

Construction of a Wavelength Tunable Ti:Sapphire Laser for
GaAs Photocathode Evaluation

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by

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Abstract

GaAs photocathodes are used to produce electron beams for all of the nuclear experiments performed at the Thomas Jefferson National Accelerator Facility, half of these experiments require polarized electrons. Qualifying these GaAs photocathodes is essential to providing a beam of sufficient quality for these experiments. A Titanium Sapphire laser is being constructed to measure the quantum efficiency of a GaAs photocathode as a function of laser wavelength. Several different laser cavity geometries are being tested and the one with the most output power and the broadest wavelength tuning range will be chosen for future use in evaluating GaAs photocathodes.

Introduction

All experiments performed at Jefferson Lab require an electron beam, about half require a polarized electron beam. There are several ways to produce polarized electrons; the Fano effect in Rb and Cs, atomic beams of Li and of He, field emission from EuS, and photoemission from GaAs. Of these only the Fano effect, GaAs photoemission and Lithium beams have been used in electron accelerators [1]. The perfect source of polarized electrons would have four characteristics: (1) high polarization (>90%); (2) ability to optically reverse the polarization, rather than mechanically or magnetically; (3) good transverse and longitudinal emittance; and (4) long lifetime. Of the sources mentioned above, the only two that have potential to meet these objectives are GaAs photoemission and an atomic He beam. The beam of atomic He has most of the preferred characteristics, but can only provide relatively low currents. Bulk GaAs produces a relatively low polarization (~40%) but advances in crystal growing techniques have created samples capable of producing electron beams with polarizations as high as 86%. The biggest drawback associated with GaAs photoemission is the requirement of maintaining the GaAs photocathode in ultra high vacuum (UHV) [2].

To ensure proper photocathode operation, the Source group at Jefferson Lab must characterize samples of the GaAs crystal. The plot of quantum efficiency (QE) as a function of wavelength of incident light provides a quantitative measure of the quality of a photocathode. The quantum efficiency of a photocathode is the ratio of emitted electrons to incident photons. The source currently used to supply this incident light is a white light monochromator, but this source is undesirably dim. A tunable titanium-sapphire laser is a much better source of incident light and is the subject of this project.

Titanium-doped sapphire is one of the most commonly used crystals for wavelength tunable lasers today. The Titanium-sapphire laser was developed by Peter Moulton in the early 1980s and first reported by him in 1986 [3]. Ti:Sapphire lasers are solid-state and optically pumped with a broad tunable range that makes them useful for many projects. It offers a useful alternative to dye lasers, which wear out relatively quickly and often contain dangerous chemicals. A joint program between the NASA Langley Research Center and Union Carbide helped create Ti:Sapphire crystals of increasingly greater quality in the early 1990s, which NASA used to measure Tropospheric water vapor and aerosol profiles [3]. The advent of diode-pumped Nd:YAG lasers in the 1990s also made them more useful and even easier to use by eliminating the need for temperamental argon-ion lasers as pump lasers.

The purpose of this project is to build a wavelength tunable light-source for measuring the quantum efficiency of GaAs photocathodes. A Ti:Sapphire laser has been determined to be the best light source, but the best geometry for the laser cavity must be determined by trial and error. The best setup of the Ti:Sapphire laser will be the one with the broadest tuning range and highest output power.

Theory

A laser is composed of a gain medium and an optical resonator. For this project, the gain medium is a solid Ti:Sapphire crystal. Amplification of light, or gain, occurs in only one plane within the Ti:Sapphire crystal. As a result, the light from a Ti:Sapphire laser is polarized in one plane.

Ti:Sapphire crystals are typically sold with “Brewster-cut faces.” This means that the crystal faces are cut at an angle relative to the long axis of the crystal. With such faces light incident on the crystal will experience no reflection loss, something that is very desirable when optimizing the power of a laser.

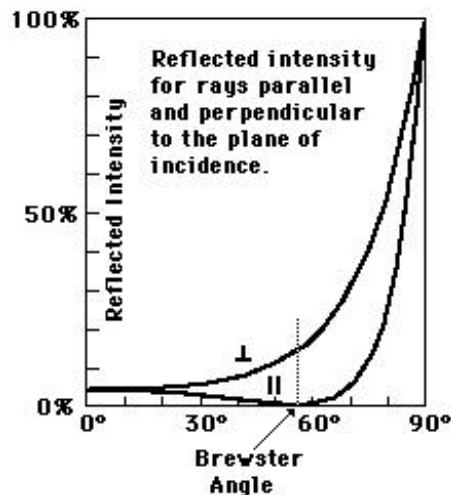


Figure 1: Graph of Reflected Intensity versus Angle of Incident Light [4].

