

Automation of Photoluminescence Measurements of Polaritons

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Methods of automating experiments that involve the variation of laser power are discussed. In particular, the automation of photoluminescence measurements of polaritons is examined through the use of various programs and devices such as a laser power controller and a spectrometer. Additionally, the theory behind the experiment and the laser power controller is briefly discussed.

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1 Motivation

1.1 The Experiment

The primary experiment to be automated involves the measurement of the photoluminescence from quasi-particles known as exciton-polaritons. These particles are formed from the strong coupling of photons with electron-hole pairs (excitons). Interest in them stems from the study of macroscopic quantum states-systems on the classical scale that require quantum mechanical descriptions. Examples of such states other than polaritons include Bose-Einstein condensates, superconductors, superfluids, and, most notably, lasers.

The experimental setup consists of a semiconductor sample contained within a cryostat kept below 10 Kelvin using liquid helium. A pump beam is focused onto the sample through a window in the cryostat at a fixed angle (see figure 1). A fiber-coupled lens is placed at a fixed distance from the sample but with a variable angle. The photoluminescent signal is collected by this fiber-optic cable and sent to a spectrometer.

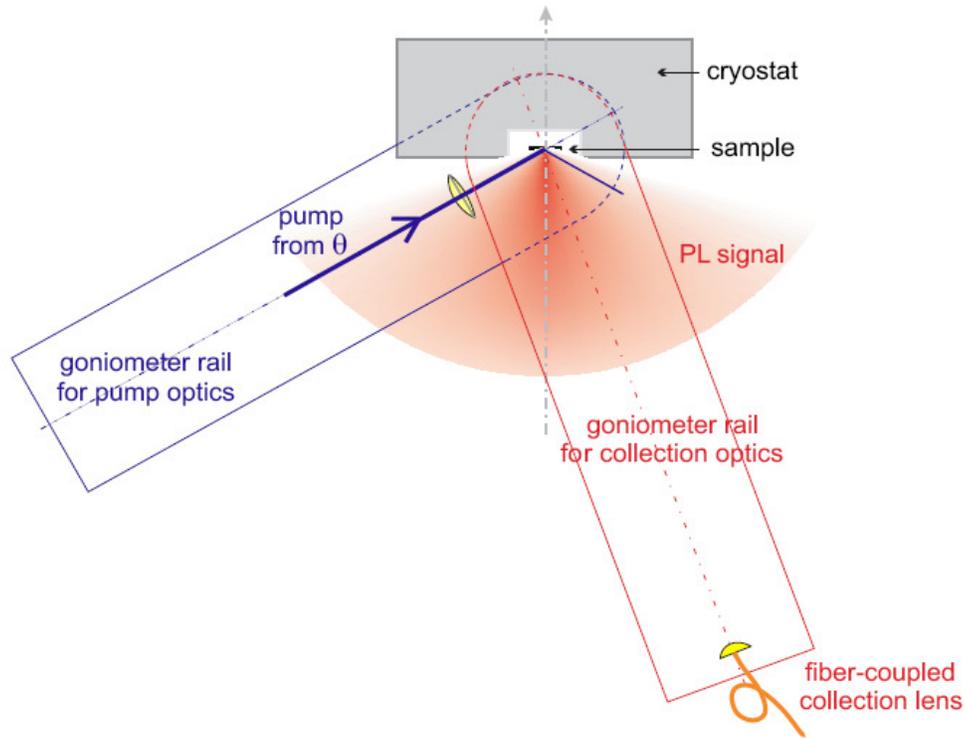


Figure 1: Experimental setup for photoluminescence measurements [1]

1.2 Theory

It is this signal that is of interest here: it consists of photons emitted from the decay of polaritons within the semiconductor. The wavelength of this signal will correspond to the energy of the polaritons while, less obviously, the collection angle will correspond to their momentum state. To develop a qualitative understanding of why this is, it is first necessary to examine what is happening within the semiconductor. The sample itself consists of a cavity layer with index of refraction n_c sandwiched between two distributed Bragg reflectors (DBRs). A DBR is a structure formed by alternating layers of material with different indices of refraction, resulting in very high reflectivity for a range of wavelengths. This occurs due to the constructive interference of many partially reflected waves whose wavelengths are roughly four times the optical thickness of the layers. Since the DBR material has a wider bandgap than the semiconductor material in

between, a quantum well (potential well with discrete energy levels) is formed with a thickness on the order of the Bohr radius of the exciton. This constricts the motion of the excitons to the plane of the quantum well, which will allow them to couple strongly with photons in the cavity.

