Fast Polarization Switch

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Chapter 2: Project Description

2.1 Background and Motivation

In the world of semiconductor technology, light and its manipulation are at its core. Being able to harness the power of light is crucial to staying on top of this innovative environment. For our senior design project, we task ourselves with mastering polarization control with the utmost precision. This mastery, while some see it as merely scientific fun, we understand is crucial to the furthering of metrology, sensing, and overall analysis of the smallest technological systems. We plan to create a fast polarization switch, that we call **Fast Polarization Switch**, that utilizes the fascinating features of birefringent crystals. Through careful selection of this crystal, we will be able to rotate it in such a way to rapidly alter the polarization of input light. This technology, while new and innovative, will considerably change the state of semiconductor manufacturing with its precision and stability. In a world where computers control our ecosystem, from the bottom of the sea to the heavens upon the stars, our project will be involved in the steppingstones that will change our future.

Inside of academia, the class senior design is modeled after the real-world hardships engineers are faced with on a daily basis. This course is designed to challenge up and coming engineers to take what we have learned through our rigorous coursework and apply it to a product that will not only innovate but advance the technological world in a way that has never been done. As a team we must create a system that is reasonably accessible to our audience as well as fully capable of completing its intended goal. To do this our team must be highly skilled and coordinated, qualities that cannot be taught and must be achieved through dedication. This type of project is the best way to spring into the world of industry and prepare us for the upcoming problems we will face. This project, while useful, is a test of teamwork, knowledge, and commitment and will show those around us that we are prepared for what's to come.

The idea of **Fast Polarization Switch** came from ASML, a leader in the field of semiconductor technology. This collaboration not only challenges but also inspires us. We are challenged by the fact that we must live up to the high standards that come from working with a world leader in such innovative technology and inspired with the knowledge that the work we do here is being used to push the forefront of technology. With their insight into the newest technological advancements, they led us to the idea of using a rotating birefringent crystal as the cornerstone of a polarization switch. This idea will not only be technically challenging but also be immensely practically valuable in the world of metrology. With their guidance, **Fast Polarization Switch** will show the industry that we can provide a global impact in the same way ASML has for so long.

2.2 Features and Functionalities

The main functionality of our product is the ability to polarize light. This is done by using crystal and the properties of birefringence to change the refractive index of light as it passes through. This allows us to change the polarization of light by altering the angle at which the light is incident upon the crystal. This will allow us to quickly and accurately change the polarization by just rotating our crystal on a rotation mount connected to a motor.

This can also act as a power modulator. By passing the polarized light through a polarized beam splitter, we are able to output a fraction of the input lights power. By changing the polarization, the amount that gets reflected will also change. As the polarization output from the crystal changes the polarization of the beam splitter, we will increase power and as we get further away from the polarizers set polarization our power will decrease. Using this functionality, our polarizing crystal can also effectively act as a power regulator.

Our system will be able to work with the entire visible light spectrum. Birefringent crystals are transparent over a large range, from UV to IR. This allows us to function across a wide wavelength range so our product can be used across a variety of applications. Our product is also thermally and mechanically stable. This stability comes from the fact that we will be using a double pass system for our crystal, meaning that we will pass light through the crystal twice. This will eliminate the beam distortions that may be induced from other polarization modulators, like electro-optic modulators. Also, because we are only mechanically moving the crystal and not changing the refractive index by changing the electric field across the crystal, like electro-optic modulators, we will not be drastically heating our crystal. This means we do not have to worry about any thermal instability that may come from this heating.

Our design will avoid the need for high power input. Unlike other polarization modulators that use voltage to control polarization we will be using solely mechanical sources. This decreases power consumption as we will not need a constant source of power to alter our light. Also, more importantly, since our product will be used in high sensitivity metrology applications, we will need our product to be as accurate as possible. By not using high voltage to control polarization we will not be worried about problems like RF interference or electronic noise. This will help us drastically increase sensitivity.

2.3 Past Projects

2.3.1 Basis Paper Summary

Fast Polarization Switch is based on prior work completed at the University of Physics, KAIST, in Korea. The title of their work “Double-pass rotating z-cut quartz plate as a rapidly variable waveplate” (Lee, Kwon et al. 2025) was published online through Optica. This work establishes the feasibility of our goals. Elucidating paths of improvement and highlighting the math used to back up their results as well. Specifically, the Jones matrices provided are used to determine the output polarization depending on rotation angle of the crystal, and the difference in angle between the optical axis and the fast axis. The double-pass alignment they use can be a basis for the system to implement fiber and negates the need to adjust the alignment based on wavelength changes. Easing the process of measuring different depths using varied wavelength sources or a frequency sweeping light source. With the characterization of their system establishing our baseline. We have clear basic objectives to achieve. Namely the ability to change the polarization between orthogonal states within a millisecond. With an extinction rate of 99.9% reducing the output power of their system by 30dB. Comparing their chosen z – cut uniaxial quartz plate to the more widely used Pockels Cells, in terms of the electro-optical effect. The quartz offered more thermal stability and was capable of handling higher power without damaging functionality. It’s CTE or (Coefficient of Thermal Expansion) being smaller when compared to typical EOM crystals reduces thermal lensing and optical degradation. Fully rotating polarization of the light within ~0.7° of controlled angular change. Noting that typical zero-order waveplates require a 45° rotation. This was the key factor in bringing the switching time to below a millisecond they remarked. Finally, they provide a way to suppress the angular vibrations that come from such quick movements. These insights are the integral components, gleaned from this work, that we utilized to complete our objectives. Further details on how each of these are going to be achieved will be explained below.

The beam that was used in the past project was characterized by divergence angle and beam waist, which was determined to 2.2 mm with a divergence angle of 100μrads they chose the (Cening optics, AR coated at 1064 nm) their crystal had a thickness of 10 mm with refractive indices of $n_o = 1.534$ and $n_e = 1.543$ at 1064 nm. The rotation of their crystal between 10˚ to 20˚ is used to measure and map changes in polarization. This offset from normal reduces back reflections. Their experiment showed that even within this range they were able to have full control over polarization and power. It also shows that the double pass configuration reduces the period by a half cycle, further lowering transition time between orthogonal polarization states. To verify its use in a wide wavelength range they not only tested at 1064 nm but also 671 nm again measuring power in both single and double pass configurations the comparisons held true, phase delay was slightly larger when comparing quartz angles to 1064 nm however the power showed similar variances with double – pass doubling the peaks and halving the period. The contrast for the 671 nm light increased with increased quartz angle, this was attributed to the AR coating being less effective and the back reflections playing a bigger role in the process.

One of the biggest hindrances to the use of quartz crystal as a variable wave plate has been the beam path shift. The comparison here between the two configurations showcase that the double-pass configuration due to the retro-reflection of the light shows no position shift in the reflected light. This can be proven using basic geometric optics. Where $D_o = \frac{d}{\cos\theta_o}\sin(\theta - \theta_o)$, $D_e = \frac{d}{\cos\theta_e}\sin(\theta - \theta_e)$ Here θ_o and θ_e can be found through Snell's law: $n_e \sin\theta_e = n \sin\theta = n_o \sin\theta_o$ to verify this in the double – pass set up they utilized a have wave plate and a beam splitter, measuring the beam shift by looking at the position of the reflected beam from the beam splitter. Theorizing that due to negligible beam shifts, new opportunities for fiber coupling arise. They compared contrast in the single and double pass configuration between free space and the fiber coupled, comparisons were similar with contrast in the double pass being much higher. When comparing coupling efficiency, it was easy to see why. The efficiency was constant with varying quartz angle in the double pass. While the single pass suffered significantly increasing losses with higher quartz angle.