Although Brewster-cut faces solve the problem of loss due to reflection, they create a big problem in the form of astigmatism. Astigmatism is defined as a defect in an optical system in which light rays that originate at the same location fail to converge at a single focal point. More simply, astigmatism is when there is a different focus in two planes. Herwig W. Kogelnick discovered that introducing a folded cavity could

compensate for this astigmatism [5]. A folded cavity, which uses mirrors to reflect light in two dimensions rather than one, is more complicated than a straight one, but is a necessity if one wishes to minimize the effects of astigmatism and have a highly concentrated focal point. The optimal fold angle for the cavity to reduce astigmatism is found according to equation (1);

$$2 * N * t = R * \sin(\mathbf{q}) * \tan(\mathbf{q}) \quad (1)$$

where R is the mirror's radius of curvature (10 cm), t is the thickness of the Ti:Sapphire crystal (2 cm), and N is given by equation (2);

$$\frac{(n^2 - 1) * \sqrt{n^2 + 1}}{n^4} = N \quad (2)$$

where n is the index of refraction of the crystal, which is 1.67. The folded cavity has the added benefits of creating a long cavity in a relatively small area and allows for the easy introduction of a wavelength tuner in the cavity.

An important measure of how well the system is lasing is the size of the waist radius of the pump beam. In an efficient set up the waist radius of the pump laser will be very nearly equal to the size of the waist of the Ti:Sapphire laser. The waist of the pumping laser, w_{pump} , can be found using equation (3);

$$w_{pump} = 1.22 * \frac{I * f}{d} \quad (3)$$

The waist radius of the beam can be taken using equation (4);

$$\frac{2pw_0^2}{I} \approx \frac{f^2}{d_2} \quad (4)$$

where f is the focal length of the pump focusing lens and d is the size of the collimated pump beam before the focusing lens.

To vary the laser's wavelength, two methods were utilized; a prism and a birefringent tuning filter. The prism works on the basis of wavelength selective beam steering. The birefringent tuning filter (BTF) works by selective rotation of different wavelengths out of plane. Only wavelengths that remain in plane with continue lasing and not experience loss because of the nature of the Brewster angle. The BTF is much easier to insert into the laser cavity than the prism but seems to create a larger power loss.

Experimental Setup

The desired tuning range of the Ti:Sapphire laser is about 100 nm, with a output power of at least 10 mW over that entire range. Once each of the separate laser cavities was built and tweaked to give its maximum output power, the output power as a function of wavelength was measured to show the tuning range of each laser. In addition, tests were done on the first laser geometry to determine whether it would be better to use a 5% transmission or a 2% transmission output coupler.

The optic mounts used in each of the laser cavities are from Thorlabs. All the lenses/mirrors used are from Spectra-physics, as is the three-plate Birefringent Tuning Filter. The quick power meter used to tweak each of the different lasers to their maximum power output is a Newport Optical Power Meter Model 1830-C. The optical multimeter is an ILX Lightwave OMM-6810B Optical Multimeter.

Before any work was done with lasers, I took a Laser Safety Course required by Jefferson Lab. Interlock systems and safety goggles were used at all times.

