Jitter reduction of the 729 nm clock laser for a Ca^+ optical frequency standard

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***Abstract*— The electric quadrupole transition between the ground state and the first metastable state of a single Ca^+ ion is an attractive choice for a frequency standard in the optical domain. Probing of the clock transition is carried out using quantum jump statistics which requires cycle times of several seconds. The spectral linewidth of the probe laser (local oscillator) must reach the hertz level for a duration at least as long as these cycle times. To reduce the TiSa laser linewidth at 729 nm, we use a KD*P electro-optic modulator (EOM) inside the laser cavity. This device shows a couple of mechanical resonances induced by piezo-electric ringing at frequencies larger than 50 kHz, limiting notably the use of the device for frequency corrections. Actual performances ($\Delta\nu$ < 1 kHz for τ < 1ms) of our laser set-up allow the observation of a preliminary spectrum with Zeeman splitting of the 729 nm transition of a single trapped Ca^+ ion.**

I. Introduction

Among the atom candidates for an optical frequency standard, a single Ca^+ ion is extremely attractive. The electric quadrupole transition at 729 nm proposed as frequency reference (clock transition) has a natural linewidth below 200 mHz corresponding to a quality factor of 2×10^{15}; the wavelengths of the required lasers all lie in the visible domain. A single Ca^+ ion, cooled in a miniature radiofrequency trap and confined in the Lamb-Dicke regime, is an almost perfectly isolated atomic system suited for long interrogation times. The main theoretical contribution to the systematic uncertainty of this frequency standard is the quadrupole shift. Thanks to the precise measurement of the quadrupole moment of the metastable $D_{5/2}$ state [1] and the already tested methods to cancel this shift [2,3], the systematic uncertainty is expected to reach $3\text{x}10^{-16}$, limited by the Zeeman effect and the precision of the quadrupole cancellation. Stability is limited by the quantum projection noise and is expected to reach $2.5\times10^{-15}\,\tau^{-1/2}$ [4]. The Ca^+ ion is expected to outperform the best microwave atomic frequency references, and to be competitive with other atomic optical frequency references.

Probing the clock transition of a single ion is carried out using quantum jump statistics which requires cycle times of several seconds. The linewidth of the probe laser (local oscillator) should reach the hertz level for a duration at least as long as the cycle time to take full advantage of the quality factor of the clock transition.

Today, lasers in the visible range can reach frequency stabilities in the Hz range [5]. While the frequency stabilisation is in general made on a high-finesse cavity, the linewidth reduction is achieved by a Pound-Drever-Hall feedback [6], where the counteractions in the various frequency ranges are applied on control elements of different sensitivity and response time. Indeed, different components can be used to fine-tune the frequency of a laser. A piezo-electric actuator which modifies the length of the laser cavity has a bandwidth of a few kHz due to mechanical resonances. Higher frequency corrections can be made by an intra-cavity mounted electro-optic modulator (EOM). We have stated that the use of certain EOMs is limited due to the existence of resonances at frequencies as low as 60 kHz. We have analyzed the behaviour of the phase modifications induced by the EOM and the existence of mechanical resonances induced by a piezo-electrical effect is clearly demonstrated.

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II. Clock laser Set-up

A. *Experimental configuration*

Our local oscillator is a lab-built titanium-sapphire laser [7] pumped with 5 W of singlemode laser radiation at 532 nm (Coherent Verdi V5). The ring cavity is composed of six mirrors and its overall length is about 1.6 m. Different frequency selective elements (Lyot filter, thin etalon, 7 mm-long thick Fabry-Perot etalon) are used to select the output frequency and to assure singlemode operation. The length of the thick Fabry Perot etalon is servoed by way of a lock-in amplifier to keep it in resonance with a unique laser mode.

The pre-stabilisation stage consists of a Pound-Drever-Hall (PDH) lock [6] onto a 30-cm Invar reference cavity. The cavity, which has a finesse of about 1000 at 730 nm, has been

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isolated from external perturbations in a vacuum chamber. The error signal is generated from the light reflected off the cavity; the sidebands created for the implementation of the lock signal are at 40 MHz.

Laser corrections are made in three different frequency intervals; the error signal from the PDH lock is applied to a piezo-electric actuator (PZT) supporting a cavity mirror for the slow but large corrections, the upper limit of this feed-back is limited to 1 kHz to avoid mechanical resonances.

