Automated Laser Beam Characterizer

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Chapter 2: Project Description

2.1: Motivation and Background

Since its invention by Theodore Maiman in 1960, the laser has become integral in many applications today. It is used in everyday objects such as bar code scanners and laser pointers, as well as more sophisticated applications such as lidar and imaging systems. When constructing these systems, it is often critical to know precisely the state of the laser beam being emitted. Basic characterizations of the laser beam include its divergence and beam waist, its M^2 factor, as well as its polarization and wavelength. While there are other aspects of the laser that are useful to know, many are either not as significant, or require interferometric techniques. This project entails designing a single system that measures all these factors. This can be useful in many applications which make use of laser technology. For instance, most laser applications require the laser beam to be as close to diffraction limited as possible, which requires an M^2 factor as close to one as possible. Additionally, many applications require knowledge of the polarization state of the laser, such as coherent lidar, imaging, as well as many laser welding and machining technologies. Similarly, many nonlinear effects in optics are affected by polarization, such as orders of harmonic generation, Pockels Effect, the Kerr effect, and many more. Thus, the state of any laser beams polarization is also critical to knowing how it will interact with other optical systems, and the accurate characterization of these things becomes essential to knowing how it will behave in a system.

2.2: Current Technologies and Existing Products

Presently, several technologies exist which measure some of these factors, however, none of them coexist in the same system. They can be broken down into four general systems. These are profilometers, polarimeters, spectrometers, and M^2 factor measurement devices. These will all be implemented into the system and are each discussed individually in the sections that follow.

2.2.1: Beam Profilers

Laser beam profilers come in two different types, based on their method of taking measurements. These two methods are the scanning slit method and the image sensor method. Both methods are used to determine the defined beam width of the laser beam at their aperture.

2.2.1.1: Scanning Slit Method

The scanning slit method consists of conducting several knife edge tests using a thin rotating fan blade in front of a power meter. The knife edge test works by recording the power on the detector as a thin blade crosses in front of the path of the beam. The derivative of the error function curve that results from this process is the profile of the beam. Then, the $1/e^2$ point on both sides of the profile is calculated and the distance between the two points is recorded. Assuming the beam is propagating in the fundamental mode, this distance is the diameter of the beam.

Below are some scanning slit profilometer products that can be found currently on the market today. The table below compares the products specifications.

Table 1: Scanning Slit Products			
Company	Ophir Optronics [1]	Thor Labs [2]	DataRay [3]
Part Number	PH00470	BP209-IR2	BeamMap2
Spectral Range	190 nm – 100 um	900 nm – 2700 nm	650 nm – 1800 nm
Power Range	5 mW – 100 W	1 mW – 10 W	< 1 W
Max Input Beam Diameter	6 mm	9 mm	3 mm

2.2.1.2: Image Sensor Method

The image sensor method simply uses an array of optoelectronic devices such as a photodiode array, CCD, or a CMOS sensor to visually record the spatial distribution of power of the laser beam on the sensor. Assuming the beam does not saturate the sensor, the peak value can be easily found, and a beam size can be calculated from the image using the $1/e^2$ point as discussed in the previous section. Below are a couple of examples of products that can be used to do this.

Table 2: Image Sensor Profilometer Products		
Company	Ophir Optronics [4]	Allied Vision [5]
Part Number	SP90404	CL-034 XSWIR
Sensor Type	InGaAs CMOS	InGaAs
Spectral Range	1.06 um – 3000 um	900 nm – 1700 nm
Dynamic Range	60 dB	69 dB
Sensor Size	320 x 320	636 x 508
Pixel Pitch	80 um	15 um

2.2.1.3: Beam Profiler Method Comparison

When comparing the two methods, each has its strengths and weaknesses. First, assuming the beam is in the fundamental mode, the scanning slit method can have much better resolution, often on the order of a single micron, whereas the image sensor is limited by the pixel size of the sensor. Additionally, the scanning slit profilometer can often accept much higher power levels and have much broader wavelength ranges than a CCD or CMOS sensor. On the other hand, when the beam is not propagating in the fundamental mode, there is often an uneven spatial distribution in the power of the laser beam, which would be much easier to see on an image sensor. This is because the scanning slit can only take a profile in one or two directions, limiting the device's ability to profile asymmetric beams. In this project, the laser will be assumed to be propagating close to the fundamental mode, where the scanning slit method will be implemented instead of an image sensor. This will be done using a simple power meter and two fan blades rotated in the path of the aperture to take the profile in the X and Y dimensions. This will offer a much cheaper option than most scanning slit profilometers on the market today while maintaining good resolution for accurate beam profiling measurements.