Data

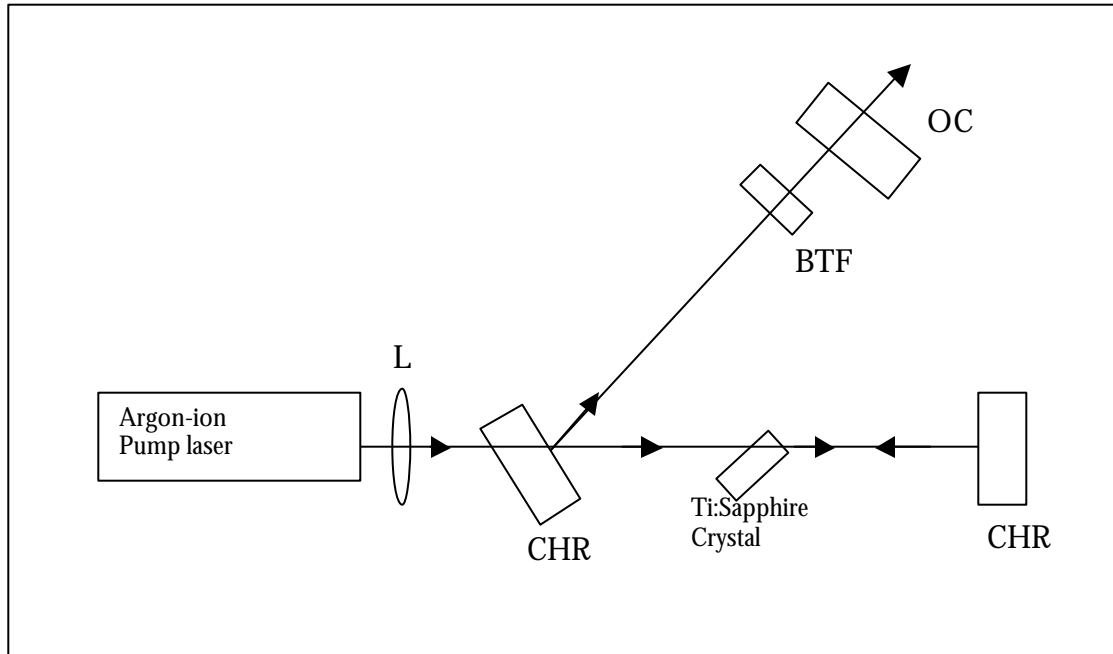


Figure 2: Schematic of 1st Ti:Sapphire laser geometry. This cavity is pumped with an Argon-ion laser. It contains three mirrors and one fold. OC, Output Coupler; CHR, Curved High Reflectivity Mirror; BTF, Birefringent Tuning Filter; L, Lens.

The first laser geometry, a simple 3-mirror resonator pumped by an Argon-ion laser is shown in figure 2. Mirrors labeled HR are both reflectivity 100% at 780 nm with a radius of curvature of 10 cm. The optic labeled BTF is a Birefringent Tuning Filter, which was used to tune the wavelength. The component labeled OC is the output coupler. Data was collected with output couplers with 2% transmission (figure 3) and 5% transmission (figure 4). The 5% transmission output coupler produced better results and was subsequently used for collecting output power versus wavelength data in each of the different laser geometries. This laser was pumped using an Argon-ion laser.

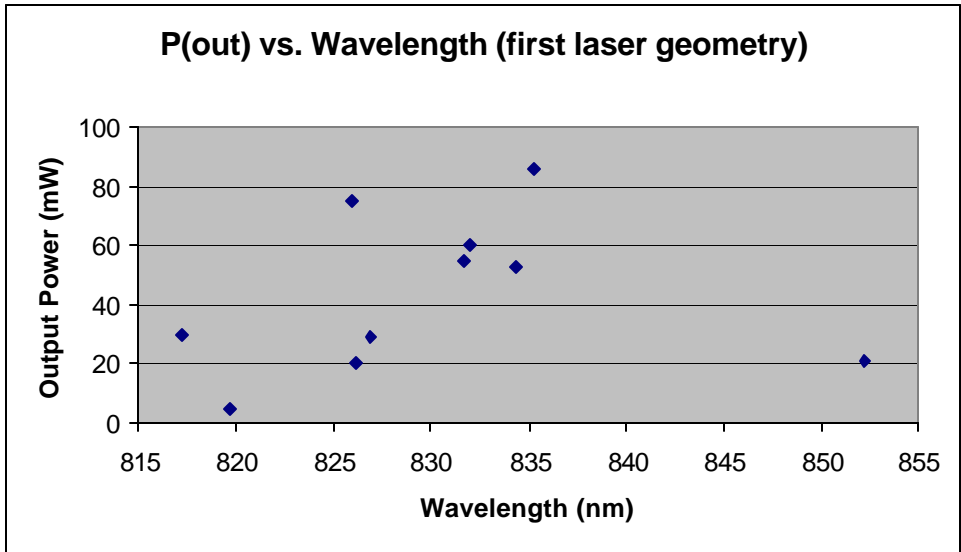


Figure 3: Graph of output power vs. wavelength in the first laser geometry.

This geometry was relatively easy to construct but produced rather poor results, only a 35 nm tuning range and output power from 20 to 86 mW.