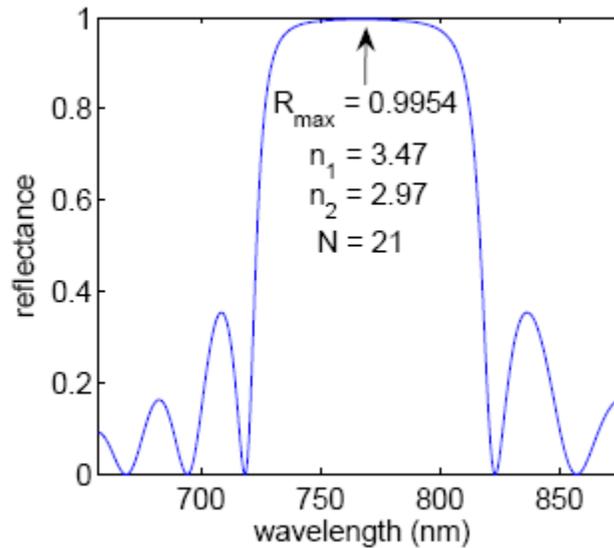


Figure 2: Reflection spectrum of a DBR with alternating indices of refraction of 3.47 and 2.97 and a central wavelength of $\lambda_c=767.3\text{nm}$. There are N layers with a refractive index of 2.97 and N+1 layers with a refractive index of 3.47 [1].

Though the DBRs have very high reflectance for the wavelengths used in the experiment, some light will find its way to the cavity layer where it will be partially contained. The cavity quality factor, defined as the average number of round trips a photon makes within the cavity before escaping, is typically on the order of 1000. The photon field will therefore be confined within the z-direction (as defined in the figure below) but not in the plane of the cavity. Since the DBR consists of two materials with different indices of refraction alternating, the overall effect is for the incident light to be refracted as though it were going from a vacuum (above the DBR) to a refractive index n_c (the cavity):

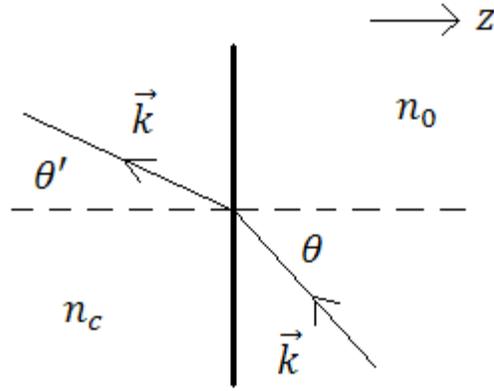


Figure 3: Effective refraction of incident light that reaches the cavity.

While the light is confined within the cavity, photons with in-plane wavenumber k_{\parallel} will couple with electron-hole pairs that have the same in-plane wavenumber. The wavenumber k_{\perp} , however, will be fixed at a constant value of $2\pi n_c/\lambda_c$ where λ_c is the DBR central wavelength. The energy dispersion of the cavity will be given by^[1]

$$E_{cav} = \frac{\hbar c}{n_c} \sqrt{k_{\perp}^2 + k_{\parallel}^2}.$$

By the same reasoning as before, light leaving the sample from the cavity will effectively follow a path shown in figure 4. From Snell's law, we see that

$$n_c \sin \theta = \sin \theta'$$

and therefore

$$k_{\parallel} = \frac{2\pi n_c}{\lambda_c} \tan \theta = \frac{2\pi n_c}{\lambda_c} \tan \left(\sin^{-1} \left(\frac{\sin \theta'}{n_c} \right) \right).$$

