PROGRESS ON A PORTABLE RUBIDIUM FOUNTAIN FREQUENCY STANDARD*

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Abstract

We are developing a simple and transportable laser-cooled rubidium (Rb) atomic fountain frequency standard. The optical package for this system uses DFB (distributed feedback) diode lasers and a frequency offset locking scheme to generate the optical frequencies needed for laser-cooling, launching, post-cooling, and detection of Rb atoms. This atomic fountain will be useful as a transfer standard and secondary standard for calibrating nontransportable frequency standards, as well as a measurement tool for the gravitational redshift. Here, we describe the progress made on this project, including our recent observation of a magneto-optical trap (MOT), and the anticipated performance of our transportable Rb fountain frequency standard.

INTRODUCTION

We have begun to develop a transportable laser-cooled Rb fountain microwave frequency standard. We consider "transportable" to mean a physics package of ~1 m^3 accompanied by a similarly sized electronics rack. Cesium fountain primary frequency standards such as NIST-F1 now achieve fractional accuracies less than 4×10^{-16}, but require much lab space (~250 m^3) and power (~100 kW). Our transportable fountain will reduce each of these spatial and power requirements by *two* orders of magnitude, while sacrificing less than of *one* order of magnitude in accuracy.

Time transfer techniques used to compare spatially separated atomic standards cannot in practice support these accuracies, due to the lengthy averaging period required. Presently, to compare two frequency standards at the 1×10^{-15} level requires 15 days of continuous comparison using common-view GPS. To achieve 1×10^{-16} would require an impractical 150 days of continuous comparison. The transportable frequency standard proposed here would be useful in such comparisons.

A compact and reliable laser-cooled standard would also be useful as a replacement for hydrogen masers in clock ensembles used to generate timescales. Although hydrogen masers are extremely reliable, with lifetimes of 10 to 20 years of continuous operation, they suffer from frequency drift and unexplained aging mechanisms.

Finally, we expect industry to eventually develop laser-cooled frequency standards as a replacement for the widely used commercial Cs beam atomic clocks. We view this research as a jumpstart for this effort.

Other portable fountain projects exist **[1-3]** and have achieved varying levels of completion and success. While shrinking the physics package is straightforward, the optical package allows for much more creativity and freedom in design. Our design of the optical package is greatly simplified relative to those of previous optical packages. For comparison, an optical system competitive with ours would be NASA's PARCS project **[1]**, meant to send a laser-cooled atomic frequency reference into space. Compared with their design, our design eliminates roughly 70% of the components, including 10 fiber collimators, 3 lasers, 14 polarizing beam splitters, 4 isolators, 7 atomic cells, 7 filters, 19 detectors, 13 half-wave plates, 7 quarter-wave plates, 6 double-pass acousto-optic modulators (AOMs), and 6 single-pass AOMs. Eliminating all these components not only reduces the cost and power consumption, but also eases assembly and increases the stability of the optics package.

The foundation of our optical package rests in the use of distributed feedback (DFB) diode lasers. A master DFB is locked to an atomic transition by use of the DAVLL **[4-6]** (dichroic atomic vapor laser lock) method. All slave DFBs are locked to the master by use of an electronic frequency offset-locking scheme to generate the optical frequencies needed for a laser-cooled fountain. Here we describe the progress made on this program, including the system design, the development of our first generation optical package, and our most recent achievements in laser-cooling. Finally, we outline the next steps in evaluating our system and how that fits into our overall goal of building a useful transportable fountain frequency standard.

PERFORMANCE GUIDELINES

In the fountain geometry, atoms spend most of the time of flight time around apogee. This means that relatively long Ramsey times are attainable in small fountain structures. If we assume a physics package 1 m in height with a molasses region built from a vacuum can ~30 cm in diameter, and microwave cavities (state selection and Ramsey) with dimensions of 2.54 cm high with a radius of 5.4 cm (this gives a resonant frequency of 6.8 GHz), we conclude that this geometry easily allows Ramsey times of ~0.4 s. Given beams of radii of 1 cm and 7 mW each, we expect to load ~10^8 atoms in ~200 ms. After state selection, we expect to get one fifth of the original atoms in the F = 1, $m_F = 0$ state. Assuming atom velocities of ~3 cm/s (i.e., multiple recoils = 0.58 cm/s) and large apertures of diameter ~2.5 cm in the microwave cavities, essentially all of the atoms will return to the detection region. Given these assumptions, and a sufficiently stable local oscillator, the potential short-term stability is $\sigma_y(\tau \approx 1\text{s}) \sim 5 \times 10^{-14}$, with a fractional long-term stability on the order of 10^{-16}.

