

# Digital Transmission in Free Space through a High-Power Laser

*UCF Senior Design I*



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## **Acknowledgements**

# 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 down to 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.

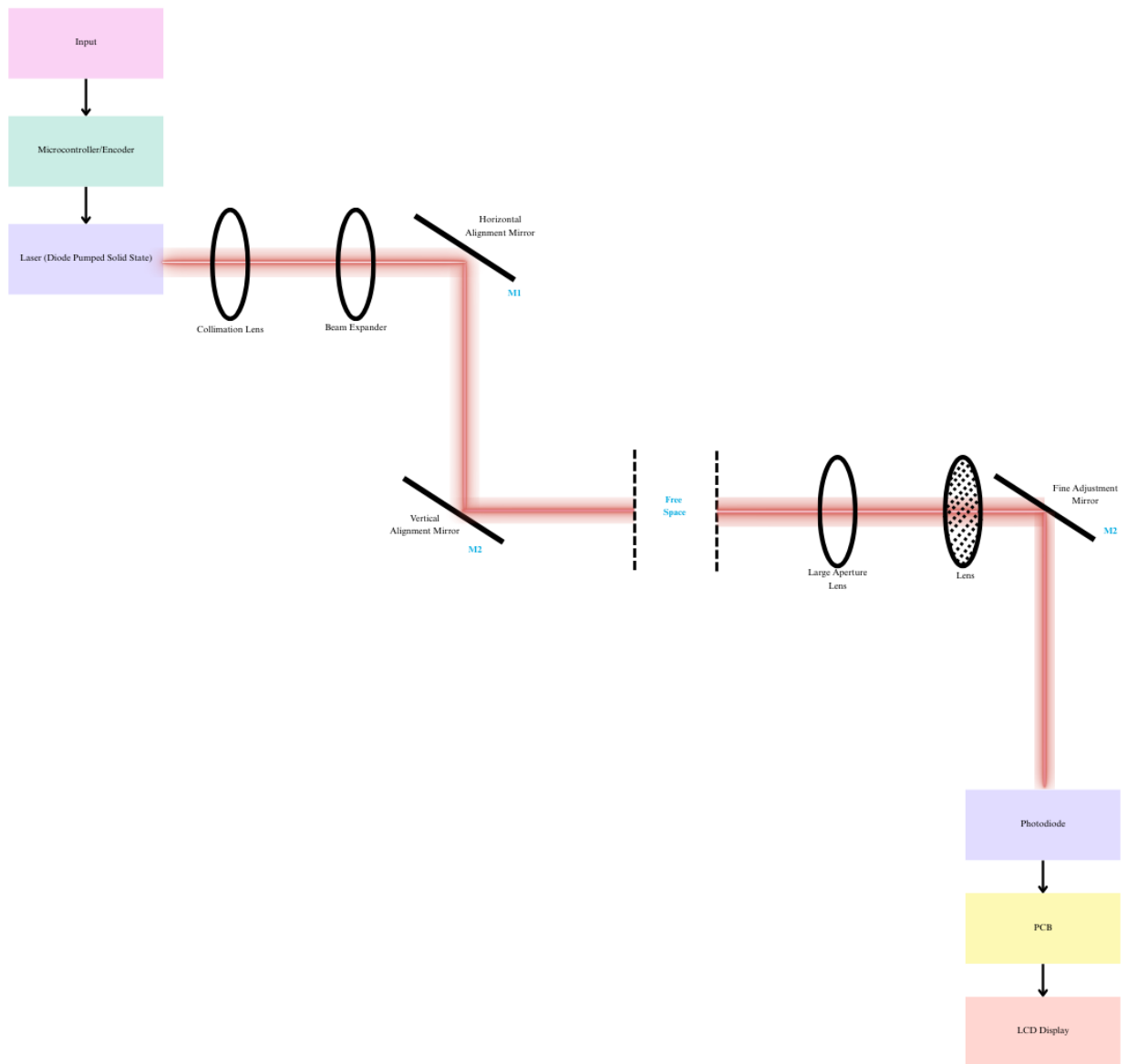


**Figure 1.1:** 2D Prototype Illustration

# 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.

Optical fibers are thin strands of glass or plastic, surrounded by cladding and protective coatings. The cladding creates total internal reflection, keeping the light contained within the core, while the coating protects the fiber physically. Optical fibers can transmit much higher data rates than metal conductors due to the high bandwidth of light and their immunity to electromagnetic interference. Additionally, optical fibers offer greater data security since they do not emit signals that can be easily tapped, unlike copper cables (Keiser, p. 5).

There are two types of optical fibers: single-mode and multi-mode. Single-mode fibers have a smaller core and allow only one propagation mode, which reduces modal dispersion and signal distortion—making them ideal for long-distance communication.

Multi-mode fibers, with larger cores, support multiple light modes and are generally used for shorter distances. Although our project does not involve long-distance transmission, we selected single-mode fiber to benefit from its lower signal loss and greater signal stability.

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 maritime, air, and land-based communications.

So far, NASA demonstrated the possibility of such a technology through their Laser Communications Relay Demonstration (LCRD), which uses lasers for ground-to-ground communications and ground-to-space communications. This experiment is open up to industries willing to invest in laser communications and will soon find its way into global broadband communications and future space missions, that require transmission of large amounts of data at high speeds.

## 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                                                       |
|---------------------------------------|------------------------------------------------------|---------------------------------------------------------------|
| <b>Optical Transmission Distance:</b> | $\geq 1$ km                                          | Ensures reliable communication over long distances            |
| <b>Decoding Accuracy:</b>             | $\geq 95\%$ Accuracy                                 | Ensures reliable binary code interpretation                   |
| <b>Data Transfer Rate:</b>            | 100 bps (50-200 bps adjustable)                      | Allows flexibility in signal speed for different applications |
| <b>Expected Power Consumption:</b>    | $\leq 5W$                                            | Optimized for low-power, battery-powered operation            |
| <b>Optimal Transmission Distance:</b> | 1-2 km                                               | Ensures optimal signal integrity and low attenuation          |
| <b>Power Efficiency:</b>              | $\geq 85\%$ efficiency,<br>$\leq 5\%$ voltage ripple | Ensures portability and long operational life                 |
| <b>Portability &amp; Durability:</b>  | Lightweight & Rugged Design                          | Suitable for field and emergency communication                |
| <b>Interference Immunity:</b>         | $\geq 40$ 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 single-mode optical fiber. This will be validated by testing signal integrity across different fiber 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                                                                  |
|---------------------------------------------|-----------------------------------------------------------------------|--------------------------------------------------------------------------|
| <b>Laser Diode:</b>                         | 520nm Green Laser, 15mW output                                        | Selected for high visibility and efficiency in fiber optics transmission |
| <b>Photodiode:</b>                          | 450-1100 nm sensitivity                                               | High-speed response for accurate signal decoding                         |
| <b>Microcontroller:</b>                     | Arduino / Raspberry Pi compatible                                     | Controls modulation, decoding, and display                               |
| <b>Voltage-Controlled Oscillator (VCO):</b> | Frequency range: 20 kHz – 40 MHz, Tuning Sensitivity: $\geq 10$ MHz/V | Controls frequency modulation with precise tuning capability             |
| <b>Op-Amp:</b>                              | Gain Bandwidth: $\geq 1$ MHz, Slew Rate: $\geq 0.5$ V/ $\mu$ s        | Ensures stable signal amplification and filtering                        |
| <b>PCB Board:</b>                           | 9cm x 7cm                                                             | Houses and integrates all electronic components                          |
| <b>Power Source:</b>                        | Rechargeable Battery Pack ( $\geq 5$ V, 2000mAh)                      | Provides power for the system                                            |
| <b>Resistors/Capacitors:</b>                | 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.