Using the approximation $k_{\parallel} \ll k_{\perp}$ and the small angle approximation for θ' , we find that

$$\frac{k_{\parallel}}{k_{\perp}} = \tan \theta \approx \theta$$

and

$$k_{\parallel} \approx \frac{2\pi n_c}{\lambda_c} \theta = \frac{2\pi n_c}{\lambda_c} \sin^{-1} \left(\frac{\sin \theta'}{n_c} \right) \approx \frac{2\pi}{\lambda_c} \theta'.$$

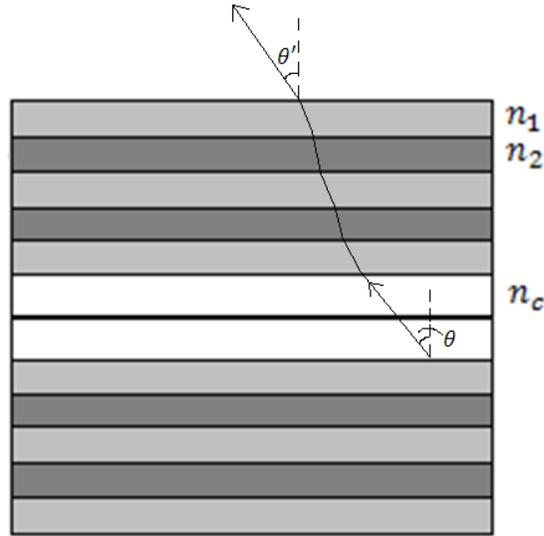


Figure 4: Illustration of the sample where the gray areas represent the alternating DBR materials, the white area represents the cavity layer, and the black line is a quantum well.

Since each photon will couple with an exciton with this same in-plane wavenumber, this demonstrates that the angle at which the photon is emitted from the sample will correspond to the momentum state of the polaritons.

While the photoluminescence measurements are taken at varying angles, they are also taken at varying power levels for the pump beam. These are the measurements that are to be automated.

In order to do this, a method of automatically adjusting the power of the pump beam and recording the data from the spectrometer is needed.

2 Automation Design

2.1 The Laser Power Controller

The power will be varied throughout the experiments with the use of a laser power controller (LPC) from Brockton Electro-Optics Corp. One of the primary components of the LPC is a liquid crystal modulator, pictured below. A liquid crystal is composed of elongated organic molecules that may flow but also possess an orientational order. There are various types of liquid crystals but only what are known as nematic liquid crystals will be discussed here. The molecules of such liquid crystals are oriented along the same direction but their positions are completely random. Light polarized parallel to the orientation of these molecules sees a higher index of refraction than light polarized perpendicular to them. Additionally, the orientation of the molecules can be rotated by the application of an electric field. Electric dipoles are induced and the electric forces exert torques on the molecules, minimizing the electrostatic energy. It is these properties that make liquid crystals useful in optical devices.