The low temperatures required for atomic fountains are achieved by laser-cooling, which is generally broken down into two stages. The initial stage involves collecting a cloud of ~10^8 atoms in either an optical molasses or a magneto-optical trap (MOT). At this stage, the cloud of atoms has a temperature on the order of 100 µK, corresponding to speeds of roughly 14 cm/s. This is not sufficient for an atomic fountain, as nearly all of the atoms would be lost to interrogation just instants after launching, resulting in a null overall signal-to-noise ratio. Therefore, a second stage of cooling, or "post-cooling" is applied. This sub-Doppler cooling stage can be achieved in a number of ways, all of which are more than sufficient for our purposes (~5 µK for 100% returning atoms), as our short toss height and large apertures relax the requirements on final temperature.

For our atomic fountain to operate in the (1, 1, 1) geometry, we will use four slave lasers plus the master. Two of those slave lasers will be used to create the six cooling (magneto-optical trap or optical molasses) and launching beams, such that one is for the three "up" beams and the other for the three "down." The third slave laser will be the repump, and the last one will be dedicated to detection. To cool and then launch atoms, the six molasses beams are initially at the same frequency, about 1.5 Γ to the red (i.e., lower frequency) of the cycling transition. (Γ is the natural linewidth of the atomic transition, which is 6 MHz.) In order to launch the atoms, the three "down" beams are then detuned further to the red, and the "up" beams to the blue (i.e. higher frequency), by 5 MHz for 1 ms. The ball of atoms is finally given a post-cool, whereby the frequencies of the beams are swept to the red by ~50 MHz in about 1 ms. This requires fast and precise frequency control of the laser beams.

OPTICAL PACKAGE DESIGN

DFB diode lasers are the source of all the light used in our system. They have relatively high output power (~80 mW), are stable, and are small (TO-3 Package) compared to an ECDL (extended cavity diode laser) system. While there are many non-DFB diode lasers with high power (>100 mW) at 780 nm that can be built into an ECDL (extended cavity diode laser) with linewidths of <100 kHz, the external cavity has severe thermal and mechanical stability issues. These lead to a continuous tuning range that typically extends only a few gigahertz without encountering a mode-hop. On the other hand, DFB lasers have the advantage that a tuning grating is built into the laser diode itself. The entire DFB fits into a standard TO-3 package, and the continuous mode-hop-free tuning range is many times greater than that of typical ECDLs. Although the linewidths (a few megahertz) are generally not as narrow as those of ECDLs, this has little impact on the laser-cooling. To mount the DFB diodes, we used a slightly modified commercially available collimating lens package (Thorlabs LDH3-P1 **[7]**) mounted in an aluminum case with protection circuitry and electrical connectors. The modification consists of drilling and tapping three holes for nylon-tipped set screws that aid in the alignment of the diode to the desired optical axis.

In many fountain systems, this control of the laser frequency has been achieved by taking a high-powered main beam and using AOMs in the double-pass configuration **[8]** to control the frequency and intensity. While this technique works well in the lab, each double-pass setup requires several expensive polarizing optical components (that are sensitive to temperature changes), roughly 1000 cm^2 of table space, precise alignment, and bulky RF power amplifiers (that consume ~15 W). Our offset locking scheme circumvents all of these issues. With a moderate servo-loop bandwidth (less than 1 MHz), we can use digital microcontrollers to individually control each slave laser. Everything from frequency sweeping, to automatic relock, to jumping far off resonance as a possible shutter effect **[9]** (or in conjunction with a mechanical shutter) can all be relegated to simple software programming.

