PHYS 450 Design Project Final Report:  
Rubidium Atomic Clock

Josh Bendavid 492-0047  
David Burns 492-0860  
Secretary Joseph Fox 496-8274  
Safety Officer Gaetan Kenway 486-7146  
Group Leader Carlos Paz-Soldan 489-3718  
Devon Stopps 490-9611

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Abstract

We report on the detailed design, construction, and performance analysis of an optically pumped atomic frequency standard based on the 6.8 GHz $^{87}$Rb hyperfine transition. Pumping of the F=1 ground state was achieved using a custom built, tunable, external-cavity diode laser, locked to the Fg=2 $\rightarrow$ Fe=2 780 nm transition of $^{87}$Rb, using a saturated absorption spectroscopy. The design features a microwave oscillator stabilized to the 6.8 GHz transition using feedback from a cyclic double resonance resolved using frequency keyed modulation of the microwave source. Short and long term timing stability measurements could not be completed due to difficulties with the microwave frequency division and acquisition. Nevertheless, in addition to optically pumping F=1 ground state, our optical configuration is also capable of resolving the hyperfine structure of the 780nm transition in both $^{87}$Rb and $^{85}$Rb, allowing for this setup to be converted into a saturated spectroscopy experiment for the advanced physics laboratory.
Acknowledgements

The contributions of the numerous individuals, friends and faculty, who aided with this work cannot be overstated. We would like to thank our supervisor, Dr. Hallin, for his invaluable insight and aid in securing the capital required to fund this work. Many thanks also to Ken for the hours you invested helping and advising us. You went far above and beyond what was required and we are appreciative. Dirk, Bernie, and Kim, without your help, this work would not have been possible; we cannot thank you enough. Andrew Joyce, thank you very much for your help with the last minute PCB fabrication, we are all certainly indebted to you. Finally, we must also thank all the other remaining faculty and friends, of whom there are many, who supported us through this project; we are grateful.
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1 Introduction

Extremely high accuracy measures of time or frequency are required in many areas of scientific research. They are also essential in the maintenance of international time standards, the operation of many telecommunications systems, and the accuracy of the GPS network. A general method of producing a very precise and accurate frequency standard, is to lock-in a microwave resonator to the atomic transitions of some species. Typically, Cesium or Rubidium are used for this purpose.

It was proposed to build an optically pumped atomic clock based on the 6.835 GHz hyperfine transition of the $^{87}$Rb $5S_{1/2}$ ground state. Pumping is achieved through the use of a tunable laser centered on the $^{87}$Rb $F=2 \rightarrow F'=2$ hyperfine transition, which effectively spin polarizes the Rb atoms in the $F=1$ ground state. A microwave is then used to complete a cyclic double resonance by re-exciting the $F=1$ atoms back to the $F=2$ state. The frequency required to engage this double resonance is known quantum mechanically, and by counting the EM oscillations this can be used to produce a highly accurate frequency standard. This frequency standard was then to be compared with both quartz oscillator reference clocks and the NIST time standard available over the GPS network. As the GPS receiver can generate time stamps accurate to $\sqrt{2} \times 10^{-6}$s over arbitrary time scales, counting the clock frequency for $10^5$ s would give an accuracy to one part in $10^{-11}$, the expected limit of this technology.

It was also proposed to turn this setup upon completion into a saturated spectroscopy experiment for the advanced physics laboratory. A higher than average budget was thus justified as the experimental setup would be reused in future years.

2 Quantifiable Objectives

Although the overall objective of the project is to build a functioning Rubidium atomic frequency standard, and to characterize its performance, doing so requires many sub-components, each with their own set of quantifiable goals. To construct an optically pumped atomic clock requires first locking a laser to the appropriate hyperfine transition, and then using that laser to lock the microwave system to the double resonance. We discuss first the performance which is required of the optical system to accomplish this task, since this serves as our objectives for this part of the experiment.

2.1 Tuneable Laser

Our goal was to design and construct a diode laser which was smoothly and approximately linearly tuneable over a range of several nanometers in wavelength about the 780nm $5S_{1/2}-5P_{3/2}$ transition in rubidium.

2.2 Absorption Spectrum of Rubidium

The next step after constructing a tuneable laser is to resolve the doppler-broadened absorption peaks in rubidium. Since our rubidium cell is a mixture of $^{85}$Rb and $^{87}$Rb, there are four doppler-broadened peaks comprising the fine structure of the 780nm transition. It was our goal to clearly resolve each of these.

In addition to the doppler-broadened absorption peaks, we also wished to resolve the peaks' hyperfine structure. (Three hyperfine peaks in each doppler peak allowed by transition rules.) In particular, we were interested in clearly resolving the $F=2$ to $F'=2$ hyperfine peak in $^{87}$Rb, since this is the transition used for the double resonance.

2.3 Optical Locking to Hyperfine Peak

Once the appropriate peak was resolved, our goal was to lock the laser to that peak, using a feedback loop, and to characterize the frequency range within which the lock is able to stabilize the laser.
2.4 Double Resonance

Once the optical setup was fully working, our goal was to resolve the shape and width of both the doppler-broadened and hyperfine double resonance peaks in the microwave cavity rubidium cell, using a modulated microwave signal. Once this was achieved, the goal would be to use a lock-in amplifier and a feedback loop to lock the microwave oscillator to the hyperfine double resonance peak, providing a stable frequency reference.

2.5 Frequency Stability Characterization

Once a stable clock signal was achieved, the final goal was to characterize the short term frequency stability and long term timing stability of the output. The goal for short term stability was to use a digital counter to make comparisons with quartz oscillators, and use those comparisons to establish the quartz oscillator stability (approximately 1 part in 10^8) as the lower limit on the short term frequency stability of the clock.

For long term stability characterization, the goal was to use comparisons with the timing output of a GPS receiver to measure or set a lower limit on the long term timing stability of the clock. For the GPS receiver we acquired provided a 1Hz pulse with 1µs jitter; hence, the maximum achievable measurement precision is 1 part in 10^12 over a counting period of one week.

2.6 Refinement of Quantitative Objectives

For the short-term stability tests, comparison to quartz oscillators should be able to establish a lower limit on (short-term) clock stability of between 10^{-6} and 10^{-8}.

For the long-term stability comparisons, we may have to revise our testing schedule depending on how much time is available for continuous running. Measurable long term stability would then approach ∼ 10^{-9}

In addition to frequency-stability measurements, we also intend to measure the shape and width of the 6.834GHz transition in ^87Rb under the double-resonance being used for the microwave frequency lock. The tunable diode laser and saturated absorption spectroscopy setup will be used to measure the absorption spectrum of the ^87Rb and ^85Rb at the sub doppler level using the saturated spectroscopy setup. The tunable laser is expected to be tunable to below 5Mhz.

3 Theory

3.1 ^87Rb-beam Optically Pumped Atomic Clock

Accurate time standards can be produced by locking a crystal oscillator to an atomic transition frequency[18]. For this design, a quartz crystal oscillator will be locked to the 6.835 GHz microwave transition between the F=1 and F=2 ground hyperfine levels of ^87Rb. The accuracy of the time standard is related to the width of the microwave resonance. Due to the doppler effect, the natural resonance is broadened to 9.4 kHz. Unlike typical commercial solutions, a design is proposed which utilizes an optical pump in order to resolve the sub-doppler natural resonance and achieve order of magnitude improvements on lock accuracy.

Six optical transitions are allowed between the 5^2S_{1/2} (ground) and the 5^2P_{3/2} (1st excited) states in ^87Rb for
\[ \Delta F = 0, \pm 1 \]  
(1)

Where F is the atom’s total spin; the vector sum of nuclear and valence electron spins I + J. An optical pumping of the F=1 ground level will be conducted (see figure 1) on the rubidium clock cell using a diode laser tuned to the F=2→F’=2 transition using saturated absorption spectroscopy (see section 3.3). Driving the microwave cavity containing the vapor cell at the 6.835 GHz transition resonance repopulates the F=2
ground state and thus reduces the transmission of the optical pump beam. The quartz oscillator is stabilized to the center of the transition resonance by performing a peak lock on the absorption spectrum detected on the photodiode resolved using a frequency shift keyed modulation of the microwave source.

![Energy level diagram of the $^{87}$Rb-beam D2 resonance line](image)

Figure 1: Energy level diagram of the $^{87}$Rb-beam D2 resonance line [18]

Due to corresponding doppler shifts in the optical resonance, pumping is only achieved for atoms stationary with respect to the beam axis in the lab frame. Similarly, the (microwave) re-pump induced optical attenuation is only resolved for the stationary atoms. The microwave lock-in apparatus is thus less sensitive to the atoms responsible for the doppler broadening, allowing the sharper natural linewidth to be resolved and locked to.

### 3.2 Littrow Configuration Tunable Diode Laser

A large and front-end loaded part of the project is the design and construction of the tunable diode laser system. Fortunately, ample literature exists on the subject [4][6][8][13][16][18][23]. The design we will be using[31] was put forward specifically with the needs of the undergraduate student in mind.

The commercially available diode laser is tuned using an external cavity Littrow configuration[5]. This is the most basic of external tunable configuration types and is the simplest implement. The laser tunability depends on the angle laser light makes with a reflective ruled grating as pictured in figure 2.