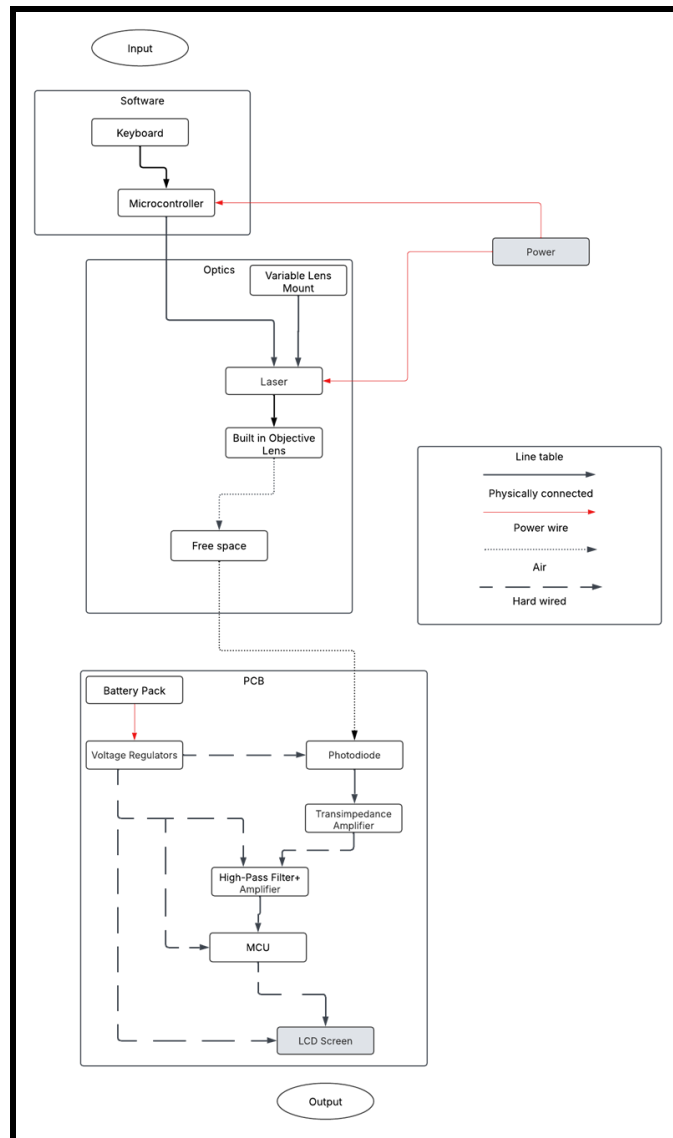


**Figure 2.2:** Hardware Block Diagram

# Chapter 3 Research and Investigation

## Overview

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

### 3.1 Optical Technology Comparison and Selection

In the development of the Optical-Radio 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 <sup>2</sup> 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                             |

|                                                             |              |              |            |               |
|-------------------------------------------------------------|--------------|--------------|------------|---------------|
| <b>Suitability for 1 km Free-Space Optical Transmission</b> | Moderate     | High         | Moderate   | Very High     |
| <b>Cost per Unit</b>                                        | \$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  $\sim 1.1$ , 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 Beam Expander Selection

Beam expanders are used to adjust the diameter of the laser beam, reducing its divergence for more efficient transmission over long distances. The choice of beam expander impacts both the optical efficiency and the overall system performance. This section compares various beam expander designs, including Galilean, Keplerian, and reflective types, assessing their expansion factors, optical efficiency, and suitability for free-space optical transmission. The selected beam expander must offer a balance of performance, cost, and size to ensure optimal beam propagation over the required range.

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

| Feature                 | Galilean Beam Expander       | Keplerian Beam Expander     | Reflective Beam Expander          |
|-------------------------|------------------------------|-----------------------------|-----------------------------------|
| Expansion Factor        | 2x - 10x                     | 5x - 20x                    | 2x - 15x                          |
| Optical Efficiency      | 90 - 95%                     | 85 - 90%                    | 95 - 98%                          |
| Lens Type               | Plano-Convex & Concave       | Two Convex Lenses           | Mirrors (No Chromatic Aberration) |
| Wavelength Range        | 400 - 1600 nm                | 400 - 1600 nm               | 250 - 2000 nm                     |
| Size & Weight           | Compact, Lightweight         | Large, Heavy                | Moderate                          |
| Chromatic Aberration    | Low                          | High                        | None                              |
| Application Suitability | General Laser Beam Expansion | High-Precision Applications | Broadband Wavelength Use          |
| Cost per Unit           | \$50 - \$200                 | \$150 - \$500               | \$200 - \$800                     |

#### Justification for Galilean Beam Expander Selection

The Galilean beam expander was chosen due to its compact design, high optical efficiency (90 - 95%), and cost-effectiveness (\$50 - \$200), making it an ideal choice for long-range free-space optical transmission. Its simple two-lens system minimizes internal optical losses while ensuring effective beam expansion, reducing divergence and maintaining beam intensity over the 1 km transmission path. Additionally, its low chromatic aberration allows for minimal distortion, preserving the quality of the transmitted laser signal.

Other beam expanders were considered but had notable drawbacks. The Keplerian beam expander, though capable of achieving higher expansion factors, was significantly larger

and heavier, making it impractical for integration into a compact optical system. The reflective beam expander, while eliminating chromatic aberration, was ultimately dismissed due to its higher cost and added complexity, which was unnecessary for a system operating at a fixed wavelength of 532 nm.

### 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 <sub>2</sub> 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 <sub>2</sub>                           | Gold               | Ag + Protective Coating  | Multilayer Dielectric       |
| Surface Flatness ( $\lambda$ ) | $\lambda/10$      | $\lambda/5$                                     | $\lambda/5$        | $\lambda/5$              | $\lambda/10$                |
| 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,  $\lambda/10$  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  $\lambda/10$ , 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 ( $\text{MgF}_2$ ) 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). Due to their low cost and prevalence in microelectronics technology, we will specifically evaluate silicon-based photodiodes.

**Table 3.5:** Comparison of Newport Corporation Microscope Objective Lenses

|                                                                        | <b>PN</b>    | <b>PIN</b> | <b>Avalanche (APD)</b> |
|------------------------------------------------------------------------|--------------|------------|------------------------|
| <b>Wavelength Range (nm)</b>                                           | 200-1100     | 300-1100   | 400-1100               |
| <b>Peak Wavelength Range (nm)</b>                                      | 600-900      | 800-1000   | 800-900                |
| <b>Responsivity (<math>A \cdot W^{-1}</math>)</b>                      | 0.5-0.6      | 0.5-0.6    | 0.4-0.6                |
| <b>Gain</b>                                                            | <1           | <1         | 10-1000                |
| <b>Dark Current (<math>I_d</math>) per <math>1 \text{ mm}^2</math></b> | 0.005-0.1 nA | 0.1-1 nA   | 1-10 nA                |

### Justification for Silicon PIN Photodiode Selection

The silicon PIN photodiode was selected mainly for its accepted wavelength range acceptance and low dark current per  $1 \text{ mm}^2$ . 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         |
|--------------------------------------|-------------------------------------------|---------------------------|------------------|
| <b>Wavelength transmission range</b> | One specific wavelength                   | Short wavelengths         | Long wavelengths |
| <b>Composition</b>                   | Shortpass + Longpass or single narrowband | Glass substrate + coating | Colored glass    |
| <b>Cost (\$)</b>                     | 70-200                                    | 100-300                   | 40-200           |

### 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 shortpass lens and a longpass lens. The flexibility of a bandpass lens also means that cheaper shortpass and longpass lenses can be bought to create an affordable bandpass setup and can rival that of 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 use 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.

**Table 3.7:** Comparison of Lens Aperture Geometries

|                    | Pinhole              | Slit           | Iris Diaphragm               |
|--------------------|----------------------|----------------|------------------------------|
| <b>Composition</b> | Fixed circle opening | A thin opening | Blades in a circular pattern |
| <b>Adjustable?</b> | No                   | No             | Yes                          |
| <b>Cost (\$)</b>   | 60-200               | 60-200         | 50-600                       |

## **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 the cheapest apertures averaging about \$50, this means that a cheaper aperture can be bought without increasing the budget too high. As the aperture is a rough circle, a typical laser beam can pass through without drastically affecting its geometry and intensity distribution.

## **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 3.8: MCU Comparison**

| <i>Feature</i>           | <b>MSP430G2452</b>       | <b>MSP430G2553</b> | <b>MSP430FR2355</b>       | <b>STM32L031K6</b>              |
|--------------------------|--------------------------|--------------------|---------------------------|---------------------------------|
| <i>Architecture</i>      | 16-bit RISC              | 16-bit RISC        | 16-bit RISC               | 32-bit ARM Cortex-M0+           |
| <i>Flash Memory</i>      | 8KB                      | 16KB               | 32KB                      | 32KB                            |
| <i>RAM</i>               | 256B                     | 512B               | 4KB                       | 8KB                             |
| <i>ADC Resolution</i>    | 10-bit                   | 10-bit             | 12-bit                    | 12-bit                          |
| <i>Clock Speed</i>       | 16MHz                    | 16MHz              | 24MHz                     | 32MHz                           |
| <i>GPIO Pins</i>         | 24                       | 24                 | 43                        | 37                              |
| <i>Power Consumption</i> | Ultra-Low                | Ultra-Low          | Ultra-Low                 | Low                             |
| <i>Operating Voltage</i> | 1.8V – 3.6V              | 1.8V – 3.6V        | 1.8V – 3.6V               | 1.8V – 3.6V                     |
| <i>Best For</i>          | Low-power sensor systems | More flash/memory  | More precision, ADC, FRAM | High-performance, low-power IoT |
| <i>Price</i>             | \$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  $\mu\text{A}$ , 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  $\mu\text{A}$  vs. 6.5  $\mu\text{A}$ ) 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  $\mu\text{A}$ ) 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 3.9: Boost Converters Comparison**

