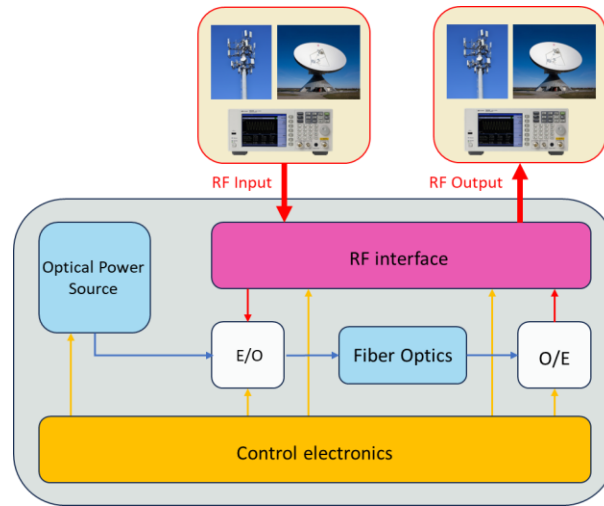# UCF Senior Design II

Switchable RF over Fiber for Low-Cost Operation of Many RF Inputs

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1. Executive Summary

RF over fiber has become a widespread and mature technology for the transmission of RF signals. Rather than traditional metal coaxial cables that send electrical RF signals, an RF over fiber system encodes the RF signal in the intensity of light traveling through a fiber optic. This has benefits in improving the bandwidth of an RF system and has orders of magnitude less losses, especially at high frequencies.

In a typical RF over fiber system, there are several necessary subsystems to receive, transmit, and detect a signal. This includes an antenna to receive the signal, RF components such as filters and amplifiers to process the signal, a laser to act as the carrier, a modulator to encode the RF signal in the intensity of light, a fiber optic to carry the light, and a photodiode to recover the signal from the light intensity.

In traditional RF over fiber setups, if you wish to send data from several antennas you will require dedicated laser sources and photodiodes for each of these antennas. For cases in which the full capacity of the link is not used by each antenna, or if only a subset of the antennas are used at once, this is an inherently inefficient design. To remedy this problem, we designed a system in which fiber optic switches and a wavelength division multiplexing (WDM) system. This system allows for real-time switching of the RF source being transmitted to any of the photodiodes. In addition, this switching is nonblocking, meaning a single antenna can have its RF signal sent to multiple receivers.

This unique capability can be used to construct an asymmetrical system in which there are more RF sources (antennas) than there are receivers (photodiodes). In this project, we demonstrate a system with three RF sources and two antennas to show a proof of concept of this asymmetrical switch-based architecture. These three antennas will operate at three different frequency ranges. Thus, we can cover three different frequency ranges with only two photodiodes. While this proof-of-concept system only adds one additional antenna, we provide analysis to show that this concept is scalable to larger numbers of antennas.

This technique provides distinct advantages over using a single wideband antenna. This is because a larger bandwidth comes with sacrifices in other qualities of an antenna, including sensitivity and noise figures. For this reason, our design provides a unique solution to covering a large range of RF frequencies while providing high quality RF detection and transmission while minimizing the amount of expensive optical hardware needed.

To develop this project, we must design, build, and integrate several subsystems of the device. First is an RF subsystem that receives the signals and then filters and amplifies them. Next, we require a laser diode system to generate the carrier

light as well as optical modulation which will be performed by a Mach-Zehnder interferometer. The switching will be performed by a system of 1x2 fiber optic switches which are electrically controlled to switch an input fiber to either of two output fibers. A diffraction grating is then used to combine the various wavelengths of light, which are then coupled into a single fiber for transmission. At the receiver end, we again used a diffraction grating for demultiplexing and then photodiodes to recover the RF signal from the light intensity. Along with this hardware we require a software system to enable control over the switching mechanism, allowing the user to easily choose which antennas are active.

In this document we detail the design of these hardware and software subsystems. Additionally, we explain how each of these subsystems will be integrated to form a fully functioning proof of concept for the project. This is followed by extensive testing at the components, subsystem, and system level to give a full understanding of the performance achieved.