The relationship between the angles is given by the familiar grating equation:

$$m\lambda = d(sin(a) + sin(b))$$

(2)

To tune the laser, the incident angle of light must be adjusted such that the first order diffraction, $b_1$ is reflected at the same angle as the incident light. This reflected light returns to the diode laser cavity and preferentially selecting the lasing mode and produces a highly monochromatic beam. Then by varying angle of incident light, slightly different wavelengths can be reflected back to the cavity thus changing the output wavelength. The linearly polarized light from the zero\textsuperscript{th} order reflection is the output which is utilized for the experiment. The difficulty is stabilizing and controlling the angle of the diffraction grating. Large, nanometer scale, shifts in wavelength can be realized with the use of an optical lens mount and fine
adjustment screws. For sub-nanometer control, a piezoelectric crystal is used to change the incident beam angle. One disadvantage of this setup is the angular change of output beam position as the wavelength changes. For the current experiment, it is not an issue since the piezoelectric crystal movement causes a negligible deviation of the output beam, allowing the optics to remain in fixed positions.

3.3 Saturated Absorption Spectroscopy

In order to perform an optical pumping of the $F=1$ ground state, the ability to selectively excite the $F=2 \rightarrow F'=1$ or $F=2 \rightarrow F'=2$ transitions of $^{87}$Rb is required, the latter of which was selected for its increased transition rate resulting in increased signal strength. Laser lines, which tend to drift with temperature and mechanical fluctuations, must be centered and stabilized using feedback control. A linear laser spectroscopy is not sufficient for discriminating the hyperfine levels of the $^{5}_{2}P_{3/2}$ state\cite{1} as doppler-broadening limits resolution to 520 MHz\cite{11}. However, a doppler free saturated absorption spectroscopy can resolve the hyperfine peaks for locking.

This method splits a frequency modulated beam into three components, probe, pump and reference. The reference beam is passed through a glass vapor cell containing thermal $^{87}$Rb and the reference spectrum is detected on a photodetector. As the laser is swept through a transition frequency, the counter-propagating pump and probe beam interact with stationary atoms; however as the stronger pump beam depletes the atoms in the ground state, the transmitted intensity of the probe increases. The differential probe-reference signal yields the doppler free hyperfine absorption peaks which the laser is locked to using piezo voltage control. The apparatus is pictured in figure 6.
4 Experimental Setup

4.1 Experimental Overview

The experimental setup utilized for this project broadly consists of two separate controlled feedback systems: optical and microwave. Each has the generation, detection, and feedback control systems necessary to lock onto the required hyperfine transitions of $^{87}\text{Rb}$. The optical-frequency EM waves are generated using a tunable laser, which is able to produce a highly coherent and stable beam. This light is then passed through the saturated spectroscopy optical table configuration and separated by polarization angle. The setup creates counter-propagating beams of asymmetric intensity through the rubidium cavity. This allows resolution beyond the doppler-broadened absorption peak. This signal is measured using a set of photodiodes, which is used to lock the tunable laser onto the desired hyperfine transition. Alternatively, this setup can function in a frequency-sweeping configuration, allowing the generation of the rubidium absorption plots shown in later sections.

The microwaves are generated using a voltage controlled quartz oscillator (VCO); the output of which is frequency shift keyed using a direct quadrature modulator and multiplexer. Frequency sweeps of the microwaves are carried out in the kHz range. The signal is injected into a microwave cavity, where the double resonance condition is detected on a photodiode monitoring the transmitted intensity of the optical pump. This signal is read with a DSP lock-in amplifier to drive an analog circuit which stabilizes the VCO center frequency. To measure the VCO frequency, a 64x frequency divider is employed after which the signal is counted using a 100 MHz GPIB counter. This time signal can then be compared with that of a GPS unit which has been set up specifically for this project. This unit has an accuracy of $\sqrt{2}\mu s$ on arbitrary time scales with respect to GPS network, synchronized to NIST time servers. Thus, a week is required to measure the clock frequency to an accuracy of $10^{-11}$, the expected limit for the apparatus.
4.2 Littrow Tunable Diode Laser

The tunable laser components are shown in figure 4. The laser diode and collimating lens are secured to aluminum blocks and then bolted to a solid aluminum baseplate. The diffraction grating is first attached to a standard mirror mount using double sided tape which is in turn bolted to the baseplate. The laser and lens are separated by a thin gap which, by way of a fine adjustment screw, allows the distance between the lens and laser to be adjusted, thus collimating the beam. Careful adjustment allows for the beam to remain collimated to 4mm diameter over several meters. For correct operation of the laser, the first order diffraction must be reflected precisely back to the laser diode. This is achieved by adjusting the horizontal (left) and vertical (right) knobs on the mirror mount. Once the laser is tuning approximately 1/2 turn on the horizontal knob will cause several nanometers change in wavelength. To aid with the saturated spectroscopy setup, a 36:1 gear reduction along with a flexible coupling was attached to the horizontal knob. This allows for more precise manual control which makes the task of locating the rubidium doppler-broadened absorption peaks significantly easier. Very fine tunability is achieved using a piezoelectric crystal inserted between the horizontal adjustment screw and the lens mount.

To achieve long term stability, the temperature of the laser and baseplate must be accurately controlled. Not shown on the diagram are two thermistors: one embedded immediately below the laser diode and the second in the side of the baseplate. These are used as input into a Proportional-Integral temperature controller which are used to control thermoelectric coolers, keeping the laser and baseplate stabilized slightly under room temperature. Finally, as the actual laser setup indicated, it is necessary to utilize large heat sinks to allow the thermoelectric coolers to dissipate the heat removed from the apparatus. (Figure 5).

4.3 Saturated Spectroscopy

4.3.1 Optics

The optics for the saturated absorption spectroscopy were designed with two chief goals in mind; achieving maximum signal to noise, and minimizing cost. The latter proved to be a more significant constraint. In order to achieve the requisite counter-propagating beams, a scheme using partially silvered mirrors would inevitably redirect light back into the diode causing massive mode instabilities. This could be rectified using
an optical isolator, however, high cost prohibited the implementation of such a device.

Counter propagation of pump and probe beams was achieved, whilst maintaining excellent optical feedback isolation using a suite of polarization optics depicted in figure 6. The tunable polarization rotation achieved using a $\lambda/2$ waveplate allowed the pump:(probe+ref) intensity ratio to be tuned for optimization of the probe signal, with the splitting achieved on polarizing beam splitter (PBS) 4. A 50:50 splitter is employed in order to separate out probe and ref beams with matched intensity, and finally feedback isolation from vertically polarized waste pump light is achieved using PBS 7. The vapor cells selected contained natural rubidium, approximately equal parts $^{85}\text{Rb}$ and $^{87}\text{Rb}$, in order to minimize cost. This was of little concern as the quantum signatures of the two atoms can be discriminated based on the relative spacing and strength of their hyperfine transitions.

4.3.2 Electronics

The laser frequency was side locked to the $F=2 \rightarrow F'=2$ transition using feedback control of grating angle with the piezo-electric transducer. A side-locking scheme was selected, as oppose to a peak-lock, as a stable optical frequency was required in order to perform the optical pumping (cavity cell) requisite in the cyclic-double resonance. This prohibited a direct modulation of the laser frequency. Down stream modulation is possible using either an acousto or electro-optic modulator, however, these devices were prohibitively expensive.

The optical-lock circuitry is given in Appendix B.1 and consists of 7 stages. The apparatus provides the ability to select between two modes of operation. In sweep mode, the piezo voltage is scanned linearly allowing the absorption spectrum to be fully resolved. During lock-in mode, a PI controller is used to stabilize the laser frequency to a position (selected during sweep mode) on the side of the selected hyperfine peak. The position is maintained as a voltage level on the differential probe-ref output controlled via tunable setpoint. In selecting the gains on the integral and proportional branches of the PI controller, a simulation of
<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>External Cavity (Littrow Configuration) Tuned Laser</td>
</tr>
<tr>
<td>2</td>
<td>10/90 Beam Splitter</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{2}$ Waveplate</td>
</tr>
<tr>
<td>4</td>
<td>Polarizing Beam Splitter</td>
</tr>
<tr>
<td>5</td>
<td>Horizontally Polarized Probe Beam</td>
</tr>
<tr>
<td>6</td>
<td>50/50 Beam Splitter</td>
</tr>
<tr>
<td>7</td>
<td>Polarizing Beam Splitter</td>
</tr>
<tr>
<td>8</td>
<td>Waste Pump Dump</td>
</tr>
<tr>
<td>9</td>
<td>Natural Rubidium Vapour Cell ($^{85}$Rb and $^{87}$Rb)</td>
</tr>
<tr>
<td>10</td>
<td>Vertically Polarized Pump Beam</td>
</tr>
<tr>
<td>11</td>
<td>Reference Beam</td>
</tr>
<tr>
<td>12</td>
<td>Probe Photodiode</td>
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<tr>
<td>13</td>
<td>Reference Photodiode</td>
</tr>
<tr>
<td>14</td>
<td>Microwave Waveguide</td>
</tr>
<tr>
<td>15</td>
<td>Microwave Cavity</td>
</tr>
<tr>
<td>16</td>
<td>Second Natural Rubidium Vapour Cell</td>
</tr>
<tr>
<td>17</td>
<td>Microwave Cavity Photodiode</td>
</tr>
</tbody>
</table>

Figure 6: Saturated Spectroscopy Setup
the control loop was conducted using MATLAB. Gain values were selected in order provide simultaneously adequate stability and noise rejection over the full frequency range of the piezo (∼1kHz).