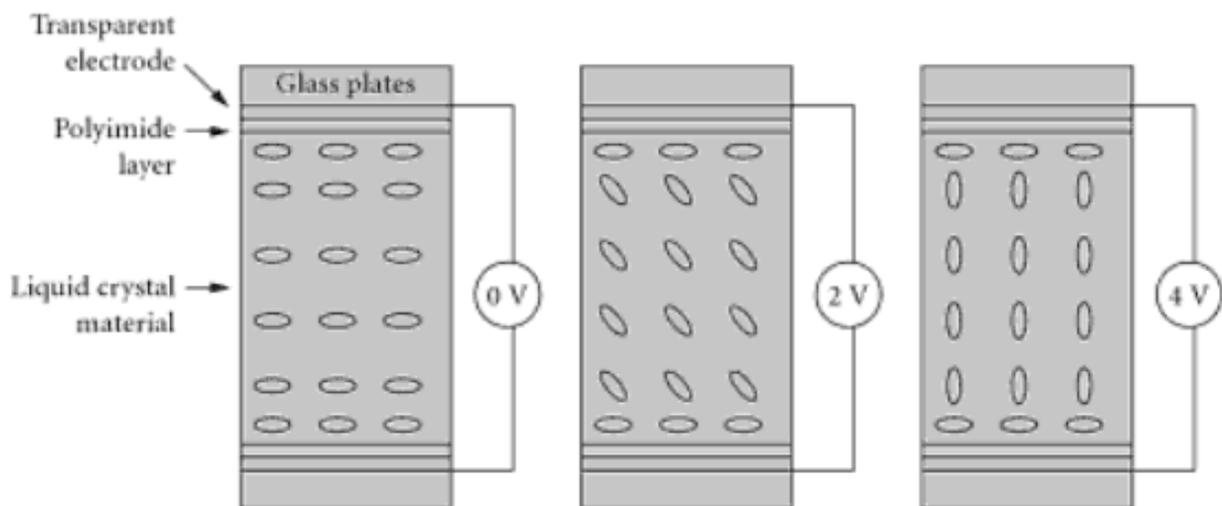


Figure 5: Liquid crystals with different applied voltages [3]

A nematic liquid crystal can be twisted by placing it between two glass plates and rubbing it so that orientation of the molecules rotates about the normal to the plates. The figure below shows this twist by taking cross sections of the material perpendicular to the axis of the twist.

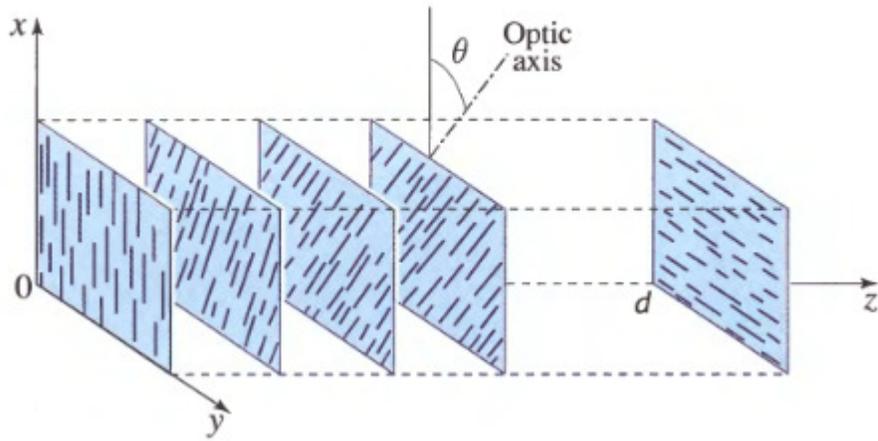


Figure 6: Twisted nematic crystal

If the angle at which the orientation of the molecules is rotated varies linearly with z such that

$$\theta = \alpha z,$$

then the phase-retardation per unit length will be given by

$$\beta = (n_e - n_o)k_0$$

where α is known as the twist coefficient, n_e is the extraordinary index of refraction (along the optical axis), n_o is the ordinary index of refraction, and k_0 is the wavenumber of the incident light in a vacuum. If $\beta \gg \alpha$ (so that the phase is retarded through many cycles before θ changes significantly), then the Jones matrix of such an optical device of width d will be given by^[4]

$$\mathbf{T} = \mathbf{R}(-\alpha d) \begin{bmatrix} \exp\left(-\frac{i\beta d}{2}\right) & 0 \\ 0 & \exp\left(\frac{i\beta d}{2}\right) \end{bmatrix}.$$

In other words, if the incident light is linearly polarized along the x -direction, then the device will act as a polarization rotator with rotation angle αd . By applying an electric field along the

axis of twist, it is possible to impose an additional twist to the nematic liquid crystal. If the field is sufficiently strong, it can become completely untwisted. With the addition of a polarizer at the end, it can be used as a voltage controlled intensity modulator:

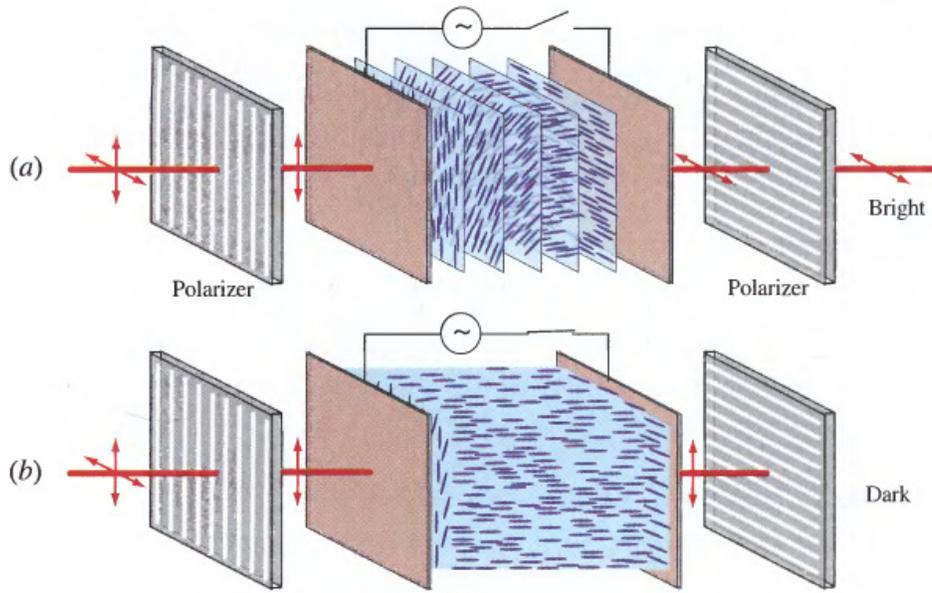


Figure 7: a) No electric field present, light is fully transmitted. b) Sufficiently strong electric fields can effectively undo the twist of the nematic liquid crystal so that almost no light is transmitted. At intermediate rotations, the light is partially transmitted [4].

When the electric field is removed, the molecules realign themselves to their original position due to the orientation of the layers near the surface (which do not lose their twisted structure).

The liquid crystal effectively has a “memory,” allowing it to be reused consistently.

This is the method through which the LPC modulates incident laser light. As seen in the diagram below, vertically polarized light is sent through the liquid crystal modulator (the optional input polarizer is used if the beam is not vertically polarized) and the output polarizer, modulating the light by a factor that depends on the voltage applied to the liquid crystal. The beam-splitter transmits 98% of the incident light (which then passes through the output aperture) and reflects 2% toward a precision photodiode. The temperature of this diode is kept constant at 33 ± 0.05

degrees Celsius in order to eliminate error due to temperature variations. The photodiode current is sent to the microprocessor which then computes the power of the output light using this information along with the stored values of the beam-splitter efficiency and the photodiode responsivity. Based on the power, the microprocessor can vary the voltage applied to the liquid crystal until the desired power is reached (a neutral density filter can be switched on for lasers over 200mW to prevent damage).

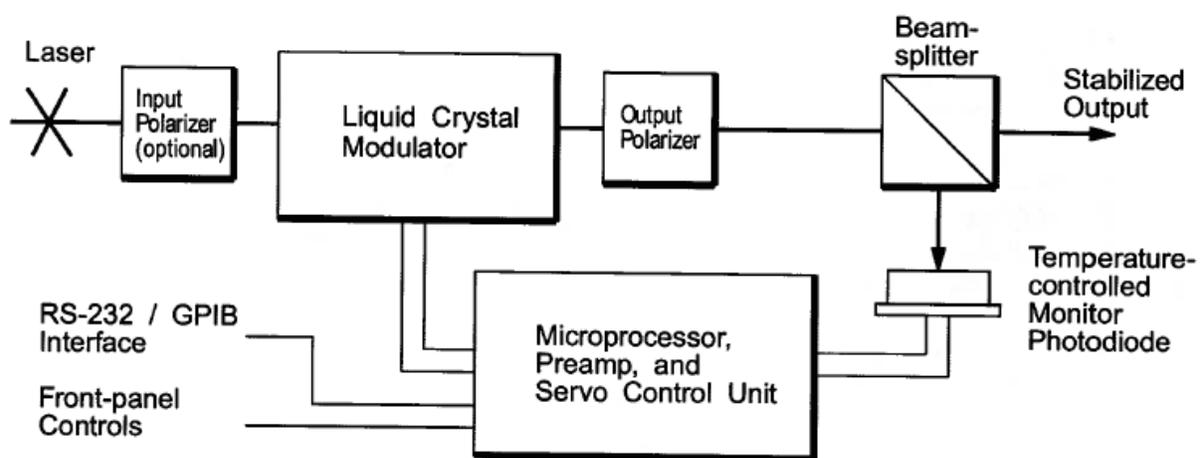


Figure 8: Diagram of the LPC [2].

