COLD ATOM MICRO PRIMARY STANDARD (CAMPS)

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Abstract

We present the progress towards developing a primary frequency standard with substantial reduction in size, weight, and power over the state of the art. Our clock is based on the microwave hyperfine transition in Rubidium-87. Unique to this effort, our focus is on special design considerations and engineering trades to realize a primary frequency standard in an ultimate 5 cc form-factor, 50mW power consumption, and compatible with a high volume, robust manufacturing process. In our approach, atoms are laser cooled from a background vapor into a magneto-optical trap. The magnetic and optical trapping forces are extinguished, allowing the atoms to freely expand, and Ramsey spectroscopy is performed to measure the clock transition between the F=1 and F=2 hyperfine states. Key to size reduction is the use of laser cooled atoms to achieve narrow linewidths in a small size, and the ability to perform all the clock functions: sample preparation, spectroscopy, and read-out, in one physical location. Using a miniaturized physics package, signal-to-noise ratio greater than 100 and clock line quality factors greater than 1E8 have been achieved. Limiting factors and prospects for improvement will be discussed.

INTRODUCTION

Timing is critical to the operation of GPS receivers. Crystal oscillators in today's GPS receivers have good short-term stability, but lack long-term stability. With the realization of the Chip-Scale Atomic Clock (CSAC), studies have been done to assess the navigation potential for using atomic clocks in GPS receivers **[1]**. There are several scenarios which would benefit. One such scenario is enhanced code reacquisition once the signal has been lost. Another scenario is improved navigation performance and/or increased durations of "clock coasting," or times when fewer than optimum numbers of clocks are visible. While a CSAC will be a powerful replacement for crystal oscillators in GPS receivers, some applications will require an improved clock or a clock with even less drift and a higher degree of stability. For these applications Honeywell Aerospace is developing a miniature primary frequency standard, CAMPS (Cold Atom Micro Primary Standard) **[2]**. The ultimate goal of the CAMPS is 5 cc, 50 mW, and a time loss of less than 5 ns/day.

The CAMPS approach is to discipline a crystal oscillator using a repeated spectroscopic measurement of the 6.8GHz ground-state hyperfine F=1 to F=2 transition in Rubidium 87. The sequence is shown in

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Figure 1. The goal is to stabilize the frequency of a local oscillator to the frequency of the F=1 to F=2 atomic transition. In our approach, Rubidium atoms are laser cooled from a dilute vapor and trapped in a magneto-optical trap (MOT). Typical temperatures for Rb atoms in a MOT are <50 μK. Prior to the spectroscopic measurement, atoms are optically pumped into the F=1 hyperfine level. Though atoms will equally populate the three magnetic sublevels in the F=1 manifold, only the atoms in so-called "clock state" or |F=1, mF=0>, will be considered in the clock measurement. The degeneracy in the F=1 manifold is lifted by the application of a stable bias magnetic field referred to as the "c-field." The magnetic and optical trapping forces are extinguished, allowing the atoms to freely expand. Since the atoms were pre-cooled, they expand very slowly. During the free expansion, we perform time-domain Ramsey spectroscopy: two resonant RF pulses are delivered to the atoms separated by a free evolution time, T_r, the Ramsey time. The clock line Q-factor scales as the Ramsey time. Near-resonant RF radiation from the local oscillator (LO) is coupled into the atoms through an antenna or waveguide structure. If the RF radiation is resonant with the atoms, the atoms will all make a transition from the F=1 to the F=2 hyperfine level. The atom population in F=2 is measured via resonant fluorescence and normalized against a measurement of the total number of atoms (F=1 + F=2), and this information is used to steer the local oscillator frequency. *Key to size reduction is the use of laser cooled atoms to achieve narrow linewidths in a small volume, and the ability to perform all the clock functions: sample preparation, spectroscopy, and read-out, in one physical location*. The CAMPS approach seeks to maximally isolate the atom from any bias or drift causing mechanisms such as wall collisions, optical fields, or magnetic fields.