2.2.2: Polarimeters

When measuring the polarization of light, the Stokes Parameters are generally used to completely characterize the wave. While the Jones Vector can also be used, it is limited to beams that are fully polarized and therefore cannot be used in cases where the light is unpolarized or partially polarized. Therefore, the Stokes Parameters provide a more complete characterization of the polarization of light.

There are two methods that can be used to measure the Stokes Parameters. One is the Classical Method, and the other is the Rotating Quarter Waveplate Method. Both require a quarter waveplate (QWP), a linear polarizer (LP) and a power meter (PM). In the Classical Method, the QWP is fixed with its fast axis aligned to the horizontal axis of the system and the LP is allowed to rotate. Four power measurements are taken, the first three with just the LP in the path of the beam and the last one with both the QWP and the LP. The first three measurements are with the LP at 0°, 45°, and 90°. The final measurement is taken with the LP at 45° and the QWP inserted into the path of the beam before the LP. The Stokes Parameters can then be calculated from the following equations, where $I(\theta,\varphi)$ is the intensity measurement at LP angle θ and retardance of φ [6], [7].

$$S_0 = I(0°, 0°) + I(90°, 0°)$$

$$S_1 = I(0°, 0°) - I(90°, 0°)$$

$$S_2 = 2I(45°, 0°) - S_0$$

$$S_3 = S_0 - 2I(45°, 90°)$$

There are a few downsides to this method. First, the QWP will absorb some optical power, which will change how the equations depending on how much is absorbed. Additionally, the QWP will have to be realigned any time a new measurement needs to be taken. For these reasons, it is beneficial to make use of the second method, the Rotating Quarter Waveplate Method.

In the Rotating Quarter Waveplate Method, an LP is fixed in the horizontal axis and a QWP is allowed to rotate in the path of the beam before the LP. According to Mueller Calculus, the QWP and LP will change the Stokes Parameters by the following transfer matrices[8]:

$$QWP(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos^2(2\alpha) & \cos(2\alpha)\sin(2\alpha) & \sin(2\alpha) \\ 0 & \cos(2\alpha)\sin(2\alpha) & sin^2(2\alpha) & -\cos(2\alpha) \\ 0 & -\sin(2\alpha) & \cos(2\alpha) & 0 \end{bmatrix}$$

$$LP(\beta) = \frac{1}{2}\begin{bmatrix} 1 & \cos(2\beta) & \sin(2\beta) & 0 \\ \cos(2\beta) & cos^2(2\beta) & \cos(2\beta)\sin(2\beta) & 0 \\ \sin(2\beta) & \cos(2\beta)\sin(2\beta) & sin^2(2\beta) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

where α and β are the angles of the QWP fast axis and the transmission axis of the LP with respect to the horizontal axis, respectively. Thus, assuming the LP is fixed at 0 degrees and the QWP fast axis is at some arbitrary angle θ, the output intensity can be written as a linear combination of the input Stokes Parameters shown in the equation below:

$$I(\theta) = \frac{1}{2}(S_0 + S_1 cos^2(2\theta) + S_2 \cos(2\theta)\sin(2\theta) + S_3 \sin(2\theta)$$

where S_0, S_1, S_2, and S_3 are the Stokes Parameters of the input laser beam. Thus, by measuring the power transmitted through the LP at different QWP angles, it is possible to completely characterize the polarization state of the laser beam [6], [7]. This is how many polarimeters operate, including those shown below.