### 4.4 Microwave Synthesis

Once the laser is locked to the appropriate hyperfine transition, detecting and locking to the double resonance with a microwave signal requires synthesizing and tuning a microwave signal at 6.835GHz, and coupling that signal into the rubidium cell. To increase signal to noise, and to produce a more stable lock-in frequency, we decided to employ a modulated peak-locking scheme, which allows the use of a lock-in amplifier to produce the error signal for our feedback loop.

In order to modulate the microwave signal, while still retaining a stable center frequency for the clock output, we used a voltage controlled oscillator (VCO) connected through an I/Q Mixer, which acts as a modulator. This provides both a stable center frequency directly from the VCO, as well as signal modulated about that frequency from the I/Q Mixer. For the purpose of obtaining an accurately centered lock on the peak, frequency-modulation with an I/Q mixer requires amplitude matched sine waves in quadrature (90 degrees out of phase), at a desired modulation frequency representing lock location on the peak. This frequency source was supplied with a quadrature oscillator circuit. The overall configuration is shown in Figure 7.

#### 4.4.1 Quadrature Oscillator

In order to produce two signals in tight quadrature at identical amplitudes, a dual op-amp integrator oscillator was used (See Figure A-4). These integrators set two poles at the desired 1/RC oscillation frequency, causing
oscillations as the loop gain crosses the zero gain point. This setup is used to stabilize a RC oscillator while
producing a complementary signal. The transfer function of this oscillator can be represented as shown in
Equation 3.

\[ A\beta = \left( \frac{1}{R_1C_1s} \right) \left( \frac{R_3C_3s + 1}{R_3C_3s(R_2C_2s + 1)} \right) \]  \hspace{1cm} (3)

In the case where \( R_1C_1 = R_2C_2 = R_3C_3 \), this transfer function can be reduced to Equation 4.

\[ A\beta = \frac{1}{(RCs)^2} \]  \hspace{1cm} (4)

The oscillation frequency is tuneable through simultaneous adjustment of the three 24-turn trim potentiome-
ters, following the relation of Equation 4, while fine tuning of the individual signals is provided through
adjustment of the the potentiometer for the respective integrator. Any output distortion was too low to be
noticeable over our range of operating frequencies; the bandwidth of the voltage feedback op-amps utilized
in this design theoretically introduces large phase error as oscillation frequency approaches a few hundred
kilohertz. This is much less of a potential problem due to the high degree of tuneability of each separate
circuit section.

4.4.2 Multiplexer

The output from the quadrature oscillator is fed into an analog multiplexer, connected to the I/Q inputs of
the mixer. This multiplexer allows switching which I/Q input is leading and which is lagging, in order to
provide frequency modulation in either phase direction. The select inputs of the multiplexer are driven with
a square wave, alternating the phase of the input to the I/Q mixer. This frequency modulated signal is then
delivered into the microwave cavity.

4.4.3 Waveguide

In order to cheaply and efficiently couple this microwave signal into the cavity, a simple waveguide and stub
antenna are used. A simulation of this waveguide using NEC2 software (Numerical Electromagnetics Code)
provides insight into the performance of the antenna and waveguide combination; Figure 4.4.3 shows this
design does result in gain, and the signal will be coupled into the cavity.

4.4.4 Feedback

Since the modulation of the microwaves is driven by the quadrature output switching by the multiplexor,
the multiplexor clock provides a natural reference signal for lock-in amplification. The signal from the
microwave-cavity photodiode is fed to the lock-in amplifier using this clock as a reference. Since the double
resonance peak is symmetric, we expect modulation to drive a non-zero lock-in signal when off-center, with
the signal approaching zero as the center frequency of the microwave modulation approaches the peak center.
This is shown schematically in Figure 9.

The lock-in output is therefore used as the error signal for a Proportional-Integral feedback loop which
controls the VCO voltage and therefore the center frequency of the modulation and the output frequency of
the clock. A schematic circuit diagram of the feedback circuit is shown in Figure 10.

4.4.5 Frequency Division

Although the output of the clock is at 6.835GHz, the digital counter at our disposal is only capable of
counting signals up to 120MHz. We have selected a VCO with an f/2 frequency divided output in addition
to the main output, however, additional frequency division is still required to produce a countable signal.
We accomplish this with the frequency counter/divider built into certain PLL IC’s. Printed circuit boards
have been fabricated for two such IC’s, shown in Figures A-2 and A-3.
Figure 8: Electromagnetic Simulation of waveguide antenna

Figure 9: Illustration of microwave modulation about a center frequency on the double resonance peak.

Figure 10: Schematic circuit diagram of the microwave feedback circuit.
4.5 Frequency/Timing Stability Characterization

In designing what is meant to be a time/frequency standard, we also required a method for characterizing the short and long term stability of the clock output in terms of frequency jitter/drift. Since measuring frequency directly with an external device inherently ties the measurement to the internal oscillator of that device, in order to cleanly measure our output, we rely on counting signal cycles using a digital counter, except when directly comparing the clock output to an external oscillator. To this end, we use a 120MHz digital counter, with external reference and external gating capabilities. The configuration for characterizing long-term stability uses a GPS receiver as a time reference.

4.5.1 Short Term Frequency Stability

To characterize the short term frequency stability of the clock, we measure the jitter in comparisons between pairs of oscillators, including the clock. The basis behind this is that the absolute frequency jitter from two independent oscillators adds in quadrature when making a frequency comparison between the oscillators. This frequency comparison is made by using one oscillator as the counter reference to measure the frequency of the second oscillator. The configuration is shown in Figure 11.

![Instrumentation setup for characterizing short term stability of the clock. Comparison is made with a 10Mhz quartz oscillator. This same configuration can also be used for comparing relative frequency stability of two quartz oscillators.](image)

Figure 11: Instrumentation setup for characterizing short term stability of the clock. Comparison is made with a 10Mhz quartz oscillator. This same configuration can also be used for comparing relative frequency stability of two quartz oscillators.

This configuration is convenient, because several of the instruments we are using for other purposes also provide a 10MHz reference output from their internal quartz oscillators.

This configuration in principle allows us to set a lower limit on the short term stability of the clock output. The first step would be to compare the clock output to several quartz oscillators. Next, the quartz oscillators are compared with each other. If the clock-quartz oscillator jitter is measureably smaller than the quartz-quartz comparisons, then this establishes the quartz oscillator stability (estimated from the quartz-quartz comparisons) as a lower limit on the short term stability of the clock frequency output.
4.5.2 Long Term Timing Stability

Characterizing the long-term stability of the clock output presents additional challenges, since it requires an extremely stable time reference. This is provided by a GPS receiver, which provides a 1Hz timing pulse synchronized to the GPS network timing (Which is in turn based on reference atomic clocks). In order to obtain consistent GPS reception, the GPS receiver has been mounted outside of the building near the lab, and an extension cable has been made and routed through the basement ceiling. The receiver has a strong and consistent signal, verified by the computer interface over many weeks. The 1Hz timing output has been configured and tested, as well as used to gate the digital counter.

![Figure 12: Testing GPS reception in outdoor mounting location.](image)

The manufacturer’s specifications for the GPS receiver state a jitter of $\pm 1 \mu s$ for the rising edge of the 1Hz pulses from the GPS receiver (This has been verified in the lab with comparisons to quartz oscillators.) Since this pulse is disciplined to the GPS network timing, however, this error is not cumulative. This means that with the GPS receiver gating the counter (as shown in Figure 13), counts can be obtained over arbitrary timescales with an absolute uncertainty in measurement time of $\sqrt{2} \mu s$. Measurement precision is then determined by how long the clock is run for. For example, running the clock for a week would provide an uncertainty of $\sqrt{2} \mu s$ over a total interval of 604,800 s, or roughly one part in $10^{12}$.

4.6 Microwave Cavity and Waveguide

In order to measure the double resonance in the rubidium cell, a microwave cavity, waveguide and mount were built.

The microwave cavity design is shown in Figure A-8. A multimode cavity was used to produce a flat distribution of microwave intensity. The waveguide design is shown in Figure A-7. A hole was drilled in the end of the waveguide for the laser beam to enter. A mount for the rubidium cell inside the cavity was created in CAD software and then printed on the rapid prototyping machine at Beamish-Monroe Hall. The
Figure 13: Instrumentation setup for characterizing long term stability of the clock. Comparison is made over a long time scale with the 1Hz reference pulse from a GPS receiver.

design can be found in Figure A-6. This was done to avoid the use of metal, which would reflect microwaves. The mount was made out of ABS plastic.

