Strontium Optical Lattice Clock with All Semiconductor Sources

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***Abstract*— We report on our progress toward the realization of an optical frequency standard referenced to strontium intercombination lines. Our current setup allows the production of ultracold Sr atoms in hundreds of ms. For high resolution spectroscopy of $^1S_0$-$^3P_0$ doubly forbidden transition we have also prepared a 698 nm clock laser stabilized on high finesse symmetrically suspended cavity and a high power 813 nm light source for the optical lattice trap at the magic wavelength. All the laser source employed are based on semiconductor device. This opens the way to the realization of compact, reliable and eventually transportable optical frequency standards.**

I. INTRODUCTION

Optical frequency standards based either on alkali-earth neutral atoms trapped in optical lattices or single trapped ions, have today demonstrated tremendous advantages in terms of short term stability (approaching 10^{-15} at 1 s [1], [2]) and ultimate accuracy (below 10^{-17} level [3]). While many optical clocks based on either neutrals and ions have already been realized and tested, these systems are far to be compact, generally requiring an entire laboratory room. At least 5 different wavelengths are necessary both for single ions and optical lattice clocks (sometimes in the UV region of the spectrum) involving frequency doubling or quadrupling stages starting from high power infrared sources. Among all candidates for an optical frequency standard, neutral strontium has the main advantage to have all the transitions required for the clock operation (cooling and trapping, repumping and clock interrogation) in the visible or near infrared part of the spectrum. This represents a huge advantage since this wavelength are easy to be produced with compact, reliable and typically inexpensive semiconductor laser sources, reducing the setup complexity.

Here we present an experimental setup we are developing toward the realization of an optical frequency standard based on neutral Strontium atoms. For this purpose two new compact laser sources have been developed: the first is a clock 698 nm frequency stabilized laser source, the second, an infrared 813 nm high power infrared source to trap atoms in the optical lattice at the magic wavelength.

II. STABLE LASER AT 698 NM

The scheme of our stable master source resonant with the intercombination $^1S_0$-$^3P_0$ transition for strontium atoms is reported in Fig. 1.

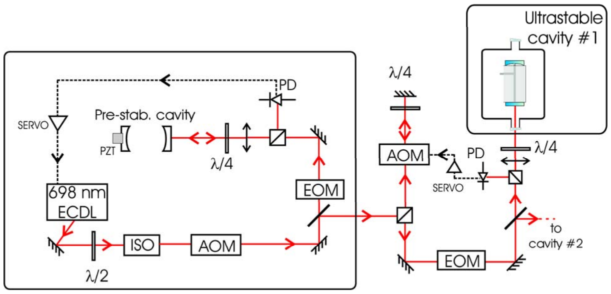

Fig. 1. *Experimental setup for the stable 698 nm laser, ECDL: extended cavity diode laser, AOM: acusto-optic modulator, OI: 30 dB optical isolator, EOM: electro-optic modulator, PMF: polarization maintaining fiber.*

The master laser is a 698 nm diode laser (non AR-coated) mounted in extended cavity configuration (Littrow configuration). The diode operates around 40 °C and delivers about 10 mW of optical power at 82 mA.

The reduction of the laser linewidth is done with a two-step Pound-Drever-Hall frequency stabilization to optical cavities: first, we reduce the linewidth to $<$ 1 kHz by locking the laser to a resonance of a pre-stabilization cavity, and then, we reduce further the linewidth by locking the pre-stabilized laser to a resonance of an ultra high finesse cavity [4], [5].

The first pre-stabilization cavity is realized with an invar spacer sitting on a v-shaped aluminium block and has a finesse of 10^4. The resonance is about 150 kHz wide. The servo signal is sent to the PZT control of the laser extended cavity up to 5 kHz, and directly to the diode current with a bandwidth of about 2 MHz [6], [7].

