

Demonstration of a transportable 1 Hz-linewidth laser

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Abstract 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 using a Ti:Sapphire frequency comb as a transfer oscillator. The generated virtual beat showed a combined linewidth below 1 Hz (at 1156 nm). The transport back to Braunschweig did not degrade the laser performance, as was shown by interrogating the strontium clock transition.

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 toward

transportable optical clocks are required and have been initiated [3–5]. 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 1 Hz, the cavity has to be isolated from all external disturbances. Usually, the cavity is mounted very loosely in a vibration-insensitive configuration [6–8] 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 paper, 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), a rolling table with the reference cavity inside a box for acoustic noise isolation (outer dimensions 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 laser breadboard includes a master-slave setup with a master laser in Littman configuration. The laser is locked to the reference cavity with the Pound-Drever-Hall technique using the laser current for fast frequency control [9]. Standard optical components were used to offer all the functionality that is needed for clock laser operation such as shifting

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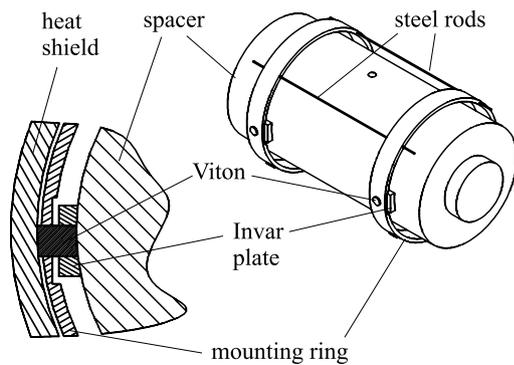


Fig. 1 Sketch of the semi-rigid mounting of the transportable reference resonator

the laser frequency with acousto-optic modulators (AOMs). In particular, the path length stabilization [10, 11] for two fibers was also set up using AOMs on the breadboard. The light from the laser was sent to the cavity via a 2 m long fiber which was not actively stabilized. The volume of the system without the electronics rack was less than 3.0 m³. For transportation the laser breadboard was packaged in a wooden box; the optical fibers and most of the electrical connections were removed. No special care was taken to isolate the laser system or the cavity against vibrations while transporting it.

The cavity is mounted in a passive, gold-plated copper heat shield inside a vacuum chamber, evacuated by a small 2 l/s ion getter pump. The vacuum system is installed on a passive vibration isolation platform, which was locked during the transport. The temperature of an aluminum tube enclosing the vacuum system was stabilized to 24°C using a heating foil as the control element. For simplicity and to avoid possible condensation, no cooling was employed. This temperature does not agree to the zero expansion temperature of the all-ULE (ultra-low expansion glass) cavity. From measurements done at similar spacers made of the same ULE batch, we expect this temperature to be at about 11°C. With a slope of the thermal expansion coefficient of $2 \times 10^{-9} \text{ K}^{-2}$, we expect at 24°C a sensitivity of the resonator frequency to temperature fluctuations of approximately -10 kHz/mK . During the transport, an uninterrupted power supply unit was used to keep the vacuum pump and the temperature stabilization of the cavity running.

The cylindrical cavity spacer has a diameter of 50 mm and is 100 mm long. One plane and one concave (1 m radius of curvature) ULE mirror (diameter 25.4 mm, thickness 6.3 mm) were optically contacted to the spacer. 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 [7, 8]. Small Viton cylinders are tightly pressed into the holes of four invar-plates glued onto the cavity spacer (Fig. 1, details given in [9]). The cylinders (and thus the

cavity) are held in mounting rings that fix the resonator position in all three directions. Sideways movement is inhibited because the Viton pieces tightly fit into holes of the mounting rings and touch the inner side of the heat shield. The suspension positions of the mounting points were optimized by finite element method (FEM) calculations. The top of the cylinders is located at the horizontal symmetry plane and 17.5 mm from the end faces of the spacer. In previous measurements [9], large frequency changes of the resonator mode were observed under accelerations. It was assumed that unintended mechanical contact of the spacer to the housing was the source of this effect.

In a refined layout the mounting rings were connected by steel rods, and great care was employed to prevent the cavity from touching the lids of the surrounding heat shield. Also, the length of the Viton cylinders was increased to allow for a tight reliable fit of the cavity. However, only a marginally lower sensitivity to vertical vibrations of $\Delta L/L \approx 2.7 \times 10^{-9}/g$ was achieved. We now attribute this effect to squeezing forces introduced by the cavity mounting. These forces arise because the Viton pieces are squeezed between the heat shield and the cavity spacer. For a force of 1 N on each cylinder we calculated a change of the cavity length $\Delta L/L \approx 1 \times 10^{-8}$ if the force acts in the axial direction or $\Delta L/L \approx 3 \times 10^{-9}$ if the force is radially squeezing the spacer. Under acceleration a reaction force of 4 N/g has to be supplied by the Viton cylinders. A 30% coupling of this force into the axial direction could explain the observed sensitivity. Also, deformations of the heat shield under acceleration can change the squeezing forces and contribute to the vibration sensitivity.