The LPC has two modes: constant power and constant transmission. In constant transmission mode, the LPC keeps the output power at a fixed percentage of the input power (the microprocessor computes the output power and adjusts the applied voltage twice per second). Constant power mode, however, is the mode that will be used in the experiments. Here, the output power is calculated and the applied voltage is adjusted to keep it at the desired value (this is repeated several thousand times per second). The effectiveness of this is shown in the figure below, a plot of the power of a 2mW HeNe laser versus time. The root mean square deviation is 0.79% without stabilization and 0.02% with stabilization.

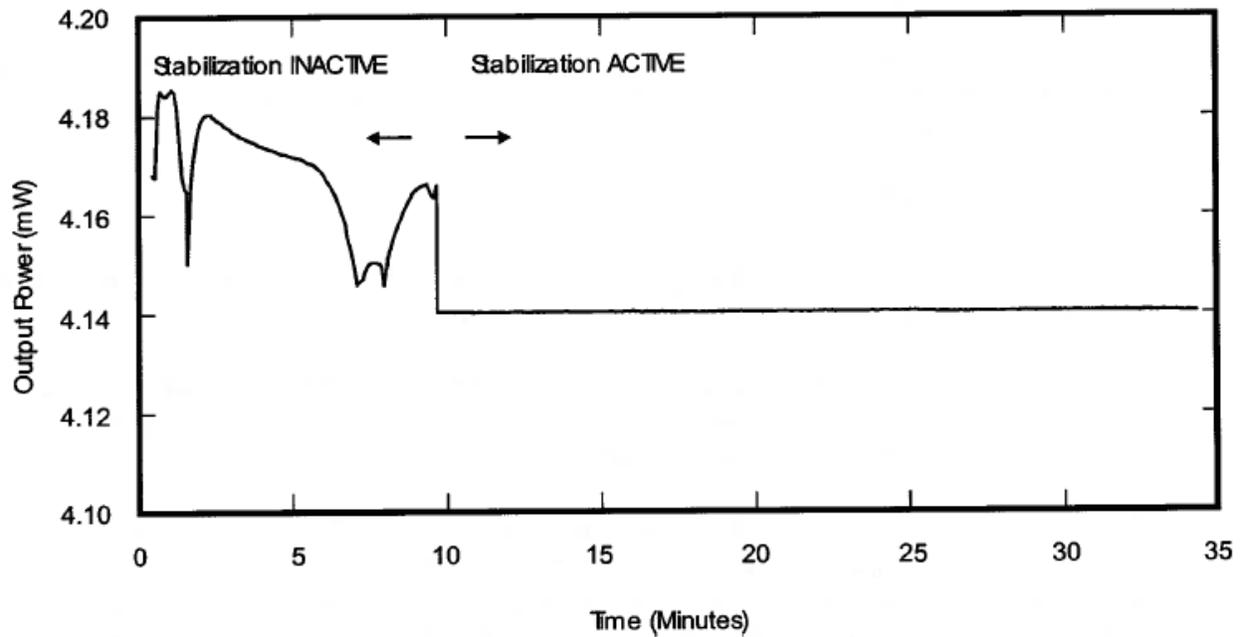


Figure 9: Plot of power of 2mW HeNe laser before and after stabilization [2]

Finally, the LPC is connected to an electronics module that displays information such as the mode, output power, set wavelength, and transmission on its front panel. These values can be adjusted from the front panel but the main interest is in controlling them from a computer. This is done by connecting the electronics module to a computer using a GPIB and communicating with it using LabVIEW.

2.2 The LabVIEW Program

LabVIEW is a visual programming language commonly used in the automation of laboratory setups. It consists of a front panel, where controls (input) and indicators (output) are displayed, and a block diagram, where the user writes the actual code. This code is written primarily with graphical icons, though text based code can be used as well.

