomy* **23**, 651–687 (2009).
3. M. Schioppo et. al, to appear in *Proc. Europ. Time and Frequency Forum 2010*,
4. S. Schiller et al., to appear in *Proc. Intl. Conf. Space Optics*, ESA (2010).
5. S. A. Webster, M. Oxborrow, and P. Gill, *Phys. Rev. A* **75**, 011801(R)–1–4 (2007).
6. T. Nazarova, F. Riehle, and U. Sterr, *Appl. Phys. B* **83**, 531–536 (2006).
7. T. Legero, C. Lisdat, J. S. R. Vellore Winfred, H. Schnatz, G. Grosche, F. Riehle, and U. Sterr, *IEEE Trans. Instrum. Meas.* **58**, 1252–1257 (2009).
8. A. Y. Nevsky et al., *Appl. Phys. B* **92**, 501–507 (2008).
9. H. R. Telle, B. Lipphardt, and J. Stenger, *Appl. Phys. B* **74**, 1–6 (2002).
10. Y. Shmaliy, *Continuous-Time Signals, Signals and Communication Technology* (Springer, 2006).