

Construction of an Extended Cavity Diode Laser for cooling of Rubidium Atoms

Abstract

A diode laser is a relatively cheap and simple to manufacture device. However, its output linewidth is far too wide to be used for laser cooling “out of the box”. This report will show that using an Extended Cavity setup a diode laser can be used in a laser cooling experiment. In addition, the purpose of a “Lock Box” in an ECDL laser cooling setup will be explained and partially constructed.



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1. Introduction

The temperature of a collection of particles is proportional to the average Kinetic energy of the collection of particles^[1]. Therefore by reducing the average speed of particles in a sample, its temperature is reduced. Laser cooling involves slowing an atom down by causing the atoms to emit photons. When the photons are emitted a scattering force (otherwise known as light pressure^[2]) acts upon the parent atom, reducing its velocity^[3].

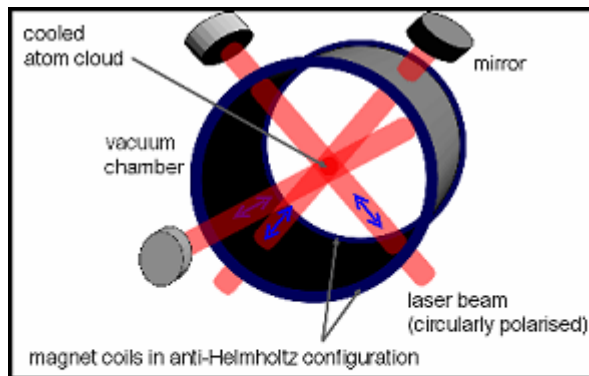


Figure 1, a diagram of a standard magneto-optical trap. The laser beams are tuned to a frequency lower than the cooling transition of the atom. This causes laser cooling to occur on atoms moving towards the beam

As shown by the Bohr model^[4], the energy of an atom is quantised into a series of levels unique to the element in question. An atom can only have energies at these levels. Therefore, for a photon to interact with an atom its energy must be equal to the spacing between the atom and the next highest level. If the energy of an incident photon deviates slightly from the spacing no interaction will occur. This fact means that the laser used for laser cooling must have a very narrow linewidth, otherwise no transitions will occur.

According to the Doppler Effect the frequency of a wave changes depending on relative motion between the source and the observer. Since the atoms are moving, the transition frequency will be different for every atom. This is overcome using an optical molasses^[5], shown in figure 1. This is an arrangement of 6 lasers: two in each of the x, y, z planes, one in the + and the other in the - directions. These lasers are tuned to slightly below the frequency of the cooling transition but due to the Doppler Effect transition occurs when atoms move toward the laser. This set up will also ensure that the scattering force is directed opposite the direction that the atom is moving in, making the laser cooling process more efficient.

2. External Cavity Diode Laser

2.1 Overview

A laser with narrow linewidth is needed for laser cooling due to the quantisation of energy levels. However, narrow linewidth lasers are generally expensive and not tuneable. Diode lasers on the other hand are relatively cheap, but have a very wide linewidth. This obstacle can be overcome by building an external cavity setup^[7]. An external cavity diode laser (ECDL, see figure 1) consists of a diode laser whose output is directed towards an angled diffraction grating. The grating is angled so the first order image is directed back into the cavity. This has two effects. Firstly, it will cause interference based on the distance, d , between the diode and the laser and secondly, it will add energy to the cavity; decreasing the laser threshold current. These two effects will change the output spectrum of the laser; a large, narrow spike will rise at a frequency based on d . By varying d the laser can be tuned to the frequency required.

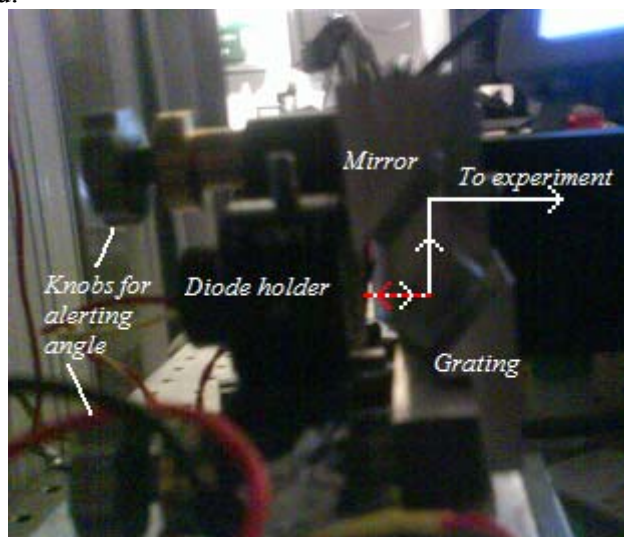


Figure 2, a photograph of the ECDL setup. The white beam is the output (0 order from grating) while the red line is the 1st order image that is reflected back into the cavity. This will narrow the linewidth and reduce the threshold current of the laser

2.2 Finding Lasing Angle

The most difficult part of building an ECDL is getting the angle of the grating correct. As mentioned above the angle must be so the first order image is reflected back into the diode's cavity. The mount of the ECDL had been built prior to the commencement of this project, but its angle was incorrect. The setup did not allow varying of the angle and a small spacer had to be placed between the grating mount and the face it screwed into to alter the angle. This proved to be needlessly complex so another member of the group added a pair of knobs to change the grating angle at will. The setup used in this experiment is shown in figure 3. It comprises of a CCD camera, beam splitter and power meter. The current supplied to the laser was set to 33mA, 3mA short of its threshold current. The CCD camera was sensitive to the near infrared frequency that the laser was operating at and was used to monitor lasing by eye. The beam was sent through a beam splitter, where the other beam was incident on a power meter. This would ensure that the angle was set to the maximum output. On the CCD

two dots could be seen, a large one representing the 0th order image and a smaller one representing the 1st order. The angle was altered using the knobs until the 0th order image brightened; at this point the 1st order image was reentering the cavity. The angle was carefully altered to find the point where the power was maximum. At 33mA, the output would be about 500 mW but when the angle was correct the output was measured as 1.5 W. As the current was increased the size of the jump also increased.