2. Project Description

2.1 Project Background

Receivers, in communications, are electronic devices that receive an electromagnetic signal and process it to obtain the information contained in it. For RF signals these waves have a frequency that can range from 3KHz up to 30 GHz according to the U.S FCC when it comes to electromagnetic waves used to transmit information, which are also generated by different electronic systems called transmitters.[1]

Radio receivers work by using a series of electronic circuits to amplify, filter, and demodulate the RF signal for the extraction of information. Radio frequency systems are essential to many aspects of modern society because they are used in a wide variety of applications such as radio broadcasting, television broadcasting, satellite communications, cellular phone networks, and wireless computer networks. Modern civilization relies on these systems to enable the possibility of information exchange, commerce, organization, and education.

A Radio over Fiber (RoF) system is a sophisticated communication technology that seamlessly integrates two fundamental domains of communication: radio frequency (RF) and fiber optics. It serves as a bridge between these two realms, allowing RF signals, typically used for wireless communication, to be converted into optical signals and transmitted over optical fibers. At the receiving end, the optical signals are converted back into RF signals. This transformation from RF to optical and back again enables high-speed, long-distance communication with minimal signal degradation. Key components of a RoF system include RF transmitters and receivers, optical modulators and demodulators, optical fibers for signal transmission, antennas for wireless connectivity (in some applications), and

signal processing units. These components work together to ensure efficient signal conversion, transmission, and reception. RoF systems find applications in various domains, including telecommunications, military and defense, 5G wireless networks, satellite ground stations, and Internet of Things (IoT) connectivity. They are particularly valuable for scenarios that require high-speed, low-latency, and reliable communication over extended distances. The advantage of RoF systems lies in their ability to combine the strengths of RF and optical communication technologies, offering robust and flexible solutions for a wide range of communication needs. Additionally, RoF systems are known for their impedance-matching benefits, which simplify system setup and enhance reliability compared to traditional RF systems.

The transmission of RF signals is of vital importance to a wide variety of industries. RF signals form the backbone of commercial communications infrastructure including radio, television, cellular networks, Wi-Fi, and satellite communications. Additionally, RF signals find use in military applications including communications as well as radar, electronic warfare, and guidance and navigation systems. Historically, RF signals have been limited to the domain of free-space communication links or coaxial cables. However, both methods of transmission suffer from high losses and electromagnetic interference which can quickly degrade the signal quality in many scenarios. In addition, these types of communication links are susceptible to eavesdropping attacks resulting in insecure communications, which is detrimental when dealing with sensitive data. Free space transmission of RF signals is also susceptible to electronic warfare attacks that can interrupt communications.

To solve this issue RF over fiber systems instead use a fiber optic cable to establish an RF over fiber system. Because RF signals can't directly propagate in a fiber optic cable, we must use optical frequencies as a carrier. For this light source, we have used an array of laser diodes. To encode the RF signal, the intensity of the laser diode is modulated. By doing so, we can encode the RF signal as the intensity of the light as a function of time. This modulated beam can then be coupled into a fiber optic cable and transmitted through the fiber. Using the fiber optic as a medium has the advantage of extremely low losses, with telecommunications-grade fiber optic cables reaching losses as low as 0.2 dB/km. This is a large improvement over coaxial cable, which at RF frequencies can exceed several dB/100ft.[2] Additionally, the use of optical carrier signals allows for optical multiplexing techniques to be used, which can greatly increase the data throughput of the communications system. We have made use of wavelength division multiplexing as it allows for large numbers of channels to be used. Because of these advantages, RF over fiber has become a widespread solution to long-haul RF signal transmission.