To experimentally prove the validity of rapid power conversion they use a pulse which rotates the crystal to an orthogonal state, in the double pass setup. With a rotation interval $\theta_f - \theta_i = 0.7˚$. Starting in the off position they find the pulse brings the output light to its full power within a millisecond. The pulse they used did cause some vibration in the crystal due to the stopping motion. They stated that this could be mitigated by shaping the pulse. Although their method increased the time to power conversion to 2.5ms. The rotator chosen could operate with an input sinewave signal with frequencies up to 300 Hz, this limit is due to its mechanical nature. Characterizing the power conversion in their experiment by measuring the power ratio between two polarizations in the double pass design. Calculating conversion ratio with $R_P = (P_{\max} - P_{\text{bg}})/(P_{\min} - P_{\text{bg}})$ where $P_{\max}$ and $P_{\min}$ are maximum and minimum power, P_{bg} is the background noise. They find the conversion ratio to be about 1000. They also determined the tolerance in offset of their retro-reflective mirror. Finding the ratio to stay above 900 when the degree change stayed between $\pm 0.015˚$ from the apex. They find a peak beam shift displacement of 9.1μm, expecting a beam shift less than 9.3μm, these are both unnoticeable when related to the beam diameter of 2.2 mm.

Due to the rapid rotation and stopping there are vibrations in the angle of the quartz, causing erratic changes in power. They studied these power shifts by studying the shift in beam position at the stopping angle, in the single pass setup. This method led to more accurate extrapolation of these differences, and lead them to find that these power fluctuations due to stopping are less than 0.1%, furthermore finding that this holds true for various types of input signals they determine that the noise level introduced by their specific operating system is low enough that their system could be used in atomic quantum simulating platforms.

The team at the University of Physics, KAIST, in Korea, was able to demonstrate that implementing a rotating z-cut quartz plate in a double-pass configuration was not only possible but could push the boundaries on tolerances and what these types of EOM systems are capable of. Highlighting its application for systems that require larger beam sizes, unable to be addressed by acousto-optic modulators. The system they created is fast, precise, with a full range of control over polarization, and intensity. With this paper as the backbone to our project we were able to not only meet those goals and objectives but push beyond.

2.3.2 History of Birefringent Crystals as Optical Modulators

The use of birefringent crystals as waveplates in optics has been documented for well over 50 years. Originally utilized as a retardation plate in 1964. Exact equations describing the phase difference and the electric field of the outgoing light were discovered using Maxwell's equations. Providing conventional solutions for calcite and quartz. Even going so far as to discuss Quartz as a quarter wave-plate and applying it to the investigation of elliptical polarization. Exploring it for the case of a monochromatic plane wave that is normally incident and briefly comparing some oblique incidences. (Holmes 1964) Later on in the "Handbook of optical constants of solids: Handbook of thermo-optic coefficients of optical materials with applications." Which came out in 1998 (Ghosh 1998) here Ghosh went into more detail on how to apply quarter – wave retardation plate as a polarizer, amongst others. Continuing in Volume 1 Section 12.7, the book references a few different ways of solving the polarization of outgoing light, using matrix mathematics and further describing the difference between positive and negative uniaxial crystals. A wonderful reference involving the finer details of Jones matrix calculations was included in this section as well.

In 2016 something akin to the single-pass setup was used to characterize the crystal using a polarizer and analyzer both orientated at a 45° angle to the crystal to maximize the power drop. Then rotating the crystal, they saw how the power fluctuated. Analyzing the data and using Jones matrices they were able to determine the angular orientation of the crystals Optical axis. (Paranin 2016) As well as Ghosh et al. in 1999 go over characterization of calcite and quartz crystals highlighting that the refractive indices. Quoting "The extraordinary and ordinary indices of refraction of the crystal are fundamental parameters to have when applying such a crystal to any optical device or system." (Ghosh 1999)These parameters were provided for both crystals as tables showing the respective indices across a variety of wavelengths. Further claiming that the progress made during that work would be foundational in discovering a standardized equation representing the birefringence of all other uniaxial crystals. (Tables to be Included in Appendix.)

2.3.2 Use of Double – Pass set up to Characterize a PSA

A paper written in 2012 uses the double pass technique to characterize a PSA (polarization state analyzer). Fascinatingly it only uses the PSA and no other polarizing element to do the characterization. Further demonstrating the possibility of this technique used do design broadband high-resolution spectropolarimetric systems. Claiming the system can be used to find the parameters of any chromatic retarder. (Zallat, Torzynski et al. 2012) This discovery in combination with the work done in the prior papers we looked into is what made us believe we can make a self-calibrating system that can work with any composition of birefringent crystal given the proper thickness. Being able to insert any crystal the right orientation and running a calibration protocol it is possible to make our system find the minimum rotation needed to switch polarizations between orthogonal states. Allowing for more adaptability to various other applications.

2.4 Goals and Objectives

The idea of this project is to build a device that takes input light and produces light of a specific chosen polarization. Our goals and objectives are listed below.

Basic Goals

- Build a device to take in visible light and polarize it at the desired speed.

  Achieving the desired speed of polarization is dependent solely on the motor speed. After inputting the desired polarization into the GUI, the system should know exactly how much the crystal needs to rotate to be able to output the desired polarization and then it needs to calculate how long it takes to activate the motor for the crystal to be in the location required. After this calculation the system will turn on the motor for the desired time and speed to rotate this crystal to the exact angle to achieve desired polarization. The wavelength range for our system needs to be between 500 and 800nm.

- Be able to produce any linear polarization desired

  This goal relies solely on the crystal selected. We needed to pick a crystal such that we can achieve the angle of rotation for the desired polarization. This selection should be thought out carefully as choosing a crystal will decide how much is needed to rotate to achieve the full polarization spectrum and the larger this rotation angle is then the larger our device will need to be to be able to rotate. Also, if the angle needed to achieve the full spectrum is too small, we may not be able to rotate the crystal precisely enough to achieve this goal which would mean we would need a higher price for our motor.

Advanced Goals

- Polarize input light that has a bandwidth of 30nm.

  For this goal we would like to be able to polarize light sources with a small bandwidth of at maximum 30nm. The system should be able to maintain a high extinction ratio and still do this in the allotted time of under 1 millisecond.

- Maintain accuracy for long term use

  For this goal, our system will have MTBF (Mean time between Failures) comparable to if not better than other polarization-based modulators.

Stretch Goals

- Operate with two different light source wavelengths at the same time

  We would like to operate our system with two different light sources with different wavelengths at the same time while maintaining 80% of our extinction rate. These light sources would be at wavelengths separated by more than 100nm.

- Enable polarization modulation continuously

  Allow the user to input a steady change between polarization states and the speed of change. This would allow the user to experience different polarizations without having to use several inputs into the system.

We can create specific objectives to be able to achieve these goals. These objectives are listed below.

Basic Objectives

- Switch between linear orthogonal polarizations in under 1ms

  For this objective we will need a highly accurate motor and driver. This is because the computer will have to calculate the desired angle of incidence the crystal needs to achieve the chosen polarization.

- Have an extinction ratio of 1000:1

  This means that when we check our output power from our polarizing beam splitter, we should be able to have a maximum power that is 1000 times higher than our minimum power. To do this, we need to have a highly accurate polarizing beam splitter. If the splitter has a low extinction rate, then we will not be able to accurately measure the crystals extinction rate as the PBS's extinction rate will be limiting the crystal.

- Works with a wavelength range of between 500-800nm

  This device will be used with a range in the visible spectrum. This means we need to be able to accurately adjust the angle of incidence needed for a specific wavelength in this range.

- Build device for under $7,000

This is the budget we were given by ASML. This budget includes everything that goes into making the polarizer. This means we will be able to use money from outside of this budget to buy light sources and testing equipment like a power meter.

Advanced Objectives

- Route light source output through fiber for extreme stability

  For this objective we would like to send our light output into fiber and then into the power detector. This would allow us to show that our device is stable and allow for easy routing of output light for the actual product, since in the product the power detector would not be needed. The user would simply have the output light from a fiber.
- Able to handle powers of up to 50mW

  Our system should be able to handle a light source of 50mW. It should keep its extinction rate at 1000:1 even at light sources of up to 50mW.