| <b>Feature</b>             | <b>TPS61322</b>                 | <b>TPS61099</b>                        | <b>TLV61070A</b>                  | <b>AP3015A</b>       |
|----------------------------|---------------------------------|----------------------------------------|-----------------------------------|----------------------|
| <i>Manufacturer</i>        | TI                              | TI                                     | TI                                | Diodes Inc.          |
| <i>Input Voltage</i>       | 0.9V – 5.5V                     | 0.7V – 5.5V                            | 0.7V – 5.5V                       | 0.9V – 6.5V          |
| <i>Output Voltage</i>      | 1.8V – 5.5V                     | 1.8V – 5.5V                            | 1.8V – 5.5V                       | 3.3V / 5V<br>Fixed   |
| <i>Max Output Current</i>  | 200mA                           | 400mA                                  | 200mA                             | 300mA                |
| <i>Quiescent Current</i>   | 6.5 $\mu$ A                     | 0.9 $\mu$ A                            | 1.9 $\mu$ A                       | 20 $\mu$ A           |
| <i>Efficiency</i>          | ~90%                            | ~90%                                   | ~90%                              | ~85%                 |
| <i>Switching Frequency</i> | 1MHz                            | 1MHz                                   | 2MHz                              | 1.2MHz               |
| <i>Package</i>             | SOT-23-5                        | WSO, SOT-23                            | SOT-23-6                          | SOT-23-5             |
| <i>Best For</i>            | Low-power, battery applications | Ultra-low power, higher output current | High-efficiency low-power designs | Simple 3.3V/5V boost |
| <i>Price</i>               | \$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  $\mu$ A 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 3.9: Battery Pack Comparison**

| <i>Alternative Model</i> | <b>Manufacturer</b>             | <b>Battery Type</b> | <b>Mounting Type</b> | <b>Terminals</b> | <b>Features</b>                | <b>Price</b> |
|--------------------------|---------------------------------|---------------------|----------------------|------------------|--------------------------------|--------------|
| <i>BH2AA-PC</i>          | MPD (Memory Protection Devices) | AA (2-cell)         | PCB, Through Hole    | PC Pins          | Similar layout, compact design | \$1.49       |
| <i>12BH322-GR</i>        | Eagle Plastic Devices           | AA (2-cell)         | Snap in              | Wired            | Slightly smaller footprint     | \$1.32       |
| <i>BH322-1</i>           | Linx Technologies               | AA (2-cell)         | PCB Mount            | Solder Tabs      | Secure, vibration-resistant    | \$5.550      |
| <b>2462</b>              | 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 Op-amps

#### 3.3.4.1 Photodiode

##### 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  $5.5\text{nV}/\sqrt{\text{Hz}}$ , 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 ( $7\text{nV}/\sqrt{\text{Hz}}$ ) 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 ( $21\text{nV}/\sqrt{\text{Hz}}$ ) 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 3.11:** Photodiode Op Amps

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

### Justification for Photodiode Op Amps 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/ $\sqrt{\text{Hz}}$ ) 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/ $\sqrt{\text{Hz}}$ ), making it less suitable for high-precision, low-noise photodiode applications

## 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 ???. 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 3.12:** Language Comparison

| Language      | HW level | Formal Structure | Object-Oriented | Scripting |
|---------------|----------|------------------|-----------------|-----------|
| <b>C</b>      | Low      | ✓                | x               | x         |
| <b>Java</b>   | High     | ✓                | ✓               | x         |
| <b>Python</b> | High     | x                | Can be          | ✓         |

### 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 3.11.

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 VS 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.

VS 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.

# 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 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.

### 4.1.3 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*).

## **4.3 Remaining Standards and Design Constraints**

### **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.

# 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

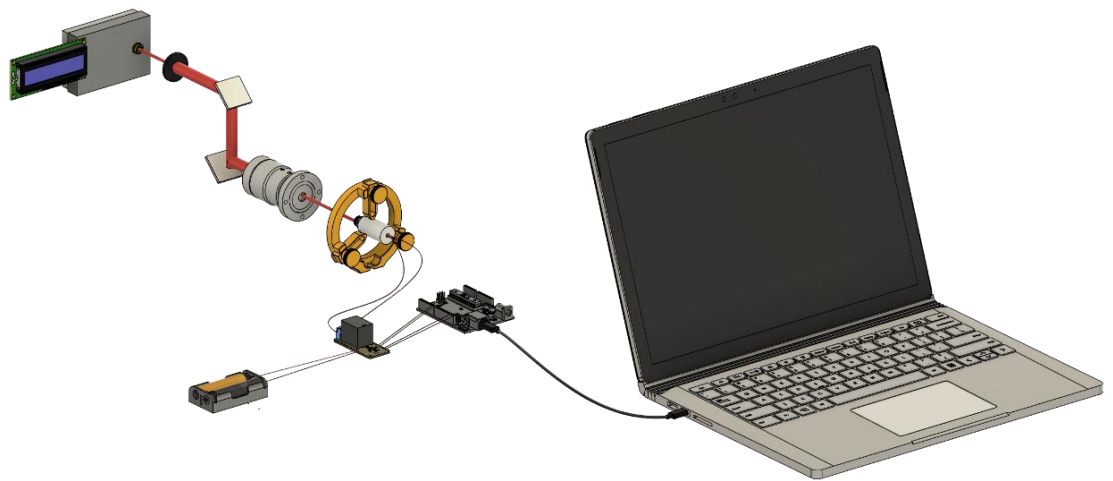


**Figure 6.1:** Hardware Prototype

### 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 in relation to the given binary code
- Optics:
  - Optical Transmission System: The laser and fiber optics direct 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
  - Signal Processing Circuit: Filters and amplifies the signal to prepare it for transmission.
  - Microcontroller (MCU): Decodes the processed signal and converts it into written text to be displayed.
  - LCD: Displays the transmitted message
- Power:
  - Connected to high power laser and controlled by a relay module
  - Provides external power to all units outside of PCB (i.e. Laser and microcontroller)