For higher frequency corrections an EOM mounted as a phase modulator is used in the laser cavity. Medium frequency range corrections are amplified (Tegam 2340) in a 400 kHz bandwidth and applied to one connection electrode of the EOM. High frequency corrections are applied directly on the second electrode of the EOM. This electro-optic modulator induces frequency modifications and has to present a linear behaviour in a range as large as DC-10MHz. This is fulfilled if the phase and amplitude response of the modulator are flat in the proposed frequency range.

B. Choice of the intracavity EOM

In the present set-up, frequency corrections in the feedback loop have been unexpectedly limited to 85 kHz, with excess noise present at this frequency. The repeatability (independent of experimental conditions) and the frequency range of this excess noise have lead to the conclusion of the existence of mechanical resonances. The intracavity EOM has been identified as the origin of this resonance, which has been subject of a more detailed investigation.

For the precise identification of the observed resonances, two different experimental configurations have been used (Figure 1) with the EOM mounted either inside the laser cavity or between the laser cavity and the pre-stabilisation cavity.

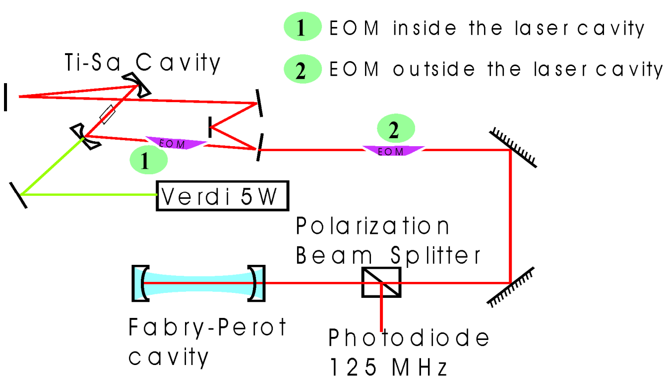


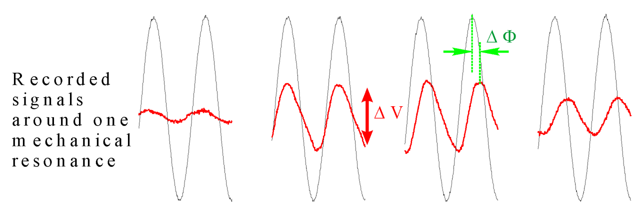
Figure 1 Experimental set-up for the measurement of the resonances of the EOM used for medium and fast frequency corrections.

In the series of measurements using an intracavity mounted EOM we have made benefit of the fact that a tiny misalignment of the direction of implementation of the neutral axis of the phase modulator in the laser cavity will convert a signal modulation in the modulator into an amplitude modulation of the laser beam. This can be measured, for instance by the photodiode which monitors the light reflected off the pre-stabilisation cavity.

A second series of measurements has been made to analyse the effect on the phase rotation induced by the EOM placed in the laser beam between the output of the laser and the Fabry-Perot cavity. Due to the much lower laser power, the measured signals are smaller, nevertheless this set-up allows to test EOMs which cannot be tested intra-cavity due to their elevated transmission losses.

The polarization state of the laser at the output mirror is horizontal. We have aligned the neutral axis of the phase modulator at 45 degree relative to the direction of polarization of the laser light just behind the output coupler of the laser. On the trajectory of the light between the laser and the Fabry-Perot cavity, several optical components select a horizontal polarization. Hence, the effect of a sinusoidal modulation applied to the phase modulator will be converted in an amplitude modulation on the photodiode which detects the light reflected by the cavity. By this straightforward method we can directly measure the response of the phase modulator in the chosen frequency range.

The phase modulator is driven by a 0-20 MHz signal from a commercial synthesizer (Agilent 33220A) and amplified by a gain of 50 (Tegam 2340). Two parameters have been monitored to control the modified laser beam: its intensity and the phase difference between the sinusoidal EOM driver signal and the intensity response measured at the photodiode output.



modulation frequency (kHz)	60.1	60.7	60.8	61
ΔV (Volt)	0.25	1.1	1.2	0.6
ΔΦ (Rad)	$+\pi/3$	0	$-\pi/4$	$-\pi/2$

Figure 2 Resonance behavior of the EOM. In the upper part of the figure, the dotted invariable background signal is the drive of the EOM while the thick foreground signal is the recorded photodiode response. The sharp increase in phase difference corresponds to a resonance behavior.

