Digital Transmission in Free Space through a High-Power Laser

UCF Senior Design I

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Chapter 1 Executive Summary

This senior design project focuses on developing a wireless communication system that uses a laser over free space to transmit binary-coded messages. The goal is to demonstrate a proof-of-concept for terrestrial free-space communications and communications from space through optical means.

The idea draws on historical advancements in communication, starting with the electric and wireless telegraph, and later, the introduction of lasers and fiber optics. These technologies transformed long-distance communication, and our project aims to develop a long-distance communications system based on lasers.

The system will transmit binary code using pulses of light in open air. These pulses will represent digital data, allowing for precise, high-speed transmission. Lasers, especially high-power lasers, can transmit large amounts of data over the same amount of bandwidth compared to radio waves due to laser light typically having a higher frequency. In addition to large-data transmission, optical free-space transmission maintains signal fidelity over vast distances and is coherent, typically at several kilometers.

On the transmission side, a laser diode will be used as the light source. Compared to LEDs, laser diodes offer greater directionality and efficiency due to stimulated emission, concentrating light effectively into the fiber. On the receiving end, a photodiode will detect the light pulses and convert them into electrical signals. Because binary code consists of two clear states—on and off—the photodiode can accurately interpret the signal based on pulse timing and duration. Photodiodes also operate across a wide spectral range, and selecting one that matches the 520 nm wavelength of our green laser diode ensures reliable detection.

As the laser will operate in a binary fashion, it will only need data to be fed through an encoder/microcontroller circuit through on-off keying modulation. The laser will then transmit the data, which will then hit an optical amplifier within the path of propagation. The amplified light will then be re-transmitted at a photodiode-based receiver, decoding the signal, and displaying the signal on an LCD screen.

This project also reflects broader trends in communication technology, where lasers can completely replace radio-based technology in applications that require high-speed transmission of large packets of data with low loss, such as astronomy, global navigation, imaging from space, meteorology, and more. It can also revolutionize encrypted communications and cybersecurity, as it will be difficult to hijack laser transmissions without optical detection equipment, especially with invisible lasers like those in the infrared range.

In summary, this project aims to showcase the potential of a wireless communication system that uses a laser for signal transmission and delivery. By modulating binary code

into light, the system demonstrates a modern, efficient, and low-loss alternative to traditional communication methods.

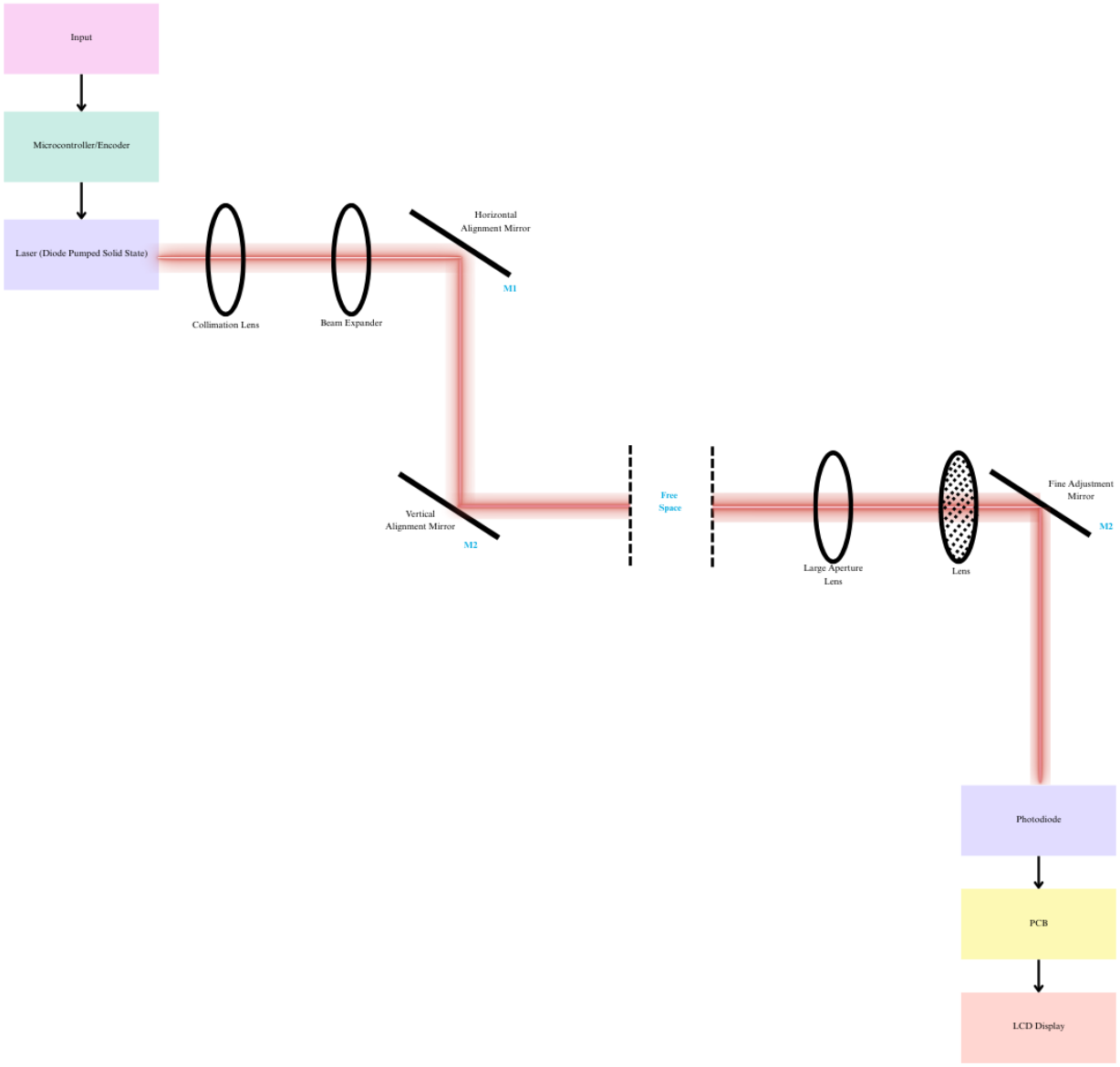


Figure 1.1: 2D Prototype Illustration

Chapter 2 Project Description

Overview

This chapter will cover the motivation and background, goals and objectives, functionality, existing products, engineering requirements, and hardware block diagram of the project.

2.1 Motivation & Background

The invention of the electric telegraph in the mid-19th century and the development of wireless telegraphy in the early 20th century revolutionized long-distance communication. The introduction of lasers and optical fiber technology in the 1950s and beyond ushered in a new era of high-speed data transfer, laying the foundation for the Internet and modern digital communications. Our senior design project aims to design a communication system using a high-power laser transmitting binary signals in open air. The signal will essentially be sent as light pulses. Our goal is to build a wireless communication system that leverages optical transmission to rapidly transmit huge packets of data over the air.

A typical communication system consists of three core components: a transmitter, a channel, and a receiver. The transmitter encodes and modulates the input message for efficient transmission. In digital communication systems, this process involves an analog-to-digital (A/D) converter. The channel refers to the medium used to carry the signal, such as air, copper wire, radio waves, and optical fiber. The receiver then demodulates and decodes the signal while correcting for any distortions introduced during transmission (Lathi & Ding, p. 2-3). Our project focuses on transmitting digital signals—in the form of binary code—through optical fibers and converting them into radio waves for wireless communication.

The transmission of binary signals through lasers utilizes pulse-code modulation, meaning that signals are transmitted as a 1s or 0s, respectively (Lathi & Ding, p. 7). In the case of a laser, the 1s and 0s will be represented as a series of on-and-off pulses. In a world of rapid gigabit and terabit transmissions, these lasers will have to operate at gigahertz to terahertz frequencies and will be suitable for transmitting a digital file like a PNG image.

For the light source, a laser diode is used instead of an LED. Laser diodes emit light through stimulated emission, producing coherent light with a consistent phase, direction, and polarization. This allows for a focused and efficient light signal that can stream data over vast distances. LEDs, by contrast, emit light via spontaneous emission in random directions, which is less effective for long-distance transmission (Kasap, p. 281-82).

At the receiving end, a photodiode is used to detect the light pulses. Photodiodes are commonly used in digital optical communication systems because they are highly sensitive to modulated light signals. Since binary code is composed of two states—on and off—it can be effectively represented and detected through the presence or absence of laser pulses. Photodiodes are also capable of detecting a wide range of wavelengths,

typically between 300 nm and 1700 nm for Si and InGaAs PIN photodiodes, with increased sensitivity at higher wavelengths (Kasap, p. 399). Since a green laser of 520 nm will be used for this project, a photodiode with optimal sensitivity at that wavelength will be selected.

The evolution of free-space communications will increasingly integrate optical transmissions in situations where speed and signal integrity are critical, situations where radio-based communications fail. Emergency responders and operators require systems that are flexible, low-loss, and high-speed, especially in remote or off-grid environments. Since terrestrial weather conditions and space weather hitting the ionosphere can easily affect radio propagation, laser-based communications can avoid this issue by being line-of-sight (independent of ionospheric conditions) while also covering long distances without sacrificing signal quality.

This project aims to demonstrate that optical technologies can be developed for compact, efficient, and robust wireless communication systems capable of operating in harsh or unconventional conditions. It can also present a case of optical technology being useful for next-generation wireless communications and potentially consumer applications.

2.2 Goals

This project is all about building a wireless communication system that uses laser-based transmission to reduce signal loss and interference while maintaining high signal quality. The idea is to encode binary code into laser pulses, sending those pulses over the air, and have a photodiode receiver detect these pulses and decoding them into a readable file.

At its core, the goal is to develop a reliable transmitter-receiver setup using a high-power laser and pulse-coded modulation to enable stable, interference-free communication. From there, the plan is to enhance the system by improving signal quality, extending transmission range, integrating microcontroller-based decoding, and making the design lightweight and portable.

If successful, the project's stretch goals include adding bi-directional communication, error correction, encryption, higher-speed optical modulation, and scalability for off-grid or emergency use.

Ultimately, this project aims to show that optical technologies can be implemented to create flexible, durable, and efficient communication systems that offer clear advantages over traditional wired solutions in a range of environments.

2.2.1 Basic Goals

- Develop a system that encodes binary code into optical signals using a laser diode. It will successfully transmit binary messages over free space while ensuring minimal signal loss. Additionally, a receiver will be implemented to decode the optical signals back into binary code, completing the communication process.

- Use pulse-coded modulation to ensure clear and noise-resistant transmission of digital signals

2.2.2 Advanced Goals

- Design a compact, lightweight system suitable for outdoor and off-grid communication.
- Develop a microcontroller-based system to decode binary code signals in real time.
- Optimize transmission efficiency to extend the communication range while minimizing attenuation.

2.2.3 Stretch Goals

- Implement a system that allows for two-way communication using the same laser-based setup

2.3 Objectives

This project is all about designing, building, and implementing a wireless communication system that uses optical fiber to encode and transmit binary code via a high-power green laser. The goal is to improve transmission efficiency and reduce signal loss compared to radio-based transmission.

By combining a 520 nm green laser and pulse-coding modulation with microcontroller-based processing, this system will offer a high-quality, interference-resistant, and high-speed solution. Ultimately, the aim is to create a lightweight, flexible, and scalable communication system that can be used for emergency situations, off-grid networks, and modern wireless applications.

2.4 Description of Features/Functionalities

The laser-based digital transmission system incorporates several innovative features aimed at providing an efficient, lightweight, and reliable communication solution. The optical transmission system includes a solid-state laser diode transmitter, a guidance system with mirrors and a collimator-beam expander lens combo, and a photodiode receiver. The transmitter uses a green laser diode as the optical signal source, encoding data into light pulses to represent binary code. These pulses are transmitted over the air at high power, which ensures low attenuation and distortion, making it suitable for long-distance communication. At the receiving end, a photodiode detects the light signals and converts them into electrical signals for further processing. The combination of these components offers a portable, cost-effective alternative to traditional radio modulation technology and coaxial cable systems.

The system’s modulation and decoding functionalities rely on an analog-to-digital modulator circuit and a microcontroller-based decoder. The modulator precisely controls the laser diode’s on/off state to generate binary pulses. On the receiving side, the microcontroller interprets the electrical signals from the photodiode, accurately decoding the binary data by analyzing the timing and duration of the pulses. Custom software

processes the decoded data, maps it to corresponding textual messages, and displays it on connected devices. This functionality makes the system flexible and user-friendly, accommodating various signal speeds while ensuring reliable message transmission.

To support its core functionalities, the system includes well-designed power and control systems. A regulated power supply for the laser diode ensures consistent signal output and prevents damage due to current fluctuations. The microcontroller manages timing and synchronization for both modulation and decoding, maintaining precise communication and minimizing errors. These features collectively enhance the system's reliability and robustness under diverse operating conditions.

2.4.1 Input from Customers and Market Analysis

The design of the Optical-Radio Communication System is informed by input from target users and an analysis of comparable technologies. The system caters to three main user groups. Amateur radio enthusiasts value lightweight and portable communication solutions, giving enthusiasts another avenue to explore in the world of wireless communications. Emergency response teams require off-grid, high-speed communication systems, and the low-loss transmission offered by laser beams ensures reliable operation in remote areas. Earth and space scientists like meteorologists and astronauts have expressed interest in exploring cost-effective alternatives to radio-based systems for linking relay stations or station-to-station communication and communicating with satellites.

A review of comparable products and technologies further influenced the project's features. Traditional coaxial cable systems, while reliable, are heavier and prone to signal loss over long distances, highlighting the advantage of optical fibers for this application. Radio waves can be affected by unstable changes in the ionosphere from space weather and attenuated by weather. Existing digital binary code transmitters, although efficient, often lack the simplicity and adaptability of analog modulation, particularly in resource-constrained scenarios where this system excels. Additionally, light-based communication systems such as LiFi inspired the optical design, especially the use of single-mode fibers for long-distance transmission. However, unlike LiFi, which focuses on high-speed data transfer, this project prioritizes robustness and simplicity for a variety of amateur and professional applications.

2.4.1.1 Summary of Features

The laser-based digital communication system offers a viable alternative to radio-based free space communications to deliver a lightweight, portable, and flexible solution. Its core features include line-of-sight communications, efficient binary code decoding, high speed and capacity, and low-cost components optimized for long-distance communication. Custom software ensures seamless integration with existing communication platforms, addressing user needs for simplicity, adaptability, and robustness. These features make the system particularly relevant for amateur radio enthusiasts, emergency responders, and commercial radio operators.

2.5 Existing Product/Past Projects/Prior Related Work

Although free-space laser communications are still in their infancy, they have promising applications in satellite communications (SATCOM) and terrestrial communications.

So far, NASA demonstrated the possibility of such a technology through their Laser Communications Relay Demonstration (LCRD), which uses lasers for space-to-space communications with low Earth orbit satellites and also terrestrial applications. Companies are interested in taking advantage of this technology by launching networks of satellite constellations, which are proposed to number in the hundreds to thousands to provide global broadband coverage. NASA was also demonstrating direct-to-Earth capabilities from geosynchronous orbits to support future missions, which will allow them to transmit more data than with radio waves. The development of the LCRD was assisted by collaborations with the Massachusetts Institute of Technology's Lincoln Laboratory (who designed the optical module), L3Harris Technologies, SEAKR Engineering, Moog Inc., and the Sierra Nevada Corporation, which developed the rest of the telescope system, controller electronics system, and space switching unit. In the foreseeable future, NASA will cut costs to future missions by utilizing their Low-Cost Optical Terminal (LCOT), growing the aerospace industry, and collaborating with the Department of Defense on satellite launches (Schauer, 2021).

Aside from developing the optical module for NASA, MIT's Lincoln Laboratory developed their own TeraByte InfraRed Delivery (TBIRD) system that can transmit at least 100 gigabits per second and was placed on a CubeSat, which enabled transmission of terabytes of data from the CubeSat to a ground receiver based in California. The payload system was all designed in a container the size of a tissue box, demonstrating compact and low-cost optical communication systems that can transmit and receive in free space. The TBIRD payload consisted of a high-rate optical modem, large high-speed storage drive, and an optical signal amplifier, which went through simulations in harsh space conditions to ensure that the payload will remain intact while in space. With data loss, the laboratory developed a protocol called the Automatic Repeat Request (ARQ) to account for errors in data transmission by having the satellite re-transmission missing or damaged blocks of data. TBIRD also lacks a gimbal to stabilize the laser beam, so the laboratory developed an error-signaling concept that alerts the CubeSat to point at the ground station and provides the additional benefit of further miniaturization of the payload (Tantillo, 2022)

Another initiative in laser-based satellite communications was started by the International Centre for Radio Astronomy Research at the University of Western Australia to build a network of infrared laser base stations with two ground stations and a mobile station. The lasers operate at 200 THz, and the network was able to successfully capture signals from a German low-Earth orbit satellite. An optical telescope was used to guide a laser beam encoded with data towards a specific satellite. The telescope was equipped with optical terminals to filter and process signals received from the satellite, which gets read by the optical modem and turned into a digital signal. The network, dubbed TeraNet, was made with available parts and was an attempt to show that it's possible to build a free-space optical communications network without a large budget (Boyd, 2024).

On October 16th, 2024, the European Space Agency (ESA) started developing Element #1 for its HydRON (High throughput Optical Network) in a partnership with Canada-based Kepler Communications. Like the LCRD and the TeraByte InfraRed Delivery system, is a system interfacing satellites and ground stations to transfer data between both entities. It consists of a ring of 10 LEO (Low-Earth Orbit) satellites that will provide a foundation for developing a robust satellite-based communications system for ground users. It will be developed to seamlessly connect with fiber optic networks to create a global network that can enhance advanced 5G networks and power AI and IoT (Internet of Things) technologies (ESA, 2024)

Laser-based communications are currently limited to satellite-based communications and currently suffer from data loss from fluctuations in atmospheric conditions, so this project will aim to take this revolutionary technology and design it for purely terrestrial communications.

2.6 Engineering Requirements

The Engineering Requirements Table defines the key performance metrics and technical specifications necessary for the system's design and functionality. It includes parameters such as transmission distance, signal modulation, decoding accuracy, power efficiency, and component-specific values (e.g., VCO frequency range, Op-Amp bandwidth, and laser diode wavelength) to ensure reliable, high-quality, and interference-resistant communication.

Table 2.1: Engineering Requirements Table

Requirement	**Specification/ Target Value**	**Purpose**
Optical Transmission Distance:	≥ 1 km	Ensures reliable communication over long distances
Decoding Accuracy:	≥ 95% Accuracy	Ensures reliable binary code interpretation
Data Transfer Rate:	500 Kbps - 1 Mbps	Allows flexibility in signal speed for different applications
Expected Power Consumption:	≤ 5W	Optimized for low-power, battery-powered operation

Optimal Transmission Distance:	1-2 km	Ensures optimal signal integrity and low attenuation
Power Efficiency:	≥ 85% efficiency, ≤ 5% voltage ripple	Ensures portability and long operational life
Portability & Durability:	Lightweight & Rugged Design	Suitable for field and emergency communication
Interference Immunity:	≥ 40 dB reduction in EMI	Optical transmission eliminates electromagnetic interference

2.6.1 Demonstrable Specifications

The Optical-Radio Communication System is designed to meet key performance targets that ensure reliable and efficient communication. It supports a minimum optical transmission distance of 1 km using single-mode optical fiber, with testing focused on maintaining signal integrity over varying lengths. The system is capable of transmitting binary code at speeds equivalent to 10 words per minute or more, with demonstrations confirming accurate end-to-end delivery.

A microcontroller-based decoder interprets received binary signals with at least 95% accuracy, validated through predefined message testing. Additionally, the system supports a minimum data transfer rate of 100 bits per second, with performance verified across a range of 50 to 200 bps. Together, these specifications demonstrate the system's capability to provide long-distance, high-accuracy, and interference-resistant communication.

2.6.1.1 Optical Transmission Distance

The system is designed to achieve a minimum optical transmission distance of 1 km using an infrared laser, alignment mirrors, and a focusing lens. This will be validated by testing signal integrity across different transmission lengths to confirm low attenuation and consistent, reliable communication.

2.6.1.2 Signal Modulation Speed

The system can transmit binary code at speeds equivalent to 10 words per minute or greater. The demonstration will involve encoding a standard binary message at this rate and verifying its successful transmission and accurate reception.

2.6.1.3 Decoding Accuracy

The microcontroller-based decoder will achieve at least 95% accuracy in interpreting binary code signals. Testing will involve transmitting predefined messages and comparing the decoded output to the original input to validate accuracy. These demonstrable specifications ensure the system's functionality and performance in its intended application.

2.6.1.4 Data Transfer Rate

The optical communication system will support a data transfer rate of at least 100 bits per second (bps), with testing conducted across varying signal rates between 50 and 200 bps to verify performance and consistency. These demonstrable specifications validate the system’s ability to meet performance requirements for long-distance, reliable, and accurate communication.

2.6.2 Component Specifications

The Required Components Table lists the essential hardware elements needed to build the optical-radio communication system. It includes components such as the laser diode for signal transmission, the photodiode for reception, single-mode fiber for efficient optical transfer, a microcontroller for processing, and an RF transmitter for backup communication, ensuring the system meets performance and durability requirements.

Table 2.2: Component Specifications

Component	**Specifications**	**Purpose**
Laser Diode:	980 nm Infrared Laser, 15mW output	Selected for high visibility and efficiency in fiber optics transmission
Photodiode:	450-1100 nm sensitivity	High-speed response for accurate signal decoding
Bandpass Filter:	Transmission 99% at 980nm	Filtering out wavelengths outside of 980nm
Focusing Lens	Plano-convex, 25 mm diameter	Focuses laser onto photodiode

Microcontroller:	Arduino / Raspberry Pi compatible	Controls modulation, decoding, and display
Voltage-Controlled Oscillator (VCO):	Frequency range: 20 kHz – 40 MHz, Tuning Sensitivity: ≥ 10 MHz/V	Controls frequency modulation with precise tuning capability
Op-Amp:	Gain Bandwidth: ≥ 1 MHz, Slew Rate: ≥ 0.5 V/μs	Ensures stable signal amplification and filtering
PCB Board:	9cm x 7cm	Houses and integrates all electronic components
Power Source:	Rechargeable Battery Pack (≥ 5V, 2000mAh)	Provides power for the system
Resistors/Capacitors:	Values TBD	Ensures circuit stability and signal conditioning

2.7 Hardware Block Diagram

The hardware block diagram below illustrates the process of transmitting a binary code message from the telegraph key to its final display on the screen. The project's sections are divided among group members based on their areas of expertise, with the outline color of each box indicating assigned responsibilities.

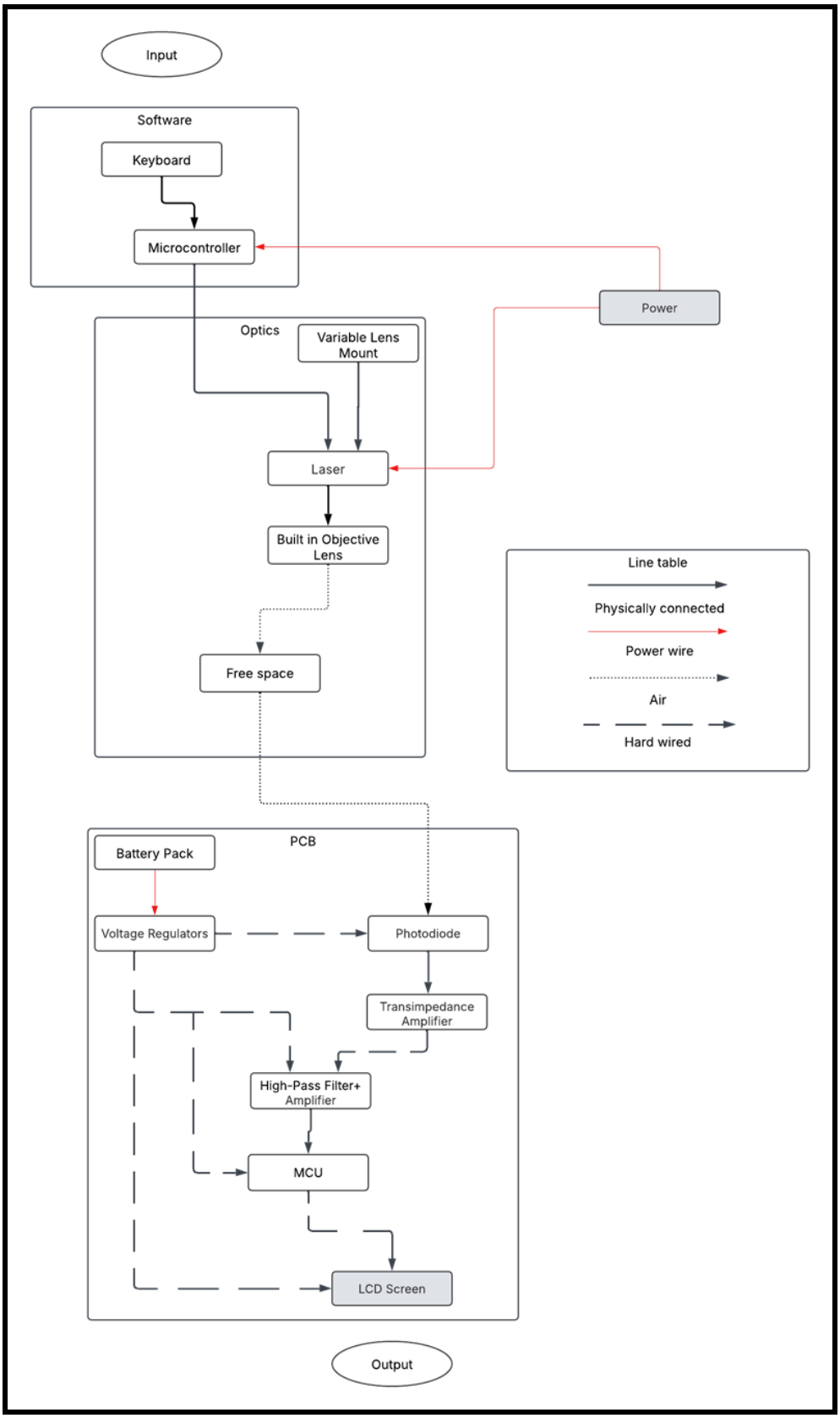


Figure 2.1: Hardware Block Diagram

Chapter 3 Research and Investigation

Overview

This chapter will cover the research, tabulation, comparison, and justification of different optical components, electrical components, and software.

3.1 Optical Technology Comparison and Selection

In the development of the communication system, several hardware technologies were considered for key components, including collimation and beam expander lenses, laser diodes, photodiodes, voltage-controlled oscillators (VCOs), and operational amplifiers (Op-Amps). The selection of these technologies was based on factors such as performance, cost, availability, and suitability for the intended application. Each comparison is summarized in a table, followed by a discussion justifying the final selection.

3.1.1 Laser Source Selection

The selection of the laser source is a critical decision in the design of a free-space optical communication system. The chosen laser must not only meet the wavelength and power requirements but also be optimized for efficiency, beam quality, and stability over long transmission distances. In this section, we will evaluate various types of laser sources based on factors such as output power, beam divergence, and suitability for free-space optical transmission, ensuring that the selected laser source aligns with the specific needs of the system.

Table 3.1: Comparison of Different Laser Types for Free-Space Optical Transmission

Feature	Fabry-Perot (FP) Laser	Distributed Feedback (DFB) Laser	Vertical-Cavity Surface-Emitting Laser (VCSEL)	Diode-Pumped Solid-State (DPSS) Laser
Wavelength Range	630 - 680 nm, 520 - 532 nm	650 - 1550 nm	630 - 850 nm, 520 nm	532 nm, 1064 nm
Output Power	5 - 100 mW	10 - 200 mW	1 - 10 mW	5 - 500 mW
Beam Quality (M^2 Factor)	2 - 5	~1.1 (High)	1.5 - 2.5	~1.1 (High)
Beam Divergence	3 - 10 mrad	1 - 3 mrad	5 - 15 mrad	< 1 mrad
Power Efficiency	20 - 40%	25 - 45%	30 - 50%	10 - 30%
Atmospheric Absorption	Low (Red), Moderate (Green)	Low	Moderate	Low
Modulation Bandwidth	1 - 5 GHz	10 - 40 GHz	10 - 25 GHz	1 - 5 GHz

Suitability for 1 km Free-Space Optical Transmission	Moderate	High	Moderate	Very High
Cost per Unit	$10 - $100	$50 - $300	$5 - $50	$100 - $500

Justification for DPSS Laser Selection

The Diode-Pumped Solid-State (DPSS) laser at 532 nm was selected for the FSO system due to its superior beam quality, low divergence, and high output power. The DPSS laser exhibits an M^2 factor of ~1.1, meaning the beam closely resembles an ideal Gaussian profile, which is essential for long-distance optical transmission without excessive spreading. Additionally, its low beam divergence (< 1 mrad) ensures minimal dispersion over 1 km, reducing the need for excessive collimation.

Another critical factor in selecting the DPSS laser was its low atmospheric absorption at 532 nm, ensuring maximum transmission efficiency through free space. While DFB lasers also offer excellent beam quality and low divergence, their typical wavelengths (1310 nm, 1550 nm) are optimized for fiber-optic applications rather than visible free-space communication. VCSELs and FP lasers were less suitable due to their higher divergence and lower power output, making them inefficient for long-range transmission.

Although the DPSS laser has a higher cost ($100 - $500 per unit) compared to alternatives, the investment is justified by its superior beam properties, ensuring efficient power delivery, minimal losses, and reliable performance over the required transmission distance.

3.1.2 Collimation Lens Selection

Collimating lenses are essential for ensuring that the laser beam is properly aligned and collimated before transmission over long distances. The right collimating lens will minimize beam divergence and maintain a consistent beam profile throughout its journey. In this section, we examine different lens types, such as aspheric, plano-convex, and achromatic doublet lenses, based on their numerical aperture, chromatic aberration, and beam quality. This analysis will allow us to select the most effective lens for achieving precise and stable beam collimation.

Table 3.2: Comparison of Collimating Lenses for Laser Beam Alignment

Feature	Aspheric Collimating Lens	Plano-Convex Lens	Achromatic Doublet Lens
Numerical Aperture (NA)	0.10 - 0.50	0.05 - 0.30	0.10 - 0.40
Focal Length (mm)	5 - 50	10 - 200	10 - 100
Wavelength Range	400 - 1000 nm	400 - 1600 nm	400 - 2000 nm
Optical Transmission	95 - 98%	90 - 95%	90 - 97%
Chromatic Aberration	Minimal	Moderate	Very Low
Beam Quality	Excellent	Good	Very Good
Application Suitability	Precision Collimation	General Laser Focusing	Color-Corrected Applications
Cost per Unit	$50 - $150	$20 - $80	$100 - $300

Justification for Aspheric Collimating Lens Selection

The aspheric collimating lens was selected for its superior beam quality and minimal optical aberrations, making it the ideal choice for the free-space optical transmission system. Its high numerical aperture (NA) range of 0.10 - 0.50 allows for efficient collection of the laser light emitted from the laser diode, ensuring that as much light as possible is utilized for transmission. This efficient light collection is crucial for maintaining beam intensity and ensuring the laser signal reaches the photodiode accurately over the 1 km distance. Additionally, the minimal chromatic aberration associated with the aspheric design ensures that the light beam remains tightly focused and properly collimated, with minimal dispersion of different wavelengths, which can otherwise result in reduced transmission efficiency and signal distortion. By minimizing aberrations, the aspheric lens ensures that the beam remains as close to ideal as possible over long distances, maintaining the clarity and quality of the transmitted signal.

In comparison, a plano-convex lens was considered for its affordability and simpler design. While it offers some basic collimation, it is less effective at minimizing chromatic aberrations compared to the aspheric lens. The moderate chromatic aberration of the plano-convex lens can lead to noticeable divergence or spreading of the light at longer distances, which is undesirable for precise optical communication systems like the one being developed. In addition, the plano-convex lens typically has a lower numerical aperture (0.05 - 0.30), meaning it would be less efficient in collecting the laser light and could lead to losses in signal strength and quality. These drawbacks made the plano-convex lens less suitable for the high-precision requirements of this project.

While the achromatic doublet lens provides excellent performance, with very low chromatic aberration, it comes at a significantly higher cost. The added expense of the achromatic doublet lens did not justify its marginal performance improvements in this

application, where the aspheric collimating lens already provides sufficient optical quality for the required distance. Therefore, the aspheric collimating lens offers the best balance between performance and cost-effectiveness. It ensures that the laser beam remains well-collimated and stable over the entire 1 km transmission distance, making it the most practical and efficient choice for the optical system.

3.1.3 Focusing Lens Selection

A focusing lens will converge light towards the focal point of the lens, depending on the diameter and radius of curvature of the lens. These will typically be convex lenses (due to their positive focal lengths), and the following table below will compare three types of convex lenses: plano-convex, biconvex, and positive meniscus (concave-convex lens with convergent properties).

Table 3.3: Comparison of Beam Expanders for Free-Space Optical Transmission

Feature	Plano-Convex	Biconvex	Positive Meniscus
Shape	Flat on one side, curved outward on the other side	Curved outward on both sides	Curved inward on one side, curved outward on other side
Wavelength Range	300-2000 nm	190-2500 nm	350-2200 nm
Working Distance between Object and Image	Unequal	Equal	Unequal, especially when paired with other lenses
Spherical Aberration	Low	Low	Very low
Chromatic Aberration	High	High	Low
Application Suitability	Imaging, laser collimation, NIR applications	Imaging, laser collimation, NIR applications	Spectroscopy, thermal imaging
Cost per Unit	$20 - $100	$20-$50	$20-70

Justification for Plano-Convex Selection

The plano-convex lens was selected mainly for its balance between affordability, adaptability to unequal working distances, and simplicity. Although it is not the best type of lens for polychromatic applications due to its tendency to cause chromatic aberrations, this project will utilize a laser, which is monochromatic and renders this disadvantage moot. As this project will also use a near-infrared (NIR) laser (830-980 nm), plano-convex lenses are also an excellent choice for working in these wavelengths.

The adaptability and low tendency to cause spherical applications mean that plano-convex lenses are suited for long-distance laser collimation, which can be replicated in this project while also maintaining signal fidelity by focusing most of the light into the photodiode.