Table 3: Polarimeter Products		
Company	Thor Labs [9]	OZ Optics [10]
Part Number	PAX1000IR2(/M)	ER-100-IR
Spectral Range	900nm – 1700 nm	850 nm – 1650 nm
Sampling Rate	30 – 400 Samples/s	Unknown
Poincare Sphere Accuracy	±0.25°	Unknown
Aperture	3 mm	Fiber coupled

2.2.3: M^2 Factor Measurements

The M^2 factor of a Gaussian beam is a number that represents the quality of the beam. In an ideal beam, the M^2 factor is one. However, if the beam is aberrated, the beam quality degrades and the M^2 factor increases. Mathematically, this is described by the equation below, where θ is the far field divergence of the beam and w_0 is smallest spot size of the beam, known as the beam waist. The M^2 factor is measured using a profilometer and measuring the size of the beam at different points along its axis of propagation. Since the Rayleigh range of most lasers is much too long to practically measure enough points to characterize the beam quality, a lens is placed in the path of the beam to shorten the Rayleigh range to a measurable value. This lens must not induce any aberrations to the beam or else the M^2 measurement will not be accurate. With beam divergence and waist much easier to measure, the profilometer can be used to measure the M^2 factor [11]. More will be said on this measurement procedure in Chapter 4 in the Final Report which will discuss the ISO Standards for this measurement.

$$\theta = M^2 \frac{\lambda}{\pi w_0}$$

Below are a couple of products that can be found in the market today that measure M^2 this very way.

Table 4: M^2 factor Measurement Products		
Company	Thor Labs [12]	Gentec-EO [13]
Part Number	M2MS-BP209IR2	BEAMAGE-M2
Spectral Range	900 – 2700 nm	350 – 1100 nm
Lens Focal Length	250 mm	200 mm – 500 mm
Effective Travel Range	200 mm	400 mm
Aperture Size	9 mm	48 mm
Max Power Density	< 1W*	CW: 10W/cm^2 @1064

Measurement Time	15 – 30 s	45 s
Measurement Accuracy	±5%	±5%

*See Figure 1 below

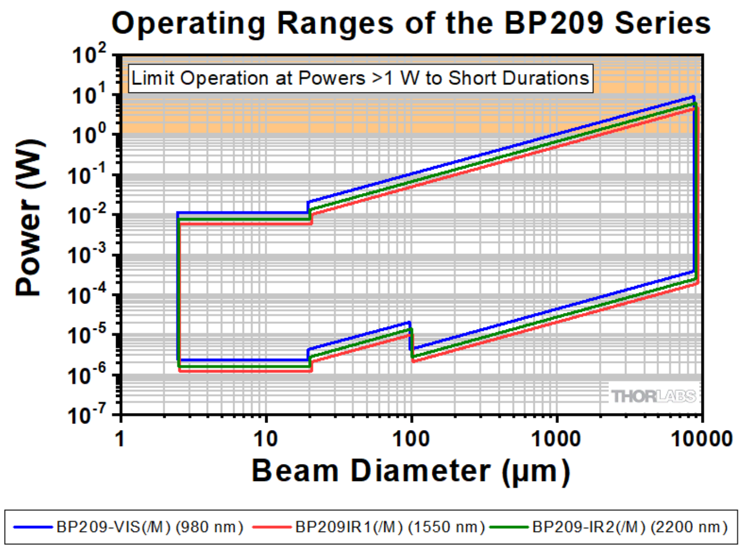

Figure 1: Thor Labs BP209 Power Density Safe Region [2]

2.2.4: Spectrometers

Spectroscopy has its roots much deeper in history than most of the rest of the topics in this project. Starting with Isaac Newton first showing how white light disperses through a prism, to Thomas Young demonstrating the wave nature of light in his famous double slit experiment, culminating in William Hyde Wollaston and Joseph von Fraunhofer independently building the first spectrometers, the wavelength of light became essential to its characterization. Most spectrometers today use a diffraction grating to disperse light into its spectral lines. Below are some commonly used spectrometers in industry today.