This experiment has been carried out with two different KD*P and one ADP phase modulators (Linos PM25). One of the KD*P EOMs has been fabricated a couple of years ago, while the second one is of recent production. For both modulators we have recorded several resonances with variable amplitude. These resonances are remarkable because the phase shift of the measured signal rotates abruptly by π radian in an interval of a few hundreds of hertz with a drastic increase of the induced modulation. In Figure 2 the variation of the signal around 60 kHz is shown. The dotted invariable background signal is the drive of the EOM as applied by the frequency synthesizer while the solid thick foreground signal corresponds to the recorded photodiode response. The sharp increase in phase difference reflects resonance behavior.

For the most recent EOM, the first resonance frequency is at 85 kHz, where an amplitude of modulation of a few volts is sufficient to clearly record the effect on the photodiode. For frequencies beyond this value a multitude of resonances can be monitored, without a measurable upper limit to the resonance frequencies.

The resonance frequencies measured with the KD*P EOMs outside the cavity are exactly identical to the frequencies measured with the EOM intra-cavity. As the quality factor of the laser cavity is about 50, the signal of the second series of measurements is reduced by this factor.

Because transmission losses at 729 nm increase the lasing threshold drastically, the ADP EOM has been tested outside the laser cavity. No mechanical resonances could be evidenced, demonstrating the importance of the crystal material and /or crystal mount.

The evidenced mechanical resonances in the frequency range of a KD*P EOM used for frequency stabilisation of a narrow laser are due to piezo-electric ringing in the EOM crystal and strongly limit the use of these devices for the proposed purpose. Mechanical strains due to the mounting of the EOM may modify the value of these resonances, in order maximize the exploitable bandwidth of the EOM. We are still testing different commercial EOMs for intracavity frequency stabilisation, the results described in the following have all been carried out with one of the KD*P EOMs showing its first resonance frequency at 85 kHz.

III. LINEWIDTH MEASUREMENT

The electronic performances of the correction loop on the 729 nm laser are tested by the analysis of the spectral density of the error signal noise as shown on Figure 3. This spectrum is limited to 24 kHz which is the bandwidth of the employed FFT analyser (Brüel&Kjaer 3560-B-040). The upper curve is obtained with only the low frequency corrections (< kHz) on the PZT actuator. This first stage of corrections keeps the laser on the cavity resonance without noise reduction. The lower curve is obtained with the three corrections loops. We observe a nearly 25dB noise reduction in the 15 kHz band where the laser jitter noise is important.

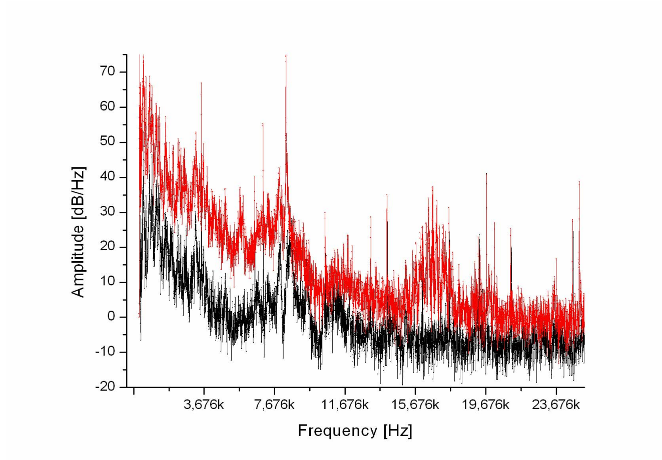


Figure 3 Spectral density of the error signal noise. On the upper curve, only low frequency corrections (<kHz) are applied. On the lower curve low and high frequency corrections are applied

The lock described has allowed us to reduce the jitter of the laser below a few kHz. This width has been measured with an auto-correlation method [8]. For this measurement, we mix two signals coming from the laser on a rapid photodiode. The first is sent through an optical fiber of 10 km length and the second passes through an acousto-optic modulator (mounted in double pass for the first order). The resulting frequency beat signal between both signals is monitored on a spectrum analyzer (HP ESA-L1500A). Some precautions are necessary to employ this technique. First of all, the resolution band width (RBW) of the spectrum analyzer should be smaller than the width of the analyzed signal. Secondly, the recording time is the limit in time on which this method can provide information. With these precautions taken, an important reduction of the spectral linewidth, obtained with the described technique, has been observed as depicted in Figure 4.

