Measuring the Exact Length of a Rubidium Atomic Vapor Cell

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Abstract

A recent 2DFT study of a potassium atomic vapor demonstrated double-quantum coherence in the system, and simulations revealed that only resonance between multiple atoms caused by dipole-dipole interactions (at densities as low as 10^{12} cm^{-3}) explain this effect. A similar effect was observed with a rubidium atomic vapor cell, but to more definitively investigate this system, we first need to accurately characterize that vapor cell, in particular by finding the exact cell thickness. In this paper, I discuss the principles and assembly of an external cavity diode laser in the Littrow arrangement and describe using this tunable laser system to perform absorption measurements on the vapor cell, from which we can recover the cell thickness. Unfortunately, I was not able to make the measurement during the time I had.

1 Introduction

1.1 Motivation: Two-dimensional spectroscopy

Two-dimensional Fourier transform (2DFT) methods are all distinguished by their ability to generate a frequency-correlation spectrum (i.e., a frequency-frequency plot) [Fig. 1b], which can be used to study coupling between states, anharmonicities, and can even provide information about the dynamics of a system, information that a one-dimensional spectrum loses by flattening into a single dimension [Fig. 1a]. The method relies on transient-four-wave mixing, a third-order nonlinear effect in which three EM waves in a system interact and product a fourth wave. To this, 2DFT spectroscopy adds a fixed delay between pulses (i.e. they are coherent) which varies less than wavelength over one-hundred. In a simple description of this scheme, there are five steps: first, a short pulse of light puts the system into a coherent superposition of states; second, the system is allowed to freely evolve for some waiting time τ; third, another pulse ‘populates’ the system, effectively storing the state of the coherence; fourth, after another delay T a third pulse generates another coherence which will radiate; fifth, the four-wave mixing signal from the system radiates into a spectrometer after some decay time t. The signal radiating from the sample is Fourier-transformed from the t time domain to frequency domain ω_2 (emission frequency) by the spectrometer, and the delay in τ Fourier transformed from the τ time domain to ω_1 (absorption frequency) [Fig. 2]. This technique was pioneered in the 1970s for studying NMR using radio-frequency pulses, but has been extended into the infrared and visible spectrum by the development of ultrafast (femtosecond) laser-pulses.

1.2 Motivation: Collective resonances in Rb atomic vapor

Recently, researchers in the Cundiff lab were able to observe an excitation signal in a gas of atomic potassium at twice the frequency of the D_1 line [1]. They concluded that because no state of a single potassium atom corresponds to this energy, “this observation must be attributed to a collective resonance involving multiple atoms,” “induced by weak interatomic dipole-dipole interactions.” They then performed a similar study of a gas of rubidium and were able to report collective resonances in the double-quantum spectra, but without accurate knowledge of the exact cell-width—the exact distance between the inner glass surfaces of the vapor cell—quantifying the contribution to the double-quantum signal due to collective resonances will not be possible.

My summer goal was therefore to assemble an external (or ‘extended’) cavity diode laser (ECDL) in order to perform an absorption spectroscopy experiment on the rubidium vapor cell, and ultimately to calculate the exact cell-width.

1.3 Diode Lasers

The basics of laser diode operation resemble those of LEDs and other diodes: a p-doped and an n-doped semiconductor material are place in contact, usually by forming one on top of the other. “P-” here means positive, indicating that a dopant with fewer valence electrons than the primary atomic component of the semiconductor crystal, resulting in a net electron-deficiency which is more typically described as an excess of positive holes; “n-” thus indicates negative, or a dopant which donates extra electrons. When brought into contact, the Fermi-levels (the chemical potential of the electrons) of the two regions are unequal, so to lower the energy charge flows across the p-n interface creating a depletion zone where the availability of net charge carriers (both holes and electrons) drops off rapidly [Fig. 3].

