Stabilization of a Tunable Diode Laser

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I Introduction.

Lasers play an important roles in various fields such as physics and chemistry, especially in techniques involving the use of spectroscopy [1] [2]. One of the uses for lasers in our lab is to perform spectroscopy on single photon emitters such as Nitrogen Vacancy centers and Silicon Vacancy centers by scanning over resonances to detect Zero phonon lines (ZPL). Once a line has been selected, the laser will be set at a constant wavelength to allow us to study the behaviour of the ZPL. The width of a ZPL is typically around 100 Mhz [3]. Setting the wavelength at the correct wavelength to study a single ZPL is a challenge since wide range tuning accuracy of the lasers is only 0.01 nm. Another problem that arises from the lasers is that the wavelength of the laser will tend to drift away from the wavelength at which a ZPLs occurs over long periods of time. The drifting of the laser's wavelength can result in the laser being off resonance with the ZPL.

The purpose of this project is to develop a software written in MATLAB to allow a user to control a tunable diode laser system with ease. The software also allows the user to lock on to an intended wavelength as well at stabilizing the laser to prevent long term drifts.

II Background.

The potential applications of color centers has become an important area of interest for researchers in photonics. Our group is interested in studying single photon sources and quantum memories based on emitters such as Nitrogen Vacancy (NV) Silicon Vacancy centers in solid state platforms. Such platforms have the potential to be implemented more easily compared to other isolated quantum systems such as trapped ions. One method used to study the properties of the color centers is by photo luminescence excitation spectroscopy (PLE)[4]. A tunable diode laser is used to scan over the zero-phonon lines (direct transitions) while monitoring the phonon side band fluorescence. Once a line is selected, the line is monitored by setting the laser to a constant wavelength corresponding to the wavelength of the direct transition line. One of the problems in doing so is due to the stability of the tunable diode laser. The bandwidth of a zero phonon line depends on multiple factors including, the lifetime of the excited state of the color center, and spectral diffusion [5]. For a high quality NV center, we expect linewidths of approximately 100 MHz [3]. However, the instability of the scanning lasers could be problematic if we are trying to monitor the zero phonon line by keeping a the wavelength of the laser constant with the corresponding wavelength of the line. Therefore, it is essential that a solution is developed to tackle the problems associated with the scanning laser. Fig 1 shows the extent to which our laser changes in wavelength over a period of about an hour. The drastic chances in wavelength in Fig 1 emphasizes the importance of creating a stabilization system to increase the reliability of the laser. This project will be important as it will allow for increased control over our scanning lasers.

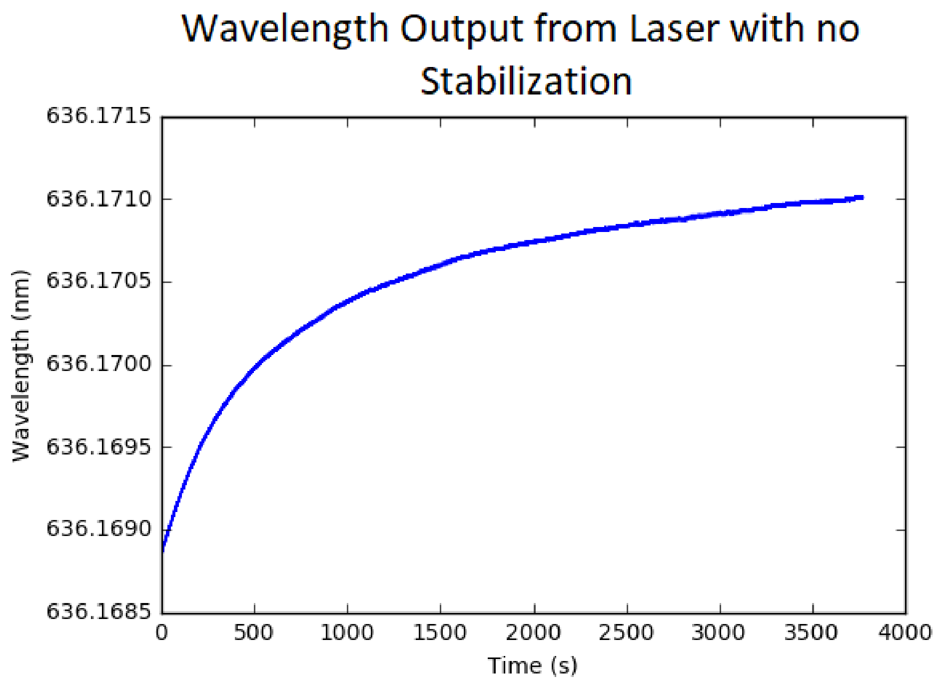


Figure 1: An unstable laser is left running over a period of time. The wavelength of the laser is measured with a wavemeter. The important feature of the plot is the increasing trend of the output wavelength. The change in wavelength is quite drastic since the wavelength drifts nearly 0.1 nm from its initial point

