

# IMPROVEMENTS TO A TRANSPORTABLE ATOMIC FOUNTAIN LASER SYSTEM

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## Abstract

*We are developing a transportable rubidium (Rb) atomic fountain frequency standard that uses independently phase-locked diode lasers for laser-cooling. At this time, we have not demonstrated sub-Doppler (microKelvin) atom temperatures using our phase-locked laser scheme. However, we present measurements indicating the problem is due to insufficient phase-coherence between the cooling lasers. We are presently building a new generation of laser-locking electronics, which we believe will allow for sub-Doppler laser cooling of the Rb atoms. Additionally, we discuss a number of improvements we have made to the system since our last publication.*

## INTRODUCTION

In this paper we address only *changes* to our laser system since our previous publications [1, 2]. We have observed the effects of laser-cooling in our system, but have been unable to achieve the sub-Doppler ( $\mu\text{K}$ ) atom temperatures necessary for the operation of a fountain frequency standard. In the process of trying to achieve sub-Doppler cooling, we have made many improvements to our system, which will make the fountain more robust and stable in the long run.

First, we present measurements indicating that our phase-locked lasers lack sufficient phase coherence to produce sub-Doppler cooling. We were also able to measure phase noise data using higher bandwidth phase-locking circuits that we borrowed from another group. The higher bandwidth circuitry yielded much improved phase coherence between the locked lasers, even rivaling the performance of an optically injection-locked system. This leaves us optimistic that by improving our phase-locking electronics we can yet achieve the necessary sub-Doppler cooling.

Next, we discuss other significant improvements we have made to the system in the last year. Many of these changes were made in an attempt to produce colder atoms but at the time did not achieve the desired results. Nevertheless, these improvements did help enable the discovery of the underlying problem, and will enhance the performance of our Rb fountain frequency standard in the long run.

One improvement was the development of a laser-housing with greater mechanical stability. We also moved to a modular optical system that incorporates more fiber-based components. A fiber optic switch/attenuator has been tested for use in controlling light amplitudes during the post-cool and microwave interrogation steps, and we have been pleased with its performance. The direct digital synthesis (DDS) system that controls the frequencies of the various lasers during the fountain operation sequence has been refined. Finally, we discuss a new vapor cell spectroscopy method we have implemented for the master laser frequency lock.

## PHASE LOCKING DISTRIBUTED BRAGG REFLECTOR LASERS

We believe that our cooling is limited by the insufficient phase coherence between the vertical laser beams (derived from different lasers). Phase-locking the Distributed Bragg Reflector (DBR) lasers that we use is a challenge because they have a relatively broad linewidth approaching 1 MHz, yet they accumulate 90 degrees of phase delay at a modulation bandwidth below 1 MHz [3]. Typically, cooling the atoms to temperatures on the order of 1  $\mu$ K is accomplished in 3D optical molasses by reducing the molasses beam intensities, and/or increasing the red detuning of the cooling laser frequency [4]. In the optical molasses, the sub-Doppler atom temperatures are due to the process of polarization gradient cooling - the atoms move in the standing wave formed by the three pairs of counter-propagating laser beams with appropriate polarizations. It can then be expected that the lack of phase coherence between the counter-propagating vertical laser beams thus affects the polarization-gradient cooling, as no standing wave with a stable spatially-dependent ac Stark shift is formed.

An example of our typical atomic laser cooling procedure is as follows. Atoms are cooled by phase-locked lasers, resulting in the formation of a bright atomic cloud in the center of the molasses zone. All cooling laser frequencies were locked  $\sim 2\Gamma$  (with  $\Gamma$  the linewidth of the excited atomic state) below the cycling optical transition  $F=2-F'=3$  of the  $^{87}\text{Rb}$   $D_2$  line. After  $\sim 500$  ms, the laser frequencies were detuned below resonance by additional  $\sim 30$  MHz in 2 ms, and the laser intensities were simultaneously reduced by 30 dB to lower the atom temperature. After the cooling laser light was fully attenuated, the atoms were repumped to the  $F=2$  ground state by the repumping laser tuned to the  $F=1-F'=2$  optical transition before mechanical shutters blocked the residual amount of light sent through the attenuator. The extinguishing of the light released the atoms from the molasses. After the atoms are released, they fall due to gravity, and cross a standing wave 20 cm below the molasses zone, formed by a laser beam tuned on  $F=2-F'=3$  optical resonance. The fluorescence from the atoms is detected by a high-gain photodetector.

