A High Power 399 nm Laser for Laser Cooling Ytterbium Atoms

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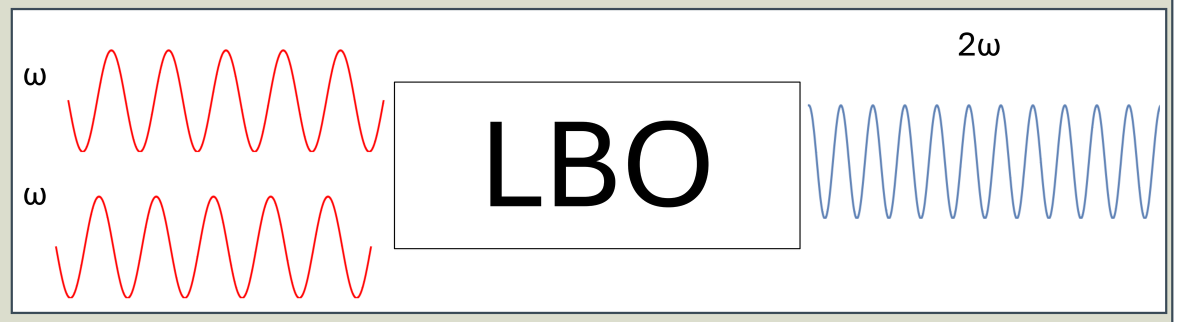
Objective

The overarching goal of the lab is to harness Ytterbium (Yb) atoms as qubits in a quantum computer. To do this, these atoms must be arranged into arrays using laser cooling and trapping. The processes of laser cooling and trapping of Yb atoms require a high-power 399 nm wavelength laser. Here we create our own taking advantage of the phenomenon of second harmonic generation (SHG) to convert a 798 nm wavelength laser to a 399 nm one.



SHG or frequency doubling is a nonlinear response of an electric field which converts 2 photons of frequency ω to one photon of frequency 2ω. We use a nonlinear crystal, Lithium Triborate (LBO), to double the frequency of a 798 nm laser.

$$P(t) = \epsilon_0(\chi^{(1)}E(t) + \chi^{(2)}E^2(t) + \cdots)$$

SHG nonlinear factor in electric field response ↑

Approach

The percentage of light which undergoes frequency doubling is very low so, to convert our 798 nm wavelength laser to a 399 nm laser of significant power we place our LBO crystal in a bowtie cavity. This allows the 399nm light generated to build up as the laser completes many passes around the cavity.