Table 5: Spectrometer Products			
Company	Ocean Optics [14]	StellarNet [15]	B&W Tek [16]
Part Number	NIRquest-512-2.5	DS-NIR-512	BWS005A-20
Spectral Range	900 – 2500 nm	900 – 1700 nm	1100 – 2200 nm
Resolution	6.3 nm	1.25 nm	13 nm
Slit Size	10 – 200 um	25 um	N/A

2.2.5: Summer/Fall 2022 UCF Senior Design Project

As it happens, a previous UCF senior design project has done something similar, though for a different purpose. In the summer and fall of 2022, a group sponsored by CMS Laser built a system that was designed to measure the beam profile and M^2 factor of a laser beam. The group was comprised of one Optical Engineer, two Electrical Engineers, and one Computer Engineer. Their application, however, focused on high power lasers, and thus their application included several reflective wedges that were used to cut the power down enough to make the required measurements. The system built for this project, however, will have a different focus, since the task consists in integrating several measurements into one system.

2.3: Goals and Objectives

In this section, the basic, advanced, and stretch goals and objectives are outlined. The goals describe some of the broad overarching things this project hopes to achieve, whereas the objectives outline the specific ways in which this project will implement technologies to achieve its goals. The basic goals and objectives should be relatively easy to achieve, whereas the advanced goals and objectives represent the more complex and difficult tasks, and the stretch goals and objectives represent those that will only be implemented if there is found to be extra time and resources to do so.

Table 6: Goals and Objectives

	Goals	Objectives
Basic	Measure Polarization	Motorized Quarter Waveplate
		Fixed Linear Polarizer
		Power meter
	Measure Wavelength	Diffraction Grating
		Photodiode array
	Measure M^2 factor	Achromat lens
		Power meter with scanning slits
	Measure Divergence	Homing location for Power meter at focal point of achromat
	Light weight	Ensure total system is under 30 lbs.
	Under Budget	Follow Bill of Materials as close as possible
	Easy User Experience	Implement reference mirror and/or irises for ease of alignment
		User friendly GUI
Advanced	Allow for large input power	Design all components to function at necessary power density level
		Implement removable ND filter
	Allow for large input beam size	Design components to have at least 25.4 mm clear aperture size
	Detect potential measurement errors in M^2	Implement checks into data processing of parameters
Stretch	Measure Input Waist Size and Location	Use M^2 measurements to calculate waist parameters
	Allow for broad range of input wavelengths	Use achromatic components
		Design Fabry Perot Etalon to measure wavelength

	Include M^2 measurement error correction procedures	Implement algorithms to fix errors in measurements that do not follow ISO standards
	Report Beam Wavelength and Polarization measurements live	Implement necessary communication protocol with PC to report new measurements continuously
	Allow for pulsed lasers	Make scanning slits fast enough to be able to profile moderately pulsed lasers

2.4: System Design

2.4.1: Hardware

Below is a general diagram of the flow of the system's hardware. The system's hardware involves not only aligning optical components, but more importantly integrating them all to work precisely and harmoniously. While the block diagram shows a general work distribution, many of the components required communication across the team to make sure the designs would fit the project. For example, when choosing a focal length, it was necessary to know the resolution that could be achieved by the stepper motor used to translate the power meter across the path of the focused beam. Since ISO 11146 Standard requires at least five points within the Rayleigh Range to obtain an accurate measurement, this means that the smallest step size of the chosen stepper motor must be at least five times smaller than the Rayleigh Range of the focused beam.

