1 Noise

1.1 Noise Requirements

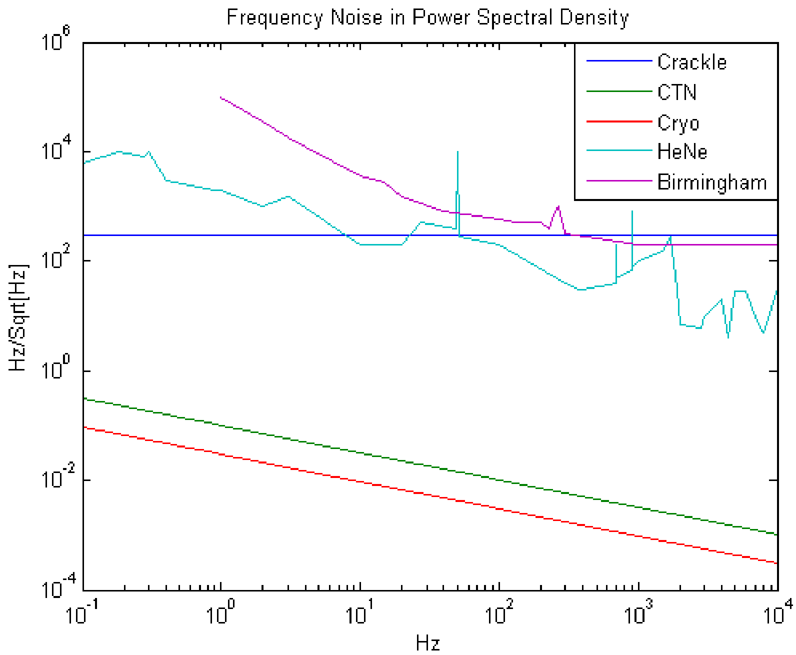
In order to create a useful ECDL, it must be capable of meeting the noise requirements of the experiment it is being used for. Thus, we need see the noise levels of the possible experiments we could perform with our ECDL and determine which experiment we will use. We collect the noise power spectral density (PSD) of several different experiments:

- Crackle experiment: This experimental setup involves a Michelson interferometer with blade springs. The blade springs are driven in unison, and any noise that arises is from 'crackling' and can be observed. Tara estimated the noise level of $300Hz/\sqrt{Hz}$ based on the shot noise limit of the setup [2].

- CTN and Cryo experiments: These experiments both aim to measure length noise in dual reference cavities. The CTN experiment is at room temperature, and the Cryo experiment is at cryogenic temperatures. In the experiment, 2 lasers are each frequency locked onto 2 reference cavities. The two transmitted beams are recombined, creating a beat frequency. The noise on the beat frequency can be used to calculate the length noise of the 2 cavities. The frequency noise requirement for CTN is about $\frac{0.1}{\sqrt{f}} \frac{Hz}{\sqrt{Hz}}$ and the frequency noise requirement for Cryo is about $\frac{0.03}{\sqrt{f}} \frac{Hz}{\sqrt{Hz}}$.

- HeNe laser: In this setup, a Fabry-Perot cavity is formed with one entirely reflective mirror and one partially reflective mirror on opposite sides of a cavity filled with helium and neon gas. Note that the HeNe data presented here is after frequency stabilization, and the actual data has significantly higher noise levels [1].

- Birmingham group: The Birmingham group built a 1064 nm ECDL, and we examine how their noise levels compare to the requirements we may use to test our ECDL [7].



Based on the possible experiments we could perform, we settle on using the Crackle experiment since it has the highest noise requirement and will therefore be the easiest standard to meet.