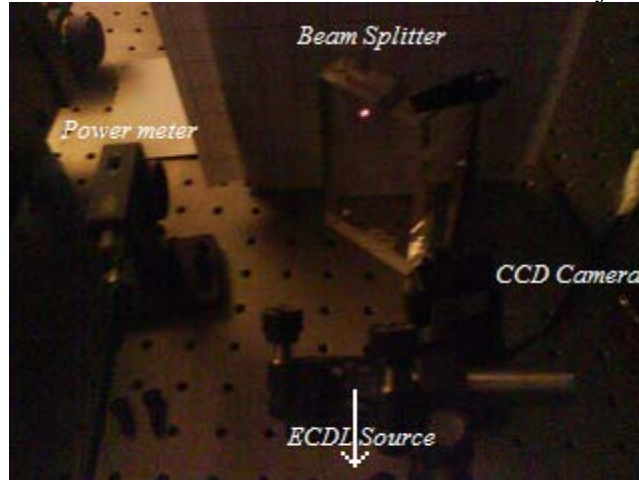


Figure 3, the lasing test setup. The output of the laser came from the bottom of the image. On hitting the beam splitter one beam entered a power meter while the other was incident on a screen being filmed with a CCD camera.

2.3 Finding Transition Frequency

The next part of the project was to find the transition frequencies of Rubidium, the element used by this group for cold atom experiments. The ECDL beam was passed through a glass cell containing Rubidium atoms. This cell is shown in figure 4.

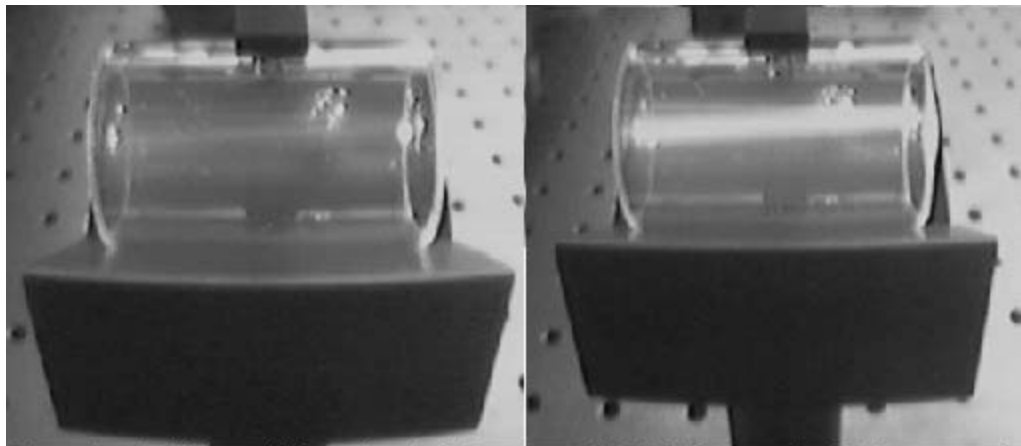


Figure 4, a Rubidium cell through which the output of the ECDL passes. In the first picture the frequency is set at a frequency less than 0.01nm from the transition frequency. In the second picture the frequency is at the transition causing a large amount of scattering by atoms resonating with the beam

The length of the cavity could be altered over distances of a few micrometers by controlling the movement using lead zirconium titanate, or PZT, connections between the grating and the cavity wall. PZT is famous for the strength of its piezoelectric effect^[6]. By varying the voltage over the PZT, the length of the cavity could be changed. In addition, the current through the PZT and the temperature of the laser had

an effect on the output wavelength. The wavelength did not vary linearly either; it would jump up and down by $\sim 0.09\text{nm}$ at certain points^[8]. A beam splitter was placed between the ECDL and the cell so the wavelength could be monitored. To reach the correct value, first the voltage was altered until the output jumped to within 0.1nm of the transition frequency. Then the current was altered until it jumped up and down again. Finally the temperature would be changed using a thermoelectric cooler (TEC) until two jumps occurred. This was repeated until the target wavelength was met. In addition to the wavelength monitor, a CCD camera was used to film the cell so the scattering could be monitored by eye.

2.4 Finding the Spectrum

The next step was to find the spectrum of Rubidium. Not only will this data be used to select the transition to use in the experiment, but it will prove that the ECDL is capable of emitting a beam with a linewidth narrow enough to be useful in a cold atom experiment. If the spectrum was to be obtained just by passing a beam through the sample, the result would be incorrect. The atoms in the cell would be undergoing Brownian motion, and as a result the Doppler Effect would come into play. Atoms moving towards the beam would cause a blueshift, while those moving away would cause a redshift. The resulting spectrum would look something like figure 6. Here the Doppler Broadening causes the Hyperfine structure to overlap over itself so specific transitions cannot be picked out.

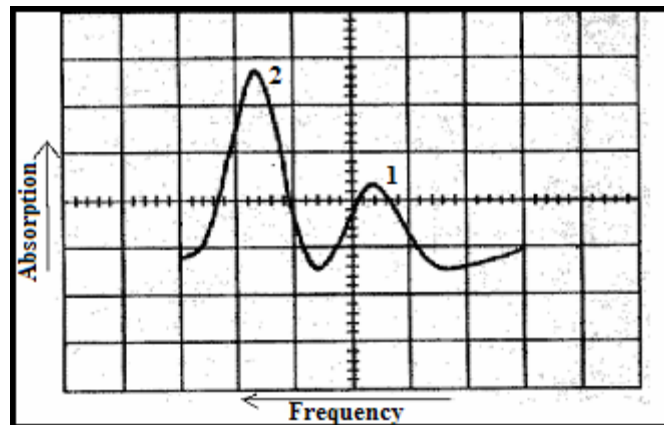


Figure 5, An example of Doppler Broadening taken from [7].

Using the setup above, this problem can be overcome. The setup involves passing two, low intensity beams through the sample. However, one beam has a large intensity “pump” beam passing through it in the opposite direction. This causes saturation along the beam. The pump beam excites all the atoms in resonance with the transition. This causes the state to deplete so the probe beam cannot be absorbed, resulting in a lower absorption for atoms at rest. However, since Doppler shifted atoms are shifted in the opposite direction absorption occurs as normal. The result shows clear dips detailing the hyperfine structure of the atom, pictured on the next page.