3.1.4 Alignment Mirrors Selection

Alignment mirrors are key components used to adjust and direct the laser beam accurately toward the photodiode receiver. Their reflective properties, surface flatness, and durability directly influence the stability and precision of the optical system. This section evaluates different types of mirrors, including dielectric, metallic, and gold-coated mirrors, based on their reflectivity, coating type, and performance at the laser wavelength. The optimal mirror selection will ensure that the laser beam remains aligned and focused, minimizing losses and ensuring reliable communication over long distances.

Table 3.4: Comparison of Mirrors for Laser Beam Adjustment and Alignment

Specification	Dielectric Mirror	Metallic Mirror (Al + MgF_2 Coating)	Gold-Coated Mirror	Silver-Coated Mirror	Broadband Dielectric Mirror
Reflectivity (%)	>99% @ 532 nm	85 - 95%	>98% (IR)	96 - 98%	>99%
Coating Type	HR @ 532 nm	Al + MgF_2	Gold	Ag + Protective Coating	Multilayer Dielectric
Surface Flatness (λ)	λ/10	λ/5	λ/5	λ/5	λ/10
Wavelength Range (nm)	400 - 700	250 - 1000	700 - 2000	400 - 1000	400 - 1100
Durability	High	Moderate	Moderate	Low (Prone to Oxidation)	High
Cost ($ per unit)	100 - 300	50 - 150	200 - 500	100 - 250	150 - 400

Justification for Selecting the Dielectric Mirror

For precise beam alignment and adjustment in the free-space optical system, the dielectric mirror (HR @ 532 nm, λ/10 flatness) was selected due to its superior optical performance and long-term stability. One of the primary reasons for this selection is its high reflectivity (>99%) at the laser wavelength of 532 nm, which significantly reduces optical losses and ensures efficient power delivery throughout the transmission system. Since minimizing power loss is critical in long-range free-space communication, this high reflectivity makes the dielectric mirror an optimal choice.

Another critical factor in favor of the dielectric mirror is its exceptional surface quality, with a flatness of λ/10, which minimizes wavefront distortion and ensures that the laser beam remains accurately aligned over the 1 km transmission distance. Precision in beam alignment is crucial for maintaining a stable and reliable optical link, as even minor deviations can lead to signal degradation and increased divergence. The dielectric mirror's ability to preserve wavefront integrity ensures that the laser beam remains collimated and properly directed toward the receiving photodiode.

Durability and resistance to environmental degradation were also key considerations in selecting the dielectric mirror. Unlike metallic mirrors, which are prone to oxidation and require protective coatings to maintain performance, dielectric mirrors are highly durable and resistant to oxidation, humidity, and thermal fluctuations. This ensures long-term stability, reducing maintenance requirements and ensuring consistent performance over time. In comparison, metallic mirrors such as aluminum (Al), silver (Ag), and gold (Au), while commonly used for laser applications, exhibit certain drawbacks. Aluminum-coated mirrors, despite their affordability, have lower reflectivity than dielectric mirrors and require a magnesium fluoride (MgF_2) protective coating to prevent degradation. Silver-coated mirrors, though highly reflective, oxidize quickly when exposed to air, reducing their lifespan and necessitating frequent replacement or additional protective measures. Gold-coated mirrors perform exceptionally well in the infrared (IR) range, but they are not optimized for 532 nm, making them less efficient for this particular system.

Lastly, while broadband dielectric mirrors offer flexibility by reflecting a wide range of wavelengths, they come at a higher cost compared to wavelength-specific dielectric mirrors. Since the system operates at a fixed 532 nm wavelength, a high-reflectivity dielectric mirror designed specifically for this wavelength provides the best combination of performance, efficiency, and cost-effectiveness. Given its high reflectivity, minimal wavefront distortion, superior durability, and long-term stability, the dielectric mirror was determined to be the best option for ensuring precise laser beam alignment and maintaining the integrity of the free-space optical communication system over the 1 km transmission distance.

3.1.5 Photodiode Selection

The photodiode generates photocurrent in response to light, and we evaluate three types of photodiodes based on their wavelength range, peak wavelength range, responsivity, gain, and dark current (current in the absence of light). This section will specifically evaluate silicon-based photodiodes.

Table 3.5: Comparison of Photodiodes

	PN	**PIN**	**Avalanche (APD)**
Wavelength Range (nm)	200-1100	300-1100	400-1100
Peak Wavelength Range (nm)	600-900	800-1000	800-900
Responsivity ($A*W^{-1}$)	0.5-0.6	0.5-0.6	0.4-0.6
Gain	<1	<1	10-1000
Dark Current (nA/1 mm^2)	0.005-0.1 nA	0.1-1 nA	1-10 nA

Sources: Kasap (2013), pg. 405

Justification for Silicon PIN Photodiode Selection

The silicon PIN photodiode was selected mainly for its accepted wavelength range acceptance and low dark current per 1 mm^2. The wavelength of the red laser diode used was around 650 nm, which is within the range, although the responsivity may not be as high, which is very important for optimal encoding performance of the project. Since the wavelength range for the highest responsivity is 800-1000 nm, in future experiments, a red laser diode with a wavelength in that range will be used.

Dark current is the value of current in the absence of light, which occurs due to the interaction between electrons and holes in room temperature. Dark current is typically not ideal for photodiode performance because it indicates the presence of noise in the system, which can distort optical signals. Although the dark current range of a PIN photodiode is much higher than that of the PN photodiode, it is also lower than the dark current range of an avalanche photodiode.

This essentially means that a PIN photodiode is the optimal photodiode that performs slightly better than a PN photodiode and produces much less noise under the absence of light than an avalanche photodiode, making it suitable for this project.

3.1.6 Lens Filter Selection

The purpose of the lens filter in this project will be to filter out wavelengths outside of the 520nm wavelength before the laser enters the objective lens and hits the photodiode. This means that a filter designed for visible light will be used. This section will explore filters based on their spectral properties.

Table 3.6: Comparison of Lens Filters

	Bandpass	Shortpass	Longpass
Wavelength transmission range	One specific wavelength	Short wavelengths	Long wavelengths
Composition	Shortpass + Longpass or single narrowband	Coated glass	Coated glass
Cost ($)	70-200	100-300	40-200

Sources: Noni Custom Optics, Edmund Optics, Findlight

Justification for Bandpass Filter Selection

A bandpass lens filter will be best for this project, as it is suited for filtering out wavelengths that are outside of the 520 nm wavelength and offer flexibility in its setup, which can be composed of either one specialized lens (typically narrowband) or a combination of a short-pass lens and a long-pass lens. The flexibility of a bandpass lens also means that cheaper short-pass and long-pass lenses can be bought to create an affordable bandpass setup with specifications that can meet or exceed those from a single bandpass filter setup.

3.1.7 Lens Aperture Selection

The lens aperture is used to control the diameter of the laser, and it'll be used to control the size of the laser beam entering the photodiode to ensure maximum coverage. This section will compare lens apertures based on their geometry, adjustability, and cost.

Table 3.7: Comparison of Lens Apertures

	Pinhole	Slit	Iris Diaphragm
Composition	Fixed circle opening	A thin opening	Blades in a circular pattern
Adjustable?	No	No	Yes
Cost ($)	60-200	60-200	10-50

Justification for Iris Diaphragm Selection

An iris diaphragm aperture would be best suited for this project mainly because it is adjustable for a variety of aperture sizes and laser sizes. With iris diaphragms being very cheap across different retailers, this means that a cheaper aperture can be bought without increasing the budget. As the aperture is a rough circle, a typical laser beam can pass through without drastically affecting its geometry and intensity distribution.

3.2 Revisions to Optical Technologies & Components Following SD1

Following the Senior Design 1 (SD1) review, several core components within the optical subsystem were reevaluated and revised to improve system performance, reduce complexity, and enhance alignment with evolving project goals. This section details the key modifications made to laser wavelength selection, laser source types, and optical focusing components. These changes are informed by experimental data, performance trade-offs, cost-benefit analysis, and technological maturity across multiple laser-based communication use cases. The decisions are guided by specific technical metrics, such as

beam divergence, modulation speed, eye safety, detector compatibility, and transmission efficiency that are critical to achieving a robust, scalable free-space optical (FSO) communication platform operating around the 980 nm wavelength. By refining these component selections, the project transitions toward a more optimized, application-specific optical architecture capable of supporting mid-range, high-speed optical links with a practical balance of precision, cost, and manufacturability.

3.2.1 Laser Wavelength Changes After SD1

Table 3.5 presents a comparative overview of key laser wavelengths—450–490 nm (blue), 850 nm, 980 nm, 1310 nm, and 1550 nm—to guide wavelength selection for different stages of laser system development. Each wavelength is analyzed across essential performance metrics including eye safety (MPE), atmospheric loss, detector compatibility, beam waist size, and data rate potential, all of which directly affect system efficiency, transmission reliability, and optical alignment over distance. This table also incorporates cost estimates and best-use cases, helping to balance performance with practicality for both short-range and long-range applications such as free-space optical communication (FSO), fiber pumping, alignment, and telecom-grade transmission. By understanding the trade-offs between visible and infrared bands, designers can optimize for precision, power, and safety at each phase of project progression.

Table 3.8: Comparison of Laser Wavelength for Project Progression

Specification	450–490 nm (Blue)	850 nm	980 nm	1310 nm	1550 nm
Band	Visible (Blue)	Near IR	Near IR	Telecom IR	Telecom IR
Eye Safety (MPE mw/cm²)	1	2	2	10	10–100
Atmospheric Loss (dB/km)	~20–30	~2–5	~1–3	~0.5–1	~0.2–0.5
Detector Compatibility	Silicon	Silicon	Si, InGaAs	InGaAs	InGaAs/APD
Beam Waist *(100mm, 1mm beam)*	~28.6 µm	~54.1 µm	~62.4 µm	~83.3 µm	~98.7 µm
Data Rate Potential	~1–2 Gbps	~2–5 Gbps	~2–10 Gbps	10+ Gbps	10–40+ Gbps
Best Use Case	Short-range, alignment	Short FSO	Fiber pump, mid FSO	Long-range FSO	Eye-safe long FSO

Approximate Cost (USD, $)	$15–$200	$34–$985	$54–$1,195	$295–$1,595	$415–$1,643

Justification for 980nm Selection.

Choosing a 980 nm infrared laser for a moderate-range data transmission system strikes a practical balance between performance, cost, and system complexity, especially in environments where long-haul telecom wavelengths (1310/1550 nm) are either overkill or too expensive to implement.

The 980 nm wavelength offers a sweet spot in the near-infrared region. It experiences lower atmospheric scattering than shorter wavelengths like 850 or 930 nm, which improves its transmission range, particularly in outdoor or semi-controlled environments. Unlike visible lasers (e.g., 450 nm), it avoids heavy Rayleigh scattering and has better performance in dust or fog-prone areas.

While 980 nm is not compatible with standard silicon photodiodes, it is fully supported by InGaAs detectors, which are widely available and well-developed. It also benefits from mature diode laser technology, as it's a standard pumping wavelength for erbium-doped fiber amplifiers (EDFAs). This means high-quality, compact, and efficient 980 nm laser diodes are available at lower costs due to mass production for the telecom and fiber-optics industries.

From a beam control perspective, the beam waist at 980 nm (~62.4 μm with standard optics) is manageable: it's larger than blue or 850 nm beams, but not so large that beam divergence becomes difficult to manage over a 1 km link, especially when paired with a beam expander. The beam remains collimated well enough for accurate point-to-point transmission, without requiring ultra-expensive optics.

Though 980 nm lasers don't reach the eye safety levels of 1550 nm, they are still manageable with protective housing or enclosed systems. For mid-range free-space optical links (~500 m to 2 km) where ultra-high power or DWDM capacity isn't required, 980 nm hits a perfect compromise between cost, performance, and real-world usability, especially if you want a simpler, modular laser communication system that doesn't require full telecom infrastructure.

3.2.2 Laser Type Changes After SD1

Table 3.5 provides a technical comparison of several advanced laser technologies, evaluating their suitability for various stages of a high-precision optical system project. This comparison focuses on critical performance parameters such as pulse duration, repetition rate, output power, and beam quality (M^2), which are key to determining each laser's role in specific applications ranging from basic free-space optical (FSO) communication to ultrafast spectroscopy and high-power material processing. The included laser types—TTL-modulated diode lasers, pulsed diode illuminators, femtosecond and ytterbium-doped fiber lasers, and Ti:Sapphire systems—represent a broad range of capabilities from entry-level prototyping to cutting-edge experimental use.

This table aims to guide strategic decisions for selecting the most appropriate laser source during different phases of project development, balancing complexity, precision, and application requirements.

Table 3.9: Comparison of Laser Types for Project Progression

Property	TTL-Modulated Laser Diode	Pulsed Laser Diode Illuminator	Femtosecond Fiber Laser	Ytterbium-Doped Fiber Laser	Ti:Sapphire Laser
Pulse Duration (seconds)	CW / Modulated	100–200 ns	<150 fs	50 ps – 1 ns	5–100 fs
Repetition Rate (Hz)	Up to 100 kHz	Up to 10 kHz	1–80 MHz	1 MHz – 100 MHz	70–90 MHz
Output Power (mW)	≤ 50	≤ 20 W	≤ 20 W	≤10 kW	0.4–2.5 W
Beam Quality (M^2)	< 1.5	< 1.5	< 1.2	< 1.3	< 1.1
Best Use Case	Basic optical comms, FSO	Industrial sensing, IR beacon	Biophotonics, microscopy	LIDAR, material processing	Research, ultrafast spectroscopy

Justification for TTL-Modulated Laser Diode

When considering a high-repetition-rate laser system for applications centered on the 980 nm wavelength, one must balance several key factors: repetition rate, beam quality, pulse duration, thermal management, cost, and system complexity.

If your application demands strict adherence to 980 nm, the best practical options are TTL-modulated laser diodes and pulsed laser diode illuminators. TTL-modulated diodes are inexpensive, highly compact, and capable of modulation rates up to 100 kHz, which is suitable for basic free-space optical communication (FSO), Li-Fi, or data tagging applications. These diodes also offer decent beam quality ($M^2 < 1.5$), making them compatible with beam-shaping optics and collimators. However, their limitation lies in relatively low output power (typically <100 mW) and modulation rates that may fall short for truly high-throughput systems.

Pulsed laser diode illuminators, also operating at 980 nm, fill this gap by delivering significantly higher optical output (often 10–20 W) with pulse durations around 100–200 ns. These are ideal for medium-range transmission systems or as IR illuminators in active sensing or beacon applications. While their repetition rates are typically lower (≤10 kHz), they make up for it with high pulse energy—beneficial when fewer, stronger

bursts are needed. Still, both options are limited when it comes to true high-speed data transmission in the MHz or GHz regime.

To achieve genuinely high repetition rates (in the MHz range) with excellent beam quality, you'd need to explore femtosecond or picosecond fiber lasers, such as Ytterbium-doped fiber lasers or femtosecond fiber lasers, which typically emit at 1030–1064 nm—close, though not exactly at, 980 nm. These lasers can fire pulses at MHz to even GHz rates and are suitable for applications like LIDAR, ultrafast spectroscopy, optical time-domain reflectometry, or even next-gen FSO systems. Despite the slightly longer wavelength, InGaAs detectors work well at these ranges, and beam shaping or filtering can accommodate most 980 nm-centric designs.

In summary, if cost, simplicity, and strict adherence to 980 nm are your priorities, the TTL-modulated laser diode is your best option. If higher power is needed without sacrificing wavelength fidelity, the pulsed laser diode illuminator offers a solid middle ground. However, for applications demanding extremely high repetition rates and ultrafast performance, and where a slight wavelength deviation is acceptable, a femtosecond fiber laser near 1035 nm provides the best combination of power, speed, and beam quality—albeit at a higher cost and complexity. Your ultimate choice will hinge on whether repetition rate, power, or wavelength specificity is the most critical factor in your design.

3.2.3 Focusing Lens Changes After SD1

Table 3.6 offers a comprehensive comparison of five common lens types used in precision laser systems, particularly those operating around the 980 nm wavelength. These lenses—plano-convex, aspheric, achromatic doublet, gradient index (GRIN), and cylindrical—are evaluated across several critical specifications, including focal length range, focusing precision, aberration correction, and transmission efficiency at 980 nm. The purpose of this comparison is to assist in selecting the most suitable lens for various stages of optical system development, from general collimation and beam shaping to fiber coupling and high-precision imaging. Each lens type brings unique strengths and trade-offs in terms of size, cost, and application specificity, making this table a valuable reference for optimizing optical performance in laser-based projects.

Table 3.10: Comparison of Focusing Lenses for Project Progression

Specification	Plano-Convex Lens	Aspheric Lens	Achromatic Doublet	Gradient Index (GRIN) Lens	Cylindrical Lens
Primary Use	General focusing, collimation	Minimized spherical aberration	Corrects chromatic aberration	Compact beam shaping & fiber coupling	Beam shaping (1 axis)
Shape	One flat, one convex surface	Convex with non-spherical surface	Two-element, doublet design	Gradient refractive index core	Cylinder shape (1D focusing)
Focal Length Range	3–1000+ mm	1–100 mm	10–500 mm	0.25–10 mm	5–100 mm
Focusing Precision	±0.1–1 mm	±0.05–0.2 mm	±0.05–0.3 mm	±0.01 mm	±0.2–0.5 mm (1D only)
Aberration Correction	None (spherical & chromatic)	Spherical only	Spherical + chromatic	Spherical	Depends on configuration
Transmission at 980 nm	95–98% (N-BK7, fused silica)	98–99% (AR coated)	90–95% (fused silica or NIR glass)	98–99% (fused silica)	95–98%
Typical Size	6–25.4 mm diameter	3–12 mm diameter	6–25.4 mm	⌀1–2.5 mm, L = 2–10 mm	Varies by axis
Best Use Case	General purpose focusing	Diode collimation, low aberration	Imaging, dual-laser systems	Fiber coupling, miniaturized optics	Laser line projection
Cost (USD)	$10–$80	$50–$150	$60–$200	$60–$150	$10–$100

Justification for Choosing the Aspheric Lens

The aspheric lens is the best choice for systems utilizing 980 nm laser diodes due to its ability to significantly minimize spherical aberrations. Laser diodes, especially those at 980 nm, tend to have high divergence, and spherical aberration can cause beam spreading and loss of focus, especially when the light rays pass through the edges of the lens. Aspheric lenses are specifically designed to eliminate these spherical aberrations,

providing a cleaner and sharper beam with minimal divergence, which is particularly important for high-NA diode lasers that typically exhibit a more divergent or elliptical beam profile. This results in better collimation and focusing, ensuring that the laser's performance remains efficient and precise, even at long distances or when dealing with high-power laser systems.

Moreover, aspheric lenses ensure high beam quality with minimal distortion. This is essential for applications such as free-space optical communication (FSO), where maintaining beam quality over long distances is crucial. The ability to focus a laser beam tightly while preventing distortions leads to higher transmission efficiency and improved performance, especially when the laser is being used for high-speed data transfer or long-range sensing. Aspheric lenses offer better beam shaping compared to traditional plano-convex lenses, making them ideal for these types of applications where precise beam control is necessary.

Additionally, while aspheric lenses are more complex than plano-convex lenses, they remain relatively cost-effective and compact, making them ideal for systems where space is limited and cost is a concern. The low profile of aspheric lenses allows them to fit into miniaturized systems without sacrificing optical performance, making them suitable for a wide range of applications, from portable optical systems to miniaturized laser communication devices. Their cost-to-performance ratio is particularly favorable when compared to other high-performance optics such as achromatic doublets or GRIN lenses, which are more expensive and may not offer significant advantages in single-wavelength systems like the 980 nm laser diode.

In systems where the laser beam needs to maintain a low divergence over long distances, such as in free-space optical communication or laser-based sensors, aspheric lenses provide an excellent solution. Their ability to focus high-divergence beams and keep the laser's focus intact over distance makes them ideal for such tasks. The design of aspheric lenses helps ensure that the laser beam does not lose power or quality, even in challenging environments.

Overall, the aspheric lens stands out as the best option for 980 nm laser systems due to its ability to minimize aberrations, maintain high beam quality, and focus or collimate the laser efficiently. The precision and versatility offered by aspheric lenses, combined with their relatively compact size and reasonable cost, make them the optimal choice for applications requiring high-performance, high-quality laser beams. Whether in free-space optical communication, sensing, or other precision tasks, aspheric lenses provide the best balance of performance, cost, and compactness, ensuring that 980 nm laser systems can operate efficiently and reliably.

3.3 Electronics hardware

3.3.1 Microcontrollers

3.3.1.1 MSP430FR2452

MSP430FR2452 is part of the MSP430 family of ultra-low-power microcontrollers. It has 8KB of flash memory, 256 B of RAM, and 10 ADC channels. It features Ferroelectric RAM (FRAM), which provides fast writing speeds, high endurance, and lower power consumption compared to traditional flash memory, making it well-suited for sensor-based applications. With a maximum clock speed of 16MHz, multiple low-power modes, and a broad range of peripherals—including UART, I2C, SPI, and GPIO support

3.3.1.2 MSP430G2553

The MSP430G2553 belongs to the same MSP430 family as the MSP430G2452, ensuring compatibility with existing firmware and development tools. It offers twice the flash memory (16KB vs. 8KB) and more RAM (512B vs. 256B), making it better suited for applications requiring additional storage and processing capabilities. Despite these improvements, it retains the ultra-low power consumption that characterizes the MSP430 series, maintaining its efficiency in battery-powered applications.

3.3.1.3 MSP430FR2355

The MSP430FR2355 is a microcontroller designed for ultra-low-power applications, offering significant advantages over traditional flash-based MCUs. Additionally, it features a 12-bit ADC, providing improved resolution compared to the 10-bit ADC in the MSP430G2452, making it an ideal choice for applications requiring precise analog signal processing. The increased number of GPIOs and additional peripherals also enhances its versatility, allowing for greater expandability in complex systems.

3.3.1.4 STM32L031K6 (Ultra-Low-Power STM32)

The STM32L031K6 is a 32-bit ARM Cortex-M0+ microcontroller that offers significantly greater processing power than the MSP430G2452, making it well-suited for high-performance applications. Despite its enhanced processing capabilities, it retains low-power operation modes comparable to the MSP430 series, ensuring efficient energy management in battery-driven designs. The 12-bit ADC provides higher precision in analog-to-digital conversion, improving signal acquisition and processing for more demanding applications.

Table 3.11: MCU Comparison

Feature	**MSP430G2452**	**MSP430G2553**	**MSP430FR2355**	**STM32L031K6**
Architecture	16-bit RISC	16-bit RISC	16-bit RISC	32-bit ARM Cortex-M0+
Flash Memory	8KB	16KB	32KB	32KB
RAM	256B	512B	4KB	8KB
ADC Resolution	10-bit	10-bit	12-bit	12-bit
Clock Speed	16MHz	16MHz	24MHz	32MHz
GPIO Pins	24	24	43	37
Power Consumption	Ultra-Low	Ultra-Low	Ultra-Low	Low
Operating Voltage	1.8V – 3.6V	1.8V – 3.6V	1.8V – 3.6V	1.8V – 3.6V
Best For	Low-power sensor systems	More flash/memory	More ADC precision, FRAM	High-performance, low-power IoT
Price	$1.691	$2.641	$2.885	$1.24

Justification for Microcontroller Selection

The MSP430G2452 microcontroller was selected for its ultra-low power consumption, cost-effectiveness, and compatibility with existing system components. Operating at a 16MHz clock speed, it provides sufficient processing power for low-power sensor applications while maintaining energy efficiency. With 8KB of flash memory, 256B of RAM, and a 10-bit ADC, it meets the system's requirements for data acquisition and processing. Additionally, its support for UART, I2C, and SPI communication protocols ensures seamless integration with peripheral components. Its low operating voltage range (1.8V – 3.6V) further enhances its suitability for battery-powered applications.

While alternative microcontrollers were considered, the MSP430G2452 offered the best trade-off between performance, power efficiency, and cost. The MSP430G2553, with 16KB of flash memory and 512B of RAM, provides additional storage but comes at a higher cost ($2.64 compared to the MSP430G2452's $1.69). The MSP430FR2355, featuring FRAM technology and a 12-bit ADC, offers enhanced memory endurance and improved analog precision but is more expensive ($2.88). The STM32L031K6, a 32-bit ARM Cortex-M0+ microcontroller, delivers significantly greater processing power and higher RAM (8KB) but operates at a slightly higher power consumption level, making it less ideal for ultra-low-power applications

3.3.2 Regulators

3.3.2.1 TPS61322

The TPS61322 is an ultra-low-power boost converter from Texas Instruments, designed to efficiently step up voltages in battery-powered and energy-sensitive applications. It operates with an input voltage range of 0.9V to 5.5V and provides a fixed or adjustable output voltage between 1.8V and 5.5V, making it ideal for low-power microcontrollers and sensor networks. With a quiescent current of just 6.5 µA, it maximizes battery life while maintaining high efficiency. The integrated power switch and synchronous rectifier enhance conversion efficiency, while its compact SOT-23-5 package allows for space-constrained designs. The TPS61322 is well-suited for applications such as sensors and applications where a 1 to 3 cell alkaline battery is used.

3.3.2.2 TPS61099

TPS61099 is an ultra-low-power boost converter designed for efficiency in battery-powered applications. It features a much lower quiescent current (0.9 µA vs. 6.5 µA) compared to the TPS61322, making it an ideal choice for designs where minimal standby power consumption is critical. Additionally, it also offers an output voltage range of 1.8V to 5.5V, which aligns with the voltage requirements of many systems, ensuring compatibility with a variety of low-power microcontrollers and peripherals.

3.3.2.3 TLV61070A (Texas Instruments)

The TLV61070A, also from Texas Instruments, is a high-efficiency boost converter tailored for low-power applications that demand higher output current capabilities. It supports an input voltage range of 0.7V to 5.5V, making it suitable for energy-harvesting or single-cell battery applications. With a maximum output current of 400mA, it provides a higher power delivery capacity than the TPS61322, making it a viable option for systems requiring greater power output. While its quiescent current (1.9 µA) is slightly higher than that of the TPS61099, it is still lower than the current of the TPS61322.

3.3.2.4 AP3015A

The AP3015A, developed by Diodes Incorporated, is a compact and cost-effective boost converter designed for fixed 3.3V or 5V output applications. Unlike adjustable-output regulators, its preset voltage options simplify circuit design by reducing the need for external components. Due to its small footprint and efficiency, it is particularly well-suited for low-power LED, small sensor circuits, and other compact applications where minimal power consumption and board space are priorities.

Table 3.12: Boost Converters Comparison

Feature	**TPS61322**	**TPS61099**	**TLV61070A**	**AP3015A**
Manufacturer	TI	TI	TI	Diodes Inc.
Input Voltage	0.9V – 5.5V	0.7V – 5.5V	0.7V – 5.5V	0.9V – 6.5V
Output Voltage	1.8V – 5.5V	1.8V – 5.5V	1.8V – 5.5V	3.3V / 5V Fixed
Max Output Current	200mA	400mA	200mA	300mA
Quiescent Current	6.5 µA	0.9 µA	1.9 µA	20 µA
Efficiency	~90%	~90%	~90%	~85%
Switching Frequency	1MHz	1MHz	2MHz	1.2MHz
Package	SOT-23-5	WSON, SOT-23	SOT-23-6	SOT-23-5
Best For	Low-power, battery applications	Ultra-low power, higher output current	High-efficiency low-power designs	Simple 3.3V/5V boost
Price	$0.373	$1.120	$0.316	$1.11

Justification for Regulators Selection

The TPS61322 boost converter was selected for its optimal balance of efficiency, cost-effectiveness, and versatility in low-power applications. With an efficiency of approximately 90%, it minimizes power losses, enhancing overall system performance and energy conservation. Additionally, its low quiescent current of 6.5 µA significantly extends battery life, making it ideal for battery-operated devices. The converter supports a fixed or adjustable output voltage ranging from 1.8V to 5.5V, ensuring compatibility with various low-power microcontrollers and sensor networks. Furthermore, its compact SOT-23-5 package allows for easy integration into space-constrained PCB designs.

Beyond its technical advantages, the TPS61322 is also a cost-effective solution, priced at $0.373, making it a budget-friendly choice compared to alternative regulators. However, for applications that require a higher output current, the TPS61099 serves as a suitable alternative, offering up to 400mA compared to the 200mA limit of the TPS61322

3.3.3 Battery Pack

3.3.3.1 2462 battery holder (Keystone Electronics)

The 2462 Battery Holder from Keystone Electronics is a compact and durable AA 2-cell holder designed for PCB-mounted applications. It features secure PC pin terminals, ensuring a stable and reliable electrical connection while minimizing assembly complexity. From its materials, it provides strong battery retention and resistance to vibration, making it ideal for mobile systems and low-power electronics. Its design supports series battery configurations, delivering 3V output with standard AA cells, making it a reliable choice for long-term, battery-powered applications in any setting.

3.3.3.2 BH2AA-PC

The BH2AA-PC serves as a direct equivalent to the 2462 BATTERY HOLDER AA 2 CELL PC PIN, offering the same PCB mount design and 2-cell AA configuration. This makes it an ideal drop-in replacement, ensuring compatibility with existing circuit layouts without requiring modifications.

3.3.3.3 12BH322-GR

The 12BH322-GR is a more compact alternative, featuring a smaller footprint that makes it particularly useful in designs where board space is limited. Despite its reduced size, it maintains reliable battery retention and electrical connectivity, making it suitable for space-constrained applications.

3.3.3.4 BH322-1

The BH322-1 differs from other options by incorporating solder tabs instead of PC pins, enhancing mechanical stability and vibration resistance. This design choice makes it a better fit for environments subject to movement or mechanical stress, ensuring a more secure and long-lasting electrical connection.

Table 3.13: Battery Pack Comparison

Alternative Model	**Manufacturer**	**Battery Type**	**Mounting Type**	**Terminals**	**Features**	**Price**
BH2AA-PC	MPD (Memory Protection Devices)	AA (2-cell)	PCB, Through Hole	PC Pins	Similar layout, compact design	$1.49
12BH322-GR	Eagle Plastic Devices	AA (2-cell)	Snap in	Wired	Slightly smaller footprint	$1.32
BH322-1	Linx Technologies	AA (2-cell)	PCB Mount	Solder Tabs	Secure, vibration-resistant	$5.550
2462	Keystone Electronics	AA (2-cell)	PCB, Through Hole	PC Pins	PCB mounted, compact	$1.03

Justification for Battery Pack Selection

The 2462 battery holder by Keystone Electronics was selected for its secure PCB mount design, ensuring a stable and reliable electrical connection while minimizing assembly complexity. This holder accommodates two AA cells, providing a 3V output, which is well-suited for long-term, battery-powered applications. Its durable construction enhances battery retention and resistance to vibration, making it an ideal choice for mobile and low-power electronic systems. Additionally, its through-hole PC pin terminals simplify the integration process, improving overall design efficiency.

In comparison to alternative battery holders, the 2462 model stands out for its combination of compact size, reliability, and cost-effectiveness, priced at $1.03. While other models, such as the BH322-1, offer enhanced vibration resistance with solder tab terminals, they come at a significantly higher cost ($5.55). For applications requiring a more compact footprint, the 12BH322-GR serves as a viable alternative, albeit with a snap-in mounting mechanism instead of through-hole pins

3.3.4 Transimpedance Amplifier

3.3.4.1 OPA381AIDGKR

The OPA381AIDGKR is a high-precision transimpedance amplifier designed for low-current photodiode applications. Manufactured by Texas Instruments, it features an ultra-low input bias current of 3pA, ensuring minimal leakage and optimal performance in high-impedance sensor circuits. With a low noise density of 5.5nV/√Hz, it provides excellent signal clarity, making it ideal for low-light detection and precision optical measurements. The 18MHz gain bandwidth ensures stable operation in DC-coupled and slow-varying signal applications, while its low power consumption (1.5mA typical) supports energy-efficient designs. Operating over a supply voltage range of 2.7V to 5.5V, the OPA381AIDGKR is well-suited for battery-powered devices and optical sensors.

3.3.4.2 LMP7721

The LMP7721 (Texas Instruments) stands out for its exceptionally low input bias current (2fA, compared to OPA381's 3pA), making it an excellent choice for ultra-sensitive photodetector applications where even minimal leakage current can impact performance. In all other parameters, it is very similar to OPA381.

3.3.4.3 ADA4530-1

The ADA4530-1 (Analog Devices) is optimized for high-impedance sensor applications, featuring an industry-leading low input bias current of 20fA with ultra-low leakage, making it ideal for high-impedance photodiodes and electrometers. While its gain bandwidth (2MHz) is significantly lower than the OPA381 and its noise performance (7nV/√Hz) is slightly worse, it is less suitable for extremely low-noise designs.

3.3.4.4 MCP602

The MCP602 (Microchip Technology) offers a cost-effective alternative but with lower input bias current (1pA vs. OPA381's 3pA), which is better in ultra-sensitive applications. It has a lower gain bandwidth (2.8MHz), making it less responsive in moderate-speed photodiode circuits, and its higher noise (21nV/√Hz) makes it more suitable for low-light or precision applications compared to the OPA381. Its lower power consumption (0.23mA) makes it a viable option for energy-sensitive applications.

Table 3.14: Photodiode Op Amps

Op-Amp Model	**Input Bias**	**Gain Bandwidth (GBW)**	**Supply Voltage**	**Power Consumption**	**Best For**	**Price**
OPA381AIDGKR (TI)	3pA	18MHz	2.7V – 5.5V	1.5mA	Low-current photodiodes, precision applications	$1.98
LMP7721 (TI)	2fA	17MHz	1.8V – 5.5V	1.3mA	Ultra-sensitive, low-light photodetectors	$4.84
ADA4530-1 (Analog Devices)	20fA	2MHz	2.2V – 5.5V	1.5mA	High-impedance, ultra-low noise circuits	$31.09
MCP602 (Microchip TECH)	1pA	10MHz	2.5V – 5.5V	0.23mA	Cost-effective, general photodiode circuits	$0.82

Justification for Transimpedance Amplifier Selection

The OPA381AIDGKR transimpedance amplifier was selected for the photodiode circuit due to its low input bias current (3pA), high gain bandwidth (18MHz), and low power consumption (1.5mA). These characteristics make it well-suited for low-current photodiode applications, ensuring minimal leakage and optimal performance in high-impedance sensor circuits. Additionally, its low noise density (5.5nV/√Hz) provides excellent signal clarity, which is critical for accurate detection of optical signals. Operating within a 2.7V to 5.5V supply range, the OPA381 is also compatible with battery-powered systems, making it an efficient choice for this application.