An approach that is used in this project to stabilize the wavelength of a tunable laser is to create a feedback loop. An error signal is generated by comparing laser's wavelength output to a target wavelength which is sent to a control system. The control system is then responsible for making the necessary adjustments to the system so that the wavelength of the laser is corrected. In other words, the addition of such a feedback loop should minimize the magnitude of the difference between the current wavelength of the laser and the target wavelength. The stabilization system discussed in this report resembles the basics of a PID controller design. A PID controller is one of the most used control design which depend on three terms; The Proportional-Integral-Derivative term [6]. We will only be concerned with the proportional term, which is simply the difference between the current wavelength output from the laser and the target wavelength. The integral and the derivative terms does not have to be accounted for in this project, since we do not require a high performing stabilization system to achieve adequate results. Creating a system that only handles the proportional term of the PID controller is sufficient to limit wavelength drifts of the laser and allow one to tune the wavelength of the laser with greater accuracy.

III Methods.

An adequate understanding of how a tunable diode laser functions will be crucial for the development of a stabilization system. Our group uses external cavity diode laser products from Newport Corporation. A diagram describing the structure of Newport's lasers is shown in Fig 2.

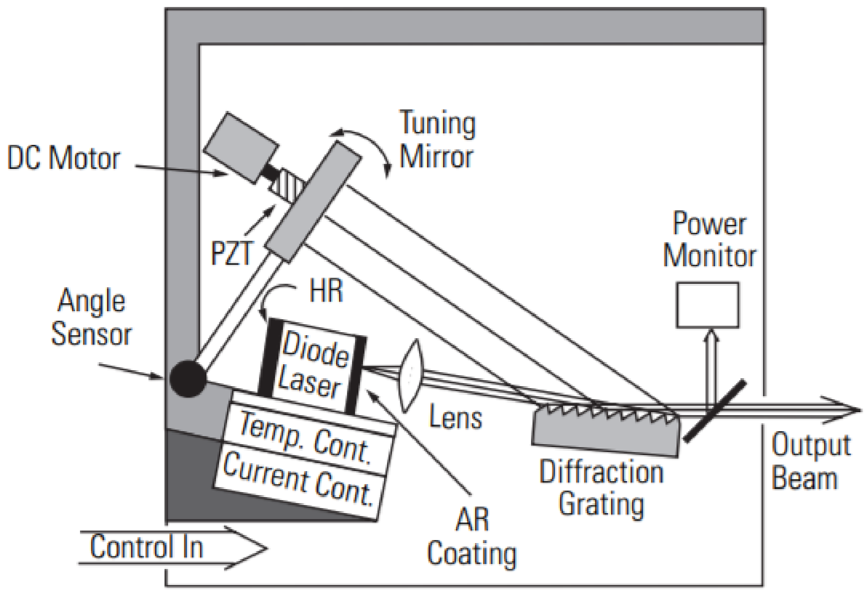


Figure 2: The figure from the laser manual shows the internal structure of a TLB model laser. Here, we can see the components that are involved in adjusting the output of the laser. From this diagram we can determine how we can control the wavelength of the laser. Reference: Users guide: The Velocity Tunable Diode Laser, Model 6300-LN. Irvine: Newport Corperation [1969]

3.1. Controlling the Laser External cavity tunable diode lasers functions by diffracting a beam of light from a laser diode source and splitting the beam into a spectrum of light with a range of wavelengths. Recall that the angle at which light diffracts is dependent on the wavelength of the light.The wavelength of light produced by the laser module is selected by positioning an adjustable mirror at an appropriate angle with respect to the diffraction grating. The beam is reflected off of the tunable mirror and then back towards the laser diode that has a reflective coating. The adjustable mirror and the reflective coating on the laser diode acts as a cavity in which light resonates and gains intensity before escaping from the cavity. The position of the mirror is adjusted with the use of a DC motor as well as a Piezo transducer. The DC motor allows for coarse tuning of the laser, and the function of the piezo transducer is to fine tune the wavelength of the laser. One of the advantages of the TLB-6700 model lasers is that it allows one to control its components with software by connection with USB. Alternatively, a voltage signal can also be applied to the laser module to adjust the piezo transducer. Both the USB connections and voltage inputs to the laser module present different ways for us to send signals to the laser to control the wavelength of the laser. Both methods work by adjusting the position of the mirror. In fact, our resulting stabilization system relies on our ability to control the position of the tuning mirrors by software written in MATLAB.

Observing Fig 2 would also suggest that a stabilization system can be implemented with the use of current and temperature. This will not be necessary since it is more difficult to control the wavelength of the laser by changing the current and temperature values of the laser. Therefore, these variables will not be accounted for in the stabilization system as it will be impractical.

