Miniature, Compact Laser System for Ultracold Atom Sensors

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ABSTRACT

As ultracold atom sensors begin to see their way to the field, there is a growing need for small, accurate, and robust laser systems to cool and manipulate atoms for sensing applications such as magnetometers, gravimeters, atomic clocks and inertial sensing. In this paper we present a frequency-agile, butterfly packaged laser source, absolutely referenced to an atomic transition. We also present the entire laser system, including a fiber-coupled optical amplifier and liquid crystal shutters, replacing a laboratory table’s worth of optics with a system the size of a paperback novel.

Keywords: laser cooling, inertial sensor, gravimeter, magnetometer, clock, atomic physics, MOT, BEC

1. INTRODUCTION

Arguably, the most technically difficult aspect of realizing an ultra-cold atomic vapor is the sophisticated laser system required. Multiple, high-power, frequency agile lasers are required, along with a suite of sophisticated opto-electronic controls. Currently, full ultra-cold atom laser systems require substantial home-built design and construction.

This lack of laser systems designed for cold-atom applications slows the development of cold-atom sensor, which in turn delays the ultimate transition into the non-R&D marketplace. Commercially available diode laser systems are designed to work in a laboratory environment, not the field, forming a significant impediment to commercial transition.

Figure 1 shows our ultimate goal. On the left is a laser systems largely built from commercial diode lasers. Four diode lasers are used to produce the needed beams and frequencies for an atom-chip experiment to generate BEC. In order to enable field-deployable sensors, we must replace the optics table full of lasers, shutters, AOMs, spectroscopy setups, oscilloscopes, and electronics with a small instrument shown on the right side of Figure 1.

![Figure 1](image1.png)

Figure 1. On the left, a major roadblock to achieving a field-deployable cold-atom sensor: an optics table worth of lasers and electro-optics. On the right, our goal: to reduce a laser system to the size of a paperback novel.

2. SYSTEM ARCHITECTURE

The goal of the laser system is to produce and control the requisite laser beams to supply a cold-atom sensor. Functionally, this necessitates a laser system capable of tuning the frequency of the laser beams between various atomic transitions. Bichromatic beams for optical repumping schemes are also needed, as two colors are often necessary in these experiments. Adequately high output powers sufficient for magneto-optical traps (MOTs) and short π-pulses are also needed, as well as the ability to temporally produce such pulses. Shuttering capabilities to extinguish the beams are...
especially needed, as stray light can often be the downfall of precision measurements. Finally, the ability to port beams onto various optical paths is critical, in order to address various experimental geometries (2-D MOTs, double-MOT schemes, separate MOT and science sections, etc.). Figure 2 shows a diagram of the laser system we have designed and built, capable of the above tasks.

Figure 2. Illustrated schematic of laser system design. Goal of system is to provide laser light capable of tuning over various atomic transitions (Agile λ_{ref}), as well as be bi-chromatic when needed (provided by the EOM). Other goals include >200 mW of optical power and short, μs pulses (SOA). Finally, shuttering and the ability to physically divert the beam onto different optical paths is needed (LC Demux/Shutter). Notice in the inset that one of the bulkier components is the free space optical isolator, unavoidable for such work.

3. AGILE λ_{REF}

The Agile λ_{ref} is at the heart of the laser system. It is slightly larger than a stack of business cards, and features: two distributed Bragg reflector (DBR) diode lasers, a Rb vapor cell for an atomic reference, a built-in photodetector and temperature stabilization hardware to control laser and vapor cell temperatures. Figure 3 below shows a solid model of the Agile λ_{ref}, as well as the fully built module before fiber coupling.

Figure 3. On the left is a solid model of Agile λ_{ref}. On the right is a packaged, built up version of the module before lid attachment and fiber coupling. The Master DBR laser, on the left of the model, locks to a Rubidium transition via saturated absorption. The back-facet radiation of the Slave DBR laser (seen on the right of the model) is spatially overlapped and collinear with a pickoff from the Master DBR laser. The heterodyned beams are later incident upon a photodetector to produce an RF beat note which is locked to a reference. The reference can be later tuned, thereby giving the Slave laser frequency agility. The front-facet output of the Slave DBR laser is taken as the primary output of the Agile λ_{ref}.  

