A diode laser stabilization scheme for $^{40}$Ca$^+$ single-ion spectroscopy

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Abstract
We present a scheme for stabilizing multiple lasers at wavelengths between 795 and 866 nm to the same atomic reference line. A reference laser at 852 nm is stabilized to the Cs D₂ line using a Doppler-free frequency modulation technique. Through transfer cavities, four lasers are stabilized to the relevant atomic transitions in $^{40}$Ca$^+$. The rms linewidth of a transfer-locked laser is measured to be 123 kHz over 200 ms with respect to an independent atomic reference, the Rb D₁ line. This stability is confirmed by the comparison of an excitation spectrum of a single $^{40}$Ca$^+$ ion to an eight-level Bloch equation model. The long-term stability with respect to the same reference is measured to be 130 kHz over a period of 2 h. The high degree of stability is demonstrated by the measured Allan deviation around $10^{-11}$ between 1 and 100 s.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since the first preparation of a single trapped Ba$^+$ ion [1], ion-trap experiments have become increasingly sophisticated. Ultra-high precision spectroscopy has lead to single-ion frequency standards [2, 3] and today the most accurate clock is based on single-ion spectroscopy [4]. Trapped ions have also developed into very promising candidates for the implementation of schemes of quantum computation, and universal gate operations [5–7] as well as quantum algorithms [8–10] have been demonstrated. In quantum communication, first building blocks of a quantum network have also been realized with ions [11]. Besides these applications, ions have proven to be textbook-like model systems to study fundamental questions in quantum optics and quantum mechanics [12].

In such experiments the ions are optically cooled and manipulated by laser light. Depending on the chosen ion and the desired application, the lasers have to be frequency-stabilized well below the typical frequencies involved such as the natural linewidth ($\approx 20$ MHz) of the optical transition that is to be driven, Zeeman splitting ($\approx 10$ MHz) or the vibrational frequency in the trap ($\approx 1$ MHz). Furthermore, data are typically collected over long periods of time, such as hours or even days, since experiments exhibit low count rates. A laser system used for single-ion spectroscopy therefore faces the requirements of offering good frequency stability over both short and long periods of time.

In early experiments the choice of ion species was governed by the availability of laser sources, typically dye lasers, at the characteristic wavelengths of the ion. Technical progress and the availability of a broad spectrum of wavelengths have made robust and inexpensive diode lasers increasingly attractive. However, significant technical effort to frequency-stabilize these lasers has remained indispensable. A popular approach is to lock a laser to a passive cavity built from ultra-low expansion material and placed in a pressure-sealed container or in vacuum [13]. This eliminates the extreme sensitivity of the cavity resonance to pressure changes due to the dependence of the refractive index of air [14]. Nevertheless such cavities are not totally drift free, they only minimize the drift of the laser frequency mostly caused by temperature fluctuations in the environment. Other approaches use scanning transfer cavities in combination with a stable HeNe reference laser. This technique is slow compared to others as it is limited by the scanning frequency of the cavity [15]. An open cavity transfer scheme combining active piezo...
and temperature stabilization of the cavity length has been used to build a difference frequency spectrometer [14], whereby a custom-made pyrex cavity transfers the stability of a HeNe laser onto another laser with a cavity modulation technique.

A scheme similar to the one we will present here has been used for high-precision frequency measurements of the D1 line of alkali atoms [16]: a reference laser is locked to the Rb D2 line by saturated absorption spectroscopy. Its 10 kHz linewidth is transferred to a second laser of the same type via an in-vacuum ring cavity. This second laser was then used to measure the absolute frequency of the Rb D1 line using a cavity modulation technique.

In the following, we describe the relevant elements of the stabilization scheme in detail.

3. Cavities

The confocal Fabry–Perot cavities are built from two mirrors\(^2\)\(^\text{(T = 99.5\%, radius = 30 cm)}\) with 15 cm distance and have 500 MHz free spectral range. Finesse and linewidth are measured to be 270 and 1.9 MHz, respectively.

The two mirrors are mounted at the two ends of an aluminium lens tube\(^3\) as depicted in figure 3. Having a high-temperature expansion coefficient, aluminium assures the temperature tunability of the mirror distance \((\Delta L / \Delta T = 3.5 \mu m \ C^{-1})\). A heating wire with 15 \(\Omega\) resistance is wound around the tube and a PT100 temperature sensor is attached. The whole tube itself is wrapped in insulating material and placed inside a bigger aluminium container that is attached. One mirror is glued to an end

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\(^2\) Layertec.  
\(^3\) Thorlabs.
Figure 2. Laser stabilization scheme for the 795 nm laser. The stability of a reference laser at 852 nm is transferred onto the 795 nm laser using transfer cavities. The elements used to stabilize the laser at 866 nm are equivalent to the ones used for the 795 nm laser and are not shown. All relevant elements of the scheme are described in detail in the text.