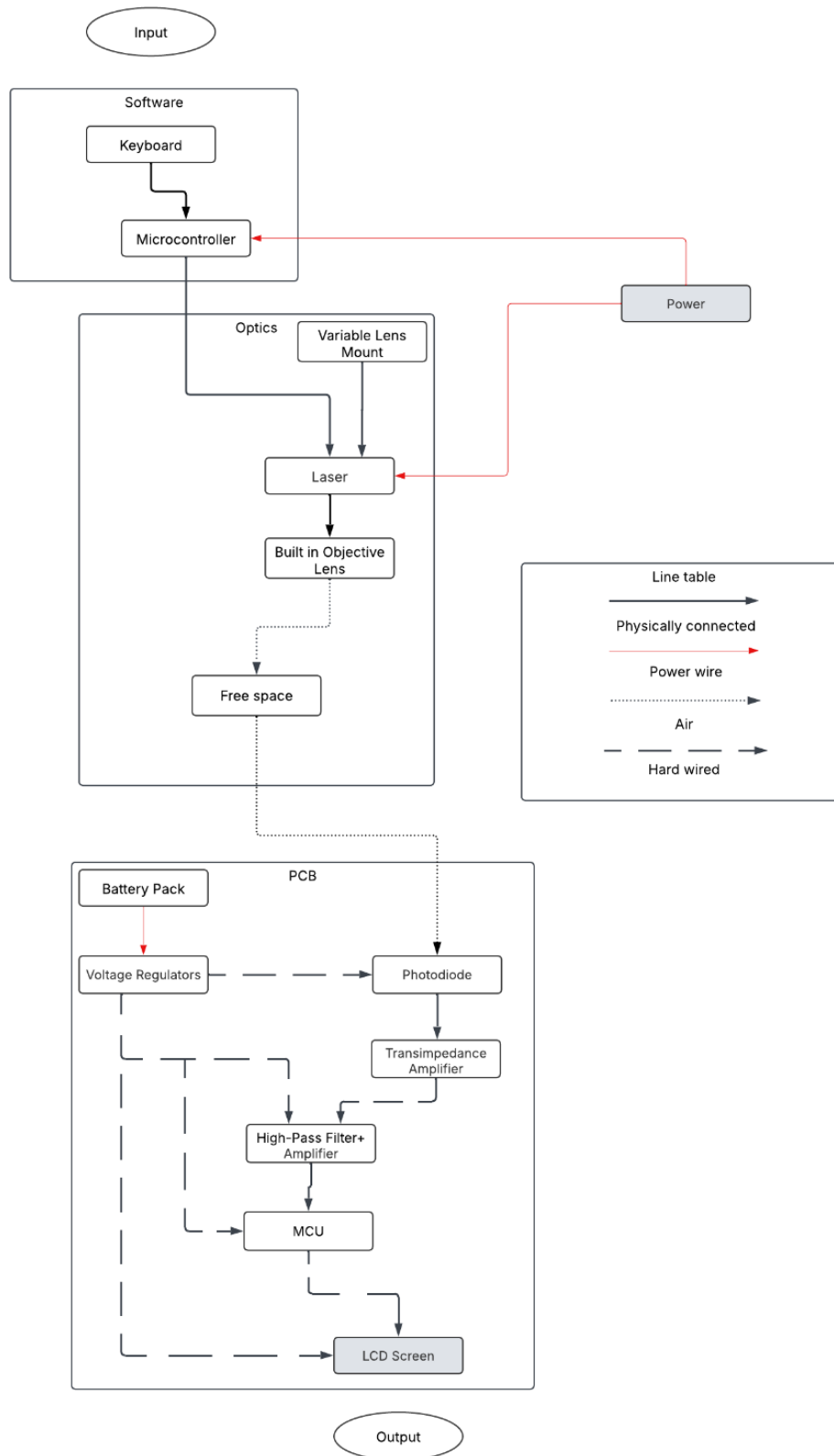


**Figure 6.2:** Block Diagram

## 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:

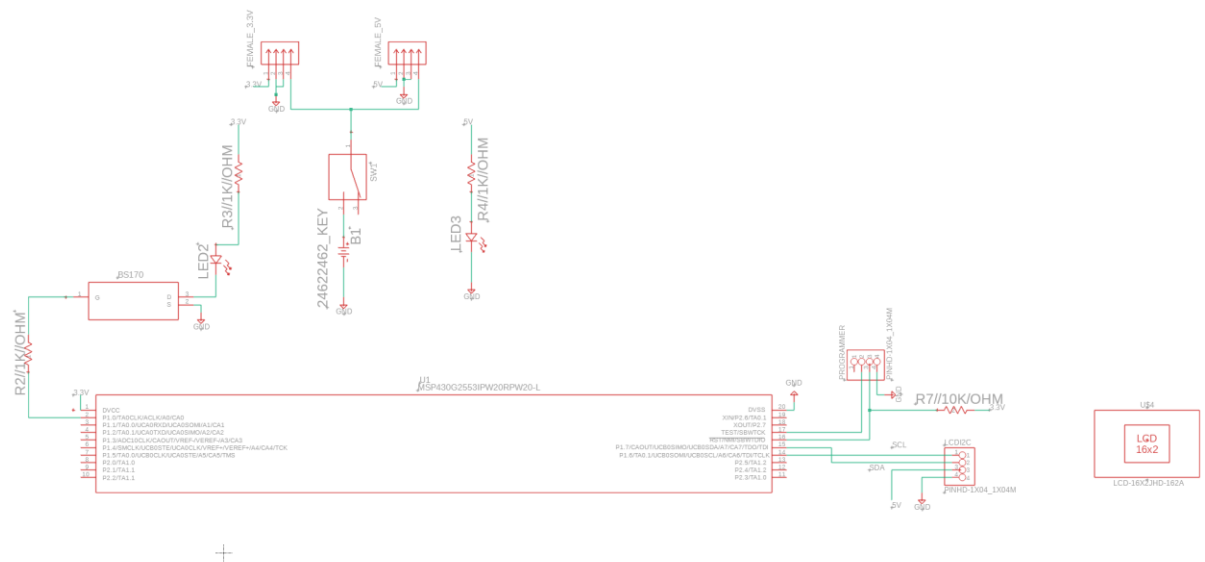


**Figure 6.3:** Overall Circuit Diagram (unfinished)

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:

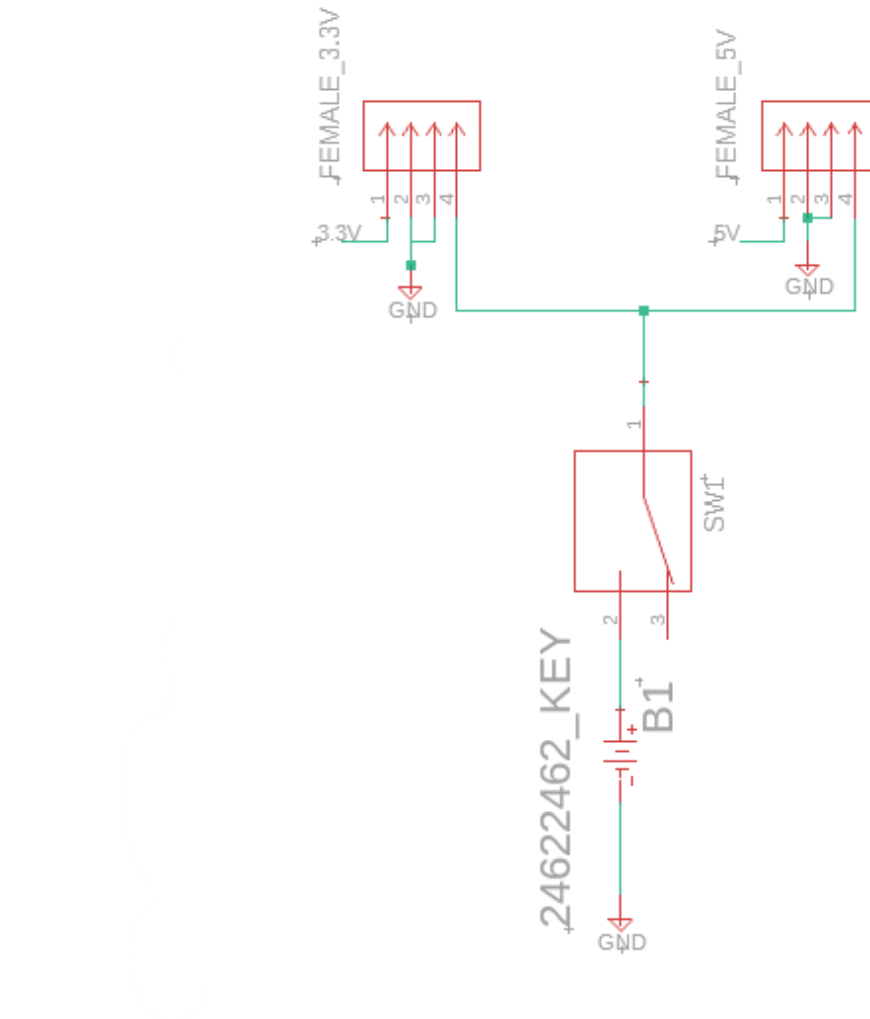


**Figure 6.4:** Battery Pack + Switch

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:

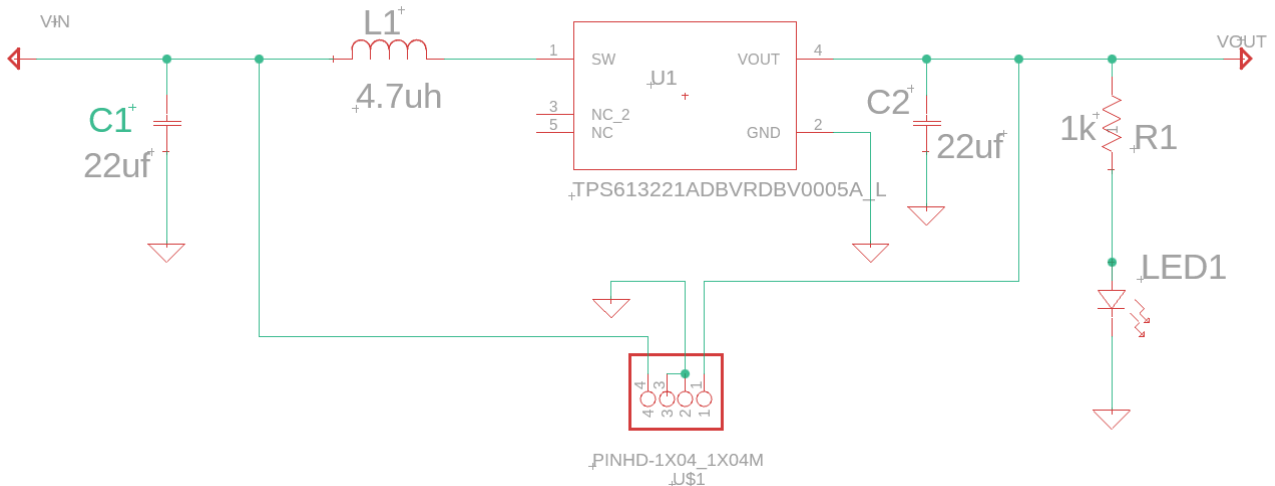


**Figure 6.5: 3.3V Regulator**

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:

