Preliminary Results of the Trapped Atom Clock on a Chip

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***Abstract*— We present an atomic clock based on the interrogation of magnetically trapped ^{87}Rb atoms. Two photons, in the microwave and radiofrequency domain excite the clock transition. At a magnetic field of 3.23 G the clock transition from |F=1, mF=–1⟩ to |F=2, mF=1⟩ is 1st order insensitive to magnetic field variations. Long Ramsey interrogation times can thus be achieved, leading to a projected clock stability in the low 10^{-13} at 1s. We use an atom chip to cool and trap the atoms. A coplanar waveguide has been integrated to the chip to carry the Ramsey interrogation signal, making the physics package as small as $(5cm)^3$. We describe the experimental setup and show preliminary Ramsey fringes of line width 1.25Hz.**

I. INTRODUCTION

Current research on atomic clocks aims at numerous purposes and applications. The development of clocks that are more accurate, and will probably lead to a new definition of the SI second, is at one extremity, with optical clocks showing accuracies as good as 5.2 10^{-17} [1]. On the other hand is the invention of miniaturized clocks, such as $10mm^3$ volume vapor cell clocks, showing stabilities of 2-3 10^{-10} at 1s [2]. Between these two lies the need of liter-sized atomic clocks with a stability of the order of 10^{-13} at 1s, for applications like navigation. Among the candidates, trapped ions clocks have shown the best stability so far [3], and a satellite-borne model of such a clock, LITE, is currently under development. The HORACE experiment showed a stability of a few 10^{-13} at 1s [4], interrogating laser cooled Cs atoms in free fall. Here we present a clock that interrogates magnetically trapped ultra-cold atoms. Being at the intersection of LITE and HORACE, the storage of trapped neutral atoms gives access to long interrogation times as well as high numbers of atoms. A compact setup is realised based on the atom chip technology. Atom chip experiments have been widely used for the study of ultra-cold gases and Bose-Einstein condensates [10-13]. They enable liter-size physics packages, low power consumption and fast atom cooling. Interesting regimes of physics such as quantum gases in low dimensions have been studied in atom chip experiments opening possible applications beyond clocks such as quantum information processing or atom interferometry. We describe our experimental setup merging atomic clocks and atom chips for the first time on a dedicated experiment. We present preliminary results in the form of Ramsey fringes.

The clock transition is defined by the two-photon transition between the $|1\rangle \equiv |F=1, m_F=-1\rangle$ and the $|2\rangle \equiv |F=2, m_F=1\rangle$ states of the ground state of ^{87}Rb. The transition is excited by a micro-wave photon near resonant with the |1> to $|F=2, m_F=0>$ transition completed with a ~2MHz RF-photon [5]. The transition frequency is first-order insensitive to fluctuations of the magnetic field at the "magic" field of 3.23G [6]. Moreover, the scattering lengths of the clock states differ by only 5%. Coherence times of up to ~2.5s seconds have been demonstrated for this transition [6], even in the vicinity of an atom chip [7]. A stability of 1.7 10^{-11} at 1s has been demonstrated [7] using a setup which was not intended for metrology. By simple technical improvements, we estimate a possible improvement of the stability by one order of magnitude. Moreover, while the second order Zeeman shift and the mean field shift have the strongest effect on the decoherence, we calculated that their compensation can make the clock frequency almost constant throughout the trap volume, potentially increasing the coherence time to 20 s [8]. Even for more conservative estimates assuming 1s of Ramsey interrogation, we predict a frequency stability near to 10^{-13} at 1s using ultra-cold thermal atoms. In a second stage we will investigate the use of BEC in this clock. The use of BEC in metrology applications has been largely discussed in the literature but so far no systematic experimental investigation has been carried out. Interesting features may lie in the cancellation of the collisional shift as suggested in [9].

II. EXPERIMENTAL SETUP

Atom chips are now widely used devices in atomic physics laboratories. They have led to major advances in the understanding and manipulation of Bose Einstein Condensates [10]. The founding idea of atom chips is to trap "low-field

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seeking" atomic states using the gradients of the magnetic field generated by micro-fabricated current carrying wires. Furthermore, one can take advantage of the industrial knowledge to integrate complex structures to the chip. Among these are fibered optical cavities [11], mechanical resonators [12] or integrated optics [13].