- Create a GUI to control polarization state and which light sources to use.

  For this objective we create a user interface to easily control the polarization the user wants and which lasers they want to turn on. The user would input a polarization, and the system would take this input and be able to calculate the time and speed of rotation for our motor.

Stretch Objectives

- Create arbitrary polarization states

  For this objective we would like to be able to create circular and elliptical polarization states. This would allow the user to have greater control over their polarizations and be able to hit every polarization state on the Poincaré sphere.

- Allow crystal swapping

  For this objective, we would use a mount that would allow us to remove the crystal and swap it for another one. This means we could use crystals that are designed for wavelengths out of our range and allow us to change crystal thickness for desired effects. This drastically increases the versatility of our system.

2.5 Specifications

Table 2.5.1 Component Specifications

Component(s)	**Parameter**	**Specification**
Electrical		
3.3 V Regulator	a) Max Output Current	a) 800 mA

	b) Max DC Input Voltage c) Min Output Voltage d) Max Output Voltage	b) 15 V c) 3.267 V d) 3.333 V
5 V Regulator	a) Max Output Current b) Max DC Input Voltage c) Min Output Voltage d) Max Output Voltage	a) 1.5 A b) 35 V c) 4.8 V d) 5.2 V
Microcontroller (ESP32-S3 Series)	a) Max Output Current b) Average Output Current c) PWM d) Functionality	a) 1500 mA b) 500 mA c) 2 Motor Control PWM d) Bluetooth
Motor Driver (L298N Dual H-Bridge)	a) Input Voltage Range b) Output Voltage Range c) Peak Current d) Input Current Range e) Max Power Consumption	a) 3.2 V to 40 V b) 5 V to 35 V c) 2 A d) 0 to 36 mA e) 20 W
Motor (TBA)	a) Motor Angle Range b) Speed c) Torque	a) 0° to 20° Maximum Step Size: 0.01° b) Min 3,334 rpm c) TBD
Optics		
405 nm Compact Laser	a) Wavelength b) Output Power c) Size (Diameter x Length) d) Beam Diameter	a) 405 nm b) 0.9 mW c) 11 mm x 60.2 mm d) 3 mm
520 nm Compact Laser	a) Wavelength b) Output Power c) Size d) Beam Diameter	a) 520 nm b) 0.9 mW c) 11 mm x 60.2 mm d) 3 mm
635 nm Compact Laser	a) Wavelength b) Output Power c) Size d) Beam Diameter	a) 635 nm b) 0.9 mW c) 11 mm x 60.2 mm d) 3 mm
Beam Splitter	a) Wavelength Range b) Extinction Ratio c) Reflection Efficiency d) Transmission Efficiency e) Size	a) 420 – 680nm b) 1000:1 c) > 95% d) > 90% e) 30 mm x 16 mm
Retroreflector	a) Wavelength Range b) Diameter	a) 350 – 2000nm b) 10 mm
Power Meter	a) Wavelength Range b) Aperture Size c) Dimensions d) Power Range	a) 400 – 1100 nm b) 9.5 mm Diameter c) 30.5 mm x 12.7 mm d) 50 nW – 50 mW
Mirror	a) Diameter b) Reflectance	a) 7 mm b) > 99% (400 – 750 nm)

	c) Material	c) Fused Silica
Crystal	a) Thickness b) Refractive Indices c) Absorption Spectra	TBD TBD TBD

Table 2.5.2 System Specifications

Parameter	**Specification**
Power Consumption	Maximum 750 W
Response Time	Maximum 5 seconds
Extinction Ratio Precision	1000:1 Minimum 80% per wavelength
Motor Precision	± 0.001°
Modulation Speed	Maximum 1 millisecond
Optical (Output) Power	Maximum 50mW
Wavelength Range	500nm to 800nm
Polarization Range	Minimum 90° Maximum 180°
Torque Tolerance	TBD
Total Cost of System	< $7,000

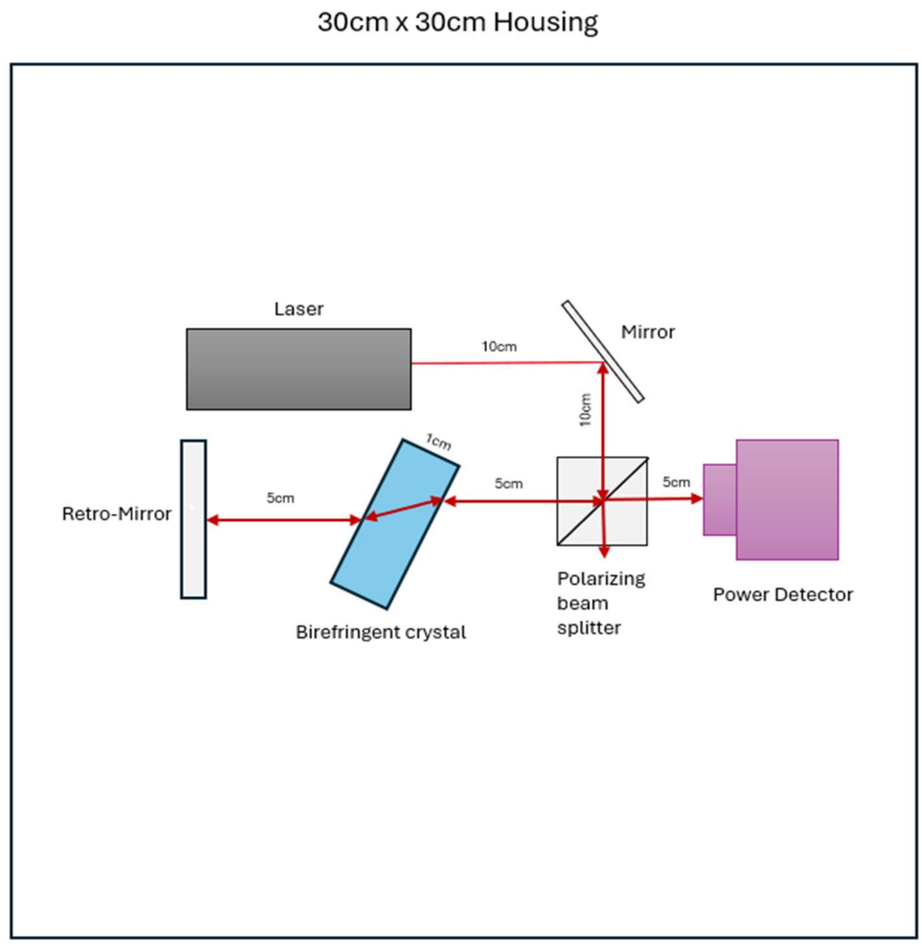


Figure 2.5.1 Optical design diagram is shown above. This demonstrates the core optical setup that will be used to achieve our goals and objectives for this project. The red arrows indicate the laser direction of travel originating at the laser component.