The coupling efficiency of the electronics system to the microwave resonator was evaluated. Unmodulated, 6.8 GHz frequency was first pumped directly into a high-frequency rectifying diode, and then indirectly through the pump antenna, waveguide, and a 1/4 wavelength pick-up antenna inserted into the cavity. The relative transmission loss in the latter case was approximately 1000 times greater. The absolute efficiency, in this case, is not the relevant parameter, as the pick-up antenna receives only a fraction of the microwave power in the cavity; however, more importantly, the functionality of the microwave chain has been demonstrated.
Results

5.1 Tunable Laser

The tunable laser system was characterized according to its various degrees of freedom. Originally, it was intended that gain curves for lasing current, diode temperature, and grating angle would be produced on the Ocean Optics spectrometer in the 5th floor labs. Unfortunately, it was found that the resolution of the spectrometer was prohibitively low for all but the grating angle. It was confirmed during the subsequent tests on our optical table that the laser was indeed sensitive to these other parameters. Each degree of freedom on the tunable laser is now be discussed in detail.

5.1.1 Angle Dependence of Lasing Wavelength

From the outset it was expected that the most coarse adjustment of the lasing wavelength would be achieved using the grating angle. Using the installed 36:1 microdrive, the wavelength response to an angular change of the tuning knob was investigated on the Ocean Optics Spectrometer. It was found that the lasing wavelength varied on the order of nanometers, which were readily observable. A series of beam profiles were recorded for various tuning knob positions, and are shown in Figure 14. Though the figure shows a wavelength shift of approximately 5 nm, it was found that the laser could tune up to 8 nm, centered around approximately 782 nm.

![Gaussian Beam Profiles at Various Tuning Knob Angles](image)

It was expected that the lasing wavelength shift would be linear with the incident grating angle change, and this was examined in Figure 15. The relationship was roughly linear, though large errors are seen on the resulting data. This is due to a number of factors. Firstly, the spectrometer is not able to resolve beyond...
its bin width, which for this calibration was on the order of 0.3 nm. The error in the resulting gaussian fits must thus be added in quadrature with this value, which dominates the final error. Secondly, the installed microdrive does not completely transfer motion to the tuning knob. Some gear slop is present for every turn on the microdrive, adding a systemic error to the suspected angular shift. There might also be slack on the screw into the lens mount being used to actually move the grating. For these reasons, the group was satisfied with the observed linearity and moved on for lack of better testing equipment.

5.1.2 Temperature Stabilization

A pair of PI temperature controllers were designed and employed on the tunable laser housing to provide the desired stability in the long term. Temperatures were measured in arbitrary voltage units using two thermistors. Once a setpoint was decided upon, it was expected that turning on the temperature controllers
would quickly bring the temperature down to the setpoint with minimal oscillations. This process is shown during different days in Figure 16. The proportional and integral gains were tuned empirically, and the results are evident from the plot. Full temperature stabilization required approximately 10 minutes and persisted for arbitrarily long time scales.

5.1.3 Constant Current Driver Performance

![Lasing Current in Constant Current Mode](image)

Figure 17: Lasing Current in Constant Current Mode

The constant current controller, purchased from Thor Labs, was also characterized over a long time scale. During the experiment, it was found that the current controller did not perform as expected; and long term drifts of the current were seen. The power supplies to the controller were replaced in favor of dedicated supplies, which greatly improved stability. However, some drift was still present on the order of tens of µA, shown in Figure 17. Though small, this drift was enough to be observed on the saturated spectroscopy setup. The source of these drifts at this time are uncertain, though they most likely lie in the internal circuitry of the Thor Labs PCB. Our group had intended on re-designing and remaking this part, were there more time for this project.

Overall, the diode laser performed adequately and was capable of fulfilling its role in the rest of the atomic clock setup.
5.2 Saturated Spectroscopy of Rubidium

The saturated absorption spectroscopy performed remarkably well. The hyperfine absorption peaks, 6 allowed for each $^{85}\text{Rb}$ and $^{87}\text{Rb}$, were resolved more clearly than seen in the published literature [27]. Figures 18 and 19 depict the probe and differential satspec signals recorded when performing linear sweeps in the laser frequency. The former shows the hyperfine peaks superimposed on the doppler broadened spectrum. The differential signal, used for the lock circuitry, is the analog subtraction of the probe and reference signals. The frequency axis was scaled in figure 18 using literature values the $^{87}\text{Rb}$ hyperfine energy levels.

![Hyperfine peaks for $^{85}\text{Rb}$ (F=3) and $^{87}\text{Rb}$ (F=2)](image)

Figure 18: Hyperfine peaks of natural rubidium. *Right* $^{85}\text{Rb}$ F=3→F’ transitions. *Left* $^{87}\text{Rb}$ F=2→F’ transitions. The $^{87}\text{Rb}$ F=2→F’=2 transition, centered at 0 MHz, is locked to during clock operation.
Figure 19: Hyperfine peaks of natural rubidium. *Left* $^{87}\text{Rb} \ F=1 \rightarrow F'$ transitions. *Right* $^{85}\text{Rb} \ F=2 \rightarrow F'$ transitions.

The peak centroids were determined using a Lorentzian fitting routine. The theoretical Lorentzian line shape modeled the hyperfine resonance peaks well (see figure 20) but for the asymmetry in the floor attributed to imperfect balance of the probe and ref signal amplitudes.

The optical lock performed satisfactorily and stabilized the laser frequency for upwards of 1 hour. Due to the nature of the side-lock, overstepping the peak would result in a permanent loss of lock which would need to be manually reset. As a result, a loss of lock would occur if sufficient amplitude acoustic vibrations, outside the loop bandwidth, were introduced into the system. However, the PI controller adequately countered lower frequency noise sources such as drifts in temperature and laser current as desired.
Figure 20: Lorentzian fitted $^{87}\text{Rb}$ F=2→F' transitions. From left to right F'=1,2,3.
Figure 21: The effect of acoustic noise on the optical lock circuit. The satspec differential signal is shown to oscillate outside the lock bandwidth at \( \sim 1.2\text{kHz} \).
Table 1: Division of Labour Chart

6 Responsibilities and Timeline

6.1 Organization of Team Activities

The current activities being undertaken by the team is repeated in Table 1, along with an indication of who is responsible for each task. It should be noted that this list is not exhaustive, as completed items have been excluded.

6.2 Gantt Chart

A gantt chart is included to summarize the progression through the project during, before, and after the allotted 12 weeks. Generally, our group put in a solid effort throughout the entire period except for the short respite to complete our thesis projects.
7 Safety

The tunable diode laser emits a 10-30mW beam at 780 nm. This is very harmful to the unshielded eye. As such, specialty laser goggles were purchased for use when calibrating and operating the diode laser. An enclosure box was also created to house the completed optical table, allowing multiple people access to the laboratory without the need of limited laser goggles. Prior to this, only people wearing goggles were be allowed near the operating laser system, which limited the number of people working on the project simultaneously.

As a matter of minor concern, natural rubidium reacts aggressively with normal skin and care would have been taken to avoid its vapour state were it to have escaped from its glass housing. Microwaves can also be harmful, though at the power levels used in this experiment, it was not seen to pose a major problem.
8 Conclusion

A design proposal was made for an optically pumped atomic clock utilizing the hyperfine transitions of $^{87}\text{Rb}$. A double-resonance condition was conceived using a parallel optical and microwave chain to lock a microwave oscillator to the sub-doppler resonance. For the optical chain, a tunable laser was built and demonstrated to reliably tune over the required transitions of $^{87}\text{Rb}$. This was detected using a saturated spectroscopy setup. An analog feedback circuit was created which was able to lock the laser frequency to the $^{87}\text{Rb} F=2 \rightarrow F'=2$ transition. Using this same setup, the tunable laser was used to characterize the $5S_{1/2} \rightarrow P_{3/2}$ state transitions of both $^{87}\text{Rb}$ & $^{85}\text{Rb}$. A microwave generation and modulation chain was designed and built, though at the time of writing the double resonance condition has yet to be observed. This was due to inadequate time for testing. A frequency divider was designed to allow the microwave signal to be counted, though it was not functioning at the time of writing. The most difficult parts of the project have been demonstrated to reliably function, fulfilling the majority of the project objectives.

9 Group Statement

From the outset it was known that this project was going to be ambitious and challenging. Though atomic clocks have existed for many decades, the diode laser technology required to make this project possible on a modest budget has only been developed in the last decade. Many components had to be innovatively designed to function within our budgetary constraints, and as a result we are confident that we have achieved good trade off between scientific value and monetary expenditures. Specifically, our microwave generation setup is completely of our own design, as is the particular setup utilized for the saturated spectroscopy technique.

The final timing results were not complete in time for this report, due to setbacks in the microwave generation and detection chain. The PCB containing much of the microwave chain was completed far later than expected, resulting in very little time for debugging. At the time of writing, the frequency divider PCB was non-functional, and this delayed the entire microwave chain. We are confident that the generation is working, though it is very difficult to detect the double resonance without an accurate knowledge of the frequencies being injected into the microwave cavity. As we have entered this project into an IEEE design competition, we intend to resume our effort on these last components upon completion of our report and exams.

Despite the setbacks, many of our key objectives have been met. A functional saturated spectroscopy setup has been created, allowing for the apparatus to be utilized in a PHYS 450 lab.