3.2. Reading the Wavelength Our ability to control the laser's components is not enough for us to implement a functional stabilization method. We also need know the current output wavelength of the laser. This can be achieved by sending the output of the laser to an optical wavemeter so that we can measure the current wavelength of the system. The wavemeter uses an interferometer to measure the wavelength of the laser. The information from the wavemeter can be retrieved by a computer. This will allow is to know if the current wavelength of the laser is where it needs to be. Otherwise, it will inform our system as to when the system needs to be adjusted. Data from the wavemeter can be continuously sent to a computer. This ability has proven to be useful as it allows us to monitor the wavelength of the laser while the system

3.3. The Stabilization Method We have now outlined the necessary components for generating an error signal as well as developing a method for one to adjust the wavelength of the laser. The error signal of the system is generated by measuring the wavelength of the laser and then comparing the current wavelength of the laser to the target wavelength. The difference between the two values is the error signal that will determine when the system should be adjusted. The system can make the necessary adjustments on the laser by fine tuning the position of the mirror within the laser so that output of the laser remains stable.

Again, the control system for the laser is software based and it is written in MATLAB. Most of the work had been focused on stabilizing the output from a TLB-6704 model (635 nm - 638 nm) external cavity tunable diode laser. This may seem impractical since we had that we had only focused on one product, but the stabilization software can be implemented in other laser models with some adjustment to the script.

It should be considered that the resulting software responsible for locking on to a target wavelength and the stabilization of the laser system will be used while performing experiments to study the NV and SiV centers. We can allow for one to access these features with ease by implementing the features into a graphical user interface (GUI). A GUI can be created by using MATLAB's GUI Development Environment (GUIDE).

3.4. Testing the Software The stabilization system should be tested in an experimental setting to test its performance. We will be performing the experiment by first, shining our scanning laser onto the structure shown in Fig 3. The image shown in Fig 3 is an image of a SiV center. The experiment is then proceeded by scanning over resonances of the vacancy center with the scanning laser. This process is to determine the wavelengths that will induce the most amount of photon emission from the SiV center. Once we have determined such a wavelength, we set our scanning laser to output a constant wavelength corresponding to one of the transition lines. The process of setting the wavelength to a constant value will allow us to determine if the software is effective in accurately locking on to the wavelength corresponding to a direct transition line. We will then be counting the emitted photons over a period of time and determine the rate of emission from the vacancy center. This will allow us to determine if the stabilization software is successful in preventing drifts in wavelength. It is expected that a drift in wavelength will result in a decreased amount of photon counts as the Vacancy center is no long in resonance with the laser.

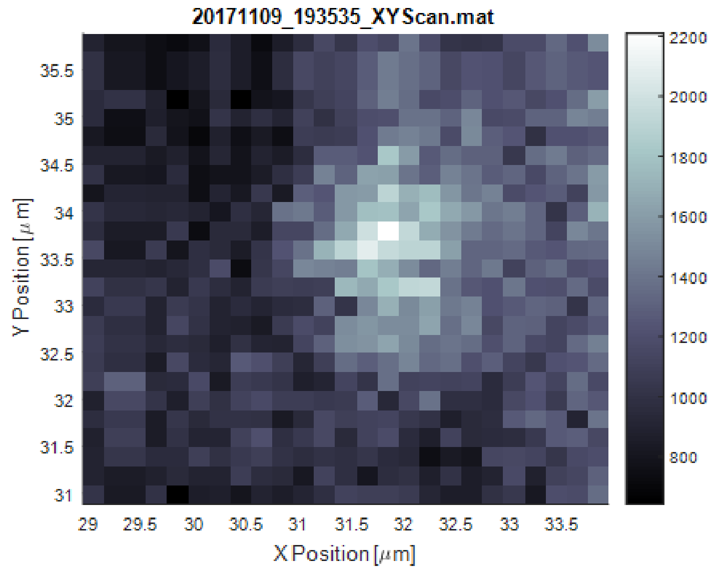


Figure 3: A close up image of a Silicon vacancy center

IV Results.

4.1. The Graphical User Interface The Graphical User Interface is created to provide a simple way for someone to access the lock-on and stabilization feature of the software. Fig 4 is the resulting GUI created for this project. The GUI includes a lock-on and a stabilization feature as mentioned. The GUI also offers additional accessory features that would prove to be useful in future experiments. The *Monitor* plots the wavelength of the laser as a function of time. This will allow the user to track the drifts of the laser. A more precise reading of the laser wavelength can be monitored under the *Current Wavelength* panel. The user can also monitor the state of the piezo in the laser by returning a percentage value of the maximum voltage that can be applied to the piezo. We refer to this value as the Piezo Percentage. This is important in ensuring that the voltage being applied to the piezo does not exceed the maximum voltage that it can handle. The panel labeled

