# Portable Optical Atomic Clock Based on a Dichroic Two-Photon Transition in Rubidium

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**We report progress on development of a next generation timing reference based on an optical transition in rubidium coupled with a compact optical frequency comb to deliver a high stability RF reference signal. Engineering models that indicate the entire system including all optical components and control electronics could occupy a volume of 25 L, have a weight of 17 kg and consume 100 W of power. Such a device would be useful in GPS denied or contested environments.**

***Keywords— optical frequency standard; portable alternate navigation and timing***

## I. INTRODUCTION

Modern society is critically dependent on timing standards typically provided by global navigation systems. With this growing dependence comes a significant single point of failure for many services and applications. This work aims to develop a commercial portable frequency reference that has improved stability over existing microwave technologies by utilizing an optical frequency transition.

Previous work has shown that an atomic clock based on the $5S_{1/2} \rightarrow 5D_{5/2}$ two-photon transition of rubidium is a promising candidate for a high-stability frequency standard [1, 2]. We build on the development of the rubidium frequency standard developed at the University of Adelaide [3], which demonstrated an exceptional frequency stability comparable to the very best commercial frequency standards. This clock configuration is unique in that it uses a two-color excitation scheme that more efficiently drives the clock transition when compared to the single-color technique [4] as it allows fine tuning of the intermediate state detuning for increased fluorescence signal at a reduced level of optical power, as well as opening the possibility of reducing light shifts [5].

We have coupled the optical frequency output to a compact optical frequency comb (OFC) to convert to a radio frequency output; a process that maintains the superior performance of an optical standard and also allows interface to conventional electronics. Our design of the OFC closely follows that reported in [6], where an RF signal is synthesized from the repetition rate of the comb.

## II. METHODS/RESULTS

The clock configuration uses two lasers at differing wavelengths, with excitation via an intermediate state, as shown in Figure 1.

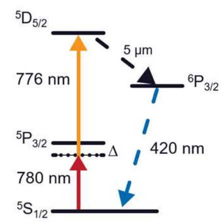


Figure 1: Energy levels exploited in the two-photon rubidium clock.

When the sum of the laser frequencies is in resonance with the two-photon transition, 420 nm fluorescence is produced from atomic decay through the $6P_{3/2}$ to the ground state. This fluorescence is spectrally separated from scattered light of the pump lasers and is the basis for our frequency lock. This scheme is technologically simple, using a thermal vapor cell at 60 degrees Celsius, and is capable of high frequency stability as the two-photon transition has a narrow linewidth and has a high signal to noise ratio. We take advantage of the competitive cost and performance of commercially available telecoms lasers and second harmonic generators to generate the required wavelengths, as shown in Figure 2.

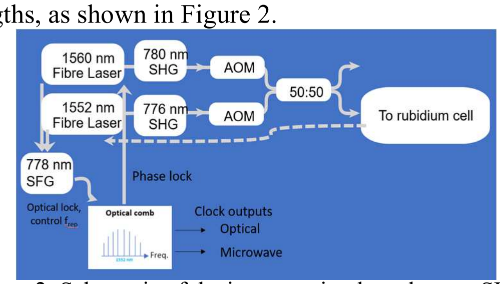


Figure 2: Schematic of the interrogation laser layout; SHG: Second Harmonic Generator, AOM: Acousto-Optic Modulator, SFG: Sum Frequency Generator

We use AOMs in the 1552 nm path to perform multiple roles: it corrects for power, applies frequency modulation for locking, as well as compensation for residual AM, while the

AOM in the 1560 nm arm is used solely for power stabilization. After interrogation of the rubidium cell, the fluorescence is detected and fed back into the 1552 nm laser, locking it to the frequency of the rubidium atoms. The comb is then locked to the SFG output of 778 nm, and finally, the 1560 nm laser is phase locked to nearby comb mode to set a fixed spacing between the two lasers. The self-referenced comb is then stable and useful for RF and optical outputs.

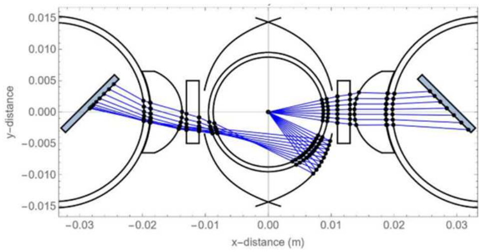


Figure 3: Increased collection efficiency of fluorescence via optimized shell design.

The efficiency of fluorescence capture directly affects signal to noise and thus overall frequency instability. Shown in Figure 3 is an end on view of the light paths of the fluorescence and parabolic shell housing the rubidium cell, which have led to an improved capture efficiency over our prototype.

The frequency stability is shot-noise limited in the short-term and dominated in the long-term by (1) light shifts induced by power variations in the pump light, and (2) collisional shifts induced by temperature fluctuations.

Light shifts (or AC Stark shifts) are the perturbation of an atom's energy levels by an oscillating electric field, proportional to the intensities of the perturbing fields ($I$):

$$\Delta f \propto \frac{\mu_1^2 I_1}{\Delta} - \frac{\mu_2^2 I_2}{\Delta} \quad (1)$$

Where $\mu_{1,2}$ are the transition matrix elements of the first and second transition of the two-photon transition, and $\Delta$ is detuning. To set the optimal detuning requires a balance between signal to noise and the magnitude of the light shift, which in our case results in a detuning of 1.5 GHz. Future work will involve optimising the power of each laser (an ability unique to the two-colour rubidium clock scheme) to reduce the light shift, detailed in [5].

Collisional shifts are due to inelastic Rb-Rb collisions driven by temperature fluctuations, where operating at elevated temperatures increases the pressure shift. We have made changes to the physics package design for increased mechanical stability, improved passive thermal isolation and improved temperature control servos. Additionally, we are investigating a possible temperature shift suppression scheme [7] that involves a change in the distribution of temperature-induced velocities because of a coupling with an asymmetry in the intermediate state detuning.

## III. DISCUSSION/INTERPRETATION

Frequency stabilities achieved in the laboratory and in the field are shown in Figure 4. In a controlled environment we have measured a fractional frequency instability of the 1 GHz output of the optical frequency comb of $1.5\times10^{-13}$ at 1 s, integrating down at $1/\sqrt{\tau}$ to $3\times10^{-15}$ at 8,000 s.

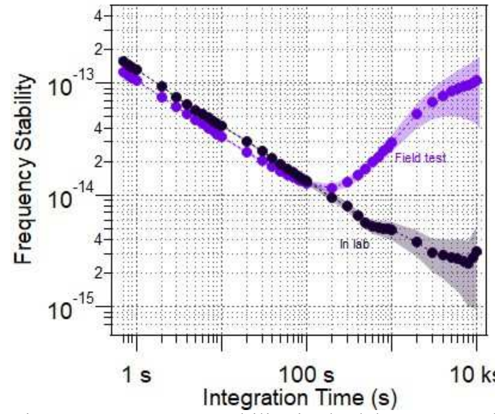


Figure 4: Frequency stability in the laboratory and in the field of the two-photon rubidium clock.

Elevated instabilities in the long term are due to dependence on temperature and vibration and will be the focus for improvements in our next iterations of this device.

## IV. CONCLUSIONS

We have presented results of a field-tested prototype compact rubidium clock. Our aim is to produce a rugged commercial product within the next few years at a competitive price and offer performance of better than $3 \times 10^{-15}$ at $10^4$ seconds, having SWaP (including optical frequency comb) of 17 kg, 100 W, and 25 L. Such a device will find use in alternate Position Navigation and Timing in GPS denied or contested environments, and potentially use in satellites as a next-generation global navigation system.

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