Figure 3. Cavity assembly consisting of a commercial lens tube system and a custom-made teflon holder. The picture shows from left to right: end cap with hole for optical access and electric connections, three piezo stacks, teflon piece guiding the piezos, aluminium washer, rubber ring, first mirror, teflon piece holding the aluminium washer and rubber ring, aluminium tube with heating wire and temperature sensor, end piece for course adjustment, second mirror, mirror holder, threaded ring to fix the mirror holder in the end piece. A piece of the tube that can be screwed in and out for course length adjustment. The other mirror is glued to an aluminium washer that is mounted in a two-piece teflon holder together with three piezo actuators and a rubber ring as shown in figure 3. The holder is designed such that the aluminium washer with the mirror is pressed by the piezo stacks\(^4\) against the rubber ring\(^5\) that sits in between the aluminium washer and the outer teflon part. The piezo stacks are guided by three holes in the inner teflon part that sits inside the outer one. They are held by an end cap that is screwed onto the aluminium tube and pre-loads the flexible rubber ring. Thereby the piezos find sufficient resistance to compress the rubber ring thus changing

\(^4\) Piezomechanik PST 150/2x3/7.

\(^5\) Inner diameter = 16 mm, thickness = 1.5 mm.
the length of the cavity. A maximum voltage of ±10 V is applied to the piezos corresponding to a length change of about 2.5 μm and resulting in a shift of the resonance over about three free spectral ranges. Scanning over a wider frequency range is attained by changing the temperature.

4. Cavity locker

The stabilization of the cavities to the reference laser is realized with a self-built electronic device called 'cavity locker' [21]. The cavity locker consists of a PDH input stage, a microcontroller, a scanning unit and outputs for low- and high-frequency feedback (figure 2). The PDH stage consists of an input amplifier, a mixer, a phase shifter and a bandpass filter, and it demodulates the photo diode signal using the rf modulation signal of the reference laser current as local oscillator (figure 2). The PDH error signal which it produces is the input for the compensator which is implemented with software on the microcontroller. In control mode the low-frequency output of the compensator drives the heating wire, and the high-frequency output drives the cavity piezos. If the control loop is open, the piezo can be scanned by the scanning unit and the temperature is stabilized to the value defined by a temperature set point potentiometer.

The compensator implemented on the evaluation board consists of two parts, one for the piezos and one for the heating wire. In closed-loop operation the heater compensator is programmed to regulate the length of the cavity in such a way that the piezos remain in their mid position (figure 4). This assures that the piezo voltage is kept within ±10 V. Both compensators are programmed (in C language) and custom-designed after analysing the response of the system, i.e. the cavity and its circuitry (figure 4). The piezo compensator consists of a combination of generic control techniques, e.g. dead beat [22], integrators, etc, while the heater compensator is implemented as proportional and differential controller. The speed of the piezo compensator loop is limited by the eigen-frequency of the piezo actuators measured to be 3 kHz.

5. Characterization

5.1. Cs spectroscopy

The right part of figure 5 shows the setup of the Doppler-free absorption spectroscopy on the Cs cell. The absorption signal detected with PD1 is shown in figure 6 together with the corresponding error signal produced by the PDH stage of the cavity locker. The transition used as reference is the \( F = 3 \rightarrow F' = 3/4 \) crossover line.

5.2. Characterization of the transfer lock

To estimate the absolute stability of the transfer locked lasers, one of them was compared with an independent atomic reference, a Doppler-free rubidium resonance in a gas cell. For this purpose a second Doppler-free absorption spectroscopy was set up and the master laser of the 397 nm SHG system was tuned to the D1 line of \(^{85}\)Rb at 794.979 nm [23]. In figure 5 this setup is shown.

The full Rb Doppler-free absorption signal obtained by scanning the frequency of the 795 nm laser is depicted in figure 7. Since the cell contains Rb isotopes in their natural abundances, absorption lines for \(^{85}\)Rb (72.2%) and \(^{87}\)Rb (27.8%) are observed. The Doppler-free hyperfine structure is well resolved, and the various hyperfine transitions are easily identified using the splittings known from the literature [24, 25].

The transfer lock is characterized by monitoring the Rb saturated absorption discriminant generated by a PDH circuit, which uses the modulation of the laser light at 20 MHz from the lock to its transfer cavity. The signal recorded with a fast photo diode (PD2) behind the Rb cell is amplified, mixed down with a mixer and filtered by a bandpass filter (see figure 2, bottom).