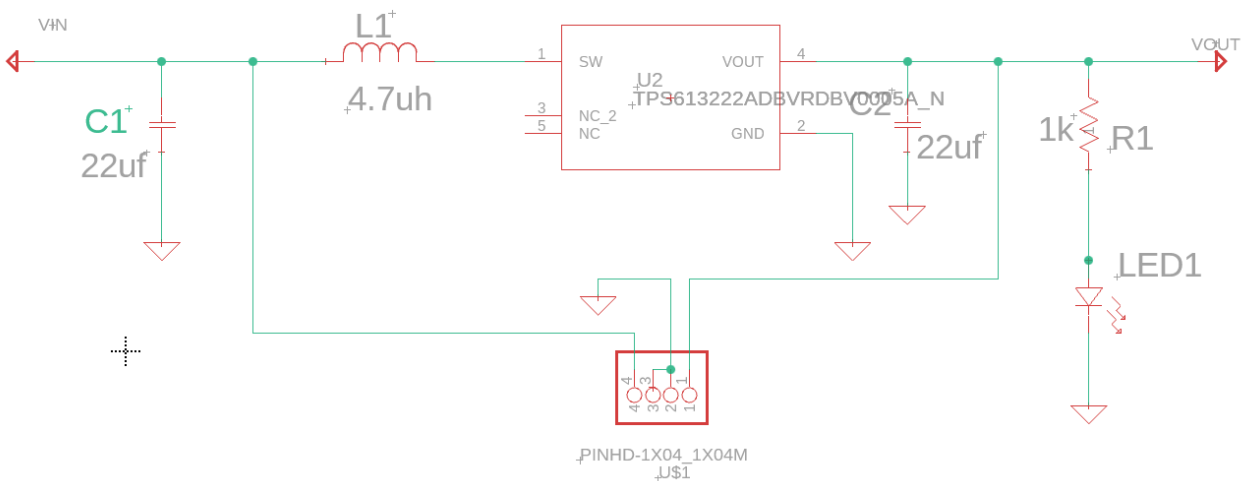


**Figure 6.6: 5V Regulator**

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:

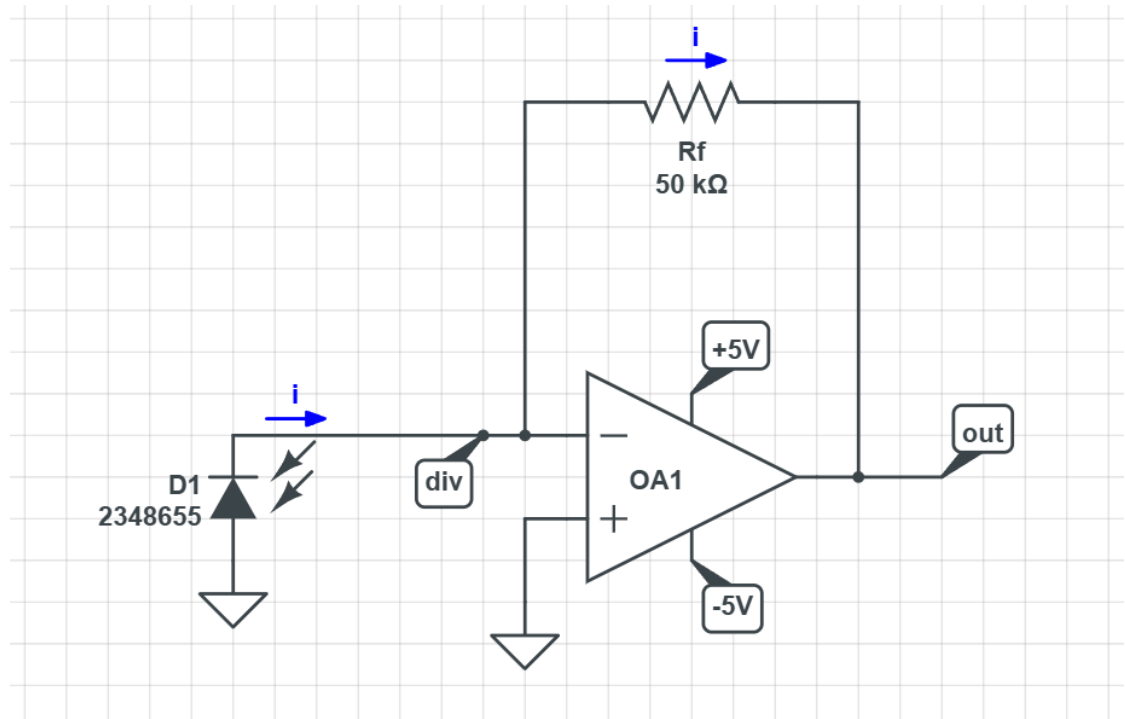


**Figure 6.7:** Photodiode Circuit

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 approximately 1V when exposed to laser illumination. The output then leads into the signal processing circuit.

High pass filter + Amp:

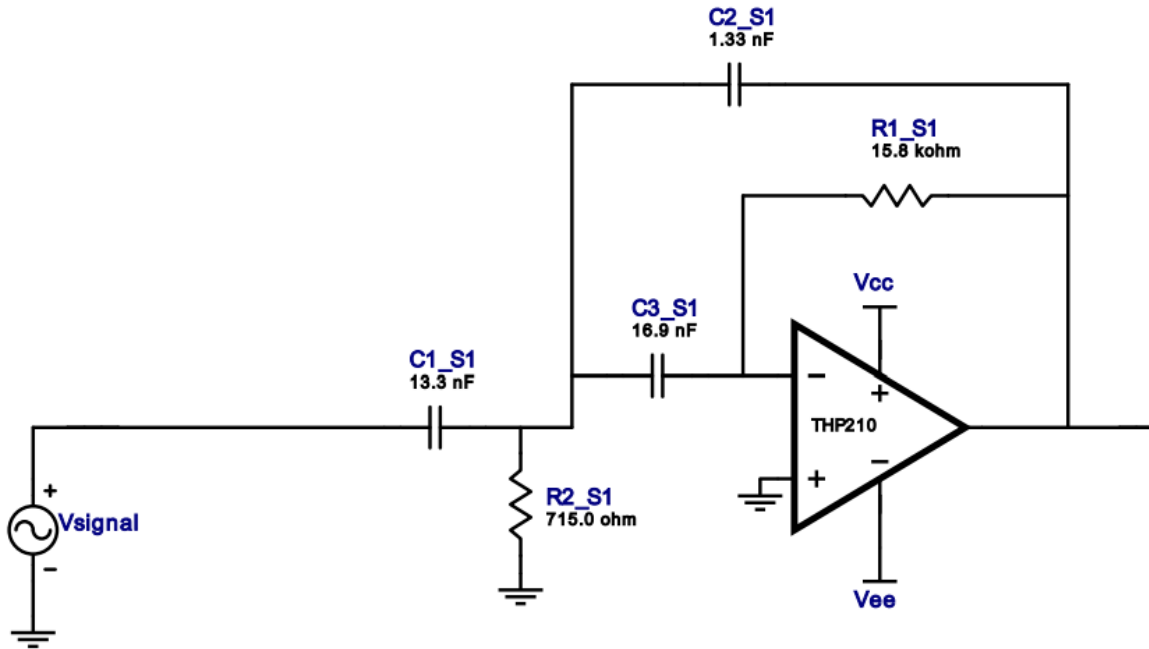


**Figure 6.8:** High Pass filter + Amp

The signal acquired from the photoresistor undergoes filtering and amplification through a Butterworth high pass filter, designed using WEBENCH Designer. This stage employs the THP210 operational amplifier from Texas Instruments, which selectively allows frequencies above 10kHz while amplifying the signal tenfold. The use of a Butterworth filter topology ensures a smooth frequency response with minimal signal distortion, enhancing overall signal integrity. This circuit is located at P1.3 of the MCU to ensure communication with the microcontroller.

MCU:



**Figure 6.9:** MCU

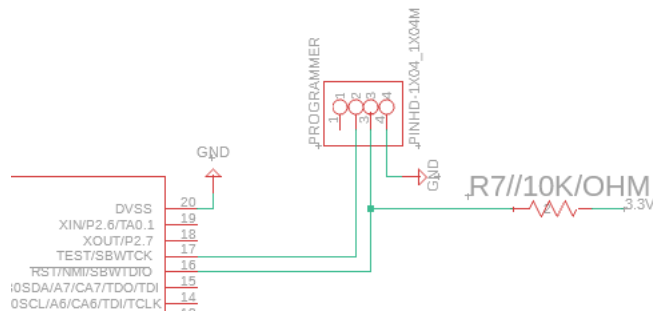


**Figure 6.10:** Four-pin programmer

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:

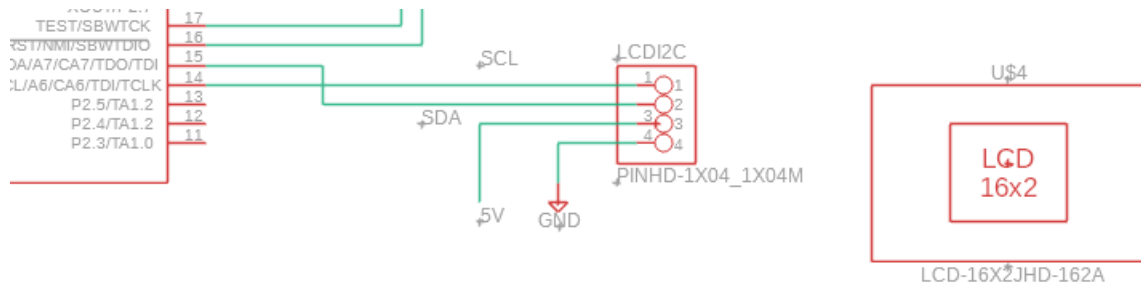


**Figure 6.11:** LCD screen

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.