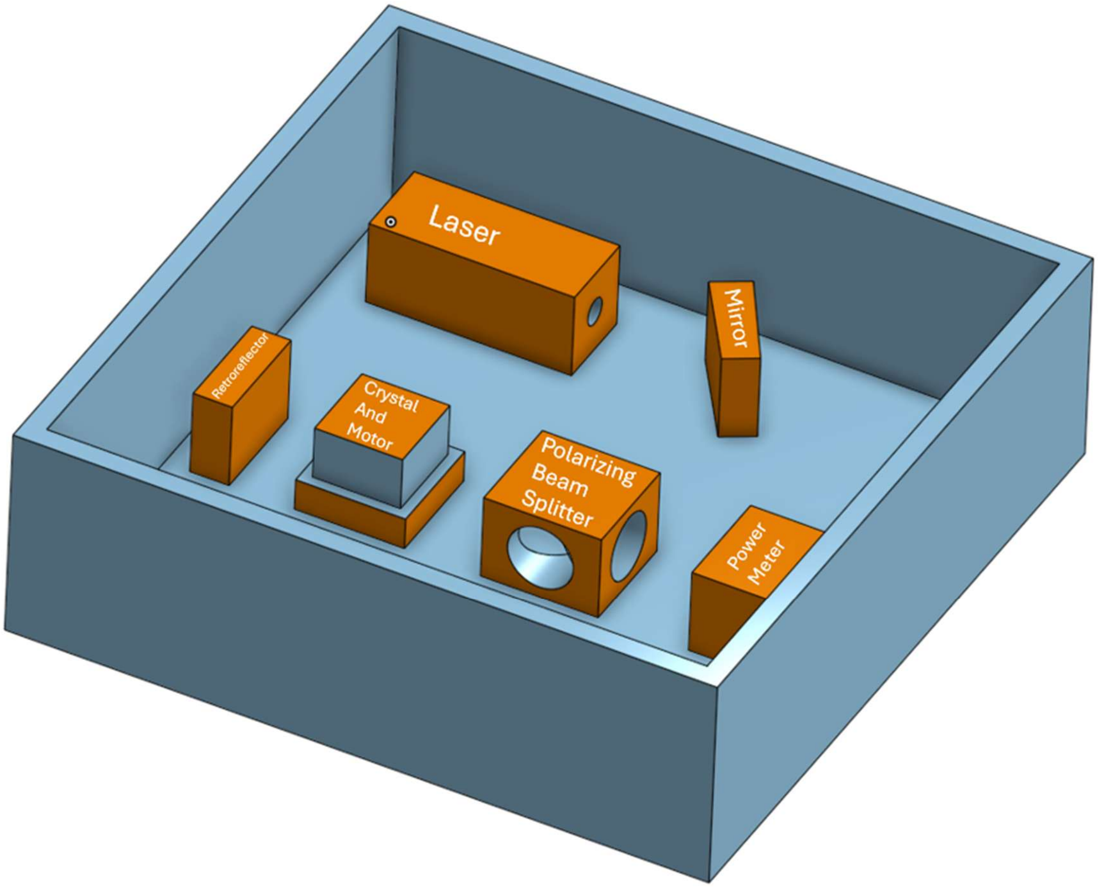
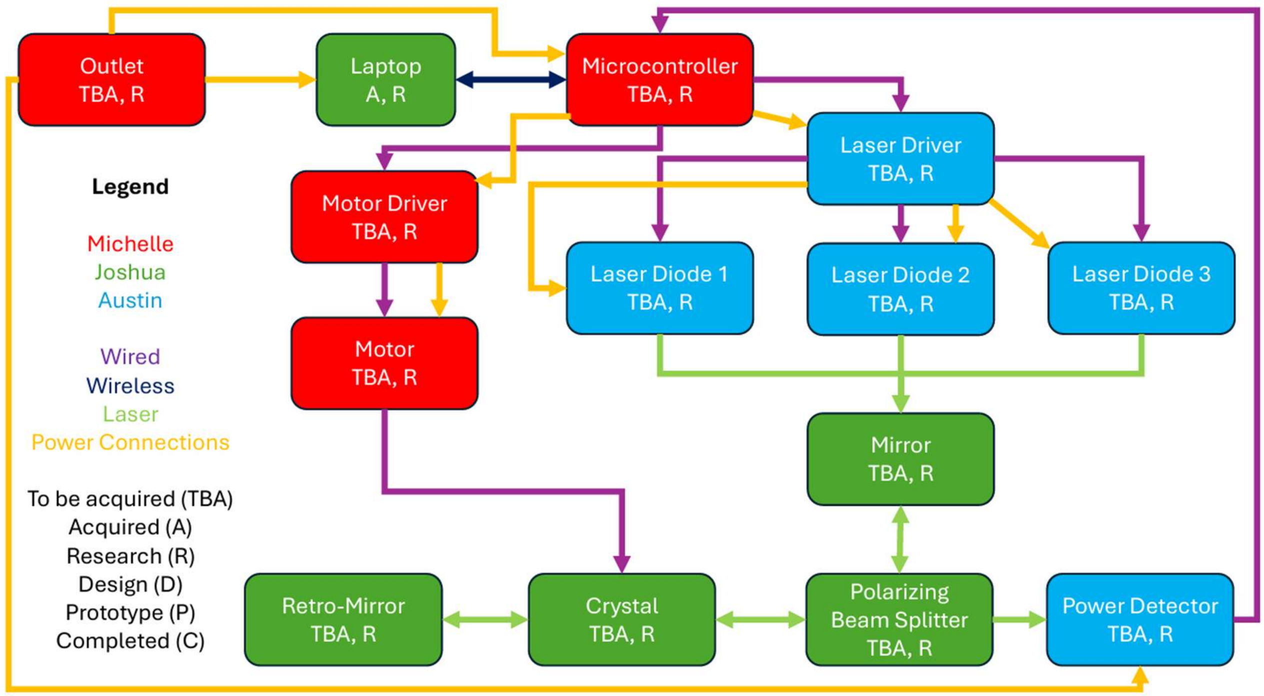
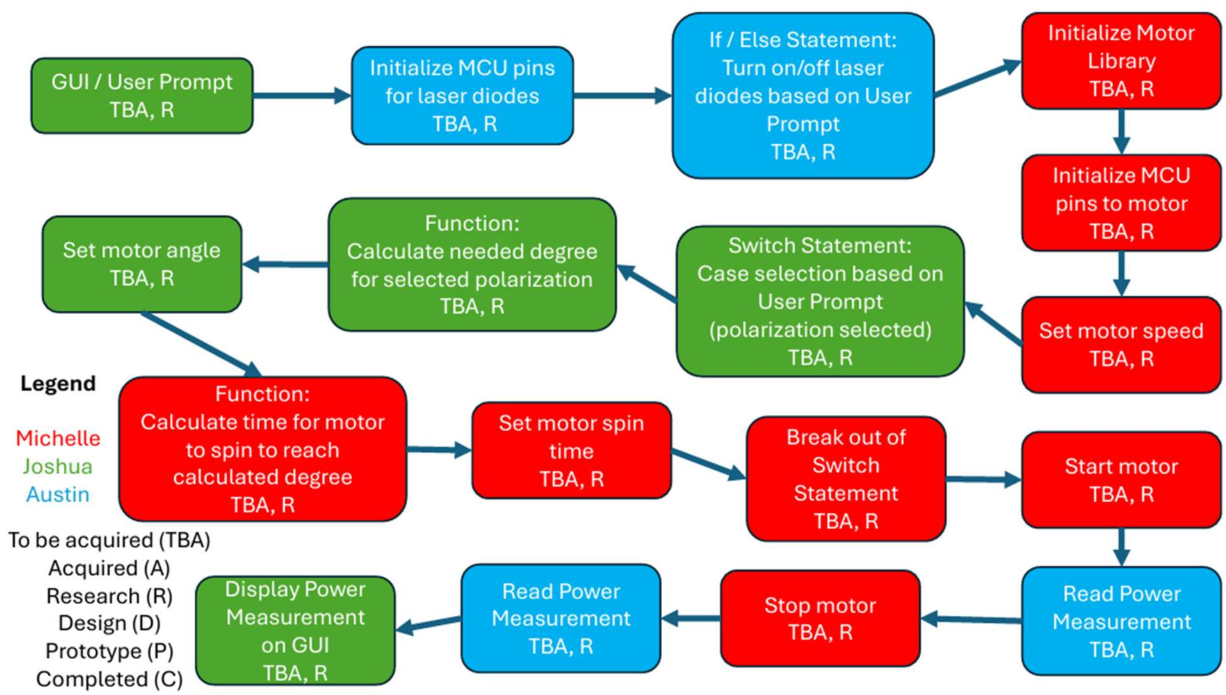


Figure 2.5.2 Prototype Illustration is shown above. This illustration is the general layout we will be using inside the housing of our system.