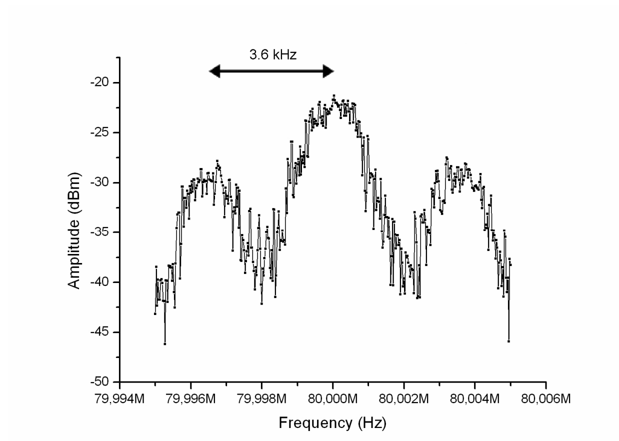


Figure 4 Autocorrelation laser spectrum with a 3.6kHz modulation

At twice the AOM driving frequency, the jitter of the laser can be seen directly, the measured linewidth of the beat signal is 2kHz. With a 10 km optical fiber, we reach the resolution limit of the technique. We also observe 3.6kHz sidebands due to amplitude modulation introduced on the thick etalon for singlemode lock. To eliminate these sidebands on the laser linewidth we modulate the laser frequency with the opposite phase by the way of the EOM [9]. The 3.6 kHz from the Fabry Perot servo is phase shifted and mixed with the PDH signal before being applied on the EOM. Figure 5 presents the autocorrelation spectrum with a 20dB attenuation of the sidebands.

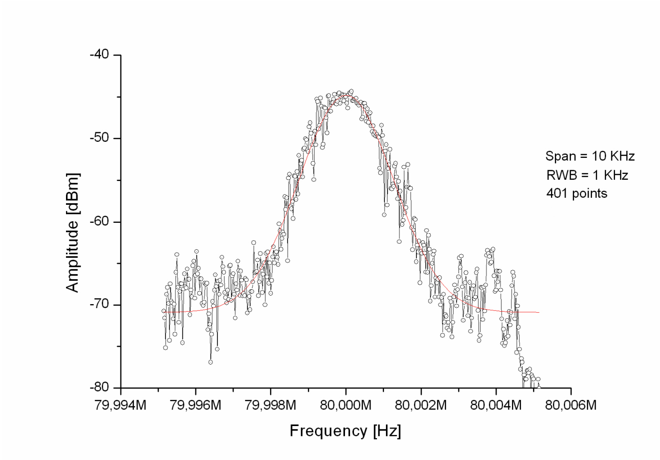


Figure 5 Autocorrelation laser spectrum corrected from the 3.6kHz modulation

IV. LONG TERM STABILISATION

A. Saturated absorption on a Rubidium cell

In a preliminary set up, to confer a frequency stability to the pre-stabilisation reference cavity on a time scale of one second, we lock it to a ^{85}Rb line by a saturated absorption setup using an additional extended-cavity diode laser at 780 nm. The linear absorption of rubidium is effectively suppressed from the detected signal by a modulation transfer technique [10]. The electronic bandwidth of this last stabilisation stage, whose aim is to eliminate the drift of the pre-stabilisation cavity, is about one hertz.

B. New design for an ultrastable cavity

Absolute frequency stabilisation of the clock laser on an ultra-stable high-finesse ULE cavity is under way. The new 15cm-long cavity will have a finesse of 100 000 (Figure 6).