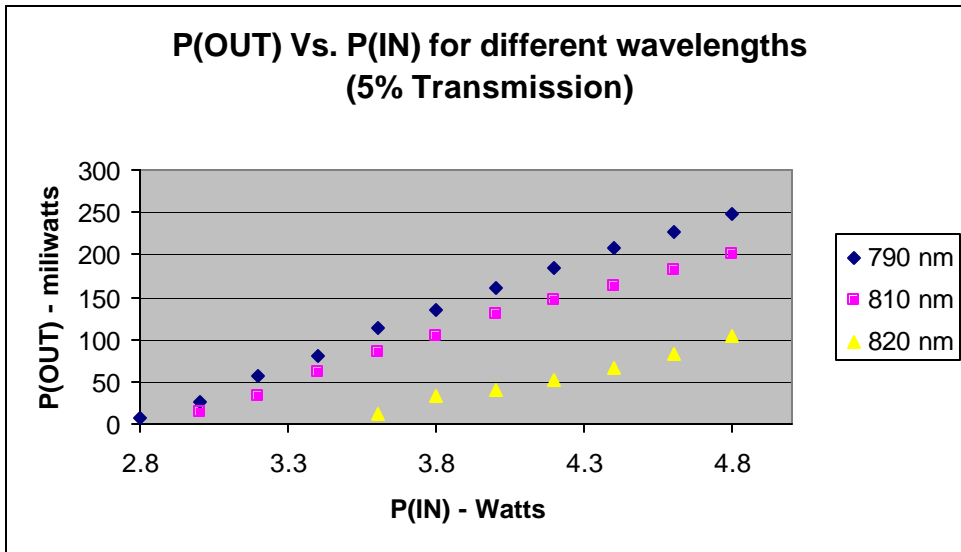


Figure 4: Graph of the output power of the Ti:Sapphire laser vs. the power of the pump laser using a 5% transmission output coupler.

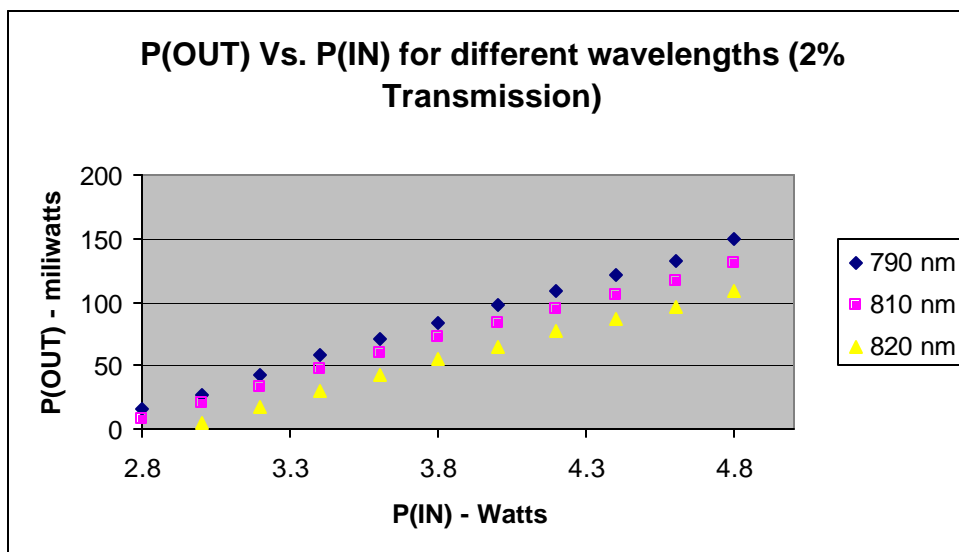


Figure 5: Graph of the output power of the Ti:Sapphire laser vs. the power of the pump laser using a 2% transmission output coupler.

By observing the results of the input power versus output power for different wavelengths tests with the 2% transmission output coupler (figure 5) and the 5% transmission output coupler (figure 4), we can clearly see that as input power increases the 5% transmission output coupler gives better output power.