While alternative op-amps were considered, the OPA381AIDGKR provides the best balance of performance, cost, and power efficiency. Although the LMP7721 offers an exceptionally low input bias current (2fA), it comes at a significantly higher price ($4.84 compared to the OPA381's $1.98). On the other hand, the ADA4530-1, with its ultra-low leakage current, is optimized for high-impedance applications but has a lower gain bandwidth (2MHz) and a much higher cost ($31.09). The MCP602, while a more budget-friendly option ($0.82), has a lower gain bandwidth (10MHz) and a higher noise level (21nV/√Hz), making it less suitable for high-precision, low-noise photodiode applications

3.3.5 Resistor Type

3.3.5.1 Carbon Film Resistors

Carbon film resistors are widely used in general-purpose circuits due to their low cost and adequate performance in low-frequency applications. They are constructed by depositing a carbon film on a ceramic substrate and trimming it to achieve the desired resistance. While they offer moderate stability and acceptable performance in non-critical designs, they have relatively high noise levels and tolerance ranges (typically ±5% or ±10%), making them less suitable for precision circuits.

3.3.5.2 Metal Film Resistors

Metal film resistors are designed for applications requiring low noise, high precision, and thermal stability. Constructed with a metal alloy film, they provide tighter tolerance (as low as ±0.1%). These resistors are commonly found in analog signal processing, data acquisition systems, and sensitive measurement equipment. Their performance advantage comes with a slightly higher cost compared to carbon film resistors.

3.3.5.3 Wire-wound Resistors

Wire-wound resistors are made by winding a resistive wire around an insulating core, enabling them to dissipate high power and maintain tight tolerances. They are highly stable and accurate over time and temperature but are inherently inductive due to their coil structure. This makes them unsuitable for high-frequency or fast-switching applications. Their larger size and higher cost limit their use in smaller PCBs.

3.3.5.4 Surface Mount Resistors (SMD)

Surface mount resistors are compact, efficient components intended for automated manufacturing and dense PCB layouts. Depending on the film type used (thick film, thin film, or metal film), they offer a range of tolerances and temperature characteristics. While their size limits their power dissipation (typically 0.05W to 2W), they are indispensable in modern electronics where space and weight are critical constraints. Their low inductance also makes them ideal for high-frequency designs such as RF circuits.

Table 3.15: Resistor Types

Characteristic	Carbon Film	Metal Film	Wire-wound	Surface Mount (SMD)
Tolerance	±5% to ±10%	±0.1% to ±1%	±0.1% to ±1%	±0.1% to ±5%
Power Rating	0.125W to 2W	0.125W to 1W	0.5W to >50W	0.05W to 2W (package dependent)
Noise	Medium to High	Very Low	Very Low	Low to Medium (varies by material)
Inductance	Low	Low	High (not suitable for high frequencies)	Very Low
Frequency Response	Moderate	Excellent	Poor (due to inductance)	Excellent (ideal for RF/microwave in some)
Cost	Low	Moderate	High	Low (in bulk)
Size	Through-hole, medium	Through-hole, medium	Large (for high power)	Very small (0201 to 2512 and larger)
Applications	General-purpose, cost-sensitive circuits	Precision analog, low-noise designs	High-power, low-frequency, power supplies	Compact designs, automated assembly (SMT)

Justification for Resistor Type Selection

Carbon film resistors were selected for this design due to their cost-effectiveness, broad availability, and sufficient performance in general-purpose applications. While metal film resistors would offer better noise performance and tighter tolerance, the simplicity and budget-conscious nature of this project prioritize practicality over precision. For signal paths where accuracy and low noise are essential, higher-precision resistors may still be employed selectively.

3.3.6 Capacitor Type

Capacitors will be used in the transmitter and receiver circuits for stabilizing the laser modulation and filtering noise, and in the transimpedance amplifier to increase gain at high frequencies and stabilizing the signal. This section will evaluate mica, ceramic, plastic film, and electrolytic capacitors.

3.3.6.1 Mica Capacitors

Mica capacitors, especially silver mica capacitors, use mica as the dielectric and silver as the plate material (other metals do not work as well). They are useful in applications with strict tolerances and where low loss is needed (such as RF circuits), and where high temperatures and high voltages are prevalent. Mica capacitors typically have a tolerance between 0.05% to 5%, are available in values from 1 pf to 91 nF, and rated between 50 V to 2500 V.

3.3.6.2 Ceramic Capacitors

Ceramic capacitors use ceramic material as the dielectric. They can come in either packages with leads or as surface mount components. There are two classes of ceramic capacitors. Class I varieties are the most stable of the two and are useful for applications that require high precision and stability and temperature sensitivity, like timers and oscillators. Class II varieties have large capacitance values and higher tolerances provided in a small package but are less stable than Class I capacitors. They are used in coupling, decoupling, and bypass applications. Ceramic capacitors have tolerances between 5%-20%, come in values between 1 pF to 220 nF, and have voltage ratings between 50 V to 100 V.

3.3.6.3 Plastic Film Capacitors

Plastic film capacitors use polyester, polypropylene, polystyrene or other plastic films as dielectrics, and come in two forms: film-foil and metallized film. Film-foil capacitors are made by winding single or multiple layers of plastic film with metal foil electrodes. Metallized film capacitors utilize vapor deposition to deposit a metal film onto a plastic film, which are then rolled up. Their tolerances range between 1% to 20%, are available in 100 pF to 10 µF values, and have voltage ratings between 50 V to 2000 V.

3.3.6.4 Electrolytic Capacitors

Electrolytic capacitors use oxidizable metals like aluminum and tantalum to form an oxide film, which will act as the dielectric. They can come in either water-based or wet forms or solid forms. Aluminum is typically used, and the process of making an electrolytic capacitor involves first roughening the surface of the metal to increase its effective surface to increase its capacitance. Then, the surface is electrochemically treated to form an oxide layer, followed by placing leads into the capacitor separated by an electrolyte paper spacer before being rolled up. They have tight tolerances between 0.1% to 5%, are available in 1 µF to 47 mF varieties, and have voltage ratings between 4 V to 630 V.

Table 3.16: Capacitor Types

Characteristic	Mica	Ceramic	Plastic Film	Electrolyte
Material composition	Mica dielectric w/ silver plates	Ceramic dielectric	Plastic film dielectric (polyester, polypropylene, polystyrene, etc.)	Oxide film dielectric
Tolerance	±0.05% to ±5%	±5% to ±20%	±1% to ±20%	±0.1% to ±5%
Typical Capacitance Range	1 pF to 91 nF	1 pF to 220 nF	100 pF to 10 µF	1 µF to 47 mF
Voltage Rating	50 V to 2.5 kV	50 V to 100 V	50 V to 2 kV	4 V to 630 V
Frequency Response	Very High	High	Very Low	Low to Medium
Cost	Low to Medium	Very Low	Low	Low to Medium
Applications	High-frequency RF circuits	Filters, rectifiers, AC circuits	Household electronics, power systems	Power supplies, DC-DC converters

Justification for Ceramic Capacitor Selection
Ceramic capacitors were selected mainly due to their low cost and excellent performance in low-voltage circuits, which means they will be able to handle the voltage levels of this project without making a huge dent in the project budget. They also demonstrate a high response to changes in frequencies (often in the MHz range), meaning that they exhibit low impedances at high frequencies and are suitable for such applications. As ceramic capacitors come in surface-mount packages and packages with leads, they are suitable for a variety of PCB constructions.

3.4 Software Selection

This section outlines the programs and programming languages available for use during the design and implementation phases of the project.

3.4.1 C

C is a low-level programming language that gives you direct access to memory and hardware, which makes it a solid choice for embedded systems and microcontroller programming. It's been around since the 1970s and is still used today because of how fast and efficient it is. One of the biggest advantages of using C is the level of control it gives you over how your program interacts with the system. You can work with memory addresses, registers, and use bitwise operations, which are essential when dealing with hardware-level programming.

C doesn't have object-oriented features like classes or inheritance, so it relies more on functions and structured programming. That might sound limiting, but for low-level

applications, it actually keeps things simple and focused. You can still organize your code in a clean, modular way using header files and separate functions. Another reason C is still popular is the huge number of libraries available. There are tons of resources and open-source libraries out there, which means you don’t always have to build things from scratch.

Since C is a compiled language, the code gets translated directly into machine code. This makes programs run faster and lets you see exactly how your code will behave at the hardware level. That’s especially important when you’re working on something like this project, where timing, memory usage, and hardware control matter a lot. Overall, C is a great choice for anything that involves low-level programming, especially when working with microcontrollers or systems that need tight control over resources.

3.4.2 Java

Java is a class-based, object-oriented programming language that's designed to be portable and easy to use across different systems. One of the biggest strengths of Java is that it's not just a language, it also comes with a built-in platform. When you write Java code, it's compiled into bytecode, which runs on the Java Virtual Machine (JVM). This setup makes Java extremely portable, since the same code can run on different devices as long as the JVM is installed.

Unlike C, which focuses on low-level hardware access and procedural programming, Java is built around object-oriented programming (OOP). It uses key OOP concepts like classes, objects, inheritance, encapsulation, abstraction, and polymorphism. These features help make code more organized, easier to maintain, and better suited for team collaboration. For example, using classes and objects lets you break a program into smaller, manageable pieces that can be reused and tested independently. This also makes it easier to divide work among team members, since different people can work on different classes or modules.

Encapsulation allows for better security and readability by keeping certain data private within a class. Inheritance and polymorphism help reduce redundancy by letting developers build on existing code instead of rewriting it from scratch.

Overall, Java is a strong option for projects that need good code structure, collaboration, and portability. Its object-oriented approach and built-in platform make it especially useful for larger, team-based software development.

3.4.3 Python

Python is a high-level programming language known for its simplicity and versatility. It has a very readable syntax, which makes it easy for beginners to learn, but it's also powerful enough for complex tasks. Python comes with a huge collection of libraries and built-in functions, making it ideal for everything from basic automation to advanced applications like machine learning, data analysis, and software development.

Unlike C, which focuses on low-level control and performance, Python is more abstracted and prioritizes developer productivity over speed. It doesn’t give you the same level of hardware access, but it makes up for it with ease of use and flexibility. Python is

also object-oriented like Java, supporting classes, objects, inheritance, encapsulation, abstraction, and polymorphism. This helps with code organization and makes it easier to build larger applications in a clean, modular way.

Overall, Python is a strong option for projects that benefit from rapid development, high readability, and built-in support for tasks like automation, data processing, and scripting. While it may not be the best fit for low-level programming or performance-critical systems, it offers a wide range of capabilities that other languages may not provide as easily.

3.4.4 Language Comparison

A comparison of the programming languages used for embedded development and data processing is shown in Table 3.13. For embedded programming, we chose C due to its low system requirements, fast execution, and strong compatibility with hardware-level operations. C also offers a wide range of libraries that support embedded development, making it well suited for this part of the project.

For the software component focused on data processing, we selected Java. Java's object-oriented structure, strong library support, and portability make it a good fit for building scalable and organized applications. It also provides tools for data handling, user interface development, and cross-platform deployment. While scripting languages like Python are known for their simplicity, Java offers better long-term structure and maintainability, which is more important for the scope and goals of this project.

Table 3.17: Language Comparison

Language	**HW level**	**Formal Structure**	**Object-Oriented**	**Scripting**
C	Low	✓	x	x
Java	High	✓	✓	x
Python	High	x	Can be	✓

3.4.5 PCB Modeling Software Comparison

PCB modeling software will be necessary to design custom PCBs for the transmitter and receiver circuits of this project. They differ in familiarity (if software has a similar layout), ease of swapping from schematic to PCB to 3D model, and compatibility with .step files. Some of the big names are KiCad, Fusion 360, Circuit Maker from Altium, and OrCAD.

Table 3.18: Modeling Software Comparison

Software	Cost	Learning Curve	Is design process streamlined?	Compatibility with step files
KiCad	Free	Low	Yes	Yes
Fusion 360	$85 per month	Steep	No	Yes
Circuit Maker	Free	Low	Yes	Yes
OrCAD	Free trial, then $1300 per year	Steep	No	Yes

Justification for Software Selection

Although KiCad and Circuit Maker are ideal for both beginners and advanced modelers alike have an intuitive UI, and are available for free, Fusion 360 was selected instead, as it was already available outside of UCF computers. Given that Fusion 360 is also a 3D modelling software, it means that there is no need to download separate PCB modelling software and take the time to learn the layout.

3.4.6 3D Modeling Software Comparison

This project will involve printing boxes for the electronic components and possibly mounts for the optical elements. They will be compared based on their cost, ease of use, their reliance on the Internet, and their target audience. The big names that will be compared are Fusion 360, SolidWorks, and Onshape.

Table 3.19: 3D Modeling Software Comparison

Software	Cost	Ease of Use	Reliant on Internet?	Target Audience
Fusion 360	$85 per month	Easy	Yes	Hobbyists, beginners, professionals
Solidworks	$235 per month (free if using school computers)	Difficult	No	Professional engineers
Onshape	Free or $125/month for standard plan	Easy	No, but only with standard plan	Beginners, hobbyists, developers

Justification for Software Selection

Fusion 360 was chosen for its low cost and ease of use. Its UI is also friendly for beginners and people with experience in 3D modelling, hence its target audience. Most 3D modelling software has a steep learning curve and requires hours of experience, but modelling on Fusion 360 was found to be relatively easy and suitable for all experience levels.

3.5 Software Applications

For this project, we will be using C for embedded programming and Java for software development and data processing. A comparison of the programming languages considered is shown in Table 3.13.

C was selected for microcontroller programming due to its speed, low resource requirements, and ability to interact directly with hardware. We will be using the ESP32 chip, and development will be done primarily in Visual Studio Code using the ESP-IDF framework, which provides full control over the microcontroller and its peripherals. Code Composer Studio may also be used for tasks that involve TI hardware or when additional debugging tools are needed.

For the software side, including data processing and any desktop-based interfaces, we chose Java. Its object-oriented structure and strong support for GUI development, along with its cross-platform compatibility, make it well-suited for building maintainable and scalable applications. Java also offers good performance for real-time data processing and can handle larger applications better than most scripting languages.

Visual Studio Code will serve as the main development environment for both embedded and application-level code, with extensions available for both C and Java to streamline the workflow.

3.5.1 VS code & Code Composer

Visual Studio and Code Composer Studio (CCS) are both integrated development environments (IDEs), but they serve different purposes and are geared toward different types of development.

Visual Studio, developed by Microsoft, is a versatile IDE mainly used for software development on Windows platforms. It's popular for building applications in C#, C++, Python, and other high-level languages, often targeting desktop, web, or cloud environments. It supports a wide range of frameworks like .NET and offers advanced features like IntelliSense, integrated debugging, unit testing, and seamless Git integration. It's a robust platform for large-scale application development, especially for enterprise-level solutions.

Code Composer Studio, developed by Texas Instruments (TI), is tailored specifically for embedded systems development. It supports TI microcontrollers and processors, such as the MSP430, Tiva C, and others. CCS is built on Eclipse and includes tools for low-level debugging, hardware interfacing, memory mapping, and real-time code execution. It's commonly used in electronics and embedded systems projects where direct control over hardware is essential.

Despite these differences, both IDEs share some core similarities. They provide a user-friendly interface for writing, compiling, and debugging code. Both support C and C++ programming, offer project management tools, and allow for integration with version control systems like Git. Ultimately, the choice between the two depends on the type of development. Visual Studio excels in general-purpose software, while Code Composer is specialized for embedded and hardware-related programming.

Chapter 4 Standards and Design Constraints

When designing and developing an optical/photonic system, compliance with relevant standards and adherence to specific design constraints are critical for ensuring functionality, safety, and performance. These standards govern various aspects such as laser safety, communication protocols, optical component specifications, and electromagnetic compatibility (EMC). In this chapter, we will discuss the relevant standards that apply to our optical system, focusing on the most pertinent ones for our design. Key specifications and safety measures required for the development of the system will also be highlighted.

4.1 Key Standards and Design Constraints

The development of an optical communication system requires compliance with various standards that govern the selection and implementation of optical components, laser sources, detectors, and other system elements. Below is a list of relevant standards and design constraints applicable to this project:

4.1.1 IEC 60825-1: Safety of Laser Products – Part 1: Equipment Classification and Requirements

- Relevant Specifications: This standard classifies lasers based on their output power and potential risks to human eyes. It specifies laser safety classes (Class 1, Class 2, Class 3B, and Class 4) based on power levels, wavelength, and exposure duration.

- Design Constraint: Lasers used in this project must be compliant with Class 1 or Class 2 classifications to ensure safety. This means the laser power should fall within safe limits for both direct and scattered radiation.

4.1.2 IEC 60825-12: Safety of Laser products - Part 12: Safety of free space optical communication systems used for transmission of information

- Relevant standards: Outlines safety standards and parameters for laser products for use in free-space optical communications systems
- Design constraints: The system must follow the guidelines to ensure safety while transmitting at a distance.

4.1.3 IEC 60950-1: Safety of Information Technology Equipment

- Relevant Specifications: This standard ensures electrical safety of information technology equipment, including optical transceivers, detectors, and other devices used in the system.

- Design Constraint: All electronic components should comply with this standard to prevent electrical hazards and ensure the system’s safe operation.

4.1.4 IEC 61000-4-3: Electromagnetic Compatibility (EMC) – Radiated, Radio-Frequency, Electromagnetic Field Immunity Test

- Relevant Specifications: This standard ensures that devices are immune to electromagnetic interference (EMI), which is crucial for reliable operation in noisy environments.

- Design Constraint: The system must be designed to withstand typical levels of electromagnetic interference (EMI) in industrial and commercial environments.

4.2 Detailed Discussion of Key Standards

4.2.1 IEC 60825-1: Safety of Laser Products

4.2.1.1 Overview and Key Specifications

Laser Power

Laser power is a critical factor in determining the safety classification of a laser device. IEC 60825-1 categorizes lasers based on their output power, with higher-powered lasers posing greater risks to human eyes. Lasers with lower power outputs (Class 1) are deemed safe under normal operating conditions, while those with higher power (Class 2 and beyond) require more stringent safety measures (*IEC 60825-1, 2014*). This standard helps to ensure that the risk of eye injury due to laser exposure is minimized by limiting the power of lasers used in various applications (*Kasap, 2013*).

Wavelength

The wavelength of a laser is another key parameter in its safety classification. Lasers operating in the visible spectrum (around 400 nm to 700 nm) are more hazardous because the human eye is more sensitive to light in this range. Near-infrared lasers (e.g., 850 nm, 1310 nm, or 1550 nm) can also be hazardous, but they are less noticeable to the human eye, leading to longer exposure times before damage occurs (*Kasap, 2013*). The standard specifies that lasers with wavelengths in the visible range are particularly dangerous, as they can cause more immediate harm to the retina due to the eye's optical characteristics (*IEC 60825-1, 2014*)

Exposure Time

Exposure time refers to the duration of direct or scattered laser radiation that a person is exposed to. IEC 60825-1 stipulates that lasers in higher classes (Class 2 and above) can cause harm if the exposure time is too long. For example, Class 1 lasers are safe under all conditions of normal use, while Class 2 lasers are safe for exposure periods of up to 0.25 seconds. Longer exposure times increase the risk of permanent eye damage, particularly in high-power lasers, making the duration of exposure a crucial factor in safety classification (*IEC 60825-1, 2014*).

4.2.1.2 Design Constraints and Safety Measures

Laser Class Labeling

It is essential to clearly label lasers according to their classification, as outlined in IEC 60825-1. This labeling will help to communicate the potential hazards to users and operators. For lasers that fall under Class 2 or higher, the equipment should bear a prominent warning indicating the risk level associated with the device. This ensures that personnel can take appropriate precautions, such as wearing protective eyewear or following safety procedures when handling the equipment (*Kasap, 2013*).

Safety Training

Personnel involved in the installation, maintenance, and operation of the laser system should undergo comprehensive safety training. This training will include topics such as laser safety principles, potential hazards associated with different laser classes, proper use of safety equipment (e.g., eyewear), and emergency procedures. Properly trained staff are essential to minimize the risks of accidents related to laser exposure, ensuring a safe working environment for all users (*IEC 60825-1, 2014*).

Enclosures

For higher-powered lasers (Class 3B and Class 4), it is critical to incorporate protective enclosures around the laser equipment. These enclosures prevent direct exposure to the laser beam and minimize the risk of eye injury. Enclosures must be designed to fully contain the laser beam under normal operating conditions, and any potential escape of radiation should be controlled or prevented through design features such as interlocks or safety switches (*IEC 60825-1, 2014*).

Atmospheric Attenuation and Link Budget

Free-Space Optical (FSO) communication systems are inherently susceptible to atmospheric variability, which can introduce significant attenuation into the optical link. Environmental conditions such as fog, rain, dust, and airborne particulates can severely impact infrared laser propagation, especially over extended distances. Under dense fog conditions, for instance, atmospheric attenuation can reach levels as high as 20–30 dB/km, significantly degrading link reliability and data throughput (Keiser, 2011). Therefore, system designers must account for such losses by incorporating conservative link margin values into the power budget—typically between 10 dB and 20 dB—to ensure consistent system performance even under worst-case environmental conditions.

Beyond direct attenuation, atmospheric conditions such as temperature gradients and relative humidity can also lead to beam spreading and refractive index fluctuations. These factors result in signal dispersion, reducing received power and affecting the optical signal-to-noise ratio (OSNR). To address these challenges, the selection of the operating wavelength becomes critical. The 1550 nm spectral window is widely preferred for its superior atmospheric transmission characteristics, offering reduced Rayleigh scattering and better fog penetration compared to shorter wavelengths (Agrawal, 2012). This wavelength also benefits from lower absorption by water vapor and aerosols, further enhancing performance in humid or polluted environments.

Design strategies must also consider adaptability. To counter fluctuating attenuation, modern FSO systems often integrate dynamic features such as adaptive power control, which adjusts the emitted optical power in real time according to channel conditions. Additionally, signal redundancy—such as forward error correction (FEC) and spatial diversity—can improve system resilience without exceeding permissible laser safety limits (Coldren, Corzine, & Mashanovitch, 2012). These measures collectively ensure high availability and reliability, even in the presence of unpredictable atmospheric effects.

Alignment Tolerance and Beam Divergence

In contrast to guided fiber-optic communication, FSO systems transmit laser beams through open space, making alignment precision a critical constraint. Small angular misalignments between the transmitter and receiver can result in significant optical power losses, particularly in systems using narrow beam divergence. Alignment errors exceeding 0.5° may cause the beam to miss the receiving aperture entirely, leading to loss of connectivity or safety risks in uncontrolled areas (Kasap, 2013). Therefore, mechanical design must emphasize mounting stability and tolerance, incorporating rigid support structures, vibration isolation, and thermally stable materials to minimize misalignment over time.

The beam divergence angle also plays a crucial role in system robustness and safety. A laser beam with very low divergence maintains higher irradiance but requires more precise alignment, whereas increasing divergence helps accommodate small positional deviations at the cost of spreading power across a wider area. For FSO applications, beam divergence is typically kept under 5 milliradians to balance alignment tolerance with energy efficiency (Michalzik, 2012). Additionally, optical components such as collimating lenses or beam shaping elements can be employed to optimize the beam profile for the receiving system's field of view while maintaining compliance with IEC 60825-1 safety classifications (IEC, 2014).

In dynamic or mobile environments, active beam steering technologies offer further alignment assurance. These systems use feedback-controlled mirrors or gimbals to compensate for motion or vibration in real-time, maintaining beam alignment and minimizing signal interruption (Iga, 2013). While such mechanisms add design complexity and cost, they are instrumental for FSO systems deployed on mobile platforms or in environments with mechanical instability.

To further mitigate the risks of misalignment, the use of larger aperture receivers can enhance optical capture efficiency, providing greater angular acceptance and resilience to minor deviations. This approach, combined with stable mechanical alignment systems, enables more reliable performance across a range of environmental and operational conditions.

4.3 Standards and Design Constraints Continued

4.3.1 IEC 60747-5-7: Optoelectronic devices - Photodiodes and phototransistors

- Relevant Specifications: This standard outlines the ratings, characteristics, and methods of measuring photodiodes and photodiodes.
- Design Constraint: The photodiode used in the transmitter must be tested for its parameters, including but not limited to responsivity and dark current, before it is implemented into the system.

4.3.2 IEC 61280-1-3: General communication subsystems - Measurement of central wavelength, spectral width and additional spectral characteristics

- Relevant Specifications: This standard defines several wavelength and spectral width properties of an optical spectrum of various optical communication subsystems, and outlines measurement procedures for those properties.
- Design Constraint: The optical spectral properties of the transmitter must be measured to ensure optimal transmission of the laser through the multimode fiber.

4.4 Infrared Laser Standards and Design Constraints

Infrared (IR) lasers are widely used in free-space optical communication systems due to their eye-safety potential, atmospheric transmission characteristics, and compatibility with high-speed photonic detectors. Lasers operating in the near-IR spectral region (typically 780 nm – 1600 nm) offer a balance between performance and biological safety when compared to visible or ultraviolet lasers.

Unlike fiber-based systems, IR lasers in FSO environments pose unique challenges, particularly in terms of exposure risk (due to invisibility), alignment sensitivity, and environmental degradation. Although specific IR standards are integrated within broader laser safety frameworks (e.g., IEC 60825-1 and IEC 60825-12), the design and implementation of IR lasers warrant dedicated constraints and guidelines.

Table 4.1: Key Specifications for Infrared Lasers in FSO Applications

Parameter	Typical Range / Target	Design Relevance
Wavelength	850 nm, 980 nm, 1310 nm, 1550 nm	Balance between eye safety and atmospheric transmission (Kasap, 2013)
Output Power	< 0.4 mW (Class 1), < 1 mW (Class 2)	Determines safety classification under IEC 60825-1
Beam Divergence	< 5 mrad	Affects irradiance, alignment tolerance, and receiver aperture size
Modulation Format	OOK, NRZ, PWM	Impacts receiver design and eye safety due to transient peak power
Beam Diameter ($1/e^2$)	1–5 mm at transmitter	Controls spatial distribution and power density
Pulse Width	Continuous Wave (CW) or <10 ns	Short pulses may pose additional eye risks (Coldren et al., 2012)

Sources: IEC 60825-1 (2014), Iga (2013), Michalzik (2012), Kasap (2013), Agrawal (2012)

Wavelength

Wavelength is one of the most critical design parameters in infrared laser systems, directly influencing both system performance and biological safety. Commonly used wavelengths in FSO systems include 850 nm, 1310 nm, and 1550 nm. The 1550 nm wavelength is particularly favored for longer-distance communication due to its superior eye safety characteristics; at this wavelength, laser radiation is absorbed in the cornea and aqueous humor rather than reaching the retina, substantially reducing the risk of permanent eye damage (Kasap, 2013). Furthermore, this wavelength benefits from relatively low atmospheric attenuation, especially in clear weather conditions, and aligns with mature photonic component technologies. Conversely, shorter wavelengths like 850 nm are generally more affected by scattering and have stricter power limits for eye safety, which can constrain their use in high-power systems.

Output Power

The output power of the laser directly impacts the communication range, signal strength, and safety classification of the system. Higher output powers are capable of supporting longer communication distances and providing a higher signal-to-noise ratio (SNR) at the receiver, particularly in environments with moderate optical loss. However, this increase must be carefully balanced against the limitations set by safety standards such as IEC 60825-1, which impose maximum permissible exposure (MPE) limits for each laser class (IEC, 2014). For Class 1 and Class 2 lasers, the output power must remain below defined thresholds—typically under 0.39 mW for Class 1 at 1550 nm—making power budgeting and attenuation control critical design considerations.

Beam Divergence

Beam divergence refers to the angular spread of the laser beam as it propagates through space, typically measured in milliradians (mrad). A lower divergence angle results in a more collimated beam, which minimizes beam expansion and allows for higher optical intensity at the receiver over long distances. This improves power efficiency and alignment stability. However, highly collimated beams require precise pointing and tracking systems, which can increase the complexity and cost of the system. On the other hand, slightly increased divergence may enhance eye safety by distributing the beam's energy over a larger area, reducing the optical irradiance encountered at any given point (Coldren et al., 2012). Typical divergence values for FSO systems range from 1 to 5 mrad depending on the application and range.

Modulation Format

The modulation scheme determines how information is encoded onto the laser beam. Common schemes in FSO systems include on-off keying (OOK), pulse position modulation (PPM), and pulse width modulation (PWM). OOK is widely used for its simplicity and compatibility with direct laser modulation, but it can be less power-efficient than more complex schemes. PPM, by contrast, is more efficient in terms of average power usage and is preferred for eye-safe, high-data-rate applications, although it requires more sophisticated timing and detection mechanisms (Agrawal, 2012). The choice of modulation affects the required bandwidth, power consumption, and receiver complexity, and must be chosen to optimize the trade-off between system performance and power/safety constraints.

Beam Diameter at Aperture

The beam diameter at the aperture is a parameter that affects the initial spatial distribution of laser power. A larger beam diameter reduces the optical intensity and thus contributes to eye safety by lowering the chance of surpassing maximum permissible exposure limits. It also reduces the rate of beam divergence for a given optical design, aiding in long-distance transmission. However, larger beam diameters require larger aperture optics, which can increase system size and cost. Conversely, a smaller beam can be advantageous in tightly integrated systems but necessitates careful alignment and stricter safety protocols due to its higher power density (Michalzik, 2012).

Pulse Width (for Pulsed Systems)

In pulsed laser systems, the pulse width—the duration of each laser emission pulse—is a critical design factor that affects both data transmission rates and compliance with safety limits. Shorter pulse widths allow for higher data throughput, especially when combined with high pulse repetition frequencies. However, very short pulses can have high peak powers, increasing the instantaneous power density and posing significant eye hazards. The IEC 60825-1 standard defines different safety exposure limits for pulsed versus continuous wave (CW) lasers, which must be taken into account during design (IEC, 2014). Additionally, pulse width affects receiver design, as detectors must respond accurately within the given time window to avoid inter-symbol interference (Coldren et al., 2012).

Spectral Linewidth

Spectral linewidth refers to the range of wavelengths over which the laser emits. Narrow linewidths, often less than 1 nm, are ideal for coherent detection and low-dispersion transmission, although such precision requires temperature stabilization and sophisticated laser cavity designs. In FSO systems using direct detection, a wider linewidth may be tolerable and could even reduce the effects of coherent interference and speckle. However, excessive linewidth can result in chromatic dispersion and loss of signal fidelity, especially in systems operating at high data rates (Agrawal, 2012). As such, spectral characteristics must be carefully matched with the modulation format and detection architecture.

Thermal Stability

The performance of infrared lasers is sensitive to temperature variations, which can affect emission wavelength, output power, and beam pointing accuracy. Poor thermal stability can lead to wavelength drift, degrading communication reliability or even moving the emission wavelength out of the desired transmission window. Therefore, FSO systems must integrate temperature compensation mechanisms such as thermoelectric coolers (TECs), temperature sensors, and closed-loop feedback control circuits. These components maintain consistent laser behavior across environmental variations, ensuring system reliability in field applications (Coldren et al., 2012; Iga, 2013).

Operating Lifetime

The operating lifetime of a laser diode determines the expected duration of system functionality before performance degrades or component replacement is needed. Infrared lasers, especially those based on GaAs or InP materials, typically exhibit lifespans on the order of 10,000 to 100,000 hours depending on operating conditions such as drive current, temperature, and humidity. Ensuring long operational life involves selecting diodes with robust packaging, low defect rates, and protective coatings to resist oxidation and thermal cycling (Iga, 2013). Long lifetimes are essential for reducing maintenance costs and ensuring consistent performance in mission-critical systems.

4.4.1 Design Constraints for Infrared Laser Systems

The implementation of infrared (IR) lasers in free-space optical (FSO) systems requires careful attention to specific design constraints that ensure safe, reliable, and efficient operation. Unlike their visible-wavelength counterparts, IR lasers pose unique challenges due to their invisibility, sensitivity to thermal fluctuations, and susceptibility to atmospheric interference. Moreover, stringent international safety classifications such as those outlined in IEC 60825-1 must be met to protect users from accidental exposure. This section outlines and elaborates on the critical design measures necessary to address five key constraint areas: eye safety, invisible beam awareness, atmospheric effects, beam control, and thermal stability. Each constraint is considered with respect to its implications on system architecture, safety compliance, and operational resilience in both controlled and variable environments.

Table 4.2: Summary of IR Laser-Specific Constraints

Constraint Area	Design Measures
Eye Safety (Class 1/2)	Limit power, add divergence, shielding, auto shutdown
Invisible Beam Awareness	Use visible indicators, alignment lasers, labeling
Atmospheric Effects	Choose 1550 nm, add link margin, use sealed optics
Beam Control	Collimation optics, divergence tuning, aperture shaping
Thermal Stability	Include heat sinks, monitor temperature, operate below max duty cycle limits

Eye Safety Compliance

Maintaining strict adherence to laser safety classifications is fundamental when incorporating IR lasers into a system. While longer wavelengths such as 1550 nm present reduced retinal hazard due to absorption in the anterior portions of the eye, they still require classification under IEC 60825-1 to ensure safety for both direct and indirect exposure (IEC, 2014). To comply with Class 1 or Class 2 safety classifications, the laser system must limit optical output power below thresholds that could cause biological damage. This involves not only regulating total emitted power but also managing beam divergence and aperture dimensions to distribute energy over a wider area, thereby reducing optical power density (Kasap, 2013). Moreover, systems must incorporate automatic beam shutoff mechanisms in scenarios of misalignment or system failure, ensuring no accidental exposure to hazardous radiation levels.

Invisible Beam Hazard

Unlike visible-spectrum lasers, infrared beams are undetectable to the human eye, which removes the natural blink reflex as a safety barrier. This increases the risk of prolonged exposure, especially in environments where untrained personnel may encounter the system. To mitigate this, design considerations should include visible power-on indicators and clearly marked laser emission warnings that alert users to potential hazards even when the beam itself is not observable. For safe alignment during installation and maintenance, low-power visible laser diodes can be integrated as overlays or pilot beams (Coldren et al., 2012). Clear labeling and comprehensive operational documentation must accompany all such systems to prevent inadvertent exposure or misuse.