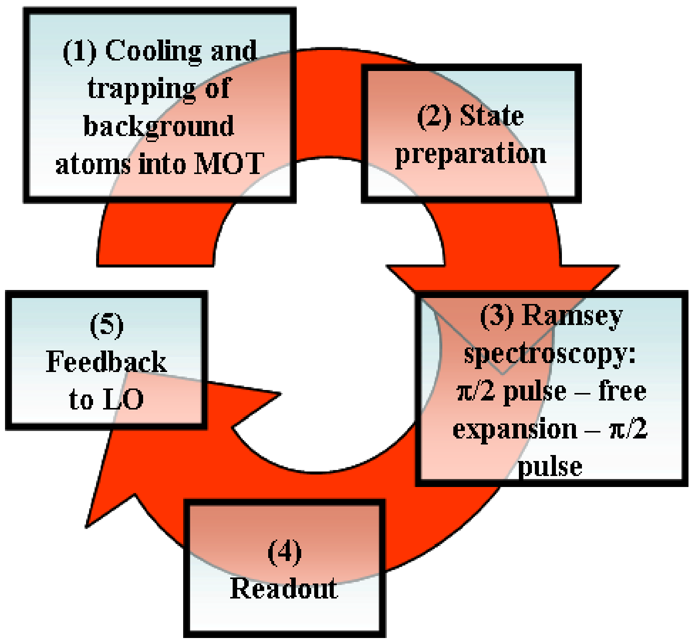

Figure 1. The CAMPS sequence.

OPTICS MODULE

Critical to the deployment of cold atom technology is the miniaturization of the device to levels beyond the state of the art. The conceptualized CAMPS optics module is shown in Figure 2. The optics module is divided into two plates: the top plate which contains the physics package, and the bottom plate which contains the frequency-stabilized laser, optical isolation, and optical shutters. The overall shape was chosen to be compatible with a low-form-factor magnetic shield. Miniaturization of the CAMPS is achieved by miniaturization of individual components and drawing maximum usage from the on-board optical components. The critical components of the optics module include: the frequency stabilized light source, the physics package, the RF transmitter, and the optical shutter.

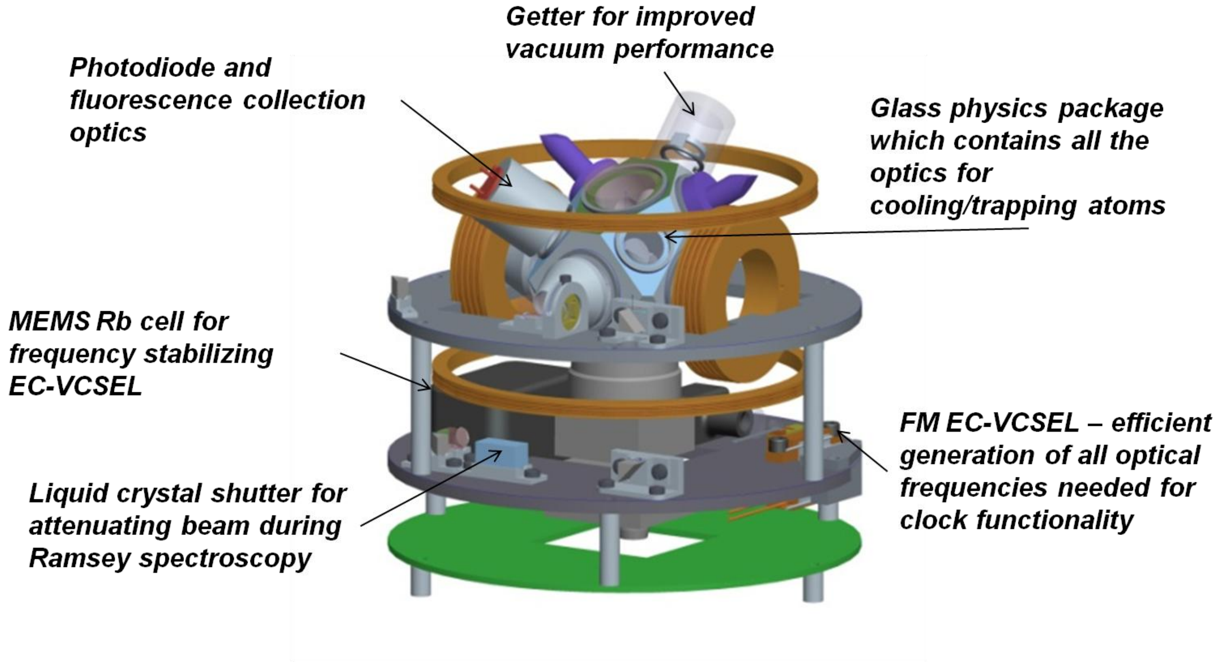

Figure 2. Conceptualized approach for the CAMPS optics module.