Our chip's feature is the integration of a coplanar waveguide (CPW) designed to transmit the 6.834GHz signal. This kind of transmission line consists of three parallel wires, with the two external wires being grounded. The microwave signal oscillates between the central wire and the external ones as it would between the core and the gain of a coaxial cable. The microwave can either propagate along the line, if it is terminated by a 50Ω load, or form a standing wave, if a total reflection is created at the end of the line. The integration of the CPW to the chip allows us to drive atomic transitions in the trapped atomic cloud without the constraint of designing a cavity or the use of a power-consuming horn. It also prevents phase instabilities due to microwave reflection, since the atoms interact with the waveguide's evanescent field.

Before being loaded to the chip magnetic trap, the atoms are pre-cooled in a magneto-optical trap (MOT) and optical molasses. Our experiment is based on the mirror-MOT technique [14], whereby two of the 6 laser beams commonly necessary for laser cooling are generated by reflection from the chip surface. In a patented vacuum cell system, the chip is glued upside-down on top of a commercial glass cell [15]. It thereby closes the vacuum system and remains accessible for power dissipation and electric connection from its back. The inner surface of the chip is coated to act as a mirror at 780 nm. The vacuum cell is surrounded by a stand-alone "optical hat" (Fig. 1) which includes both coils for the generation of homogeneous magnetic fields and optics to provide the cooling and detection light.

A. *The Chip*

Our chip (Fig. 2) is a two-layer AlN chip similar to the one described in [16]. A 24x28 mm^2 "science chip" is glued onto a 38x45.5mm^2 "base chip" which closes the vacuum cell. The "science chip" includes the coplanar waveguide that carries both the microwave signal for the Ramsey spectroscopy and a D.C. current for magnetic trapping. It has been designed to have maximum transmission at 6.834 GHz. The atoms, held at a distance of 150 μm from the chip interact with the waveguide's evanescent field. No micro-wave signal is radiated, avoiding phase instabilities due to reflections. Sufficiently high (typically kHz) Rabi frequencies can be achieved with reasonable microwave power (~ 0 dBm).

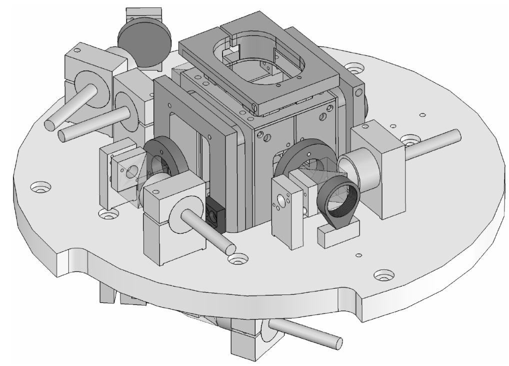

Figure 1. The optical hat. A small optical platform carries laser beam expanders and magnetic field coils. All components are prealigned and the hat is slipped over the (5cm)^3 vaccum cell containing the atom chip.

The second photon is provided by a RF signal, which is also carried by the science chip on a standard wire. RF is equally used for the evaporative cooling, where Zeeman transitions eject the hottest atoms from the magnetic trap leaving the remaining atoms at sub-micro Kelvin temperatures.

Our 2-layer chip design prevents wire crossings and thereby uncontrolled micro-wave reflection with the CPW. All science chip wires are parallel to the CPW and provide transverse trapping. Orthogonal wires giving longitudinal confinement have been put on the base chip. They can be used to generate different types of traps such as Ioffe-Pritchard (Z), quadrupolar (U), or dimple traps [17]. The base chip also provides all the electrical connections including mini-SMP connectors for the microwave signal. These are placed outside the vacuum.