2.2 Project Motivation

The main unique aspect of this project is the asymmetrical design with regard to the number of transmitters and receivers, which is enabled by a switching mechanism that is integrated into the multiplexing. In an RF system, there is a limited range of frequencies that can be received and transmitted. This is known as the bandwidth, and it is limited by the bandwidth of the individual components such as filters, antennas, or amplifiers. To achieve a wide bandwidth, sacrifices on quality must be made on other parameters, making it difficult to design a system that can handle frequencies across the entire RF range of frequencies. To resolve this problem, we have made use of several RF chains consisting of an antenna or other source along with the associated filters and amplifiers. We have a number of WDM channels, each with a specific photodiode they are linked to. There will be three RF chains, but only two WDM channels. This allows us to demonstrate the unique capabilities of our system to have more RF bands than there are photodiodes. The system can then switch these outputs (photodiode and associated WDM channel) to any of the inputs (RF subsystem at associated RF band). The motivation for this capability is situations in which a system needs to have the ability to receive signals from a wide range of frequencies but does not need to be able to receive all of the bands simultaneously.

This project is a corporate sponsorship by Critical Frequency Design (CFD), whose expertise in photonic communications aligns well with the project topic. The personal motivation behind undertaking a RoF (Radio-over-Fiber) system as a senior design project stems from the diverse career interests of our team members and the exciting platform it offers for interdisciplinary collaboration. Comprising both photonic, microwave, and computer engineering students, our team possesses a unique blend of skills in fiber optics, lasers, optoelectronics, antennas, communication engineering, embedded systems, digital signal processing, and programming. By delving into the development of a RoF system, we aim to utilize this diverse skill set and gain a comprehensive understanding of cutting-edge optical communication technology, engineering design, and systems engineering.

2.3 Project Goals

2.3.1 Basic Goals

1. Generate RF signals using a function generator
2. Integrate low-noise RF amplifiers
3. Design an optical modulation system using a Mach-Zender modulator to encode the RF signal into the optical carrier
4. Have a system bandwidth supporting RF frequencies up to 433 MHz
5. Have a low bit error rate to enable essentially error-free communication
6. Increase data throughput with wavelength division multiplexing (WDM)
7. Use basic encryption using ASCII value scrambling or matrix methods
8. Design and manufacture a bandpass filter for 433 MHz
9. Design 3x2 non-blocking optical switching system

10. Implement simple modulation schemes such as on off keying (OOK)

2.3.2 Advanced Goals

1. Increase system bandwidth to 2.4 GHz
2. Use more advanced encryption using existing Python libraries
3. Integrate the RF photonic link with a software-defined radio interface to provide programmable and flexible modulation and demodulation options
4. Improve the signal-to-noise ratio in order to use higher-order modulation schemes
5. Implement more advanced modulation schemes such as QPSK and QAM

2.3.3 Stretch Goals

1. Increase system bandwidth beyond detector bandwidth with heterodyne detection
2. Extend the frequency range up to 12.6 GHz
3. Integrate phased-array antennas to enable beamforming and adaptive beam steering for enhanced communication performance and coverage.
4. Incorporate RF or optical circulators to allow the communication link to be full or half duplex

2.2 Project Objectives

1. Design/align a diffraction grating-based wavelength division multiplexing system
2. Design a 3x2 optical switching mechanism based on 1x2 fiber-optic-based switches
3. Design/align a laser diode system to generate and efficiently couple light from the laser diodes to the switches
4. Design/align a photodiode system capable of measuring frequencies up to the system bandwidth
5. Use an optical modulator to modulate the intensity of light to carry an RF signal
6. Run tests to measure the bit error rate
7. Run tests to measure data throughput
8. Run tests to measure system bandwidth
9. Study existing encryption algorithms and supporting libraries in Python or Matlab
10. Obtain access to a lab with spectrum analyzers, VNAs, signal generators, and power sensors to test and troubleshoot RF amplifiers, transmitters, and receivers.
11. Perform a link budget analysis to ensure that the transmitted RF signals can be adequately detected at the receiving end
12. Simulate the RF photonic system in Simulink or LabView to analyze the system's behavior

13. Choose an appropriate bandpass filter topology (e.g., Chebyshev, Butterworth) based on the project requirements, and consider factors like roll-off rate and passband ripple.
14. Perform S-parameter analysis to evaluate the filter's insertion loss, return loss, and bandwidth, ensuring compliance with the project's performance requirements.
15. Optimize the impedance matching at the input and output ports of the bandpass filters and amplifiers to minimize reflections and maximize power transfer.