The depletion region operates as a potential barrier which then must be overcome before any more charge transport over the junction can occur. When the a bias is placed across the diode, this potential barrier can be overcome and electrons in the conduction band flow from the n-doped to p-doped side, while electron-holes in the valence band flow from the p-doped to n-doped semiconductor, effectively a current through the diode; these two may then recombine, emitting light with energies corresponding to the bandgap. There are considerable and subtle fabrication challenges to building an effective diode laser which operates at room temperature. For instance, a very low-defect crystalline structure and the development of heterojunction AlAs-GaAs devices (i.e., the p and n-type regions of the junction are made of semiconductors with dissimilar crystalline structure) were necessary to prevent excessive power-dissipation in the crystal which rapidly destroyed them [3]. In addition, some means of producing a laser cavity is necessary, and there are many ways to accomplish this—a gradient in the index of refraction, produced by a gradations in dopant concentration, confines the light in the transverse direction, while the cleaved facets of the semiconductor itself typically act as the mirrors of the laser cavity [Fig. 4] [2].

The light-emitting area of the of the diode laser's surface is a very small rectangle, on the order of (0.1 μm by 0.3 μm), so the beam divergence is large and elliptical, usually around 30° perpendicular to the junction and 10° parallel to the junction [Fig. 4] [2]. To control for this a lens must be used, and these are typically available packaged in a lens tube designed to hold the diode canister.

1.4 External Cavity Diode Laser

It is difficult to create a laser diode with a precise desired wavelength, but the diodes are capable of tuning as much as 20 nm by controlling temperature and current. Unfortunately, the temperature tuning is not continuous, as the diode laser will discontinuously change modes as the temperature changes, and current tuning is limited by both the lasing threshold and the maximum current rating of the laser. To smooth out these spectral gaps, we use an extended cavity by reflecting first-order diffraction from a grating back into the cavity. The grating acts to select the wavelength the laser will emit by finely adjusting the angle (with a piezo, in this case) between the grating surface normal and the laser cavity [Fig. 5]. This arrangement for an ECDL is known as the Littrow set-up. One disadvantage of the Littrow arrangement is that in order to tune the laser, one must change the direction of the output beam. A more sophisticated setup, Littman-Metcalf, uses an independent mirror to reflect the 1st order diffraction back into the laser cavity and avoids this problem, but at the expense of higher power-loss.

2 My Work

2.1 The temperature controller

Before purchasing and assembling components to build my ECDL, I first familiarized myself with the JILA temperature and current control rack, using an older ECDL to attempt to reach a stable temperature. This involved frequently utilizing the expertise of the JILA Electronics Shop. We found that the circuit was configured such that the bias across the thermo-electric cooler (TEC) was unipolar, and could only heat the laser—with their help I reversed the polarity on two transistors to make the board. Then I observed that the temperature controller typically overshot the desired temperature from both directions while hitting the ceiling of the servo gain, and therefore would continue to oscillate about the desired temperature indefinitely. To fix this, I learned how to tune the temperature controller such that the oscillations were slightly underdamped—essentially, you tune a resistance until the servo provides appropriate gain and add capacitors to the differentiator and integrator circuits. After a few weeks on this project, my temperature controller was working and I was ready to order components to build a new ECDL.

2.2 Buying and installing components for the ECDL

The external electronics for the temperature-control circuit include a thermistor (or 'thermocouple'), a TEC (thermo-electric cooler, sometimes called a Peltier device after its namesake effect) and an AD590 temperature-to-current transducer for a separate measurement of the temperature, all of which are relatively inexpensive components. The JILA temperature controller comes configured for use with a 25kΩ thermistor (i.e., this is the resistance at 25° C). The aluminum box housing the laser is designed to accommodate two TECs, one rated for 3.0 A about one centimeter below the laser, and another rated for 6.0 A which thermally isolates the block holding the laser from the exterior aluminum shell. The AD590, attached with thermal epoxy to the aluminum piece between the TEC and laser tube, is used only to give a temperature reading for display on the temperature controller.