References


## A Purchased Parts List

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Subtotal $2,299.09
Taxes $344.86
Total $2,643.95

Table A-1: List of purchased components for the experiment
B Circuit Schematics

B.1 Optical Lock

1. Power Supply Stage for ref and probe diodes

2. Bessel low pass Sallen Key filter. Chosen for flat phase response, buffering, and high frequency noise rejection.

Figure A-1: Satspec optical side-lock circuitry schematic

4. Second differential amplifier; produces the error signal as the difference between differential output and setpoint.

5. Integral branch of control loop

6. Proportional branch of control loop

7. Adder and high voltage gain stage. Produces the piezo control signal as the sum of the piezo setpoint and either the signal generator output for performing frequency sweeps or the lock feedback during operation.
Figure A-2: PCB top section is quadrature oscillator, bottom is high frequency divider
Figure A-3: PCB for serial-controlled frequency divider
Figure A-4: Schematic showing quadrature synthesis and switching
B.3 Temperature Controller
Figure A-5: P+I Temperature Control Circuit for Laser Diode and Baseplate
C  CAD Drawings

The following pages present the engineering drawings which were used during the manufacture of custom components for the project.
Figure A-6: Rubidium cell mount
Figure A-7: Waveguide design

- Title: Waveguide
- Material: Copper
- Sheet: 1 of 1
- Scale: 1:1
- Dimensions: UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES

Key Measurements:
- Width: 1.715
- Height: 0.364
- Thickness: 0.157
- Hole Diameter: 0.250
- Hole Depth: 0.461
- Other Dimensions: 3.914, 0.920, 0.581
Note: External Plate Dimensions are approximate
Figure A-8: Microwave cavity design
D Sample Code

The following pages present some of the various MatLab and Maple code utilized for design and data analysis.
clear all;
close all;

knoboutfile='eplots/knobcalib2-10apr.eps';

%-----------------------
infile='data/-3.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Degs(1)=-30;
WaveL(1)=peakfitvalues(2);
WaveLsigma(1)=peakfitsigmas(2)+.125;

%-----------------------
%-----------------------
infile='data/-2.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Degs(2)=-20;
WaveL(2)=peakfitvalues(2);
WaveLsigma(2)=peakfitsigmas(2)+.125;

%-----------------------
%-----------------------
infile='data/-1.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Devs(3)=-10;
Wavel(3)=peakfitvalues(2);
Wavelsigma(3)=peakfitsigmas(2)+.125;

infile='data/0.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-{lambda-A(2)}.^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Devs(4)=0;
Wavel(4)=peakfitvalues(2);
Wavelsigma(4)=peakfitsigmas(2)+.125;

infile='data/1.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-{lambda-A(2)}.^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Devs(5)=-10;
Wavel(5)=peakfitvalues(2);
Wavelsigma(5)=peakfitsigmas(2)+.125;

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tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-{lambda-A(2)}.^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Devs(6)=20;
Wavel(6)=peakfitvalues(2);
WaveLsigma(6)=peakfitsigmas(2)+.125;

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tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;
fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./(counts+1));
startvals=[0.2,780,2];
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)
Degs(7)=30;
WaveL(7)=peakfitvalues(2);
WaveLsigma(7)=peakfitsigmas(2)+.125;

%--------------------------------------------------------
fitfun=@(A,Degs) A(1).*Degs+A(2);
%axis([775 800 0 0.25]);
startvals=[0.01,770];
damnaxis=axes('FontSize',12);
xerror=2*ones(1,7);
errorbarxy(Degs,WaveL,xerror,WaveLsigma,xerror,WaveLsigma,'.','blue');
hold on;
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,Degs,WaveL,WaveL)
Degs2 = linspace(-40,40,100);
plot(damnaxis,Degs2,peakfit(Degs2),'r','LineWidth',2,'color','red');
	xlabel(damnaxis,'Knob $\theta$ (degrees)','Interpreter','latex','FontSize',14)
ylabel(damnaxis,'Center Wavelength (nm)','Interpreter','latex','FontSize',14)
fitentry=advancedfitlegend(peakfitvalues,peakfitsigmas,rchi2,'$A \theta + \lambda_{0}$',
     {'$A$','$\lambda _{0}$'}); gcf;
legend({'Observed Data',fitentry},'Interpreter','latex','FontSize',12, 'Location','NW');
%--------------------------------------------------------
print('-depsc2',knoboutfile)
%This can be used to generate plots of the laser 
clear all;
close all;
outfile='eplots/knobcalib1-10apr.eps';
knoboutfile='eplots/knobcalib2-10apr.eps';

%----------------------- 
infile='data/m15-0degrees.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);

%tempcounts=data(1750:1795);
sums=sum(tempcounts(1750:1795));
counts=tempcounts(1750:1795)./sums;

lambdas=lambdas(1750:1795);

fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs(counts).^(1/2);
w=abs(1./counts);
startvals=[0.2,780,2];
%damnaxis=axes('FontSize',16);
plot(lambdas,counts,'xr','LineWidth',2)
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w)

Degr(1)=0;
WaveL(1)=peakfitvalues(2);
WaveLsigma(1)=peakfitsigmas(2);
hold on;
ftype = fittype('gauss1');
%[peakfit,errors] = fit(lambdas,counts,ftype);
lambdas2=linspace(770,800,1000);
plot(lambdas2,peakfit(lambdas2),'r','LineWidth',2,'color','red')

%title('Tunable Laser - Knob Adjustment Profile','Interpreter','latex','FontSize',18); 
xlabel('Wavelength, (nm)','Interpreter','latex','FontSize',14); 
ylabel('Intensity (normalized)','Interpreter','latex','FontSize',14);
%[peakfitvalues,peakfitsigmas] = fitparams(peakfit);

%fitentry=fitlegend(peakfit,errors,'$A e^{-\frac{(\lambda - \lambda _{(0)})}{(\sigma)^2}}$','$A$','$\lambda _{(0)}$','$\sigma$');
%fitentry=advancedfitlegend(peakfitvalues,peakfitsigmas,rchi2,'$A e^{-\frac{(\lambda - \lambda _{(0)})}{(2\sigma)^2}}$','$A$','$\lambda _{(0)}$','$\sigma$');

%-------------------------------------------------
infile='data/m15-45degrees.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;

fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./counts);
startvals=[0.2,780,2];
plot(lambdas,counts,'xb','LineWidth',2);
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w);

Degr(3)=45;
WaveL(3)=peakfitvalues(2);
WaveLsigma(3)=peakfitsigmas(2);

ftype = fittype('gauss1');

infile='data/m15-90degrees.Master.sample.txt';
data=dlmread(infile);
lambdas = data(:,1);
tempcounts = data(:,2);
sums=sum(tempcounts(1750:1850));
counts=tempcounts/sums;

fitfun=@(A,lambda) A(1).*exp(-(lambda-A(2)).^2/(2.*A(3).^2));
dcounts=abs((counts)).^(1/2);
w=abs(1./counts);
startvals=[0.2,780,2];
plot(lambdas,counts,'xk','LineWidth',2);
[peakfit,peakfitvalues,peakfitsigmas,rchi2]=advancedfit(fitfun,startvals,lambdas,counts,w);

Degr(5)=90;
WaveL(5)=peakfitvalues(2);
WaveLsigma(5)=peakfitsigmas(2);

ftype = fittype('gauss1');

lambdas2=linspace(770,800,1000);
plot(lambdas2,peakfit(lambdas2),'b','LineWidth',2);
fitentry3=advancedfitlegend(peakfitvalues,peakfitsigmas,rchi2,'$A e^{-\frac{(\lambda - \lambda _{0})^2}{(2\sigma)^2}}$','$\lambda _{0}$','$\sigma$');

axis([775 800 0 0.25]);
legend({'0 Degrees',fitentry1,'45 Degrees',fitentry3,'90 Degrees',fitentry5},'Interpreter','latex','FontSize',10, 'Location','NE');
print('-depsc2',outfile);
This Maple File was used to design the Sallen-Key Filter for the Optical Electronic Circuit. It was desired to obtain a 10kHz lowpass bandwidth two-pole filter.

> with(plots):

> R := 1000; m := 100; C := 10^(-9); n := 2;

\[
R := 1000 \\
m := 100 \\
C := \frac{1}{1000000000} \\
n := 2
\]

> R1 := m*R; R2 := R; C1 := evalf(n*C); C2 := evalf(C);

\[
R1 := 100000 \\
R2 := 1000 \\
C1 := 2.000000000 \times 10^{-9} \\
C2 := 1.000000000 \times 10^{-9}
\]

> Fc := evalf(1/(2*Pi*R*C*sqrt(m*n))); Q := evalf(sqrt(m*n)/(m+1));

\[
Fc := 11253.95394 \\
Q := 0.1400211448
\]

> H := s -> 1/(1+R*C*(m+1)*s+m*n*R^2*C^2*s^2);

\[
H := s \rightarrow \frac{1}{1 + R C (m + 1) s + m n R^2 C^2 s^2}
\]

> lnH := ln(H);

\[
\ln H := \ln(H)
\]

> loglogplot(H, 1..1000000)
E Data Sheets

E.1 Tunable Laser Components

The following pages contain copies of the datasheets relevant to the tunable laser.
HL7859MG
Visible High Power Laser Diode

Description

The HL7859MG is a 0.78 µm band GaAlAs laser diode with a multi-quantum well (MQW) structure. It is suitable as a light source for optical disc memories and various other types of optical equipment. Hermetic sealing of the small package (φ5.6 mm) assures high reliability.