The high finesse cavity is realized with a 10 cm long ULE (High grade Corning 7972 glass) spacer with two optically contacted SiO_2 mirrors. The ULE spacer has a 'slotted' shape to allow the possibility to symmetrically support the cavity along the optical axis and reduce the sensitivity to mechanical vibrations.

The cavity is supported horizontally under vacuum (10^{-8} Torr, maintained with a 20 l/s ion pump) with two aluminium arms connected by three low-expansion iron shafts. The effective supporting points are four square areas (about 2 mm^2 in size) with Viton square pieces (0.5 mm thickness) between the aluminium supporting points and the ULE spacer surface. The vacuum chamber is done with thick aluminium walls (5 cm) to improve the thermal inertia of the system. The temperature of the outside surface of the vacuum can is actively stabilized at 25 °C by controlling the current passing through a high resistance (Alumel) cable rounded around the can itself. The measured time constant of the system in that condition is about 3 hours, while the residual temperature error is below 50 mK peak to peak. Two identical cavities have been mounted inside independent vacuum systems to allow performance tests of the frequency stabilized laser.

The finesse of the cavity has been deduced both by measuring the photon cavity lifetime τ=43(2) μs and by directly observing the linewidth $\Delta\nu$=3.7(0.5) kHz of the TEM$_{00}$ mode of the cavity. The two independent measurements give for both cavities a finesse of 4.1*10^5 within 4% of error corresponding to 7 ppm total losses for each mirror and a cavity quality factor of 1.2 10^{11} [8].

The second stabilization loop acts at low frequencies (up to 1 kHz) on the PZT of the pre-stabilization cavity to compensate for low frequency drifts, and at high frequency (up to 50 kHz) to the AOM used to shift the frequency of the laser through the driving RF frequency generator. The power coupled into the high finesse cavity, when the laser is locked to the lowest TEM$_{00}$ mode of the cavity is about 60%, while the transmission is typically of the order of 15% . This value is consistent with the measured losses of the mirror.

In fig.2 it is reported the frequency noise of the 698 nm clock laser source, measured by sending part of the light, frequency shifted with an AOM, to the second independent cavity sitting on the same optical table, and analyzing the error signal obtained when the frequency of the beam is steered around the resonance of the second cavity.

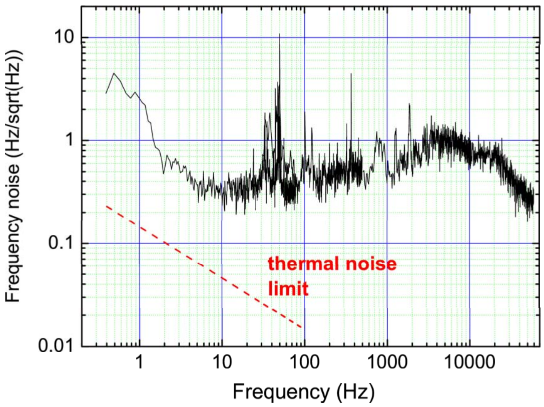

Fig. 2. *Frequency noise of the stable 698 nm laser source locked to the high finesse cavity. The dashed line represents the calculated thermal noise limit due to the contribution of the ULE spacer, the SiO$_2$ mirror substrate and the Ta$_2$O$_5$/ SiO$_2$ coating .*

The thermal noise limit, estimated taking the value for ULE, fused silica and mirror coating reported in [9], for this cavity is also shown in fig.2. This noise level is about 3 times smaller with respect to the noise level in vertical cavities realized at the same wavelength for similar purpose [5] limiting the frequency stability at 3.7*10^{-16} level. The laser is far to be limited by the thermal noise contribution of the cavity, and optimization of the servo loop parameters and reduction of seismic and acoustic noise contribution is under development. From the analysis of the error signal on the second stabilization loop, we can calculate a laser linewidth of the order of 1 Hz.