2.5.3 Hardware Diagram. This diagram shows how the components of our system will interact to ultimately produce our end goals. The colors of each block indicate the student tasked with researching and designing that component. The colors of each arrow indicate the connection between components.



2.5.4 Software Diagram. This diagram shows how the software of our project will interact in the final prototype. The color of the boxes indicates who oversees which section of the software. The arrows indicate the timeline of events.

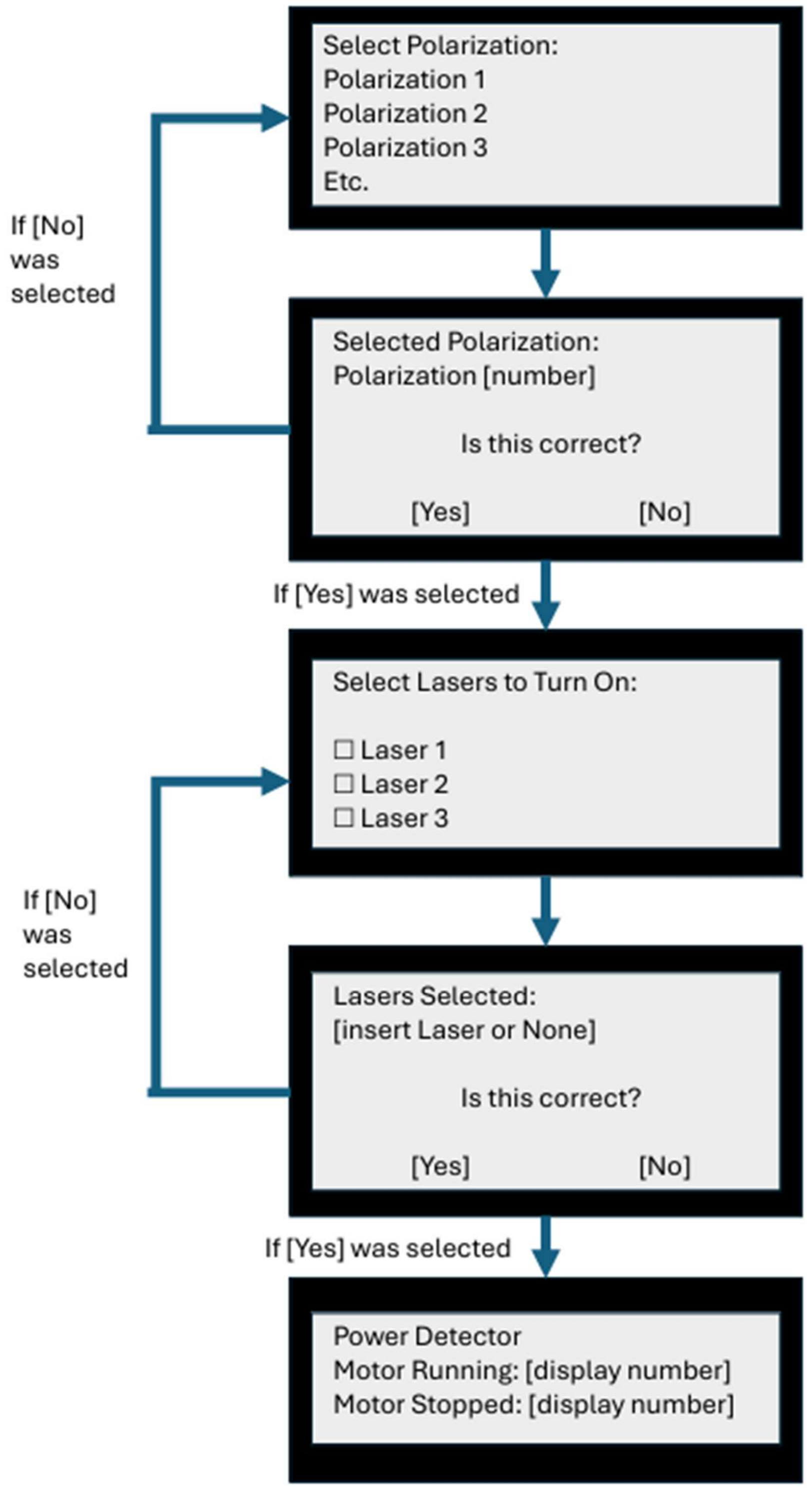
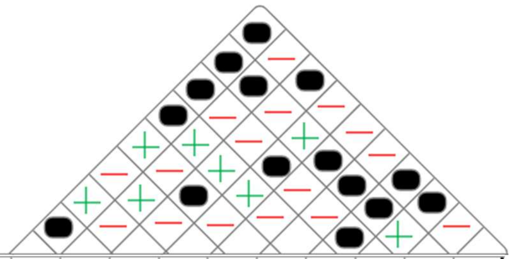


Figure 2.5.5 User Interface Diagram. This diagram shows how the GUI will function and the prompts it will give to the users.



Customer Requirements / Product Requirements	Output Power ▼	Switch Time ▼	Cost ▼	Number of Polarization ▲	Power Consumption ▼	Response Time ▼	Degree Accuracy ▲	Wavelength Range ▲	Extinction Ratio ▲	Stability ▲
Responsiveness ▲	o	↑↑	↓	o	↓	↑↑	↓	o	o	↓
Portability ▲	o	o	↑↑	↓	↑	o	↓	↓	o	↓
Affordability ▲	↓	↓	↑↑	↓	↑	o	↓	↓	o	↓
Ease of Use ▲	o	↑	↑	↓	o	↑	↓	o	o	↓
Longevity ▲	o	o	↑	o	↑	o	o	o	o	o
Reliability ▲	o	↑↑	↑	↑	↑	↑	↑↑	↑	↑	↑
Power Efficiency ▲	↑	↓	↑↑	↓	↑↑	↓	↓	↓	o	o
Versatility ▲	↑	o	↓	↑↑	↓	o	↑↑	↑	↑	↑
Cost of Maintenance ▼	o	o	↑↑	o	↑	o	↓	↓	o	↑
Upgradable ▲	o	o	↓↓	↑	↓	↓	↑	↑	↑	↑
Targets for Engineering Requirements	Maximum 50 mW	Maximum 1 ms	Maximum $7,000	Minimum 2 Polarization	Maximum 750 W	Maximum 5 s	± 0.001°	500 nm to 700 nm	Minimum 80% per wavelength	TBA Torque Tolerance

Correlation	
Positive	+
Negative	-
None	⬛

Relationship	
Strongly Positive	↑↑
Weakly Positive	↑
No Relation	o
Weakly Negative	↓
Strongly Negative	↓↓

Direction of Desirability	
High	▲
Low	▼

Figure 2.5.6 House of Quality. This figure provides a visual aid of engineering tradeoffs for the project. The left-handed column is the requirements important to the user. The top column indicates product requirements that we may need to make tradeoffs for.