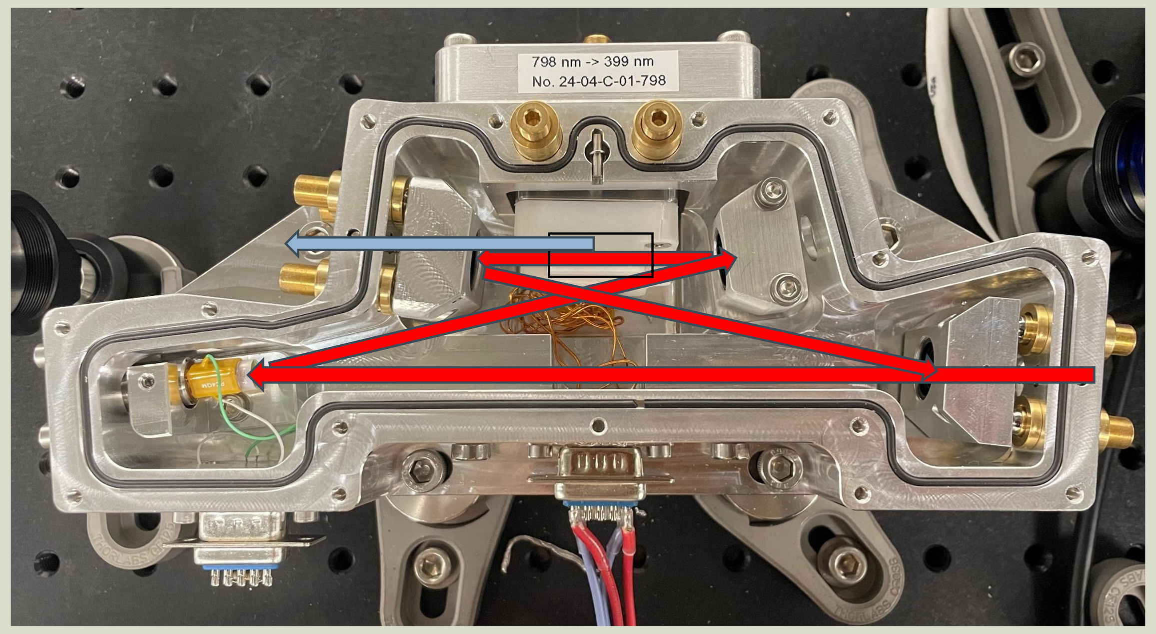
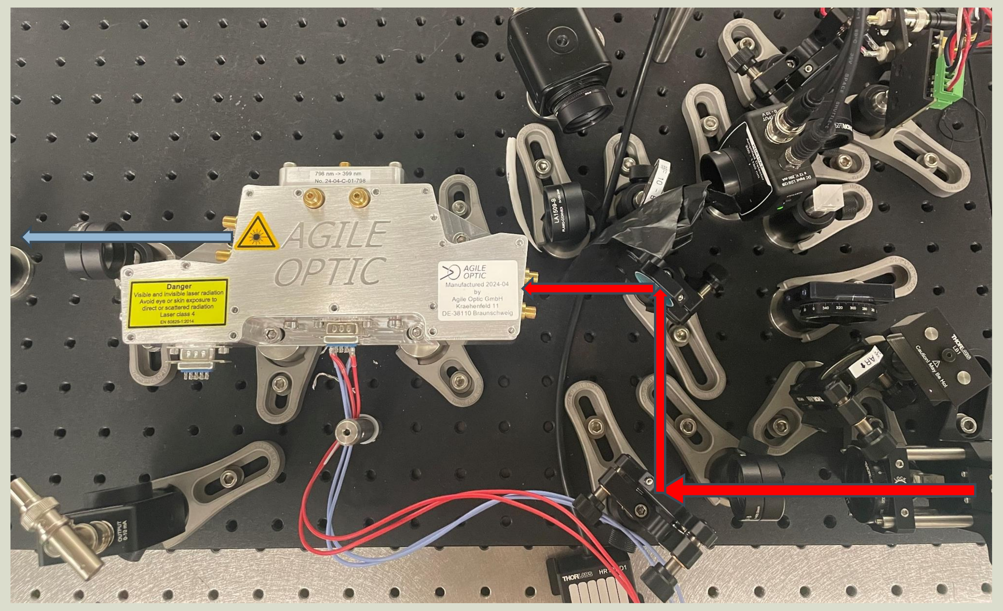


Fig. 798 nm (red) and 399 nm (blue) beam paths in cavity. LBO crystal represented by black rectangle.

To optimize the conversion to 399 nm, the incoming 798 nm laser must be coupled to the cavity. In other words, the beam should be most focused at the crystal where the conversion occurs to maximize the amount of light converted. The beam should also be well contained in the cavity so it is able to complete many round trips through the crystal and build up power.



Incoupling and Mode Matching

We want to match the incoming laser to the beam circling in the cavity to maximize the conversion to 399 nm and to minimize loss of power from the cavity. To do so, we create an incoupling set up to align the beams. The beam trapped in the cavity has a smallest point, or waist, at the center of its lower arm that we know to be about 195 µm. We can calculate where and what size the smallest point of the incoming laser will be and can adjust our incoupling optics to match it to the circling beam's waist.