Application

• Optical disc memories.

Features

• High output power : 35 mW (CW)
• Visible light output : λp = 775 to 795 nm
• Small package : φ 5.6 mm dia.
• Low astigmatism : 5 µm Typ (P_o = 5 mW)
### Absolute Maximum Ratings ($T_C = 25^\circ\text{C}$)

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical output power</td>
<td>$P_O$</td>
<td>35</td>
<td>mW</td>
</tr>
<tr>
<td>Pulse optical output power</td>
<td>$P_O$ (pulse)</td>
<td>42 *</td>
<td>mW</td>
</tr>
<tr>
<td>Laser diode reverse voltage</td>
<td>$V_{\text{R(LD)}}$</td>
<td>2</td>
<td>V</td>
</tr>
<tr>
<td>Photo diode reverse voltage</td>
<td>$V_{\text{R(PD)}}$</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>$\text{Topr}$</td>
<td>–10 to +60</td>
<td>°C</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>$\text{Tstg}$</td>
<td>–40 to +85</td>
<td>°C</td>
</tr>
</tbody>
</table>

Note: Pulse condition: Pulse width = 1 $\mu$s, duty = 50%

### Optical and Electrical Characteristics ($T_C = 25^\circ\text{C}$)

<table>
<thead>
<tr>
<th>Items</th>
<th>Symbols</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical output power</td>
<td>$P_O$</td>
<td>35</td>
<td>—</td>
<td>—</td>
<td>mW</td>
<td>Kink free *</td>
</tr>
<tr>
<td>Threshold current</td>
<td>$I_{\text{th}}$</td>
<td>—</td>
<td>35</td>
<td>60</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>Operating voltage</td>
<td>$V_{\text{OP}}$</td>
<td>—</td>
<td>2.1</td>
<td>2.5</td>
<td>V</td>
<td>$P_O = 35$ mW</td>
</tr>
<tr>
<td>Slope efficiency</td>
<td>$\eta_s$</td>
<td>0.65</td>
<td>0.80</td>
<td>mW/mA 21 (mW) / ($I_{28 \text{mW}} - I_{7 \text{mW}}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lasing wavelength</td>
<td>$\lambda_p$</td>
<td>775</td>
<td>785</td>
<td>795</td>
<td>nm</td>
<td>$P_O = 35$ mW</td>
</tr>
<tr>
<td>Beam divergence parallel to the junction</td>
<td>$\theta//$</td>
<td>8</td>
<td>9.5</td>
<td>12</td>
<td>deg.</td>
<td>$P_O = 35$ mW</td>
</tr>
<tr>
<td>Beam divergence perpendicular to the junction</td>
<td>$\theta\perp$</td>
<td>18</td>
<td>23</td>
<td>28</td>
<td>deg.</td>
<td>$P_O = 35$ mW</td>
</tr>
<tr>
<td>Monitor current</td>
<td>$I_s$</td>
<td>0.2</td>
<td>—</td>
<td>2</td>
<td>mA</td>
<td>$P_O = 35$ mW, $V_{\text{R(PD)}} = 5$ V</td>
</tr>
<tr>
<td>Asitgmatism</td>
<td>$A_S$</td>
<td>—</td>
<td>5</td>
<td>—</td>
<td>µm</td>
<td>$P_O = 5$ mW, $\text{NA} = 0.4$</td>
</tr>
</tbody>
</table>

Note: Kink free is confirmed at the temperature of 25°C.
Curve Characteristics

- **Optical Output Power vs. Forward Current**
  - $T_C = 25^\circ C$
  - $T_C = 0^\circ C$
  - $T_C = 60^\circ C$

- **Monitor Current vs. Optical Output Power**
  - $V_{R(PD)} = 5V$
  - $T_C = 25^\circ C$

- **Slope Efficiency vs. Case Temperature**
  - $\eta_s$ vs. $T_C$ ($^\circ C$)

- **Threshold Current vs. Case Temperature**
  - $I_T$ vs. $T_C$ ($^\circ C$)
Thorlabs Model LD1255
Laser Diode Constant Current Driver

Description:

The LD1255 was developed for operating laser diodes in a constant current mode up to a maximum of 250mA. The LD1255 allows the laser anode to be grounded for added ESD protection of lasers that have their anode electrically connected to the case. The laser operating current can be set with an on-board 12-turn trim pot, an external analog voltage (0 to +5VDC) or a combination of both. A disable pin and diode protection circuitry have been provided to limit voltage transients produced by the power supply during start up, shut down or by static shock.

New Feature:

• Low Current Noise
• Low Temperature Drift
• Added ESD Protection
• Enable / Disable Pin

Specifications:

- Output Current: 0.2 to 250mA
- Operating Mode: Constant Current
- Internal Current Control: 12 turn potentiometer (on board)
- Ext. Current Control: 0 – 5 Volt analog input voltage (J1 pin 4)
- Output Current Drift: 2 $\mu$A/°C (Typ)
- Current Noise: < 1 $\mu$ARMS
- Operating Voltage: +/- 8 to 12 Volts
- Dimensions: 2.5” x 1”
- ESD Protection: 160 msec slow start circuit
  - 3.3V zener diode (forward voltage protection for LD)
  - Schottky diode (reverse voltage protection for LD)
  - LD DISABLE pin
- Signal Bandwidth: 1.2 kHz
- Monitor Photo Diode
- Transimpedance Gain: 1000 $\mu$V/µA (note warnings in Photodiode monitor current section)
- Max LD forward voltage: 3.3 Volts
- Operating Temp.: 10 to 30 °C
- Storage Temp.: -20 to 50 °C
- Warm-up Time: 30 min.
LD1255 OPERATION:

The LD1255 was designed to be used as either a stand alone circuit or a hybrid circuit that can be soldered to another circuit board (using the standard 0.1” headers provided). Four clearance holes are provided at the corners of the board for mounting the LD1255 to stand-offs. These holes may be enlarged to accommodate up to #4 screws.

The LD1255 operates the laser anode at ground potential for added protection against ESD (most laser manufactures mount the laser with the anode to the laser case for thermal benefits). This requires that the LD1255 use a negative power supply to “pull” current from the ground-referenced laser anode. Grounding the laser case helps prevent ESD damage.

There are two single row connectors located on the top of the LD1255. The 10 pin connector is used for the power supply input, the laser interface, and monitor signals. Table 1 lists the signals on J1:

<table>
<thead>
<tr>
<th>J1 Pin Number</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+V (+5 to +12VDC, 10mA)</td>
</tr>
<tr>
<td>2</td>
<td>COMMON</td>
</tr>
<tr>
<td>3</td>
<td>-V (-6 to -12VDC, 0.3A) provides power to laser</td>
</tr>
<tr>
<td>4</td>
<td>EXTERNAL CURRENT CONTROL (0 to +5V, or -V to (-V + 5) )</td>
</tr>
<tr>
<td>5</td>
<td>DISABLE</td>
</tr>
<tr>
<td>6</td>
<td>LASER DIODE ANODE (internally connected to pin 2 ground on LD1255)</td>
</tr>
<tr>
<td>7</td>
<td>LASER DIODE CATHODE</td>
</tr>
<tr>
<td>8</td>
<td>MONITOR PHOTO DIODE ANODE (from laser) see Note 1.</td>
</tr>
<tr>
<td>9</td>
<td>PHOTODIODE MONITOR OUTPUT (-1V / mA)</td>
</tr>
<tr>
<td>10</td>
<td>LASER CURRENT MONITOR OUTPUT (10mV / mA)</td>
</tr>
</tbody>
</table>

Table 1 - J1 Laser & Power Supply Interface

Note 1: The LD1255 photodiode monitor circuit only supports lasers that have a photodiode with an isolated anode. It will not support common cathode lasers such as the CQL7825/D and CQL7840/D.

The 5 pin connector, J2, is used for selecting the External Current Control Mode of operation as shown in Table 2:

<table>
<thead>
<tr>
<th>J2 Pins to Jumper</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>Mode 1. COMMON referenced External Current Control</td>
</tr>
<tr>
<td>2 to 3</td>
<td>Mode 2. Disable External Current Control</td>
</tr>
</tbody>
</table>

Table 2 - J2 External Current Control Mode Select

SETUP:

Laser & Power Supply Connection:

The LD1255 requires a clean (not switching) DC bipolar power supply for optimum operation. The positive supply is used only for biasing low power amplifiers and only needs to supply 10mA of current. The laser drive current is derived from the negative power supply output therefore, it should be capable of providing up to -300mA of current.

1. Attach the DC power supply to J1 according to Table 1.
2. Attach the laser diode to J1 according to Table 1.
3. Select the desired Current Control Mode using J2 (see section below).
4. Turn the Current Control Potentiometer a full 12 turns counter clockwise to ensure the laser current is at a minimum.
5. Apply power to the LD1255 and slowly turn the Current Control Potentiometer clockwise until the desired operating current is achieved. Connect a DVM from Pin 10 of J1 to Pin 4 of J2 to monitor the laser current.
Circuit Disable

A disable pin has been provided to allow the user to turn the laser diode output on or off without turning the units power supply off. The advantage to this is the elimination of turn-on/turn-off transients produced by the power supply. If the disable switch is shorted to ground, a transistor will provide a short circuit across the laser diode.