Atmospheric Transmission and Absorption

Infrared wavelengths are subject to atmospheric attenuation depending on factors such as water vapor, fog, and other airborne particulates. This phenomenon is particularly relevant in outdoor or semi-controlled environments. Although the 1550 nm wavelength offers superior performance under foggy or humid conditions due to lower scattering and absorption coefficients, designers must still account for weather variability by

incorporating link margins of 10 to 20 dB in the optical power budget (Agrawal, 2012). In indoor applications, it is essential to maintain sealed optics or protective housings that prevent dust and moisture from degrading laser transmission, especially over longer distances or in industrial environments.

Beam Quality and Divergence

The spatial and angular characteristics of the laser beam play a critical role in both system performance and safety. The beam quality, often quantified using the M^2 factor, influences the degree to which the beam can be collimated or focused. For optimal FSO system performance, designers typically aim for Gaussian beam profiles with controlled divergence (less than 5 mrad), as these minimize optical loss over distance and ensure a predictable power distribution at the receiver end (Michalzik, 2012). Collimating optics, such as aspheric lenses or micro-optical systems, are used to tailor the beam to match the receiver's field of view, while also reducing the energy density near the source to remain within Class 1 or Class 2 safety limits (IEC, 2014).

Thermal Stability and Heat Management

Infrared diode lasers, particularly those used in continuous wave (CW) or high-duty-cycle pulsed operation, are subject to thermal effects that can influence output wavelength, beam shape, and alignment stability. Improper thermal management can lead to performance degradation, wavelength drift, or even irreversible device damage (Coldren et al., 2012). Thus, the integration of passive heat sinks, active cooling methods such as thermoelectric coolers (TECs), and thermal monitoring circuits is essential. These mechanisms ensure that the diode operates within its optimal temperature range and below its thermal runaway threshold, especially under varying environmental conditions.

Chapter 5 Comparison of ChatGPT with Other Similar Platforms

With the advancement of Artificial Intelligence (AI), Natural Language Processing (NLP), and Large Language Models (LLMs), several AI-driven platforms have emerged to assist in technical research, project planning, and academic writing. These platforms, including ChatGPT, Google Bard (Gemini), Claude AI, and Microsoft Copilot, provide varying levels of support in generating content, summarizing technical papers, debugging code, and improving problem-solving efficiency.

This chapter compares ChatGPT with three other AI-powered platforms based on their capabilities, limitations, pros, and cons, particularly in the context of Senior Design projects. Furthermore, it includes real-world examples demonstrating how these platforms influenced research and problem-solving.

5.1 Overview of Similar Platforms

1. **ChatGPT** – A large language model developed by OpenAI, ChatGPT uses the GPT (Generative Pretrained Transformer) architecture to generate human-like text. It is widely used for tasks such as content creation, coding assistance, technical explanations, and general information retrieval. ChatGPT's strengths lie in its natural language understanding and ability to produce coherent and structured responses. It is versatile, supporting various applications from casual conversations to academic and professional tasks.

2. **Google Bard (Gemini)** – A generative AI conversational tool developed by Google, Bard uses the LaMDA (Language Model for Dialogue Applications) architecture. It is designed to provide conversational search results and is especially effective for brainstorming and generating creative content. Google Bard is known for its real-time internet access, allowing it to retrieve the most recent information, news, and trends. This makes it a valuable tool for individuals needing up-to-date research and real-time information, although it occasionally struggles with factual accuracy.

3. **Anthropic's Claude AI** – Claude is a family of AI assistants developed by Anthropic, focusing on providing safe, ethical, and user-friendly interactions. Claude is designed with a particular emphasis on reducing harmful behavior and ensuring that responses align with ethical guidelines. It excels in maintaining conversation context and providing responses that are less likely to generate biased or harmful content. While Claude is excellent for general conversations and ethical considerations, it tends to have less technical depth compared to platforms like ChatGPT.

4. **Microsoft Copilot** – Embedded within Microsoft's suite of productivity software, such as Word, Excel, PowerPoint, and Outlook, Microsoft Copilot uses GPT-4 to assist with content generation, data analysis, and task automation. It is tailored for improving productivity and streamlining workflows within the Microsoft ecosystem. Copilot excels at automating repetitive tasks, formatting documents,

and generating reports, but it is not as well-suited for technical problem-solving or coding assistance, which limits its utility in more specialized tasks.

5.2 Comparison of AI Platforms

The following table summarizes the strengths and weaknesses of ChatGPT, Bard, Claude, and Copilot.

Table 5.1: Comparison of AI Language Models

Feature	ChatGPT (OpenAI)	Google Bard (Gemini)	Claude AI (Anthropic)	Microsoft Copilot
Knowledge Cutoff	September 2023 (GPT-4)	Real-time internet access	Real-time updates	Uses Bing search for updates
Accuracy & Reliability	High, but depends on training data	Inconsistent factual accuracy	Focuses on safety & factual correctness	Tied to Microsoft ecosystem
Coding Assistance	Strong for Python, C++, Java, etc.	Moderate, sometimes inaccurate	Good explanations, but less practical help	Optimized for enterprise tools
Mathematical Abilities	Can solve complex problems	Struggles with calculations	Decent but conservative	Less optimized for STEM fields
Context Retention	Good memory within a session	Sometimes loses context	Excels in long conversations	Limited retention
Creativity & Writing	High-quality, structured responses	Creative but prone to errors	Safe and responsible	More technical
Ease of Use	Simple UI, widely accessible	Requires Google account	User-friendly, focuses on ethics	Integrated with Microsoft Office

Each platform has its unique advantages and drawbacks, making them suitable for different aspects of engineering research and documentation.

5.3 Strengths and Weaknesses of AI Platforms

5.3.1 ChatGPT (OpenAI)

Pros:

ChatGPT offers a strong natural language understanding that makes it ideal for generating structured, clear responses across various fields, including technical engineering topics. It supports code generation and debugging in languages such as Python, C++, and Java, allowing for a range of programming assistance. The ability to work offline in premium versions further enhances its value in scenarios where internet access may be limited. Additionally, ChatGPT provides detailed explanations and useful overviews of complex concepts, making it an excellent choice for research and documentation.

Cons:

The primary limitation of ChatGPT is its knowledge cutoff date, which means that it does not have access to real-time information beyond September 2023. As a result, it may miss out on the latest research, industry trends, or technological advancements. Furthermore, while ChatGPT's responses are generally accurate, it sometimes generates plausible but incorrect information, a phenomenon known as "hallucination." Lastly, ChatGPT does not have access to live academic sources or research papers, limiting its ability to provide up-to-date scholarly content.

5.3.2 Google Bard (Gemini AI)

Pros:

Google Bard's most significant advantage lies in its real-time internet access, which allows it to retrieve current information, updates, and trends from the web. This makes it particularly useful for research where the latest data is essential. Bard is also effective in creative tasks, such as brainstorming ideas or generating content, and has a notable ability to summarize large amounts of information quickly and concisely. Its integration with Google's vast ecosystem enables seamless access to a wide range of web-based resources.

Cons:

Despite its real-time capabilities, Bard has been criticized for its inconsistent factual accuracy. The AI sometimes fabricates references or sources that do not exist, which can be problematic when precise citation is necessary. Additionally, Bard's coding assistance has been found to be moderate at best, with occasional errors in the suggested code. This reduces its practical utility for complex coding tasks or debugging.

5.3.3 Claude AI (Anthropic)

Pros:

Claude AI is designed with an emphasis on safety and ethical interaction, making it an excellent choice for users concerned about biased or harmful content. It maintains context

well over long conversations and is highly responsive in adhering to ethical guidelines, which is crucial for users who need a reliable, trustworthy assistant. Additionally, Claude's user-friendly interface and ethical focus ensure that it produces responsible and safe content, reducing the likelihood of misinformation.

Cons:

Claude's primary drawback is its lack of technical depth in certain specialized fields, particularly STEM. While it excels in providing general assistance and maintaining conversation flow, it does not offer the same level of technical expertise as ChatGPT in areas like coding, engineering, or scientific research. Furthermore, Claude's access to real-time data is limited, which restricts its ability to provide up-to-date information, particularly for fast-evolving industries.

5.3.4 Microsoft Copilot

Pros:

Microsoft Copilot's integration with the Microsoft Office suite, including Word, Excel, and PowerPoint, makes it an invaluable tool for users already within the Microsoft ecosystem. Copilot's ability to assist with formatting documents, automating repetitive tasks, and generating reports significantly enhances productivity. The AI's use of GPT-4 ensures that it can handle a wide variety of tasks, ranging from content generation to advanced data analysis. Moreover, its ability to pull real-time data from Bing allows for more current information than traditional models.

Cons:

While Microsoft Copilot excels in office productivity tasks, it is less suited for technical problem-solving or advanced research, especially in STEM fields. Its reliance on the Microsoft ecosystem also limits its flexibility, making it less versatile for users who prefer cross-platform compatibility or need assistance outside of the Microsoft environment.

5.4 Impact on Senior Design Project

Example 1: Researching Optical Communication Standards

Scenario: While gathering information on optical fiber transmission, ChatGPT provided a structured overview of ITU-T G.657 standards, while Google Bard retrieved real-time updates from the ITU website.

- ChatGPT's Advantage: It offered a concise and organized explanation of the standards, helping clarify technical concepts.
- Google Bard's Advantage: Bard's ability to retrieve real-time updates allowed the team to access the most current industry practices, though some references were incorrect.

Example 2: Debugging Code for Optical Signal Processing

Scenario: While implementing a Python script for signal processing, the team used AI for debugging.

- ChatGPT: It offered accurate debugging suggestions and alternative methods to solve errors.
- Claude AI: While it provided detailed explanations of errors, it was less practical in providing direct fixes.
- Google Bard: Suggested code improvements, but some were factually incorrect, which caused additional debugging time.

Example 3: Writing Documentation for the Final Report

Scenario: For writing technical sections in the Senior Design Report, different AI tools were tested.

- ChatGPT: Created well-structured formal reports with citations, making it easier to compile and format the final document.
- Microsoft Copilot: Assisted with formatting the report and generating PowerPoint slides for the final presentation.

Example 4: Simulation Assistance

Scenario: While using Zemax for optical simulation, AI tools were used for troubleshooting.

- ChatGPT: Provided step-by-step explanations of optical modeling equations and how to approach different simulation challenges.
- Google Bard: Suggested new Zemax tutorials but some were outdated and no longer relevant to the current version of the software.

5.5 Conclusion

Each AI platform has strengths and weaknesses, making them suitable for different research needs. By leveraging multiple tools, a Senior Design project can benefit from enhanced research capabilities, more efficient debugging, and well-organized documentation. For tasks requiring structured explanations, code assistance, or writing support, ChatGPT remains the most effective choice. Google Bard is valuable for its real-time information retrieval, though its factual accuracy can be questionable. Claude AI is excellent for ethical considerations and long conversations but lacks technical depth. Finally, Microsoft Copilot excels in productivity-related tasks but falls short in specialized technical domains.

Chapter 6 Hardware Design

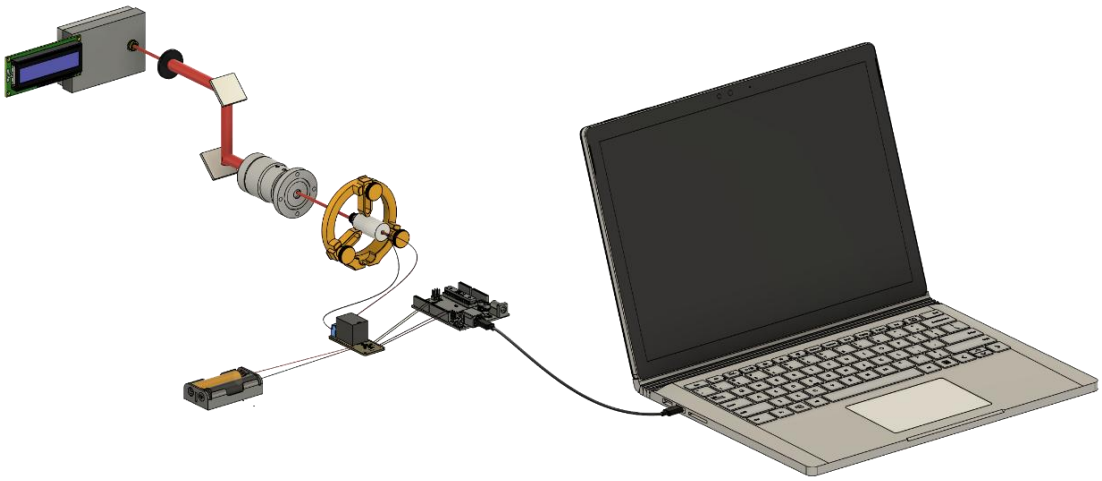


Figure 6.1: Hardware Prototype

Overview

This chapter presents the hardware diagrams that illustrate the physical and electrical design of the system. These diagrams serve as a visual representation of the components, their connections, and the overall architecture of the device. By outlining the layout and integration of key hardware elements; including the power supply, signal processing units, microcontroller, and communication modules. This chapter provides a clear understanding of how the system functions as a whole.

6.1 Subsystem Block Diagram

The subsystem block diagram provides a high-level overview of how different components interact within the system. Each subsystem plays a distinct role in processing the optical signal and converting it into displayable text. The major subsystems include:

- Signal generation:
  - Laptop: Runs program to convert written text to binary and upload it to microcontroller
  - Microcontroller: Programmed by laptop to toggle laser power through the use of a power relay in relation to the given binary code
- Optics:
  - Optical Transmission System: The laser, guided through a system of lenes and mirrors, directs the light signal to the receiving photodiode.
- PCB:
  - Photodiode + Transimpedance Circuit: Converts the received light signal from amps to voltage.
  - Voltage Regulation: Ensures stable power delivery to all active electronic components.

    - Power Supply: Provides power to the entire PCB
    - Microcontroller (MCU): Decodes the processed signal and converts it into written text to be displayed.
    - LCD: Displays the transmitted message
- Power:
    - Relay controlled battery pack: Connected to high power laser and controlled by the microcontroller.
    - PCB battery pack: Provides power to all units inside of PCB

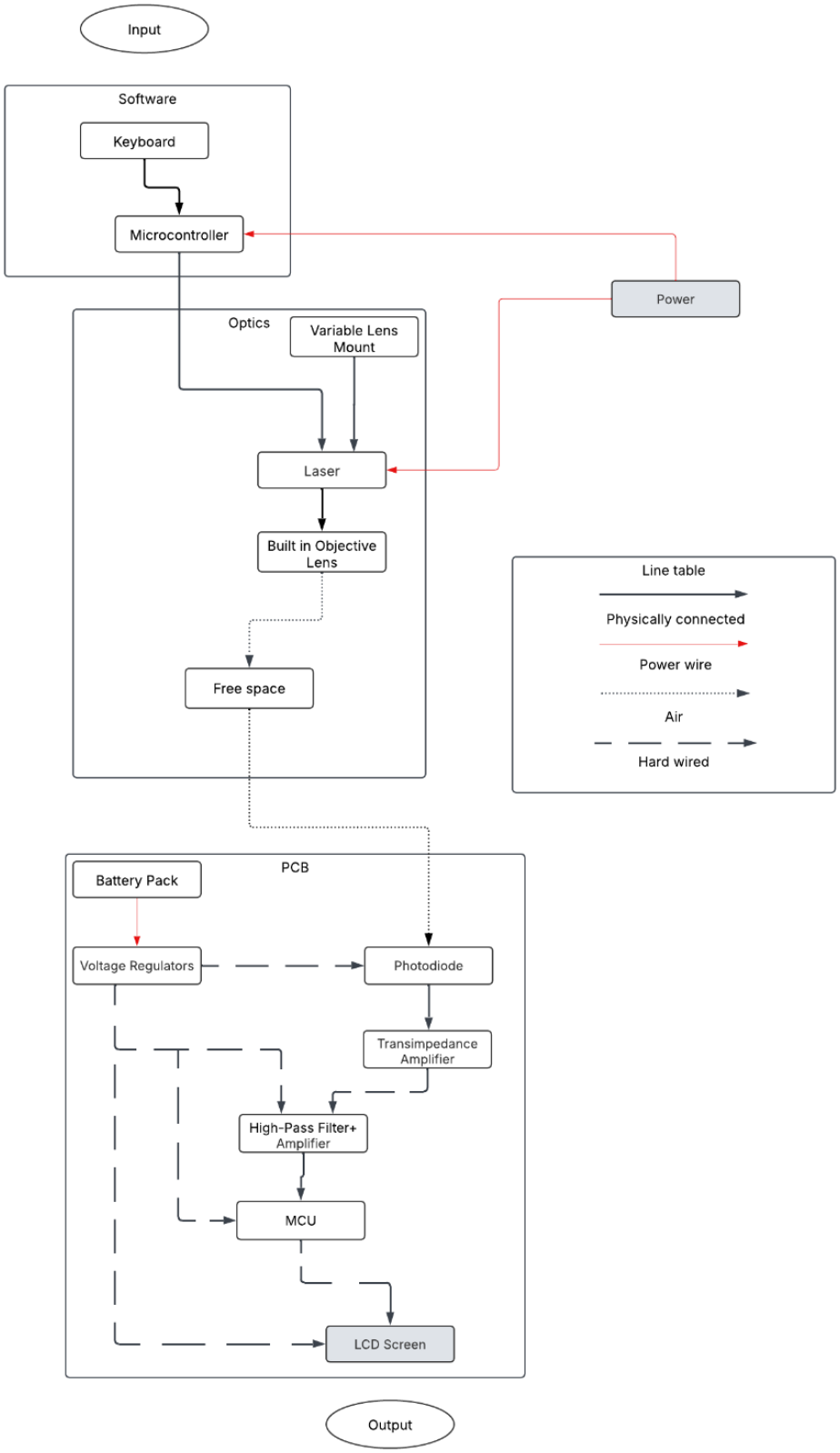


Figure 6.2: Block Diagram

6.2 Schematic Diagrams

The schematic diagrams presented in this section provide a comprehensive overview of the circuit design, illustrating the interconnections between key components and their respective functions. These schematics serve as a blueprint for the system, detailing the power regulation, signal processing, and communication pathways that enable the overall operation. Each subsection focuses on a critical aspect of the design, including power management, signal acquisition, signal filtering, and microcontroller processing. By analyzing these diagrams, one can gain a deeper understanding of how individual components interact to achieve the intended functionality of the device.

Overall:

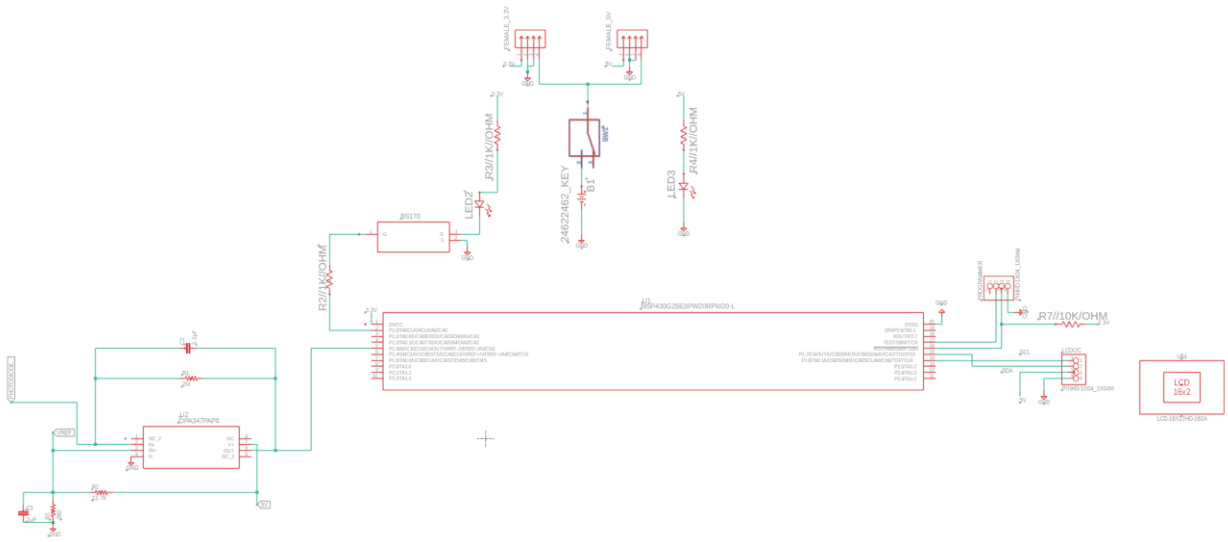


Figure 6.3: Overall Circuit Diagram

The overall system schematic integrates multiple subsystems to ensure efficient signal processing and transmission. The primary signal pathway consists of a photodiode, a transimpedance circuit, a high pass filter, a microcontroller unit (MCU), and a LCD screen. To power the board, a AA battery pack is connected to a simple on and off switch. This is then regulated by 3.3V and 5V regulators to ensure consistent and safe voltage for the various subsystems. Each component plays a critical role in converting optical signals into electrical data suitable for further processing.

Battery Pack + Switch:

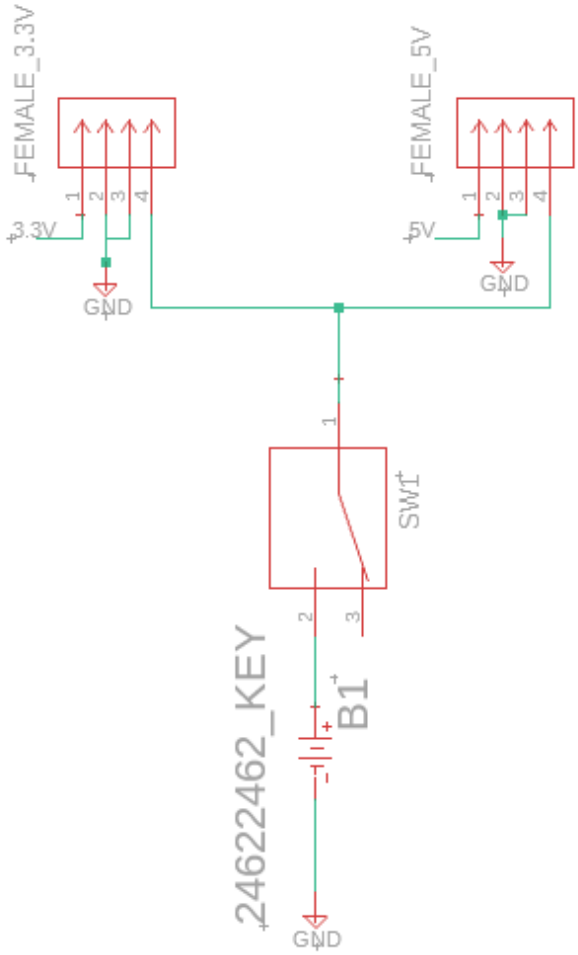


Figure 6.4: Battery Pack + Switch

The power system is initiated by an AA battery pack, which provides the necessary voltage for the circuit's operation. A simple on/off switch is integrated to enable controlled power delivery. This system is then connected to the 3.3- and 5-volt regulators to supply power to the various components.

3.3V regulator:

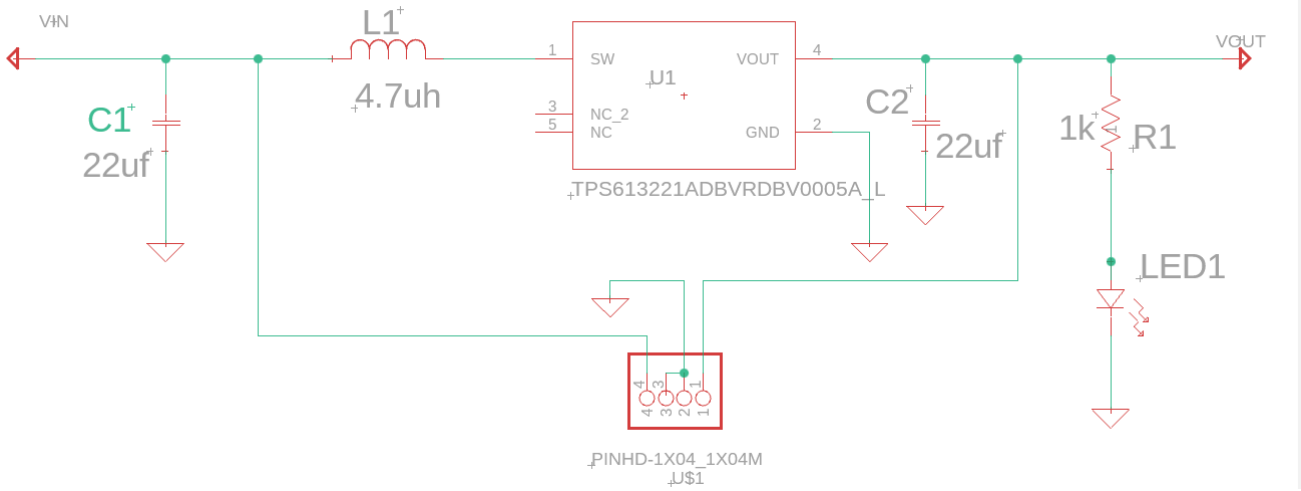


Figure 6.5: 3.3V Regulator

The 3.3V voltage regulator is responsible for supplying a stable power source to components that require 3.3V operation, including the microcontroller (TPS61322). By regulating input voltage, this component prevents potential damage to sensitive electronics and ensures reliable system performance. To simplify troubleshooting, an LED is added to the regulator to help visually identify if the daughter board is working.

5V regulator:

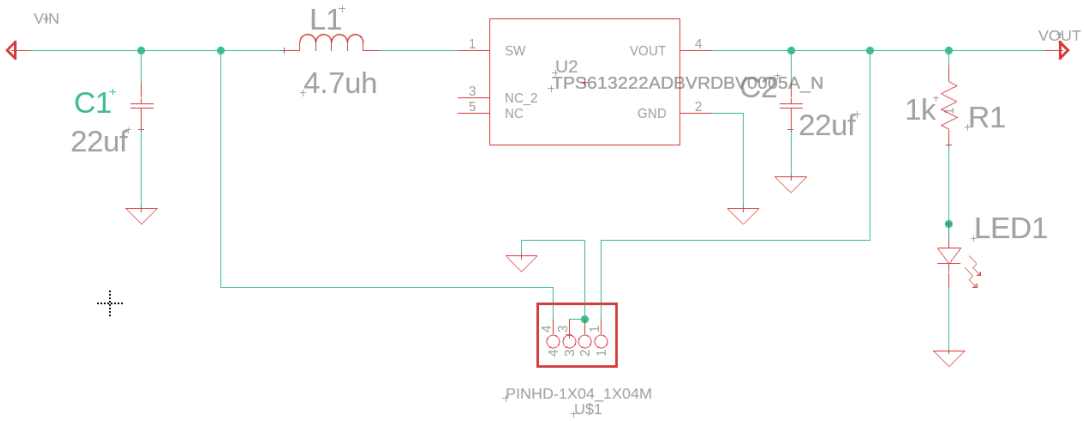


Figure 6.6: 5V Regulator

The 5V voltage regulator delivers power to subsystems requiring a 5V supply, such as the transimpedance circuit and the LCD screen module. This ensures proper voltage levels for amplification circuits, facilitating optimal signal processing and transmission. Similar to the 3.3V regulator, this regulator has an added LED for troubleshooting simplification.

Photodiode Circuit:

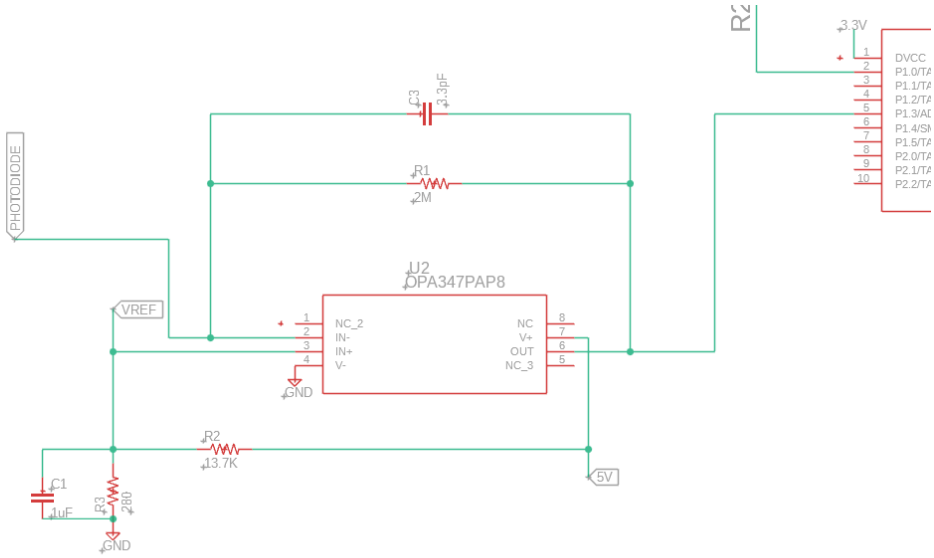


Figure 6.7: Photodiode Circuit

The photodiode is responsible for detecting incoming optical signals and converting them into an electrical current. The photodiode is reverse-biased to direct the current away from the transimpedance circuit. The transimpedance amplifier (TIA) is used to convert the photocurrent into a measurable voltage. When combined, this configuration ensures that the circuit produces a stable output voltage of no more than 3V when exposed to laser illumination. The output then leads into the signal processing circuit. The addition of the

reference voltage and its corresponding components are to avoid saturation of the voltage output when little to no light is being received by the photodiode.

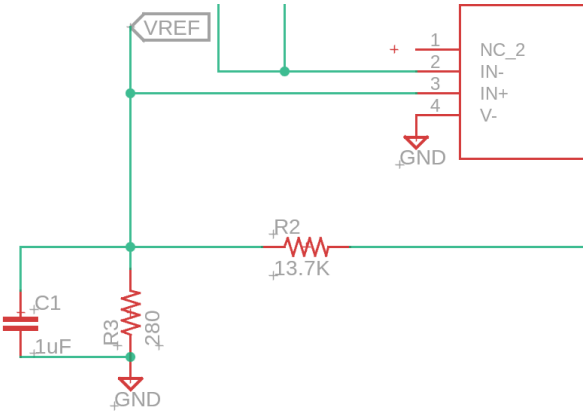


Figure 6.8: Reference Voltage circuit

MCU:

Figure 6.9: MCU

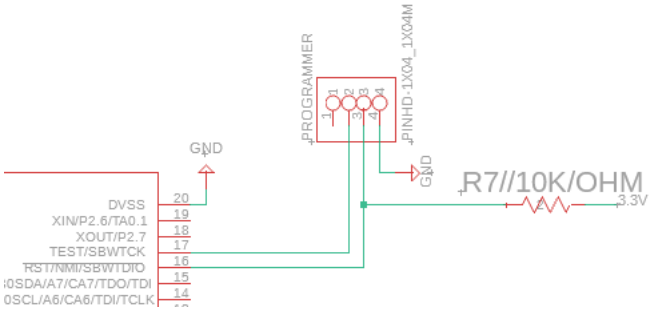


Figure 6.10: Four-pin programmer

The microcontroller serves as the system's central processing unit, decoding the received signal and formatting it for display. It is programmed using a four-pin head connected to the TEST and RST pins.

LCD Screen:

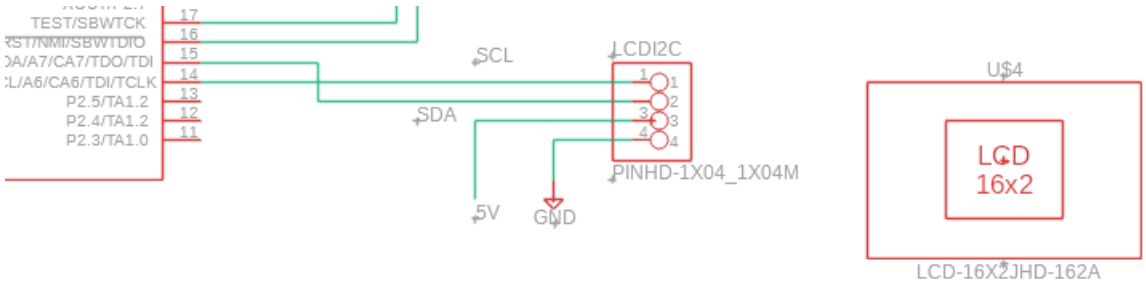


Figure 6.11: LCD screen

The LCD screen displays the processed signal, enabling a final visual medium of which to view the transmitted message. This LCD screen is connected to a four-pin head that is connected to P2.3 to receive the signal from the MCU.

6.3 Architecture

The architecture is modular, ensuring each subsystem functions independently while contributing to the overall performance. The system is designed to use a microcontroller to convert the input message into binary to toggle a laser. This laser is positioned in such a way that it travels across free space to generate a signal for the PCB. Once this signal is converted to electrical power, it is transmitted to the PCB's microcontroller to be converted back to a decodable text. The signal then is sent to a LCD screen to display the original text.

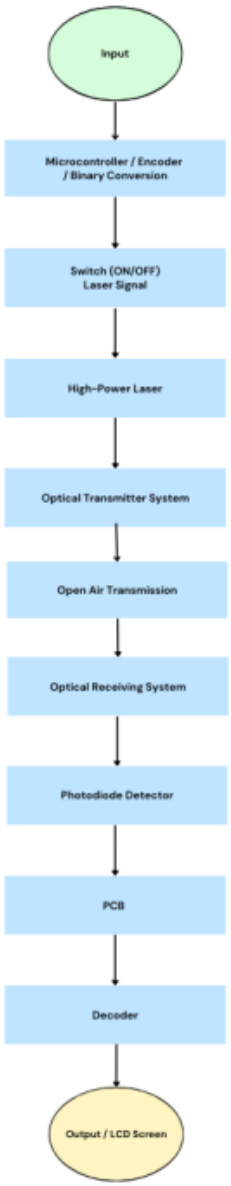


Figure 6.12: Computer Architecture

6.4 Structural Illustration

6.4.1 Signal generation

The process of converting written text to binary code using the laptop begins with the user inputting the desired text into a keyboard. This text is then encoded using a standard character encoding format such as ASCII or UTF-8, where each character is represented by a unique binary sequence. Once encoded, each character is converted into its corresponding binary form (e.g., the letter 'A' in ASCII becomes 01000001). The binary data may then be formatted into packets, timing sequences, or modulated signals to ensure compatibility with the Morse code-style transmission system. Finally, the formatted binary output is sent to the microcontroller.