With the whole stabilization chain locked, i.e. the master laser at 795 nm is locked via the transfer cavity to the stable reference laser, the laser was tuned to resonance with the strongest line in \(^{85}\)Rb, the \( F = 3 \rightarrow F' = 2/3 \) crossover line. Scanning the AOM of figure 5 we identified the desired transition and set the frequency to resonance, i.e. to the point

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6 Analogue Devices EVAL-ADUC7026QSZ.
7 New Focus model 1801 (bandwidth 125 MHz).
8 Mini Circuits ZAD-1H.
9 Mini Circuits SIF-21.4+. 
Figure 5. Setup for the characterization of the transfer lock. The master laser of a frequency doubling stage at 795 nm is locked to a Doppler-free Cs resonance in a gas cell by three consecutive PDH stabilizations using a transfer cavity. To characterize the frequency stability of the laser a PDH error signal is derived from Doppler-free absorption spectroscopy on $^{85}$Rb.

Figure 6. Cs Doppler-free absorption spectroscopy signal (bottom) and corresponding error signal (top) for the $F = 3 \rightarrow F' = 2, 3, 4$ transitions and its crossover lines. The abscissa shows absolute frequency.

Figure 7. Full spectrum of the Rb D$_1$ line, obtained via Doppler-free absorption spectroscopy. The frequency axis was calibrated using the literature values [24] of the $^5S_{1/2}$ ground state hyperfine splitting of $^{87}$Rb and of the transition frequency of the $^5S_{1/2}$ to $^5P_{1/2}$ transition of the same isotope; possible errors, for example due to pressure shifts in the recorded spectrum, are below the resolution of the display.

with the steepest slope of the discriminant. Figure 8 shows the discriminant of the $F = 3 \rightarrow F' = 2/3$ crossover line obtained by scanning the AOM.

The discriminant also serves as a frequency gauge for converting the voltage recorded with the oscilloscope into frequency. For this purpose the AOM is linearly scanned with $\pm 2$ MHz amplitude around the resonance. The observed line broadening, compared to the natural line width of 6 MHz, is predominantly power broadening, as expected for the employed laser intensity and Rb pressure.

The discriminant of the $^{85}$Rb, the $F = 3 \rightarrow F' = 2/3$ crossover line. The signal was recorded by scanning an AOM with the laser locked to an atomic Cs reference. The observed line broadening, compared to the natural line width of 6 MHz, is predominantly power broadening, as expected for the employed laser intensity and Rb pressure.
discriminant was recorded with a computer. A Labview program read out the voltage from the oscilloscope and stored the mean value over the time $\Delta \tau = 1$ s for a duration of 2 h. The mean value ($\Delta \tau = 1$ s) of the discriminant drifted by about one short-term rms deviation ($\Delta \tau = 200$ ms), i.e. about $130$ kHz, during these 2 h.

The main cause of instability is acoustic noise or pressure drifts, to which open transfer cavities are particularly sensitive: there is a remaining systematic error resulting from the different refractive indices of air at the wavelengths of the two lasers [14]. This differential refractive index change cannot be compensated for with the presented scheme (i.e. without lasers [14]). This differential refractive index change cannot be compensated for with the presented scheme (i.e. without monitoring the atmospheric pressure in the laboratory) and represents its fundamental limitation. Since among the Ca$^+$ lasers and the Cs reference the difference in refractive indices is largest for 852 and 795 nm, the error for the 795 nm laser can be regarded as an upper limit for all lasers.

An analysis following [14] reveals that the observed drift is equivalent to a pressure change of 1 mbar. This is the order of magnitude of the daily cyclic variation of the atmospheric pressure for our latitudes, dynamic fluctuations apart. Since the pressure in our lab is not controlled, it is reasonable to assume that the frequency drift is caused by a pressure drift. This assumption, however, would have to be confirmed by a long-term measurement monitoring the ambient pressure in parallel. Such a measurement, on the other hand, would open the possibility of eliminating the pressure-induced error through appropriate feedback; without it, the sensitivity to pressure fluctuation is the main limitation of schemes using open transfer cavities.

5.3. Allan deviation

For a full characterization of the stability of the 795 nm laser oscillator, the Allan deviation [26] was calculated from the three short-term measurements as well as from the long-term measurement. The four results are plotted in figure 9. The three measurements over 200 ms show good agreement between $\tau = 10^{-2}$ and $\tau = 10^{-2}$ s. The Allan deviation $\sigma_\tau$ decays with $\tau^{-1/2}$ over these two orders of magnitude, down to the $10^{-11}$ region. This indicates the presence of white frequency noise caused in electronic components. It is expected that the accuracy of an oscillator increases with further integration time until other effects, such as long-term drifts, start to dominate [27]. In accordance with this the Allan deviation for the long-term measurement rises again starting from $\tau = 10^3$ s up to $\tau = 10^3$ s. The slope is proportional to $\tau^{1/2}$ indicating that the dominant noise type is a random walk of frequency noise caused by the environmental conditions. This is in agreement with the observation of high sensitivity to pressure fluctuations.