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The Agile $\lambda_{\text{act}}$ serves two distinct functions. The first is to provide an absolute atomic reference, via a saturated absorption peak lock to a hyperfine transition in Rubidium. The second is to provide a frequency agile laser, whose frequency is offset from the Master laser by a user specified amount. In this way both frequency-agility and absolute accuracy are ensured. These two functions are described as follows.

### 3.1 Master laser

The Master laser is peak-locked via saturated absorption to a hyperfine transition in Rubidium. For the data presented here, the feature was the $F = 3 \rightarrow 3'/4'$ crossover transition in the $F = 3$ spectra of $^{85}\text{Rb}$. The leftmost graph in Figure 4 shows the saturated absorption signal that will be later used for locking. We modulate the laser current at 4 MHz, and later demodulate the saturated absorption signal to produce a derivative signal. This derivative signal is what is later used for locking. This allows one to lock to the peak of a transition, thereby reducing sensitivity to DC offsets of the laser power.

![Master laser spectroscopy](image)

Figure 4. On the left, an example of the resolved hyperfine spectra from the Rb atomic reference, as measured on the internal saturated absorption detector. On the right, a plot of the average frequency deviation.

The right side of Figure 4 shows the stability of our peak lock error signal. This data was taken by measuring the frequency of a beat note between a laser locked to the Rb atomic reference and another laser locked to a commercial saturated absorption module (Vescent D2-110). The frequency was measured with an RF frequency counter. The average frequency deviation ($\sigma$) in a measurement time ($\tau$) is taken as

$$\sigma(\tau) = \sqrt{\frac{1}{2(N-1)} \sum_{n=1}^{N-1} \left( f_{n+1}(\tau) - \bar{f}_n(\tau) \right)^2} \tag{1}$$

Where $\bar{f}_n(\tau)$ is taken as the average frequency over a measurement time, $\tau$. The subscript $n$ denotes that is was the $n^{\text{th}}$ measurement taken for that measurement time. Notice that after 2 hours the deviation is still less than 100 kHz, negligible compared to the 6 MHz natural linewidth of the atomic transitions.

### 3.2 Slave Laser

The Slave Laser provides frequency agility via an offset phase lock to the Master laser. We take advantage of the radiation from the back, DBR facet, to heterodyne against a pickoff of the master laser for offset locking. The mode quality is centrally important in order to achieve maximal contrast with the Master laser. In light of this we worked with our laser diode vendor (Photodigm, Inc.) to reclave the back-facets of our lasers to improve the mode quality. The leftmost graph in Figure 5 shows our results. Testing our offset phase lock electronics set a threshold of 40 dB signal-to-noise ratio (SNR) in a 10 MHz bandwidth for locking. As the figure shows, our beat note performance was closer to 55-60 dB SNR in a 10 MHz bandwidth.
The central and right plots in Figure 5 demonstrate the frequency agility of the Slave laser. For this data the offset frequency of the Slave laser was swept. The signal is taken from a commercial saturated absorption spectroscopy module. As the data illustrates, the laser is able to address the atomic transition of one’s choosing, with a controllable amount of detuning, if desired. This feature allows one to detune the laser frequency without the use of power-hungry AOMs, as is standard in many laboratories.

Arbitrary control over the laser’s color also allows the laser to be parked well away from the atomic transition when not in use, giving another mechanism to shutter the attenuate the laser. In the low-intensity limit the scattering rate, $\Gamma_{\text{scatter}}$ goes as $(\Gamma/\Delta)^2$, where $\Gamma$ is the natural linewidth of the atomic transition and $\Delta$ the detuning from the transition. With the system we have demonstrated here 6 GHz of detuning is easily achievable, effectively giving the experimenter 60 dB of shuttering.