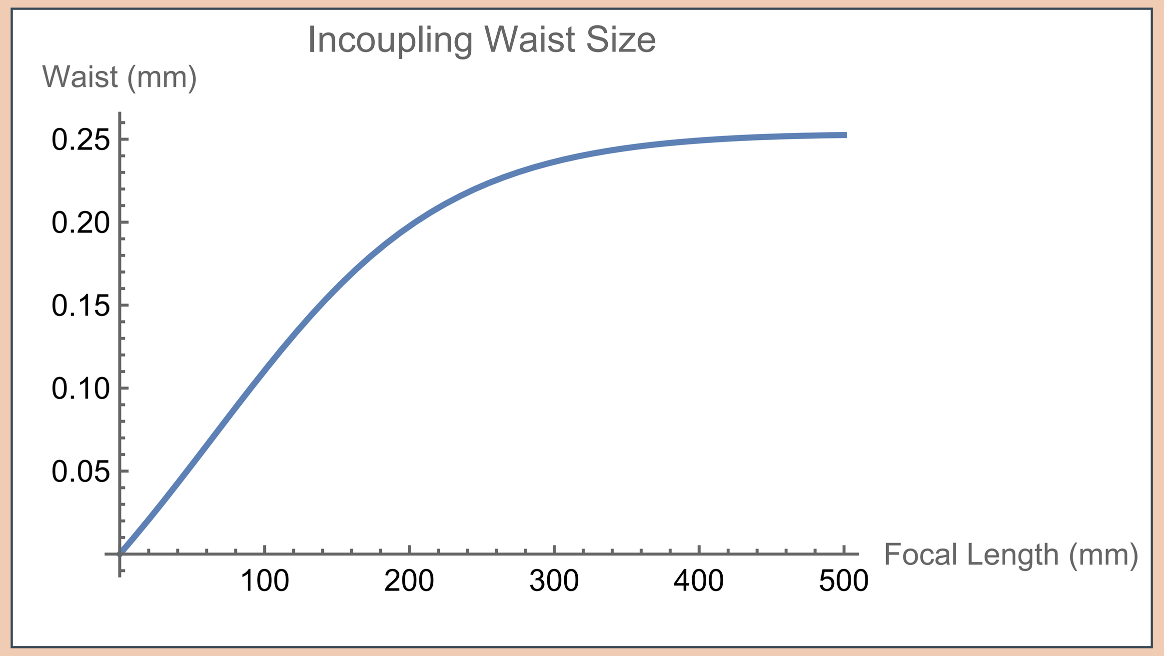
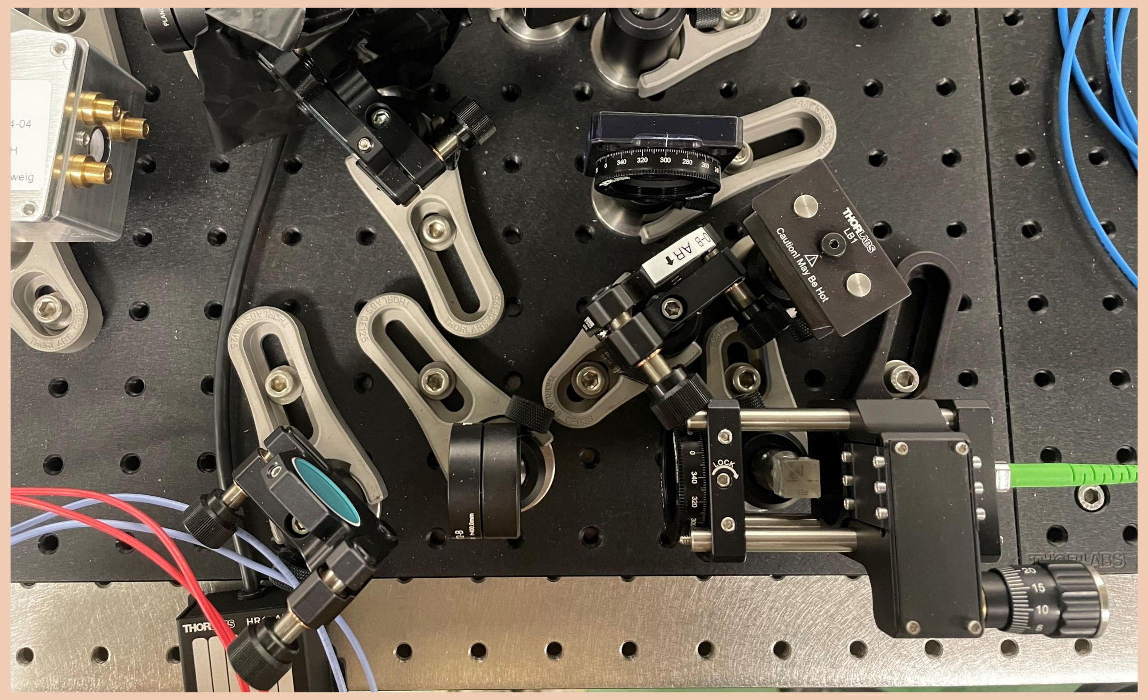