Long- and short-term measurements connect well for time scales of $\tau = 10^{-2}$–$10^1$ s. Although there are data missing between 0.02 and 1 s, the available data are consistent with a flat behaviour of $\sigma_\tau \propto \tau^0$ and an expected flicker noise floor for intermediate frequencies.

For the long-term measurement each data point was averaged by the oscilloscope over 1 s, with no dead time between subsequent points. This ensures that no fast oscillations were disregarded by the measurement apparatus. The three short-term measurements were only sampled, i.e. each data point was recorded after the sampling period specified in figure 9. To make sure that there is no high frequency noise present, an additional fast Fourier transform (FFT) of the Rb saturated absorption discriminant was recorded with the oscilloscope. Figure 10 shows the FFT for a bandwidth of 5 MHz. All noise with higher frequency than that is filtered by the bandpass filter (figure 2). The most prominent peak at $250$ kHz with an amplitude of $45.4$ dBm is still accounted for in the Allan deviation measurement with the sampling rate 2 $\mu$s. For higher frequencies there is no significant noise present. Therefore, sampling without averaging on the time scale of the short-term measurements is expected to not miss any higher frequency noise contributions.

![Figure 9. Allan deviation for three short-term measurements with different sampling rate and 200 ms integration time, and one long-term measurement with 2 h integration time. The dashed-dotted line ($\tau^{-1/2}$) indicates the dominating white frequency noise for high frequencies. The dashed line ($\tau^{1/2}$) indicates the dominating random walk frequency noise for long time scales. The deviations are plotted for time scales allowing for at least 10 data points for each averaging time.](image)

![Figure 10. Fast Fourier transform (FFT) of the Rb error signal for a bandwidth of 5 MHz.](image)
Rabi frequencies fitted curve the experimental parameters are calibrated as follows: calculation based on an eight-level Bloch equation model. From the detection in the direction of the B field. The red solid line is a respect to Rb, as described in section 5.2.

Figure 11. Excitation spectrum of a single $^{40}$Ca$^+$ ion in a linear Paul trap with excitation under 45$\degree$ to the B field and fluorescence detection in the direction of the B field. The red solid line is a calculation based on an eight-level Bloch equation model. From the fit also accounts for slight deviations of the laser polarizations from their ideal values ($<3\%$).

6. Single-ion spectroscopy

To test the stabilization scheme, excitation spectra of single $^{40}$Ca$^+$ ions have been recorded using the ion trap setup described in [28]. The ion is continuously excited by two lasers at 397 nm and 866 nm, and the fluorescence light is red-detuned to provide Doppler cooling. Figure 11 shows the excitation spectrum of a single ion with excitation under 45$\degree$ to the B-field direction. The 397 and 866 nm beams were set to vertical and horizontal polarization, respectively. Each data point represents the count rate on the PMT integrated over 100 ms. The complex structure of the spectrum is caused by two-photon (dark) resonances between the S$_{1/2}$ and D$_{3/2}$ levels. The eight Zeeman sublevels involved in the interaction with 397 and 866 nm light give rise to eight distinct dark resonances (dips in the excitation spectrum). Their positions and sizes depend on the magnetic field and the orientation of the lasers extracted from the fit are $\delta\nu_{397} = 268$ kHz for the blue laser and $\delta\nu_{866} = 128$ kHz for the infrared laser. This is consistent with the linewidth measured with respect to Rb, as described in section 5.2.

7. Conclusions

We have described a laser frequency stabilization scheme for $^{40}$Ca$^+$ single-ion spectroscopy with high short- and long-term stability. The residual rms deviation of 123 kHz is well below all significant transition linewidths of $^{40}$Ca$^+$ and allows us to resolve well dark resonances in the excitation spectra. The Allan deviation proves high long-term stability limited only by pressure changes in the laboratory. The scheme is particularly well suited for measurements with low count rates that require stable conditions over a long time period. For the longest experimental run until the submission of this paper, stable conditions for 40 h were achieved. During this time no noticeable frequency drift on the MHz scale was observed.

The advantage in comparison with other transfer stabilization schemes lies in the use of open table-top cavities. The cavities are built mostly from off-the-shelf parts; no vacuum or ultra low expansion material is needed. A combined temperature and piezo length stabilization of the transfer cavities controlled by a microcontroller is at the heart of the system.

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