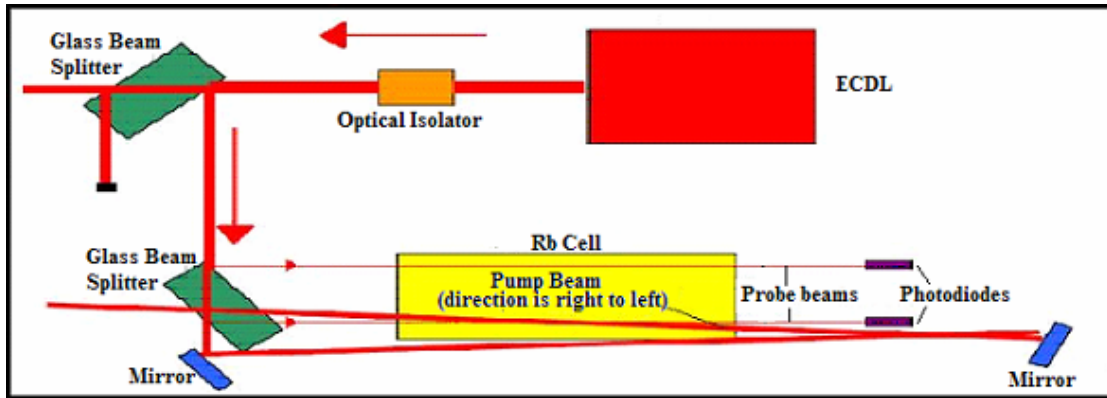


Figure 6, The setup for the final ECDL experiment^[7]. The Pump beam causes saturation along the second probe beam, causing dips to appear at the transition frequencies.

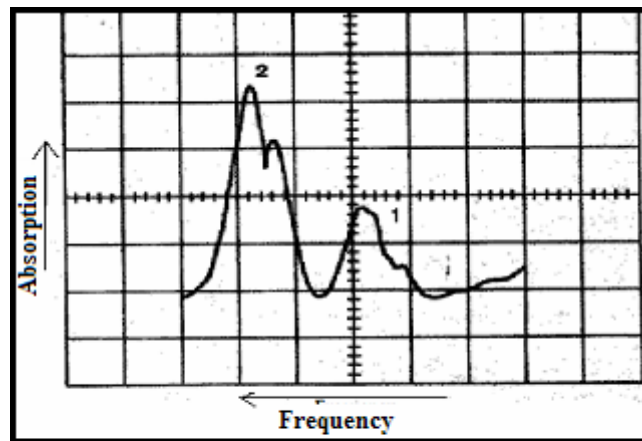


Figure 7, An image of the absorption signal for a pumped probe beam taken from [7]. The dips are where the transitions would occur if there was no doppler broadening

A similar apparatus, shown in figure 8, was used to find the spectrum of the Rubidium cell shown earlier. It is clear that this is more or less the same as the apparatus above only many unnecessary mirrors and beam splitters have been removed. In this case the pump beam is a direct reflection from a gold mirror perpendicular to the beam while the unpumped beam is made by putting the mirror at an angle large enough to prevent overlap in the cell while short enough to stay far from the pumped beam.

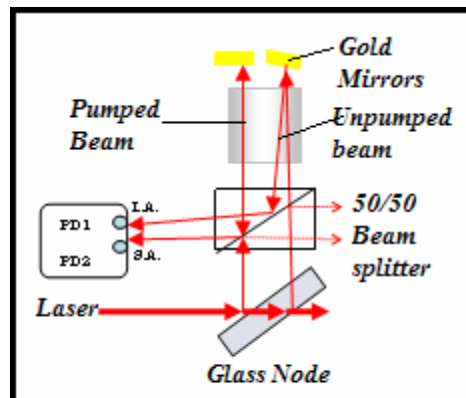


Figure 8, the apparatus used to demonstrate the possibility of finding the Hyperfine Structure of Rb using the ECDL

To get a more accurate display of the spectrum, the difference pumped and unpumped beams had to be calculated. This is simply finding taking the pumped signal away from the unpumped signal. The result is ~ 0 except at points where transitions occur. Figure 9 shows the output for a sample of Rb85.

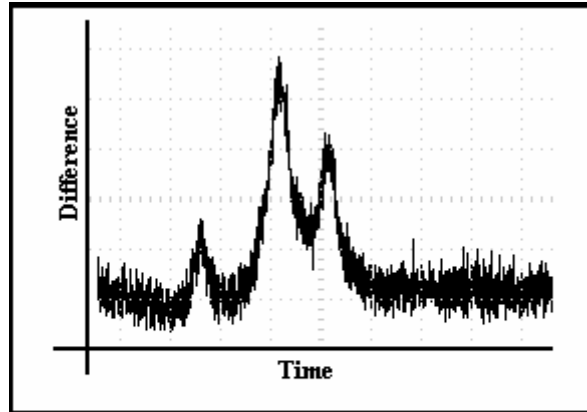


Figure 9, the difference between the two signals as Frequency decreases. Using a lock box the noise can be greatly reduced, but even then the Hyperfine structure is still easy to see

The time axis represents the time it took the laser to change its frequency. If the rate of change of frequency and the energy spacing between two given levels is known, the ratio between the time difference between the two relevant peaks will convert the x axis to give the frequency of light used to cause the jump. The sharpness of the peaks prove that an ECDL can be tuned to a linewidth narrow enough for efficient laser cooling.

3. Building the Lockbox

3.1 Overview

The second part of the project involved building a circuit known as a “lockbox”. The lockbox, otherwise known as a lock-in amplifier and servo loop, is a complicated circuit used to make the ECDL scan over a range of frequencies, filter the output from the photodiodes to reduce error and, with a slight modification, lock the laser at a chosen frequency¹. An image of the portions of the circuit that were built is given below.