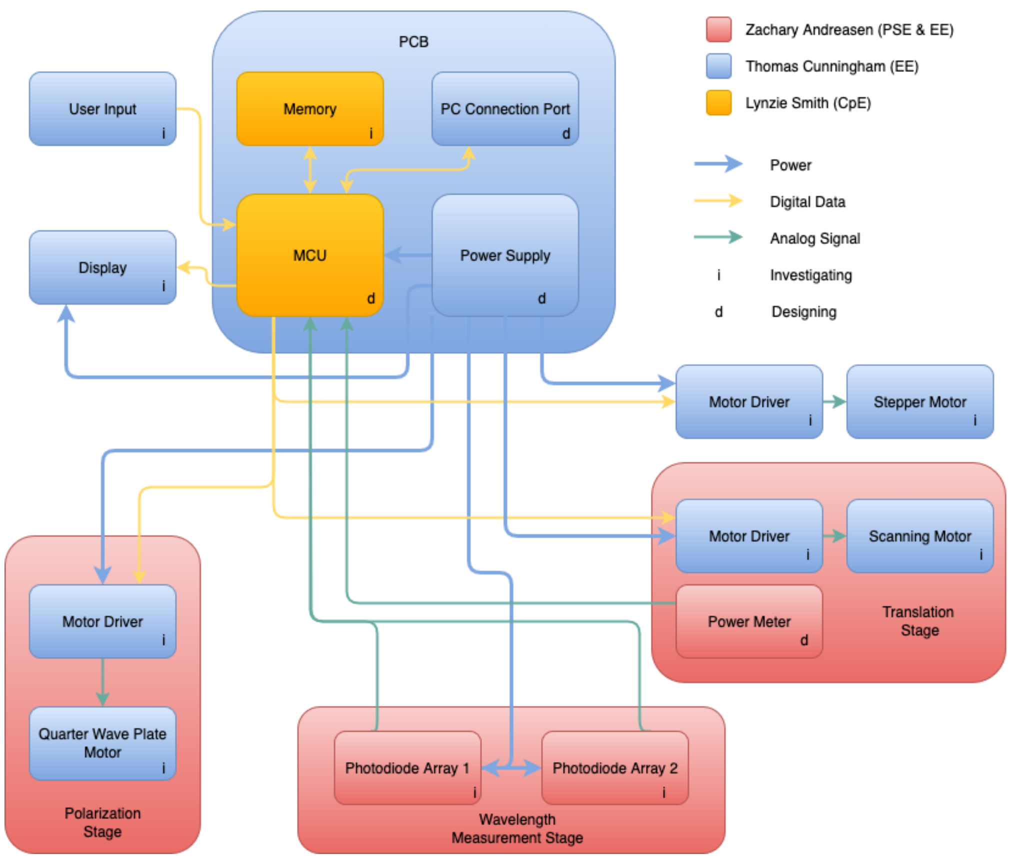

Figure 2: Laser Beam Characterizer Hardware Block Diagram

2.4.1.1: Optics

Below is a general sketch of the layout of the optics in the system. As can be seen, the system is designed to have minimal deviations to the laser beams path to minimize the possibility of misalignment. The system is laid out such that the polarimeter components come first, followed by the diffraction grating, and then the M^2 analysis section.

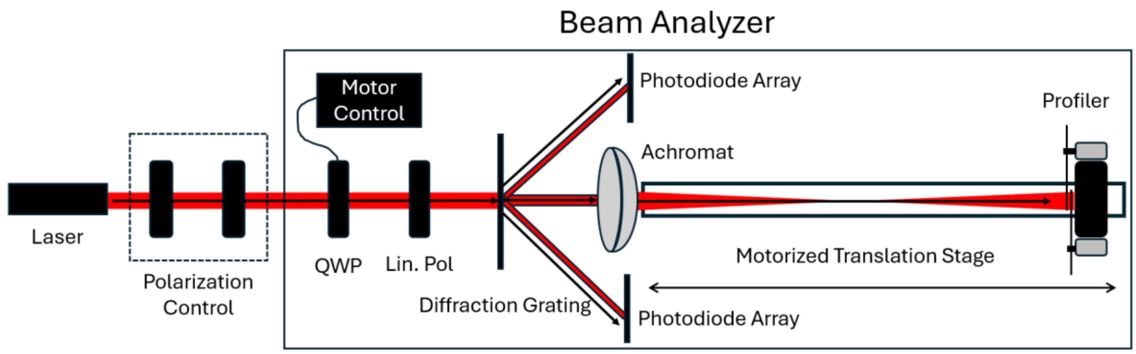

Figure 3: Layout of Optical System Components: Quarter Waveplate (QWP) and Linear Polarizer (Lin. Pol) will be used in the polarimeter setting; the Photodiode Arrays will be used to measure the wavelength; the profiler will be moved across the motorized translation stage to take the M^2 measurement

2.4.1.2: Motors

We are using a stepper motor for the translational stage combined with a lead screw for its dimensional accuracy. Stepper motors provide precise angle control, and when combined with a lead screw provide accurate dimensional control as well. A common application of this setup can be found on CNC machines.