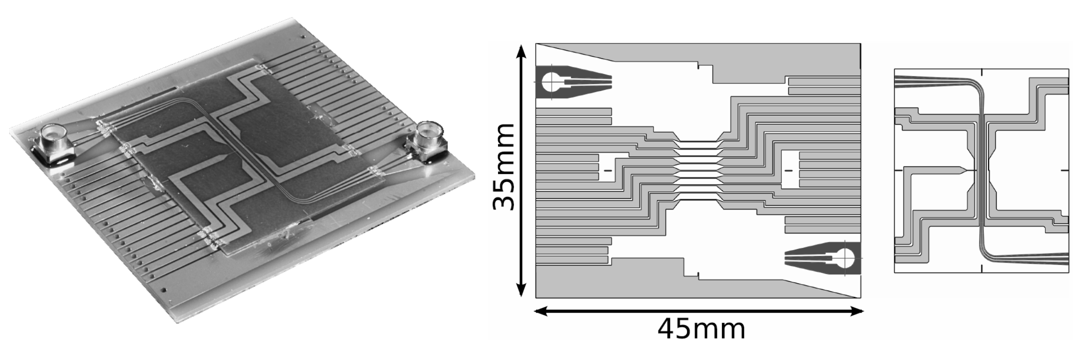

Figure 2. Right: the actual chip. Left: schematics showing base and science chips. In dark grey is the CPW.

B. *The Optical Hat*

The optical hat (Fig. 1) is a compact optical table that fits around the chip and vacuum cell. The light is brought in by optical fibers from a $60x80cm^2$ optical breadboard. The optical hat also holds three pairs of coils for the generation of homogeneous magnetic fields. All components are pre-aligned such that the hat can easily be slipped-over (and be removed from) the vacuum cell. Once installed, set-screws give mechanical contact with the vacuum system to avoid vibrations. Two layers of magnetic shielding enclose the optical hat giving a magnetic field stability below 50 μG.

C. *Experimental Sequence*

The experimental sequence is as follows: a magneto-optical trap is used to collect and pre-cool atoms from a room-temperature vapour. Optical molasses cools the atoms to 10 μK before an optical pumping pulse transfers them into the clock ground state. A first magnetic trap is ramped on containing ~66% of the atoms. Compression of the trap increases the collision rate and accelerates cooling through rf evaporation. The evaporation must both decrease temperature and increase the phase-space density to reach the onset of Bose Einstein condensation [18]. The atoms are typically cooled to a few 100 nK, near – above or below – the critical temperature. The trap is then decompressed to perform the Ramsey interrogation in a shallower confinement. This reduces the second order Zeeman shift as well as the mean-field shift. Finally detection is carried out by releasing the atoms and imaging their absorption 1 mm below the chip. Currently, one clock cycle takes about 10 s, where 6 s count for the initial MOT loading and 3 s for the evaporative cooling. A second generation set-up will bring substantial reduction of this dead time to by loading from an additional 2D MOT in much less than 1 s and optimised evaporation lasting 1 s.

III. First experimental results

A. *Preparation of Bose Einstein Condensates*

The cooling of atoms from a thermal atomic cloud down to the quantum degeneracy is a spectacular phenomenon as well as a technical challenge. Although near to a hundred experiments exist world-wide, care must be taken, in particular to prevent heating due to technical noise or bad vacuum. When building a metrology experiment, this is all the more useful, as good control of the experimental parameters is required. Obtaining a BEC with our setup is therefore a natural first step demonstrating its correct operation.

We are currently able to load a 6000 atoms pure condensate of the clock ground state.

We perform evaporation in a stiff confinement with trap frequencies of {95Hz, 1kHz, 1kHz}. The RF cooling frequency is exponentially ramped from 25 MHz to 4.2MHz, resulting in a sample of 40000 atoms at less than 500nK. Further descent to 4.09 MHz produces a pure condensate of 6000 atoms. "Fig. 3" shows three atom clouds prepared by decreasing cooling frequencies after release from the trap and 16 ms of free fall. A thermal cloud (left) is characterised by a broad isotropic distribution indicating high thermal velocities. Atoms in a condensate (right) have almost negligible velocity resulting in a strongly peaked distribution.