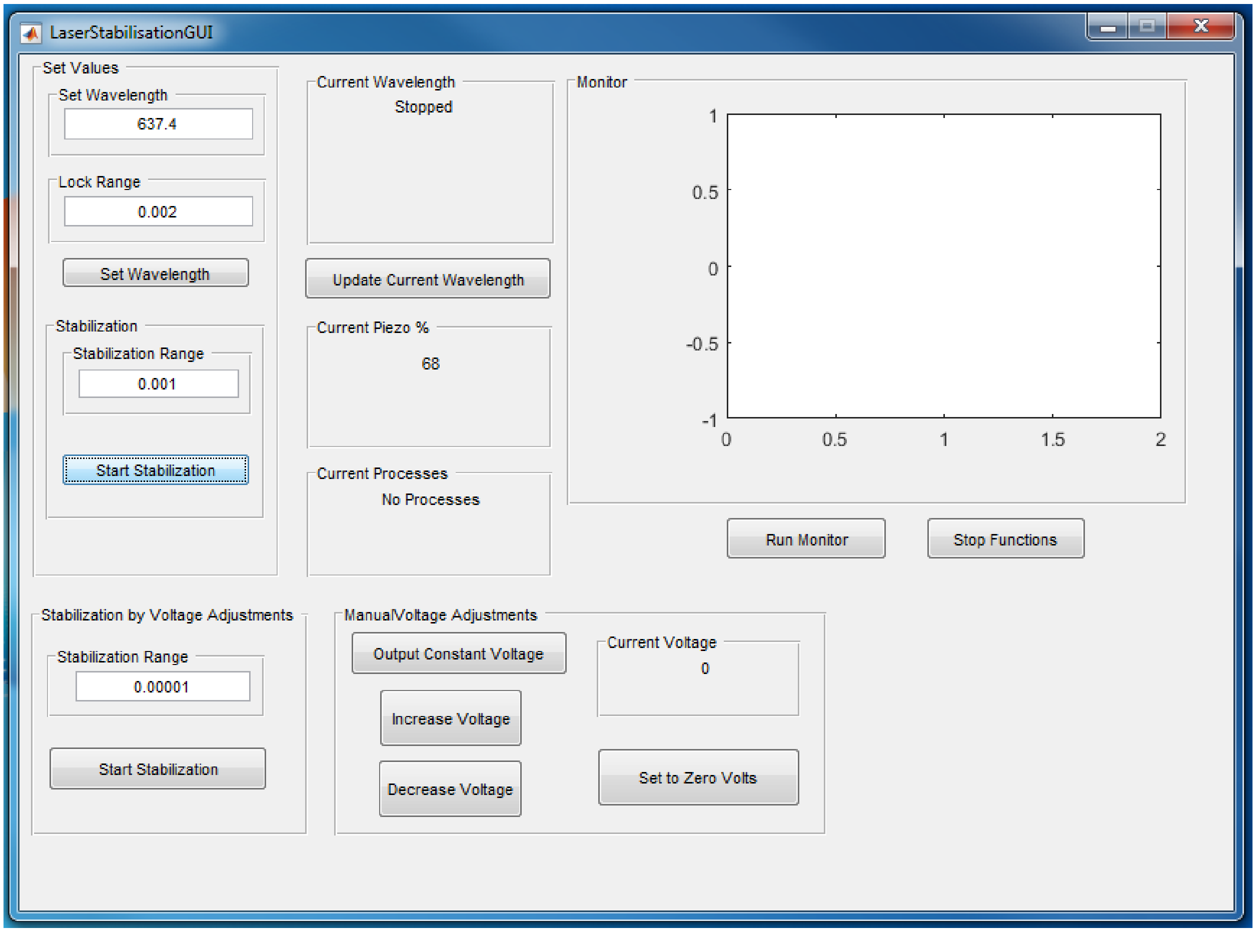


Figure 4: The Graphical User Interface created during the project

'Manual Voltage Adjustments' allows the user to manually change the voltage being applied to the piezo. This is mostly for testing purposes and does not play a significant role in stabilizing or adjusting the laser.

The remaining panels in Fig 4 implements the functions that are more relevant to the project. The laser can be set to new wavelengths by entering the target wavelength value in the *Set Wavelength* panel located in the top left corner of the GUI. The text box labeled *Lock Range* is essentially the acceptable precision that one will allow for the wavelength of the laser. The software is designed to tune to the target wavelength specified in the *Set Wavelength* panel and will stop making fine adjustments when the wavelength is within the acceptable precision specified under the *Lock Range* panel.

The panels labeled *Stabilization* and *Stabilization by Voltage Adjustments* in Fig 4 will both adjust the laser whenever the wavelength drifts outside of a range specified in the *Stabilization Range* box. The functions of both panels are the same, in that selecting either panel will perform a stabilization on the laser system. However, "Stabilization by Voltage Adjustments" adjust the piezo by generating a voltage signal that will be applied to the piezo transducer in the laser whereas the other option will adjust the laser through a USB connection with the laser module. The Advantage/Disadvantages of either approach will be discussed in a later section.