STABILIZED LASER SOURCE

While conventional cold atom devices typically have multiple lasers, CAMPS will have only one laser. This laser will be used for performing all essential functions: the laser cooling process, optical pumping, and optical read-out of the energy level populations after the spectroscopy. Initial implementations will use edge-emitting DBR lasers. Such lasers are commercially available at the relevant wavelength and have sufficient linewidth for Doppler-free spectroscopy, but typically have poor electrical efficiency at low optical output powers. Lower power consumption should be made possible with the advent of narrow linewidth vertical cavity surface emitting lasers (VCSEL) which have demonstrated efficiency >40% for low output power. The challenge with this technology is to demonstrate the required linewidth (<1 MHz) and the required output power (>5 mW).

The laser will be frequency-stabilized to be slightly red-detuned from the F=2->F′=3 cycling transition in Rb-87, then frequency modulated to produce sidebands which correspond to the F=1->F′=2 transition. This will be the repumping transition for the MOT. The RF source for the sideband will be a derivative from the clock’s local oscillator. The optical pumping from F=2 to F=1 is performed by extinguishing the RF sidebands. Absent light at the repumping frequency, atoms will scatter photons at the cycling transition frequency but will eventually accumulate in the F=1 level. Spectroscopic readout is performed by measuring the atomic population in F=2 by collecting the atomic fluorescence during a short pulse of the cycling-transition light, followed by collection of the fluorescence from a pulse with the cycling transition and the repumping sideband to measure the total number of atoms. Finally, variations in the optical power, background atomic vapor, and scattered light are subtracted by taking a measurement of the light without the atom sample present.

The light source is frequency stabilized with a reference cell containing Rb gas. In the CAMPS, the cell will be a MEMS vapor cell, modified from the Honeywell CSAC. Honeywell's Rb cell fabrication is a batch process that begins with the micromachining of a silicon wafer to produce the cavities for a Rb reservoir and a vapor chamber. Pyrex-like glass is bonded to one side of this silicon wafer, forming a transparent bottom. Rb droplets of precise volume are deposited in the reservoir in an inert environment, and then another glass wafer is bonded to the top, sealing the chamber and reservoir at very low pressure. Metal patterns are then created on both surfaces that allow the Rb cell to be heated from both sides to raise the vapor pressure of the Rb and also keep the windows clear of Rb. The wafer is then diced to create several hundred individual die.

For use in the CAMPS, the individual Rb cell is further integrated with periphery optics and photodiodes, and saturated-absorption spectroscopy is used to resolve the Rb hyperfine levels. The light source is frequency-stabilized by locking the carrier to the side of the F=2 to F′=3 transition. Alternatively, permanent magnets can be used to create an axial homogeneous magnetic field, and a dichroic atomic-vapor laser lock (or DAVLL) **[3]** can be used to stabilize the carrier frequency.

PHYSICS PACKAGE

The physics package consists of an ultra-high vacuum evacuated glass block, the requisite magnetic coils, the RF transmitter, and photodiodes for detecting the atomic fluorescence. The glass block contains the Rb source from which the background vapor is created.