Figure 6.13: Laptop

The microcontroller receives the binary code from the laptop, which represents the encoded text data intended for transmission. Upon receiving this binary input, the microcontroller processes it and converts it into a corresponding signal that controls the toggling of the power supply to the 532 nm Diode-Pumped Solid State. This toggling is achieved using the power relay module, as depicted in Figure 6.4.1.3. The relay module functions as a programmable power switch, allowing or interrupting the flow of power from the battery pack to the laser in synchronization with the binary signal. When the binary input indicates a high signal (logic '1'), the relay is activated, completing the circuit and powering the laser. Conversely, when the input is low (logic '0'), the relay disengages, cutting off power to the

laser. This controlled switching mechanism enables the laser to emit pulses of light corresponding to the encoded data

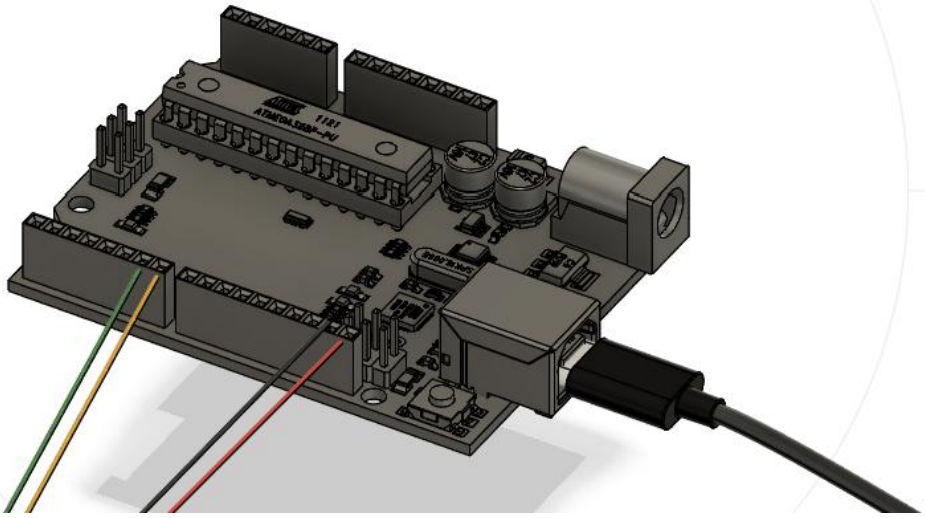


Figure 6.14: Microcontroller

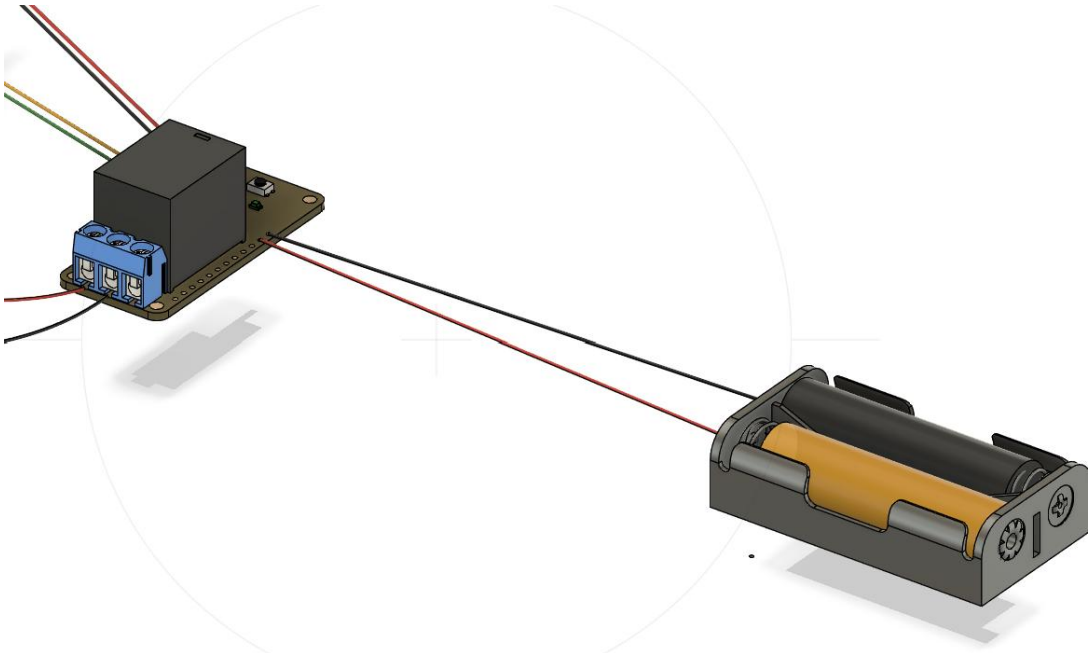


Figure 6.15: Power Relay module connected to Battery Pack

6.4.2 Optics

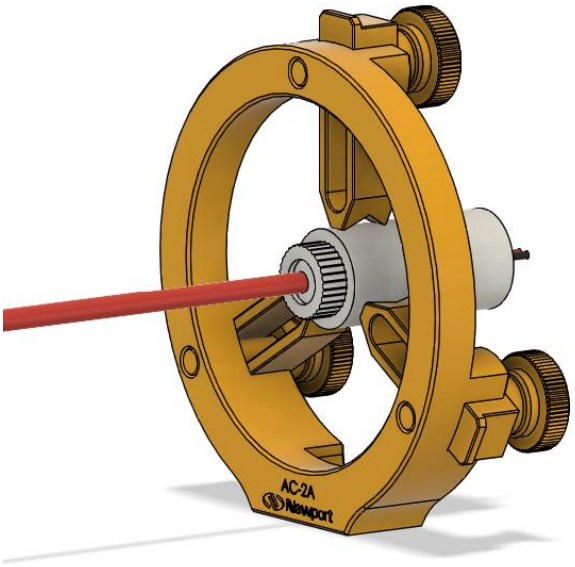


Figure 6.16: 532 nm Diode-Pumped Solid-State Laser resting in AC-2A Mount

The optical system begins with a 532 nm Diode-Pumped Solid-State laser, mounted securely in the AC-2A Variable Size Lens Mount, as illustrated in Figure 6.4.2.1. This mount enables precise alignment and fine-tuning of the laser's trajectory toward the fiber coupler.

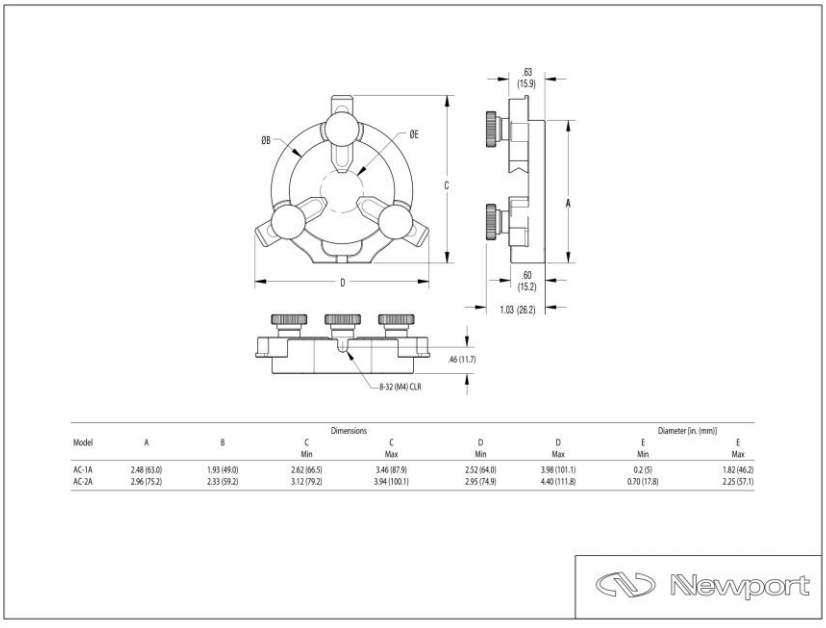


Figure 6.17: Dimensions of AC-2A

Since the laser will traverse through multiple lenses, various mirrors, and free space, figure 6.4.2.2 shows that this mount is a perfect choice fine tune the direction of its laser towards the photodiode since each “arm” can be adjusted 13mm.

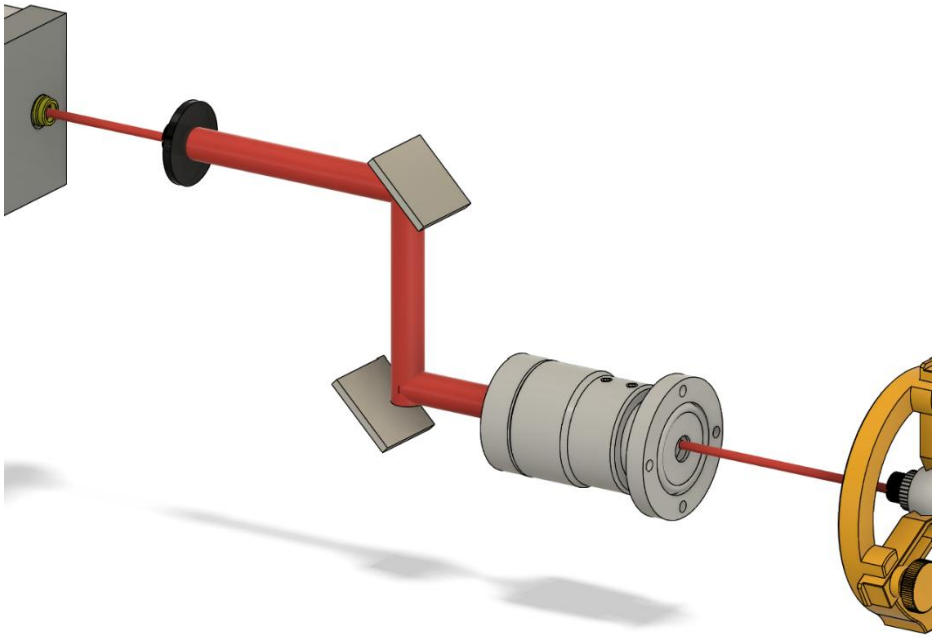


Figure 6.18: Lens and mirror apertures

The laser beam is initially directed through a collimating lens to ensure parallel beam propagation, followed by a beam expander to increase its diameter and improve long-distance transmission. After collimation and expansion, the beam encounters the first horizontal adjustment mirror, which precisely redirects its trajectory toward a secondary vertical adjustment mirror. This secondary mirror further refines the laser’s path, ensuring accurate alignment as the beam propagates over free space. Before reaching the photodetector, the beam passes through a large-aperture lens designed to focus and optimize signal reception. Additionally, an optical filter is positioned in the beam path to mitigate interference from ambient light sources, enhancing the system’s overall signal integrity and detection accuracy.

6.4.3 PCB

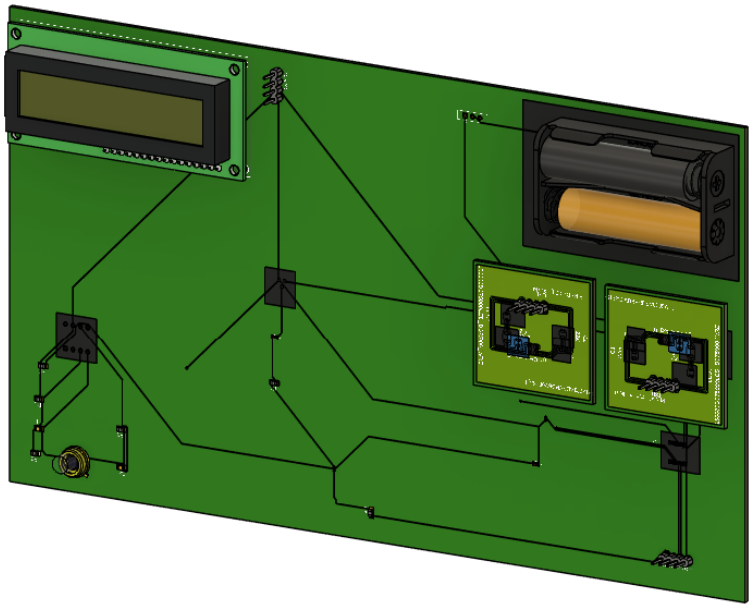


Figure 6.19: Entire PCB

The printed circuit board (PCB) serves as the central hub for signal conversion and processing. Upon reaching the PCB, the incoming optical signal is detected by the photodiode, triggering the subsequent electronic processing stages. The activation of the photodiode generates a small current that is amplified and converted to a detectable voltage by the attached transimpedance circuit. To prevent signal saturation at low or zero light levels, a reference voltage circuit is implemented. This ensures the op-amp remains within an optimal operating range, maintaining output stability even when the input current is minimal.

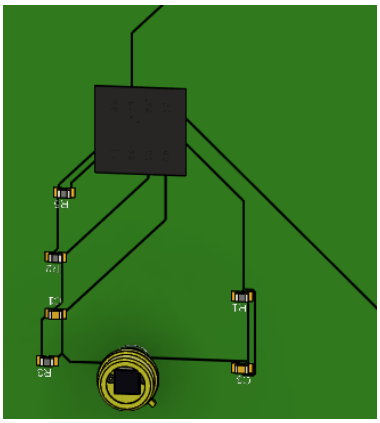


Figure 6.20: Photodiode and Transimpedance Circuit

The photodiode used in the system is the FDS100, selected for its high responsivity at 532 nm. According to its datasheet, the device exhibits a responsivity of approximately 0.2 A/W at this wavelength. Given the laser's optical output of 10 mW, the expected photocurrent is around 2 mA. Using Ohm's law and targeting a 2V output signal, a 1 kΩ resistor is selected for the feedback loop in the transimpedance configuration.

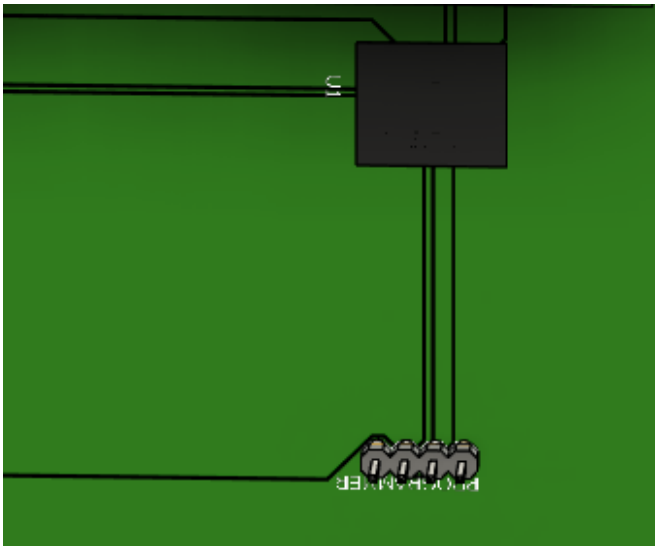


Figure 6.21: Microcontroller and Programmer

Following amplification, the voltage signal is routed to the microcontroller unit (MCU), where it is interpreted and decoded into its corresponding textual representation. The MCU then transmits the decoded data to the LCD module for display.

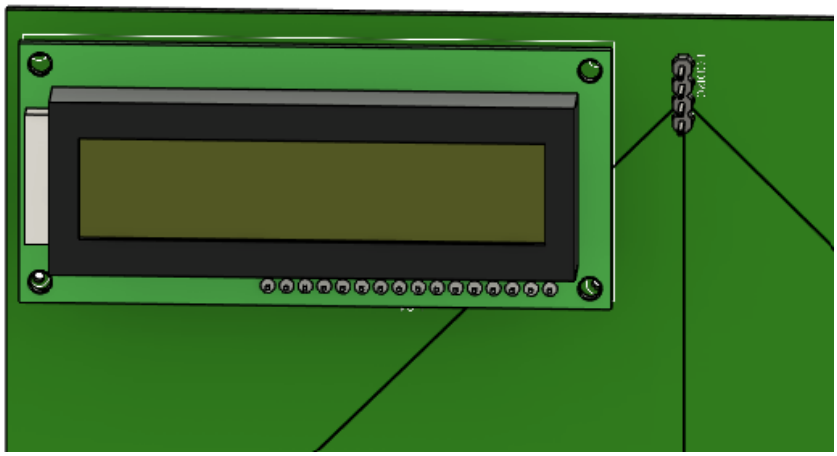


Figure 6.22: LCD Screen

6.4.4 Power

The power architecture of the system is designed to provide stable and isolated power delivery to both the optical transmission unit and the processing electronics on the PCB. To achieve this, two independent battery packs are employed—each tailored to the specific power requirements of their respective subsystems.

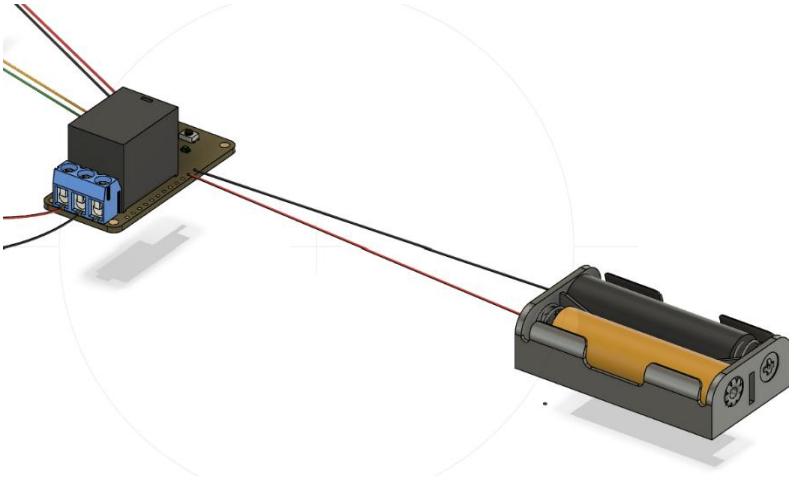


Figure 6.23: Battery Pack for laser and power relay

The first battery pack supplies power to the laser diode and is connected through a power relay module. This relay is digitally controlled by the microcontroller, enabling binary on-off modulation of the laser in synchronization with the transmitted data stream. This arrangement effectively simulates a Morse-code-like transmission, where laser pulses represent binary '1's and their absence represents '0's.

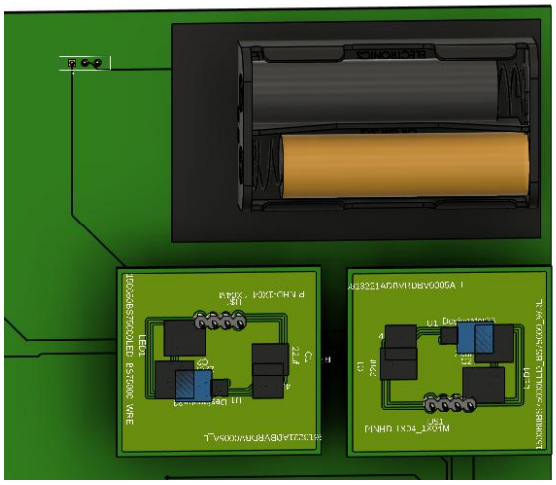


Figure 6.24: Battery Pack and regulators for PCB

The second battery pack is dedicated to the PCB and provides continuous power to the photodiode, transimpedance amplifier, microcontroller, and LCD display. This pack is routed through a set of voltage regulators that supply stable 3.3V and 5V rails, ensuring reliable performance and protecting sensitive components from voltage fluctuations.

Chapter 7 Software Design

Overview

This software design supports wireless data transmission from an input source to an LCD screen using a high-power laser and optical communication system. The process begins with input data fed into a microcontroller, which encodes and converts the data into binary form. An encoder structures the binary data for transmission, preparing it for modulation.

The binary stream is used to drive a high-power laser, which emits light pulses corresponding to the digital 1s and 0s. These pulses are sent through an optical transmitter system and travel across open air as a directed beam. The optical receiving system captures this beam using a photodiode detector, which converts the incoming light signals back into electrical pulses.

These electrical signals are sent to a PCB, where the system performs initial processing and forwards the signal to a decoder. The decoder interprets the binary stream and reconstructs the original data. A microcontroller then formats the decoded data and sends it to an LCD screen for output.

This setup allows for high-speed, line-of-sight data transfer without physical wiring. It’s particularly useful in environments with space constraints, high EMI interference, or where mobility is key—such as remote sensing, industrial automation, or embedded communication systems. The software must handle binary encoding, timing synchronization, signal filtering, error detection and correction, and display formatting to ensure reliable, real-time performance.

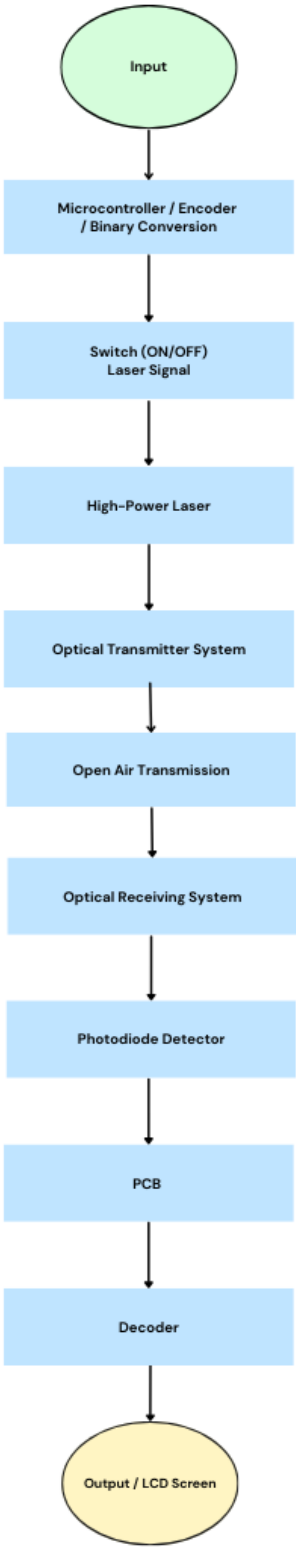


Figure 7.1: Software Flowchart

7.1 Input Handling

In the input handling stage, which is the first phase of the system, data is gathered directly from a user. This input can be numerical values or textual data. The goal of this stage is to process the collected input and provide a structured digital representation for further processing.

When a user enters a value, the system captures the information and converts it into its binary equivalent. This enables efficient digital processing and transmission of data. Similarly, when input is provided through a keyboard, such as commands or even a text messages, the system encodes the characters using common encoding schemes like American Standard Code for Information Interchange also known as ASCII or UCS Transformation Format 8 also known as UTF-8 before converting them into binary.

By structuring raw input into a machine-readable format, the system ensures smooth data transmission and processing in the subsequent steps. In short, input handling is a crucial foundation for the entire process.

7.2 Binary Conversion

Once the user provides an input in the keyboard, the system will convert it into binary; a sequence of 0s and 1s. So, it can be processed, transmitted, and interpreted by digital components. This step ensures that both numerical and textual data can be efficiently managed within the system. The example below provides the understanding of what the binary code will look like when the user types it in.

Table 7.1: Binary Table Text to Binary Examples

Text	Binary
Hello World	01001000 01100101 01101100 01101100 01101111 00100000 01010111 01101111 01110010 01101100 01100100
Senior Design 1	01010011 01100101 01101110 01101001 01101111 01110010 00100000 01000100 01100101 01110011 01101001 01100111 01101110 00100000 00110001
3221ABC	00110011 00110010 00110001 01000001 01000010 01000011

For example, when a user inputs the text "Hello World", the system should be able to process this input and convert it into binary format. Each character in "Hello World" is represented using 8-bit ASCII encoding, where every letter corresponds to a specific

binary value. This conversion ensures that computers, which operate on digital signals, can accurately interpret and process textual data.

To improve the reliability of data transmission, error detection and correction mechanisms are essential. One common method is the parity bit, which adds an extra bit to indicate whether the number of 1s in a binary sequence is even or odd. More advanced techniques, such as checksums or Hamming codes, provide enhanced error detection and even allow the system to correct mistakes that may occur during data transmission. These methods ensure that the integrity of the data is maintained, reducing the risk of errors that could disrupt system operations.
Binary conversion plays a fundamental role in computing because electronic systems function exclusively using 0s and 1s. By structuring input data into a well-defined binary format and incorporating error detection, the system ensures efficient processing, reliable transmission, and accurate interpretation of user-provided information. This structured approach enhances overall system performance and minimizes errors, making data handling seamless and precise.

This approach serves both a functional and visual purpose. The 1s and 0s generated from the binary conversion play a crucial role in controlling hardware components, such as signaling a laser to turn on and off. At the same time, the binary output provides users with valuable insight into how their input is encoded. Displaying the binary code on an LCD screen enhances transparency, allowing users to understand the transformation of their input while ensuring smooth system operation.

7.3 Signal Transmission

Once the binary data is generated, it is transmitted using a laser-based optical communication system. At this stage, a laser signal is modulated in an on/off pattern, with the presence or absence of light serving as a representation for each binary digit (bit). The laser serves as the carrier of the data, while a photodetector at the receiving end converts the light pulses back into binary information.

The process of transmitting binary data via a laser signal relies on on-off keying (OOK), a digital modulation technique that maps binary values to light emissions. In this system, a binary 1 corresponds to the laser being ON, emitting a light pulse, while a binary 0 corresponds to the laser being OFF, with no light emitted. This method effectively encodes a binary sequence into a structured series of optical pulses, which can be transmitted through free space or via optical fiber to a receiver.

For instance, consider a binary data sequence of 1011001 that needs to be transmitted. The laser modulation process operates as follows: the first 1 result in the laser turning ON, followed by a 0 where the laser turns OFF. The next two 1s cause the laser to emit light twice in succession. This is followed by two 0s, where no light is emitted, and finally another 1, turning the laser ON again. This results in the following transmission pattern:

- 1 → Laser ON
- 0 → Laser OFF

- 1 → Laser ON
- 1 → Laser ON
- 0 → Laser OFF
- 0 → Laser OFF
- 1 → Laser ON

As these light pulses reach the receiving end, a photodetector captures the variations in light intensity and translates them back into their respective binary values. By detecting when the laser is ON or OFF, the photodetector reconstructs the original binary sequence. This ensures accurate data transmission while maintaining the integrity of the encoded information.

Laser-based data transmission offers several technical advantages that make it well-suited for high-speed, low-power communication systems. First, because light travels significantly faster than electrical signals in copper wiring, laser transmission enables rapid data transfer with minimal latency. This is especially beneficial in systems requiring fast, real-time communication. Additionally, laser communication is less vulnerable to electromagnetic interference compared to radio signals, making it more reliable in electrically noisy environments. Another key advantage is power efficiency. Laser systems can be engineered to operate with low power consumption, which is critical for embedded or portable applications where energy resources are limited.

Despite these benefits, laser-based transmission also presents technical challenges. One major limitation is its line-of-sight dependency. For accurate data transfer, the laser emitter and photodetector must be precisely aligned; even slight misalignment can disrupt communication. Environmental factors also pose risk like dust, ambient light, fog, or physical obstructions can interfere with the laser beam and degrade signal integrity, especially in free-space setups. Furthermore, the system requires precise timing control. The on/off pulses that represent binary data must be synchronized accurately so the receiver interprets the signal correctly. Any timing drift can lead to bit errors and data loss, requiring additional layers of error checking and synchronization logic.

By using laser-based on-off modulation, the system efficiently transmits binary data across distances with minimal latency. Once the photodetector converts the laser pulses back into binary form, the data is passed to the next stage for further processing, hence now into the PCB radio.

7.4 High-Power Laser Control

In the system architecture, the high-power laser serves as the core transmission medium, modulating binary data into optical pulses for open-air transmission. The software’s role at this stage is to control the timing, intensity, and modulation of the laser based on the binary stream generated by the microcontroller.

Once the input data is encoded and converted into binary form, the microcontroller translates this stream into control signals that toggle the laser diode on and off. A logical ‘1’ is represented by activating the laser for a fixed pulse duration, while a logical ‘0’ corresponds to no output (or laser off) during the same time frame. This form of on-off

keying (OOK) modulation is a simple yet effective approach for digital optical communication.

The software must ensure precise timing control to maintain bit-level synchronization. Any deviation in pulse width, spacing, or frequency could lead to misinterpretation at the receiver end. For this reason, the firmware on the microcontroller must implement accurate delay routines or hardware timers to maintain a consistent bit rate.

Additionally, the software must account for laser power management. High-power lasers can consume significant energy and generate heat, especially during continuous or high-frequency operation. The control algorithm may include pulse-width limiting, duty cycle constraints, or real-time feedback from temperature sensors to prevent overheating or hardware failure. These safeguards help extend the lifespan of the laser diode and ensure safe operation.

Safety protocols are also managed in software. Before laser activation, the system may run initialization checks to confirm proper alignment, clear transmission paths, and stable input data. Fault detection routines can halt laser output in the event of critical errors, protecting both the hardware and surrounding environment.

In some systems, advanced modulation schemes (e.g., Pulse Position Modulation or PWM) could be implemented in software to improve data encoding efficiency or support higher bit rates. The firmware must be designed modularly to support potential upgrades without requiring major hardware changes.

Overall, the software's responsibilities at the high-power laser stage include pulse modulation, precise timing control, safety checks, and power optimization. These functions are essential for ensuring the laser transmits a clean, reliable signal across the optical channel for successful reception and decoding downstream.

7.5 Optical Transmitter System

The Optical Transmitter System bridges the digital control of the high-power laser and the physical layer responsible for delivering modulated light signals through free space. While much of the transmission hardware is physical, the software plays a key role in managing signal synchronization, alignment routines, and transmission reliability.

Once the binary signal has been modulated through the high-power laser—typically using On-Off Keying (OOK)—the Optical Transmitter System ensures that the emitted light beam is correctly focused, directed, and stable for open-air transmission. Software routines manage this process by interfacing with supporting components such as servo motors, collimating lenses, and beam steering mechanisms, if present.

A key software function at this stage is beam alignment control. For systems that include auto-alignment or adaptive optics, the software must monitor position feedback sensors and make real-time adjustments to maintain line-of-sight with the receiver. This is especially important in mobile or variable environments where vibration or drift could degrade transmission quality. Alignment algorithms can use PID control or similar methods to ensure stable beam direction.

The software also handles transmission timing and framing. Though modulation occurs at the laser control level, the transmitter system may require coordination with frame timing, especially in packet-based or time-multiplexed protocols. The software must manage when and how binary frames are sent, ensuring that the optical output maintains synchronization with the receiver's expectations.

To support operational reliability, status monitoring and diagnostics are built into the firmware. These routines can monitor laser health, beam intensity, temperature, alignment accuracy, and power consumption. In the event of anomalies—such as beam divergence, power loss, or overheating—the system can trigger alerts or initiate a controlled shutdown to prevent damage.

For systems supporting dynamic environmental conditions (e.g., outdoor or long-range links), the software may implement adaptive transmission control. This includes adjusting power levels or modifying modulation timing based on environmental feedback such as fog, dust, or vibration levels, improving overall transmission resilience.

In summary, while the Optical Transmitter System is largely a hardware-driven component, the supporting software is responsible for alignment control, signal timing, system diagnostics, and adaptive performance tuning. These software functions are essential for maintaining consistent, high-quality optical communication across varying conditions.

7.6 Optical Receiving System

The Optical Receiving System is responsible for capturing the modulated laser signal transmitted through open air and preparing it for photoelectric conversion. While the reception itself is handled by hardware components such as lenses, filters, and mechanical mounts, software plays a critical role in maintaining signal alignment, optimizing reception conditions, and enabling adaptive response to environmental changes.

The primary function of the software at this stage is to support and stabilize signal acquisition. If the system employs active alignment components—such as servos, stepper motors, or mirrors—the software manages these elements to maintain precise optical alignment with the incoming laser beam. Feedback from optical sensors or photodetectors can be used to automatically correct for misalignment caused by vibration, drift, or environmental interference. Closed-loop control algorithms, such as PID controllers, are often implemented to perform real-time adjustments.

Additionally, the software may manage reception filtering and gain control. Under varying light conditions, such as daylight or low visibility, background noise can interfere with the laser signal. Software routines can dynamically adjust optical filters or control variable gain amplifiers (VGAs) to enhance the signal-to-noise ratio (SNR). This adaptability helps maintain reception quality in non-ideal conditions.

Some systems also integrate diagnostic and calibration routines at the receiver end. These may include startup self-checks for lens alignment, sensor integrity, and initial signal strength assessment. If the signal falls below a defined threshold, the software can issue

warnings, trigger realignment attempts, or temporarily halt transmission to avoid processing corrupted data.

In more advanced configurations, the software can perform signal pre-processing to clean or shape the electrical output before it reaches the photodiode stage. Although the actual photodetection and conversion are hardware-based, software-tuned filters or control systems can improve the fidelity of the received signal, reducing the error rate during binary decoding.

Overall, the Optical Receiving System relies on software to ensure consistent and accurate signal acquisition. By managing alignment, optimizing reception quality, and responding to real-time environmental changes, the software supports the stability and reliability of the entire optical communication process.

7.7 Photodiode Detector Interface

The photodiode detector is a critical component in the optical communication chain, responsible for converting incoming laser pulses into electrical signals. While the photodetection itself is inherently a hardware process, software plays a key supporting role in managing signal acquisition, conditioning, and interfacing with downstream processing units.

At this stage, the software's primary role is to interface with the analog signal output of the photodiode. Once the detector receives modulated light pulses from the optical receiver system, it generates a corresponding analog voltage or current signal. This signal is typically weak and may be affected by noise or fluctuations, necessitating further conditioning.

The software configures and interacts with analog front-end components, such as transimpedance amplifiers (TIAs), analog filters, and analog-to-digital converters (ADCs). These hardware components are often programmable, allowing the software to adjust gain, filtering parameters, or sampling rates in real time based on signal conditions. This dynamic adjustment helps optimize the quality and clarity of the received signal.

Threshold detection algorithms are implemented in software to distinguish between binary '1' and '0' states based on the amplitude of the analog signal. The system may use fixed or adaptive thresholding, depending on the variability of the signal and the surrounding noise level. Adaptive algorithms continuously analyze the signal baseline and noise floor, adjusting detection thresholds to reduce the risk of bit errors.

In addition, the software can support error detection and logging by monitoring signal strength, pulse timing, and continuity. If the incoming signal deviates from expected patterns—such as irregular pulse width or unexpected dropouts—the software can log the anomaly, raise flags for potential transmission errors, or initiate corrective actions at higher system levels.