4.2. Locking on to a Target Wavelength The Wide-Tuning of the laser is only accurate to 0.01 nm as mentioned in a previous section. However, our software can allow for a more accurate tuning of the laser. The acceptable precision of the wavelength adjustments are set in the panel that is labeled ”Lock-Range” in Fig 4. For example, one can tune the laser’s output to 636 nm with a precision of ± 0.001 nm. The course tuning of the laser will adjust the wavelength of the laser to a value that is around ± 0.01 nm of the target wavelength by only adjusting the mirror with a DC motor. Our software will then make fine adjustments with the piezo until the wavelength of the laser is within ± 0.001 nm of the target wavelength, as intended by the user. We can visualize the tuning process since we can plot the real-time data from the wavemeter to allow us to see the changes to the wavelength of the laser as a function of time as shown in Fig 5. The initial wavelength of the laser is 636.8999 nm, and the target wavelength was 636.9 nm. Some of the important features to note in Fig 5 is that the accuracy of the laser’s final output is much more accurate than 0.01 nm given by the laser’s specifications. The large increase in wavelength at around 6 seconds in Fig 5 is caused by the coarse adjustment made by the DC laser. We can see that adjustment by the DC motor will cause the wavelength output of the laser to overshoot by about 0.03 nm. The plot begins a downward slope towards the target wavelength. This downward slope is due to the fine adjustment of the wavelength using the piezo transducer.

4.3. Stabilization of the Laser The magnitude of drift occurring in a laser is quite significant over a period of just a few minutes as we can see in Fig 1. We saw that our stabilization system was effective in stabilizing the wavelength of the laser from long term drifts. The stabilization system uses two separate methods to control the wavelength of the laser. One method was to control the piezo transducer of the laser by USB connection from the laboratory computers to the laser module. Fig 6 shows stabilization software adjusting the wavelength of the laser so that the wavelength remains within ± 0.001 nm of the target wavelength. One important feature in Fig 6 is