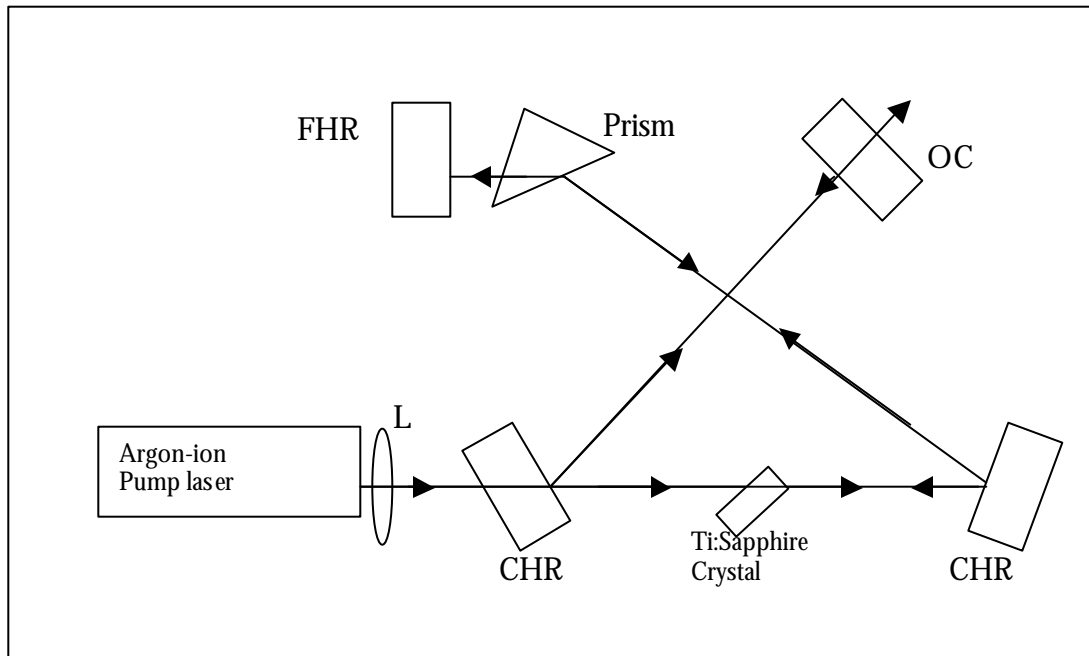


Figure 6: Schematic of 2nd Ti:Sapphire laser geometry. This laser is pumped with an Argon-ion laser. It contains three mirrors and two folds. OC, Output Coupler; CHR, Curved High Reflectivity Mirror; FHR, Flat High Reflectivity Mirror; L, Lens.

A slight variation on the first laser cavity, a double folded standing wave resonator with a prism as a wavelength selector is shown in figure 6. The optical components labeled CHR and OC are the same as in Figure 2. The component labeled FHR is a flat mirror behind a prism. The pumping laser for this resonator is still the Argon-ion blue/green laser, which has a maximum output of 5 watts of laser light.

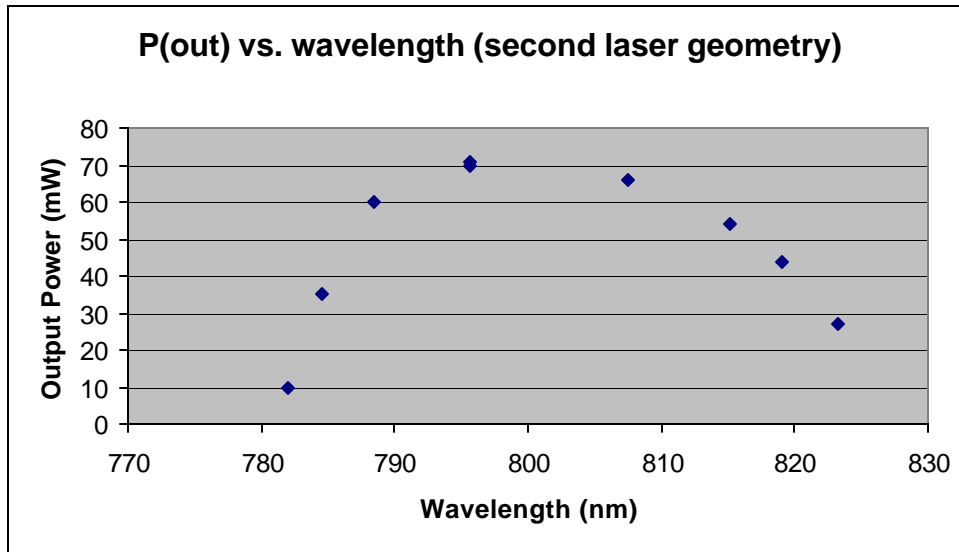


Figure 7: Graph of output power vs. wavelength in the second laser geometry.