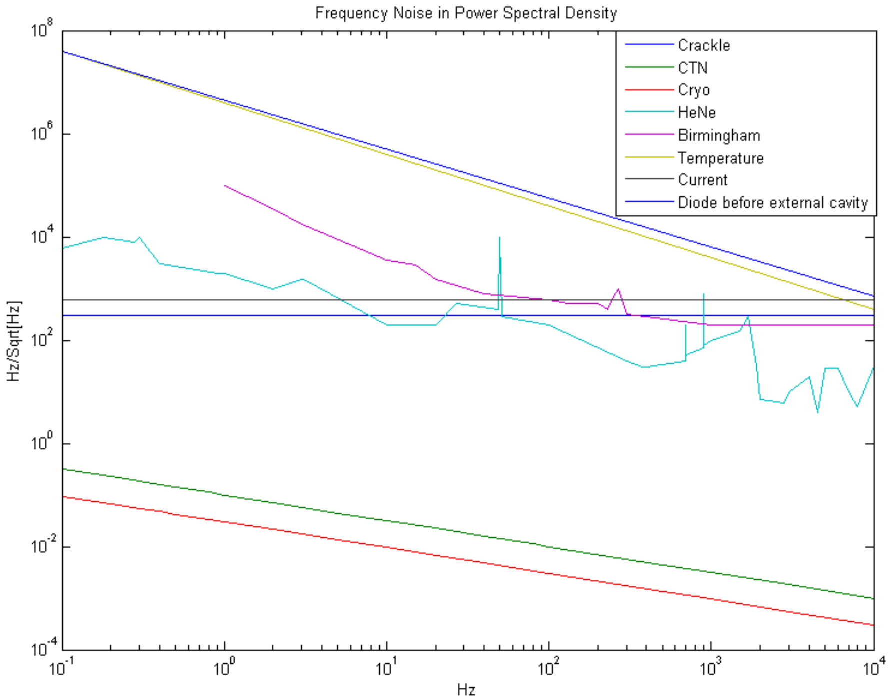
1.2 Estimated Noise of Bare Diode Laser

First, we need to determine the intrinsic noise of the diode laser (and thus its predicted linewidth). We consider two sources of noise in this analysis:

1. Noise from current: We plan to use the D2-105 laser controller from Vescent Photonics (which is based on the Libbrecht and Hall design). This has a PSD noise of 200 pA/ $\sqrt{Hz}$. The oscillation frequency of a GaAs laser changes due to current fluctuations at 3 GHz/mA. We conclude that the noise from current fluctuations is $6 * 10^2$ Hz/$\sqrt{Hz}$.

2. Noise from temperature: We plan to use the TEC built into the laser diode mount from Thorlabs HLD001. We will have some intrinsic noise from the laser, of about $2 * 10^{-4}/f$ K/$\sqrt{Hz}$. The oscillation frequency of a GaAs laser changes due to temperature fluctuations at about 20 GHz/K. We conclude that the noise from temperature fluctuations is $4 * 10^6/f$ Hz/$\sqrt{Hz}$.

The noise in PSD adds in quadrature; that is, $S = \sqrt{S_1^2 + S_2^2}$, so the total noise will be $S(f) = \frac{\sqrt{3.6 * 10^5 f^2 + 1.6 * 10^{13}}}{f} Hz/\sqrt{Hz}$.



This gives us the noise in power spectral density across different frequencies.

1.3 Estimated Noise of Diode Laser with External Cavity

Next, to estimate the factor by which the noise is reduced, we need to estimate parameter X [6, p.963]. l_1 is the length of the laser cavity, l_2 is the length of the external cavity, S is the scattering matrix for the laser, and Γ_1 and Γ_2 are the complex amplitude reflection coefficients. From Saito,

$$X = \frac{\tau_1}{\tau_2}|S_{12}S_{21}\Gamma_2/S_{11}| = \frac{\tau_1}{\tau_2}(\frac{R_{eff}}{R_2})^{1/2}$$

where $\tau_1 = \frac{2l_1}{c_1}$, $\tau_2 = \frac{2l_2}{/}c_0$, R_{eff} is the effective reflectivity of the external grating, and R_2 is the laser diode reflectivity. Simplifying, we find

$$X = n\frac{l_2}{l_1}(\frac{R_{eff}}{R_2})^{1/2}$$

$l_1 = 0.0015m$ for the Thorlabs 200 mW diode M9-A64-0200, $R_{eff} = 0.002$ based on the efficiency of the Thorlabs 1200 grooves/mm 1 μm diffraction grating GR25-1210, $R_2 = 0.85$ based on estimates from the Saliba paper [5, p.6964], and $n = 3.5$ for GaAs.