The Agile $\lambda_{\text{ext}}$ produces between 5 and 6 mW of light. This light is supplied through an angle polished, polarization maintaining fiber. The output side of the laser (before the fiber) has two isolators, providing ~70 dB of isolation, particularly important due to potential back-reflections from the fiber.

4. ELECTRO OPTIC (EO) MODULATOR

The electro optic modulator (EOM) used in our system is a commercial, fiber coupled unit manufactured by EOSPACE. With roughly 5 mW of RF power we should be able to put 10% of the optical power into a sideband for repumping. These sidebands can be turned on and off as the user so chooses. We will be taking a 3 dB hit in optical power after going through the EOM, but this is largely mitigated by following the modulator with an amplifier.

5. SEMICONDUCTOR OPTICAL AMPLIFIER (SOA)

Semiconductor optical amplifiers (SOAs) have been used in the telecom industry for years now as a cost-effective means to both amplify light levels, as well as to produce short optical pulses, while in the cold-atom community tapered amplifiers (TAs) are typically chosen when more power is needed. Our laser system has been designed with both of these in mind, and will use a TA in the first implementation. We are furthering our development of a 780 nm SOA device for future versions of the system and present our results thus far. We will also compare the relative strengths and weaknesses of the differing technologies.

For our SOA design we employed a waveguide ridge that is angled slightly to the normal of the front and back facet. In this way back reflections do not couple back into the waveguide. This is important as we want to ensure that the gain medium does not lase, and instead acts solely as an amplifier. Figure 6 shows both the concept of the SOA (upper left), as well as the amplification performance. As an amplifier the SOA gave a max gain of ~23 dB for 1 mW of seed light at 500 mA drive current. This corresponds to 200 mW total output from the device, suitable for most cold-atom applications. Increasing the seed laser power does not significantly improve the total output power, as the device is
beginning to saturate at 200 mW output. Our SOA laser diode vendor (Intense Inc.) predicted that these devices would produce 400-500 mW output. Slightly lower laser powers, however, are not surprising, as this was our first iteration at making these devices. We are hopeful that our results will lead to improvements in the laser diode design to give the higher output powers.

![SOA performance graph](image)

Figure 6. Upper left: a picture illustrating the concept of the SOA, a straight waveguide ridge, intercepting the front and back facet at an angle with respect to normal. Lower left: an energized SOA, before testing. Right: measured SOA performance, yielding an output greater than 200 mW.

The SOA devices also work well as optical attenuators. Not surprisingly, the gain medium is quite opaque with no charge carriers present. For a typical seed power we measured an attenuation of 40 dB, and measured an overall attenuation of 59 dB from the fully on state to the fully off state.

The SOA also has the capability of producing the types of short pulses necessary for many cold-atom applications. We measure pulse rise times of 4 μs, and fall times of 1 μs. These measurements were limited by our drive electronics, and we are hopeful that after further revisions of our electronics for pulsing purposes will significantly improve upon these performance numbers. For such fast pulses we do expect to observe chirp in the frequency of the radiated light. This is a result of the gain medium’s refractive index changing, corresponding to the rapid increase in injection current. We measured the chirp in a homodyne scheme and observed 4 kHz of chirp within 200 μs. This should be an acceptable level of chirp for most applications. More work will need to be done to see how bad the chirp is for the shortest of pulses.

The spatial mode of the SOA radiation is quite different than that of a TA. Tapered amplifiers suffer from a fair amount of astigmatism that changes as a function of injection current. Typically, the output is collimated at a specified injection current. This precludes tapered amplifiers being used for short optical pulses. At the specified injection current, a large fraction of the TA’s power is in the TEM$_{00}$ mode. SOA devices differ in that there should be markedly less power in the TEM$_{00}$ mode compared to a TA, due to the output facet not being normal to the output radiation. The beam profile, however, is stable as a function of current, and hence factors such as aging of the diode should not couple back into the laser system after being in use for a number of years.