The master reference DFB laser is locked to a Rb optical transition by means of the DAVLL (dichroic atomic vapor laser lock) method. As seen in Figure 1, the DAVLL layout is much simpler than the usual saturation absorption spectrometer. There are fewer optical and electrical components, and alignment is trivial. A small amount of linearly polarized light (less than 1 mW) is picked off and directed through a Rb vapor cell. The cell is in a magnetic field that is collinear with the laser beam. The magnetic field Zeeman shifts some of the hyperfine magnetic sublevels up in frequency, and others down. This results in two separate Doppler-broadened peaks that preferentially absorb either right or left circularly polarized light. These two circular polarizations can be extracted from the linearly polarized light by a quarter-wave plate and polarizing beam splitter. One beam is then subtracted from the other, yielding a dispersion curve that can be fed directly back to the diode current source for locking, eliminating the need for any modulation and demodulation stages. The fact that the error signal is Doppler-broadened means there is a large lock region that allows the system to compensate for large perturbations. Furthermore, having only a single lock point makes auto-locking easy. The possibility of inferior lock performance due to a Doppler-broadened transition, as opposed to a narrow hyperfine feature, is mediated by the stronger signal strength. In fact, the signal strength compensates for the broader linewidth, such that the product of the signal-to-noise ratio with the linewidth is roughly equivalent to that of a saturated absorption lock.

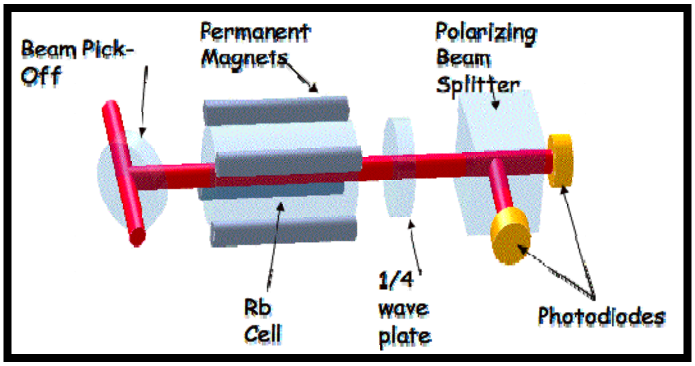

Figure 1. Diagram of a DAVLL system.

The four slave lasers are controlled by means of an offset-locking scheme. A block diagram that illustrates this offset-locking scheme is shown in Figure 2, where the slave laser represents one of the four slave DFBs. Each slave laser is beat against the master laser, and the beat note is detected with a high-bandwidth photodiode amplifier. This beat note signal is sent to a frequency/phase detector and compared to a reference. The error signal is fed back onto the slave laser, locking it to the master with frequency offset defined by the reference. All the necessary optical frequencies needed for cooling, launch, and post-cool are produced by changing the frequency of the reference, which can be done rapidly and accurately with a digital microcontroller. As previously mentioned, this scheme eliminates the use of AOMs and high-powered RF sources.

Polarization-maintaining fiber optic splitters will be used to divide the power between the three up beams as well as the three down beams. This system uses two fixed splitters (a 50%/50% and a 67% /33%) and two variable-ratio splitters. The fixed splitters provide a coarse adjustment on the power levels, and the fine adjustment is provided by the variable-ratio splitters. This provides the control necessary for power-balancing the optical molasses.