2.5 Requirements Specification:

Components	Specification	Values
Photodiode, Mach-Zehnder modulator, and RF filters	System Signal Bandwidth	30 MHz to 5 GHz
Mach-Zehnder modulator and fiber optic	Data Transfer Rate	1 GB/s
Link budget across all components	Signal-to-Noise Ratio (SNR)	25 dB
RF filters and amplifiers	Spurious-Free Dynamic Range	60 dB
Fiber optic	Transmission Distance	2 km
Entire system	Bit Error Rate (BER)	$< 10^{-3}$
Laser diodes	Wavelength Channel Spacing	20 nm
Laser diodes	Optical Power Output	15 mW
Entire system	Total System Power Consumption	<50 W
1x2 Fiber Switch	Switching Time	<25 ms
Laser diodes	Number of WDM Channels	2
Diffraction Grating	WDM Free Spectral Range	750 nm
Fiber collimating/focusing lenses	Fiber coupling losses	<1.5 dB @ 30 cm separation

Photodiode	Optical bandwidth	1530-1625 nm (C+L bands)
Collimating lens	Collimated Beam Size	< 3 mm
Collimating lens	Coupling losses	< 1.5 dB
Multiplexing system	Size	10x10x10 cm
Entire System	Total system cost	< $15,000

Table 1: Overall System Specifications

2.6 House of Quality Analysis:

	Polarity	RF Signal Bandwidth	Data Transfer Rate	Signal to Noise Ratio	Spurious-Free Dynamic Range	Transmission Distance	Bit Error Rate	Wavelength Channel Spacing	Optical Power Output	Total System Power Consumption
Polarity		+	+	+	+	+	-	O	O	-
Cost	-	-	--	--	-	-	-	-	-	O
Power Consumption	-	O	O	-	O	O	O	O	-	++
Data Throughput	+	++	++	++	+	-	+	O	+	O
Scalability	+	O	O	O	O	O	O	++	-	O
Transmission Distance	+	--	-	-	O	++	-	O	++	+
Switching Time	-	O	O	O	O	O	O	O	O	O
Project Specifications:		300 MHz -5 GHz	1GB/s	- 25dB	60 dB	2 km	10^{-3}	20 nm	5 mW	<50 W

Figure 1: House of Quality Diagram

2.7 Project Block Diagrams:

The process begins with the generation of an RF signal, typically in the microwave frequency range. This signal carries voice, data, or video information and originates from sources like cell phones, Wi-Fi routers, or radar systems. Before transmission, the RF signal will undergo conditioning processes such as amplification, filtering, and modulation. These operations prepare the RF signal for conversion into an optical signal. The conditioned RF signal is then fed into an optical modulator. Optical modulators are devices that convert electrical signals (RF) into optical signals (light). In our system, this modulation will be performed by a Mach-Zehnder modulator which varies the intensity of transmitted light to encode the RF signal in the intensity of the beam. The modulated optical signal is now transmitted through optical fibers. These fibers serve as the transmission medium, guiding the optical signal over long distances with minimal signal loss. The use of optical fibers is a hallmark of RoF systems, as they provide low attenuation and high bandwidth. Upon reaching the receiving end, the optical signal is directed into an optical demodulator. Like the optical modulator, the optical demodulator is often an electro-optic device. It reverses the process by converting the optical signal back into an electrical RF signal. In our system we have utilized a high bandwidth photodiode to convert the light intensity back to an electrical signal. The original RF signal, which may have undergone conditioning earlier, is now effectively reconstructed. The reconstructed RF signal may undergo further signal processing, including amplification, filtering, or demodulation (if it was initially modulated) to recover the original information. The final RF signal, now reconstructed and processed, is ready for utilization. Depending on the specific application, it may be fed into various devices or systems such as cell phones, base stations, radar systems, or data centers.
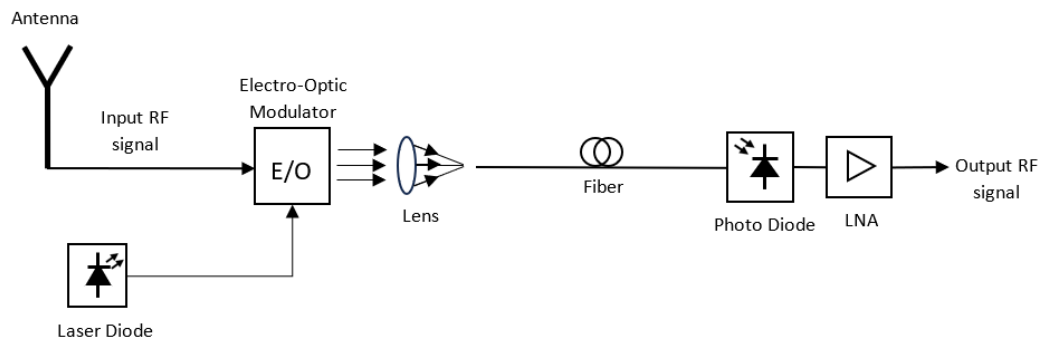
Figure 2: The general architecture of an RF over fiber link