The tuning range for this setup was 41 nm with power ranging from 10 to 71 mW. The smoother curve found in figure 7 compared to figure 3 is partially attributed to using a prism rather than a BTF to vary the wavelength; more regular intervals between data points were easier to produce.

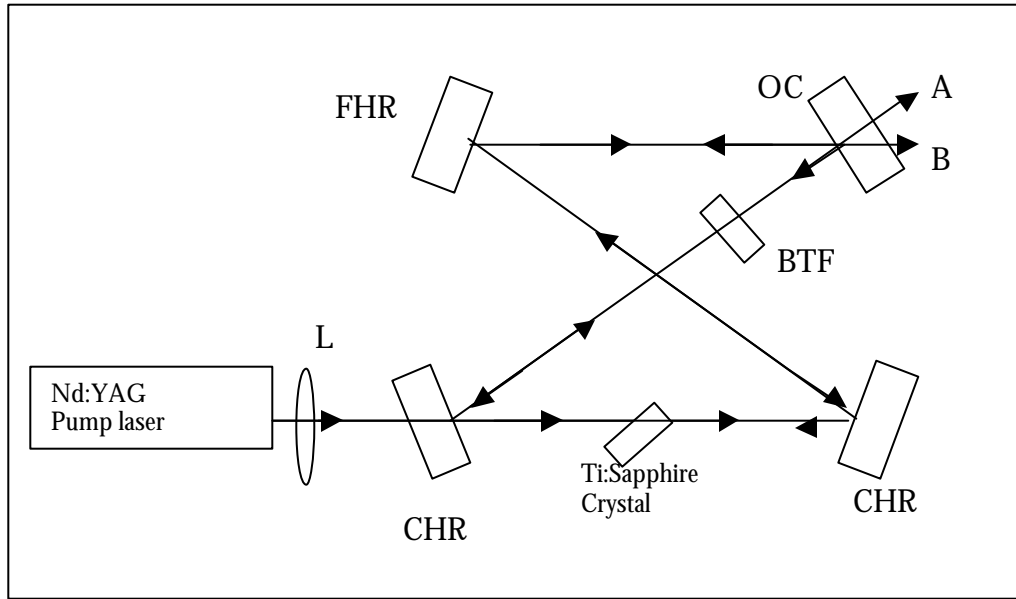


Figure 8: Schematic of 3rd Ti:Sapphire laser geometry. This cavity is pumped by a Nd:YAG Laser. It contains 4 mirrors and 4 folds. OC, Output Coupler; CHR, Curved High Reflectivity Mirror; FHR, Flat High Reflectivity Mirror; A, output beam A; B, output beam B; L, Lens; BTF, Birefringent Tuning Filter.

Figure 8 is a radical jump from the previous laser geometries. This 4-mirror reversing cavity has two output beams. All the mirrors are 100% reflectivity at 780 nm except for the output coupler, which uses the 5% transmission lens chosen in the first configuration. In the initial path, the light comes out the Ti:Sapphire crystal then around the mirrors and comes out the output coupler to form output beam B. The light which is reflected by the output coupler goes backwards through the system then out the output coupler in the form of beam A. The sum of beams A and B is the total output power of the laser. This system can be forced to only allow light out in the form of one of the two beams with the help of an optical diode, unfortunately we did not have this device at our disposal. This system used a frequency doubled Nd:YAG laser to pump the Ti:Sapphire laser. This laser can produce up to 10 watts of laser light, which allows us to slightly

extend the tuning range and increase the output power simply by increasing the pump laser power.