As suggested in ref [12], a vertical mounting will avoid deformations, bending of the cavity and tilting of the mirrors due to gravity. A pyramidal form will limit the relative displacement of the two mirrors. The cavity will be supported in the proximity of the median plan. To optimise the height of the holder that minimise the relative displacement of the mirrors we have used a finite-element analysis with the Cosmosworks© module of Solidworks©. It is a static analysis of elastic deformation for a cavity in a 1g vertical acceleration, similar to the modelisation made in [12]. Tests with different mesh sizes and various contact points were made. Residual relative variation $\Delta L/L$ of the cavity length below 10^{-13} are expected.

The high-finesse cavity will be extremely isolated from environmental conditions. The cavity will be mounted in a vacuum chamber on a vibration isolation platform to eliminate mechanical noise. Two stages of acoustic screening and a passive thermal isolation associated with an active thermal stabilisation are expected to assure the invariability of the ULE cavity length.

Corrections of the PDH stabilisation of the output of the pre-stabilised laser on the ULE cavity will be applied on the Invar pre-stabilisation cavity for the slow part and to an acousto-optic modulator (AOM) for the high frequency part.

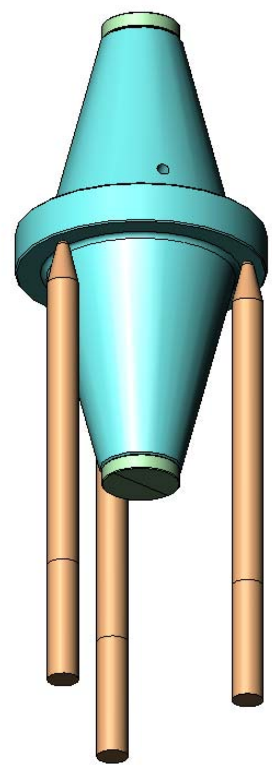


Figure 6 New ULE cavity design

V. ION EXCITATION

A. Fiber transmission

Frequency stable light of the laser is transfered to the ion in a single mode fiber. However, such signal transmission is sensible to acoustic pressure variations leading to a frequency noise of a few kHz in a 10m long fiber. A phase noise cancellation system that modulates the phase of the input beam with the negative of the fiber noise [13] is under way. Using the retro-reflected light from the output of the optical fiber, only one AOM is necessary to create the error signal and apply the corrections.

B. Spectrum of the clock transition of the cooled ion

A single $^{40}Ca^+$ ion is confined and laser cooled in a radiofrequency trap whose dimensions and rf excitation lead to secular frequencies of $\omega_x = 0.7$ MHz and $\omega_z = 0.9$ MHz. A 2 Gauss magnetic field is applied. The applied 729 nm laser power is several microwatts. An experimental spectrum is presented on Figure 7 where the Zeeman splitting is visible.

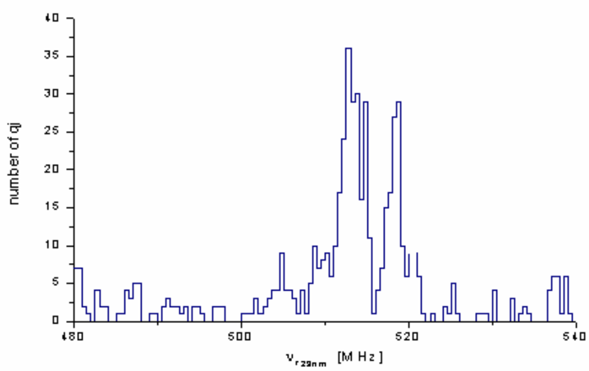


Figure 7 Spectrum of the 729nm transition of a single trapped Ca^+ ion.

This spectrum has been recorded by monitoring the quantum jump probability as a function of the 729 nm laser frequency. Each frequency value has been probed 100 times in a random sequence. It takes about one hour to realise such a spectrum requiring an excellent long term stability of the laser. The resolution is 0.5 MHz.

VI. CONCLUSION

We have described the experimental configuration for the linewidth reduction of the Ca^+ clock laser at 729 nm. The choice of the intracavity EOM for use as a phase modulator for the application of fast frequency corrections is crucial. Low-frequency mechanical resonances in the EOM due to piezo-electric ringing may limit a carefully designed high-bandwidth electronic feedback loop. Absolute frequency stabilization on a high-finesse ULE cavity will allow the clock laser to reach frequency stabilities suitable for the use as a local oscillator in a future optical frequency standard.

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