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Utilising diffractive optics towards a compact, cold atom clock

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***Abstract*—Laser cooled atomic samples have resulted in profound advances in precision metrology [1], however the technology is typically complex and bulky. In recent publications we described a micro-fabricated optical element, that greatly facilitates miniaturisation of ultra-cold atom technology [2], [3], [4], [5].**

Portable devices should be feasible with accuracy vastly exceeding that of equivalent room-temperature technology, with a minimal footprint. These laser cooled samples are ideal for atomic clocks. Here we will discuss the implementation of our micro-fabricated diffractive optics towards building a robust, compact cold atom clock.

I. INTRODUCTION

The continued research into atomic clocks in recent decades has lead to a considerable rise in the achievable accuracy and stability. This stability is most notable in the atomic fountain and lattice clocks, measuring frequencies at the $10^{-16}\tau^{-1/2}$ and $10^{-18}\tau^{-1/2}$ level respectively [6], [7], [8], [9]. This research has also lead to profound advancement of compact metrological devices, achieving frequency stabilities in the low $10^{-10}\tau^{-1/2}$ in package volumes measuring only a few tens of cubic centimetres [10], [11].

However, the majority of the current compact clocks are based around room temperature apparatus that use buffer gasses and cell wall coatings in order to minimise collisional spin flips, benefiting the system with increased contrast and interrogation times [12]. Ultimately, these coatings and buffer gasses limit the long term performance achievable in a clock due to cell degradation and temperature dependent pressure shifts.

To overcome this, a move towards cold atoms is favourable, with the benefit of long interrogation times and narrow linewidths. To date, attempts at miniaturising cold atom clocks remain confined to thousands of cubic centimetre packages. We begin by proposing the grating magneto-optical traps, GMOT, as a step closer to bridging the gap between high performance cold atom apparatus and the scale of a thermal package. This project aims at reaching a frequency stability better than $10^{-12}\tau^{-1/2}$ in a package on the scale of tens of cubic centimetres.

II. CPT INTEROGATION

Our study begins with the realisation of an atom chip that integrates the laser cooling apparatus into a compact device. The GMOT achieves equalised radiation pressure from balancing the intensities of a single incident beam by the diffracted orders from the grating surface [2], [3]. Previous optical tools for simplifying laser cooling and trapping have been demonstrated [13], [14], [15], [16], however, as discussed in previous work, the GMOT out-performs these devices on size, reproducibility, robustness and trapping capabilities [5]. These properties make the GMOT the ideal candidate for a compact atomic clock.

To convert this device to a clock experimentally we propose to derive the ground state frequency splitting of ^{87}Rb by means of coherent population trapping, CPT [17]. The experimental set-up used is illustrated in Figure 1. We lock a home made external cavity diode laser, ECDL, to the cooling transition of ^{87}Rb and use an electro-optical modulator, EOM, to frequency modulate a sideband at the re-pumping frequency. An acousto-optical modulator, AOM, is used for switching on and off the cooling beam, that is fibre coupled and circularly polarised before reaching the diffraction grating. The magnetic field zero point, created by anti-Helmholtz coils, is centred on the light overlap volume for trapping the cold atomic sample. For an incident intensity of ≈ 40 mW/cm^2 in a 20 mm beam we trap 10^8 atoms. When sub-Doppler cooling mechanisms are introduced we bring 3×10^7 atoms down to 15 μK.

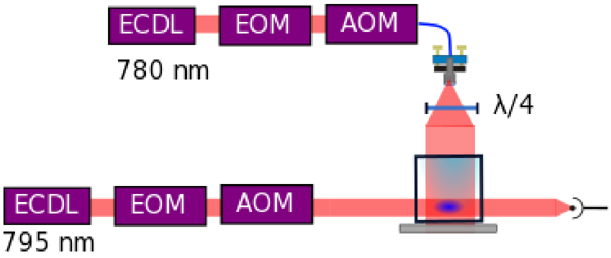

Fig. 1. Simplified grating MOT schematic for the cooling and probing beams. EOM: Electro-optical modulator. AOM: Acousto-optical modulator. ECDL: External cavity diode laser. $\lambda/4$: Quarter wave-plate.

When the cold atoms are free from external perturbation and in ballistic expansion, we apply a Raman probe beam to resolve the ground state clock transition. For this probe beam, a 795 nm laser is used to drive to the D1 states of ^{87}Rb. Once locked, an EOM is used to generate sidebands of equal amplitude to the carrier to couple the two ground states to the $F = 1$ excited state. With a small magnetic field is applied parallel to the clock beam, one can lift the degeneracy of the excited state enough to resolve CPT features of individual sub-levels, as can be seen in Figure 2. A few tens of μW's of laser power is enough to resolve a full width half max, FWHM, of the $m_F = 0$ state to be 5 kHz.

To achieve a narrower clock feature we will convert the CPT procedure to a Raman-Ramsey sequence. The technique has been demonstrated to produce narrow fringes at higher

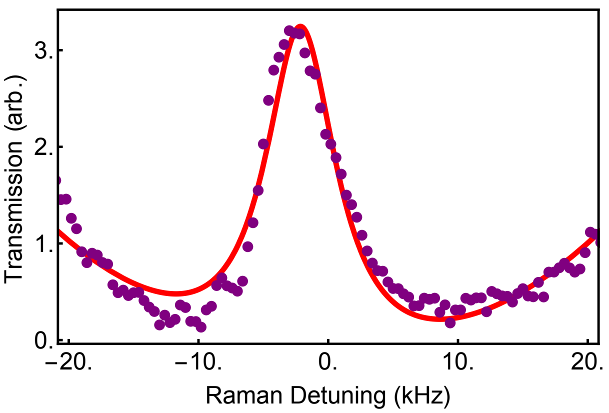

Fig. 2. Coherent population trapping transmission peak for the $m_F = 0$ sub-level of ^{87}Rb. Black line: The experimental data of the peak resolved with a Raman scan through the cold atomic medium. Red line: Lorentzian best fit to the experimental data

contrast than the original CPT feature, benefiting the measured frequency stability [18], [19].

III. CONCLUSION

The grating magneto-optical trap provides a compact means to cool and trap a large number of atoms, proving beneficial for precision measurements such as atomic clocks. With a coherent population trapping signal optimised to 5 kHz, the apparatus will be used to demonstrate Raman-Ramsey interrogation for a narrow clock reference.

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