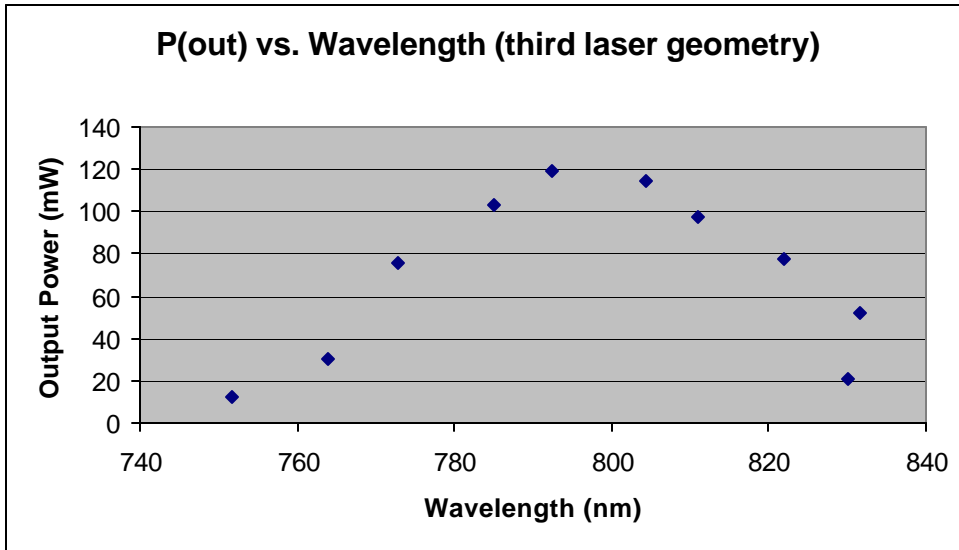


Figure 9: Graph of output power vs. wavelength in the third laser geometry.

We were able to get a tuning range of 80 nm with this laser. Output power ranging from 10 to 120 mW was obtained using the Nd:YAG laser set to provide 8 watts of pump power.

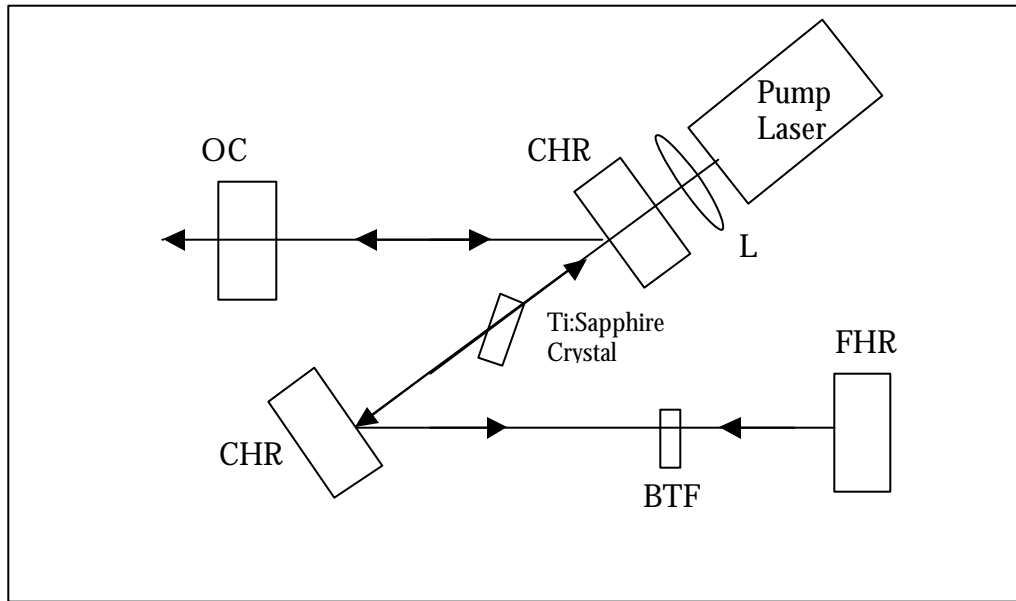


Figure 10: Schematic of 4th Ti:Sapphire laser geometry. This cavity is pumped by an Nd:YAG laser. It contains three mirrors and two folds. OC, Output Coupler; CHR, Curved High Reflectivity Mirror; FHR, Flat High Reflectivity Mirror; L, Lens; BTF, Birefringent Tuning Filter.

Figure 10 shows the z-style double folded standing wave cavity. Like the previous configuration, this one is also pumped with a frequency doubled Nd:YAG laser. All the mirrors are 100% reflectivity at 780 nm except for the output coupler, which uses the 5% transmission lens chosen in the first configuration.