The remaining components are directly related to optical concerns. The laser diode we used is an inexpensive model with operating current in the range 20-40 mA and typical power of 10-12 mW. To collimate the diverging beam we used a simple aspheric, AR-coated lens, held relatively fixed with respect to the diode by a collimation tube. In addition, we purchased a piezoelectric actuator designed to expand up to 9.1 μm, with a maximum operation voltage of 100 V. For our wavelength-selective grating, it was very important to use the grating equation appropriate for the Littrow setup in order to select the appropriate grating for our experimental wavelength, particularly to ensure that the output beam from the ECDL would exit at nearly 90° from the bare laser diode output beam. We chose a grating with a blaze angle of 26° 44′ and a groove density of 1800 mm^{-1}, coated for efficiency in the visible range, which for a 780 nm beam yields an angle of 89.09°. All of these components are installed and wired inside of a standard aluminum box machined by the JILA shop.

2.3 Coarse-tuning the laser

After both adjusting the distance between the diode and lens to collimate the beam, and aligning the diffracted feedback into the laser cavity, I began attempting to adjust the wavelength to be within about 0.1 nm of the D_2 line for rubidium, about 780.24 nm. As I noted in Section 1.4, there are three parameters which can be varied to tune the wavelength of a diode laser: temperature, current, and diffraction-grating angle (coarse-tuned with micrometer screws). Tuning the temperature generally gives widest range, as diode lasers will continue operating at about a 60-K range centered on room temperature, down to 0° C (and beyond) and up to around 55° C; the (approximately linear) slope is about ⅓ nm/°C, with wavelength decreasing as temperature does. However, diode lifetime is much reduced at higher temperatures, making it preferable to remain below the mid-20° range; in addition, if the laser cavity is exposed to atmosphere, at low temperatures water condensation becomes a concern. Several of the “780 nm” laser diodes we purchased we had their spectral peak 3-4 nanometers above 780, such that cooling down to 12°C did not move them to 780.2 nm, but on a rather humid day for Boulder—relative humidity of above 20%—caused condensation inside the laser cavity [Fig. 5]. Luckily, the last of the diodes we had purchased lased at 780 nm at 23°C, so no extraordinary measures to control condensation were required.

On timescales longer than 1 μs, current tuning does little beside change the temperature tuning due to Joule heating [2]. Because the diffraction grating only offers frequency selection when the first-order diffraction goes back into the laser cavity, there is a very limited range over which the wavelength can be tuned without misaligning the feedback. Therefore, the grating and current only offer fine tuning, along with some control over the mode stability. Despite the ideal behavior predicted by the relationships governing temperature, current, and grating-angle tuning, the laser diodes we used frequently experienced strong mode-competition and seemingly inexplicable mode-switching (for instance, jumping to a mode with wavelength two nanometers higher when cooled by less than 0.2°C), so it was by no means a trivial task to locate a (seemingly arbitrary) set of parameters which resulted in mode stability lasting longer than half an hour.

2.4 Optical and electronic apparatus

Having stabilized my ECDL at a wavelength near the D_2 line of rubidium, I needed to arrange optics and electronics to allow me to measure the optical density (also known as 'spectral absorbance') of a rubidium vapor cell. First we measure the power without the vapor cell in the beam path, and then again with the cell in the beam path and modulating the piezo at about 20 Hz. We modulate the piezo to finely adjust the wavelength about the exact D_2 transition, such that we will see a minimum in the signal corresponding to maximum absorbance, and modulating at less than 20 Hz helps the laser maintain mode-stability. The required electronics are as follows: I used a photodiode, for its faster response time than an optical spectrum analyzer (OSA), to measure the power output of the laser; a function generator and piezo driver—the driver merely amplifies the voltage coming out of the function generator, which has nowhere near enough overhead to reach the maximum 100 V—to supply a triangle wave modulation to my piezo; and an oscilloscope to monitor the output of the photodiode and to trigger off the function generator signal [Fig. 7].

The optical setup was similarly simple: the beamline included one neutral density (ND) filter beyond the ECDL to cut down the power uniformly and prevent saturation of the sample, and another ND filter screwed onto the photodiode to prevent it from saturating. Then the cell, a beam splitter to direct part of the beam to the photodiode and another portion to the OSA, two mirrors to direct the split beams into the photodiode and the OSA, and 10 cm lens to focus the one beam on the photodiode crystal [Fig. 8].