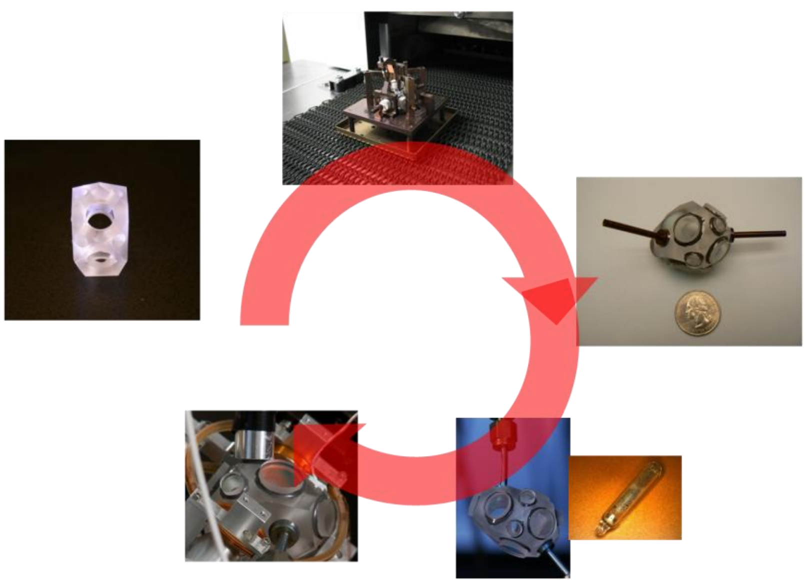

Figure 3. Fabrication and assembly process for vacuum sealed glass block with attached optics.

The process for fabricating the glass block is shown in Figure 3. The glass block is fabricated from bulk BK-7 glass. Bores are drilled into the glass for beam paths and are sealed either with optics or another functional component. Optics include windows and mirrors which are attached to the block via a high-temperature frit process. By attaching the optics directly to the block, the block becomes increasingly robust against vibrations, and parasitic scattered light is reduced by minimizing the number of surfaces the light must pass through. Two titanium (Ti) tubes are also fritted to the block. One Ti tube is used to perform the initial evacuation of the block on a pump-out station; the other fill tube contains a miniature Rb source which is packaged under vacuum and released after completion of the vacuum processing. The initial glass block was 17 cc; the second iteration of blocks will be 7 cc (Figure 4). Coils for creating the MOT and C-field are positioned around the block. A photodiode with imaging optics is attached to additional window-ports and captures approximately 1% of the fluorescence per port; four ports are available for this function.

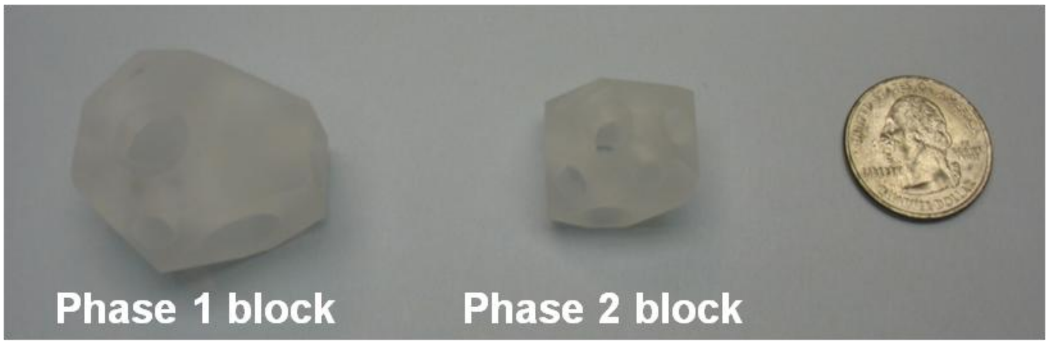

Figure 4. Comparison of the first iteration physics package cell used in Phase 1 of the DARPA IMPACT program and the second iteration package which will be used in the Phase 2 effort.

A challenge for cold atom technology is providing the required vacuum performance. The number of atoms loaded into the MOT is the steady-state balance between the loading rate and the loss rate, τ. In the quantum projection noise (QPN) limit, the clock signal-to-noise ratio (SNR) will scale as the Sqrt(N), where $N=N_0e$^($-T_r/\tau$) is the number of measured atoms after the Ramsey time, and N_0 is the number of atoms in the steady-state MOT. To first order, the density of background Rb vapor does not impact the steady-state number of atoms. Non-Rb background atoms will contribute to loss via two-body collisions with atoms in the MOT. For optimum operation, the partial pressure for non-Rb atoms needs to be much less than the Rb vapor pressure, which is 1E-7 Torr at room temperature. In laboratory scale experiments, ion pumps, often used in concert with passive getter pumps or sublimations pumps, are used to maintain the required pressure. Currently, commercially available active pumping technology is not compatible with a 5cc form factor. Demonstrating a pump-less system is the holy grail for cold atom systems and will be revolutionary. Our approach is two-fold: (1) utilize high-quality sealing technique, low-permeability materials, and state-of-the-art vacuum processing techniques to limit out-gassing and leak rates, and (2) explore the use of getter technology to take care of remaining low-grade leaks and out-gassing. We have applied techniques learned from manufacturing precision inertial sensors and have qualitatively observed improved vacuum performance without active pumping; however, this alone is not sufficient for long duration operation. Next-generation devices will contain passive vacuum components. Vacuum performance is assessed by measuring the rate at which atoms are loaded into the MOT and inferring the lifetime based on a steady-state model. This property makes cold atoms a very sensitive pressure gauge.