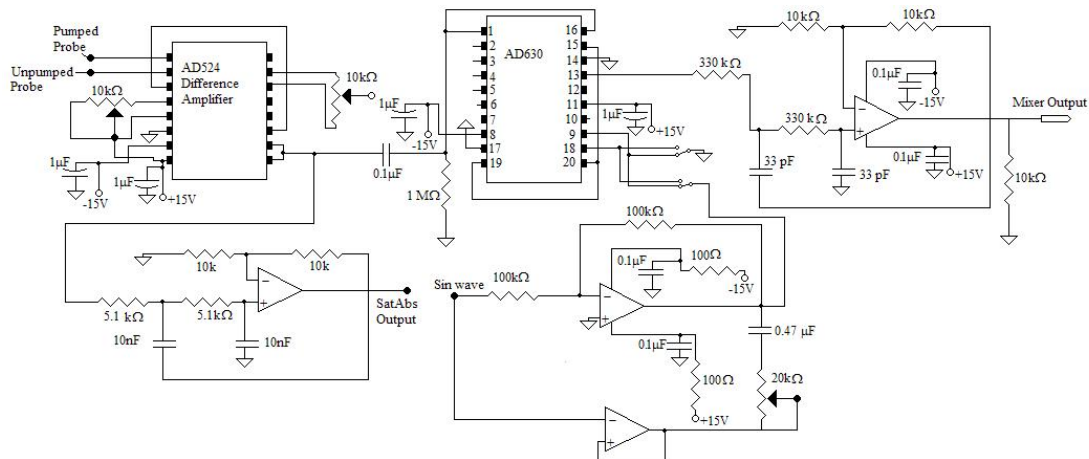


Figure 9, the lock box circuit. This circuit takes the input from the photodiodes where the ECDL scans over a range of frequency caused by oscillating the PZT input. This circuit will give the Doppler free spectrum of the Rubidium sample.

The circuit built is shown above. At first the circuit looks very intimidating but closer inspection shows it is actually 4 relatively simple “subcircuits”. Each can be built and tested independent of the others, which makes it easier to spot errors.

The circuit diagram supplied had an additional subcircuit: an oscillator. The oscillator’s output went to the “Sin Wave”(in practice would be a triangle wave rather than a sin wave) input on the diagram and, after some simple electronics, into a modulator output. This was to be fed into the PZT governing the cavity length. This would cause the PZT to oscillate while data is being taken which is how the spectrum over a range of frequencies can be recorded^[8]. At first, a clock chip^[11] was to be used as a replacement, but the programming the chip to oscillate was deemed too time consuming; building and testing the rest of the circuit was still possible, albeit not with the laser cooling setup.

¹ The circuit diagram was supplied by a former member of the group, but its source was not supplied so it cannot be cited

3.2 Difference Amplifier

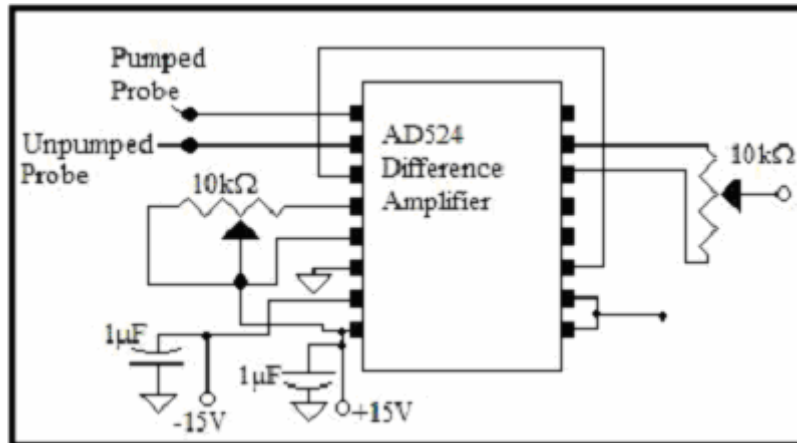


Figure 11, the difference amplifier portion of the circuit. This set up finds the difference between the two inputs (pumped probe and unpumped probe in this case) and multiplies the result by 100.

The first subcircuit that was constructed was a different amplifier with a 100x gain. This circuit will be used find the difference between the two photodiode signals in the laser cooling experiment, making the hyperfine structure clearer. The high gain is necessary since in many cases the difference would be very small. In addition, the size of the difference does not matter for this experiment; it is simply their presence we wish to find. This circuit was taken straight from the AD524 data sheet example for a 100x gain circuit^[9]. A close up of the circuit diagram is given in Figure 11, and a photograph of the soldered is shown in figure 12.

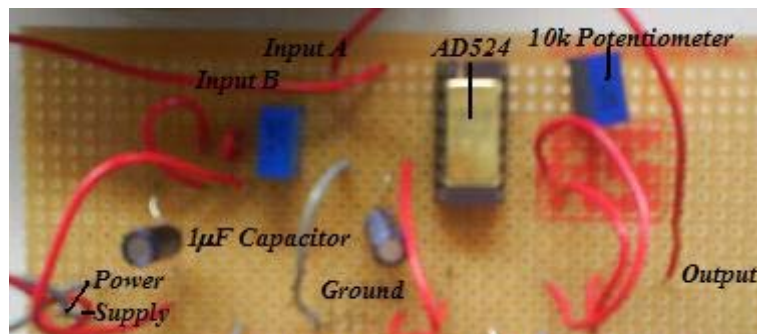


Figure 12, a photograph of the difference amplifier circuit soldered onto a circuit board. The grey wires are negative and the red wires are positive.

This circuit was first built on a breadboard to make sure it was wired correctly before soldering. It was found to be a success, as can be seen in figure 13. However, when soldered the output did not match. This will become a common theme in circuits from this moment on. No image of the incorrect output from the soldered circuit was saved; but the output was always ~13V no matter what the input, and a back voltage through the inputs could be measured.