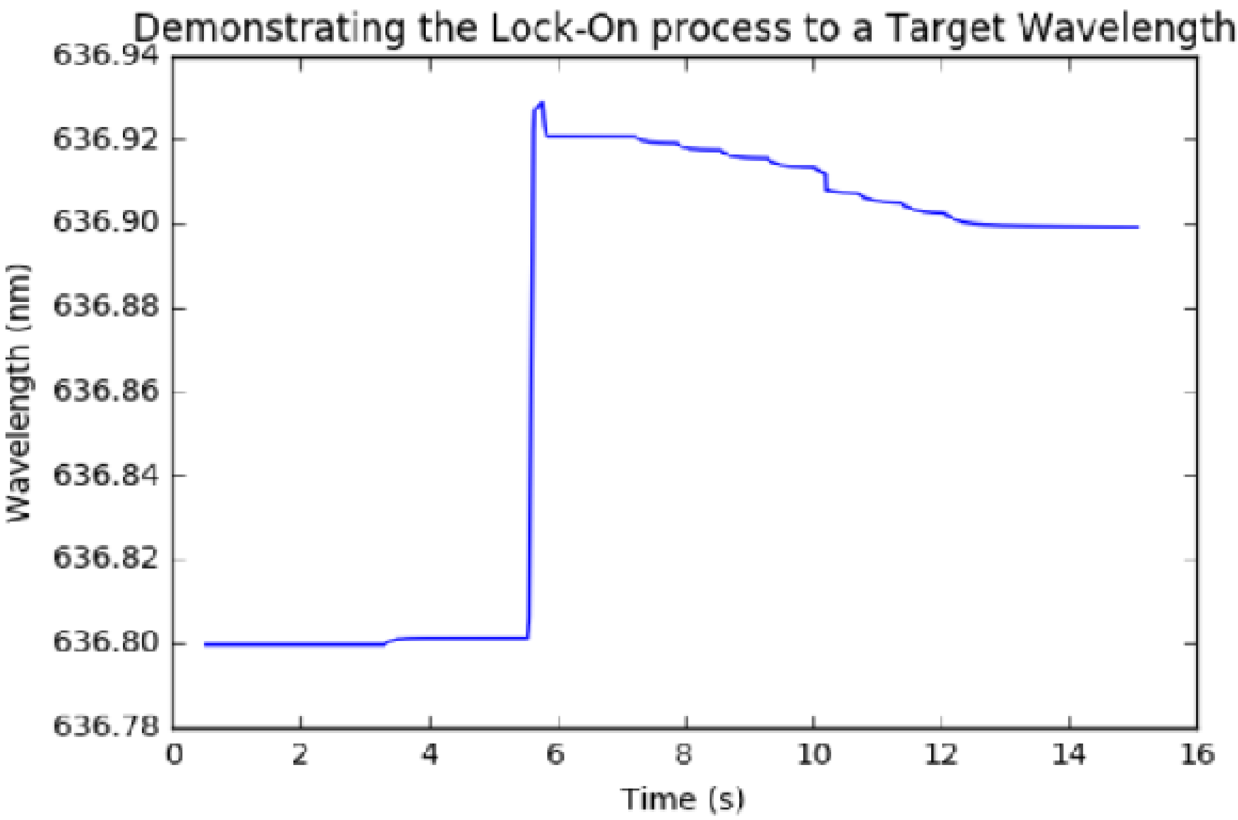


Figure 5: The process of tuning the laser and locking on to a target wavelength. The initial wavelength of the laser was 636.7992 nm. A target value was set to 636.9 nm. The adjustment of the laser starts at 6 seconds when the DC motor tunes the wavelength to 636.92 nm. The system begins to fine tune the laser with the piezo until the wavelength reaches 636.8999 nm.

the wavelength drifting from times $t = 1$ s to $t = 12$ s. The sudden increase in wavelength at time around $t = 14$ s is due to the software detecting that wavelength of the laser is drifting out of range and adjusting the wavelength so that it is closer to the target wavelength of 637.2134.

Unfortunately, there is no presentable data showing the stabilization process by applying a voltage signal to the laser. The exported data had not been sampled properly to show any significant details.

We noted that there are certain advantages as disadvantages associated with both stabilizing the laser using a USB connection and by sending a voltage signal to the laser. Sending a voltage signal to the laser to finely adjust the position of the tuning mirror resulted in much more high frequency noise in the wavelength output comparing to the regular USB connection. We can observe this feature in Fig 7. Fig 7 shows both the signal from the wavemeter when there is no voltage input to the laser module and with an applied voltage to the laser. Despite what we see Fig 7, we hypothesized that controlling the laser with a voltage signal has the potential of allowing for a faster stabilization method. Our reasoning comes from the fact that using a voltage input to the laser will allow for a more direct access to the piezo transducer. On the other hand, a signal from a USB connection would have to be processed by software before adjusting the piezo transducer itself. Our hypothesis was not tested in this project but it may be worth testing in the future.

4.4. Testing the Software in an Experimental Setting The next step is to test the performance of the system by using it in as part of an experimental set-up. We can see from the previous results that the laser system was now capable of locking on to a target wavelength and stabilizing its own

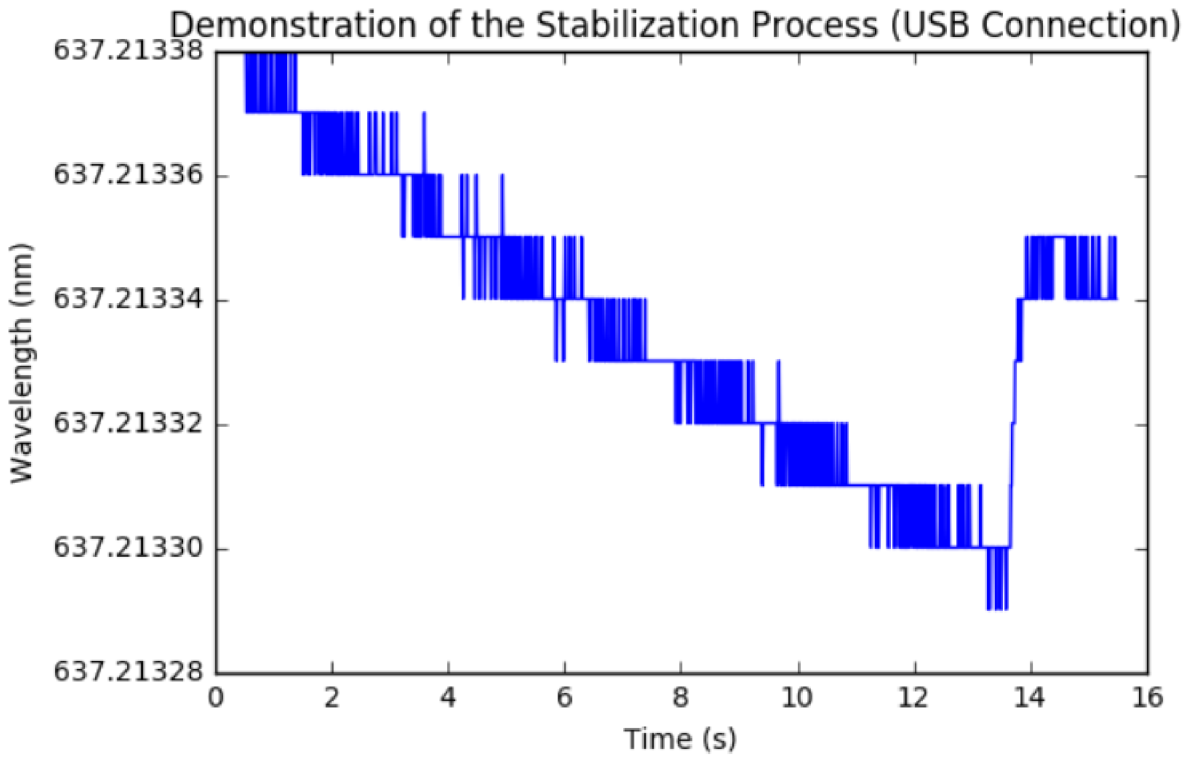
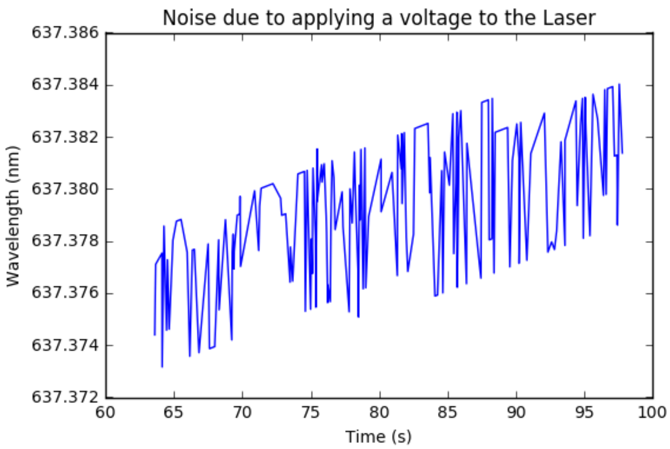