RF TRANSMITTER

In large-scale atomic frequency standards, such as the fountain clock, RF transitions are driven by passing the atoms through a cylindrical RF cavity which supports the TE_{011} mode. Previous publications have reported use of a quarter-wave antenna but resulted in reduced Ramsey fringe contrast **[4]**. We have demonstrated very high SNR Ramsey fringes using a co-planar waveguide (CPW) shown on the right in Figure 5. Since the physics package is small, the CPW can be placed in close proximity to the atoms and the efficiency of the RF excitation will increase as the physic package dimensions continue to decrease. Ramsey fringes with QSNR>2E10 have been demonstrated (Figure 5). All data shown in this presentation utilized a co-planar waveguide to drive the RF excitations.

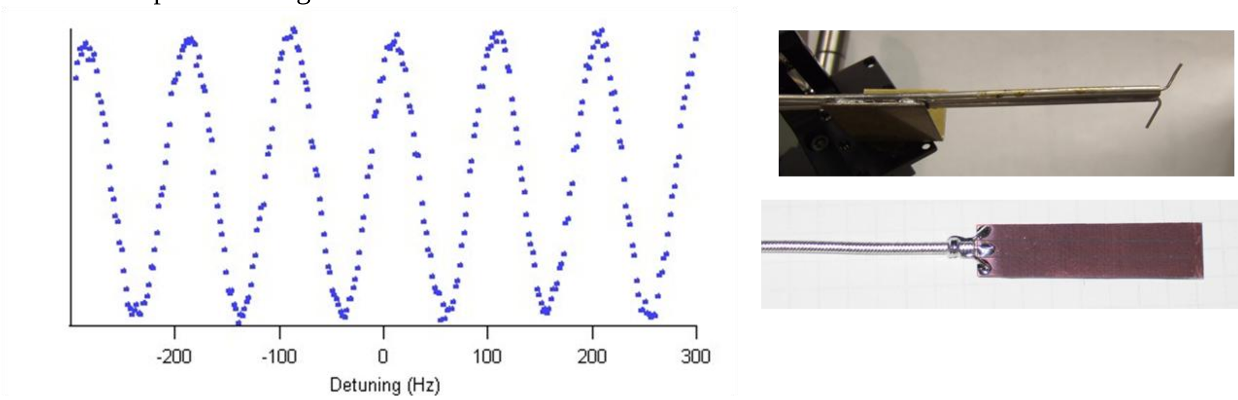

Figure 5. (Left) High SNR Ramsey fringes using co-planar waveguide structure to drive RF excitations in the atoms. (Right) Sample structures used to drive RF excitations.

OPTICAL SHUTTER

AC Stark shifts of the clock transition can be large and can lead to large systematic shifts. Ideally, all laser light is perfectly extinguished during the Ramsey time, but in practice perfect extinction is difficult, especially when constrained in size and power. A perfect shutter would allow for high extinction (>80 dB), low transmission losses (<<1 dB), fast rise times (<50 μs), and could be driven with a low-power, low-voltage source. The attenuation requirement can be mitigated by detuning the light during the Ramsey spectroscopy, but detunings need to be large (>1 GHz), making reacquisition of the correct frequency a challenge. Finding an optical-shutter technology which meets these requirements remains one of the biggest challenges for substantial miniaturization of cold atoms clocks. Honeywell is exploring both an electro-optic approach which uses low-loss miniature liquid crystals, and an electronic approach which directly acts on the light-source current to attenuate the light. Thermal management, diode lifetime, and frequency stability are challenges which must be overcome for the latter approach to be successful.