When light from the same slave laser was used for both vertical molasses beams, and another slave laser delivered the light for the four horizontal beams, a very cold atom cloud was detected  $\sim 210$  ms after the atom release from the molasses zone, as expected for freely falling atoms. Temperatures well below 10  $\mu$ K were observed, indicating highly effective sub-Doppler laser cooling. Similar results were obtained when one of the vertical beams was produced by a retro-reflecting mirror.

When light from two independent slave lasers was used for each of the two vertical molasses beams, the atoms in the detection zone arrived much earlier than expected from free-fall considerations. Also, the atomic temperatures were significantly higher, as determined by the width of the time-of-flight signal. In

the experiment, the laser frequencies were deliberately chosen to be the same, thus providing no additional vertical velocity for the atoms. The optical fiber alignment was also identical, as the Fiber-AOM module from Figure 3 was used. The width of the time-of-flight curve suggests that the atom temperature is significantly higher than 1  $\mu$ K. As the sub-Doppler cooling requires the formation of a spatially stable standing wave, the lack of coherence between the two phase-locked lasers was suspected as the reason for the high atom temperature.

The left plot of Figure 1 shows the beat-note spectra between the master and one of the phase-locked lasers used for the vertical molasses beam. The measurements were done by use of a spectrum analyzer with a 30 kHz resolution bandwidth. The right plot shows the phase noise of the beat note between the master and the slave laser measured with a commercial phase noise analyzer. The black trace corresponds to the current home-built phase-locked loop (PLL) system. An improved version of the PLL [5] results in the red trace, showing reduced pedestal and increased signal-to-noise. The blue trace corresponds to the case when the slave laser was injection-locked optically by the master, removing the slave's optical isolator and delivering 1 mW of light from the master laser via an optical fiber for injection locking. The optical frequency of the slave laser was shifted by 110 MHz with an acousto-optic modulator before the light reached the beat-note photodetector.

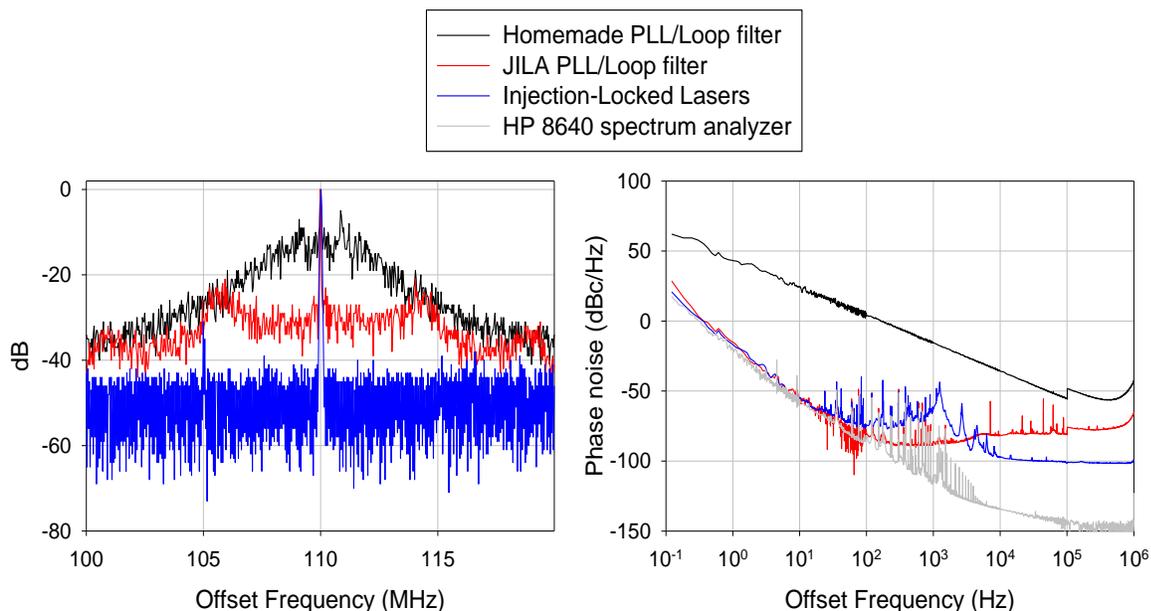


Figure 1. Beat-note spectra of master/slave DBR. Left plot – beat note spectrum, right plot - phase noise spectrum. Black trace - homemade PLL/Loop filter; Red trace - JILA PLL/Loop filter; Blue trace - injection-locked lasers. Gray trace – phase noise of the HP 8640 spectrum analyzer used as a local oscillator for the DDS.