Figure 6: Stabilization of the laser by adjusting the piezo by USB connection with one of the laboratory's computer. The Target Wavelength was 637.2134 nm. We set the precision range to be +/- 0.001 nm from the target wavelength. The sudden increase in wavelength at 14 seconds is due to the software detecting a drift from the target wavelength, and adjusting the laser back within range



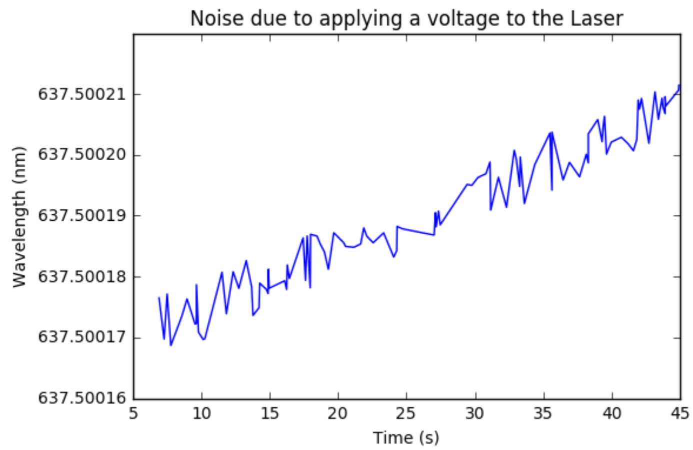


Figure 7: The two plots in the figure compares the noise signals in two different cases. The left-most plot shows the noise from a voltage being applied to the laser module. Applying a voltage to the module is one of the methods we can use to adjust the piezo transducer. Alternatively, we can adjust the laser with a USB connection to the laser module instead. The right plot shows plots the wavelength from the laser. We can see that there is much more high frequency noise in the right plot; when a voltage is being applied to the laser.

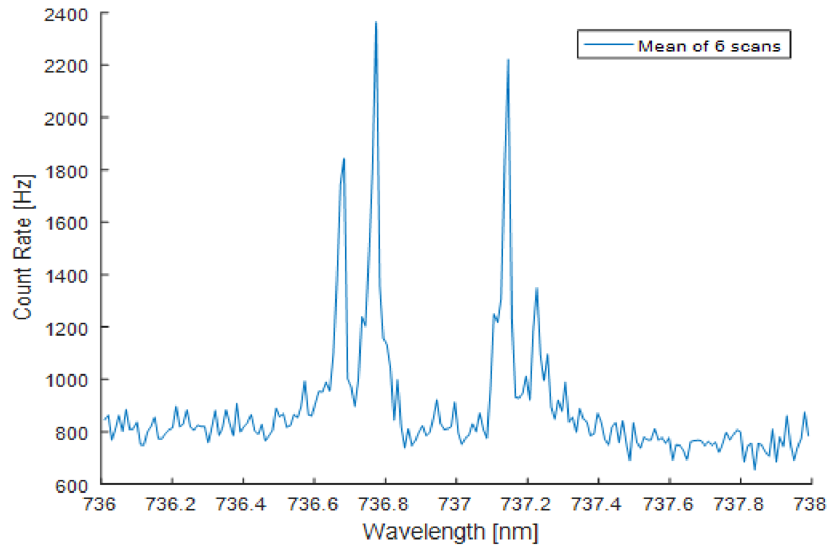


Figure 8: **The result from performing a Wide range Scan over a range of frequencies showing all transitions. We used a (730 nm - 739 nm) laser to scan over the resonances of the SiV center. Afterwards, we selected one of the transition lines to measure the photon emission rate**

output to reduce drifts. The experiment is carried out using the general procedure described in the methods section. It should be noted that the lasers used in the experiment was a TLB-6711 730 - 739 nm laser as well as the TLB-6704 (635 nm - 638 nm). Although the stabilization software was implemented using the TLB-6704 model laser, the software only required little changes to the script so that it can be implemented in the TLB-6711 laser as well.