2.5 Current controller noise

After collimating and aligning my laser, and arranging the optical and electronic components of my experiment, I checked the noise in the photodiode signal and was surprised to see that on top of a 1.5 V signal, there was a 15 mV (peak-to-peak) ripple with a frequency of 60 Hz. Because of the gain, this would result from a 0.02 mA ripple in the current controller output, far too low to see directly on an oscilloscope. The JILA electronics shop and I eventually surmised this was because the current controller I was using had been configured to provide up to 2.6 A of current, far greater than the standard 140 mA current controllers and far more than my 30 mA diode required. Because of the higher current and voltage this board required, resistors—in particular, the sense-resistor in the servo circuit—had been substituted for less resistance, to prevent excessive power-drain. Because the gain in the servo-loop is directly proportional to the resistance of that sense-resistor, the servo for this high-current board was less sensitive, and less effective at controlling for AC-line noise.

I was able to switch to a smaller current controller, and this immediately solved the line-noise problem, reducing the (no longer 60-Hz) noise to 800 μV peak-to-peak on a 1.5 V signal, or less than one part in one thousand [Fig. 9]. Having assured myself that noise was now manageable, we could try modulating the piezo to see how that affected the photodiode signal.

2.5 Setbacks which prevented a result, suggestions for moving forward

Several catastrophic diode failures resulted in some week-long delays, and even after successfully tuning a laser diode to the correct wavelength, stability (especially when modulating the piezo) remained a major concern. Though our piezo had a maximum rated bias of 150 V, just modulating 5.0 V peak-to-peak caused persistent mode instability. This instability prevented us from modulating in a wide-enough range or fine-tuning the set wavelength, as this was more likely to result in a mode-jump of 0.50-1.00 nm than a 0.10 nm shift. This in turn made it very difficult to search for maximum absorption in our sample.

However, the laser-head has been assembled now, and it would be a matter of a few hours to replace the diode. Replacing the current laser diode with a higher-quality, more stable model would likely make the experimental setup effective for performing the absorption measurement. Reviewing all the progress I have made in preparing this apparatus, much of the ground-work has been laid: the temperature-controller is tuned to that laser-head precisely; noise due to the current controller was solved by using a controller independent of the temperature controller; all components were ordered and installed, and the functionality of this system (with the exception of diode stability) has been demonstrated. All of this took perhaps seven weeks alone, so once more laser stability can be accomplished, taking the measurement is more or less all that remains to be done.

3 Acknowledgements

I would like to thank Dr. Cundiff for letting me into his lab despite my complete absence of knowledge about optics or experience in experimental physics; it has been an excellent and wholly unfamiliar learning experience. To Hebin Li, who designed most aspects of my project and patiently guided me through its execution, I am very grateful. I owe many thanks to Bo Sun, who took over the role of my mentor—after Hebin moved on to begin a professorship —and provided helpful advice on my project and invaluable criticism of this work. Thanks to all the members of the Cundiff group for their generosity with their experience, equipment, and encouragement, and for sharing coffee, meals, and idle conversation with me. To Akil, thanks for the many political, ethical, and imaginative debates. Last but hardly least, thank you to Drs. Jin and Dessau for coordinating this project and making this experience possible.