Meticulous elimination of vibrations coupling to the vibration isolation platform led to acceptable laser performance. We also used the virtual beat with an ultra-stable laser at 657 nm [7] 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 clock laser for the Düsseldorf ytterbium lattice clock is based on a 1156 nm diode laser [12] with an external Litrow configuration cavity and containing a home-made intracavity electro-optic phase modulator for fast frequency corrections. The free-running linewidth is less than 100 kHz. The output radiation (approximately 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 [8], with 100 mm length, 50 mm diameter, and a 30 mm deep cut-out starting 4 mm below the mid-plane.

The 578 nm reference cavity is housed in a massive gold-plated copper box, and both are contained in a compact

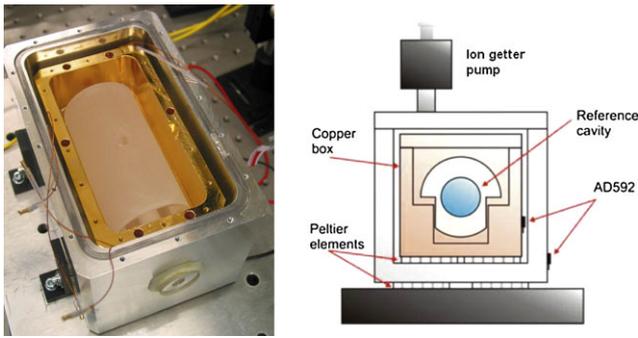


Fig. 2 *Left:* photograph of the reference cavity inside the compact vacuum chamber with removed cover and insulation. *Right:* schematic of the vacuum chamber, showing the elements of the two-stage temperature stabilization system with AD592 temperature sensors (insulation box is not shown)

(11 cm \times 11 cm \times 18 cm) aluminum vacuum chamber (see Fig. 2). The two entrance windows are glued to the vacuum chamber using Torr Seal epoxy. The chamber is machined out of a single aluminum block; the cover is attached to the chamber using M4 screws and indium foil for sealing. A vacuum of about 5×10^{-8} mbar is maintained using a 2 l/s ion getter vacuum pump attached to the cover plate. The vacuum chamber and the vacuum pump are covered with a thermal and acoustic insulation box.

Both the vacuum chamber and the copper housing are independently actively temperature stabilized by Peltier elements and two AD590 temperature sensors. With this two-stage temperature stabilization system, which includes a temperature stabilized electronic controller, we reach a temperature instability of 0.15 mK at 100 s and 0.07 mK at 10 000 s integration time, as measured by the in-loop sensor on the copper box.

The temperature of the cavity is kept close to the ULE's thermal expansion coefficient zero crossing at approximately 20°C. The described construction demonstrated a remarkable performance as measured with the frequency comb in comparison to a GPS disciplined hydrogen maser. No influence of the residual temperature instability on the resonator frequency could be detected within the stability of the maser (approximately 10^{-12}). Over a period of 35 days, the average drift of the cavity frequency was 56 mHz/s.

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 1–10 s was obtained (after subtraction of the differential cavity drift of approximately 0.1 Hz/s).

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

locked to its ULE cavity in Düsseldorf within one day after the start of loading in Braunschweig. Some realignment of the optical path had to be done after the transport because two mirror holders were not fixed well enough, but there was no indication that the cavity had moved inside its mounting. 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 sent via fibers to the frequency comb, and the fiber noises were actively canceled.

The optical frequency synthesizer is a commercial Ti:Sa-based frequency comb (Menlo Systems), modified in-house for higher long-term stability and expanded emission range. The 698 nm and 1156 nm laser beams (frequencies ν_{698} , ν_{1156}) are individually superposed with the comb via two beat lines. In these beat lines the laser beams are coupled out of their fibers and superposed with the corresponding modes from the comb. Appropriate band-pass filters block the unnecessary comb modes before the overlap. The generated beat notes are detected by two photodetectors. 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 GPS disciplined hydrogen maser. Counting Δ_{1156} and Δ_{698} enabled absolute frequency measurement of the two clock lasers to be performed simultaneously.

The virtual beat technique [13] consists in generating by electronic means an RF signal oscillating at the frequency $\Delta_{vb} = (f_{\text{CEO}} + \Delta_{1156}) - (m_1/m_2)(f_{\text{CEO}} + \Delta_{698})$, which 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, mixed down to a few hertz, and then sampled by an analog-digital converter. A record of the spectrum analyzer is shown in Fig. 3 together with a short sample of the digitalized beat (inset).

The fractional Allan deviation shown in Fig. 4 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 [14]. 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. 3. From 1 s to 10 s a noise floor of 2×10^{-15} is reached. Beyond 10 s, the residual differential cavity drift dominates the stability. We conclude from Allan deviation and the virtual beat spectrum that both lasers have a linewidth close to 1 Hz.