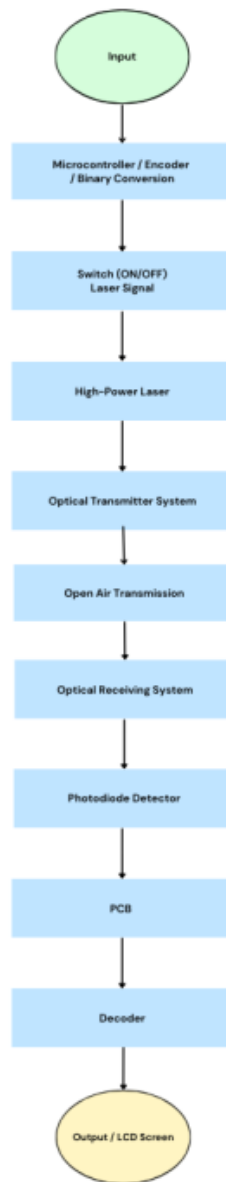


**Figure 6.12:** Computer Architecture

## 6.4 Structural Illustration

### 6.4.1 Signal generation

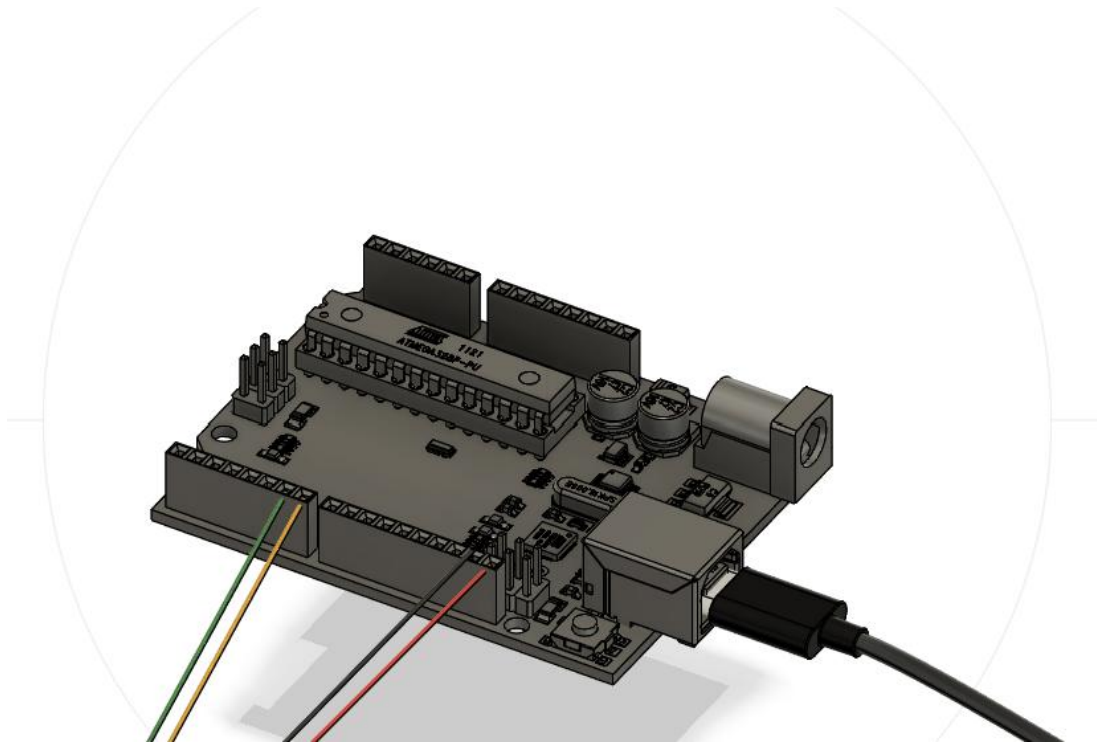
The process of converting written text to binary code using the laptop begins with the user inputting the desired text into a keyboard. This text is then encoded using a standard character encoding format such as ASCII or UTF-8, where each character is represented by a unique binary sequence. Once encoded, 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

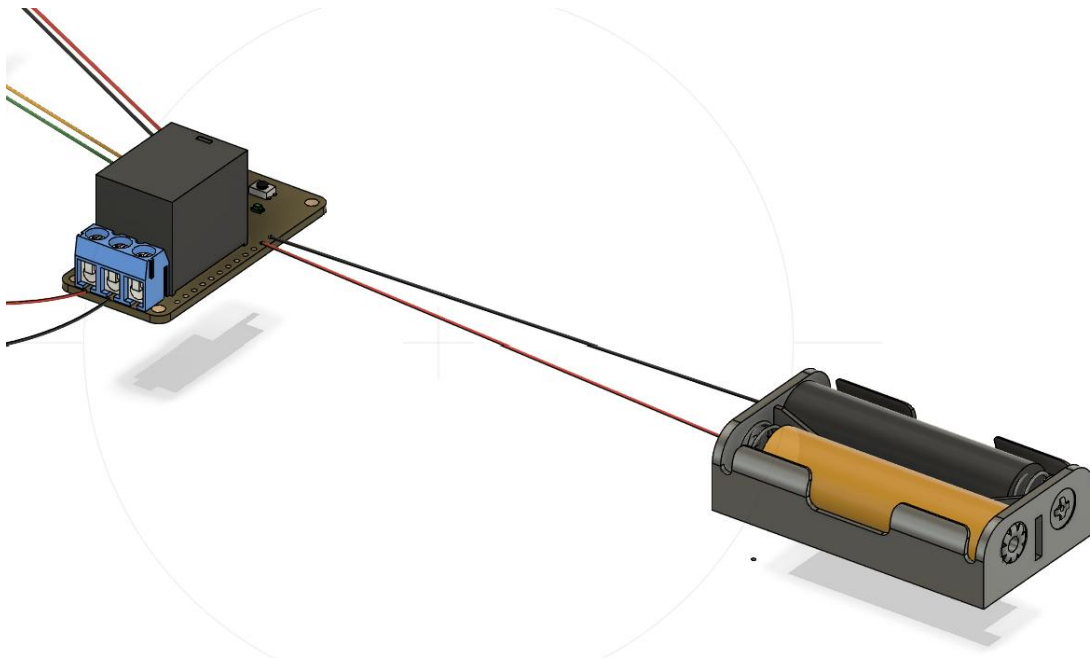


**Figure 6.15:** Power Relay module connected to Battery Pack

## 6.4.2 Optics

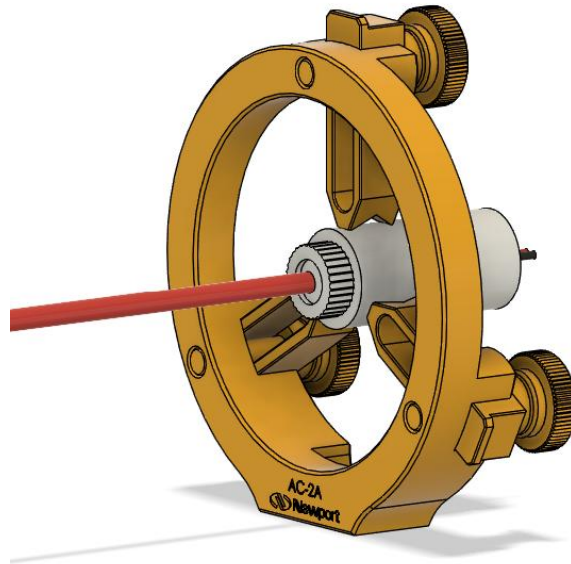


**Figure 6.16:** 532 nm Diode-Pumped Solid-State Laser resting in AC-2A Mount

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.

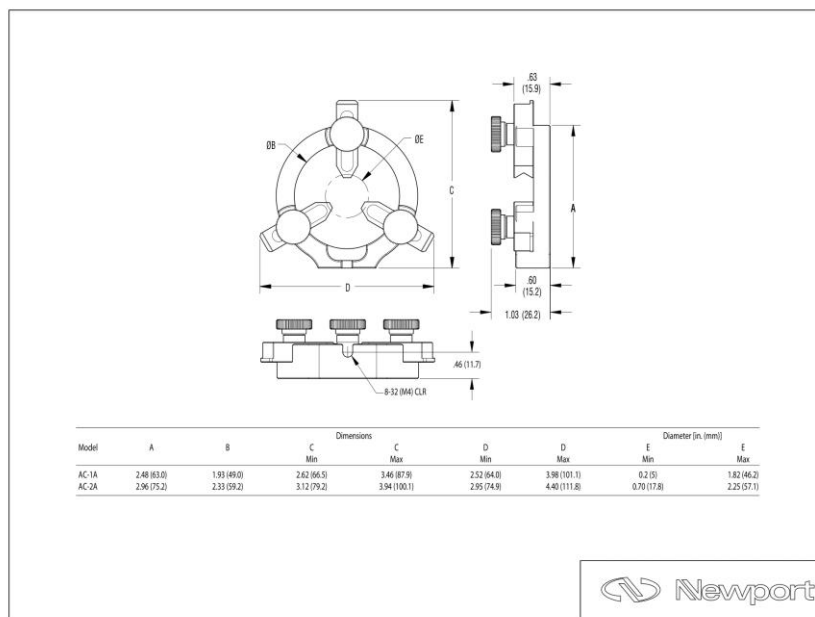


**Figure 6.17:** Dimensions of AC-2A

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.