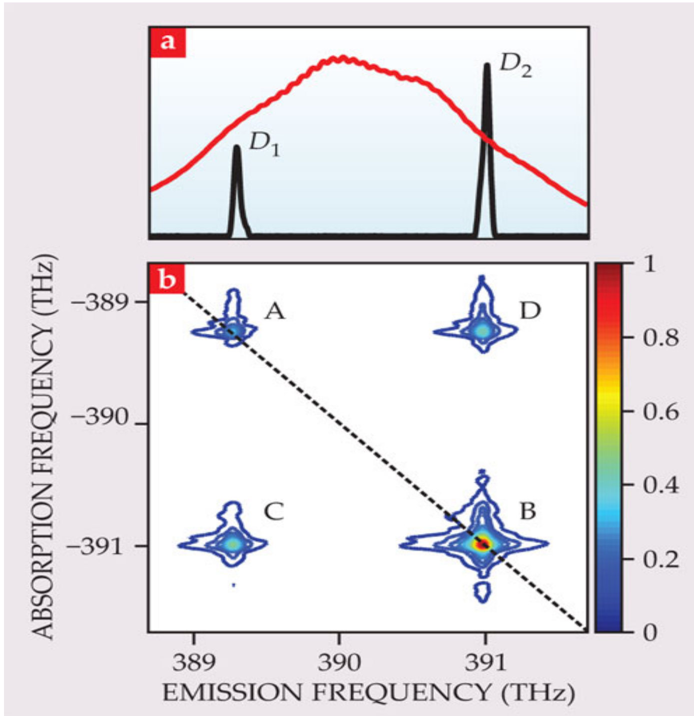

Figure 1: 1a shows the same spectrum in a more typical one-dimensional fourier spectrum, demonstrating how much information is lost. 1b shows an example two-dimensional Fourier spectrum, where signals along the dashed line (A,B) indicate absorption and emission occur at the same frequency. The off diagonal peaks (C,D) correspond to coupling between the excited states. Figure from from [4].

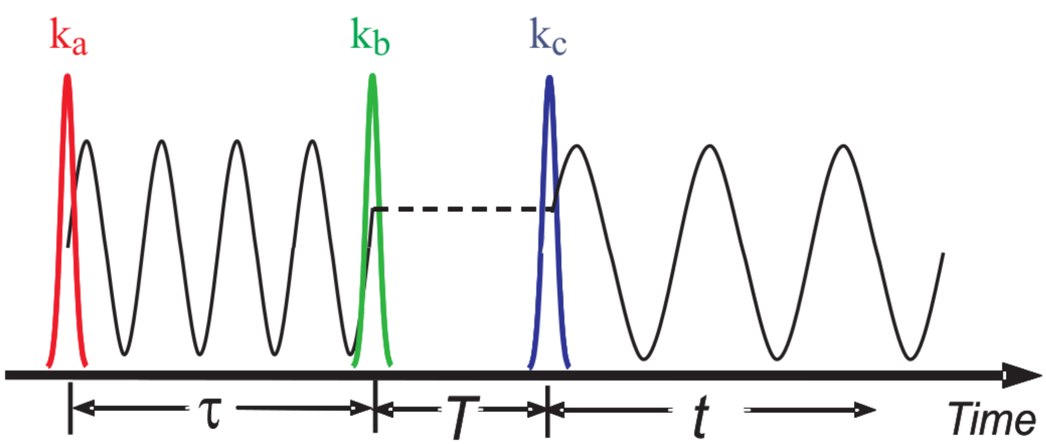

Figure 2: Illustration of pulse sequence and oscillating superpositions in 2DFT. The first pulse, k_a, creates coherence, k_b populates the system with excited states, and k_c generates a coherence that will radiate away the transient four-wave mixing signal to the spectrometer. T is typically held constant and does not appear in the final frequency correlation graph. From [5].

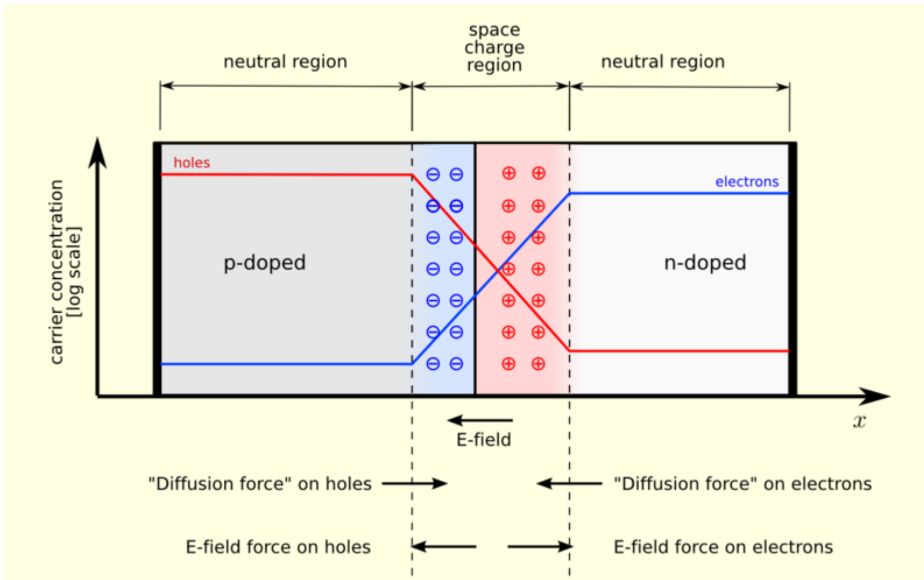

Figure 3: A simple P-N junction diagram, from
https://en.wikipedia.org/wiki/File:Pn-junction-equilibrium.png