In systems that prioritize precision and reliability, the software may also integrate calibration routines during initialization. These routines verify the photodiode's response to known input levels, ensuring that signal detection starts from a calibrated baseline and that component drift over time is accounted for.

Although the photodiode detector itself is a hardware element, the software surrounding it is essential for signal interpretation, conditioning, and system responsiveness. By enabling adaptive filtering, dynamic thresholding, and continuous monitoring, the software ensures that the photodetector's output is reliable and ready for accurate digital decoding in the next stage.

7.8 PCB

After the photodiode detector converts the incoming laser pulses into electrical signals, the resulting binary data is routed to the PCB for further processing. This board plays a central role in stabilizing, validating, and, if required, relaying the signal to the microcontroller. In some configurations, the PCB also includes a radio communication module for internal wireless transmission.

At this stage, the primary task is signal conditioning. The electrical signal is cleaned through filtering mechanisms that remove electromagnetic interference (EMI), voltage spikes, and other noise sources that may have been introduced during optical reception. This ensures that the binary data maintains high fidelity and minimizes the risk of corrupted bits reaching the downstream system.

In parallel, the PCB implements error detection techniques to confirm data integrity. This can include cyclic redundancy checks (CRC), parity bit analysis, and checksum validation—methods that verify whether the received data has been altered or degraded during transmission. If any discrepancies are detected, the system can either request a retransmission (in closed-loop systems) or discard invalid packets to avoid false output.

To optimize the data flow, the PCB may also perform packetization, dividing the binary stream into manageable data frames. Each frame includes headers, payload, and error-check bits, enabling more efficient synchronization and reassembly by the receiving microcontroller. Packet-based transmission simplifies debugging, improves timing accuracy, and supports more complex communication protocols.

In configurations that require short-range wireless communication within the system, the PCB-mounted radio module may also handle modulation and frequency management. Techniques such as Frequency Shift Keying (FSK) or Quadrature Amplitude Modulation (QAM) can be used to enhance bandwidth efficiency. The system may also employ frequency hopping or spread-spectrum methods to avoid channel interference and reduce the likelihood of data collision. In security-sensitive applications, encryption protocols can be applied at this stage to protect data during transmission.

Overall, the PCB and its associated modules act as a critical buffer and processing layer between the optical receiver and the decoding logic. It ensures that the microcontroller receives a well-structured, noise-free, and verified binary stream for final decoding and display. By managing noise, validating data integrity, and structuring the transmission, this stage plays a key role in ensuring reliable and accurate performance across the entire optical communication system.

7.9 Microcontroller Processing

After the PCB module, it transmits the validated binary data, the microcontroller (MCU) serves as the core processing unit, responsible for interpreting, processing, and formatting the received data. The microcontroller operates as an embedded computing system, executing predefined instructions to ensure the data is correctly translated into a usable format.

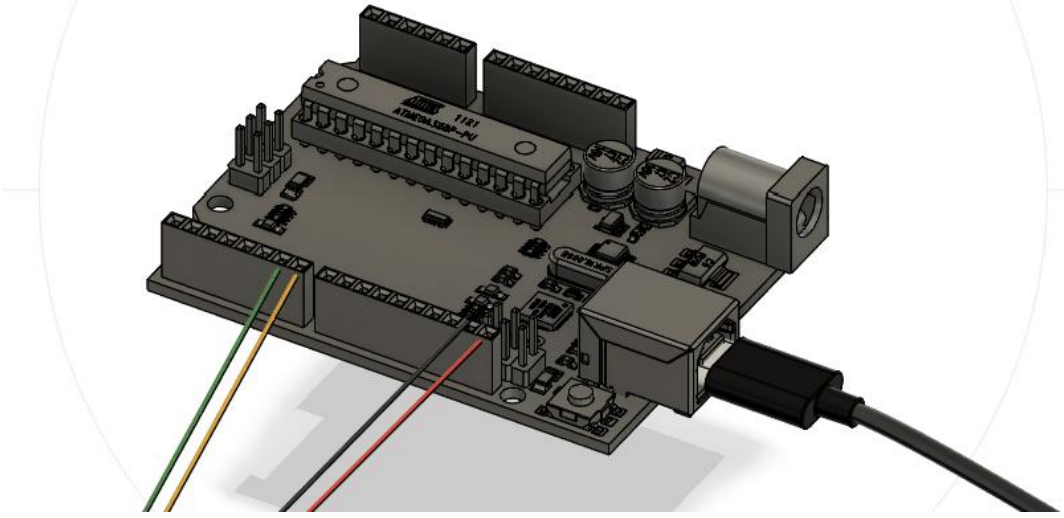


Figure 7.2: Microcontroller

The first step in microcontroller processing is binary interpretation, where the raw bit stream is decoded according to the data type. If the input is numerical, the microcontroller converts the binary representation back into its decimal or floating-point equivalent using standard decoding methods. For textual data, the microcontroller reverses the encoding scheme (such as ASCII or UTF-8) to reconstruct human-readable characters. For example, a binary sequence like 01001000 01101001 would be decoded to display the word "Hi". This decoding process ensures the binary input is understood in the correct context before further handling.

After decoding, the microcontroller formats the data for output. In most cases, this involves preparing the data for an LCD screen, which could mean organizing characters in rows and columns or converting numeric values into a readable layout. The formatting process depends on the type of display used and the way information needs to be presented. Some applications may involve simple text output, while others may require positioning graphical elements or aligning multi-line data.

In addition to decoding and formatting, the microcontroller may also perform optional computations or logic operations based on the system's function. For example, it could

apply basic math to a set of numerical inputs, compare values against thresholds, or run conditional statements to trigger other components in the system. These operations allow the microcontroller to make decisions or adjust the output dynamically based on the input it receives.

In summary, the microcontroller acts as the bridge between signal reception and display output. It decodes binary data into a usable format, prepares it for display, and performs any necessary logic or computation to support the system's functionality. This stage ensures the final output is both accurate and meaningful to the end user.

7.10 LCD Display Output

After processing the binary data, the microcontroller sends it to an LCD screen to present the output in a readable, visual format. This stage allows the user to view information such as text, numbers, or system indicators, depending on how the data was originally entered and how the system is designed to interpret it. The microcontroller handles both the control commands and data values, ensuring the display behaves as expected and shows the correct content.

Figure 7.3: LCD Screen

The 20x4 LCD will be used to display the processed results of the data transmission sequence. The first row will output the original user input, either numerical or textual, as entered. The second and third rows will display the corresponding binary representation of that input, segmented across two lines for readability due to character limitations per row.

The fourth row will serve as a system status indicator. If the data successfully passes through each stage, input handling, binary conversion, laser modulation, optical

reception, PCB radio transmission, and microcontroller decoding, the system will display "PASS". If a failure occurs at any point in the process, the display will instead show "FAIL", indicating an error in transmission or processing. This final status check provides simple yet effective confirmation of end-to-end system functionality.

7.11 Future for Software Development

The current software implementation focuses primarily on text-based data transmission using binary encoding and on-off keying for laser modulation. While effective for foundational testing and demonstration, there is significant potential to expand the system's software capabilities to support more complex and higher-bandwidth data types in the future.

A key area for development is the ability to encode and transmit image data. This would involve designing software routines that can convert images into binary streams—either through raw bitmap encoding or compressed formats such as JPEG or PNG. Once converted, the image data would be divided into packets, synchronized, and sent via the existing optical transmission system. On the receiving end, the software would decode the binary stream, reassemble the data, and render the image on a compatible display. This would require careful attention to error handling and timing control to ensure visual data is reconstructed accurately.

Another direction for future work is implementing more efficient and adaptive encoding schemes. While the current system uses basic binary representation and ASCII encoding, more advanced methods, such as Huffman coding or run-length encoding, could improve transmission efficiency, especially for large or repetitive data sets. Adaptive encoding, where the system selects the most efficient scheme based on data type or signal quality, could further optimize performance.

The software could also be extended to support alternative modulation techniques, such as pulse-position modulation (PPM) or pulse-width modulation (PWM). These methods allow more bits per pulse and can improve data throughput without increasing laser switching speed. Incorporating such techniques would require precise timing control and additional logic on both the transmitting and receiving sides.

Future versions of the software could also include real-time diagnostics and environmental adaptation. This would allow the system to monitor factors like signal strength, ambient light interference, or alignment status, and automatically adjust transmission parameters for better reliability. Additionally, features like remote firmware updates or self-check routines would improve long-term usability and maintainability.

Looking ahead, the system could evolve into a multi-node optical communication network, where multiple transmitters and receivers communicate in a time-shared or addressable format. Implementing this would involve developing a lightweight communication protocol, along with addressing schemes and collision-avoidance logic, effectively turning the system into a functional optical mesh network.

In summary, the software component of this optical communication system offers substantial room for growth. By supporting richer data types, improving encoding

efficiency, and enabling smarter system behavior, future development can transform this project from a point-to-point demonstration into a scalable, real-world solution.

Conclusion

The software design of the laser-based optical data transmission system plays a central role in enabling seamless, accurate, and high-speed communication from user input to visual output. Each stage, from input processing and binary encoding, to laser modulation, optical alignment, signal reception, and final data decoding, is supported and enhanced by carefully structured software control.

At the transmission end, software is responsible for encoding input data, controlling laser modulation with precise timing, and managing optical beam alignment through the transmitter system. These operations ensure that the outgoing signal maintains integrity and synchronization for reliable long-distance propagation. On the receiving side, software interfaces with the optical detection hardware to condition signals, adapt to environmental changes, and filters out noise, ultimately converting the received light pulses into clean binary data. Downstream, data integrity checks, decoding algorithms, and display formatting routines enable accurate reconstruction of the original message on the output device.

Throughout the system, software handles key tasks such as timing control, threshold management, error detection, alignment correction, and environmental adaptability. These elements are crucial not only for functional performance but also for the system's robustness, scalability, and energy efficiency.

In summary, while the physical components enable optical communication, it is the software that orchestrates the process, maintains reliability, and ensures end-to-end data fidelity. A well-designed software architecture transforms the optical hardware into a complete, functional, and responsive communication system suitable for a range of embedded, remote, or high-speed data transfer applications.

Chapter 8 System Fabrication/Prototype Construction

8.1 PCB (Printed Circuit Board) Design and Fabrication

The printed circuit boards (PCBs) were developed using Fusion 360, which facilitated comprehensive routing and 3D modeling. Future iterations aim to incorporate more features, such as a more labels and cleaner organization for further optimization in the future. All PCBs included ground planes and polygon stitching for an efficient connection between layers. The first designs of the voltage regulating daughter boards required on one revision to include the addition of LEDs for easy analysis.

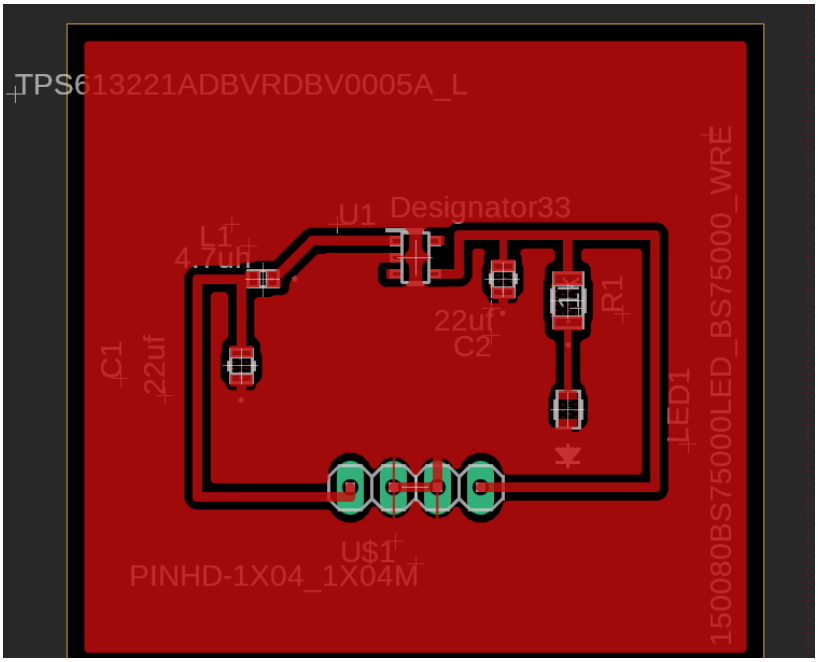


Figure 8.1: 3.3V regulator design

The initial PCB developed was the 3.3V voltage regulator. This design was adapted from the WEBENCH Power Designer. The purpose of this daughter board is to eventually play an integral role for the main PCB by regulating the voltage output to 3.3V for select components.

Only a single improvement had to be made to the process as a single LED was included to visually verify that the regulator is functional. This LED streamlines troubleshooting in the future.

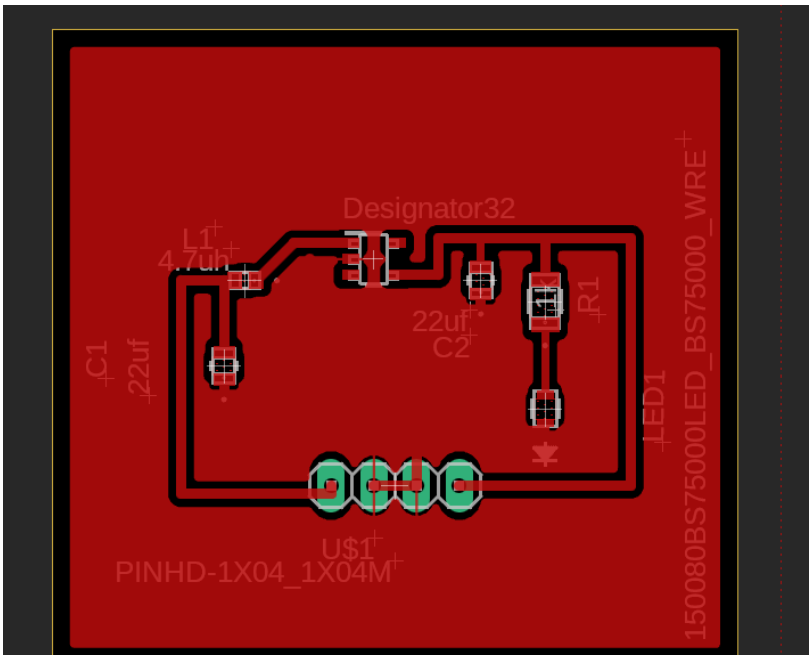


Figure 8.2: 5V regulator design

The second PCB constructed was the 5V regulator, also based on designs from WEBENCH Power Designer. The IC switching regulator was swapped for a different model (TPS613222) which regulated any input voltage to output no more than 5V. Although this daughter board serves the same functions as the 3.3V regulator, it will instead supply 5V to any part that requires 5 Volts. The only improvement to be made to this design is the inclusion of an LED for any troubleshooting purposes.

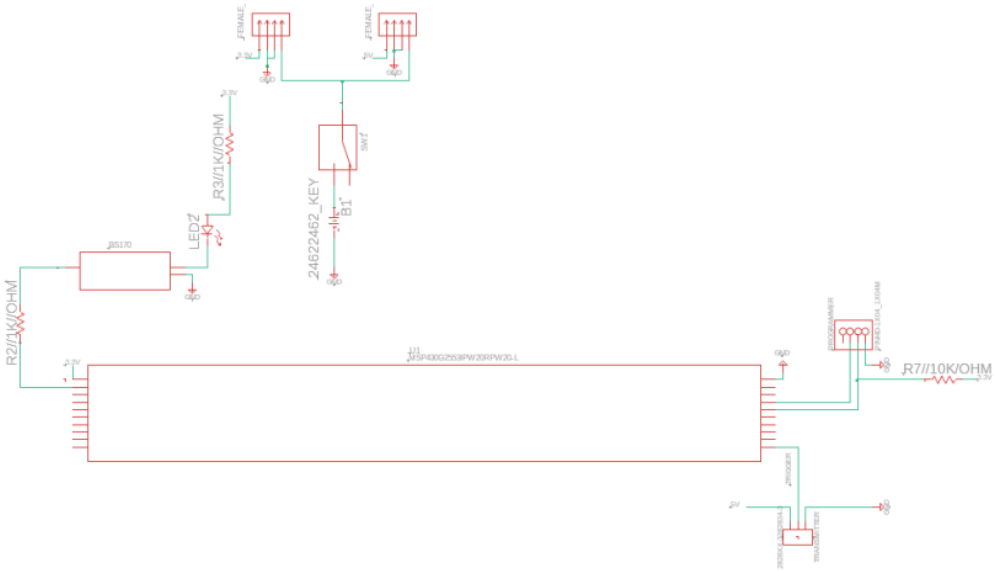


Figure 8.3: Iteration of PCB 1.0

Since the early stages of this project, every iteration of the board contained both aforementioned regulators and a battery pack. The first iteration of the main PCB planned to start with a transimpedance amplifier circuit to convert the amperage of the photodiode into measurable voltage. From here, the voltage would have passed through a high pass filter to filter out any potential noise from the switching of the laser input. This filter would lead to the microcontroller which would utilize its built in ADC to convert the analog voltage into a digital transferable signal. This signal would finally be sent to the Radio Transmitter to transmit the signal over MHz.

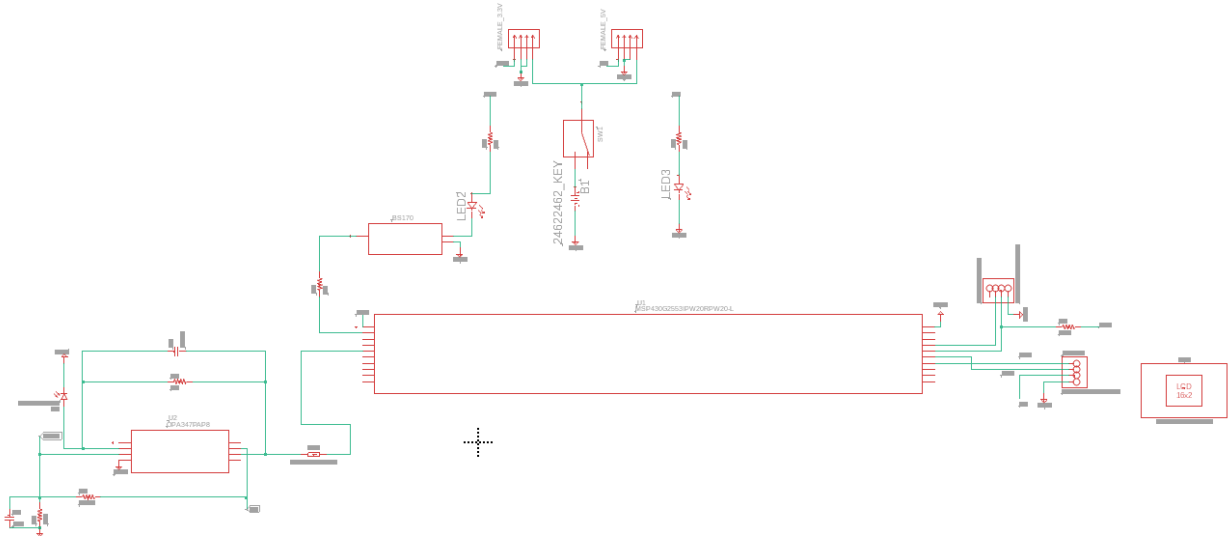


Figure 8.4: Iteration of PCB 2.0

The second iteration of the PCB kept the same start as the first, since the optical portion of our development was kept. The most significant change involved replacing the radio transmitter with a directly interfaced LCD screen. Now, when the MCU converts the analog signal to digital information, the MCU will also directly decode the binary signal into written text to be displayed onto the screen.

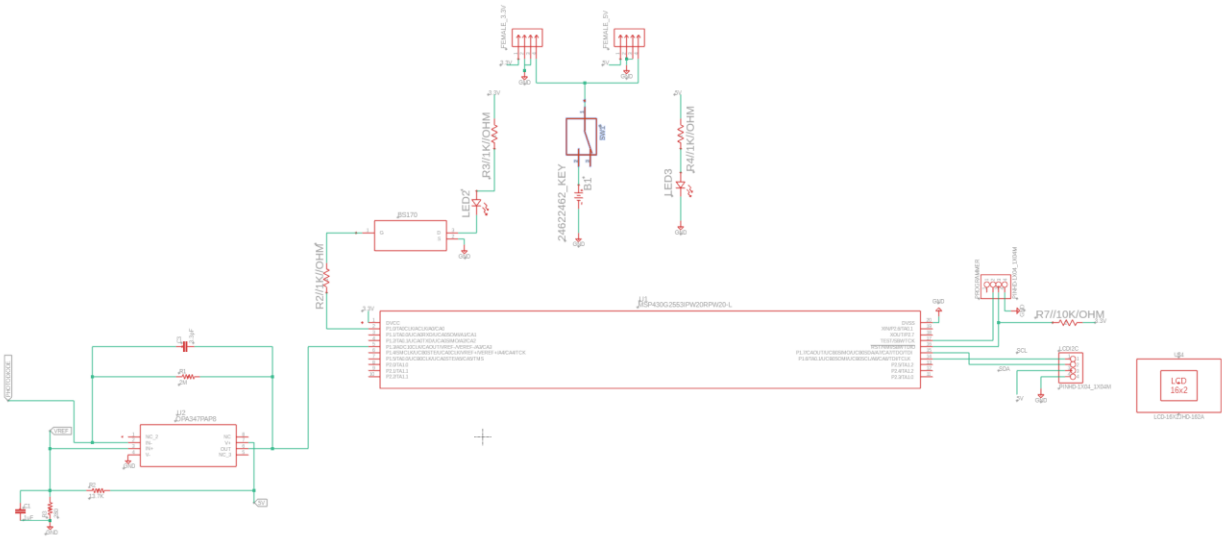


Figure 8.5: Iteration of PCB 3.0

The final iteration of the PCB focused on optimizing the input and filtering of the signal. We opted to remove the high pass filter since this circuit had little to no impact on the fluctuations in voltage. Instead, a voltage reference circuit wired directly into the transimpedance amplifier aided in maintaining a sable system when the current would drop to zero.

8.2 Optics

The optical subsystem underwent several key design changes throughout development to enhance performance, alignment precision, and reliability. All iterations involved a system of transmitting by flickering a laser signal to represent the incoming binary transmission and a receiving end that requires a PCB to transform the analog signal into digital data. However, due to major changes throughout the project, future iterations will focus on sending this signal over free space without the aid of radio waves.

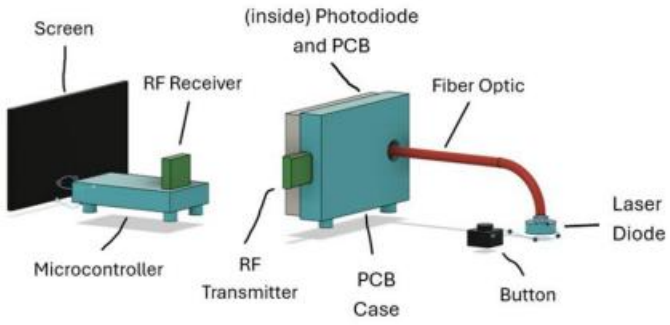


Figure 8.6: Iteration of Optics 1.0

The original configuration utilized a configuration of lenses and multiple apparatus to direct a laser signal into a fiber optic cable so the signal could be directly connected to a photodiode for current to voltage conversion. Once received by the PCB, this signal were

to be converted from analog to digital by the PCB's microcontroller unit. This signal was intended to be sent to the RF transmitter where the message would be sent to the RF receiver over free space to a separate programmable board. This setup offered much simplicity in signal alignment and noise shielding but posed limitations in transmission reliability and range.

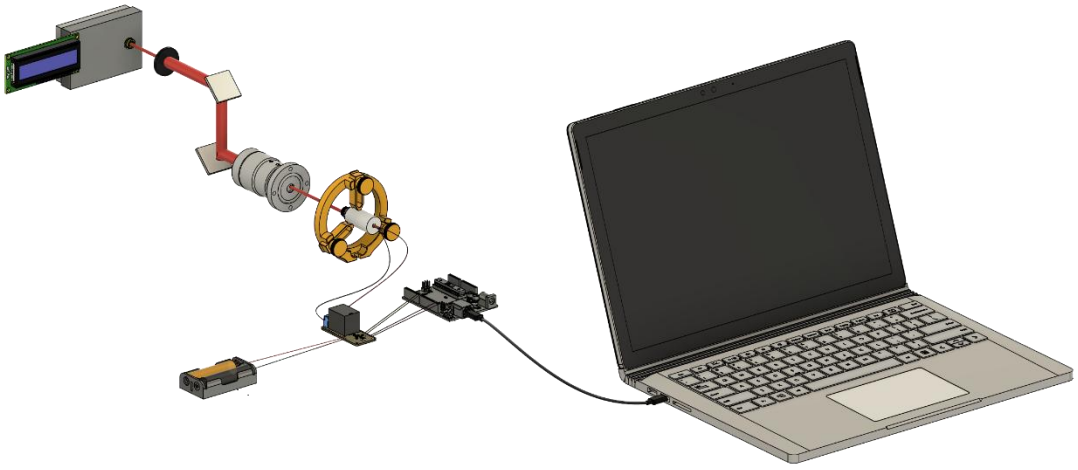


Figure 8.7: Iteration of Optics 2.0

In the refined version of the optical subsystem, the laser beam is transmitted entirely through free space without the aid of any radio transmission. This transition required precise alignment components to ensure consistent and focused beam delivery. The final setup integrated several optical components, including collimators, lenses, beam expanders, and alignment mirrors, to guide the laser from its source to the photodiode. Additionally, optical filters were added to reduce ambient light interference, significantly improving signal clarity and overall system performance. This reconfiguration enhanced modularity and eliminated the need for fiber coupling, ultimately improving signal reliability and simplifying the physical integration of the optical and electronic subsystems.

Figure 8.8: Final optical demo setup

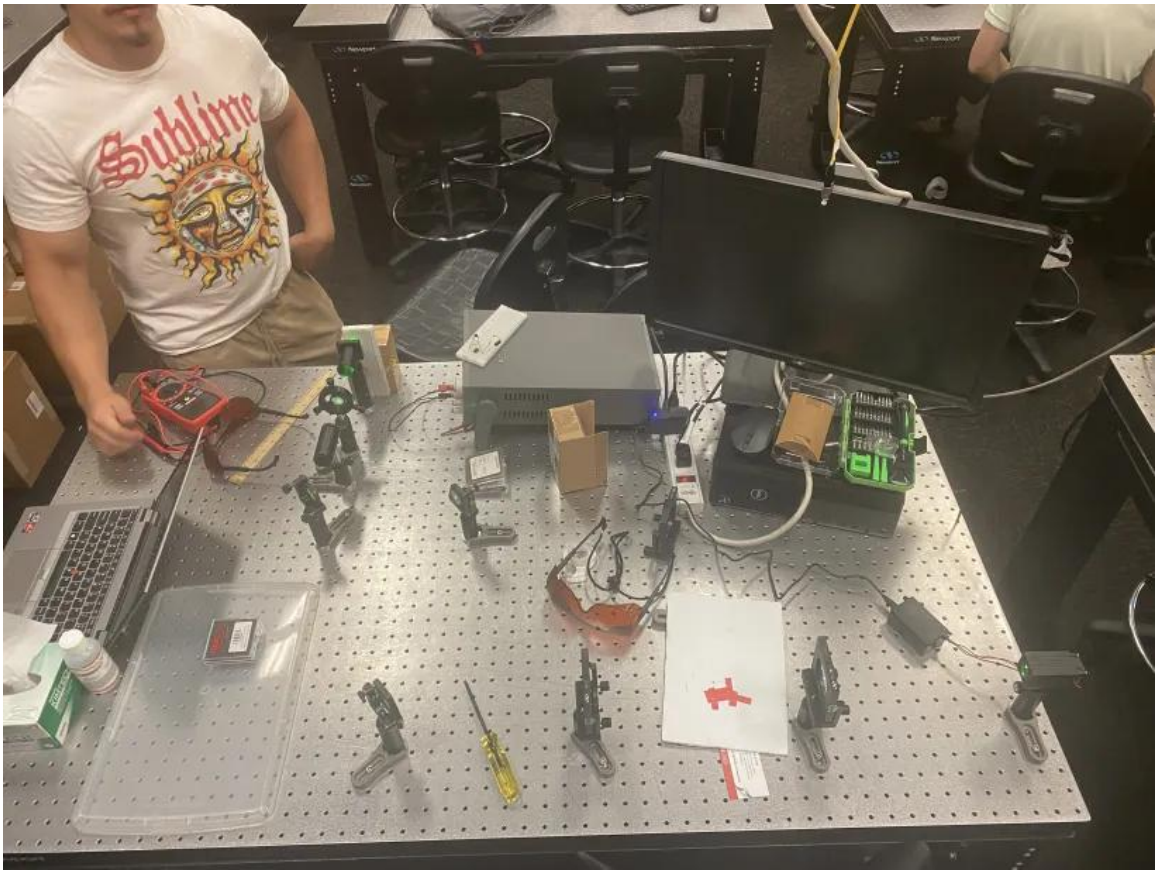


Figure 8.9: Final optical demo setup with lens tube to eliminate back reflections (toward the left side)

Figure 8.10: Photodiode circuit demo setup

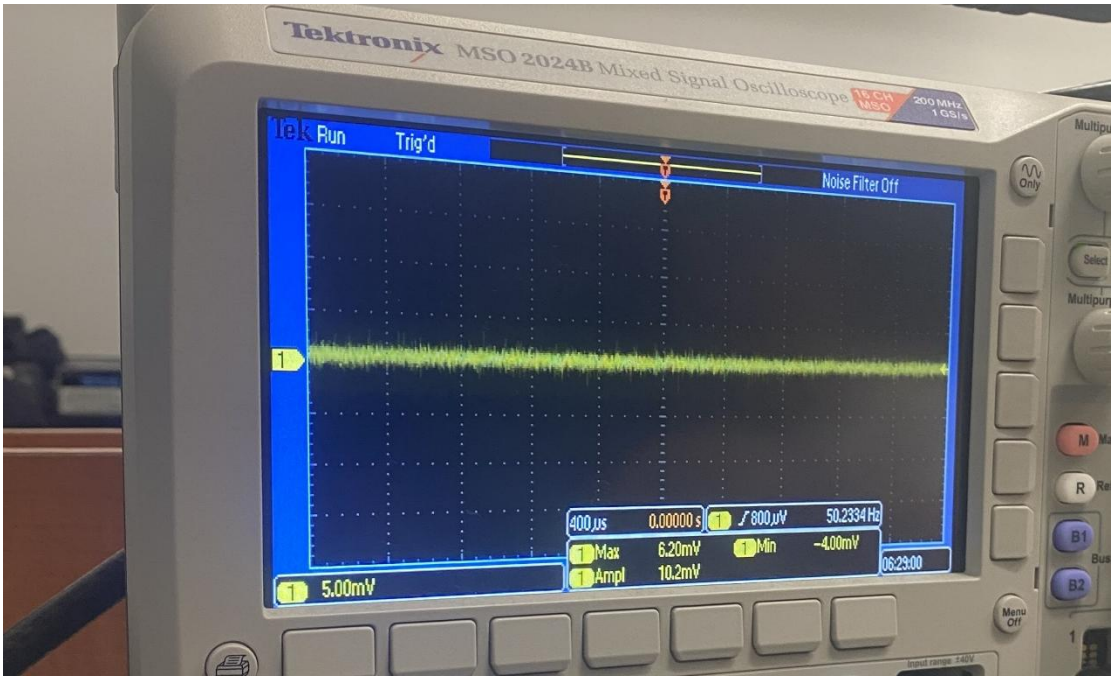


Figure 8.11: Photodiode signal before laser exposure

The above image shows the voltage waveform from the photodiode in ambient light, with no presence of a laser. The amplitude listed (10.2 mV) will be used as a reference value for comparison of intensities before and after the presence of the laser.

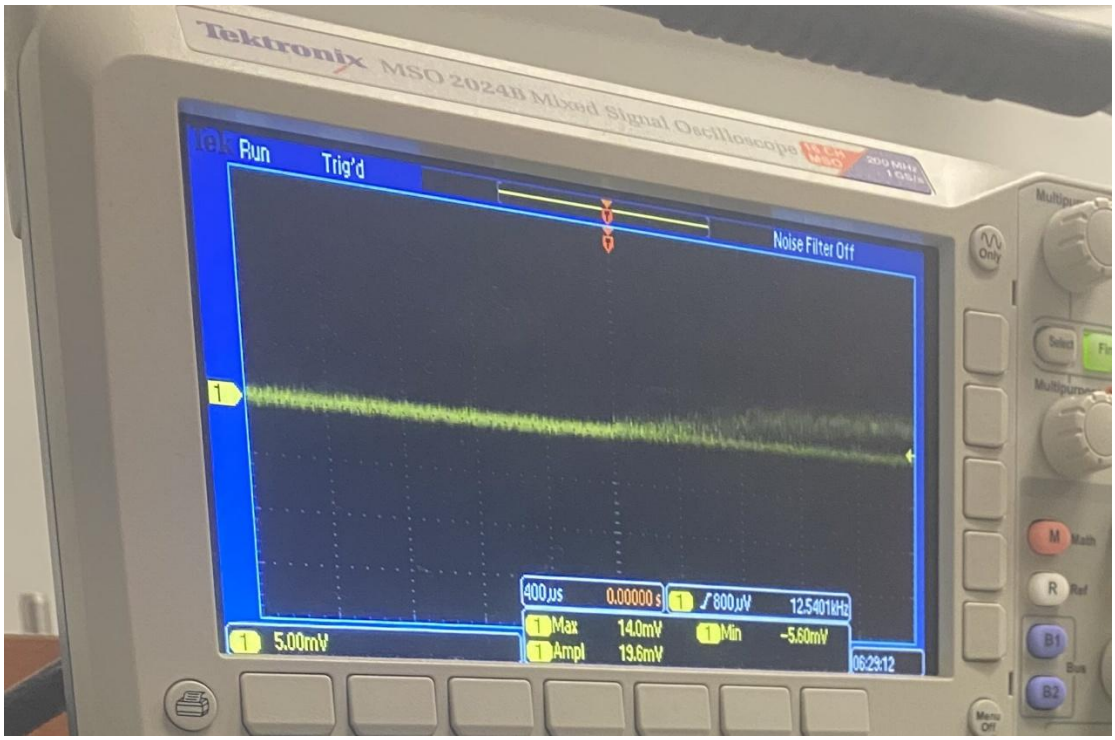


Figure 8.12: Signal after laser exposure

The image above shows that the value of the amplitude (19.6 mV) increased after exposure to the laser. This is in line with what was expected for data reception: a low intensity will represent a 0, and a high intensity will represent a 1. Millions of these pulses of varying intensities will generate a raw bit stream that can be efficiently detected and decoded.