We intend to incorporate wavelength division multiplexing (WDM) into our system in order to allow multiple channels to be carried over a single fiber optic cable. WDM operates by combining multiple optical signals with varying wavelengths using prisms or diffraction gratings and then transmitting them over a single optical fiber.

Each wavelength serves as an independent channel for data transmission, enabling multiple data streams to coexist with minimal crosstalk. At the receiver end is a demultiplexer which performs the reverse function of the multiplexer, using a diffraction grating to separate the component WDM channels to separate photodiodes. Thus, each WDM channel will be linked to a certain photodiode. We have also introduced an optical switching subsystem which will allow for any of the WDM channels to be directed to any of the modulators in the system. As each modulator is linked to a given receiver antenna, this optical switching will enable us to choose which antenna's signal is sent over which WDM channel. And since we have already seen that each WDM channel is tied to a certain photodiode, we are effectively connecting any antenna to any photodiode.

The chosen architecture for the RF receiver is the widely recognized and extensively documented superheterodyne receiver. This decision stems from its prevalence in the field, ensuring that engineers have access to a wealth of documentation and research material. The initial stage of this system is the antenna, a pivotal component that will be meticulously tailored to harmonize with the operating frequency of the system and align with its current objectives.

If we opt to pursue the stretch goals, it's worth noting that every component within this schematic will necessitate modification to align with the desired operating frequency. This, in turn, will prompt the design and construction of a new system configuration that is aptly calibrated. Despite these adjustments, the underlying architecture itself can remain consistent across varying frequencies. This inherent flexibility stands as a notable advantage of this system, affording us the adaptability needed to meet our specific requirements while preserving the integrity of the overall architecture. This adaptability is poised to be a key asset as we navigate through the evolving demands of the project.
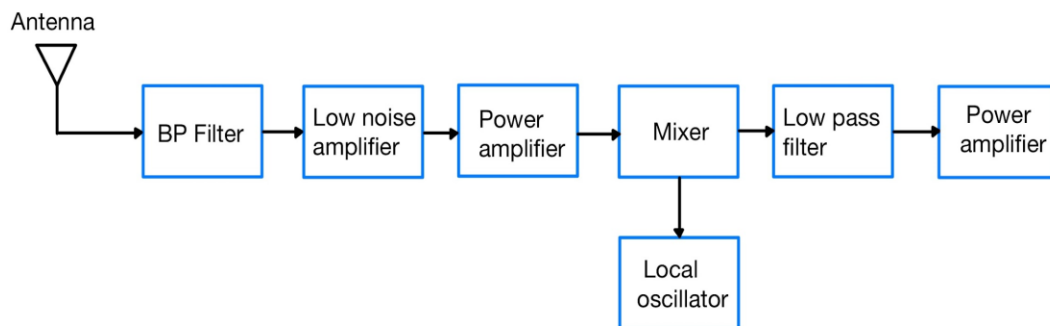
Figure 3: RF Front end architecture