with

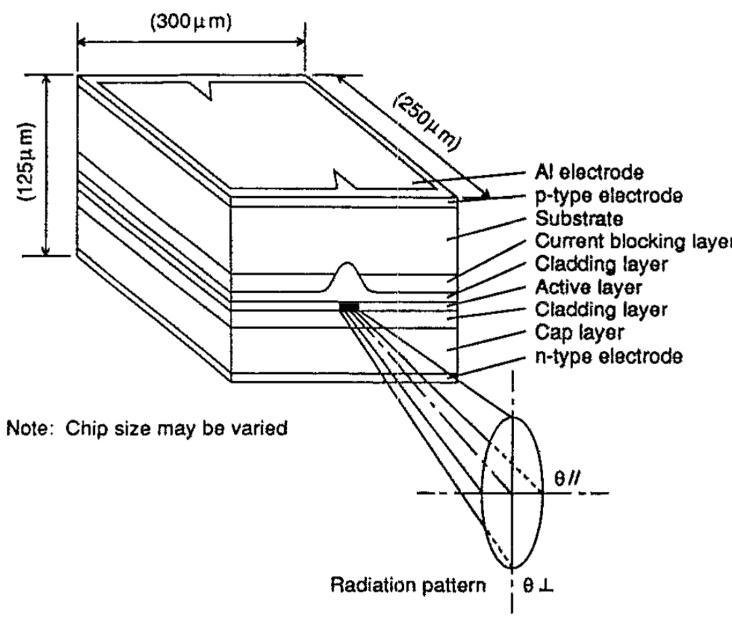

Figure 4:
Simple diagram of a diode laser, illustration of the elliptical beam divergence. From [2].

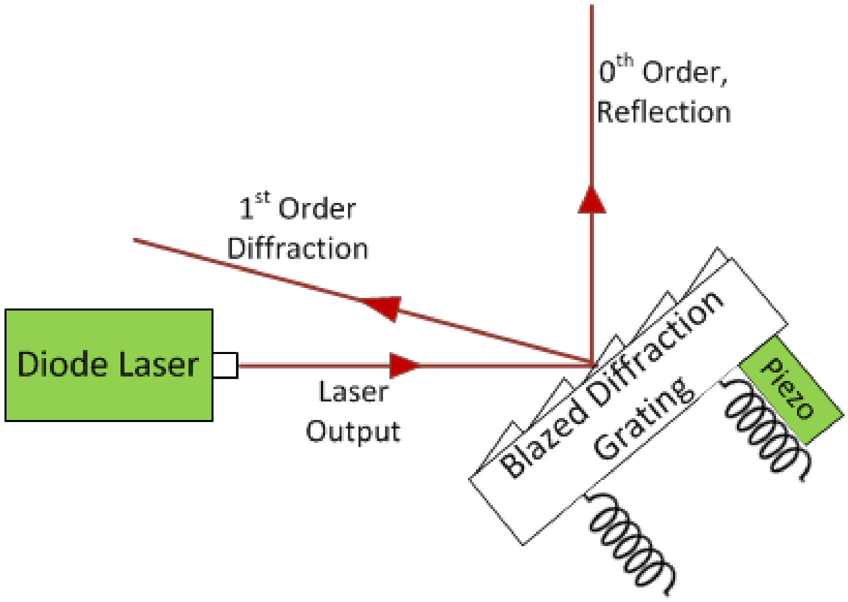

Figure 5:
External cavity diode laser in the Littrow arrangement. The 1st order diffraction is not precisely aligned back into the laser cavity only for illustrative clar
Figure 5: Laser Spectrum without the diffraction grating, demonstrating temperature tuning which was not sufficient, without measures to prevent condensation, to reach 780.2 nm. The power dependence on temperature is also easy to observe.