Since the experiments to be done will require measurements to be taken at various constant powers, a program that will tell the LPC to vary the output beam power is needed. Below is a

2.3 The WinSpec Program

Data from the spectrometer including plots of intensity versus wavelength need to be recorded at various power levels. This is achieved through the use of WinSpec, a program by Princeton Instruments designed for the spectrometer made by the same company. One feature of particular interest in the automation of measurements is the ability to take and save measurements over a set period of time, demonstrated in figure 11. Ten spectra of a 765nm were taken with a 0.5 second exposure. A file for each individual spectrum was automatically saved. This would allow the photoluminescent measurements to be automatically taken while the power control program goes through a range of powers.

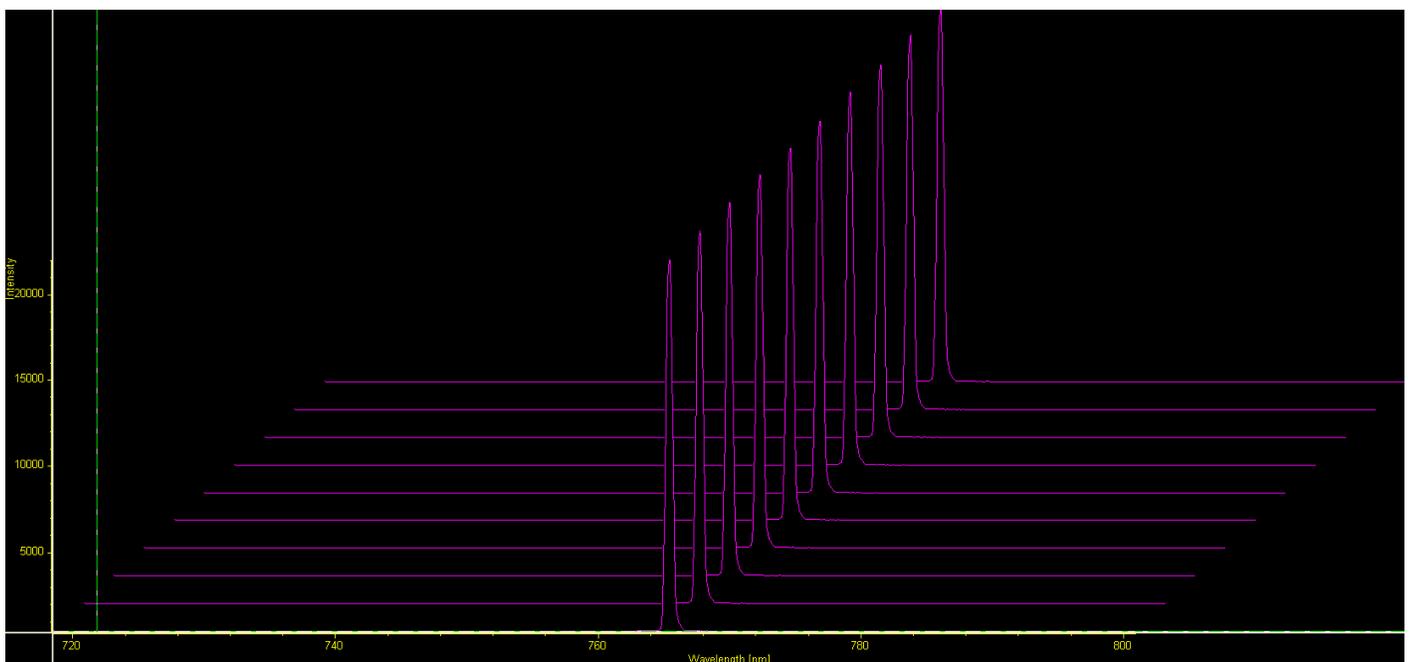


Figure 11: Ten spectra of a 765nm laser (intensity vs. wavelength), demonstrating the use of WinSpec in automation.

2.4 The Power Meter

It will also be necessary to ensure that the output beam power is truly at the level specified by the LPC. To do this, we make use of a power meter from Thorlabs along with LabVIEW programs

available for it. The output beam from the LPC is sent through a partial mirror with known reflection and transmission coefficients. The reflected beam is sent to the power meter, which sends data to the computer. The LabVIEW program allows the user to read the current recorded power level and, with a simple modification to the code, the beam power used in measurements can be calculated from the reflection and transmission coefficient (similar to the method used in the LPC). This data can then be used in conjunction with the power meter program to tell the LPC to adjust the power until the value read from the power meter reaches a specified value.

