Progress Towards a Compact Cold-Atom Microwave Clock

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***Abstract*—Here we present progress towards a compact cold-atom microwave clock. The system we have developed is currently a demonstrator for a clock architecture whereby a cloud of laser-cooled caesium atoms are dropped and interrogated during free fall. We describe the experimental sequence as well as show preliminary results related to signal-to-noise ratio limits and Rabi microwave spectroscopy.**

***Index Terms*—compact, cold-atom, microwave clock, laser cooling, caesium, magneto-optical trap, signal-to-noise, Rabi spectroscopy**

I. Introduction

Compact atomic clocks are crucial for numerous applications such as: GNSS (global navigation satellite systems) holdover, telecommunication synchronisation, energy grid synchronisation, operational timescales, radio astronomy, and navigation systems. Most existing compact atomic clocks operate using thermal atoms confined in vapour cell. Inside the vapour cell is a buffer gas which acts to slow the atoms down, and prevent them from colliding with the walls of the cell. This extends the achievable interrogation time. However, the presence of the buffer gas leads to a temperature-dependent frequency shift which limits the long-term stability [1] [2].

To mitigate this, the atoms can be laser cooled. With laser cooling, atomic temperatures of a few tens of μK can be reached. At these temperatures, the kinetic velocity is a few orders of magnitude slower and a buffer gas is no longer needed. Thus, the atoms can be interrogated for longer which allows for a narrower Fourier-limited linewidth of the clock transition. This leads to an improvement of the short-term stability. Furthermore, the long-term stability is no longer limited by the presence of a buffer gas. However, the experimental complexity accompanying laser cooling usually increases the overall clock size. Hence, in recent years there have been several research efforts to develop compact laser-cooled atom microwave clocks [3] [4] [5].

We report on the development of a compact cold-atom microwave clock. The experiment is a demonstrator for a clock architecture where a cloud of laser-cooled caesium (Cs) atoms are dropped through an interrogation region. This type of architecture has previously been explored using rubidium [6] [7]. The target performance for this clock technology is a short-term stability in the region of low $10^{-12}\ \tau^{-1/2}$.

The work reported here is supported by an EPSRC industrial-CASE studentship.

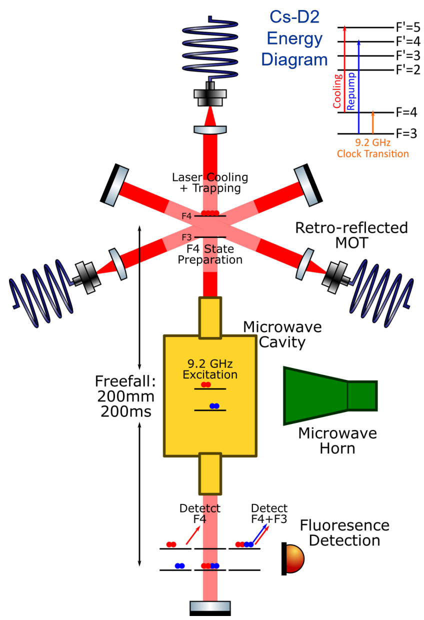

Fig. 1. Schematic of the experimental architecture. Cs atoms are first trapped in a MOT, then dropped under gravity through an interaction region where the clock transition is excited. Then fluorescence detection is performed using the same vertical beam from the MOT.

II. Experimental Sequence

The experimental sequence of the clock is as follows. Cs atoms are first laser-cooled and trapped in a retro-reflected magneto-optical trap (MOT), after which there is a brief second stage of polarization-gradient cooling. The laser light is then completely extinguished with the repump being left on momentarily. This ensures the atoms are optically pumped into the $F4$ ground state. The cloud then falls under gravity down the vacuum chamber into the interrogation region. Interrogation of the clock transition is performed using a 9.192 GHz microwave source. The cloud continues to fall into a detection region at the bottom of the flight tube. The same vertical beam from the retro-reflected MOT is reused to perform fluorescence detection. An initial pulse of cooling light induces fluorescence of the $F4$ atoms whilst also optically pumping them to the $F3$ state. A brief repump pulse pumps everything back up to $F4$ including what was initially in $F3$. A final pulse of cooling light again induces fluorescence which will now come from $F4 + F3$ atoms. An additional background BG pulse is taken a sufficient time after the cold atoms have dispersed. $N = (F4 - BG)/(F4 + F3 - BG)$ determines the normalised fraction of atoms which have undergone the clock transition [8]. An example of these detection pulses can be seen in the figure 2 inset. The experimental sequence is run continuously and the resulting fraction from each cycle is used to discipline the output from a 10 MHz crystal oscillator. A schematic of the physics-package is shown in figure 1.

III. Microwave Source

We have initially performed microwave interaction using a horn antenna. However, we intend to replace this with a resonant microwave cavity. To utilise the full drop time of 200 ms, the atoms would need to be interrogated as soon as they are released from the MOT. A Ramsey interrogation with a dark time of ∼150-200 ms is the goal. The cavity design is yet to be decided but there are a few aspects which we would like to incorporate. The cavity will form part of the vacuum chamber as well as supporting the resonant microwaves. A low loaded-Q (∼few thousand) cavity will relax the requirement for temperature stabilisation. A single microwave feed to the cavity will simplify the phase adjustment between the two interaction regions. These design aspects will help to maintain experimental simplicity.