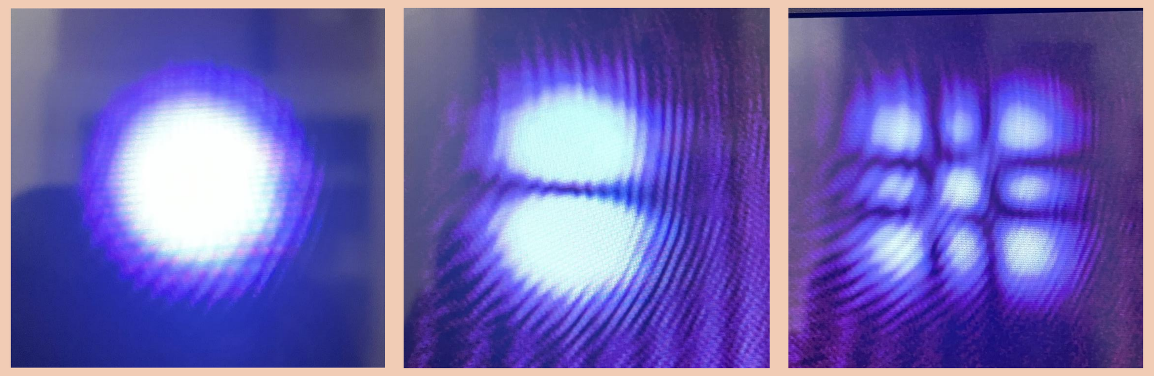
Fig. Graph of the incoupling beam waist size as a function of the focusing lens' focal length.

We used this and similar calculations to design the incoupling setup shown in the 'Approach' section.



After choosing our incoupling setup, we made fine adjustments to mode match the incoming laser to the cavity. The mode of a beam describes its intensity profile as it travels. In a cavity, this develops as the beam's many passes around the cavity interfere with each other. If this intensity pattern remains as the beam expands and focuses, it is a mode. We want to match to the TEM00 mode shown below because it is easiest to work with and obtain the highest intensity of converted light.