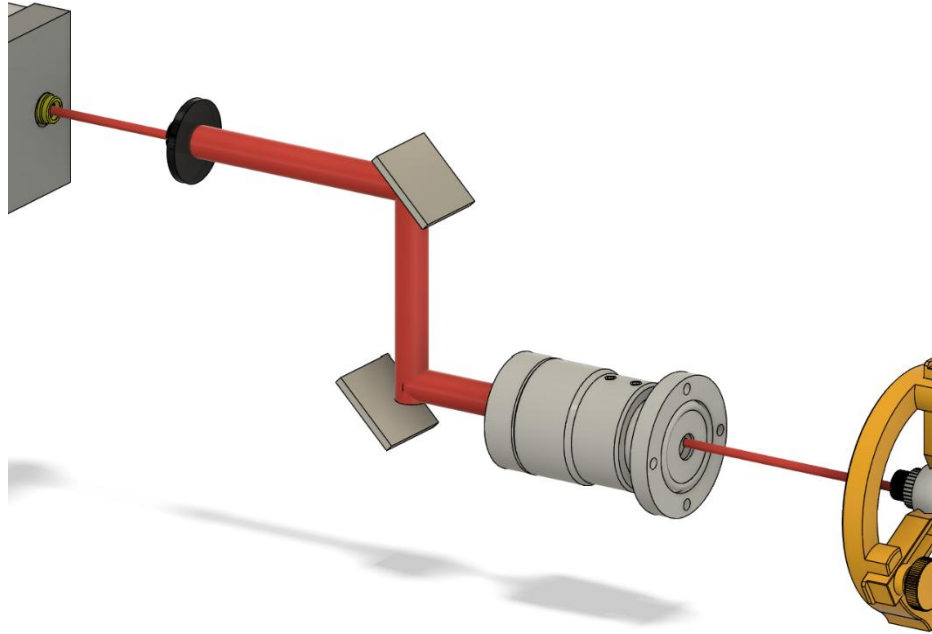


**Figure 6.18:** Lens and mirror apertures

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.

# 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.

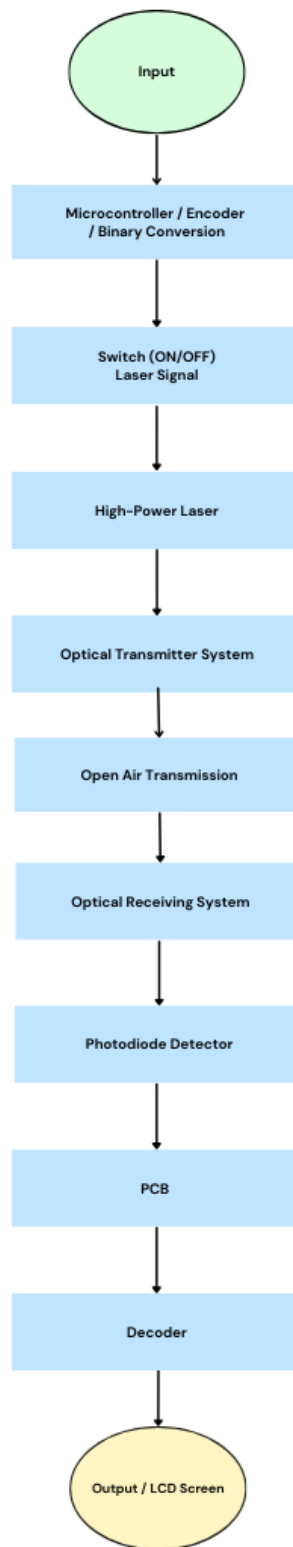


**Figure 7.1:** Software Flowchart

## 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 the 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<br>01101111 00100000 01010111 01101111<br>01110010 01101100 01100100                                        |
| Senior Design I | 01010011 01100101 01101110 01101001<br>01101111 01110010 00100000 01000100<br>01100101 01110011 01101001 01100111<br>01101110 00100000 00110001 |
| 3221ABC         | 00110011 00110010 00110001 01000001<br>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 results 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 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.

## 7.5 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.

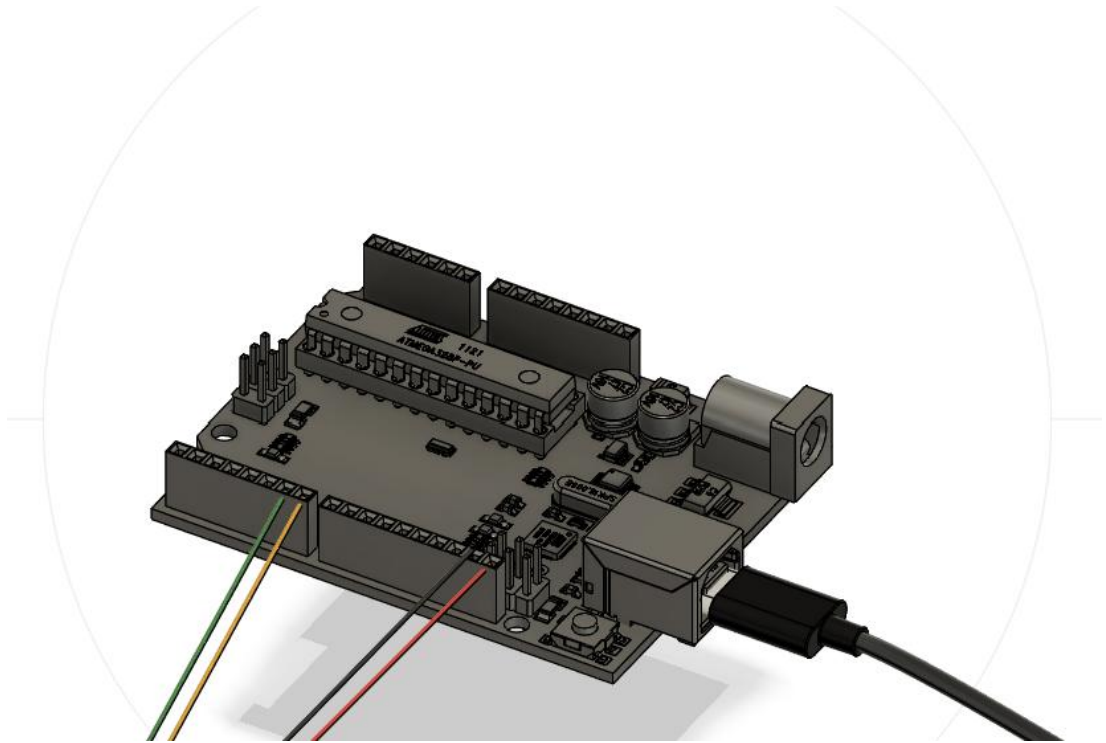


**Figure 7.2:** Microcontroller

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.

## 7.5 LCD Display Output

After processing the binary data, the microcontroller sends it to an LCD (Liquid Crystal Display) 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.

# Chapter 9: System Testing and Evaluation

## 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.

For this project, PIN photodiodes were selected due to their low noise characteristics, high-speed response, and stable performance in optical communication systems. Compared to 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.

### **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. This arrangement prevents high voltages from affecting the receiving circuit, therefore isolating the two circuits. This project will not use opto-isolators mainly because it will not utilize high voltages.

### **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.

## **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.

## **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 received optical signal 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.

## **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.

### **Zemax Simulations for Optical Component Modeling**

Zemax was used to model light propagation through optical components (such as the microscope objective 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.

### **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.

## 9.5 Equations and Calculations

### Beam Divergence

The divergence angle  $\theta$  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),
- $\lambda = 532 \text{ nm}$
- $w_0 = 1 \text{ mm}$  (initial beam waist).

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

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

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

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

$$D = 2w_0 + 2L * \theta_{final} = 2 * 1 \text{ mm} + 2 * 1000 * 0.0186 \text{ mrad}$$

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

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  $f_t = 50 \text{ mm}$

- **Receiving lens** (focusing): focal length  $f_r = 100\text{mm}$

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  $L=1\text{km}$  is modeled as:

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

Where:

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

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

This 4.6% loss is acceptable for short-range line-of-sight communication in clear weather. However, in fog,  $\alpha$  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  $\pm 0.2$  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  $R_L=50 \Omega$ , and a bandwidth  $B=1 \text{ GHz}$

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

Where:

- $k=1.38 \times 10^{-23} \text{ J/K}$
- $T=300 \text{ K}$
- $B=1 \text{ GHz} = 1 \times 10^9 \text{ Hz}$

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

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

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{7.78 * 10^{-5}}{4.14 * 10^{-12}} = 1.88 * 10^7$$

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

## 9.5 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 9.1:** 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 $\mu$ W  |
| 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  $\mu$ W, which was within 1% of the theoretical estimate of 78.5  $\mu$ W. 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  $10^{-9}$  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  $10^{-6}$  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.