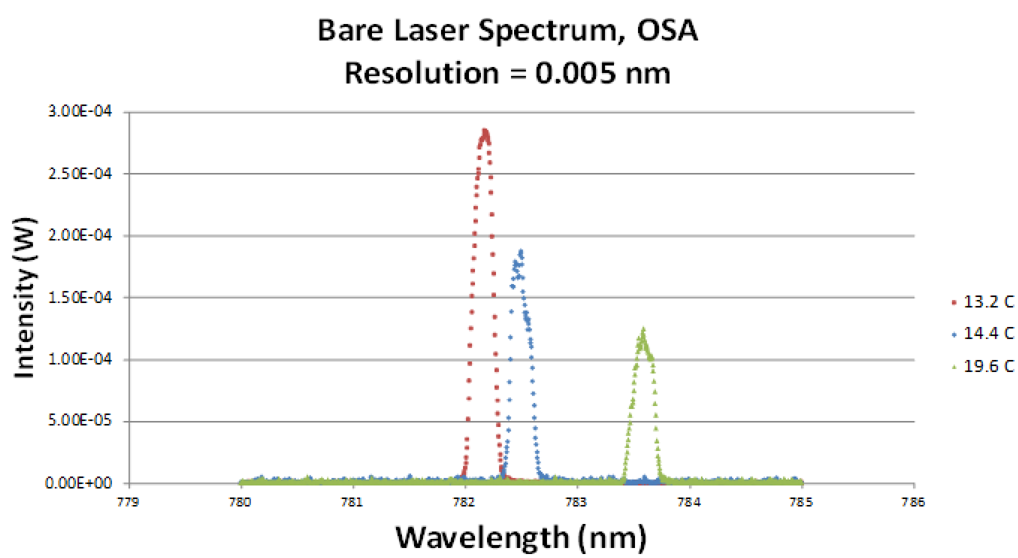

Figure 6: Laser Spectrum without the diffraction grating, demonstrating temperature tuning which was not sufficient, without measures to prevent condensation, to reach 780.2 nm. The power dependence on temperature is also easy to observe.

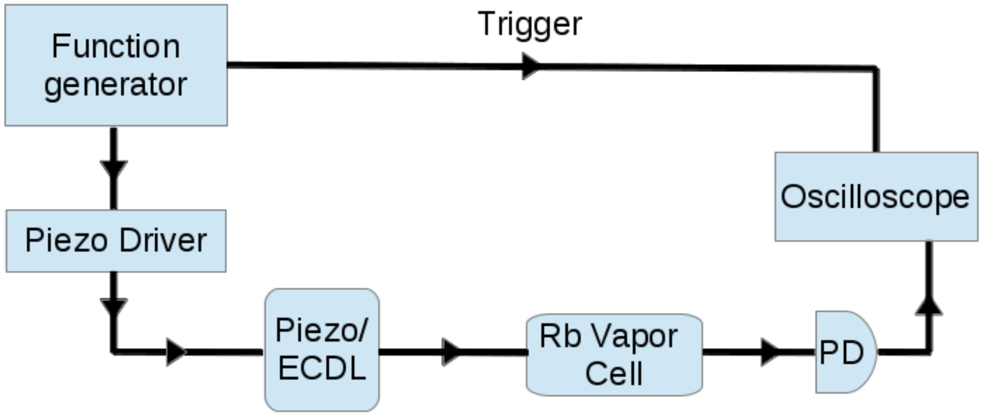

Figure 7: Electronics setup. Current and temperature controller not shown, but can be considered part of the laser system. “PD” indicates the photodiode, while arrows indicated the direction signals travel.