Hermite-Gaussian Modes



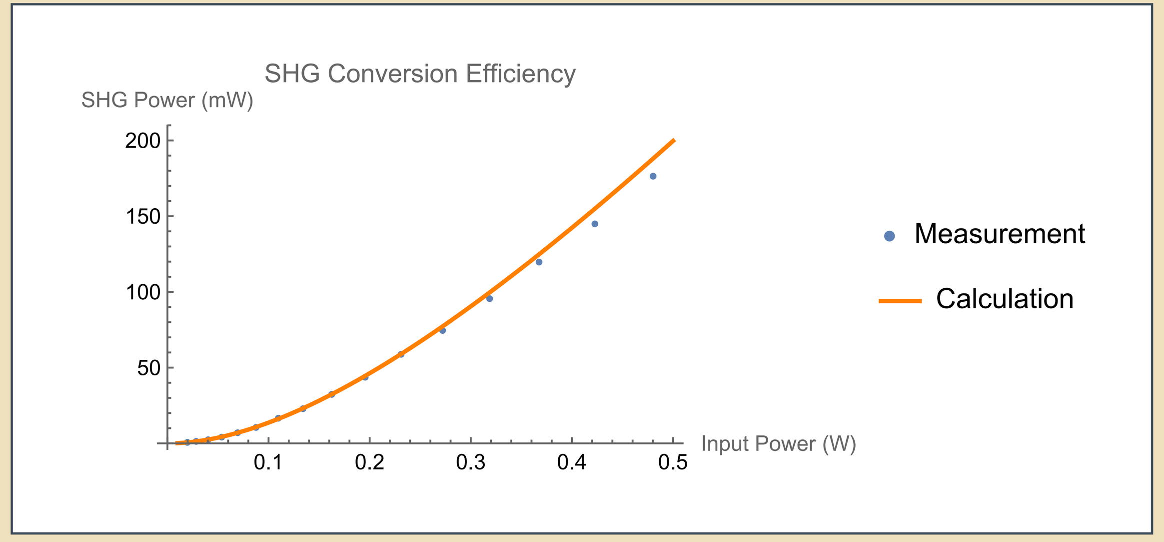
TEM00 TEM01 TEM22

Efficiency and Loss

The power of the outcoming 399 nm wavelength light can be related to the power of the light circling in the cavity by the following equation;

$$P_{out} = E_{nl}P_{circ}^2$$

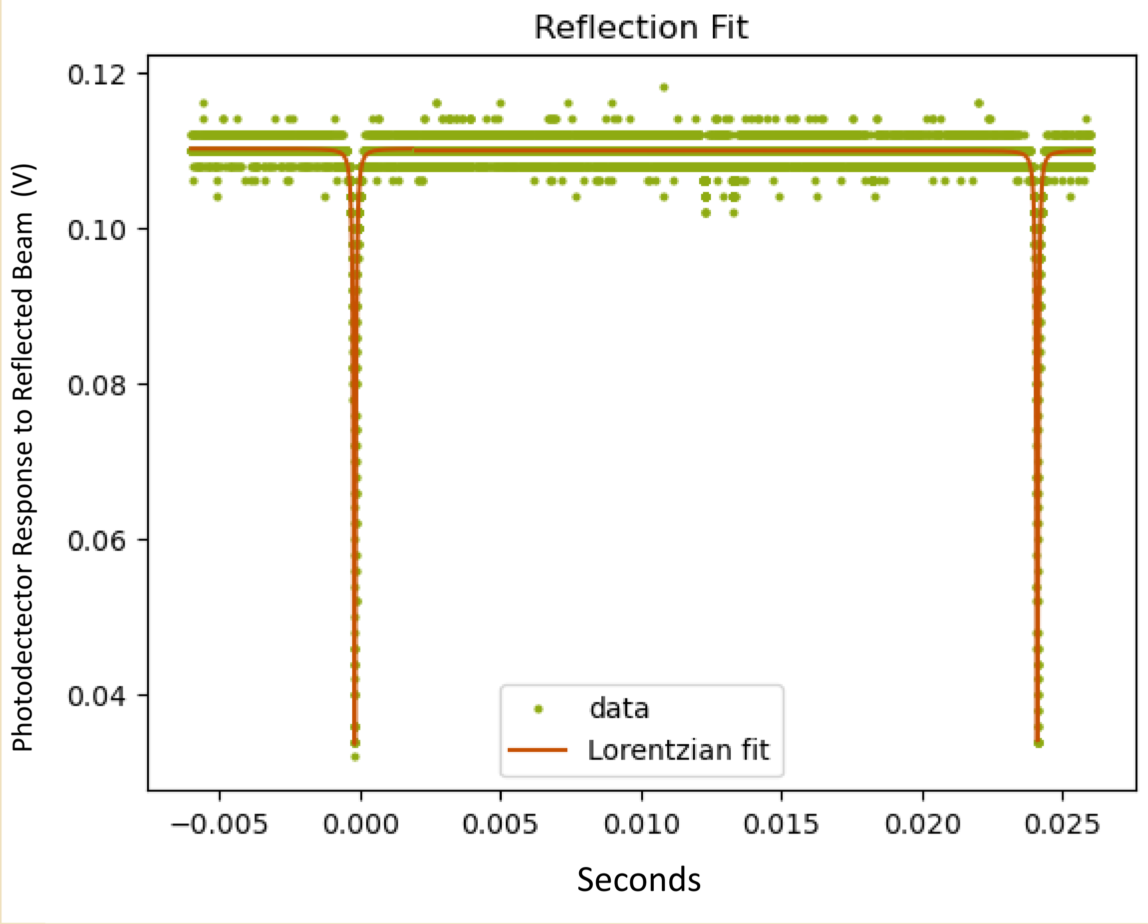
Where E_{nl} is the nonlinear coefficient. We can use this as a measure of the conversion efficiency from 798 nm to 399 nm. The E_{nl} was measured to be roughly 7 x 10^{-5}. With this and calculations for reflection and cavity losses, we project the output power of the SHG beam. Below is a comparison of our measured SHG beam power and the calculated power.