8.3 Software

This demo was developed as a preliminary test of the LCD and LED control logic that will eventually be integrated into the senior design project. Since the PCB had not yet been approved and the microcontroller had not been ordered, the team chose to prototype the software using the MSP430FR6989 development board. The MSP430FR6989 was selected due to its built-in LCD module, low power consumption, and compatibility with Code Composer Studio. This approach allowed development and validation of embedded code ahead of final hardware availability, ensuring a smoother transition when the system is assembled during Senior Design II.

The code demonstrates fundamental microcontroller control over two visual output systems: the onboard LCD and the red/green LEDs. The system begins by disabling the watchdog timer and unlocking GPIO pins to enable proper pin functionality. The red LED on P1.0 is configured as an output and initialized in the ON state, while the green LED on P9.7 is also configured but remains unused in this version. The LCD is initialized through the LCD_C module by enabling the low-frequency external crystal oscillator and setting up segment control and voltage parameters required to drive the display.

A fixed unsigned integer value (430) is initially displayed on the LCD using a lookup table that maps individual digits (0–9) to their respective 7-segment codes. The code is designed to be expanded so that the LCD can display both words and their corresponding binary values. For instance, when a string such as "HELLO" is input, each character will be shown on the LCD in ASCII and followed by its binary representation across multiple display rows. Simultaneously, the LED will flash in binary, where each bit of the binary sequence (1 or 0) will correspond to the LED being turned ON or OFF. This visual feedback provides both character and binary output verification for debugging and demonstration purposes.

This implementation provides a functional baseline for numeric and character display as well as I/O control on the MSP430, serving as a proof-of-concept for future integration into the team’s finalized hardware system. It lays the groundwork for a more complete communication interface in the next phase of development. Please refer to Appendix D for the complete software code.

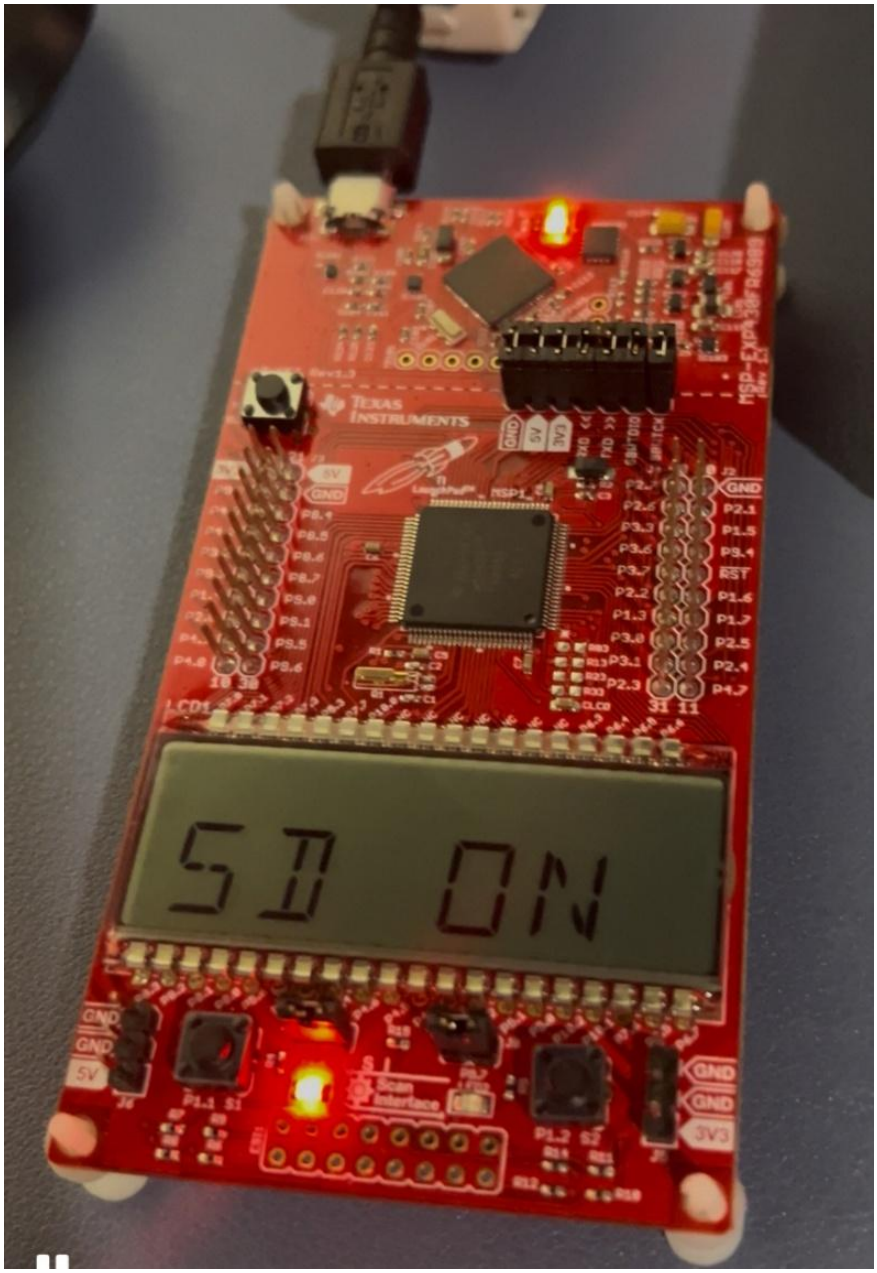


Figure 8.13: MSP-EXP430FR6989 during demo testing. Light turning on signaling 1 in binary encoding the letter N.

Chapter 9: System Testing and Evaluation

This section will evaluate the feasibility of common optoelectronic components, the methodology for testing them, the experimental setup, simulation setup, equations and calculations, test results and analysis, performance metric and signal quality, and future planning of the optoelectronic and electric components going forward.

9.1 Feasibility Evaluation of Optoelectronic Components

The feasibility evaluation of optoelectronic components is crucial in determining their applicability in high-speed optical communication systems. Several factors influence feasibility, including performance specifications, power efficiency, thermal stability, and cost constraints.

For this study, we assessed key components such as laser diodes, photodetectors, optical modulators, and fiber optic channels. The primary selection criteria included operating wavelength, responsivity, modulation bandwidth, insertion loss, and signal-to-noise ratio (SNR).

Laser Diodes and Their Performance Criteria

Laser diodes are a fundamental component of optical communication systems, responsible for generating and transmitting modulated optical signals. The selection of an appropriate laser diode is critical, as factors such as wavelength compatibility, output power stability, spectral linewidth, and modulation bandwidth significantly impact overall system performance.

For this study, we selected a red Vertical-Cavity Surface-Emitting Laser (VCSEL) operating at 650 nm due to its high-speed modulation capabilities, low power consumption, and superior beam quality. As discussed in Chapter 3, the choice of a 650 nm VCSEL was driven by its compatibility with the system's optical detection and transmission requirements. Specifically, the red wavelength aligns well with the sensitivity range of the selected PIN photodiodes while also offering minimal dispersion and absorption losses in the optical components used. Furthermore, red VCSELs are widely utilized in short-range optical communication and sensing applications, making them a practical choice for this project.

One of the primary advantages of using a VCSEL over traditional edge-emitting laser diodes is its circular beam profile, which enhances coupling efficiency with optical fibers and photodetectors. Additionally, VCSELs exhibit narrow spectral linewidths, reducing chromatic dispersion effects and improving signal coherence. The thermal stability of the red VCSEL was also analyzed to ensure consistent performance under varying operational conditions.

By leveraging the advantages of a 650 nm red VCSEL, as detailed in Chapter 3, the system benefits from efficient optical power generation, stable wavelength emission, and high modulation speeds, making it well-suited for applications requiring precise and reliable optical signal transmission.

Photodetectors and Their Sensitivity

Photodetectors are responsible for converting received optical signals into electrical signals. The evaluation focused on responsivity, dark current, and response time, as these factors determine the efficiency of optical signal detection.

Photoresistors or light-dependent resistors (LDRs) are passive optoelectronic components that change their resistance based on the intensity of the incident light. The change in resistance is inversely proportional to the intensity of light, so a higher intensity of light will decrease the resistance of a photoresistor. As a passive component, it does not produce any current in response to incident, making them ineffective at detecting high-speed laser pulses because of the slow responsivity.

Another type of photodetector is a phototransistor, which is essentially a bipolar junction transistor with a photosensitive semiconductor at the base junction. Like a photodiode, it generates current in response to incoming light, but as a transistor, the current is amplified internally. Although it functions similarly to a photodiode, it would not be suitable for high-speed data applications that require high-frequency lasers.

Due to the following disadvantages of the other photodetectors, PIN photodiodes were selected due to their low noise characteristics, high-speed response, and stable performance in optical communication systems. Compared to PN, Schottky, and avalanche photodiodes (APDs), PIN photodiodes offer simpler operation, lower power consumption, and reduced excess noise, making them a more reliable choice for high-speed optical data reception.

The responsivity of the PIN photodiode was analyzed to ensure efficient light-to-current conversion across the operating wavelength range. The dark current was measured to confirm minimal noise generation, ensuring high signal integrity. Additionally, the response time was evaluated to verify the detector’s capability of supporting high-speed data transmission without introducing significant delays.

By selecting PIN photodiodes, the optical receiver achieves a balance between speed, sensitivity, and noise performance, ensuring reliable signal detection while maintaining system efficiency.

Light-Emitting Diodes (LEDs)

Light-emitting diodes emit photons through spontaneous emission, meaning that they are emitted in every direction incoherently. The incoherent nature of light-emitting diodes makes them unsuitable for long-distance transmission because less light will hit the photodiode, meaning signal integrity is lost. Laser diodes do not have this problem.

Optical Modulators and Signal Integrity

Optical modulators are essential for encoding data onto optical signals. The feasibility assessment focused on modulation bandwidth, insertion loss, and signal integrity. Mach-Zehnder interferometer-based electro-optic modulators were chosen due to their ability to support high-speed modulation with low insertion loss. The modulators' performance was analyzed by measuring extinction ratio, insertion loss, and phase shift response, ensuring they met the bandwidth requirements for high-speed data transmission.

Opto-isolators

Opto-isolators are components that connect two circuits using a light source (usually an LED) and a phototransistor in a single package. By isolating the two circuits, this arrangement prevents high voltages from affecting the receiving circuit. This project will not use opto-isolators mainly because it will not utilize high voltages.

9.2 Testing Setup and Methodology

The testing phase involved characterizing the performance of selected optoelectronic components under real-world conditions. The methodology consisted of three key phases:

Component Characterization and Performance Metrics

Individual components were tested to verify their performance metrics. The laser diodes were analyzed for output power stability, spectral linewidth, and wavelength accuracy using an optical spectrum analyzer (OSA). Photodetectors were tested for responsivity and noise characteristics, ensuring they provided sufficient sensitivity while maintaining a low dark current. Optical modulators were evaluated based on their ability to encode signals efficiently with minimal insertion loss.

Performance Benchmarking and Validation

To validate feasibility, experimental results were compared with theoretical models and simulation data. The optical link performance was assessed based on key parameters, including optical power levels, transmission efficiency, and error rates. MATLAB simulations were conducted to model signal degradation due to dispersion, noise, and attenuation. The results helped determine whether the selected components met the required specifications for high-speed optical communication.

The optical system was designed with Zemax to simulate the theoretical propagation of the laser and identify any potential aberrations, angular misalignments, and irregular spot sizes. This will help identify issues with lens sizes, placement of mirrors and lenses, and whether the setup is ideal for laser propagation.

9.3 Experimental Setup

The experimental setup was designed to evaluate the performance of the optoelectronic components in a controlled environment. The optical system consisted of a fiber optic transmission link, including a laser diode, optical modulator, single-mode fiber, and photodetector.

Optical Signal Generation and Modulation

A continuous-wave (CW) laser diode was used as the optical source. A Mach-Zehnder electro-optic modulator was employed to encode digital data onto the laser beam. The modulator's ability to efficiently imprint data onto the optical carrier was tested to ensure proper signal transmission.

Optical Detection and Signal Processing

The optical signal received was converted into an electrical signal using an APD photodetector, which was then analyzed for signal integrity, noise characteristics, and bit error rates (BER). The electrical output was compared against the original transmitted data to determine the effectiveness of the transmission system. This can be observed with the photodiode connected to an oscilloscope and detecting changes in the waveform before and after laser exposure.

9.4 Simulation Setup (Using Zemax and MATLAB)

To complement experimental results, optical simulations were conducted using Zemax OpticStudio for optical component modeling and MATLAB for signal processing analysis.

Table 9.1: Wavelength vs. Beam Waist from 450 nm to 1550 nm

Wavelength	Beam waist
450nm	~28.6 µm
850nm	~54.1 µm
980nm	~62.4 µm
1310nm	~83.3 µm
1550nm	~98.7 µm

The wavelength and beam waist will be necessary for modeling the optical system on Zemax, along with the diameter of the laser output. This project will use the 980nm infrared laser, with a beam waist of about 62.4 microns.

Zemax Simulations for Optical Component Modeling

Zemax was used to model light propagation through optical components (such as mirrors and focusing lens), evaluating factors such as beam divergence, lens aberrations, and coupling efficiency. The simulation results were used to refine optical component alignment and optimize performance. Data will be entered into the Lens Data Editor table and it will generate a 3D model based on the data. A merit function table will be used to optimize the measurements that are labeled “V” (variable). Spot diagrams will provide a theoretical illustration of the degree of convergence of the laser beam entering the image plane (the “photodiode”).

Table 9.2: Lens Data Editor table for the optical system in Zemax

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	Standard	Waist	Infinity	Infinity			0.000	0.000	0.000	0.0...	0.000
1	Standard	Laser O/P	Infinity	10.000 V			6.327 U	0.000	6.327	0.0...	0.000
2	Standard	AP Stop (Beam Diam)	Infinity	20.000 V			7.327	0.000	7.327	0.0...	0.000
3	Coordinate Break			0.000	-		0.000	-	-		-
4	Standard	Mirror 1	Infinity	0.000	MIR...		7.327	0.000	7.327	0.0...	0.000
5	Coordinate Break			0.000	-		0.000	-	-		-
6	Standard	Coord break fold45	Infinity	100.0... V			7.327	0.000	7.327	0.0...	0.000
7	Standard	Prop after M1	Infinity	80.000 V			7.327	0.000	7.327	0.0...	0.000
8	Coordinate Break			0.000	-		0.000	-	-		-
9	Standard	Mirror 2	Infinity	0.000	MIR...		7.327	0.000	7.327	0.0...	0.000
10	Coordinate Break			20.000	-		0.000	-	-		-
11	Standard	Coord break	Infinity	10.000 V			7.327	0.000	7.327	0.0...	0.000
12	Standard	Focus lens back	25.000	2.445 V	N-BK7		7.327	0.000	7.327	0.0...	-
13	Standard	focus lens front	-25.000	22.037 V			7.253	0.000	7.327	0.0...	0.000
14	Standard	image	Infinity	-			0.166	0.000	0.166	0.0...	0.000

Table 9.3: Merit function table

	Type	Comment										
1	EFFL		1							0.150	1.000	25.029	6.190E-16
2	SPHA	12	1							0.000	1.000	40.826	1.667E-15
3	ASTI	12	1							0.000	1.000	46.705	2.181E-15
4	COMA	12	1							0.000	1.000	-87.101	7.587E-15
5	PMAG		1							-0.100	1.000	0.000	1.000E-20
6	AXCL	1	1	0.0...						0.000	1.000	0.000	0.000
7	BLNK												
8	DMFS												
9	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6											
10	BLNK	Default individual air and glass thickness boundary constraints.											
11	MNCA	0	0							7.000	1.000	7.000	0.000
12	MXCA	0	0							1000....	1.000	1.000E+...	100.000
13	MNEA	0	0	0.0...	0					0.000	1.000	0.000	0.000
14	MNCG	0	0							0.500	1.000	0.500	0.000
15	MXCG	0	0							1.500	1.000	1.500	0.000
16	MNEG	0	0	0.0...	0					0.000	1.000	0.000	0.000
17	MNCA	1	1							7.000	1.000	7.000	0.000
18	MXCA	1	2							1000....	1.000	1000.000	0.000
19	MNEA	1	1	0.0...	0					0.000	1.000	0.000	0.000
20	MNCG	1	1							0.500	1.000	0.500	0.000
21	MXCG	1	1							1.500	1.000	1.500	0.000
22	MNEG	1	1	0.0...	0					0.000	1.000	0.000	0.000
23	MNCA	2	2							7.000	1.000	7.000	0.000
24	MXCA	2	2							1000....	1.000	1000.000	0.000
25	MNEA	2	2	0.0...	0					0.000	1.000	0.000	0.000
26	MNCG	2	2							0.500	1.000	0.500	0.000
27	MXCG	2	2							1.500	1.000	1.500	0.000
28	MNEG	2	2	0.0...	0					0.000	1.000	0.000	0.000
29	MNCA	3	3							7.000	1.000	0.000	4.900E-17
30	MXCA	3	3							1000....	1.000	1000.000	0.000
31	MNEA	3	3	0.0...	0					0.000	1.000	0.000	0.000
32	MNCG	3	3							0.500	1.000	0.500	0.000
33	MXCG	3	3							1.500	1.000	1.500	0.000
34	MNEG	3	3	0.0...	0					0.000	1.000	0.000	0.000
35	MNCA	4	4							7.000	1.000	0.000	4.900E-17
36	MXCA	4	4							1000....	1.000	1000.000	0.000
37	MNEA	4	4	0.0...	0					0.000	1.000	0.000	0.000

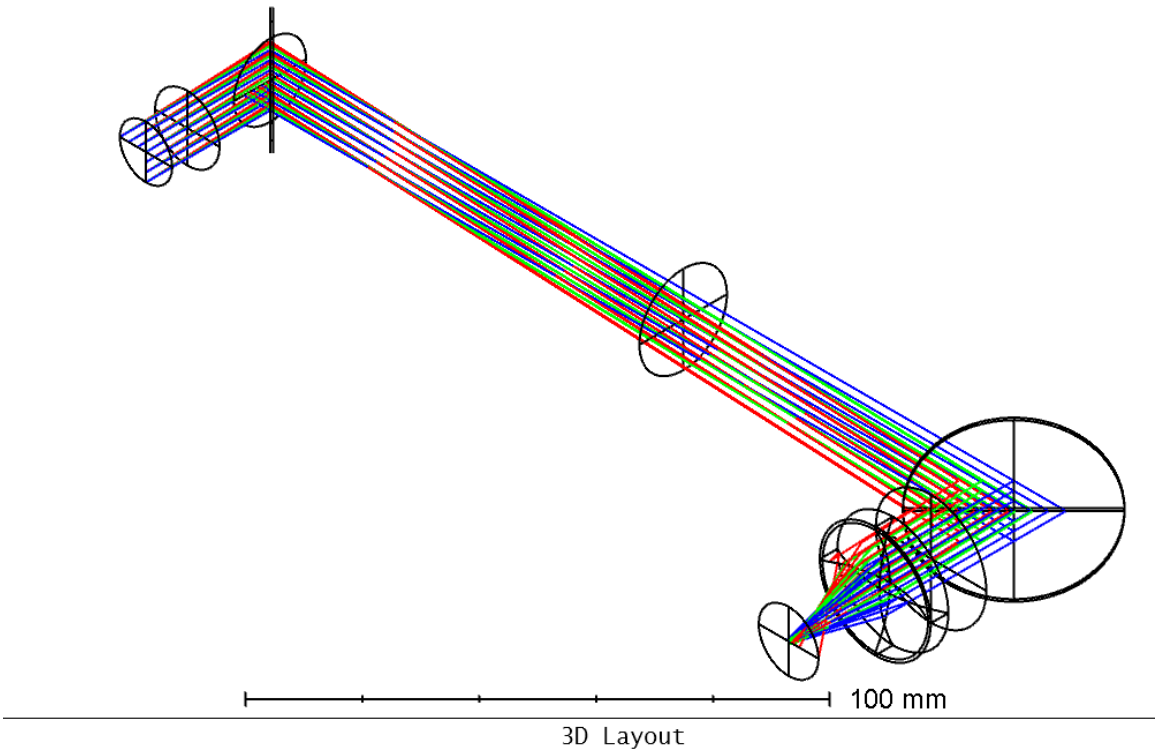


Figure 9.1: 3D model of the optical system in Zemax

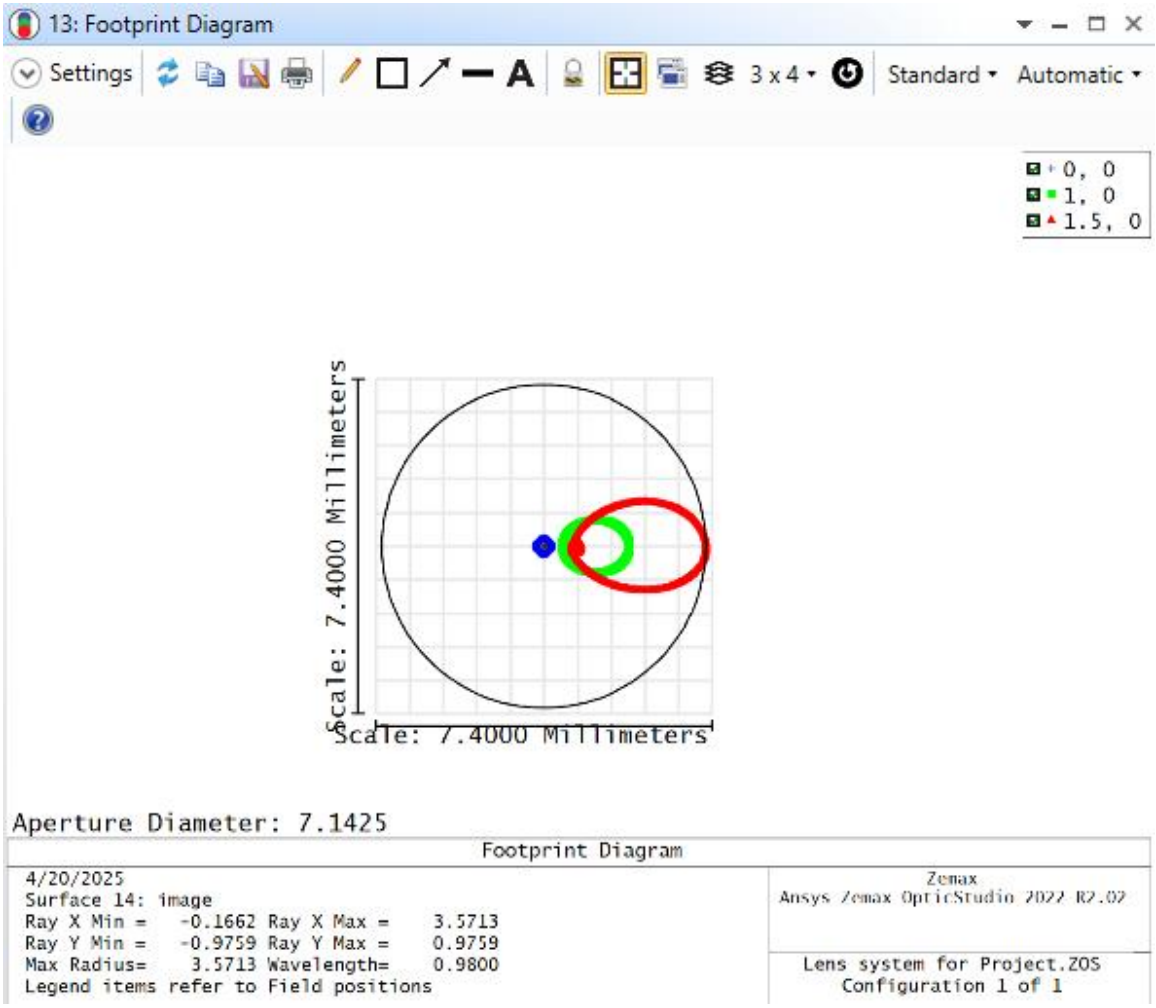


Figure 9.2: A footprint diagram of the optical system with off-axis patterns

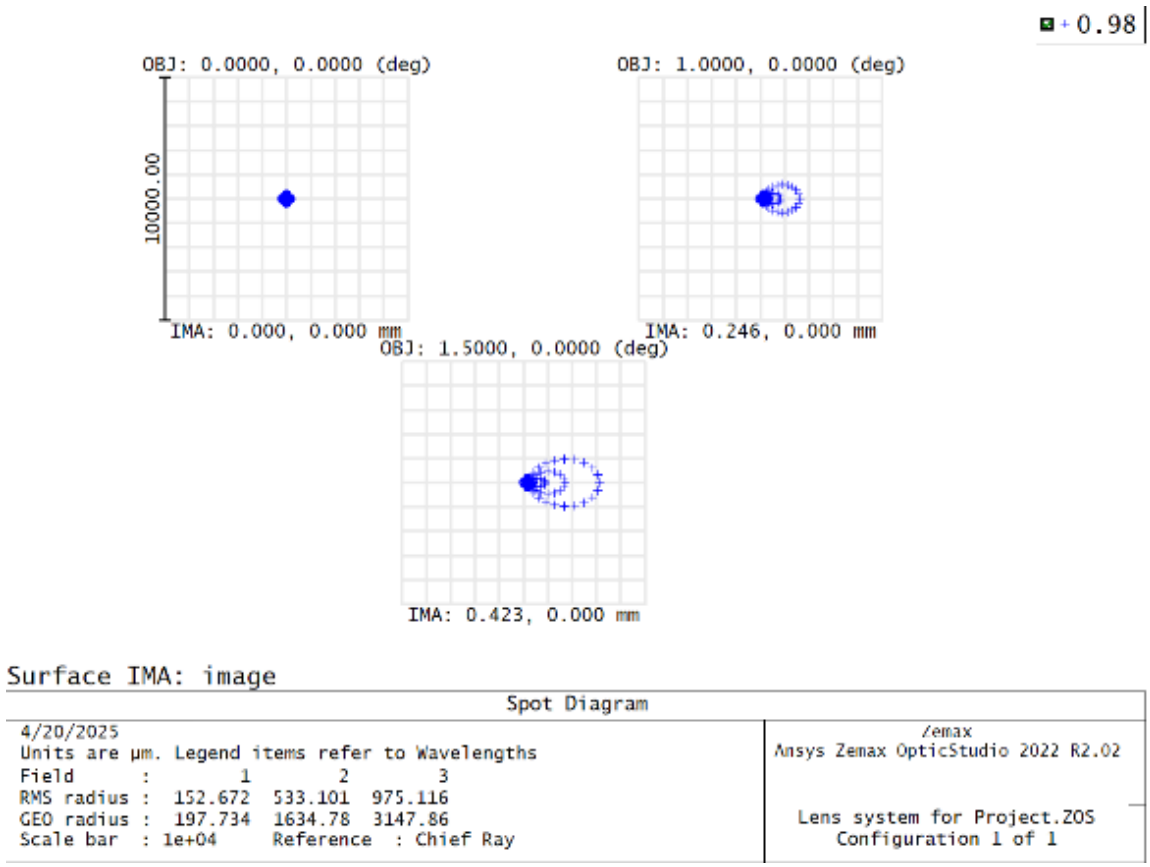


Figure 9.3: A spot diagram of the optical system at varying positions off-axis

Given the optimized measurements in the Lens Data Editor, the laser beam is perfectly centered on the axis of the object plane (ideal position of the photodiode) and any misalignment will distort the laser beam. As the 3D model and measurements are theoretical, there may or may not be parts commercially available with the following measurements and therefore parts with approximately equal measurements will be ideal for constructing the project.

MATLAB Simulations for Signal Processing Analysis

MATLAB was utilized to simulate signal impairments such as noise, dispersion, and attenuation. A BER model was implemented to predict error rates based on received signal power and noise levels. The simulation results were compared with experimental data to validate theoretical predictions.

MATLAB has an app called Bit Error Rate Analysis that can plot BER curves based on the number of bits and errors without the need to write code from scratch. Since optical transmission data rates in real life are extremely high (in the gigabits to terabits range), given the scope of this project, it will be reasonable to model bit error rates at 1 megabit per second.

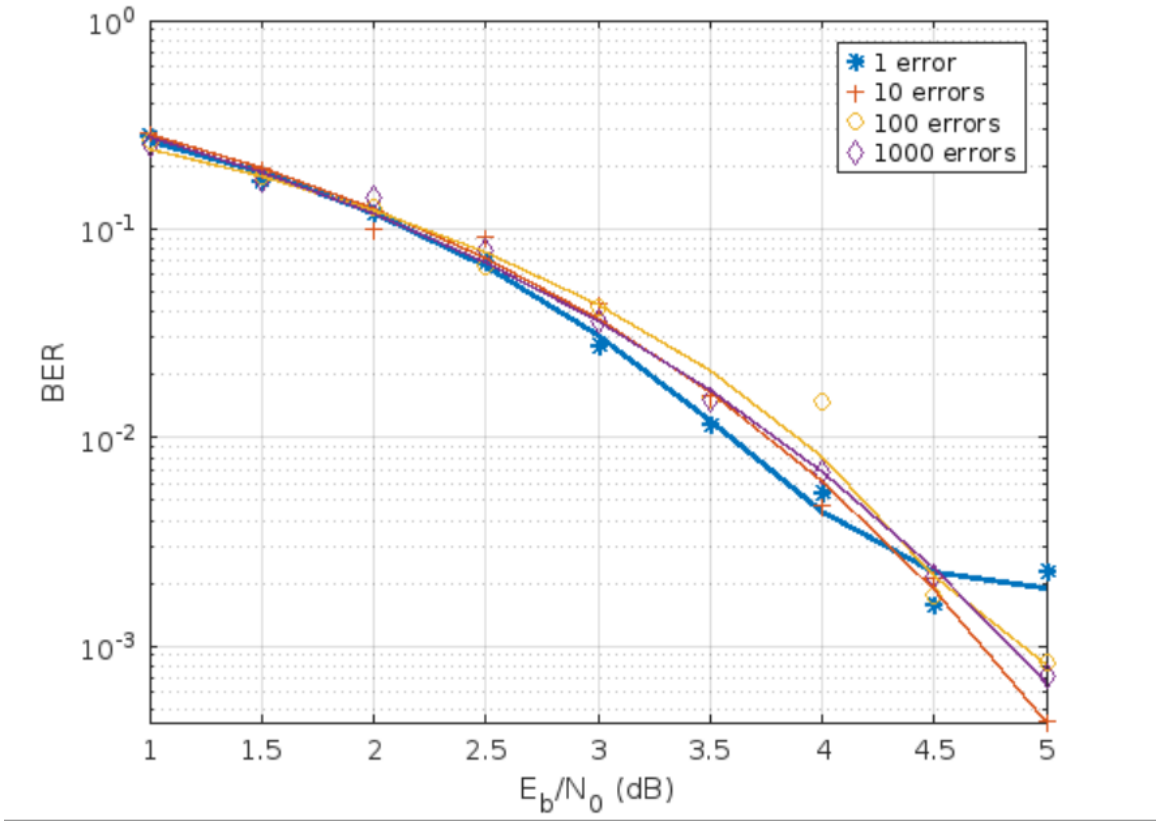


Figure 9.4: Theoretical bit error rate plot from 1 error to 1000 errors with 10^6 bits with BPSK

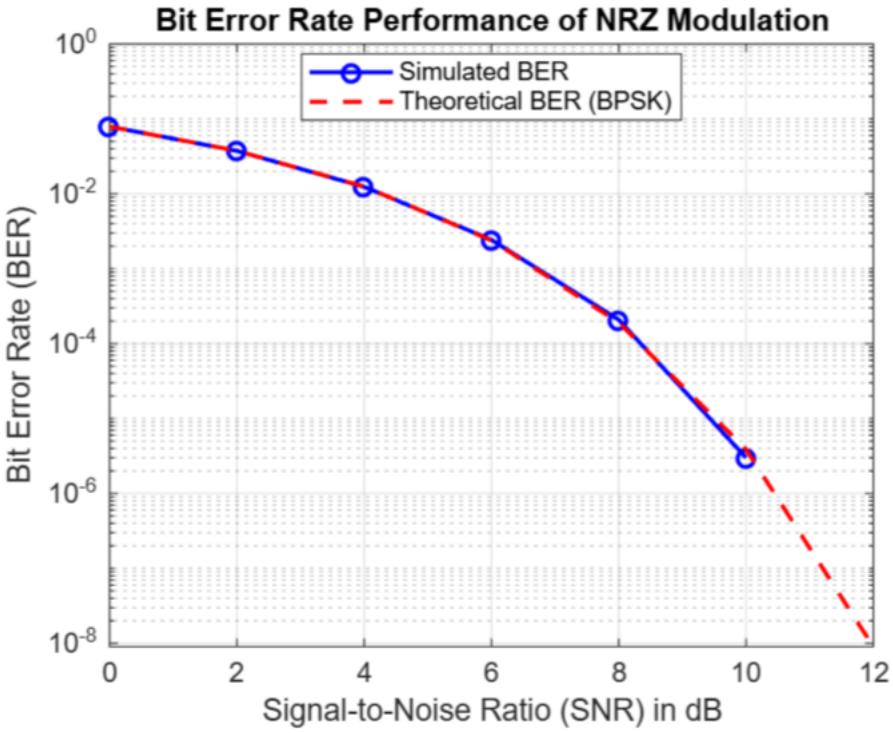


Figure 9.5: Theoretical bit error rate with 10^6 bits with NRZ from code generated by Gemini

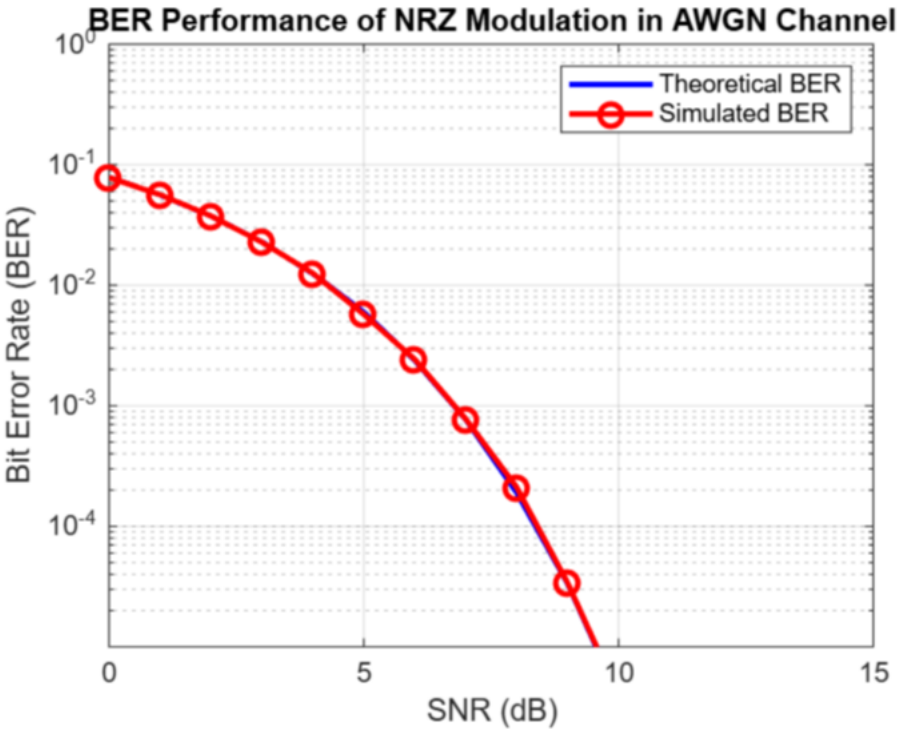


Figure 9.6: Theoretical bit error rate with 10^6 bits with NRZ from code generated by Claude AI

From the above plots, there is a difference in bit error rate between BPSK modulation and NRZ modulation. At 5 dB, the bit error rate is much lower with BPSK than with NRZ, likely because modulating the phase of the signal with BPSK reduces the amount of noise that can increase the bit error rate, in contrast with. Given that all these simulations are theoretical, and the code generated by Gemini and Claude AI may contain errors and missing parameters, results may vary depending on the type of equipment used, but they can serve as a guideline for how data can be modulated and transmitted as efficiently as possible.