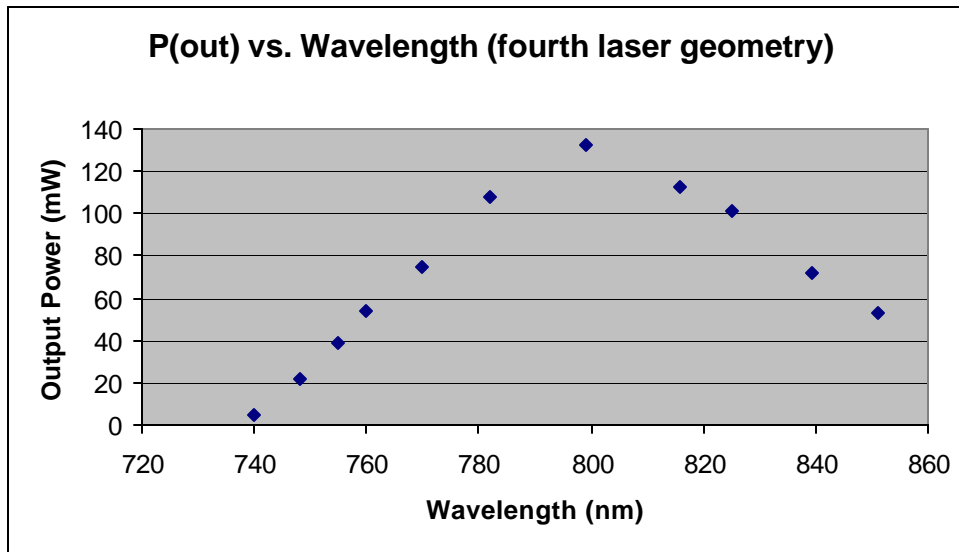


Figure 11: Graph of output power vs. wavelength in the fourth laser geometry.

The tuning range for this setup ran from 740 to 850 nm with power outputs ranging from 5 mW to 132 mW. The Nd:YAG pump laser set to provide 5 watts of pump power.

The laser geometries used in this project are all rather bulky, getting the output beam to the GaAs photocathode would be difficult without the use of a fiber optic cable. By measuring the power before and after the beam was coupled into the fiber it was observed that the beam coming through the fiber had 40% of the power it had before the coupling.

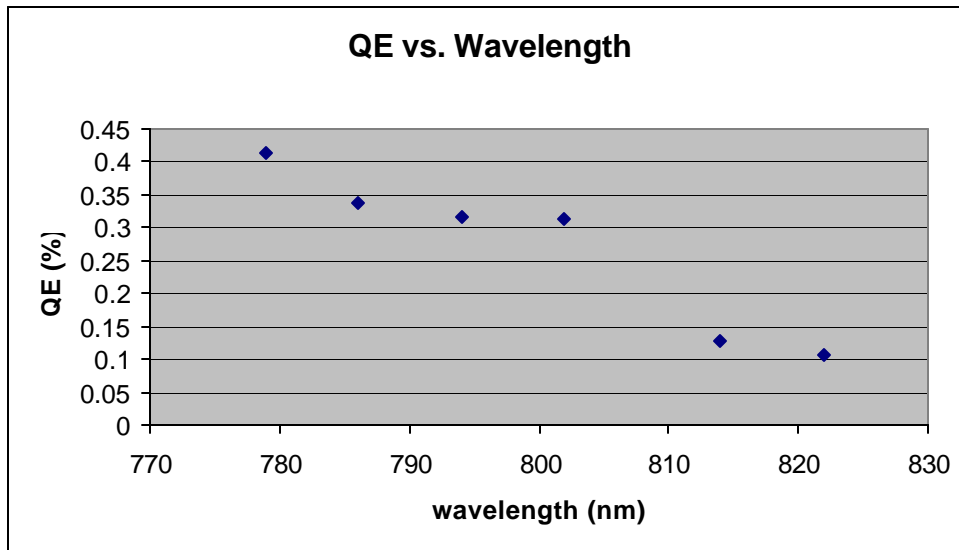


Figure 12: Graph of quantum efficiency of the photocathode vs. wavelength of incident light.

A plot of the quantum efficiency of the GaAs photocathode versus the wavelength of incident light is shown in figure 12. The incident light used to collect this data is produced by the Ti:Sapphire laser. More data will be collected using the Ti:Sapphire laser to further test the quantum efficiency of this and other GaAs photocathodes.

Conclusions

The purpose of this project was to build a light source sufficient to test the quantum efficiency of a GaAs photocathode. This light source will be required to deliver a range of wavelengths from 750 to 850 nm with sufficient power (~10 mW). Of the four laser geometries tried, the z-style double folded standing wave cavity was the only one to complete these requirements.

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