## **9.7 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.

## 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 website (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 website (4/4/25)          |
| 13                            | Begin on working on PCB                                                   |
| 14                            | Continuing 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 I - Spring 2025 |                                                    |
|-------------------------------|----------------------------------------------------|
| Week                          | Task                                               |
| 1-2                           | Order PCB, Order Components                        |
| 3                             | PCB Assembly                                       |
| 4-5                           | Begin to research ways to put everything together. |
| 6-8                           | Start Assembly                                     |
| 7-8                           | Test Prototype                                     |
| 9                             | Test for any malfunctions or potential mistakes.   |
| 10                            | Implement solutions for those potential mistakes.  |
| 11                            | Test/Optimize                                      |
| 12                            | Demonstrate 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 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<br>(if applicable)                                                                                                                                                                                                                                                                                                                                      |
|-------------------|---------|-----------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Button switch     | \$6.95  | 1<br>(big pack) | 14 types, pack of 140        | <a href="https://www.mpja.com/14-Types-140-pcs-Micro-Pushbutton-Switch/productinfo/33908+SW/">https://www.mpja.com/14-Types-140-pcs-Micro-Pushbutton-Switch/productinfo/33908+SW/</a>                                                                                                                                                                               |
| Laser diode       | \$15.69 | 2               | Model:<br>520nm Laser Module | <a href="https://www.amazon.com/520nm-Laser-Module-Industrial-adjustable/dp/B0CSYSVPS9?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;psc=1&amp;smid=A1708U969TLM8D&amp;gQT=1">https://www.amazon.com/520nm-Laser-Module-Industrial-adjustable/dp/B0CSYSVPS9?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;psc=1&amp;smid=A1708U969TLM8D&amp;gQT=1</a> |
| Photodiode        | \$8.05  | 5               | Model:<br>MTD5052W           | <a href="https://www.digikey.com/en/products/detail/marktech-optoelectronics/MTD5052W/2798875">https://www.digikey.com/en/products/detail/marktech-optoelectronics/MTD5052W/2798875</a>                                                                                                                                                                             |
| Fiber optic cable | \$21.60 | 1               | Single Mode                  | <a href="https://www.amazon.com/VANDESAIL-Singlemode-Single-Optical-Transceiver-1m/dp/B0DDPDXGZS?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;sm">https://www.amazon.com/VANDESAIL-Singlemode-Single-Optical-Transceiver-1m/dp/B0DDPDXGZS?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;sm</a>                                                       |

|                                                        |         |   |                                              |                                                                                                                                                                                                                                                                                                                                                                         |
|--------------------------------------------------------|---------|---|----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                        |         |   |                                              | <a href="#">id=A2C3RI8VTVPBOW&amp;gQT=1&amp;th=1</a>                                                                                                                                                                                                                                                                                                                    |
| LCD screen                                             | \$26.60 | 2 | Compatible w/<br>Arduino and<br>Raspberry Pi | <a href="https://www.amazon.com/gp/product/B01GPUMP9C/ref=ox_sc_act_image_1?smid=ADHH624DX2Q66&amp;th=1">https://www.amazon.com/gp/product/B01GPUMP9C/ref=ox_sc_act_image_1?smid=ADHH624DX2Q66&amp;th=1</a>                                                                                                                                                             |
| Op-amp                                                 | \$0.27  | 5 | Model:<br>LM358AP                            | <a href="https://www.mouser.com/ProductDetail/Texas-Instruments/LM358AP?qs=Zu35EjizYSShld7Gr9Muww%3D%3D&amp;mgh=1&amp;gQT=2">https://www.mouser.com/ProductDetail/Texas-Instruments/LM358AP?qs=Zu35EjizYSShld7Gr9Muww%3D%3D&amp;mgh=1&amp;gQT=2</a>                                                                                                                     |
| VCO                                                    | \$7.66  | 3 | Model:<br>SN74S124NE4                        | <a href="https://www.mouser.com/ProductDetail/Texas-Instruments/SN74S124NE4?qs=gb35HGp1gQIQA4UksLxehA%3D%3D&amp;mgh=1&amp;gQT=1">https://www.mouser.com/ProductDetail/Texas-Instruments/SN74S124NE4?qs=gb35HGp1gQIQA4UksLxehA%3D%3D&amp;mgh=1&amp;gQT=1</a>                                                                                                             |
| Radio<br>transmitter<br><br>+<br><br>Radio<br>receiver | \$8.95  | 2 | for Arduino<br><br>&<br><br>Raspberry Pi     | <a href="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">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</a> |

|                          |         |                 |                             |                                                                                                                                                                                                                                                                                                                                                                                               |
|--------------------------|---------|-----------------|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                          |         |                 |                             |                                                                                                                                                                                                                                                                                                                                                                                               |
| PCB                      | \$5     | 3               | 9 by 7 cm<br>+\$20 shipping | <a href="https://www.pcbway.com/">https://www.pcbway.com/</a><br><a href="https://jlcpcb.com/">https://jlcpcb.com/</a>                                                                                                                                                                                                                                                                        |
| Resistors/<br>Capacitors | N/A     | Already<br>have | Various types               | N/A                                                                                                                                                                                                                                                                                                                                                                                           |
| Power<br>source          | \$16.98 | 2               | battery Pack                | <a href="https://www.amazon.com/Rechargeable-Batteries-Electronics-Equipment-Bluetooth/dp/B0B1JKSY46?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;psc=1&amp;smid=AXR0N95R0RRTF&amp;gQT=1">https://www.amazon.com/Rechargeable-Batteries-Electronics-Equipment-Bluetooth/dp/B0B1JKSY46?source=ps-sl-shoppingads-lpcontext&amp;ref=fplfs&amp;psc=1&amp;smid=AXR0N95R0RRTF&amp;gQT=1</a> |



Photonics  
Components



Computational  
Components



Electrical  
Components

## Chapter 11 Conclusion

# 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:*

```
python
import numpy as np
import matplotlib.pyplot as plt

# Generate a signal
fs = 1000
t = np.arange(0, 1, 1/fs)
signal = np.sin(2 * np.pi * 50 * t) + np.sin(2 * np.pi * 120 * t)

# Compute FFT
fft_output = np.fft.fft(signal)
frequencies = np.fft.fftfreq(len(signal), d=1/fs)

# Plot the spectrum
plt.plot(frequencies, np.abs(fft_output))
plt.show()
```

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.

## Appendix B – copyright permission

## Appendix C – data sheet (if necessary)

- Analog Devices, ADA4530-1 Femtoampere Low-Noise Op Amp, Datasheet, Available: <https://www.analog.com/media/en/technical-documentation/data-sheets/ADA4530-1.pdf>.
- Diodes Incorporated, AP3015A Step-Up DC/DC Converter, Datasheet, Available: <https://www.digikey.com/htmldatasheets/production/1364556/0/0/1/ap3015ktr-g1.html>.
- Eagle Plastic Devices, 12BH322-GR AA Battery Holder, Datasheet, Available: <https://www.mouser.com/datasheet/2/209/EPD-200612-1171453.pdf>.
- Keystone Electronics, 2462 AA Battery Holder, Datasheet, Available: <https://www.keyelco.com/userAssets/file/M65p28.pdf>.
- Linx Technologies, BH322-1 AA Battery Holder, Datasheet, Available: <https://www.farnell.com/datasheets/3747238.pdf>.
- Memory Protection Devices, BC2AA-PC AA Battery Holder, Datasheet, Available: <https://www.memoryprotectiondevices.com/datasheets/BC2AAPC/BC2AAPC-datasheet.pdf>.
- Microchip Technology, MCP602 Low-Power Op Amp, Datasheet, Available: <https://ww1.microchip.com/downloads/en/DeviceDoc/21314g.pdf>.
- STMicroelectronics, STM32L031K6 Ultra-low-power ARM Cortex-M0+ MCU, Datasheet, Available: <https://www.st.com/resource/en/datasheet/stm32l031k6.pdf>.
- Texas Instruments, LMP7721 Ultra-Low Input Bias Current Op Amp, Datasheet, Available: <https://www.ti.com/product/LMP7721>.
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- Texas Instruments, TLV61070A High-Efficiency Boost Converter, Datasheet, Available: <https://www.ti.com/lit/ds/symlink/tlv61070a.pdf>.
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## Appendix D – software code (if necessary)

## Appendix F – References

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- <https://www.edmundoptics.com/knowledge-center/application-notes/optics/optical-filters/>

- <https://www.findlight.net/blog/optical-apertures/>
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