Chapter TBD

TBD Design

TBD Mathematical Principals

The mathematical principals behind the polarization control using the z – cut quartz can be determined when assuming a monochromatic and collimated beam. The change in phase delay $\Delta\phi(\theta)$ as a function of rotation angle is written as

$$\Delta\phi(\theta) = 2\pi\,\frac{\Gamma(\theta)}{\lambda} = \frac{2\pi}{\lambda} n_o d\left(\sqrt{1-\frac{\sin^2\theta}{n_e^2}} - \sqrt{1-\frac{\sin^2\theta}{n_o^2}}\right) \quad (1)$$

Here λ is the wavelength d is the thickness of the quartz plate and n_o , n_e are the refractive indices for the ordinary and extraordinary components. Where the Jones Matrix of the Rotating z – cut quartz is shown to be

$$\boldsymbol{Q}(\beta,\theta) = \begin{pmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{pmatrix} = \begin{pmatrix} \cos^2\beta + e^{i\Delta\Phi}\sin^2\beta & \left(1-e^{i\Delta\Phi}\right)sin\beta cos\beta \\ \left(1-e^{i\Delta\Phi}\right)sin\beta cos\beta & \sin^2\beta + e^{i\Delta\Phi}\cos^2\beta \end{pmatrix} \quad (2)$$

Here β is the angle of pitch applied to the crystal by how the rotator is mounted, if $\beta = 0\,,{}^{\pi}/_{2}$, Parallel or orthogonal to the optical axis, the $\boldsymbol{P}$ and $\boldsymbol{S}$ polarizations will not experience rotation due to $\boldsymbol{Q}$ becoming a diagonal matrix. These positions of the mounted crystal will not function as a waveplate, to ensure those off diagonal components having a value for β of ${}^{\pi}/_{4}$ can be achieved by applying a 45˚ pitch to the rotator mount.

Using the Jones matrix, we can solve the electric field of the incident beam for single and double pass configurations. Those expressions are

$$\boldsymbol{E}^{(\boldsymbol{S})} = \begin{pmatrix} E_x^{(S)} \\ E_y^{(S)} \end{pmatrix} = \boldsymbol{Q}\left(\frac{\pi}{4},\theta\right)\cdot \boldsymbol{E_i} = \frac{1}{2}\begin{pmatrix} 1-e^{i\Delta\Phi} \\ 1+e^{i\Delta\Phi} \end{pmatrix} \quad (3)$$

$$\boldsymbol{E}^{(\boldsymbol{D})} = \begin{pmatrix} E_x^{(D)} \\ E_y^{(D)} \end{pmatrix} = \boldsymbol{Q}\left(-\frac{\pi}{4},\theta\right)\cdot \boldsymbol{M}\cdot \boldsymbol{E}^{(\boldsymbol{S})} = \frac{1}{2}\begin{pmatrix} 1-e^{i2\Delta\Phi} \\ -(1+e^{i2\Delta\Phi}) \end{pmatrix} \quad (4)$$

Here $\boldsymbol{M}$ is the Jones matrix for a mirror under normal incident light and $\boldsymbol{Q}\left(-\frac{\pi}{4},\theta\right)$ is the matrix representing the retro – reflected light. Implementation of a polarizing beam splitter (PBS) allowed them to vary the transmitted power this variance is given by $\mathrm{P}_x^{(S)}, P_Y^{(D)}$ for the single and double pass configurations respectively. These are

$$\mathrm{P}_x^{(S)} = \left|E_x^{(S)}\right|^2 = sin^2\,(\Delta\phi/2)\ (5),$$

$$P_x^{(D)} = \left|E_x^{(D)}\right|^2 = sin^2(\Delta\phi)\ (6)$$

Chapter 10

10.1 Budget

Our project was sponsored by ASML, and they therefore set limits on the design. One of these limits is our budget which they selected to be under $7,000 and preferably below $5,000. This budget encompasses every component that we may need including a light source and polarized beam splitter which are expensive items. This budget also encompasses any replacements we may need, including the PCB and other electronic parts that may be changed in the production of our project. A breakdown of expected costs and budget distribution is provided in the Bill of Materials section.

10.1.1 Bill of Materials

Product	Part Number	Cost
405 nm compact Laser	PL205	$246.67
520 nm compact laser	PL201	$199.63
635 nm compact laser	PL202	$146.40
420 nm - 680 nm Mounted Beam Splitter	CCM5-PBS201/M	$331.75
TIR Retroreflector	PSS974M-A	$205.91
USB Power Meter, Standard Photodiode	PM16-120	$743.59
Metric Breadboard 30 cm x 30 cm	MBY3030/M	$369.15
Mini-series Optical Post	MS1R/M	$7.96
Mini-series Post Holder	MSH075	$39.10
M3 Cap Screw Kit	HW-KIT5/M	$123.30
Dielectric mirror 400 nm - 750 nm	BB03-E02	$49.85
Mini-Series Fixed 7 mm, M3 Tap	MFM7/M	$31.15
ESP32 S3 Development Board	1965-ESP32-S3-DEVKITC-1-N8R8-ND	$15.00
Breadboard	B0BRQX6G3T	$3.99
3.3 V Regulator	497-1491-5-ND	$0.72
5 V Regulator	497-1443-5-ND	$0.50
Breadboard Cable Wires	EL-CP-004	$6.98
L298N Motor Driver	CECOMINOD012186	$6.99
Galvanometer Motor	GVM-2510	$3,500.00

10.2 Milestones

Table 10.2.1 Senior Design 1 Milestones

Milestone	Start Date	End Date
D&C Report Submission	8/26/2025	9/5/2025
Committee Formation	9/2/2025	9/5/2025
D&C Meeting	9/8/2025	9/8/2025
Rough Draft Midterm	9/8/2025	10/3/2025
Midterm Report	9/8/2025	10/24/2025
Simulation Results	9/15/2025	10/24/2025
Compile and Submit	10/25/2025	10/30/2025
Mid Project Demo Component Acquisition	10/30/2025	11/18/2025
Final Report Draft	10/31/2025	11/18/2025
Sim Results	10/25/2025	11/18/2025
Compile and Submit Final	11/18/2025	11/25/2025
Mid Project Demo Assembly	11/18/2025	11/24/2025

Table 10.2.2 Senior design 2 Milestones

Milestone	Start Date	End Date
Acquisition of Final Components	TBD SD2	TBD SD2
Program Software Control	TBD SD2	TBD SD2
Build GUI to Control System	TBD SD2	TBD SD2
Sim results for timing of the system	TBD SD2	TBD SD2
Characterization of Polarization Switch	TBD SD2	TBD SD2
Final adjustments to meet expectations	TBD SD2	TBD SD2
Review and Adjust Report or Sim	TBD SD2	TBD SD2
Accomplish Stretch Goals	TBD SD2	TBD SD2

Work Distributions

Electrical Engineering	Responsibilities: Software	Hardware
Michelle Nguyen	• Initialize Motor Library • Initialize MCU pins to motor • Set motor speed	• Power Supply • Microcontroller • Motor Driver • Motor

	• Function: Calculate time for motor to spin to reach calculated degree • Set motor spin time • Break out of Switch Statement • Start motor • Stop motor	
Optical Engineering		
David "Austin" Rich	• Initialize MCU pins for laser diodes • If / Else Statement: Turn on/off laser diodes based on User Prompt • Read Power Measurement	• Laser Driver • Laser Diode 1 • Laser Diode 2 • Laser Diode 3 • Power Detector
Joshua Hendry	• GUI / User Prompt • Function: Calculate needed degree for selected polarization • Switch Statement: Case selection based on User Prompt (polarization selected) • Set motor angle • Display Power Measurement on GUI	• Laptop • Mirror • Retro-Mirror • Crystal • Polarizing Beam Splitter

Appendices

Appendix A: References

Ghosh, G. (1998). Handbook of optical constants of solids: Handbook of thermo-optic coefficients of optical materials with applications, Academic Press.

Ghosh, G. (1999). "Dispersion-equation coefficients for the refractive index and birefringence of calcite and quartz crystals." Optics Communications **163**(1): 95–102.

> The refractive index, birefringence and their dispersions are analyzed accurately in a physically meaningful model of a dispersion equation having only five coefficients for the calcite and quartz crystals. This dispersion equation is based on the average electronic absorption gap in the UV region and the effective lattice resonance absorption gap in the IR region. The five coefficients of the dispersion equation are different for each fundamental parameters. The dispersion equation for the birefringence leads to represent a standardized equation describing the birefringence of all optical materials.