6. LIQUID CRYSTAL (LC) DEMUX / SHUTTER

The final element of the laser system is the Liquid Crystal (LC) Demux / Shutter. This is an active element that is based on LC technology that serves to both port the laser beam onto different optical paths (demux), as well as offering shuttering and pulsing capabilities. Where liquid crystals have proven their utility in the commercial electronics marketplace, their adoption into the atomic physics community has been slow. If the ultimate goal is field deployment,
However, LCs offer numerous advantages in terms of power savings compared to their electro-optic cousins acousto and electro optic modulators.

The left side of Figure 7 shows a picture of a completed LC Demux/Shutter with the laser beam paths illustrated with red arrows. The first function of the device is to port the light onto different optical paths when needed. This is accomplished with an LC cell followed by a polarizing beam splitter (PBS) cubes. When a port is chosen the LC rotates the polarization of the incident light such that it reflects off of the PBS cube a specified amount. These pickoffs (LC cell + PBS cube) can operate from fully on to ~15 dB of attenuation when closed. All four channels are fully independent, meaning light can be put onto any or all of the four paths electronically.

After the pickoffs the light travels through two independent stages of PBS-LC-PBS shutters. The liquid crystal responds quickly when energized, but relax on much slower timescales in the other direction. The two shutter stages are arranged so that one is normally open and the other normally closed, allowing the device to operate in an “armed state” for pulsing. Two examples of the pulses are shown to the right of Figure 7. It is important to note that there is a refractory time of 100 µs necessary between consecutive pulses, in order to return the device to the armed state. Additionally, using the two shutter stages in the closed state provides greater than 55 dB of attenuation. If the pickoff stage is used in conjunction with these the LC Demux / Shutter can provide as much as 75 dB of attenuation.

Figure 7. Complete build of LC Demux/Shutter, with arrows illustrating entry and exit of laser beams on the left. On the upper right is data corresponding to a short, 12 µs pulse, where the pulse edges are clearly rolling over. On the lower right is a longer, 100 µs pulse, with sharper pulse edges.

It should be noted that we are still working through reliability issues associated with the LC Demux / Shutter. Much of the data presented here was taken with devices that worked properly after initial build, but then experienced degradation in performance after a few months of use. LC degradation over time is a problem we have encountered before, and we are hopeful that these issues will be resolved in later builds.

7. CONCLUSION

In conclusion we have built a small, compact laser system for cold-atom research. The system was designed and built with an eye towards eventual field deployment, with the number of components kept to a minimum, as well as boasting a completely non-mechanical architecture.

Table 1 lists our performance parameters, as well as the Size Weight and Power (SWaP) performance of the system.
Table 1. Size Weight and Power (SWaP) performance of Vescent’s Miniature, Compact Laser System.

<table>
<thead>
<tr>
<th>Component</th>
<th>Size (mL)</th>
<th>Weight (kg.)</th>
<th>Power Consumption (mW)</th>
<th>Power Throughput (mW)</th>
<th>Shuttering (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agile $\lambda_{\text{ref}}$</td>
<td>10</td>
<td>0.085</td>
<td>900</td>
<td>5</td>
<td>60 ($\Delta = 6$ GHz)</td>
</tr>
<tr>
<td>EOM</td>
<td>5</td>
<td>0.056</td>
<td>5 (RF)</td>
<td>2.5</td>
<td>n/a</td>
</tr>
<tr>
<td>SOA</td>
<td>1.5</td>
<td>0.018</td>
<td>1500</td>
<td>200</td>
<td>59</td>
</tr>
<tr>
<td>Optical Isolator</td>
<td>60</td>
<td>0.38</td>
<td>n/a</td>
<td>184</td>
<td>n/a</td>
</tr>
<tr>
<td>LC Demux / Shutter</td>
<td>62</td>
<td>0.028</td>
<td>48</td>
<td>165</td>
<td>75</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>139</strong></td>
<td><strong>0.57</strong></td>
<td><strong>2450</strong></td>
<td><strong>165</strong></td>
<td><strong>194</strong></td>
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