IV. Results

The results from the demonstrator system have primarily been focused on characterisation of the cold-atom cloud. We have measured the cloud temperature to be ∼12 μK using a release and recapture method [9] [10]. Furthermore, we determine the number of atoms trapped after a 500 ms MOT load time to be $\sim 10^6$.

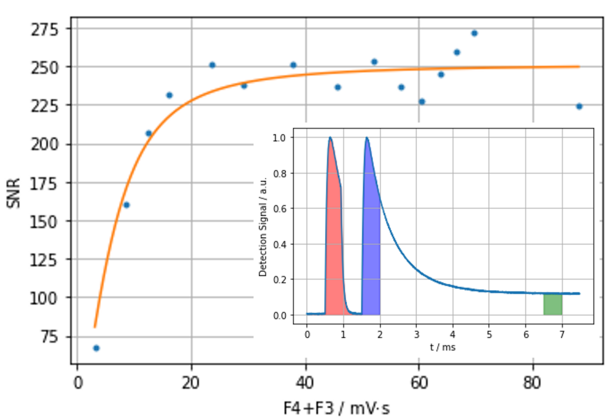

Fig. 2. SNR vs $F4 + F3$ detection signal. This detected signal is the integrated signal under the 2nd detection pulse (blue) and hence has units of mVs. $SNR = \bar{N}/\sigma_N$. Towards large signal sizes the SNR quickly tends towards a limit of ∼250. The inset shows an example of the detection pulses. Red: atoms in $F4$, blue: atoms in $F4 + F3$, green: background BG.

Currently, the state preparation involves optically pumping all the atoms into the $F4$ state where they will be evenly distributed across the nine Zeeman levels. There is no additional state-selection process. This means the useful clock signal fluorescence sits atop a background from the other non-clock state atoms. The result is that the microwave interaction only induces a small fractional change (5-11%) of the clock signal. To resolve this we need a relatively strong signal-to-noise ratio (SNR) in the detection system. In figure 2, we investigate the detection SNR performance by plotting SNR against the fluorescence induced by the 2nd detection pulse (blue). This fluorescence is from $F4 + F3$ atoms, and is hence related to the total atom number. The atom number can be varied by loading the MOT for different times. The signal in SNR is the average of the population fraction N from 100 experimental shots, and the noise is its standard deviation. The 100 shots are performed without the microwave interaction and thus on average N should be 1. Towards large signal sizes the SNR quickly tends towards a limit of ∼250. This lack of dependence on signal size indicates some form of proportional noise source limiting the SNR. Potential noise sources could be from laser intensity noise, laser frequency noise, or possibly environmental fluctuations such as magnetic field.

We have performed prelimnary microwave spectroscopy which can be seen in figure 3. We drop the atoms a short distance within the MOT chamber during which we perform a brief 5 ms Rabi pulse.

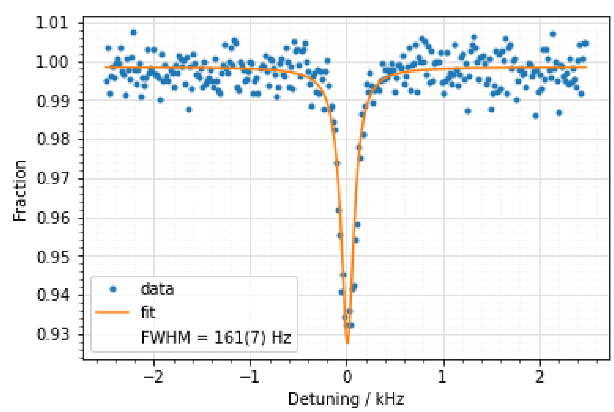

Fig. 3. 5 ms Rabi pulse using the horn antenna. A Lorentzian is fitted to the data which shows a linewidth of 161 Hz. The error quoted is the standard deviation returned from the fitting procedure.

V. Summary

Here we report on the experimental progress towards a compact cold-atom microwave clock. This system is a demonstrator for a clock architecture in which a cloud of laser-cooled Cs atoms are dropped through a clock state interrogation region. We have constructed an optical setup for laser cooling/trapping and clock state detection, custom electronics for controlling the experimental sequence, and a vacuum chamber for the physics-package. Currently, our demonstrator physics-package is size-limited by the lack of magnetic shielding and a bespoke vacuum chamber. We envisage a second iteration of this system could be made much smaller if these aspects were incorporated. Furthermore, a resonant microwave cavity will allow us to unlock the full potential of the 200 ms drop time. Preliminary results indicate that the SNR of our detection system is currently limited to ∼250. We have also performed preliminary Rabi spectroscopy using a horn antenna. We intend to conduct further optimisation to both of these areas before implementing closed-loop clock operation.

ACKNOWLEDGEMENTS

The authors would like to thank the NPL compact-clocks group, NPL fountain group, Yb-Ion microwave group, and Yuri Ovchinnikov for their useful discussions and help troubleshooting issues in the lab. Additionally, Peter Tsoulos and Gary Hockley have provided invaluable help and advice related to the electronics and software design.

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