PERFORMANCE

Early CAMPS data was taken in a system which contained a miniaturized 25 cc physics package (based on a 17 cc glass cell) but used an external commercial laser system. Commercially available rack electronics were used. The laser was fiber-coupled and brought to the physics package via optics on a small mounting plate. The small optics plate mimics the functionality of the top plate in Figure 2 but with a larger form factor. The physics package remained on an ion pump station, and was actively pumped during the data set. It is expected that a passive vacuum solution will be found, eliminating the need for the ion pump. We perform detuned Ramsey spectroscopy at the 3dB point on the left (red-detuned) and right (blue-detuned) side of the center Ramsey fringe. A photodiode mounted on the physics package cell measures the fluorescence first from atoms in F=2 and then from all the atoms (F=1 + F=2). Data are shown in Figure 6 along with the DARPA IMPACT program Phase 1 and Phase 2 metrics.

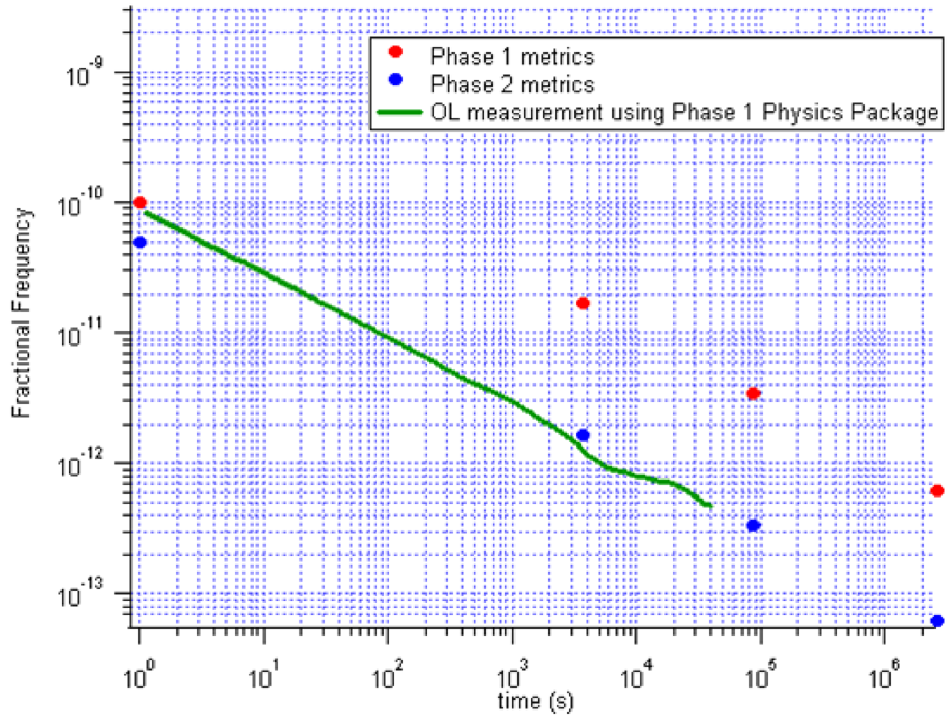

Figure 6: Overlapping Allan Deviation for CAMPS device

In agreement with Figure 5, the clock line shape Q is 100,000,000 with S/N of 100. We estimate ~2E6 atoms in F=2 measured at the 3dB-points. The QPN-limited S/N for this number of atoms is >1000; future efforts will focus on decreasing the detection noise to approach the QPN limit while narrowing the clock linewidth. Both efforts will be necessary as it is expected that the signal will decrease in future miniaturization efforts. Nonetheless, it is projected that Q*S/N can be increased by at least 5x in the 2nd iteration package (shown in Figure 4).

CONCLUSIONS

We are developing a cold atom based primary frequency standard which will ultimately have unprecedented size, weight, and power while maintaining performance comparable to the clocks on today's GPS satellites. Critical to miniaturization is pre-cooling the atoms prior to performing Ramsey spectroscopy and performing all the clock functions (trapping, state preparation, spectroscopy, and detection) in one location. Progress so far has been focused on demonstrating initial clock performance in a miniature 25 cc physics package. High contrast Ramsey fringes have been demonstrated using a coplanar wave guide. Fractional frequency stability of 1E-10 at 1 second has been achieved. Current efforts are focused on further miniaturization of the entire clock optics module.

ACKNOWLEDGEMENTS

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