To check independently this value and the residual cavity drifts due to temperature variations we also lock the frequency of beam delivered from the source to the second cavity and beat the two beams independently locked to the two resonances of the cavities. The recorded beat note is reported in fig.3. For convenience the frequency has been down-converted from 200 MHz to about 3 kHz. In the inset is shown also the Allan variance calculated removing the linear drift (residual drift of 4 Hz/s due to residual thermal control instability) with a computer controlled RF generator.

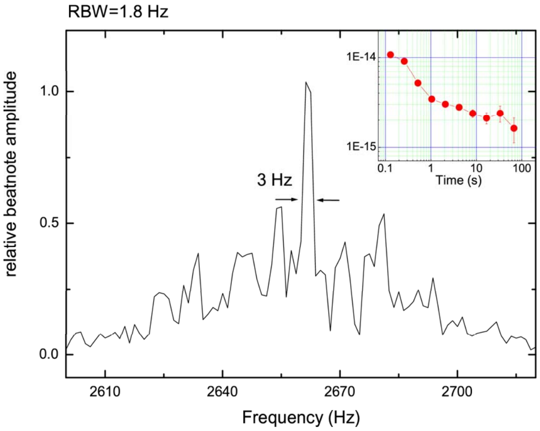

Fig. 3. *Beatnote of two beams frequency locked independently to two resonances of independent cavities. The linewidth observed with a resolution bandwidth of 1.8 Hz is about 3 Hz. In the inset is shown the Allan variance of the counted beatnote (0.1 s counter gate time) after removal of residual drift.*

A preliminary measurement of the thermal expansion coefficient near room temperature has been done by changing the temperature of one of the cavities while maintaining the other one stabilized and measuring the relative shift in the TEM$_{00}$ mode of the two cavities. We found a mean value of 5 10^{-8} for the CTE coefficient in the temperature range of 22 - 25 °C. This value is larger than we expected from ULE specification, and might be due to the residual temperature expansion coefficient of the two SiO$_2$ mirrors [10].

Ultimately, we checked the sensitivity to acceleration of the stabilized laser system, by observing the frequency noise imposed into the laser by acceleration in the vertical and horizontal direction. We found a value of 30 kHz/g and

240 kHz/g for the sensitivity respectively for vertical and horizontal directions, in good agreement with the results of our FEM simulations of the cavity static distortion induced by accelerations.

III. FIBER NOISE CANCELLATION

We have also tested fiber noise cancellation schemes. This will be necessary to transfer the coherence of the clock laser source to the Strontium cold atoms lab placed in a different building 200 m apart from the clock laser room.

Preliminary tests have been performed with a 25 m long polarization maintaining fiber. The scheme of the apparatus is similar to the one reported in [11], [12].

We realize a standard interferometer configuration, where part of the light coming from the stabilized 698 nm ECDL is sent to the fiber and reflected back (after a frequency shift), and part of the light used as a reference. The phase noise added by the fiber can be observed directly at low frequency by mixing the beatnote between the two beams with a reference oscillator. To enlarge the capture range of the servo system we choose a fast digital phase and frequency detector (PFD). The response of this devices is linear over 4π rad with high rejection to resonant AM noise. The error signal obtained is then used to modulate a voltage controlled oscillator (VCO) that drives the AOM at around 80 MHz.

We obtain a of about 40 dB reduction of phase noise at 10 Hz with a loop bandwidth of 1 kHz . The residual phase noise level (see fig. 4)is sufficiently low for transfer a 1 Hz linewidth laser without a degradation in linewidth at the far end of the fiber.