The traces show that both the beat-note spectral width and the phase noise can be significantly improved by using an improved PLL versus the homemade PLL. The improved PLL demonstrates a phase noise approaching that of the injection-locked lasers. No significant effort to optimize the injection-locking was made, and the increased phase noise at 1 kHz is probably due to residual optical feedback. Such optical feedback was observed from the surface of the collimator/fiber system delivering the light from the master laser, and was subject to mechanical sensitivity. Injection-locked lasers are routinely used in atomic fountains to obtain atom temperatures around 1  $\mu$ K [6]. As the beat-note phase noise of the lasers locked with the improved PLL (red trace on Figure 1) does not deviate significantly from that of two

injection-locked lasers (blue trace on Figure 1), we expect to achieve sub-Doppler cooling and atom temperatures on the order of 1  $\mu$ K by using phase-locked lasers.

## STABLE LASER MODULE AND FIBER-BASED COMPONENTS

Our previous laser housing design was driven by two main concerns: first, the challenge of achieving optimal injection into a single-mode polarization-maintaining (PM) optical fiber, and second the ease of diode replacement. The laser diodes that we initially used had unreliable lifetimes, so we designed a mount on a three-axis translation stage that expedited diode replacement. Now that we have migrated to a new distributed Bragg reflector (DBR) laser diode, which has a much longer lifetime, we found the translation stages to be more of a liability, due to their inherent mechanical instability.

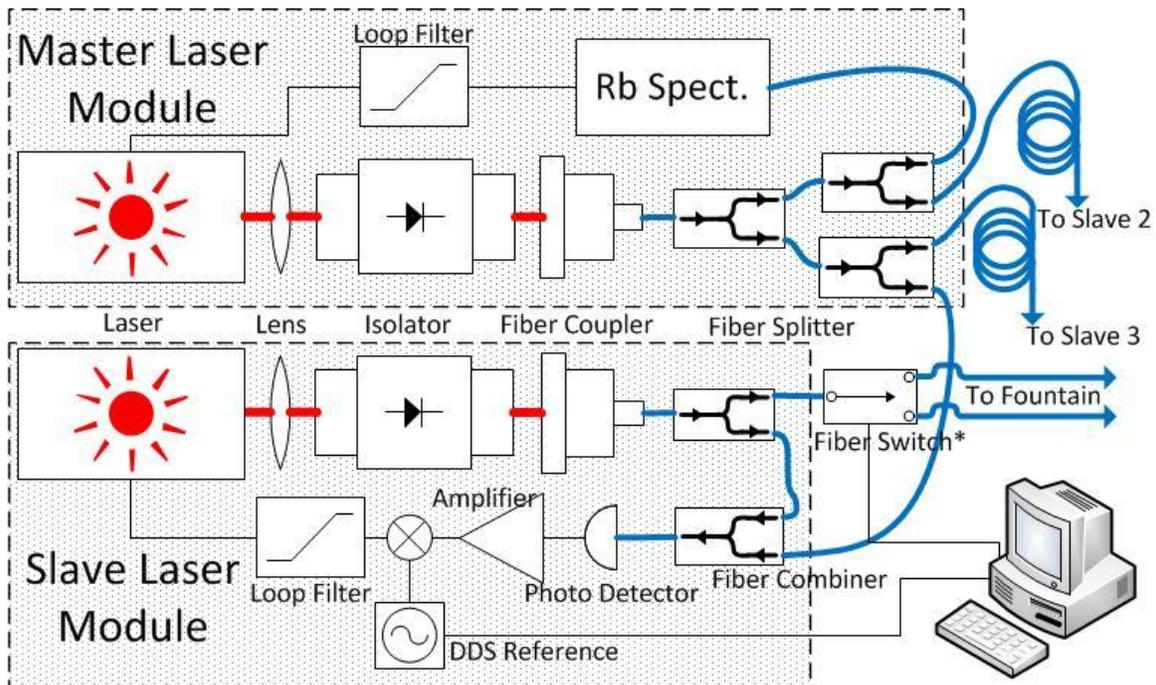


Figure 2. Laser system diagram. Each additional slave laser module is a replica of the one shown here. \*Note that, we currently only have one true Fiber Switch, therefore the two slave lasers providing the vertical cooling beams instead pass through the Fiber-AOM module shown in Figure 3.