We are also using a stepper motor system to rotate the QWP for angular accuracy. We need to be able to precisely rotate the QWP to sync with the power measurements.

On the power meter we will use a DC motor with velocity control to operate the scanning slits. We need a constant velocity to perform the optical calculations. A DC motor is a good choice because it is very simple and effective.

2.4.1.3 Microcontroller

We're choosing an STM32 as the main MCU because it gives us the best mix of precise motion control for the motor systems and stable data capture. Its advanced timers make stepper moves (QWP, polarizer, slit) smooth and repeatable which is important for data collection and measurements, and its SPI + DMA handles a 24-bit ADC without jitter while we sample power and profiles of the laser beam. It also gives us USB/Ethernet for a quiet, reliable link to the PC/UI.

We had first thought of using an ESP32 MCU, but we had concerns about its processing power for all the calculations and measurements needed for this project. After realizing that the STM32 had better processing capabilities and it was more suitable for motor control we ultimately decided to go with the STM32 instead of ESP32.

2.4.2: Software

On the MCU side of the software process, it will be running a simple loop: move, settle, sample, send. It uses the hardware timers built into the microcontroller to make the motion repeatable, reads the 24-bit ADC, averages a handful of samples, and timestamps the result. For polarization and M^2,it does light math computations on the fly and returns raw data point or computed numbers.

For the PC/UI side, we will need to be able to pick what measurement (polarization, M^2, wavelength) and set the parameters for those measurements (angles, z-positions, samples per point, wavelength). The PC/UI will send the plan to the MCU, which runs its loop, then shows live plots as the data arrives – intensity vs angle with a fitted curve and a polarization ellipse. It should display clean numerical values, logs all setting and results, and can export a CSV/PDF report at the end. Below is a block diagram that shows how this software process will work.

Figure 4: Laser Beam Characterizer Software Block Diagram

2.5 Specifications

Table 7: System Specifications

Input Beam Specifications	
Parameter	**Value**
Wavelength	At least 1um
Max Power	1 - 10W
Minimum Power	1 - 50mW
Beam Diameter	12.7 - 35mm
Measurement Specifications	
Measurement	**Accuracy**
Normalized Stokes Parameters	±0.1 for all parameters
Wavelength	±10 nm
M^2 factor	±0.1
Beam Divergence	±10 urad
Total Power	Within 1%

Table 8: Component Specifications

Optical Components		
Component	**Parameter**	**Specification**
QWP	Spectral Range	Cover 1 um
	Phase Delay	π/2 @ 1um
Linear Polarizer	Extinction Ratio	<-30 dB
Power Meter	Aperture Size	4 - 10 mm
	Power Intake*	1mW – 1W
ND Filter	OD Level	2
Achromat Lens	Spectral Range	800 nm – 1550 nm
	EFFL	600 - 1000 mm
Diffraction Grating	Lines/mm	250
Electrical Components		
Photodiode Array	Spectral Range	Accept 1 um
	Resolution	< 2.5 mm
Scanning Slits	Scan Rate	10-20 Hz
Translation Stage	Step Resolution	< 50 um
QWP Rotation Stage	Angle Resolution	< 22.5 deg
Computer Components		
MCU	GPIO sample frequency	At least 200 Hz

*Power level of Power meter can be less than system input power when ND filter is applied