Note: It is highly recommended that the laser diode be disabled prior to a power supply turn-on or turn-off to prevent any transients from damaging the laser diode.

Selecting External Current Control Mode:

The current can also be externally controlled by a voltage source applied to J1 pin 4 (function generator, DAC output, etc.). The External Current Control voltage must be referenced to the common output of the power supply. The total drive current is determined by the sum of the manual set point and the External Current Control Voltage.

WARNING: One of the following Operating modes must be selected BEFORE turning the LD1255 on. Otherwise, the laser will be overdriven and damaged.

Mode 1. COMMON-referenced External Current Control voltage (i.e. 0 to +5V). An internal level shifter allows the negatively-biased laser to be controlled by a COMMON-referenced control voltage. To enable this mode jumper pin 1 to 2 on J2.

In Mode 1, the laser current is: \( I_{LD} = 50 \times V_{PIN4} \) (mA)

Mode 2. If the External Current Control is not to be used, it should be disabled by jumpering pins 2 and 3 on J2.

Laser Current Monitor:

The laser drive current can be monitored from pin 10 of J1. This output is referenced to the negative supply (J1 Pin 3 or J2 Pin 4) and has the following transfer function:

\[ V_{PIN10} = -V + I_{LD} \times 10 \]

Hint: Using a DVM, the laser current can be read without having to compensate for the -V offset by attaching the (-) lead to J2 Pin 4 and the (+) lead to J1 Pin 10.

Photodiode Current Monitor:

Warning: The LD1255 has a photodiode monitor circuit that only supports lasers having the laser anode attached to the photodiode cathode (such as all of the Toshiba lasers and the Philips laser diodes with the exception of the CQL7825/D and the CQL7840/D).

The use of the monitor input with common cathode lasers will cause damage to the laser. However, the LD1255 can be used safely with common cathode lasers as long as the photodiode is not connected to the driver.

An on-board transimpedance amplifier is provided for lasers with internal monitor photodiodes that are supported by the LD1255 (see warning note above). The amplifier converts the photodiode current to a voltage that can be measured on J1 Pin 9 for monitoring the relative laser output power. The output of Pin 9 has the following transfer function:

\[ V_{PIN9} = -1000 \times I_{PD} \] (V)
If the exact monitor current is known for a given laser power, this output can be converted to laser power as follows:

Eq. 2 \[ P = V_{PINB} \times \alpha \ (\text{mW}) \]

Where \( \alpha \) is the monitor photodiode conversion factor (mW / mA).

IMPORTANT NOTE: The LD1255 operates diode lasers only in a constant current mode. Caution must be used to avoid over driving the laser when operating the laser over widely varying temperatures. Diode lasers become more efficient as their operating temperature decreases. It is possible to over drive the laser when operating the laser near the maximum drive current if the laser temperature is lowered. Please consult the laser manufacturers data sheets.

If you have any questions, please call Thorlabs and an engineer will be happy to assist you.

Thorlabs, Inc.
435 Route 206 N
Newton, NJ 07860
(973) 579-7227 Phone
(973) 300-3600 Fax
www.thorlabs.com
Aspheric vs. Spherical Lenses

In laser diode systems, difficulties with aberration correction are compounded by the beams' high divergence angle. Since individual spherical lenses can refract light at only small angles before spherical aberration is introduced, three or four elements are often required to collimate laser diode light. A single aspheric lens collimates without introducing aberrations.

Conversely, when coupling into fiber, it is often necessary to focus the laser light to a diffraction limited spot. Single spherical elements are typically not capable of achieving such a small spot size. Spherical aberration is the dominant factor rather than the diffraction limit. Because the aspheric lenses are corrected to eliminate the spherical aberration, only diffraction limits the size of the focal spot. At this point it is necessary to use Gaussian beam optics to describe the behavior of laser light.

Price: $86.00 Each, Euro: €86.00
Availability: In Stock Weight: 0.00 lbs, 0.00 kg
FDS1010 Si Photodiode
--Large Active Area
--Low Capacitance

Electrical Characteristics

- Spectral Response: 400-1100nm
- Active Area: 9.7 x 9.7mm
- Rise/Fall Time (RL=50Ω): 45ns (5V)
- Bandwidth (RL=50Ω, -3dB, 5V): 8 MHz (typ.)
- NEP@900nm: 5.5 x 10⁻¹⁴ W/√Hz
- Dark Current: 600nA max (5V)
- Junction Capacitance (Cj): 375pF @ 5V (typ)
- Package: 0.45” x 0.52” ceramic wafer

Maximum Ratings

- Damage Threshold CW: 100 mW/cm²
- Max Bias Voltage: 20V
- Storage Temperature: -10 to 60 °C
- Operating Temperature: -20 to 70 °C

The Thorlabs FDS1010 photodiode is ideal for measuring both pulsed and CW light sources, by converting the optical power to an electrical current. The Si detector is mounted on a 0.45”x0.52” ceramic wafer package with an anode and cathode. The photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity $\mathcal{R}(\lambda)$, can be read from Figure 1 to estimate the amount of photocurrent to expect. This can be converted to a voltage by placing a load resistor ($R_{LOAD}$) from the photodiode anode to the circuit ground. The output voltage is derived as:

$$V_o = P \times \mathcal{R}(\lambda) \times R_{LOAD}$$

The bandwidth, $f_{BW}$, and the rise time response, $t_R$, are determined from the diode capacitance, $C_j$, and the load resistance, $R_{LOAD}$, as shown below. Placing a bias voltage from the photo diode cathode to the circuit ground can lower the photo diode capacitance.

$$f_{BW} = 1/(2\pi \times R_{LOAD} \times C_j), \quad t_R = 0.35/f_{BW}$$

Related Thorlabs Products

FDS010, FDS100, PDA55, PDA155, PDA255, PDA400, WS02, TM2448
Typical Circuit Diagram

![Typical Circuit Diagram](image)

Typical Plots

![Typical Plots](image)

Figure 1: Typical Responsivity curve using Thorlabs calibration services.
PNZ300, PNZ300F (PN300, PN300F)

Silicon PIN Photodiodes

For optical control systems

- **Features**
  - Fast response which is well suited to high speed modulated light detection
  - Wide spectral sensitivity
  - Low dark current and low noise
  - Good photo current linearity and wide dynamic sensitivity
  - Narrow directivity (PNZ300)
  - Wide directivity (PNZ300F)

- **Absolute Maximum Ratings (Ta = 25°C)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Ratings</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse voltage (DC)</td>
<td>V_R</td>
<td>50</td>
<td>V</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>P_D</td>
<td>100</td>
<td>mW</td>
</tr>
<tr>
<td>Operating ambient temperature</td>
<td>T_opr</td>
<td>–25 to +85</td>
<td>°C</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>T_stg</td>
<td>–30 to +100</td>
<td>°C</td>
</tr>
</tbody>
</table>

Note) The part numbers in the parenthesis show conventional part number.
## Electro-Optical Characteristics (Ta = 25°C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>min</th>
<th>typ</th>
<th>max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark current</td>
<td>(I_D)</td>
<td>(V_R = 10V)</td>
<td>0.1</td>
<td>10</td>
<td></td>
<td>nA</td>
</tr>
<tr>
<td>Photo current</td>
<td>(I_L)</td>
<td>(V_R = 10V, L = 1000 \text{lx}^1)</td>
<td>30</td>
<td>55</td>
<td></td>
<td>(\mu\text{A})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>7</td>
<td></td>
<td>(\mu\text{A})</td>
</tr>
<tr>
<td>Peak sensitivity wavelength</td>
<td>(\lambda_p)</td>
<td>(V_R = 10V)</td>
<td></td>
<td></td>
<td>800</td>
<td>nm</td>
</tr>
<tr>
<td>Response time</td>
<td>(t_r, t_f^2)</td>
<td>(V_R = 20V, R_L = 50\Omega)</td>
<td>1</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Capacitance between pins</td>
<td>(C_t)</td>
<td>(V_R = 10V, f = 1MHz)</td>
<td>7</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Acceptance half angle</td>
<td>(\theta)</td>
<td>Measured from the optical axis to the half power point</td>
<td>10</td>
<td></td>
<td></td>
<td>deg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td>deg.</td>
</tr>
</tbody>
</table>

\(^1\) Measurements were made using a tungsten lamp (color temperature \(T = 2856K\)) as a light source.

\(^2\) Switching time measurement circuit

\[\begin{align*}
\lambda_p &= 800\text{nm} \\
V_R &= 10\text{V} \\
R_L &= 50\Omega
\end{align*}\]
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### Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
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<tbody>
<tr>
<td>Global Part Number</td>
<td>7BB-27-4</td>
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<tr>
<td>Previous Part Number</td>
<td>7BB-27-4</td>
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<tr>
<td>Resonant Frequency</td>
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<tr>
<td>Resonant Impedance</td>
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<tr>
<td>Capacitance</td>
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<td>Measurement Condition of Capacitance</td>
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<tr>
<td>Plate Size</td>
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<tr>
<td>Element Size</td>
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</tr>
<tr>
<td>Electrode Size</td>
<td>18.2mm</td>
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<td>Thickness</td>
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<td>Plate Thickness</td>
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<td>Plate Material</td>
<td>Brass</td>
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<tr>
<td>Drive Type</td>
<td>External Drive</td>
</tr>
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</table>

### Minimum Quantity

- 180mm Paper Tape
- 180mm Embossed Tape
- 330mm Paper Tape
- 330mm Embossed Tape
- Bulk Case
- Bulk(Bag)
- Ammo Pack
- 320Reel
- Magazine
- Box 1500

Product specifications in this catalog are as of January 2007, and are subject to change or obsolescence without notice. Please approve our product specifications or transact the approval sheet before ordering. Please read rating and Cautions first.