Holmes, D. A. (1964). "Exact Theory of Retardation Plates*." Journal of the Optical Society of America **54**(9): 1115–1120.

> The conventional solutions to the problem of normally incident light transmission through homogeneous, birefringent, nonoptically active, nonabsorbing, crystalline plate are not exact. When it is treated as a boundary value problem in electromagnetic field theory, exact expressions are obtained for the retardation or phase difference and the electric field amplitude ratio. The two solutions differ in some interesting ways that become of substantial importance in the examination of laser light. The nature of the exact solutions is examined in detail and numerical comparisons with the conventional solutions are given for the cases of calcite and quartz, neglecting the optical activity of crystalline quartz. For quartz it is shown that one can obtain a quarter-wave plate by using any one of a number of different crystal thicknesses. The application of wave plates in the investigation of elliptically polarized light is briefly discussed. For small angles of incidence, the effects to be expected for light which is obliquely incident on the plate surface are investigated.

Lee, B., et al. (2025). "Double-pass rotating z-cut quartz plate as a rapidly variable waveplate." Optics Express **33**(13): 28739–28751.

> We demonstrate a rapidly tunable waveplate based on a rotating z-cut quartz plate in a double-pass configuration. In contrast to previous single-pass implementations, where angular rotation of birefringent crystals causes significant beam path displacement, we show that the double-pass geometry effectively suppresses beam walk-off, reducing lateral shifts to below 10 μm, which is stable enough to

have a fiber coupling. We present a full theoretical description of the polarization changes using Jones matrix calculations and verify it through polarization-resolved measurements. Additionally, the retardation is stable across a broad spectral range without requiring wavelength-specific optimization. When combined with a polarizing beam splitter, the system functions as a high-speed optical power modulator, achieving a dynamic power conversion in 1 ms with its contrast about 1000:1. This compact and robust design is particularly suited for atomic, molecular, and optical (AMO) physics experiments requiring rapid and precise control of light intensity.

Paranin, V. D. (2016). "Determination of the optical axis in Z-cut uniaxial crystals by a polarization-based method." Technical Physics Letters **42**(6): 559–562.

A polarization method is proposed for determination of the orientation of the optical axis in a Z-cut uniaxial crystal. The applicability of the method for controlling the deflection angles of the optical axis from the normal to the crystal surface ~0.01° was shown using the example of lithium niobate crystal with a thickness of 514 μm. Peculiarities of the practical implementation of this method and approaches for increasing its accuracy and throughput are considered.

Zallat, J., et al. (2012). "Double-pass self-spectral-calibration of a polarization state analyzer." Optics Letters **37**(3): 401–403.

We present a new method that allows efficient spectral calibration for a polarization state analyzer. The procedure does not require any additional polarization optical element other than the polarization state analyzer itself. It uses a double-pass technique that can be achieved up to a very good precision. The method is illustrated using real measurements done at several wavelengths with a rotating wave plate polarization state analyzer. Alignment of axis as well as true retardation at a specific wavelength are easily obtained by a standard function fitting.

Appendix B: Data Sheets and Reference Figures

Table 2. Comparison of the experimental and computed values of refractive index for the ordinary rays of calcite crystal

Wavelength (μm)	**Refractive index**		**Difference**	**R.I. (calculated) [2]**	**Difference**
	Experimental [1]	**This work**			
0.2040	1.88224	1.882184	0.000056	1.884897	−0.002657
0.2080	1.86733	1.866589	0.000741	1.868397	−0.001067
0.2110	1.85692	1.855997	0.000923	1.857550	−0.000630

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.2140	1.84558	1.846232	−0.000652	1.847669	−0.002089
0.2190	1.83075	1.831551	−0.000801	1.832931	−0.002181
0.2260	1.81309	1.813794	−0.000704	1.815199	−0.002109
0.2310	1.80233	1.802752	−0.000422	1.804197	−0.001867
0.2420	1.78211	1.782239	−0.000129	1.783761	−0.001651
0.2570	1.76038	1.760496	−0.000116	1.762065	−0.001685
0.2630	1.75343	1.753303	0.000127	1.754873	−0.001443
0.2670	1.74864	1.748894	−0.000254	1.750460	−0.001820
0.2740	1.74139	1.741830	−0.000440	1.743380	−0.001990
0.2910	1.72774	1.727493	0.000247	1.728974	−0.001234
0.3030	1.71959	1.719253	0.000337	1.720668	−0.001078
0.3120	1.71425	1.713869	0.000381	1.715229	−0.000979
0.3300	1.70515	1.704727	0.000423	1.705972	−0.000822
0.3400	1.70078	1.700410	0.000370	1.701590	−0.000810
0.3460	1.69833	1.698037	0.000293	1.699179	−0.000849
0.3610	1.69316	1.692717	0.000443	1.693764	−0.000604
0.3940	1.68374	1.683418	0.000322	1.684272	−0.000532
0.4100	1.68014	1.679808	0.000332	1.680578	−0.000438
0.4340	1.67552	1.675209	0.000311	1.675864	−0.000344
0.4410	1.67423	1.674022	0.000208	1.674645	−0.000415
0.5080	1.66527	1.665186	0.000084	1.665564	−0.000294
0.5330	1.66277	1.662745	0.000025	1.663052	−0.000282
0.5600	1.66046	1.660471	−0.000011	1.660711	−0.000251
0.5890	1.65835	1.658364	−0.000014	1.658543	−0.000193
0.6430	1.65504	1.655139	−0.000099	1.655229	−0.000189
0.6560	1.65437	1.654470	−0.000100	1.654542	−0.000172
0.6700	1.65367	1.653788	−0.000118	1.653842	−0.000172
0.7000	1.65207	1.652444	−0.000374	1.652465	−0.000395
0.7680	1.64974	1.649868	−0.000128	1.649834	−0.000094
0.7950	1.64886	1.648985	−0.000125	1.648935	−0.000075
0.8010	1.64869	1.648797	−0.000107	1.648745	−0.000055

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.8330	1.64772	1.647844	−0.000124	1.647778	−0.000058
0.8670	1.64676	1.646908	−0.000148	1.646831	−0.000071
0.9050	1.64578	1.645937	−0.000157	1.645852	−0.000072
0.9460	1.64480	1.644964	−0.000164	1.644874	−0.000074
0.9910	1.64380	1.643964	−0.000164	1.643873	−0.000073
1.0420	1.64276	1.642899	−0.000139	1.642812	−0.000052
1.0970	1.64167	1.641811	−0.000141	1.641732	−0.000062
1.1590	1.64051	1.640638	−0.000128	1.640572	−0.000062
1.2290	1.63926	1.639359	−0.000099	1.639311	−0.000051
1.2730	1.63849	1.638570	−0.000080	1.638535	−0.000045
1.3070	1.63789	1.637965	−0.000075	1.637940	−0.000050
1.3200	1.63767	1.637734	−0.000064	1.637714	−0.000044
1.3690	1.63681	1.636866	−0.000056	1.636862	−0.000052
1.3960	1.63637	1.636388	−0.000018	1.636392	−0.000022
1.4220	1.63590	1.635926	−0.000026	1.635939	−0.000039
1.4790	1.63490	1.634910	−0.000010	1.634940	−0.000040
1.4970	1.63457	1.634587	−0.000017	1.634623	−0.000053
1.5410	1.63381	1.633793	0.000017	1.633841	−0.000031
1.6090	1.63261	1.632548	0.000062	1.632614	−0.000004
1.6820	1.63127	1.631183	0.000087	1.631263	0.000007
1.7610	1.62974	1.629666	0.000074	1.629756	−0.000016
1.8490	1.62800	1.627922	0.000078	1.628012	−0.000012
1.9460	1.62602	1.625924	0.000096	1.626000	0.000020
2.0530	1.62372	1.623621	0.000099	1.623659	0.000061
2.1720	1.62099	1.620926	0.000064	1.620888	0.000102
			RMSD=0.0003		RMSD=0.0009