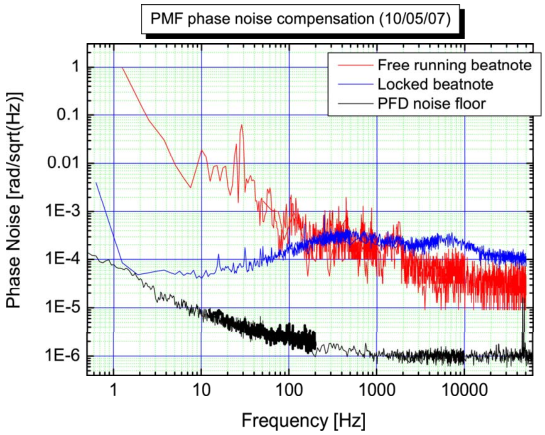

Fig. 4. *Phase noise of the laser transmitted over the 24 m PM fiber. The three lines indicates repectively the uncompensated noise, the residual phase noise with the compensation loop active, and the noise floor of the digital phase-frequency detector.*

IV. INFRARED LASER AT 813 NM FOR TRAPPING STRONTIUM AT MAGIC WAVELENGTH

We developed and tested an all-semiconductor 813 nm light source to trap atoms in optical lattice. The source is based on an extended cavity AR coated diode laser delivering up to 40 mW at 813 nm and a tapered amplifier.

With typical injected optical power of 20 mW and a driving current of about 1.6 A it is possible to obtain 600 mW at the output of the tapered amplifier at . About half of that power is then coupled into a polarization maintaining fiber, delivering up to 300 mW to the atoms in standing wave configuration. The whole source is mounted on a 50 cm x 50 cm breadboard.

With this optical configuration we could transfer more than 10% of the atoms from the MOT operating on the ${}^1S_0$-${}^3P_1$ transition (see below). We observed a trapping lifetime of 2 s limited by background collisions.

This source represents a valid alternative to more expensive and more complex Ti:Sa laser systems used so far to trap Strontium neutral at the magic wavelength [13].

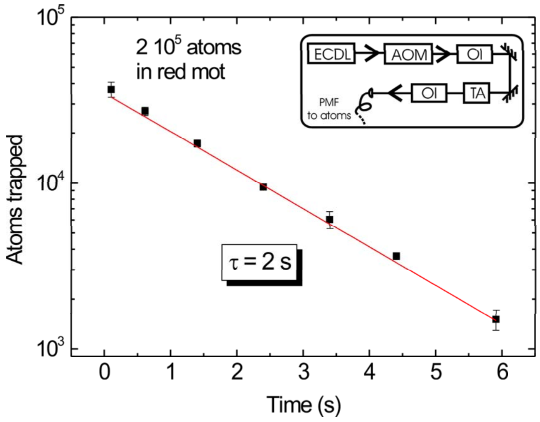

Fig. 5. *Measurement of the lifetime ^{88}Sr atoms trapped in the 813 nm 1D lattice. In the inset the laser setup is presented. ECDL, Extended cavity diode laser, AOM, acusto-optical isolator, OI optical isolator, TA tapered amplifier.*

V. COOLING AND TRAPPING STRONTIUM

The experimental setup used to trap and cool strontium atoms has been described in detail elsewhere [6], [14], [15]. With the current setup it is possible to cool and trap more than 10^7 Sr atoms at μK temperatures in hundreds of ms. The laser sources for trapping and cooling are all semiconductor based. For the first cooling and trapping stage on the ${}^1S_0$-${}^1P_1$ transition we used two frequency doubled infrared lasers delivering repectively 200 mW at 461 nm (922 nm extended cavity diode laser amplified with a tapered amplifier and doubled in doubling cavity with PPKTP crystal) and 1 mW at 497 nm (994 nm ECDL frequency doubled with $KNbO_3$ crystal). For the second stage cooling on the ${}^1S_0$-${}^3P_1$ transition, a frequency stabilized ECDL at 689 nm is employed. To detect the clock transition with maximum S/N ratio with shelving technique, it is possible to use additional repumpers at 679 nm and at 707 nm that also could be realized with simple ECDLs.

VI. CONCLUSION

We presented new laser sources and the experimental apparatus to be used for precision spectroscopy of intercombination lines of strontium. All the laser sources employed to cool, trap, and interrogate Sr neutral atoms are based only on semiconductor devices. The compactness and reliability of such sources represent one of the first steps towards the realization of a transportable optical frequency reference to be employed in fundamental and applied physics on Earth and in space.

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