First, we started by selecting a SiV center from an array of SiV centers. The SiV was selected based on its quality and its ability to emit photons when excited by an external light source. A selected vacancy center is then scanned over a range of wavelengths with the scanning laser.

The wavelength was set to a constant value after a specific line had been selected. We set the laser to output a constant wavelength of 736.6987 nm. It was noted at this point that the software had no problem tuning to the specified wavelength. The equipment was left running over a period of time while stabilizing the output from the laser to we can measure the detection rate of photons emitted by the Vacancy center. We repeated the process again to measure the detection rate, but without stabilizing the output from the laser to see if we can note any changes in photon detection rate. The results of this experiment is shown in Fig 9.

Two plots were produced describing the photon count rate in the cases where the wavelength of the laser was stabilized and not stabilized. Fig 9 $a)$ shows the count rate of photons from the vacancy center while the laser was stabilized. Excluding the random variations from the data, the overall trend of the plot remained constant through out the run.

The trend of the plot in Fig 9 $b)$ was different as opposed to its counterpart. There is an observable decrease in the detection rate for increasing times. This is likely due to the fact that the wavelength of the laser is drifting away from the wavelength that corresponds to the transition line. Although the decrease in the count rate does not appear to be significant. However, the background detection rate was about 800 Hz. So the decrease in the rate of counts from Fig 9 from 1800-1600 Hz is effectively a drop from 1000 to 800 Hz from Fig 8. The decrease in detection rate would effectively be 20% which is relatively significant. It may very well be the case that the signal would continue to decrease as the wavelength of the laser continues to drift away from the intended wavelength also.

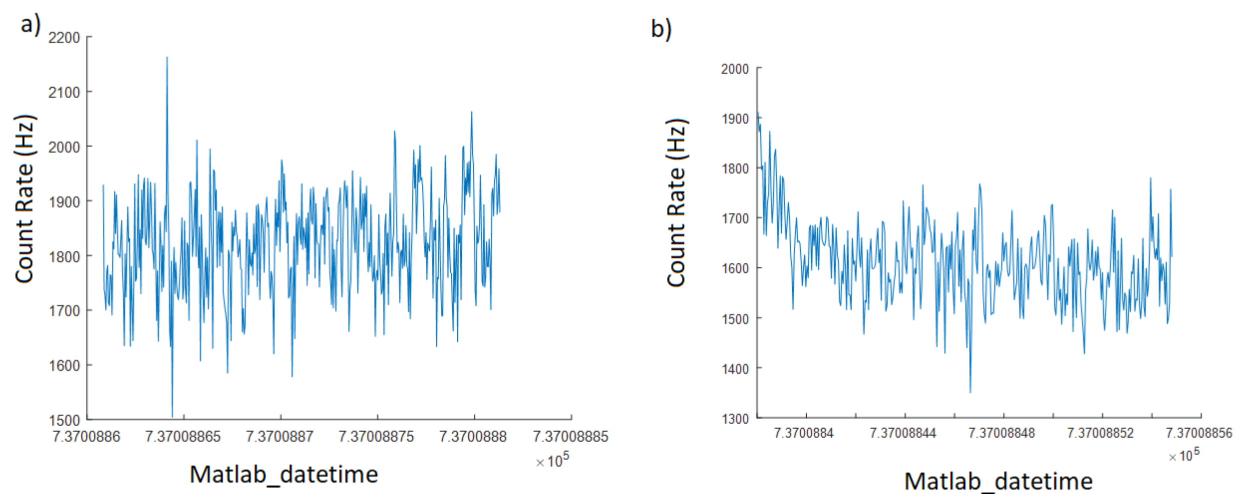


Figure 9: The upper most plot in the figure labeled a) is the count rate from the transition line while stabilizing the laser. The lower plot labeled b) is the count rate from the transition line while the laser is not stabilized. We can see that there is decreased rate of photon counts at later times due to the drifting of the laser. The comparison these plots show the effectiveness of the stabilization system

V Conclusions.

The software created at the end of the project performs well in terms of locking on to a target wavelength and stabilizing the output from the tunable diode laser. The lock-on and the stabilization function was implemented and easily accessed through a graphical user interface as intended. We tested the performance of the software by scanning over resonances of a SiV center. We also saw that the laser was capable was able to lock on to a constant wavelength to study a single transition line, and the stabilization feature resulted in a stable rate of photon detection. In this single experiment, the results show that the software will be reliable in future experiments. Especially experiments involving spectroscopy of NV centers and SiV centers.

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