2.6 House of Quality

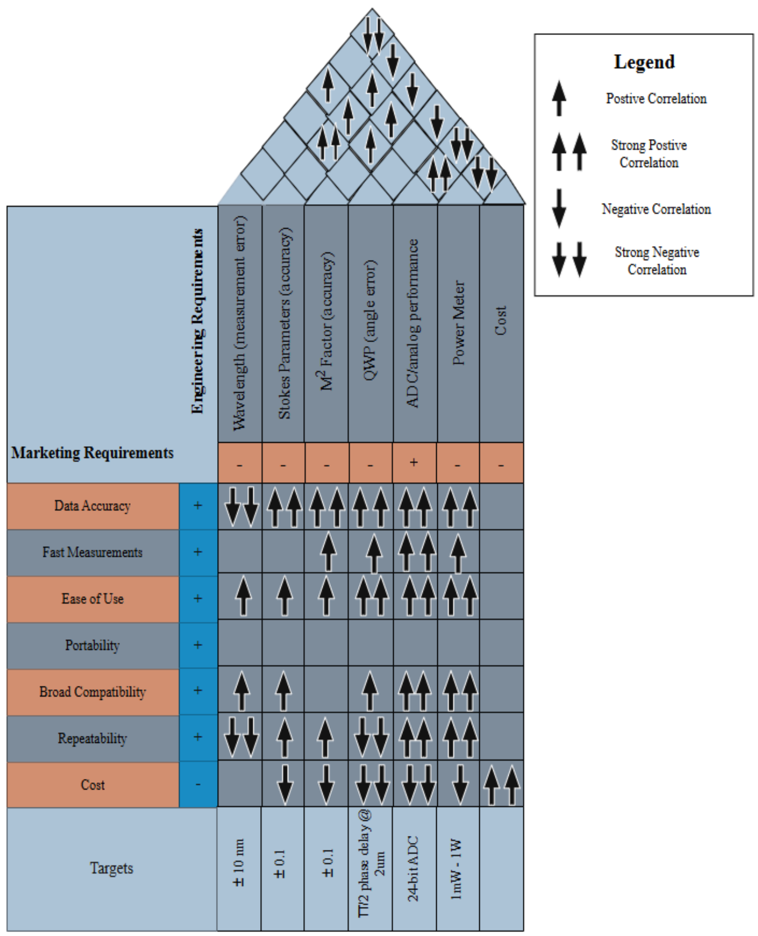

Figure 5: Laser Beam Characterizer House of Quality

Chapter 10: Administrative Content

10.1 Bill of Materials

	Component	Quantity	Estimated Unit Price	Cost
Optics	QWP	1	$250	$250
	Linear Pol.	1	$800	$800
	Diff. Grating	1	$50	$50
	Photodiode Circuit	2	$300	$600
	Achromat	1	$1000	$1000
	ND Filter	1	$50	$50
Motors	Translation Steppers	1	$30	$30
	Rotation Mount Steppers	1	$30	$30
	Scanning Slits	2	$15	$20
MCU	STM32	1	$100	$100
Misc.	Power Meter	1	$500	$500
			Total	$3330
			Budget	$3500

10.2 Milestones

10.2.1 Senior Design 1 Milestone Table

Milestone Number	Milestone Description	Start Date	Anticipated End Date
1	Group Forming	8/18/2025	8/26/2025
2	Project Idea Finalized	8/18/2025	9/5/2025

3	D&C Document and Committee Formation	8/25/2025	9/5/2025
4	D&C Meeting	9/8/2025	9/10/2025
5	Midterm Milestone Report	9/30/2025	10/31/2025
6	Midterm Milestone Report Revision	11/3/2025	11/7/2025
7	Final Report	10/31/2025	11/25/2025
8	Mini Demo Video	11/17/2025	11/25/2025

10.2.2 Senior Design 2 Milestone Table

Milestone Number	Milestone Description	Start Date	Anticipated End Date
1	PCB Testing	1/12/2026	1/30/2026
2	System Integration/Testing	2/2/2026	3/2/2026
3	Documentation Finalized	2/2/2026	4/13/2026
4	Final Presentation Practice	4/14/2026	4/20/2026
5	Final Presentation	TBD	TBD

Appendices

Appendix A - References

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