Following the antenna, we encounter the crucial bandpass filter, an indispensable component tasked with isolating the signal of interest from neighboring and undesired frequencies. It's worth noting that while passive bandpass filters are

effective in this regard, they introduce a caveat of signal attenuation, necessitating subsequent amplification stages for accurate processing.

Given the attenuation incurred through path loss and the bandpass filter, amplification becomes imperative. However, this amplification process must be executed judiciously, as a critical metric to monitor is the system's noise level. Amplifiers have the potential to exacerbate the noise, thereby compromising signal integrity.

To mitigate this, the architecture incorporates a low noise amplifier immediately after the filter. This component serves to amplify the signal while keeping noise generation to a minimum. Subsequently, a power amplifier is deployed to further bolster the signal before it undergoes mixing. It's important to note that there exists some flexibility in the implementation of power amplifiers.

As depicted in the diagram, power amplifiers can be positioned after the low noise amplifier and following the low pass filter. However, their inclusion may be optional contingent on the signal integrity. In cases where the signal's integrity is sufficiently high for seamless processing, unnecessary amplification could be circumvented, potentially necessitating signal attenuation instead. This thoughtful consideration and adaptability in the amplifier implementation are key aspects of our design approach, ensuring that each stage is optimized for performance without compromising signal fidelity.

To illustrate the optional architecture where power amplifiers are not needed, see the diagram below.
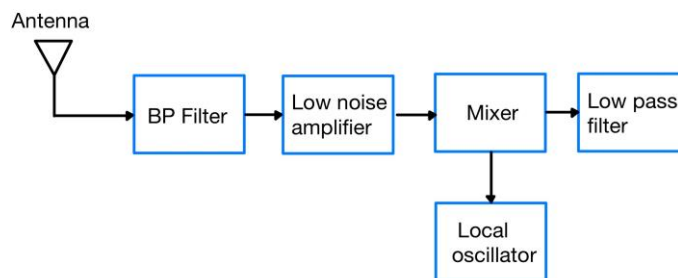
Figure 4: RF Front end alternative architecture

The following segment of the power amplifier is the mixer. The purpose of this component is to multiply the signal with another signal whose frequency is close to the center frequency. The purpose of doing this is to obtain more signals with their center frequency at the difference and sum of the signals' frequency. However, we are obtaining other frequencies besides the one we want, and to solve this problem, a low pass filter is implemented as a subsequent stage after the mixer to filter out the higher frequency signal.

This is known as the inter-modulation frequency, which is downconverted for it to be processed by a digital signal processor. The down conversion is necessary because of the sampling rate used for the digitization process. This sampling rate has to be at least double the frequency of the signal, and for digital signal processors, that is not easy to achieve. However, with a good design whe could be able to generate a signal with a local oscillator close enough to the received signal so that when the signal is received and multiplied by the local signal, an intermediate frequency signal will have the difference of frequencies resulting in this way a very low frequency signal suitable for sampling with a microcontroller.