The trailing off of our measured data at higher powers is likely due to saturation of the power meter used in measurement. So, our results may be even closer to our calculations. We expect to achieve almost 1 W of power for our 399 nm beam at 1.5 W input power.

Finesse Calculation

To quantify how lossy the cavity is we take measurements of beams lost through both reflection and transmission while scanning over the frequency of the input laser. Scanning over the frequency allows us to see peaks where the laser is resonant with the cavity which correlate to a drastic dip in reflection and increase in transmission. Using these measurements we calculate the finesse of the cavity, the ratio of the free spectral range (FSR) (distance between peaks) and full width at half maximum (FWHM) of these peaks. We fit the data to Lorentzian distributions as shown below and take these parameters from the fit to caclulate a finesse of around 359. This value suggests that, despite relatively high power output, we have an unknown source of loss.



Converted Beam Correction

The 399 nm wavelength laser produced has an elliptical spot shape due to one polarization being favored for conversion by the LBO. There are also other aberrations of an unknown origin that resemble an interference pattern. To correct the beam shape, we first collimate the major axis while also focusing the minor axis . Then we calculate where the major and minor waists will be the same size (see graph below) and place a cylindrical lens there to collimate the minor axis.

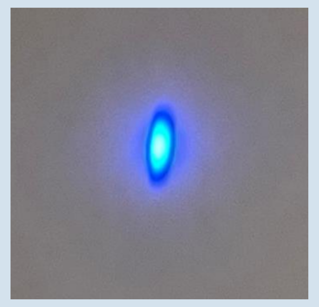
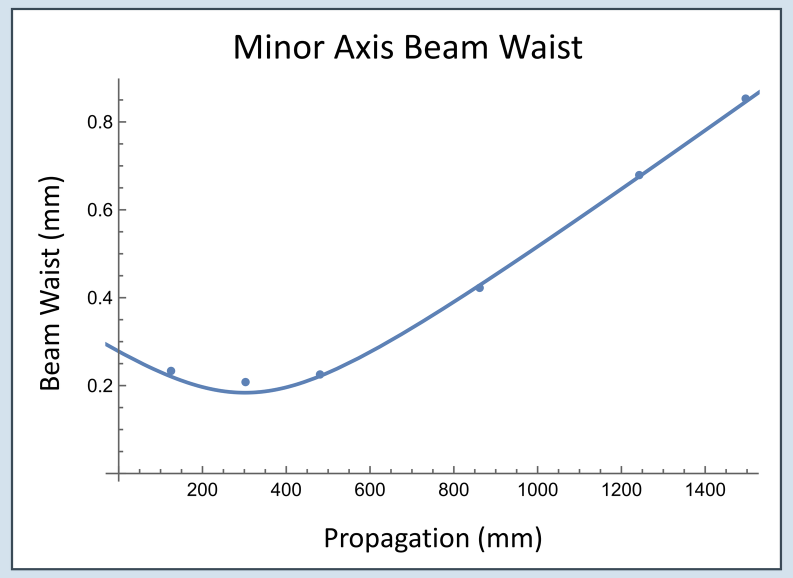
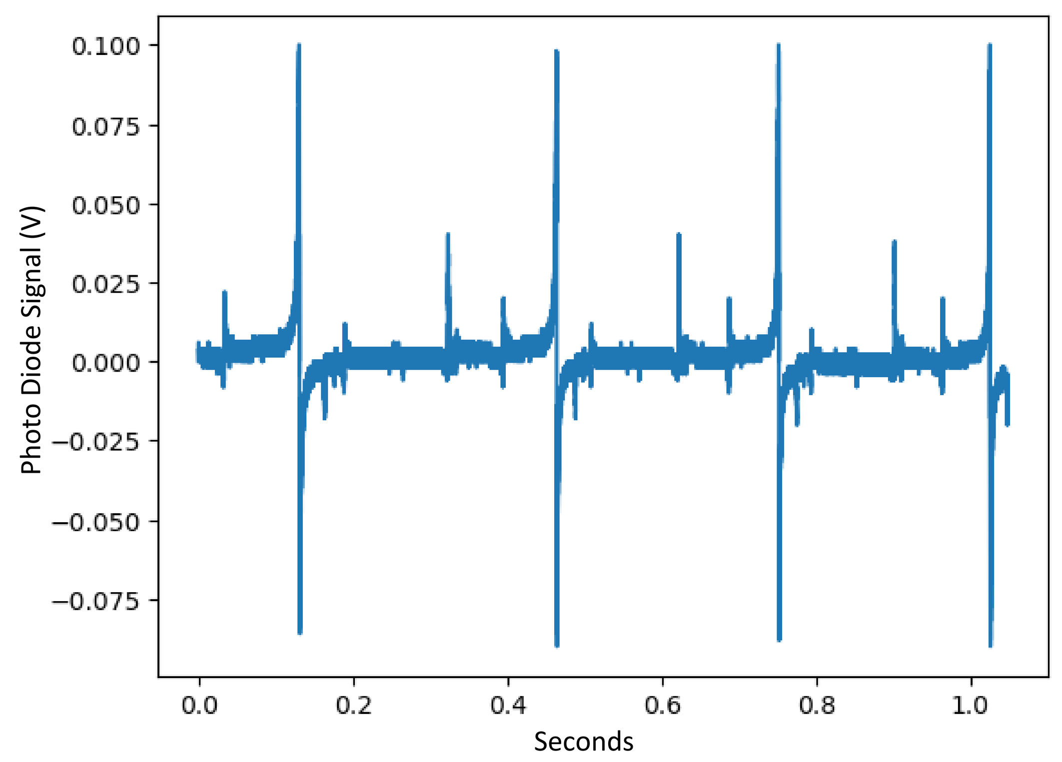


Fig. SHG output beam with astigmatism



Future Work

The next step is to lock the cavity, a process where we maximize the coupling of the input laser to the cavity via a feedback loop. To do so, we must generate an error signal that represents how resonant the laser is with the cavity. We use the difference in phase of the different polarizations of light present in the beam to generate this signal. Only one polarization enters the cavity so by mixing them and taking their difference, we can see how much of that polarization is actually being transmitted into the cavity from difference in their phases. The below error signal will then be sent to a piezo attached to a mirror in the cavity that changes size depending on applied current, changing the length of the cavity with it.



References

- arXiv:1401.1623v3 [physics.optics] 21 May 2014
- Boyd, R. W. (2020). *Nonlinear optics*. Academic Press.

Acknowledgements

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