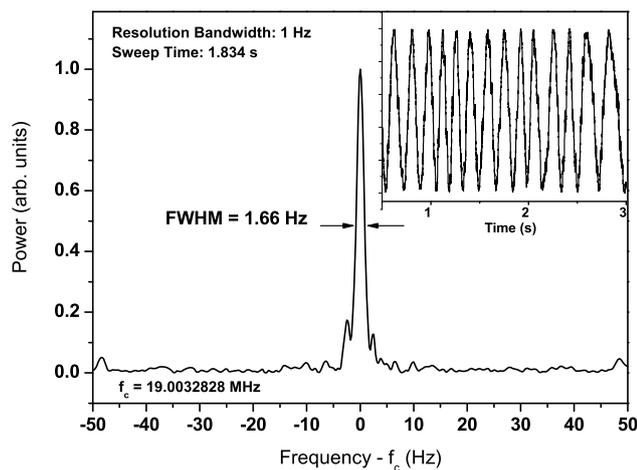


Fig. 3 Virtual beat at 259 THz (1156 nm) monitored with a spectrum analyzer. The *inset* shows 2.5 seconds of the digitized virtual beat signal mixed down to a few hertz. The two measurements were taken at slightly different times

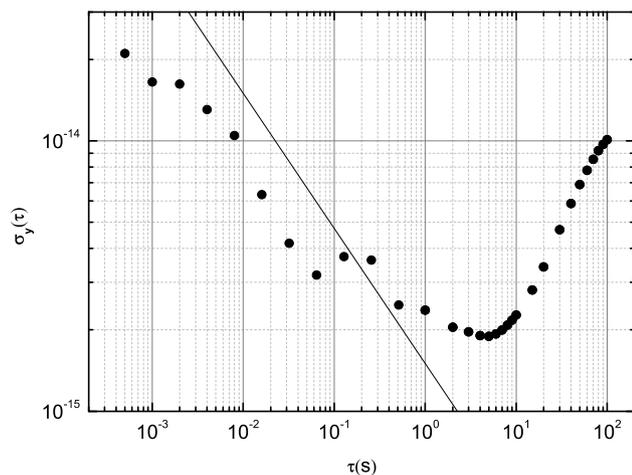


Fig. 4 Fractional Allan deviation of the virtual beat between the two clock lasers during a quiet period. For times shorter than 1 s the values were derived using the Hilbert transform of the mixed down beat signal (also see text). For longer times we used a frequency counter. Linear and quadratic cavity 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

We have monitored the resonance frequency of the transportable cavity over more than 200 days including the time in Düsseldorf. A shift of about 2 MHz measured after arrival in Düsseldorf (hatched area in Fig. 5) was probably due to a change in the cavity temperature. During the transport the temperature of the aluminum tube enclosing the vacuum system remained unchanged as monitored by the error signal of the temperature control. However, at Düsseldorf the laboratory temperature was above the set point of the temperature control that allowed heating only. This caused an increase in the temperature by about 0.4 K before the prob-

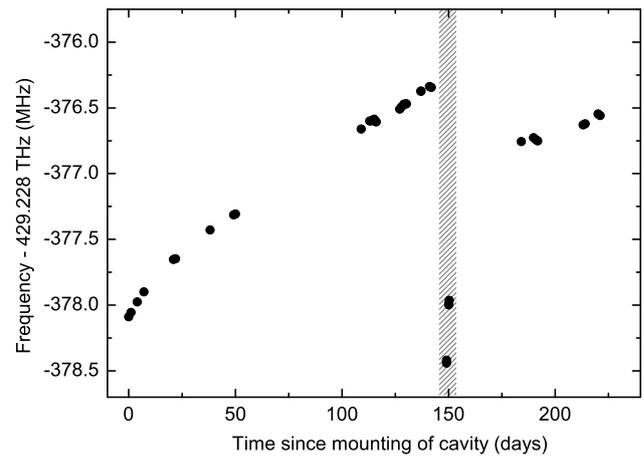


Fig. 5 Frequency of one cavity mode plotted over 8 months. The *hatched area* shows the measurements during the one-week stay in Düsseldorf

lem was discovered and the room temperature was lowered again. The very large drift rate of 5.3 Hz/s observed during the first day of measurement could be explained by the cavity cooling down to its set temperature at a rate of -2 mK/h. Back in Braunschweig, the original resonance frequency of the cavity was nearly recovered. 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. Apart from the changed drift rate we did not observe any degradation of the system's performance. Before and after the transport the laser was regularly used to record spectra of the $^{87}\text{Sr } ^1\text{S}_0 - ^3\text{P}_0$ transition with a Fourier-limited linewidth of 9 Hz and close to 90% excitation probability [15].

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

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