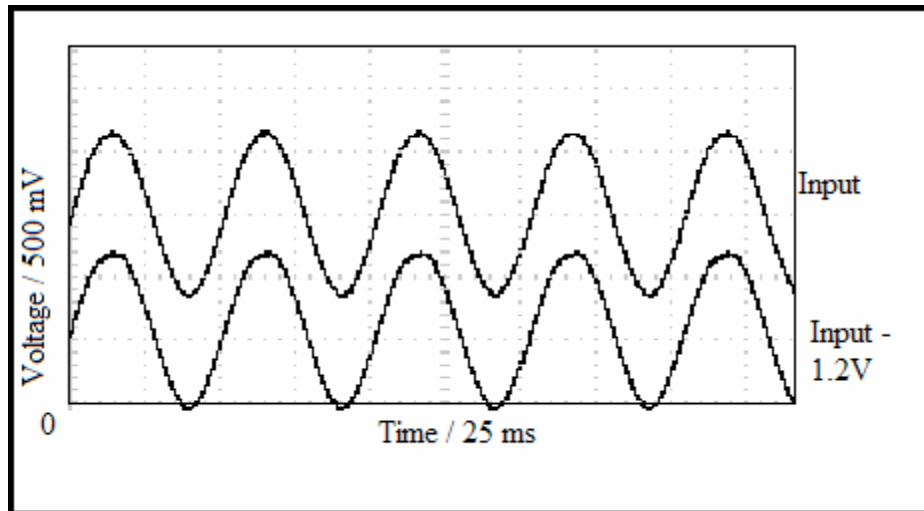


Figure 13, an image of the output from the difference amplifier on the breadboard. The 100x gain was not active at this point.

3.3 Low-Pass filter.

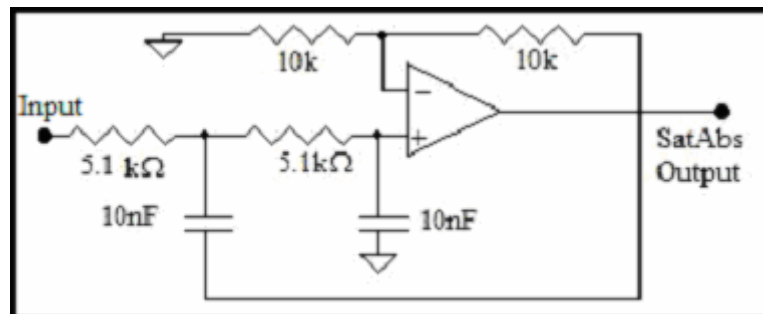


Figure 14, the circuit diagram of the low pass filter. The theoretical circuit does not contain the two 10 kΩ resistors and its critical frequency would be $1/2\pi(5.1 \text{ k}\Omega)(10 \text{ nF})$.

The next subcircuit was the low pass filter, closeup shown in Figure 14. This circuit, also known as a Sallen Key low pass filter, was designed to remove noise from the signal. The theoretical circuit does not include the 10k resistors and lowers the amplitude of any signal with a frequency higher than $1/2\pi RC$ where R is the resistance and C is the capacitance of the relevant components. The values of C and R are chosen to be about the same as the frequency the PZT is oscillating at. A photograph of the soldered circuit is shown in figure 15. In general, noise takes the form of a sum of high frequency signals(c.f. figure 9 for an example before noise filtering), so by blocking signals with frequency higher than the oscillation of the PZT much of the noise is blocked out.

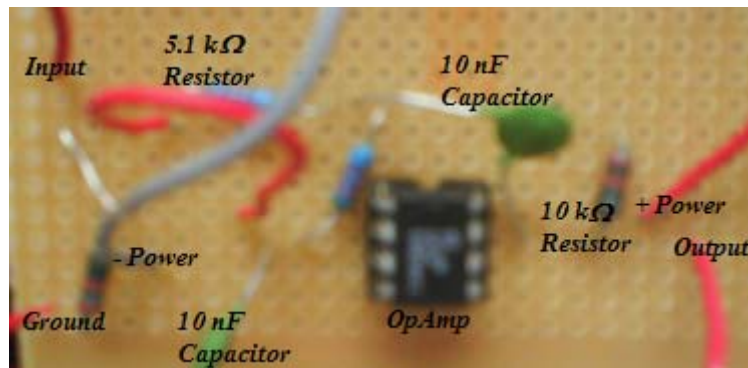


Figure 15, a photograph of the Low pass filter circuit. Gray wires are negative and red wires are positive.

When building the real circuit on the breadboard this setup was seen to have a critical frequency ~ 1 kHz. When soldered the output was not what was expected. Ironically, it seemed to be more efficient. For the breadboard circuit there was a minimum amplitude that the output signal would have which depended on the input peak to peak amplitude; for example for a signal from -3v - $+3\text{v}$ the minimum output was -1.5v to 1.5v . The difference between minimum output and input rose as the input rose. When soldered, the critical frequency rose to 50 kHz and there was no minimum output (c.f. figure 16 for examples). However, there was a back EMF, there was a phase change and for signals less than 40 kHz the output would be amplified. No images of the breadboard outputs and inputs were saved. If a bias was introduced between the difference amplifier and the low pass filter to prevent the back EMF from affecting other sections, this circuit should be adequate for the experiment.