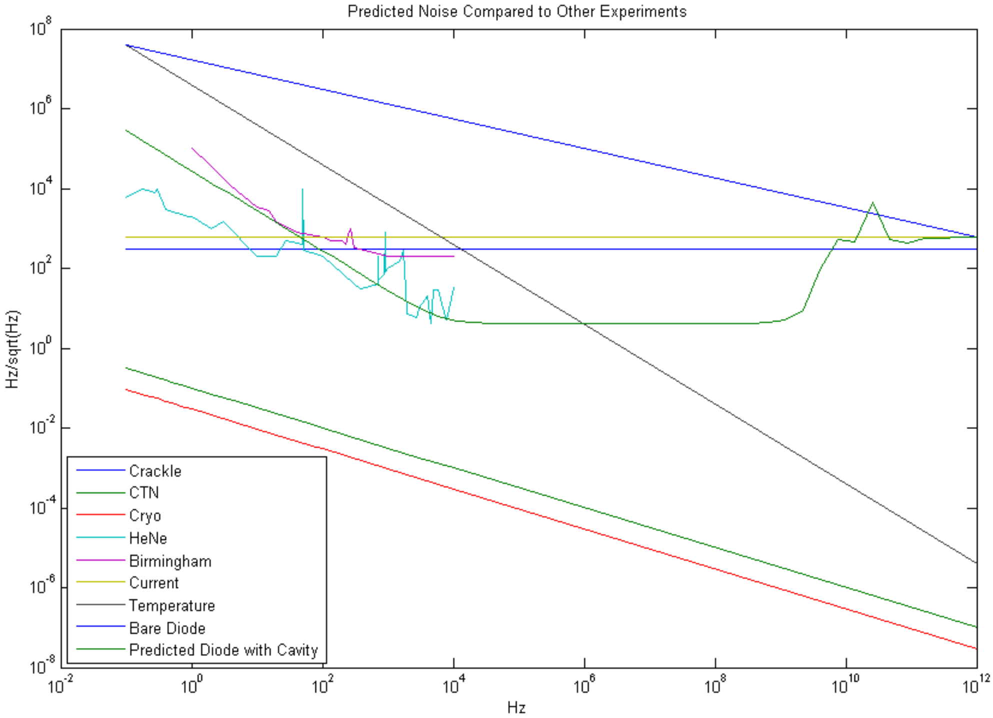
If we take the external cavity to be about 10 cm (0.1 m) as a starting point, we get X = 11 for this setup (note that making the external cavity longer increases X which would decrease the linewidth more... this can be done using a lens to focus the beam if we do not want to actually make a very long cavity).

From Saito [6, p.965], we have an equation which predicts how the noise transforms in power spectral density:

$$S^E(f) = \frac{S(f)}{(1 + Xsin(f\tau_2)/(f\tau_2))^2 + X^2(1 - cos(f\tau_2))^2/(f\tau_2)^2}$$

This reduction of noise is independent of frequency for small frequencies, where $f\tau_2 \leq 0.3$ [6, p.965], where f is the oscillation frequency in the external cavity. In our case, $\tau_2 = 6.7 * 10^{-10}s$ so we certainly have values of $f\tau_2$ that satisfy the condition necessary for this approximation. Once $f\tau_2$ becomes close to 1, we see an increase in noise due to the jump from one axial mode to another in the external cavity. See Saito paper for further explanation of this approximation.

This is apparent if we plot the reduced noise compared to the noise from other experiments.



We see that in frequency ranges below about 100 Hz and above about 10 MHz, we do not meet the noise requirements for the Crackle experiment.We would require a parameter X of about 3000 in order to meet the Crackle noise requirements at low and high frequencies.

1.4 Estimated Noise of ECDL with servo

Next, we are interested if the addition of a servo like that used by NPRO to suppress noise will be sufficient to reduce our noise levels. In order to do this, we must determine the transfer function for the servo.

We experience the same frequency discriminator gain (D) and gain function (G) but the actuator gain (A) will be different. For a PZT, we can take $\sim 15\mu m/V$, based on a value quoted by MacAdam et al. [3]. The change in length due to the PZT actuator will change the allowable frequencies in the external cavity, so we determine how the cavity mode spacing changes. According to Mroziewicz,

$$\Delta\nu = \frac{c}{2(nl + L)}$$

where n is the refractive index of the laser material, l is the length of the laser cavity, L is the length of the external cavity, and c is the speed of light [4]. When L changes, we can see how the mode spacing changes by differentiating:

$$\frac{d(\Delta\nu)}{dL} = \frac{-c}{2(nl + L)^2}$$

so plugging in our numbers, we find that the mode changing changes by $1.35 * 10^{20} Hz/m$. Applying the coefficient of this change, we find that $A = 900 Hz/V$.