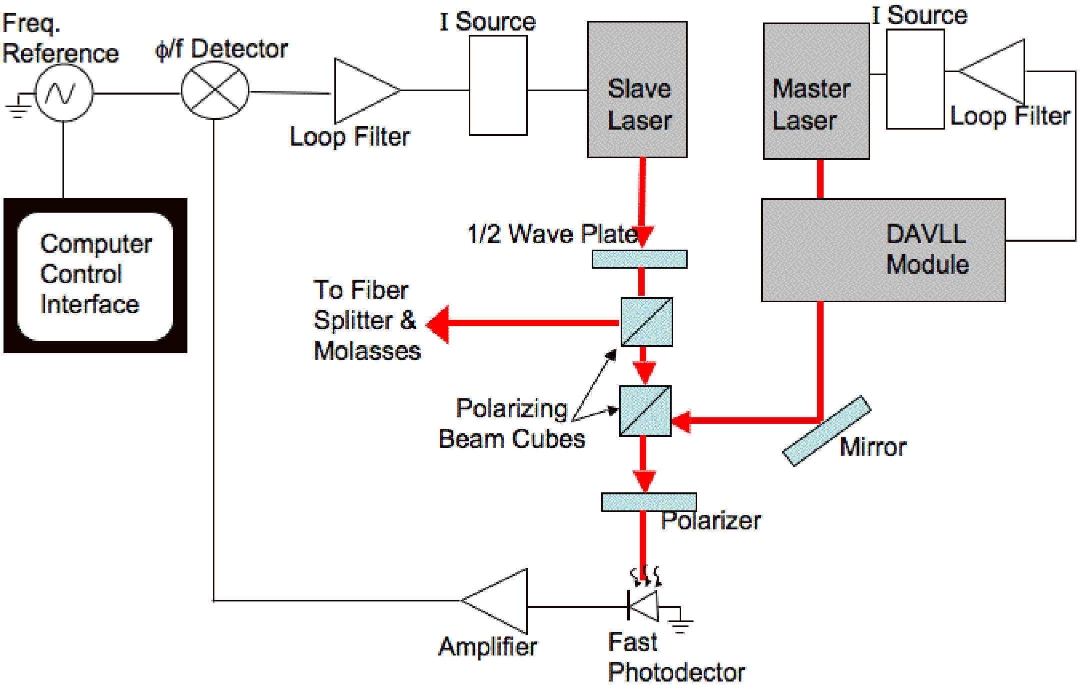

Figure 2. Block diagram of laser and optical system. For clarity, additional duplicate slave lasers are not shown.

CURRENT STATUS AND NEXT STEPS

The first generation of our optical system has been built and is functioning. It deviates slightly from the design described above in two minor ways. First, the repump laser is not offset-locked to the master, but is instead independently locked by use of the saturated absorption method. The reason for this is that we have not yet assembled a photodiode amplifier with the necessary 10 GHz bandwidth. Second, we decided to postpone the implementation of the fiber optic splitters in favor of free-space beams. This facilitated rapid assembly and ease of modification as we began our initial evaluations of the system.

In order to carry out the optical system evaluations, we built a vacuum system, pictured in Figure 3, with a cooling chamber at the top and a detection chamber below. This design allows for multiple laser-cooling schemes and straightforward time-of-flight temperature measurements of the atoms. We recently observed a MOT, seen in Figure 4, the first stage of laser-cooling on the way to an atomic fountain.

The next steps in evaluating our optical package will be to perform sub-Doppler cooling and confirm that we achieve sufficiently cold temperatures for atomic fountain operation. Once this is done, a fountain physics package will be built, and then overall system evaluations will begin.

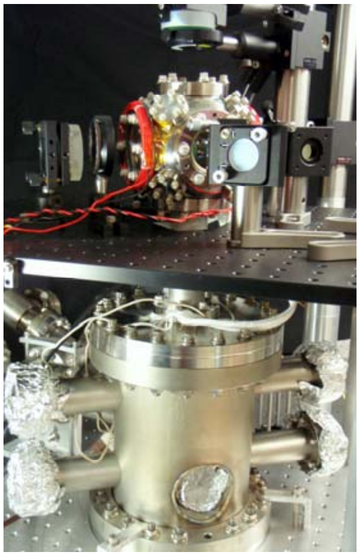

Figure 3. Vacuum chamber used for evaluating the optical package.

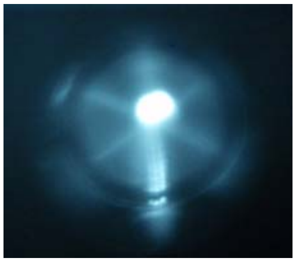

Figure 4. Rubidium atoms confined in a MOT, made by use of independently offset-locked DFB lasers.

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