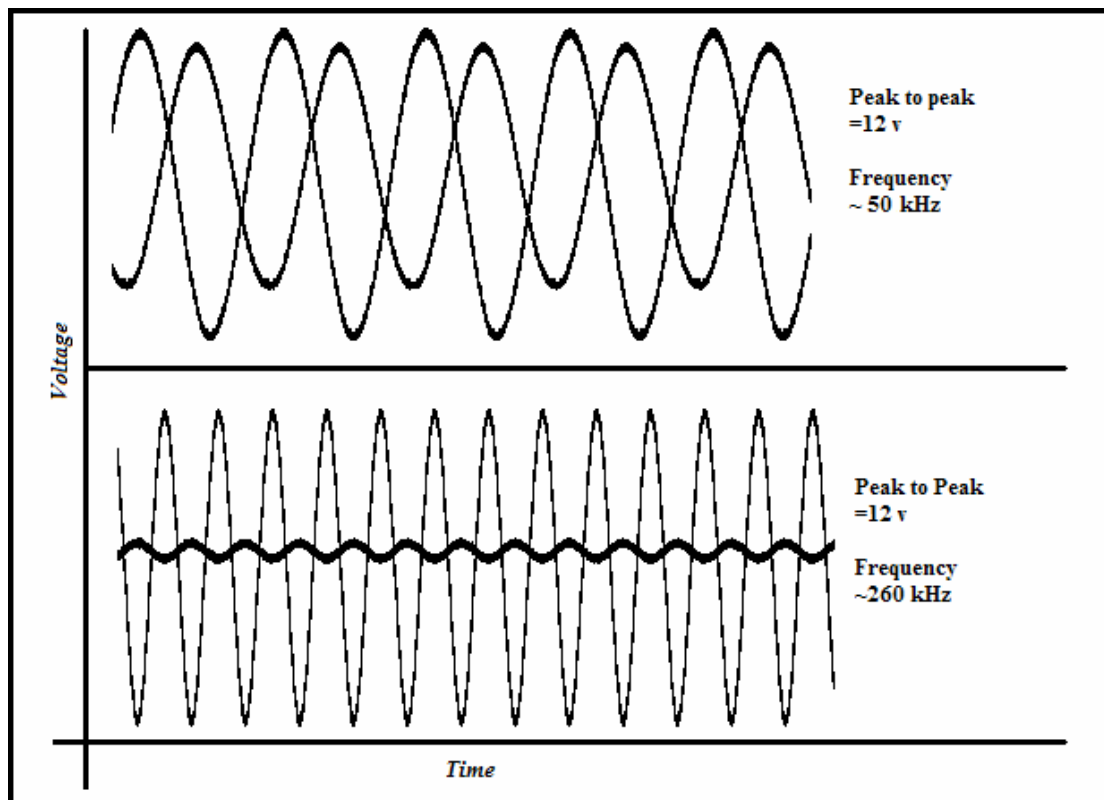


Figure 16, Images of the input and output of the soldered Low Key pass. The Voltage scale is identical for each, but not the time scale. The Input is the larger of the two superimposed signals. The 12v refers to the output of the signal generator, the back EMF caused the input on the oscilloscope to fall.

3.4 Phase Shifter

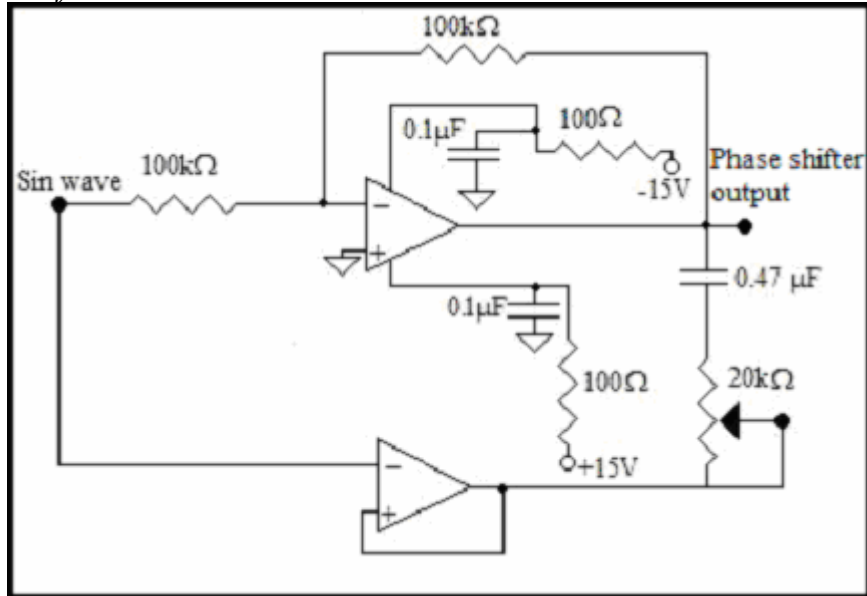


Figure 17, a circuit diagram of the phase shifter. This circuit will shift the phase of a periodic input by π .

The penultimate subcircuit, and final tested circuit, was the phase shifter (shown in figure 17). This circuit shifted the phase of the input by π . It should be noted that the power supply for the two operational amplifiers, in series with 100 Ω resistor + in parallel with capacitor connected to ground, was identical for both devices (in fact a dual OpAmp chip was used as shown in figure 18) but removed to make the diagram easier to comprehend. This circuit's purpose will be explained in more detail in the next section.

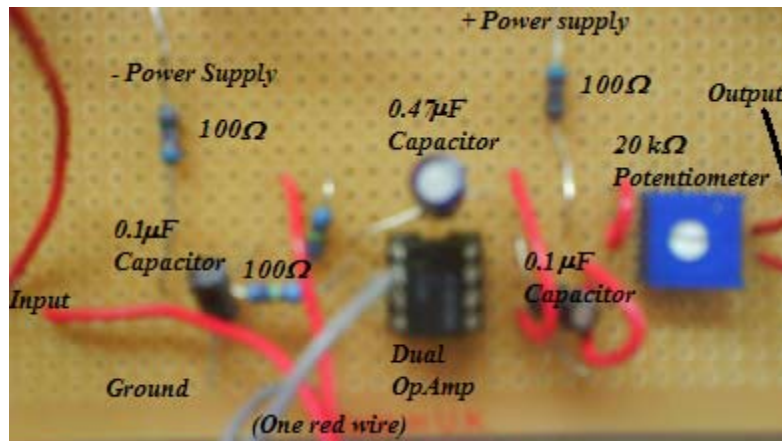


Figure 18, a photograph of the circuit. The Output is to the right, just out of the picture. Red wires are positive and grey wires are negative.

Both the outputs for this circuit for breadboard and circuit board were taken for this circuit (shown in Figure 19). Like the previous circuits, it failed to work when soldered. In case the error was propagating through the circuit through the common ground/power supply terminals this circuit was disconnected from the preceding circuits. However the result was unchanged.

The constant presence of similar errors in the circuits, especially the back EMF present in each, leads to the conclusion that user error is unlikely. A problem with the soldering iron, solder or even circuit board used may be the source of problems.