B. *Ramsey Fringes*

Having established the atom preparation, we probe the clock transition starting with non-condensed atoms. We can selectively image the atoms in the ground or excited state by adding or not repumping light to the detection light. Since the atoms are prepared in the ground state, detecting the excited state alone quantifies the excitation probability.

The two-photon Rabi frequency is set to about 500 Hz, by adjusting the RF and microwave powers to be roughly equal. The detuning of the intermediate state (F=2, m_F=0) is set to about 500 kHz to avoid atom lost from coupling to un-trapped states. We then perform Rabi spectroscopy in order to coarsely localize resonance frequency, before changing to Ramsey interrogation.

We use Ramsey fringes in the time domain to measure the coherence time (fig. 4). The measured coherence time is 450ms for our preliminary parameters of trap frequencies {50 Hz, 300 Hz, 300 Hz} and a magnetic bias field detuned from the magic field by about 100 mG. We set the Ramsey interrogation time to 0.4 s, close to this coherence time and perform Ramsey spectroscopy. Fig. 5 shows Ramsey fringes measured in the frequency domain. The fringe FWHM is 1.25 Hz and the contrast is 40%.

Figure 3. Atom distribution after evaporatif cooling. Left: A thermal ensemble of atoms at 300 nK. The broad distribution reveals the residual thermal velocity. Right: A pure Bose Einstein condensate containing 6000 atoms. The strongly peaked distribution idicates the almost negligible atom velocity.

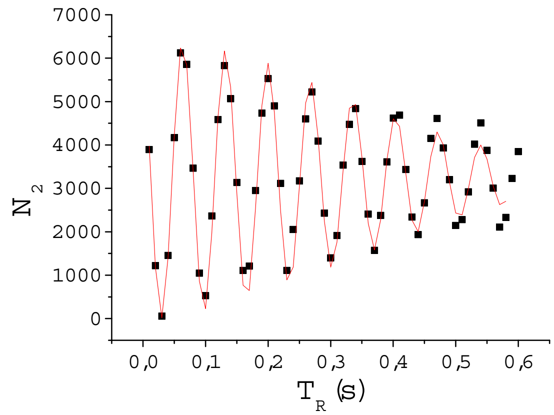

Figure 4. Ramsey Fringes in the time domain. The number of excited atoms is given as a function of the delay between the two Ramsey pulses. The Rabi frequency is set to 500 Hz. The oscillation shows an exponential descrease of the constrast giving a coherence time of 450 ms.

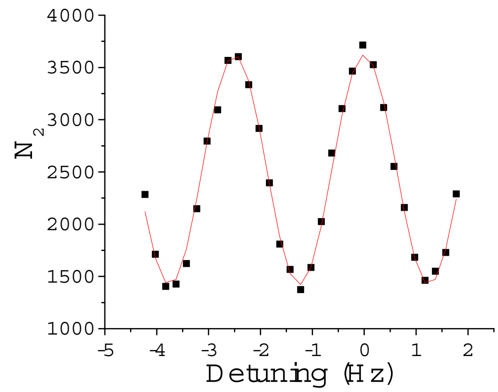

Figure 5. Ramsey spectroscopy of the clock transition. The number of excited atoms is plotted against the detuning from the atomic transition. The FWHM the central fringe is 1.25 Hz. Its contrast is 40%.

The observed coherence time lacks behind published measurements by more than a factor 5. Possible explanations lie in the non-optimised trap parameters as well as in the fact that the magnetic shield is yet to be installed. In addition the atomic density plays an important role. The lifetime of the excited clock states is measured to differ by more than a factor of three from that of the ground state. Better results are expected when transferring the atoms to an even shallower trap.

IV. Conclusion

Preliminary results of an atomic clock using magnetically trapped atoms on an atom chip have been presented. The preparation of a Bose-Einstein condensate containing 6000 atoms has been installed. Ramsey interrogation of thermal ultra-cold atoms in a preliminary magnetic trap realised a 1.25 Hz line width. Completion of the experimental set-up and optimisation of the trap parameters will allow more than a factor 5 line width reduction. Renormalization of the atom number and shot-noise limited detection will enable a clock stability of 10^{-12} at 1s or better.

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