Table 3. Comparison of the experimental and computed values of refractive index for the extraordinary rays of calcite crystal

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.2040	1.57081	1.570667	0.000143	1.571153	−0.000343

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.2080	1.56640	1.566086	0.000314	1.566326	0.000074
0.2110	1.56327	1.562883	0.000387	1.562984	0.000286
0.2140	1.55976	1.559863	−0.000103	1.559855	−0.000095
0.2190	1.55496	1.555197	−0.000237	1.555060	−0.000100
0.2260	1.54921	1.549340	−0.000130	1.549099	0.000111
0.2310	1.54541	1.545575	−0.000165	1.545298	0.000112
0.2420	1.53782	1.538317	−0.000497	1.538024	−0.000204
0.2570	1.53005	1.530226	−0.000176	1.529982	0.000068
0.2630	1.52736	1.527455	−0.000095	1.527240	0.000120
0.2670	1.52547	1.525733	−0.000263	1.525538	−0.000068
0.2740	1.52261	1.522933	−0.000323	1.522775	−0.000165
0.2910	1.51705	1.517101	−0.000051	1.517029	0.000021
0.3030	1.51365	1.513654	−0.000004	1.513638	0.000012
0.3120	1.51140	1.511364	0.000036	1.511386	0.000014
0.3300	1.50746	1.507405	0.000055	1.507492	−0.000032
0.3400	1.50562	1.505505	0.000115	1.505623	−0.000003
0.3460	1.50450	1.504452	0.000048	1.504587	−0.000087
0.3610	1.50224	1.502071	0.000169	1.502242	−0.000002
0.3940	1.49810	1.497838	0.000262	1.498069	0.000031
0.4100	1.49640	1.496173	0.000227	1.496425	−0.000025
0.4340	1.49430	1.494035	0.000265	1.494310	−0.000010
0.4410	1.49373	1.493481	0.000249	1.493762	−0.000032
0.5080	1.48956	1.489333	0.000227	1.489643	−0.000083
0.5330	1.48841	1.488186	0.000224	1.488499	−0.000089
0.5600	1.48736	1.487121	0.000239	1.487433	−0.000073
0.5890	1.48640	1.486139	0.000261	1.486449	−0.000049
0.6430	1.48490	1.484658	0.000242	1.484955	−0.000055
0.6560	1.48459	1.484355	0.000235	1.484648	−0.000058
0.6700	1.48426	1.484049	0.000211	1.484336	−0.000076
0.7000	1.48353	1.483452	0.000078	1.483728	−0.000198
0.7680	1.48259	1.482345	0.000245	1.482589	0.000001

Wavelength (µm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.7950	1.48216	1.481980	0.000180	1.482209	−0.000049
0.8010	1.48216	1.481904	0.000256	1.482129	0.000031
0.8330	1.48176	1.481522	0.000238	1.481729	0.000031
0.8670	1.48137	1.481159	0.000211	1.481345	0.000025
0.9050	1.48098	1.480798	0.000182	1.480958	0.000022
0.9460	1.48060	1.480451	0.000149	1.480582	0.000018
0.9910	1.48022	1.480114	0.000106	1.480211	0.000009
1.0420	1.47985	1.479776	0.000074	1.479832	0.000018
1.0970	1.47948	1.479455	0.000025	1.479463	0.000017
1.1590	1.47910	1.479135	−0.000035	1.479087	0.000013
1.2290	1.47870	1.478817	−0.000117	1.478700	0.000000
1.3070	1.47831	1.478503	−0.000193	1.478305	0.000005
1.3960	1.47789	1.478185	−0.000295	1.477887	0.000003
1.4970	1.47744	1.477861	−0.000421	1.477441	−0.000001
1.6150	1.47695	1.477516	−0.000566	1.476942	0.000008
1.7490	1.47638	1.477155	−0.000775	1.476389	−0.000009
1.9090	1.47573	1.476745	−0.001015	1.475729	0.000001
2.1000	1.47492	1.476269	−0.001349	1.474921	−0.000001
3.3240	1.47392	1.472766	0.001154	1.468373	0.005547
			RMSD=0.0004		RMSD=0.0008

Table 4. Comparison of the experimental and computed values of refractive index for the ordinary rays of quartz crystal

Wavelength (µm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.1980	1.65087	1.650902	−0.000032	1.652553	−0.001683
0.2310	1.61395	1.613860	0.000090	1.614267	−0.000317
0.3400	1.56747	1.567554	−0.000084	1.567528	−0.000058
0.3940	1.55846	1.558504	−0.000044	1.558488	−0.000028
0.4340	1.55396	1.553960	0.000000	1.553956	0.000004
0.5080	1.54822	1.548240	−0.000020	1.548257	−0.000037
0.5893	1.54424	1.544206	0.000034	1.544238	0.000002

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
	Experimental [1]	This work			
0.7680	1.53903	1.538998	0.000032	1.539048	−0.000018
0.8325	1.53773	1.537711	0.000019	1.537763	−0.000033
0.9914	1.53514	1.535126	0.000014	1.535179	−0.000039
1.1592	1.53283	1.532823	0.000007	1.532872	−0.000042
1.3070	1.53090	1.530905	−0.000005	1.530949	−0.000049
1.3958	1.52977	1.529752	0.000018	1.529792	−0.000022
1.4792	1.52865	1.528651	−0.000001	1.528687	−0.000037
1.5414	1.52781	1.527813	−0.000003	1.527846	−0.000036
1.6815	1.52583	1.525857	−0.000027	1.525883	−0.000053
1.7614	1.52468	1.524690	−0.000010	1.524712	−0.000032
1.9457	1.52184	1.521832	0.000008	1.521845	−0.000005
2.0531	1.52005	1.520048	0.000002	1.520056	−0.000006
			RMSD=0.0003		RMSD=0.0004

Table 5. Comparison of the experimental and computed values of refractive index for the extraordinary rays of quartz crystal

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
Empty Cell	Experimental [1]	This work	Empty Cell	Empty Cell	Empty Cell
0.1980	1.66394	1.663972	−0.000032	1.665774	−0.001834
0.2310	1.62555	1.625459	0.000091	1.625948	−0.000398
0.3400	1.57737	1.577457	−0.000087	1.577594	−0.000224
0.3940	1.56805	1.568093	−0.000043	1.568306	−0.000256
0.4340	1.56339	1.563393	−0.000003	1.563673	−0.000283
0.5080	1.55746	1.557478	−0.000018	1.557888	−0.000428
0.5893	1.55335	1.553306	0.000044	1.553871	−0.000521
0.7680	1.54794	1.547917	0.000023	1.548871	−0.000931
0.8325	1.54661	1.546583	0.000027	1.547698	−0.001088
0.9914	1.54392	1.543901	0.000019	1.545459	−0.001539
1.1592	1.54152	1.541508	0.000012	1.543614	−0.002094
1.3070	1.53951	1.539513	−0.000003	1.542172	−0.002662
1.3958	1.53832	1.538312	0.000008	1.541337	−0.003017
1.4792	1.53716	1.537166	−0.000006	1.540556	−0.003396

Wavelength (μm)	Refractive index		Difference	R.I. (calculated) [2]	Difference
Empty Cell	**Experimental [1]**	**This work**	Empty Cell	Empty Cell	Empty Cell
1.5414	1.53630	1.536292	0.000008	1.539970	−0.003670
1.6815	1.53422	1.534253	−0.000033	1.538623	−0.004403
1.7614	1.53301	1.533036	−0.000026	1.537831	−0.004821
1.9457	1.53004	1.530055	−0.000015	1.535911	−0.005871
2.0531	1.52823	1.528194	0.000036	1.534722	−0.006492
			RMSD=0.00004		RMSD=0.003

(Ghosh 1999)

Appendix C: LLM Prompts and Responses