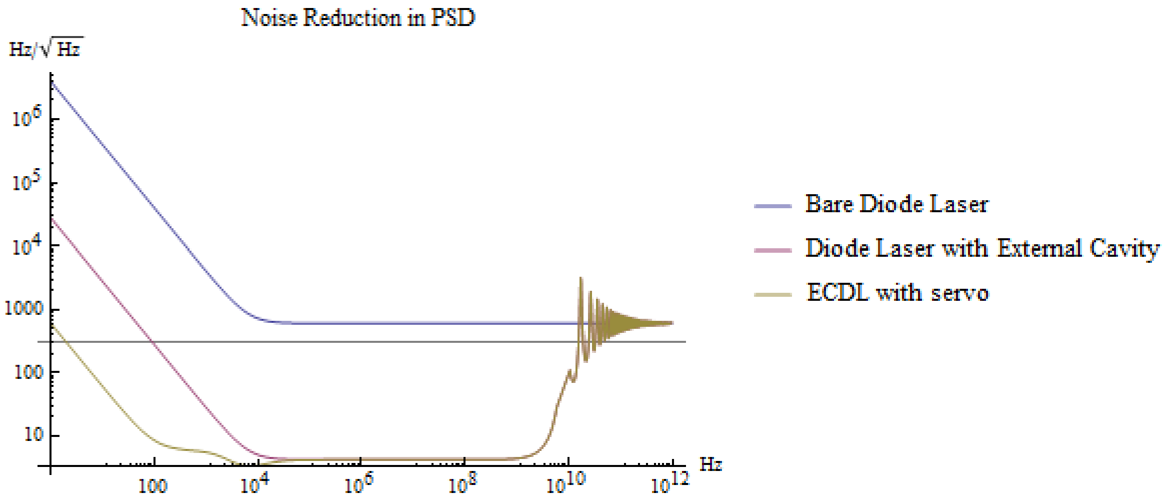
Tara gave me some Matlab code which calculates TFservo = GAD in terms of the fourier frequency of the noise. The parameters for this, based on the ones used in the LIGO lab now, are:

- $G = 1.5 * 10^5$
- $pole1 = 100$
- $zero1 = 10^4$
- $pole2 = 987$
- $zero2 = 2 * 10^3$
- $zero3 = 1.5 * 10^3$
- $pole3 = 5 * 10^3$
- $pole4 = 10^4$
- $p1 = \frac{pole1}{if + pole1}$
- $p2 = \frac{pole2}{if + pole2}$
- $p3 = \frac{pole3}{if + pole3}$
- $p4 = \frac{pole4}{if + pole4}$
- $z1 = \frac{if + zero1}{zero1}$
- $z2 = \frac{if + zero2}{zero2}$
- $z3 = \frac{if + zero3}{zero3}$
- $TFservo = G * |p1 * p2 * p3 * p4 * p4 * z1 * z2 * z3|$

These values reflect an actuator gain of A= 3 MHz. The transfer function is given by $\frac{1}{1+GAD}$, so we can express our final noise level reduced by the servo by

$$\frac{S_{ECDL}}{1+\frac{900*TFservo(f)}{3*10^6}}.$$

This yields the following plot of bare diode noise, noise after reduction from the external cavity, and noise after further reduction from the servo.



While it reduces noise to below $300Hz/\sqrt{Hz}$ at low frequencies, it does not solve the problem we have at 10 MHz and greater. We need to brainstorm ways to deal with this if we want this ECDL to be useful...

1.5 Other mechanical components we need to consider for experimental setup

- Adapter for mounting the diffraction grating on a mirror mount (which will be screwed to an optics table). Based on the size of the diffraction grating we chose, we should order Thorlabs KGM40 if we do not already have a mount in the lab.
- We plan to use the laser diode mount from Thorlabs HLD001 with built in TEC. We probably have a multi-axis flexure platform to fix the laser diode mount onto? Need to check with Tara...
- Piezo actuator to stabilize the external cavity? Need to check with Tara...

References

[1] Akito Araya. Master's thesis, The University of Tokyo, 1992.

[2] Tara Chalermsongsak. Frequency noise requirement for laser used in crackle experiment. ELOG: PSL lab entry, April 2013.

[3] C. Wieman K. B. MacAdam, A. Steinbach. A narrowband tunable diode laser system with grating feedback, and a saturated absorption spectrometer for cs and rb. *American Journal of Physics*, 60(12):1098–1111, December 1992.

[4] B. Mroziewicz. External cavity wavelength tunable semiconductor lasers - a review. *Opto-Electronics Review*, 16(4):347–366, 2008.

[5] Robert E. Scholten Sebastian D. Saliba. Linewidths below 100 khz with external cavity diode lasers. *Applied Optics*, 48(36):6961–6966, December 2009.

[6] Yoshihisa Yamamoto Shigeru Saito, Olle Nilsson. Oscillation center frequency tuning, quantum fm noise, and direct frequency modulation characteristics in external grating loaded semiconductor lasers. *IEEE*, QE-18(6):961–970, June 1982.

[7] University of Birmingham. *Low-cost 1064nm light source for table-top interferometry based on a frequency stabilized external cavity diode laser*, LVC meeting, Bethesda, Maryland, USA, March 2013.