We now rigidly mount the laser to an optical breadboard, which has significantly improved the stability of the fiber coupling. Obtaining satisfactory fiber injection is still a challenge with the new diodes, and fine control over the degrees of freedom for aligning the beam-shaping optics is still necessary. For the free-space laser collimating optics, we have made some custom modifications to a small, commercially available fiber-coupling device. We have also moved towards a modular laser system that incorporates more fiber-based components. The laser-housing module measures roughly 7 cm x 7 cm x 25 cm, and consists of the laser, beam-shaping optics, optical isolator, and fiber coupler.

Out of the laser module we use a PM fiber splitter to pick off some of the light used for phase-locking. That picked-off light is connected to a fiber-combiner, which overlaps the master and slave beams into a single fiber and directs them onto a fast photodetector. This configuration reduces the optical alignment

requirements to a single, initial fiber injection, and eliminates some free-space optics, thereby making our system more compact. The light from the other port of each slave fiber splitter, (90% - 95% of all fiber-coupled light), passes through the Fiber Switch (horizontal laser beams) or the Fiber-AOM module (vertical laser beams) discussed below, and then is delivered to the physics package.

For sub-Doppler cooling, a controlled attenuation of the intensity of the cooling laser beams is optimal. Initially, we used individual mechanical shutters to control the attenuation of the light for the horizontal and the two vertical laser beams. Also, the mechanical shutters help avoiding light shifts during the fountain operation by completely extinguishing the cooling laser beams.

The shutters are components that we have struggled with. The use of mechanical shutters caused the light attenuation and extinction to be insufficiently synchronous and repeatable. Some of the shutters also introduced noticeable noise spurs on the lasers. We initially worried that the shutters were the culprit behind our ineffective laser cooling as the cooling beams were switched off at different times, but have since eliminated them as a potential limitation through the following two strategies.

For the Fiber switch, which provides the horizontal beams' attenuation, we purchased a voltage-controlled fiber attenuator. The control voltage determines the splitting ratio between the two output ports, or in other words the attenuation of the light in a single output port. It is a solid-state device with no moving parts and provides repeatable switching with  $\sim 30$ dB of attenuation and 300ns minimum response time. Another feature of this device is that it allows efficient use of the input light. One port of the switch is used for the horizontal cooling light, and the other port of the switch for detection of the atoms. This avoids a permanent beam pick-off for the detection light, leaving more light for cooling. So far we only have one fiber switch, as we wanted to evaluate its performance, and will use additional devices in the rest of the system.

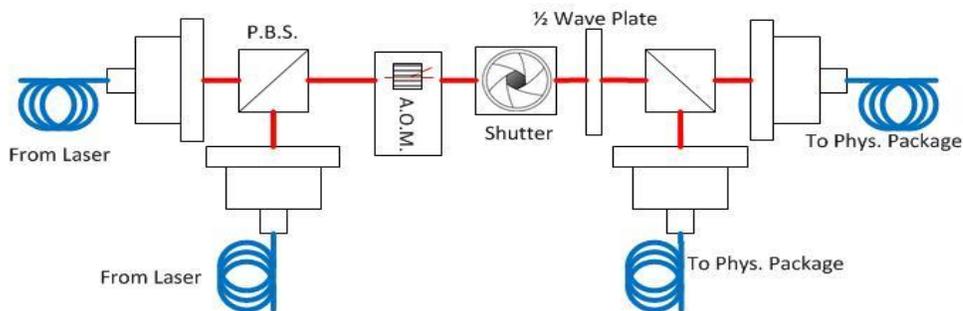


Figure 3. The Fiber - AOM module used for the two vertical laser beams instead of the “Fiber Switch”. The AOM is used to control the light attenuation, and the mechanical shutter to extinguish the light completely.

For the moment, we built a single Fiber-AOM module shown in Figure 3, used for the simultaneous attenuation of both vertical fountain beams. After trying multiple configurations, we decided to resort to an acousto-optic modulator (AOM) in front of a mechanical shutter. AOM's have a very fast and reliable optical extinction rate, and are extensively used in primary atomic-fountain frequency standards. We set up a module where the up and down beams are collimated out of fibers and overlapped onto each other. The overlapped beams then pass through the AOM and mechanical shutter. The deflected first diffraction order contains light from both lasers but with orthogonal polarizations. The polarizations are separated by use of a waveplate and a polarizer, and finally sent through fibers to the physics package. Each deflected beam can be efficiently coupled in both output fibers, thus ensuring a good spatial overlap of the two beams. A bonus feature of this configuration was that with the turn of a half-wave plate we could swap the up and down beams, or send light from each laser into both up and down beams (though in this

configuration the atoms cannot be launched). This setup turned out to be quite helpful for discovering the cause of the ineffective sub-Doppler cooling. The mechanical shutter can be omitted except when the light shift is important, as the extinction of the first diffraction order is quite effective.