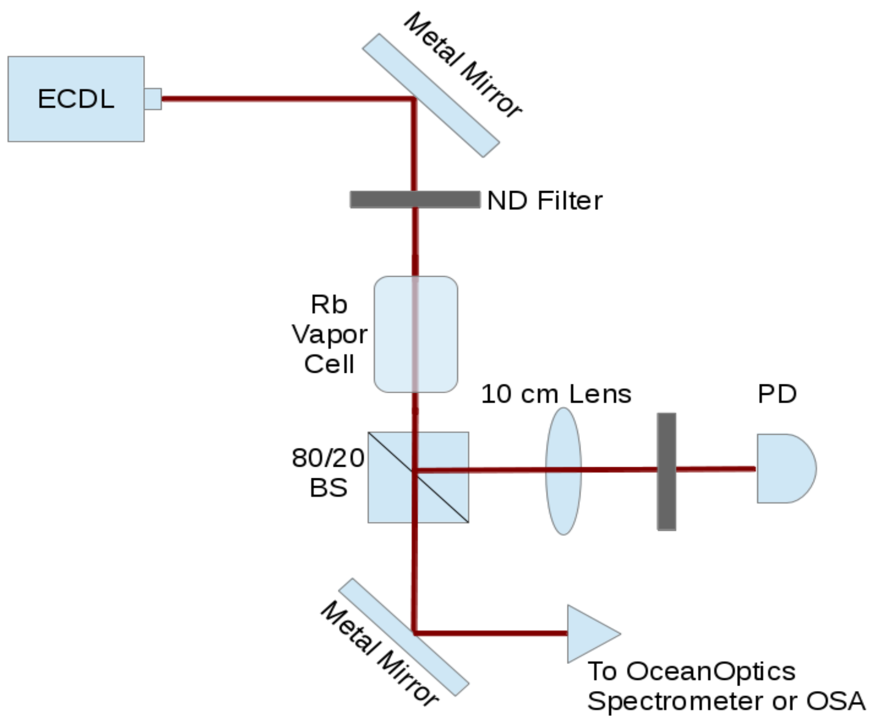

Figure 8: A diagram of the optics in the beampath for my experiment.

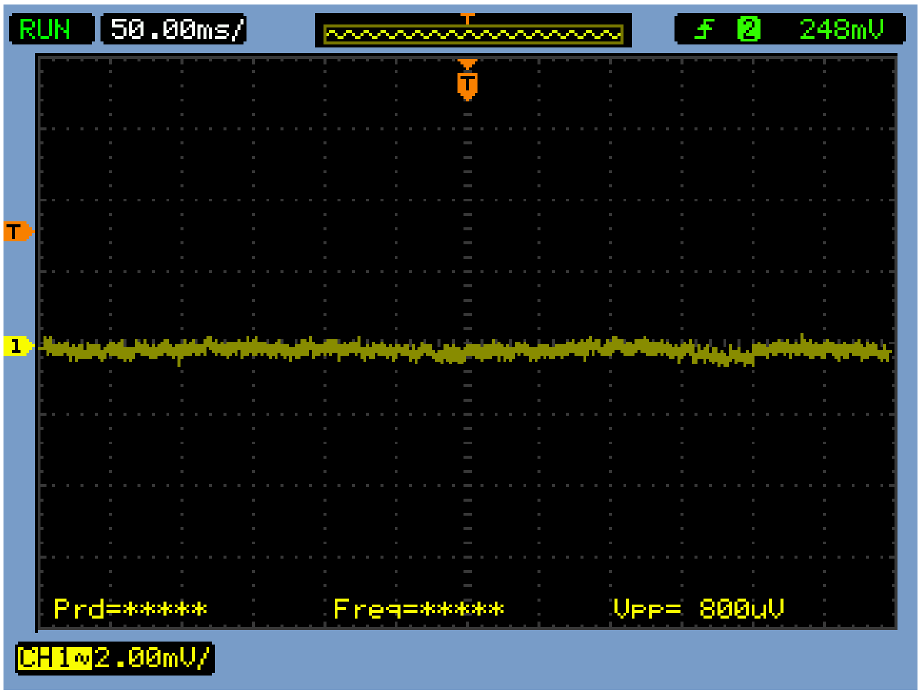

Figure 9: Oscilloscope screenshot of the photodiode noise, with the DC signal subtracted away.

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