All products and company names herein are trademarks or registered trademarks of their respective owners.
All products and company names herein are trademarks or registered trademarks of their respective owners.
Please do not touch the component with bare hand because electrode may be corroded.

The component may be damaged if mechanical stress over this specification is applied.

Please pay attention to protect operating circuit from surge voltage provided by something of force such as falling, shock and temperature changing.

If DC voltage is applied to the component, silver migration may occur. Please pay full attention not to subject the component to DC voltage for long periods.

The resistor should be used as shown in Fig. A. A suitable resistance value should be chosen, preferably 1kΩ to 2kΩ. Instead of this measure, a diode may also be applied as shown in Fig. B.
New thermoelectric devices, prepped with a temperature cutoff switch. Originally intended for 12Vdc use in picnic and automotive coolers/ heaters. 127 thermocouples per device. \( \Delta T_{\text{max}} = 79 \text{degC}, \ T_{\text{hot}} = 50 \text{degC}, \ V_{\text{max}} = 16.1 \text{V}. \) 30MM x 30MM x 3.3MM. \( Q_{\text{max}} = 38.7 \text{ Watts}, \ I_{\text{max}} = 3.9 \text{A}. \)

**CAT# PJT-5**

Your Price: $9.75 each

**Special Quantity Discounts!**
10 or more $ 9.00 each

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Customer Comments

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Avg. Customer Review: ★★★☆☆
Number of Reviews: 1

5 of 10 people found the following review helpful:

★★★★☆ **Peltoer fogureof merit**

Reviewer: **Dr JKeffery Lewins** from Ca,nbridge, England

I would be grateful if this academic enquiry could be passed on to your technical staff. Writing up my teaching notes on Peltier coolers I am unsure of the definition of the conventional figure of merit \( Z \) outside the linear range. In the linbear range we have \( Z = S q d T \) where \( T \) is the absolute temperature abd \( S \) a Seebeck term that can either be the Seebeck ratio (the voltae diference across the junctions divided by the temperature difference) or the first Seebek coefficient, the slope of the voltag with temperature at the non-ambient junction \( dV/dT. \) In the linear nae there is no difference but outside this range, is tere any standard practice? If the ratio is taken, this is easier to measure exerimentallu but would require a knwoedge of th ambinet temperature for use. If the ist voefficient is employed,
E.2 Microwave Components
HMC507LP5 / 507LP5E

**MMIC VCO w/ HALF FREQUENCY OUTPUT 6.65 - 7.65 GHz**

**Typical Applications**

Low noise MMIC VCO w/ Half Frequency, for:
- VSAT Radio
- Point to Point/Multi-Point Radio
- Test Equipment & Industrial Controls
- Military End-Use

**Features**

- Dual Output: \( F_o = 6.65 - 7.65 \text{ GHz} \)
  \( F_o/2 = 3.325 - 3.825 \text{ GHz} \)
- Power output: \(+13.5 \text{ dBm} \)
- Phase Noise: \(-115 \text{ dBc/Hz @100 kHz Typ.} \)
- No External Resonator Needed
- QFN Leadless SMT Package, 25 mm²

**General Description**

The HMC507LP5 & HMC507LP5E are GaAs InGaP Heterojunction Bipolar Transistor (HBT) MMIC VCOs. The HMC507LP5 & HMC507LP5E integrate resonators, negative resistance devices, varactor diodes and feature a half frequency output. The VCO's phase noise performance is excellent over temperature, shock, and process due to the oscillator's monolithic structure. Power output is \(+13.5 \text{ dBm} \) typical from a +5V supply. The voltage controlled oscillator is packaged in a leadless QFN 5x5 mm surface mount package, and requires no external matching components.

**Functional Diagram**

- The HMC507LP5 & HMC507LP5E are GaAs InGaP Heterojunction Bipolar Transistor (HBT) MMIC VCOs.
- The VCO's phase noise performance is excellent over temperature, shock, and process due to the oscillator's monolithic structure.
- Power output is \(+13.5 \text{ dBm} \) typical from a +5V supply.
- The voltage controlled oscillator is packaged in a leadless QFN 5x5 mm surface mount package.

**Electrical Specifications, \( T_A = +25^\circ \text{C}, Vcc = +5V \)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
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<tr>
<td>Frequency Range ( Fo )</td>
<td>6.65 - 7.65</td>
<td>3.325 - 3.825</td>
<td>GHz</td>
<td>GHz</td>
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<tr>
<td>Frequency Range ( F_o/2 )</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Output ( RFOUT )</td>
<td>+11</td>
<td>+4</td>
<td>+16</td>
<td>dBm</td>
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<tr>
<td>Power Output ( RFOUT/2 )</td>
<td>+11</td>
<td>+4</td>
<td>+16</td>
<td>dBm</td>
</tr>
<tr>
<td>SSB Phase Noise @ 100 kHz Offset, ( Vtune = +5V ) @ ( RFOUT )</td>
<td>-115</td>
<td></td>
<td></td>
<td>dBc/Hz</td>
</tr>
<tr>
<td>Tune Voltage ( Vtune )</td>
<td>2</td>
<td>13</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Supply Current (( Icc ) @ ( Vcc = +5.0V ))</td>
<td>200</td>
<td>230</td>
<td>270</td>
<td>mA</td>
</tr>
<tr>
<td>Supply Port Leakage Current (( Vtune = 13V ))</td>
<td></td>
<td>10</td>
<td></td>
<td>( \mu A )</td>
</tr>
<tr>
<td>Output Return Loss</td>
<td>2</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Harmonics/Subharmonics</td>
<td>1/2</td>
<td>35</td>
<td></td>
<td>dBc</td>
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<tr>
<td></td>
<td>2nd</td>
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<td>24</td>
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<tr>
<td></td>
<td>3rd</td>
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<td>dBc</td>
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<tr>
<td>Pulling (into a 2.0:1 VSWR)</td>
<td>8</td>
<td></td>
<td></td>
<td>MHz pp</td>
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<tr>
<td>Pushing @ ( Vtune = 5V )</td>
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<td>15</td>
<td></td>
<td>MHz/V</td>
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<tr>
<td>Frequency Drift Rate</td>
<td></td>
<td>0.9</td>
<td></td>
<td>MHz/°C</td>
</tr>
</tbody>
</table>
**Typical Applications**

The HMC525LC4 is ideal for:
- Point-to-Point and Point-to-Multi-Point Radio
- VSAT

**Functional Diagram**

![Functional Diagram](image)

**Features**

- Wide IF Bandwidth: DC - 3.5 GHz
- Image Rejection: 40 dB
- LO to RF Isolation: 50 dB
- High Input IP3: +23 dBm
- RoHS Compliant 4x4 mm SMT Package

**General Description**

The HMC525LC4 is a compact I/Q MMIC mixer in a leadless “Pb free” RoHS compliant SMT package, which can be used as either an Image Reject Mixer or a Single Sideband Upconverter. The mixer utilizes two standard Hittite double balanced mixer cells and a 90 degree hybrid fabricated in a GaAs MESFET process. A low frequency quadrature hybrid was used to produce a 100 MHz USB IF output. This product is a much smaller alternative to hybrid style Image Reject Mixers and Single Sideband Upconverter assemblies. The HMC525LC4 eliminates the need for wire bonding allowing use of surface mount manufacturing techniques.

**Electrical Specifications, $T_A = +25^\circ C$, IF= 100 MHz, LO = +15 dBm**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
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<td>4.0 - 8.5</td>
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<td>5.5 - 7.5</td>
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<td></td>
<td></td>
<td>GHz</td>
</tr>
<tr>
<td>Frequency Range, IF</td>
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<td>DC - 3.5</td>
<td></td>
<td></td>
<td></td>
<td>GHz</td>
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<tr>
<td>Conversion Loss (As IRM)</td>
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<td>11</td>
<td>7.5</td>
<td>9.5</td>
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<td>Image Rejection</td>
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<td>30</td>
<td>40</td>
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<td>1 dB Compression (Input)</td>
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<td>+15</td>
<td></td>
<td>dBm</td>
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<td>LO to RF Isolation</td>
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<td>50</td>
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<td>LO to IF Isolation</td>
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<td>17</td>
<td>20</td>
<td>dB</td>
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<td></td>
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<tr>
<td>IP3 (Input)</td>
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<td>dBm</td>
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<td>0.2</td>
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<td></td>
<td>dB</td>
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</tr>
<tr>
<td>Phase Balance</td>
<td>8</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>Deg</td>
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</table>

* Unless otherwise noted, all measurements performed as downconverter.