## **THE DIRECT DIGITAL SYNTHESIS (DDS) SYSTEM AND NEW MASTER LASER FREQUENCY LOCK**

The programmable DDS system that we developed uses a commercially available DDS chip on an evaluation circuit board, in addition to a home-built interfacing circuit board. The various frequency sweep profiles needed for cooling and launching the atoms were stored in the DDS memory. Occasionally the system would execute the wrong sweep profile. This was due to the TTL triggering signals, which selected the desired profile and triggered its execution, not being sufficiently synchronous for the high-speed DDS chip. We improved the circuit design and made a new circuit board. Additionally we reduced the frequency of the DDS reference clock, and therefore its output frequency range as well. These modifications significantly reduced the rate of occurrence of the glitches, but did not eliminate them altogether. In order to eliminate them we will have to discard the off-the-shelf evaluation board and incorporate the DDS chip directly onto the home-built circuit board.

The reduction of the DDS frequencies meant that we needed to adjust the beat frequencies between the master and slave lasers by a corresponding amount in order to bring the slave diode frequencies to the desired values through the fountain cycle. There are a variety of methods for achieving this, but we came up with an alternate master laser-locking scheme that has served well. Previously, we locked the master laser to the prominent  $F'=2/3$  crossover peak in a standard saturated spectroscopy scheme, which results in a nominally 130 MHz beat frequency. In the new scheme we lock to the cycling transition peak directly, and use an AOM to create the desired offset for beat-note locking (in this case 40 MHz). The AOM also enables the dithering of the saturation beam's frequency, which we use for obtaining a true derivative error signal.

The spectroscopy configuration that we devised enhances the cycling transition peak and suppresses the other peaks in the manifold. This is done by use of a circularly polarized saturation beam that optically pumps the atoms towards a stretched state. The probe beam with linear polarization can be decomposed into right-hand and left-hand circular polarization components. The two components pass through the vapor cell and a quarter-wave plate, and are detected on individual photodetectors. The signals from the two photodetectors are subtracted. The optical pumping due to the saturation beam causes the absorption of one component of the probe beam to increase while suppressing the other component [7]. Subtracting the two signals highlights the difference, enhancing the depth of the cycling peak while diminishing the other nearby peaks. This master laser-locking scheme has proven robust, staying locked for days at a time.

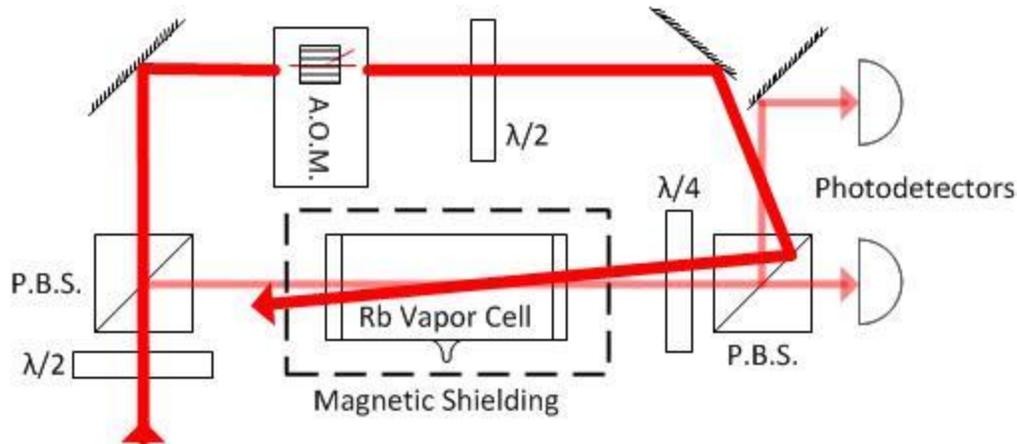


Figure 4. The spectroscopy configuration for frequency locking the master laser.

## CONCLUSION

We have made a number of improvements to our laser system over the last year, and now have solid data indicating that we can obtain sub-Doppler cooled atoms with independently phase-locked DBR lasers. We have recently designed new phase-locking circuits that closely mimic the higher performance version, and will be testing them soon.

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