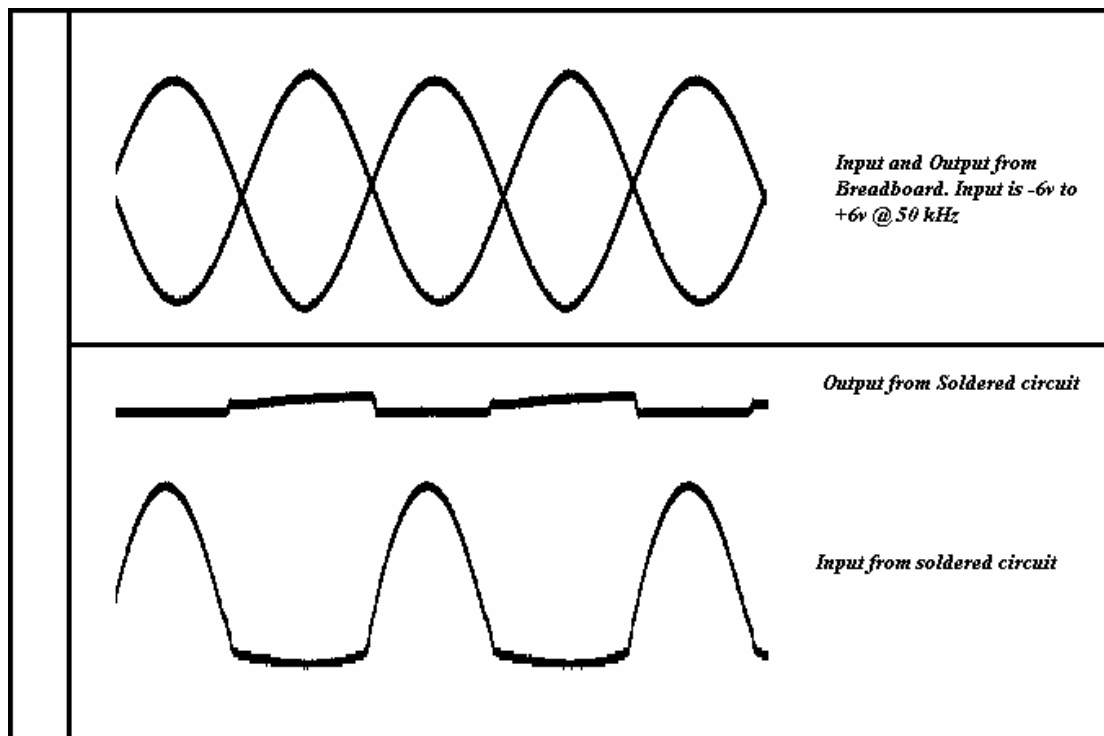


Figure 19, the signals from the phase shifter for the Breadboard and Soldered circuits respectively. Note that the same inputs were used with each but the presence of the back EMF changes the recorded signal.

3.5 Demodulator

The purpose of the Demodulator was to remove any errors due to the oscillation of the PZT. This circuit combines the Differentiator output with the Cos wave. But, what is the purpose of this wave? In order to achieve a spectrum the ECDL must be made to scan through a range of frequencies. In order to do this, the Voltage signal across the PZT must vary over time. Usually a triangle wave is used, this causes the laser to scan across a given range at a constant velocity and then scan back in the other direction. The result is a periodic signal comprised of the spectrum and its mirror image repeated ad nauseum. The point of the Demodulator is to remove any errors caused by this process, for example, deceleration of the PZT at peaks. When built and used in a laser cooling experiment this circuit will reduce errors and sharpen the transition peaks.

The chip used was an AD630^[10], a balanced modulator/demodulator which advertises itself as being a good choice for a lock-in amplifier circuit. The reactive feed back caused by building the circuit in this manner will amplify low frequency signals. This circuit was partially built on the breadboard. If it was to be tested, a wave signal at a known offset would be sent to the differentiator input while the same wave at 0 offset and out of phase by π would be sent through the phase shifted input. The correct output would be a DC signal equal to the differentiator's offset. Figures 20 and 21 display the circuit diagram and photograph of what was built respectively.

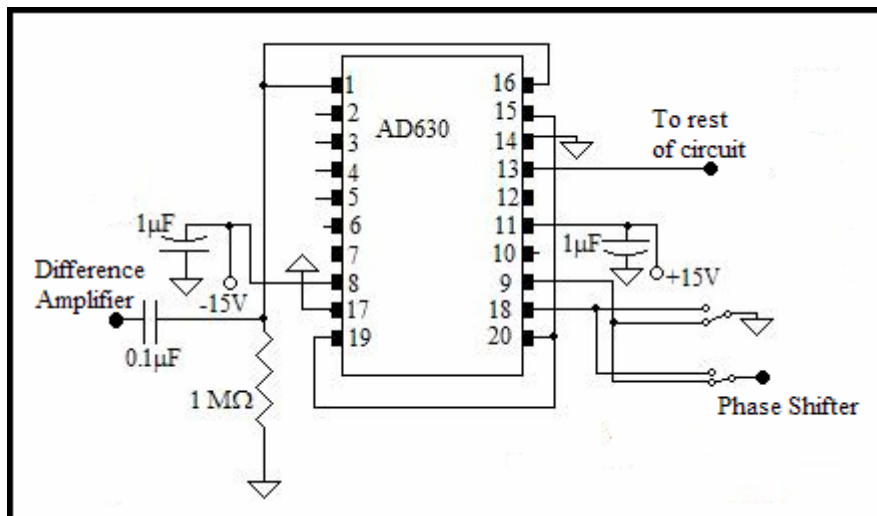


Figure 20, the portion of the Demodulator that was built. Note that the contacts are labelled in the correct order; this was to make the circuit less confusing to draw.

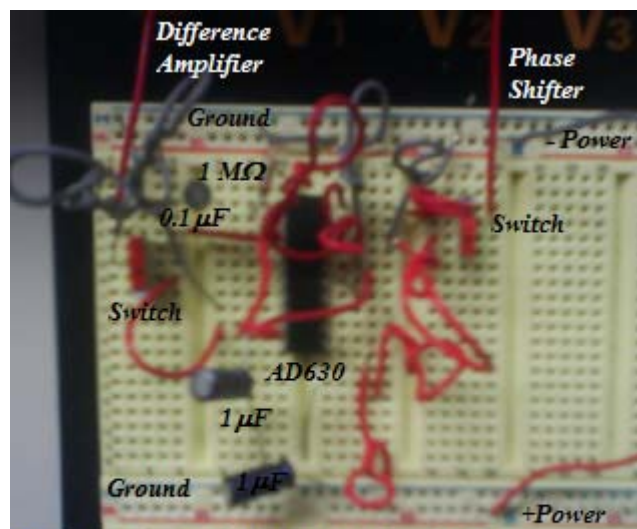


Figure 21, a photograph of the partially built demodulator on the breadboard. Red wires are positive and gray wires are negative. The two ground lines are linked off picture to ensure that all grounds are common

4. Conclusion

There were three main objectives to this project. The first, and most obvious, was to use the time to aid the group in a current experiment. The second was to get a feel of what postgraduate research in physics would be like while the third, and some cases least obvious, was to actually learn something.