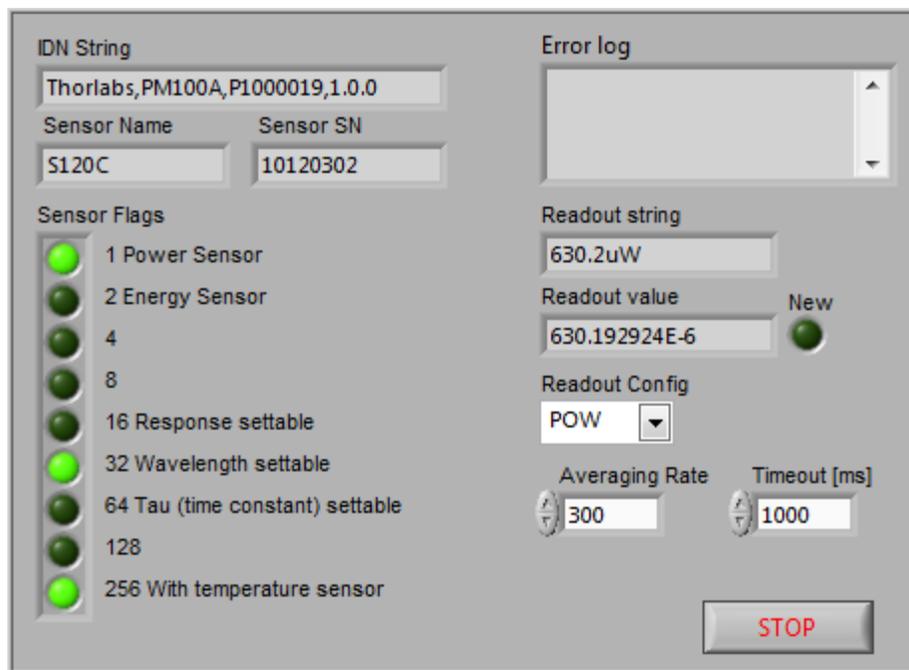


Figure 12: Front panel of the LabVIEW program used with the power meter. Here, it's reading a power of about 0.63mW due to background light in the room.

2.5 Alternative Method

Due to difficulties in communicating with the LPC, an alternative method for controlling the laser power is proposed here. By using a neutral density filter with a universal rotator (motorized

mount) from Newport (figure 13), the laser power can be attenuated with a precision that depends on the input power. The motor in the universal rotator has a resolution of one degree and a typical neutral density filter from Newport has an optical density gradient that varies from 0.05 to 2.0 over 270 degrees. Optical density for an input beam of intensity I_0 and an output beam of intensity I is given by

$$A_\lambda = \log_{10} \left(\frac{I_0}{I} \right).$$

Assuming a linear increase in optical density, this suggests that, for an input beam with an intensity of 50mW, this device would be able to adjust the power to within 1mW. Whether or not this is sufficient is dependent on the experiment being performed.



Figure 13: Universal rotator with neutral density filter.

Finally, the motor is fully compatible with LabVIEW and has pre-written programs available for it. With some small modifications, a program could be used to rotate the filter until a specified power is reached (determined from the power meter), wait a set amount of time, and repeat.

3 Conclusion

Though the LPC itself has been successful at adjusting the power of the input beam when controlled through the front panel, further work is needed to successfully communicate with the LPC so that it can be controlled by a computer. Slight alterations to the circuitry can be made to allow for communication through an RS-232 cable. If such attempts also prove unsuccessful, then it may be necessary to return it to the manufacturer to have it checked. If this problem can be fixed, then a test of the methods to automatically take measurements can be done and any necessary adjustments can be made. Additionally, the programs used could be modified to allow for measurements in other experiments where a varying power level is needed.

4 References

[1] H. Deng, *Dynamic condensation of semiconductor microcavity polaritons*, thesis (Ph.D.), Stanford University. (2006)

[2] *Laser Power Controller User's Manual*, Brockton Electro-Optics Corp (2006)

[3] Bass. 2009. *Handbook of Optics*. 3rd Edition. McGraw-Hill Professional

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