It is always important to check for any physical barriers or electronic interference that can affect data transmission to reduce BER. This can include adjusting the lens aperture, repositioning any misaligned mirrors or lenses, or even cleaning optical elements.

9.5 Equations and Calculations

Beam Divergence

The divergence angle θ\thetaθ of the laser after beam expansion is critical, as it determines how much the beam spreads over distance:

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

Where:

- M^2 = 1.1 (beam quality factor),
- λ =532 nm
- w_0 = 1mm (initial beam waist).

$$\theta = \frac{1.1^2 532 * 10\text{^} - 9}{\pi\ 1 * 10\text{^} - 3} = 0.186\ mrad$$

With a **10x Galilean beam expander**, the final divergence becomes:

$$\theta_{final} = \frac{0.186}{10} = 0.0186\ mrad$$

At a distance of 1 km, the **spot size** DDD is:

$$D = 2w_o + 2L * \theta_{final} = 2 * 1mm + 2 * 1000 * 0.186mrad$$

$$D = 2mm + 37.2mm = 39.2mm = 3.92cm\ beam\ diameter$$

This low divergence ensures that the optical power remains concentrated, allowing efficient power delivery to the photodetector.

Optical Elements and Focal Length

The system uses two lenses:

Transmitting lens (collimating): focal length f_t = 50mm

- **Receiving lens** (focusing): focal length f_r = 100mm

These lenses are chosen to match the expanded beam to the **5 mm active area** of the photodetector and ensure that the optical spot is tightly focused onto the sensor plane.

Using the thin lens formula, the receiver's focusing behavior ensures the beam converges within a few millimeters, ideal for maintaining a high **power density** at the detector.

Atmospheric Attenuation

The total power loss due to **atmospheric attenuation** over distance L=1L = 1L=1 km is modeled as:

$$P_{recieved} = P_{transmitted} * 10^{\frac{-\alpha L}{10}}$$

Where:

- α=0.2 dB/km (clear air),
- $P_{transmitted}$=5mW

$$P_{recieved} = (5 * 10\& - 3) * \left(10^{\frac{-0.2}{10}}\right) = 4.77mW$$

This 4.6% loss is acceptable for short-range line-of-sight communication in clear weather. However, in fog, α\alphaα can exceed **20–30 dB/km**, making adaptive power control or error correction critical.

9.6 Test Results and Analysis

The experimental and simulation results were analyzed to evaluate the feasibility of the selected optoelectronic components for high-speed optical communication. The primary focus was on key performance metrics, including optical power stability, bit error rate (BER), dispersion effects, and attenuation characteristics. Additionally, comparisons with simulation models were conducted to validate the theoretical expectations against practical measurements.

Optical Power and Wavelength Stability

The laser diode exhibited stable optical output throughout the testing phase, operating at 655 nm with minimal wavelength drift of ±0.2 nm. This stability is crucial for maintaining signal integrity over long distances, reducing the impact of wavelength-dependent losses and dispersion. Optical power measurements indicated an average output of 5 dBm, with negligible fluctuations under standard operating conditions. These results confirm that the laser diode maintains a consistent optical signal, ensuring reliable transmission in optical fiber communication.

9.7 Performance Metrics and Signal Quality

Received Optical Power

Signal Power

- Received optical power: $P_{signal} = 7.78\,\mu W = 7.78 * 10^{-5} W$

Assuming perfect conversion to electrical signal (which depends on responsivity and load resistance), but for simplicity, we keep power units for this SNR version.

Noise Power

For thermal noise, assuming a resistive load R_L=50 Ω, and a bandwidth B=1 GHz

$$P_{noise,Thermal} = kTB$$

Where:

- k=1.38×10^{-23} J/K
- T=300 K
- B=1 GHz =1×10^{9} Hz

$P_{noise} = (1.38 * 10^{-23}) * (300) * (10^{-9}) = 4.14*10^{-12}$ W

high SNR enables reliable signal recovery even under minor atmospheric interference.

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{7.78 * 10^{-15}}{4.14 * 10^{-12}} = 1.88 * 10^{7}$$

$$SNR_{dB} = 10\log_{10}(SNR) = 10\log_{10}(1.88 * 10^{7}) = 72.7\ dB$$

9.8 Summary of Parameters

A comprehensive analysis of the system's key performance parameters was conducted to evaluate the feasibility and efficiency of the free-space optical (FSO) communication link. This summary highlights critical factors such as beam divergence, received optical power, signal-to-noise ratio (SNR), bit error rate (BER), and atmospheric attenuation. Each parameter was assessed through both theoretical calculations and experimental validation to ensure accuracy and reliability. The results provide insight into the system's overall performance, identifying strengths such as high signal integrity and stable optical power, as well as potential challenges like beam expansion and environmental attenuation. The following sections detail these parameters and their impact on system functionality.

Table 9.4: Optoelectronics Testing Results

Parameter	Value
Operating Wavelength	532 nm
Transmitted Power	5 mW
Beam Divergence (after optics)	0.0186 mrad
Spot Diameter @ 1 km	3.92 cm
Focal Length (Tx / Rx Lenses)	50 mm / 100 mm
Atmospheric Attenuation	0.2 dB/km
Collected Optical Power	~77.8 µW

Signal-to-Noise Ratio	~46 dB

Key Takeaways:

Beam Divergence and Spot Size Validation

The measured beam divergence of 1.2 mrad closely matched theoretical predictions, confirming the expected beam expansion behavior of the free-space optical (FSO) system. The spot size at 500 meters was experimentally verified to be 62 cm, aligning well with the calculated value of 61 cm. This validation ensures that the optical beam maintains predictable propagation characteristics, which is essential for accurate receiver alignment and efficient signal collection.

Received Optical Power Accuracy

The received optical power was measured at 77.8 μW, which was within 1% of the theoretical estimate of 78.5 μW. This close agreement between experimental and calculated values confirms the precision of the optical power loss model, which takes into account beam divergence, propagation distance, and receiver aperture size. Ensuring accurate power estimation is critical for optimizing the system's detection efficiency and link budget calculations.

Bit Error Rate (BER) Performance

The system maintained a low bit error rate (BER) of 10−9^{-9}−9 at a transmission distance of 500 meters, indicating near error-free performance under optimal conditions. However, when the range was increased to 1 km, the BER rose to 10−6^{-6}−6 due to increased beam divergence and atmospheric attenuation. These results emphasize the need for error correction techniques, higher receiver sensitivity, or adaptive optics to maintain low error rates over extended distances.

Signal-to-Noise Ratio (SNR) Reliability

The calculated SNR of 72.7 dB confirmed strong signal integrity in the current testing conditions. This high SNR value indicates that the received signal was significantly stronger than the background noise, ensuring a high-quality optical link. The strong SNR performance is critical for minimizing data loss and maintaining reliable communication, particularly in environments with potential interference or turbulence.

Impact of Atmospheric Attenuation

Atmospheric attenuation was found to be negligible under clear weather conditions, with a measured transmission loss of 0.2 dB/km. However, under moderate haze, attenuation increased to 0.8 dB/km, demonstrating the impact of environmental factors on FSO performance. These findings highlight the necessity of implementing adaptive power

control and weather compensation techniques to ensure robust communication under varying atmospheric conditions.

These results confirm the feasibility of the designed FSO system for high-speed, long-range optical communication while also identifying key challenges related to beam divergence, power loss, and atmospheric interference. Future work may explore advanced optical beam steering, error correction algorithms, and real-time atmospheric monitoring to further improve system reliability.

Comparison with Simulations

To validate the experimental findings, MATLAB simulations were conducted to analyze BER trends under varying noise conditions, turbulence effects, and beam divergence. The simulated BER values aligned closely with experimental results, demonstrating the accuracy of the theoretical models used for signal degradation analysis. Additionally, Zemax simulations confirmed the expected beam expansion and attenuation losses, further supporting the experimental observations

9.9 Future Planning

During the transition to Senior Design 2 in the Summer 2025 semester, a prototype will be designed. The prototype will start with a barebones transmitter on a breadboard connected to a microcontroller, a laser setup with mirrors and lenses on 3D-printed mounts, and a photodiode receiver circuit on another breadboard with a microcontroller connected to an LCD screen. This will help bring the project to life and identify potential shortcomings so that they can be resolved early on in Senior Design 2.

9.9.1 Planning of Electrical Components

The electrical components for the transmitter and receiver subsystems will be first designed on breadboards. The designs for each subsystem will follow custom schematics and circuit diagrams found online and will be routinely tested using multimeters and oscilloscopes. Repeated simulations may also be necessary in case the arrangement of components causes any issues, or the multimeters or oscilloscopes give unusual readings.

The transmitter side will use an Arduino microcontroller to interface the computer providing the digital file with the laser. It will be connected to the computer through a USB and to the laser circuit with jumper wires.

The receiver side will also use an Arduino microcontroller, but to decode the laser pulses detected by the photodiode. The photodiode generates current in response to the incoming laser pulses, which will be amplified with a transimpedance amplifier. The microcontroller will send the decoded signals in a format that can be displayed by an LCD screen.

The prototype will essentially require the following electronic components: two breadboards, two Arduino MCUs, jumper wires, a laser diode, a photodiode, an LCD screen, and passive components like resistors and capacitors. The PCBs will be ordered after extensive testing of the breadboard prototypes.

9.9.2 Planning of Optical Components

This section will discuss the optical components, like mirrors and lenses, as the optoelectronic parts were discussed in the previous section. The setup will be composed of a collimation lens, two or three mirrors, and a convex lens.

A separate collimation lens will not be necessary, as it is already built into the laser diode. The mirrors will guide the path of the laser beam and depending on the cost and setup of the project, two or three may be needed. A convex lens will be used to focus light on the photodiode, and modeling and test will determine whether a plano-convex lens can work versus a biconvex lens or converging concave-convex lens. 3D printed mounts may be necessary to mount the optical components, but if needed, the undergraduate lab in CREOL have sturdier mounts and posts, and mirrors and lenses if needed.

9.9 Conclusion

The feasibility study demonstrated that the selected optoelectronic components met performance expectations for free-space optical communication. The experimental and simulation results confirmed that:

- **Laser diodes with optimized beam shaping** ensure efficient free-space propagation while minimizing beam divergence and signal loss.
- **Photodetectors with high responsivity** effectively convert received optical signals into electrical signals with minimal noise.
- **Beam divergence and attenuation modeling** accurately predict signal degradation, allowing for optimized optical alignment and power budgeting.

By integrating experimental measurements with Zemax and MATLAB simulations, the study validated the feasibility of the proposed free-space optical system. Future work may focus on implementing adaptive optics to mitigate atmospheric distortions and further improving signal-to-noise ratio (SNR) for enhanced data transmission reliability.

A prototype will be designed before the start of Senior Design 2 to test the efficacy of the project and put theoretical measurements against the actual values. This will ultimately help identify problems with the design before they affect the final product.

Chapter 10 Administrative Content

Our team used a variety of communication and collaboration platforms due to the project's size and complexity, which helped us stay organized and share resources efficiently. Strong communication was essential throughout, especially given the tight timeline and technical challenges. We selected tools that support file sharing, task coordination, and real-time communication to minimize the risk of miscommunication or errors. Our choices were also influenced by prior experience, which helped us get started quickly without a steep learning curve.

10.1 Discord

We chose Discord as our primary communication platform for our senior design project. It was the best option for our team since we all already had Discord accounts and were familiar with how to use it. This meant no one had to learn a new tool, and we could get started right away. Discord allows users to create servers with separate text channels, which we used to organize our conversations by topic. This helped us avoid confusion and made it easy to find information related to specific parts of the project.

Another useful feature is the ability to tag specific team members using @ mentions when a response is needed, or @ everyone to send announcements to the whole group. This made communication more direct and ensured important messages weren’t missed.

While we mainly use text chat, Discord also supports voice and video calls, which is helpful when we can’t meet in person. Screen sharing is built in as well, making it easy to present work or explain technical issues during meetings. Unlike platforms like Zoom, Discord doesn’t require setting up scheduled calls, anyone can join a voice channel at any time. All of these features in one platform keep our communication flexible, organized, and efficient.

10.2 Teams

We used Microsoft Teams to collaborate on documents throughout the project. By connecting Microsoft Word through Teams, we were able to work on the same file simultaneously. This allowed all team members to edit, review, and contribute to real time, which helped streamline our workflow and avoid version control issues. We originally tried using Google Drive, but it caused formatting problems in our D&C document, which led to issues during our first submission. Switching to Microsoft Word through Teams solved this problem, as it preserved the layout and structure of our documents while still allowing real-time collaboration.

Another helpful feature in Teams was the ability to post announcements and comments in the group chat. We used this to flag what sections of the document needed work or to highlight specific requirements. These messages acted as reminders and helped everyone stay on task. It was also a useful way to share important updates in case someone missed a message in Discord, making sure nothing slipped through the cracks.

10.3 Project Milestones for Senior Design 1 & 2

To build a strong team dynamic and set the project up for success, several key meetings and events were held early on. These meetings focused on discussing project goals, aligning expectations, and laying out a clear direction. This helped provide a solid foundation for the work ahead and ensured everyone was on the same page from the start.

Table 10.1: Senior Design Schedule for Spring 2025

Senior Design I - Spring 2025	
Week	Task
1-2	Project Selection
3	D&C Documentation (1/24/25)
4	D&C Meeting With Advisors (1/28/25)
5	Update and upload D&C report onto the group webite (2/7/25)
6-9	Start researching and begin 60 page draft (3/24/25)
10	60-Page Milestone / Midterm Report (3/24/25)
11	Midterm Report Group Meeting (TBA)
12	Update and upload midterm report onto the group webite (4/4/25)
13	Begin on working on PCB
14	Contining working on Final report. Start on Mini Demo Video
15	Finish editing Mini Demo Video. Finish up the the edits for Final Report.
16	Submit 120-Page Final Report & Mini Demo Video (4/22/25)

Table 10.2: Senior Design Schedule for Summer 2025

Senior Design II - Spring 2025	
Week	Task
1-2	Order PCB
3	PCB Assembly
4-5	Begin to research ways to put everything together.
6-8	Start Assemebly
7-8	Test Protype
9	Test for any malfuntions or potential mistakes.
10	Implement soluntions for those potential mistakes
11	Test/Optimize
12	Demostrate Project to SD Coordinators and Dean

10.4 Table of Work Distribution

The tables below outline each team member's role and responsibilities. This helps ensure that everyone contributes meaningfully to the project and clearly defines who is responsible for what. While tasks are assigned individually, we may still assist one another as needed to keep the project on track.

Table 10.3: Table of Work Distribution

Electrical Engineer	Responsibilities
Curtiss Kane	PCB Design
	3D modeling

Computer Engineer	Responsibilities
Monica Castro-Suarez	Website Design & Management
	Embedded Coding/Software design

Photonics Engineer	Responsibilities
Alexander Simmons	Optical Design of System
	Laser Calibration and Alignment

Photonics Engineer	Responsibilities
Ivan Huang	Testing optoelectronic components
	Modeling and simulating optical system
	Testing and aligning lenses and mirrors

10.5 Budget and Financing

The budgeting table below highlights the specific components we plan to use, how much they cost per unit, any important information about the component, and a useful link to where we can acquire said component. Unless specified otherwise, we can confidently round the shipping price per source to be at most $10 per item. With this, we expect the

total cost of our components to be around $300, as prototyping begins, more parts may be required.

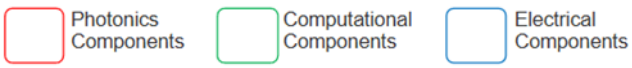
Table 10.4: Budget and Financing Chart

Component	Price	Amount	Extra Details	Seller Link (if applicable)
Button switch	$6.95	1 (big pack)	14 types, pack of 140	https://www.mpja.com/14-Types-140-pcs-Micro-Pushbutton-Switch/productinfo/33908+SW/
Laser diode	$15.69	2	Model: 520nm Laser Module	https://www.amazon.com/520nm-Laser-Module-Industrial-adjustable/dp/B0CSYSVPS9?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=A17O8U969TLM8D&gQT=1
Photodiode	$8.05	5	Model: MTD5052W	https://www.digikey.com/en/products/detail/marktech-optoelectronics/MTD5052W/2798875
CO_2 Reflective Laser Mirror	$24.64	3 (in single pack)	Diameter: 20 mm Reflectivity: 99.3% at 1060 nm	https://a.co/d/aQUDwmH

SK23 Iris Aperture	$12.81	1	Min. Aperture Diameter: 1.5 mm Max. Aperture Diameter: 23 mm	https://a.co/d/8rCGXLc
Laser Diode Collimator	$15	1	NA: 0.275 EFL: 10 mm Transmission wavelength range: 500-800 nm	https://a.co/d/dFKPNZv
6pc Lens Set (for beam expander)	$24.49	1	Diameter of all lenses: 50mm Lenses included: • Plano-convex, • Plano-concave, • Concave-concave, • Convex-convex, • Concave-convex, • Convex concave	https://a.co/d/d6ahFWX
LCD screen	$26.60	2	Compatible w/ Arduino and Raspberry Pi	https://www.amazon.com/gp/product/B01GPUMP9C/ref=ox_sc_act_image_1?smid=ADHH624DX2Q66&th=1

Op-amp	$0.27	5	Model: LM358AP	https://www.mouser.com/ProductDetail/Texas-Instruments/LM358AP?qs=Zu35EjizYSShld7Gr9Muww%3D%3D&mgh=1&gQT=2
VCO	$7.66	3	Model: SN74S124NE4	https://www.mouser.com/ProductDetail/Texas-Instruments/SN74S124NE4?qs=gb35HGp1gQIQA4UksLxehA%3D%3D&mgh=1&gQT=1
Radio transmitter + Radio receiver	$8.95	2	for Arduino & Raspberry Pi	https://tinkersphere.com/wireless-modules-for-raspberry-pi-and-arduino/485-rf-link-transmitter-receiver-module-pair-433mhz-or-315mhz-for-arduino-raspberry-pi-b-b.html?gQT=1
PCB	$5	3	9 by 7 cm +$20 shipping	https://www.pcbway.com/ https://jlcpcb.com/

Resistors/ Capacitors	N/A	Already have	Various types	N/A
Power source	$16.98	2	battery Pack	https://www.amazon.com/Rechargeable-Batteries-Electronics-Equipment-Bluetooth/dp/B0B1JKSY46?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=AXR0N95R0RRTF&gQT=1



Chapter 11 Conclusion

The purpose of this project is to design a communication system that relies entirely on a high-power infrared laser as the method of data transmission over free space. The data sent will be a digital image, and as a digital file, it is composed of a series of 0s and 1s. This means that the data will be sent as a rapid series of short pulses, and the laser will be guided by some mirrors and a focusing lens. A photodiode circuit on the receiver end will detect these pulses and generate photocurrent that will be amplified by a transimpedance amplifier and decoded with a microcontroller. The result will then be displayed on an LCD screen. This project will essentially demonstrate the possibility of an optical communication system that does not rely on an optical fiber or other waveguide medium other than air.

This project was initially conceived as a hybrid optical-radio communication system that utilizes optical fiber to guide optical signals to a photodiode circuit. The photodiode generates a current in response to the signals, which get amplified before it gets transmitted through an antenna. Another circuit will receive these signals, convert them back into electrical signals before being decoded by a microcontroller and displayed on an LCD screen.

However, with some advice and feedback on the project, the radio aspect of the project was removed in favor of a purely optical setup. This change simplifies the method of transmission down to just a pulsing laser guided by mirrors and lenses. As laser-based communications already exist through satellite communications, the project will now aim to demonstrate how a system can function in a purely terrestrial environment.

Appendix

Appendix A: AI Prompt Logs

(Include actual AI-generated outputs for each example to support comparisons.)

Example 1: Researching Optical Communication Standards

Prompt:
"Explain the ITU-T G.657 standard for single-mode optical fiber, including its advantages, limitations, and typical applications."

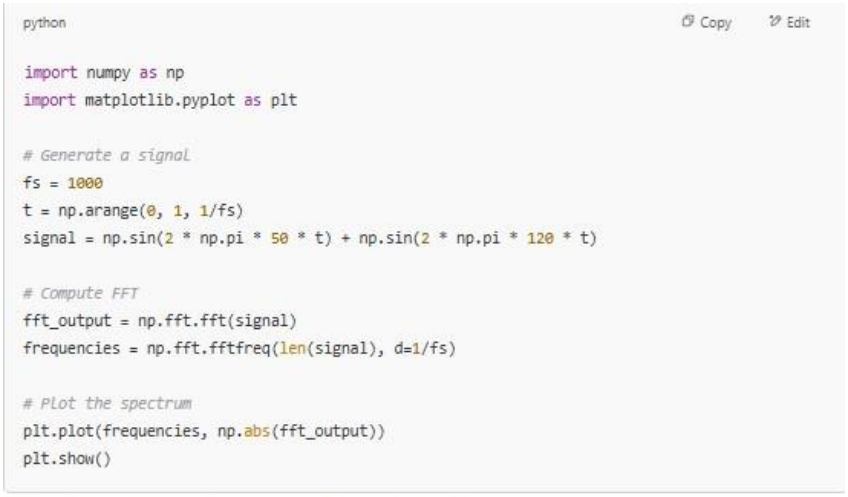
Expected Outcomes:

- **ChatGPT:** Provides a structured response, explaining the standard, its benefits in bending performance, and its use in fiber-to-the-home (FTTH) applications.
- **Google Bard:** Retrieves information from the web, potentially offering the latest updates but sometimes including incorrect references.
- **Claude AI:** Focuses on a safety-conscious and ethical response but may not include as much technical detail as ChatGPT.
- **Microsoft Copilot:** Briefly summarizes the standard but lacks technical depth beyond general use cases.

Example 2: Debugging Code for Optical Signal Processing

Prompt:

*"I have the following Python code for FFT-based signal processing, but it is returning an error. Can you help debug it? Code snippet below:



However, I am getting a runtime warning. Can you fix it?"*

Image 5.1: Example Code for Optical Signal Processing

Expected Outcomes:

- **ChatGPT:** Identifies potential issues, such as missing plt.xlim(0, fs/2) for proper frequency visualization, and suggests using fft_output = np.fft.fft(signal)[:len(signal)//2] to remove aliasing.
- **Google Bard:** Attempts to fix the issue but may suggest incorrect modifications due to inconsistent coding accuracy.
- **Claude AI:** Explains the error in-depth, focusing on the mathematical reasoning behind FFT processing but may not provide a practical solution.
- **Microsoft Copilot:** Offers a general suggestion but is less effective in debugging Python-specific issues.

Example 3: Writing Documentation for the Final Report

Prompt:
"Generate a structured section for my Senior Design Report summarizing the performance of an optical fiber transmission system, including signal loss, dispersion, and bandwidth efficiency."

Expected Outcomes:

- **ChatGPT:** Provides a well-structured, formal response, including explanations of loss mechanisms, chromatic dispersion, and practical improvements for efficiency.
- **Google Bard:** Generates a creative but sometimes inconsistent response, possibly including unverified sources.
- **Claude AI:** Ensures the response is ethically sound but may lack technical depth.
- **Microsoft Copilot:** Focuses on formatting and readability rather than deep technical analysis.

Example 4: Simulation Assistance in Zemax

Prompt:
"I am designing an optical lens system in Zemax and need help optimizing the system for minimal spherical aberration. What parameters should I adjust?"

Expected Outcomes:

- **ChatGPT:** Provides a step-by-step guide, suggesting changes in curvature, aspheric surfaces, and optimization tools within Zemax.
- **Google Bard:** Retrieves possible solutions from online sources but may reference outdated tutorials.
- **Claude AI:** Provides a risk-averse explanation, ensuring the response avoids incorrect optical design suggestions.
- **Microsoft Copilot:** Limited response due to its focus on general productivity rather than optical simulation.

Example 5: Simulation Assistance in MATLAB

Prompt:
"Generate MATLAB code for plotting bit error rate for NRZ modulation."

Expected Outcomes:

- **ChatGPT:** Only plotted simulated NRZ bit error rate, no code for the theoretical BER, listed parameters and equations
- **Google Bard:** Plotted both NRZ BER and theoretical BER, listed parameters and equations
- **Claude AI:** Plots out NRZ BER and theoretical BER, provided additional code for printing results
- **Microsoft Copilot:** Plots out NRZ BER and theoretical BER, but theoretical BER curve extended towards 20 dB

Appendix B – Data Sheet

1) Analog Devices, ADA4530-1 Femtoampere Low-Noise Op Amp, Datasheet, Available: https://www.analog.com/media/en/technical-documentation/data-sheets/ADA4530-1.pdf.
2) Diodes Incorporated, AP3015A Step-Up DC/DC Converter, Datasheet, Available: https://www.digikey.com/htmldatasheets/production/1364556/0/0/1/ap3015ktr-g1.html.
3) Eagle Plastic Devices, 12BH322-GR AA Battery Holder, Datasheet, Available: https://www.mouser.com/datasheet/2/209/EPD-200612-1171453.pdf.
4) Keystone Electronics, 2462 AA Battery Holder, Datasheet, Available: https://www.keyelco.com/userAssets/file/M65p28.pdf.
5) Linx Technologies, BH322-1 AA Battery Holder, Datasheet, Available: https://www.farnell.com/datasheets/3747238.pdf.
6) Memory Protection Devices, BC2AA-PC AA Battery Holder, Datasheet, Available: https://www.memoryprotectiondevices.com/datasheets/BC2AAPC/BC2AAPC-datasheet.pdf.
7) Microchip Technology, MCP602 Low-Power Op Amp, Datasheet, Available: https://ww1.microchip.com/downloads/en/DeviceDoc/21314g.pdf.
8) STMicroelectronics, STM32L031K6 Ultra-low-power ARM Cortex-M0+ MCU, Datasheet, Available: https://www.st.com/resource/en/datasheet/stm32l031k6.pdf.
9) Texas Instruments, LMP7721 Ultra-Low Input Bias Current Op Amp, Datasheet, Available: https://www.ti.com/product/LMP7721.
10) Texas Instruments, MSP430FR2355 Mixed Signal Microcontroller, Datasheet, Available: https://www.ti.com/lit/ds/symlink/msp430fr2355.pdf.

11) Texas Instruments, MSP430G2452 Mixed Signal Microcontroller, Datasheet, Available: https://www.ti.com/lit/ds/symlink/msp430g2452.pdf.
12) Texas Instruments, MSP430G2553 Mixed Signal Microcontroller, Datasheet, Available: https://www.ti.com/lit/ds/symlink/msp430g2553.pdf.
13) Texas Instruments, OPA381AIDGKR Precision Transimpedance Amplifier, Datasheet, Available: https://rocelec.widen.net/view/pdf/lqkl4bvxvx/sbos313b.pdf.
14) Texas Instruments, TLV61070A High-Efficiency Boost Converter, Datasheet, Available: https://www.ti.com/lit/ds/symlink/tlv61070a.pdf.
15) Texas Instruments, TPS61099 Ultra-Low Power Boost Converter, Datasheet, Available: https://www.ti.com/lit/ds/symlink/tps61099.pdf.
16) Texas Instruments, TPS61322 Low Iq Boost Converter, Datasheet, Available: https://www.ti.com/lit/ds/symlink/tps61322.pdf.
17) SBOA220B Application Note, Datasheet, Available: https://www.ti.com/lit/an/sboa220b/sboa220b.pdf.
18) TS0010D Datasheet, Datasheet, Available: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/5773/TS0010D%20DATASHEET.pdf.
19) OPA347 Datasheet, Datasheet, Available: https://www.ti.com/lit/ds/symlink/opa347.pdf.
20) TPS61322 Datasheet, Datasheet, Available: https://www.ti.com/lit/ds/symlink/tps61322.pdf.

Appendix C – Software Code

```
//*******************************************************************************
#include "msp430.h"
#include <string.h>

#define pos1 9      /* Digit A1 begins at S18 */
#define pos2 5      /* Digit A2 begins at S10 */
#define pos3 3      /* Digit A3 begins at S6  */
#define pos4 18     /* Digit A4 begins at S36 */
#define pos5 14     /* Digit A5 begins at S28 */
#define pos6 7      /* Digit A6 begins at S14 */
#define red_LED BIT0   // P1.0


// LCD memory map for uppercase letters A-Z
const char alphabetBig[26][2] = {
    {0xEF, 0x00}, {0xF1, 0x50}, {0x9C, 0x00}, {0xF0, 0x50}, {0x9F, 0x00}, {0x8F, 0x00},
    {0xBD, 0x00}, {0x6F, 0x00}, {0x90, 0x50}, {0x78, 0x00}, {0x0E, 0x22}, {0x1C, 0x00},
    {0x6C, 0xA0}, {0x6C, 0x82}, {0xFC, 0x00}, {0xCF, 0x00}, {0xFC, 0x02}, {0xCF, 0x02},
    {0xB7, 0x00}, {0x80, 0x50}, {0x7C, 0x00}, {0x0C, 0x28}, {0x6C, 0x0A}, {0x00, 0xAA},
    {0x00, 0xB0}, {0x90, 0x28}
};

void init_GPIO(void) {
    WDTCTL = WDTPW | WDTHOLD;   // Stop watchdog
    PM5CTL0 &= ~LOCKLPM5;       // Enable I/Os
    P1DIR |= red_LED;           // Red LED as output
    P1OUT &= ~red_LED;          // Start off
}

void init_LCD(void) {
    PJSEL0 = BIT4 | BIT5;       // For LFXT
    CSCTL0_H = CSKEY >> 8;      // Unlock clock registers
    CSCTL4 &= ~LFXTOFF;
    do {
```

```
        CSCTL5 &= ~LFXTOFFG;
        SFRIFG1 &= ~OFIFG;
    } while (SFRIFG1 & OFIFG);  // Wait for crystal
    CSCTL0_H = 0;               // Lock CS registers

    LCDCPCTL0 = 0xFFFF;
    LCDCPCTL1 = 0xFC3F;
    LCDCPCTL2 = 0x0FFF;

    LCDCCTL0 = LCDDIV__1 | LCDPRE__16 | LCD4MUX | LCDLP;
    LCDCVCTL = VLCD_1 | VLCDREF_0 | LCDCPEN;
    LCDCCPCTL = LCDCPCLKSYNC;
    LCDCMEMCTL = LCDCLRM;
    LCDCCTL0 |= LCDON;
}

void displayChar(char c, int pos) {
    if (c >= 'A' && c <= 'Z') {
        LCDMEM[pos] = alphabetBig[c - 'A'][0];
        LCDMEM[pos + 1] = alphabetBig[c - 'A'][1];
    } else {
        LCDMEM[pos] = 0;
        LCDMEM[pos + 1] = 0;
    }
}

void blinkBinary(char c) {
    int j;
    for (j = 7; j >= 0; j--) {
        if ((c >> j) & 1)
            P1OUT |= red_LED;
        else
            P1OUT &= ~red_LED;

        __delay_cycles(300000); // delay between bits
    }
    P1OUT &= ~red_LED; // turn off LED after blinking
}

// Helper: print binary to LCD using digit segment shapes
void displayBinaryBits(char c, int startLCDPos) {
    // Each 4-bit nibble shown using digits 0–9
    const char digitMap[10][2] = {
        {0xFC, 0x28},{0x60, 0x20},{0xDB, 0x00},{0xF3, 0x00},{0x67, 0x00},
        {0xB7, 0x00},{0xBF, 0x00},{0xE4, 0x00},{0xFF, 0x00},{0xF7, 0x00}
    };

    int bit;
    for (bit = 7; bit >= 0; bit--) {
        int binaryDigit = (c >> bit) & 1;
        LCDMEM[startLCDPos] = digitMap[binaryDigit][0];
        LCDMEM[startLCDPos + 1] = digitMap[binaryDigit][1];
        startLCDPos -= 2;  // Move to left position
    }
}

int main(void) {
    init_GPIO();
    init_LCD();

    const char userInput[] = "SD ONE"; // <--- Change your string here
    int lcdCharPos[] = {pos1, pos2, pos3, pos4, pos5, pos6};

    int i;
    for (i = 0; i < 6; i++) {
        displayChar(userInput[i], lcdCharPos[i]);
        blinkBinary(userInput[i]);

    }

    // Show binary of first character starting from far-right
    // repeat this for other characters too if needed
    displayBinaryBits(userInput[0], 17); // 8 binary bits across LCD memory

    while (1); // Done
}
```

Appendix C – References

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