For the first objective, did this project aid the group? Yes, it did. The purpose of this experiment was to build and test both an ECDL and a Lock-in amplifier for use in the next generation of laser cooling experiments, an example of which is pictured right. The ECDL was completed and shown to be working. For the circuit some sections, such as the low pass filter, did not have full listings of its components. In the case of the low pass filter the resistors and capacitors used to determine the critical frequency had to be determined prior to wiring the circuit. Furthermore, while the circuit is not working the components are in the correct positions, as shown by the breadboard graphs above, so it is only a case of someone with better electronics knowledge discerning the problem and then imitating the order of components. While not as successful as one wished, it was enough to save the group a substantial amount of time.

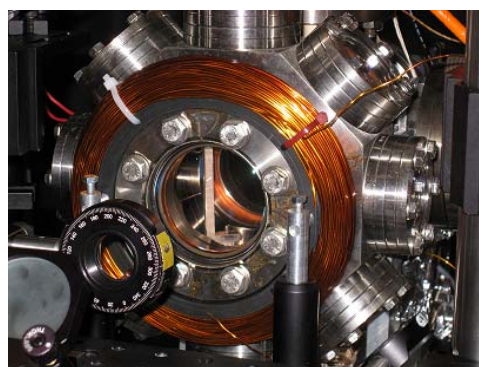


Figure 22, a photograph of the MOT used by the Quantum Optics group. This ECDL will be used to cool atoms contained within the device

The second objective was to gain an insight into postgraduate physics research. There are three quintessential situations an experimental physics researcher can find themselves in. First of all, there can be a wait for equipment preventing work from being done. Second of all, there's trying to jerry-rig an experimental setup with what can be found in the hope that it will work the same way. Last, but no means least, there's witnessing errors out of nowhere with no idea of the cause or solution. These three moments were all experienced during the project. A new input for the ECDL had to be installed before it could be tested; at one stage a reprogrammed real time clock chip^[12] was going to be used as an oscillator but abandoned due to time constraints (which is usually how such attempts end); and soldered circuits not working for seemingly no reason. It is safe to say that this objective was met during the course of this experiment.

The final objective was to actually learn something. The course here is very theoretical, so much so that something as simple and fundamental to experimental research like soldering was not thought. In addition to learning this skill, a more in depth knowledge of electronics was gained through the project. In addition the basics of Laser cooling and MOT design and use were introduced.

In conclusion the project was successful. Not only was an ECDL built and demonstrated to be of use, but valuable hands on experience, the type of which cannot be thought in a class room, was gained.

5. Appendix: Wiring the Thermoelectric Cooler Switcher

While waiting on parts to arrive and to gain more soldering experience for the final part of the project a simple switcher circuit (figure 23) was soldered (figure 24). As mentioned before, the purpose of a TEC is to control the temperature of the laser. The laser is sensitive to slight changes in temperature so one must ensure that the temperature of the laser remains constant throughout the experiment.

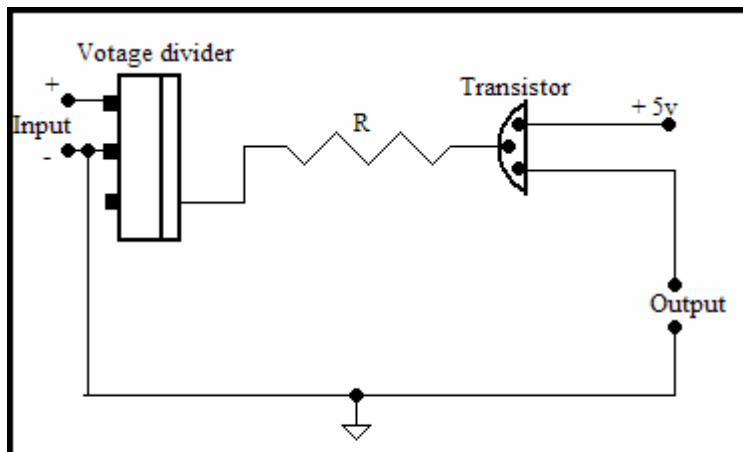


Figure 23, a sketch of the switcher circuit. This is not a standard circuit diagram bu a sketch of how the parts look to make building the circuit simpler



Figure 24, a photograph of the circuit. There are 4 circuits here all working from the same input. White wires are positive, black wires are negative

The TEC is a Peltier heat pump^[12], a device that creates a heat flux between two sections of an object by passing a current through it. The direction of the heat flux is dependent on the direction of the current. Therefore one can heat or cool an object at will using a TEC.

The TEC on hand was not compatible with the rest of the experimental setup. Specifically, its output was the opposite of what it was meant to be. To rectify this mistake a “switcher” had to be wired. The switcher is a simple circuit that changes the value of an input based on its relation to a trigger point governed by the resistor in the circuit. The output of the circuit is shown below.

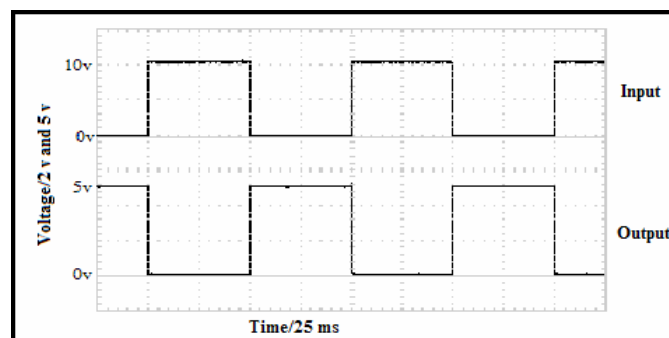


Figure 25, the switcher output. A 10v input was chosen to show that the input voltage did not affect the output.

6. References

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