As shown below, there are two methods for the modulation of the laser beam to carry the RF signal: either direct modulation of the current through the laser or an independent optical modulator. Due to the high bandwidth requirements of our system, we have used the option of an external Mach-Zehnder modulator rather than direct modulation of the laser.
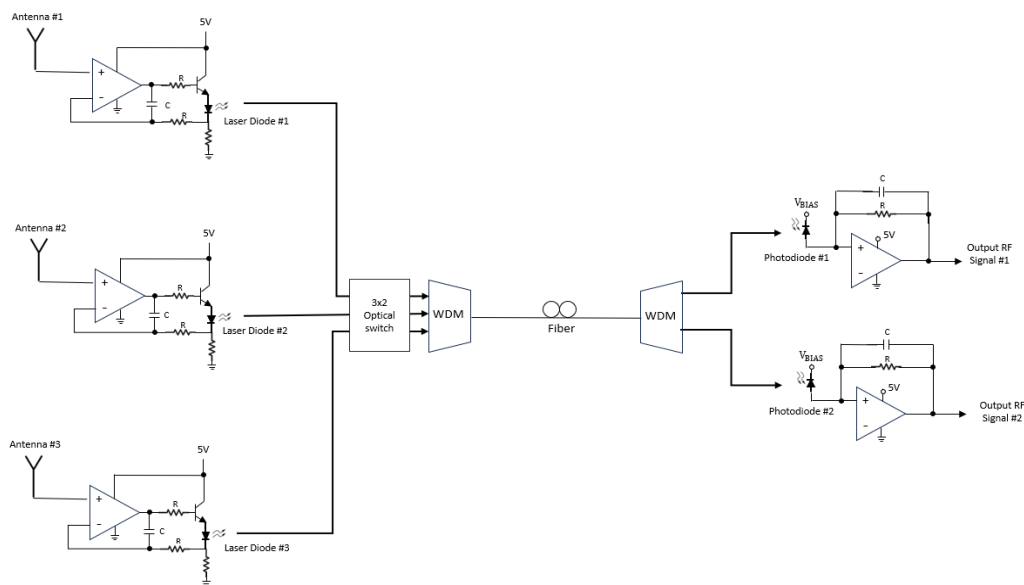
Figure 5: A possible realization of an RF over fiber link using direct modulation between the RF signal and the laser diodes
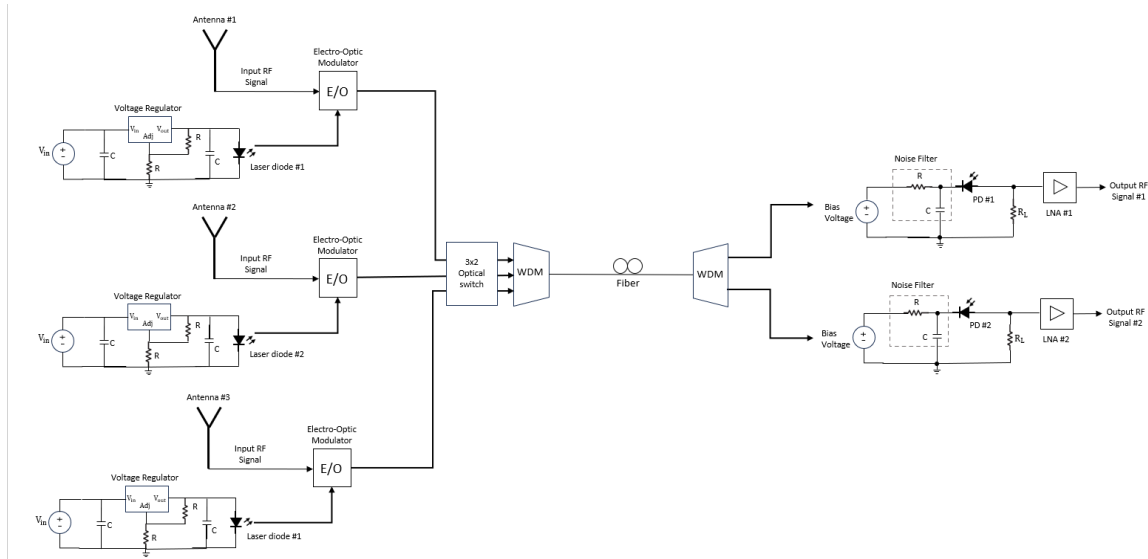
Figure 6: Alternative realization of an RF over fiber system using external modulation using an electro-optic modulator between the RF signal and the laser diode

Here we show all of the hardware that will be used to realize the architecture in Figure 7.

2.7.2 Hardware Block Diagram

Below is the block diagram demonstrating the major subsystems of the project as well as the primary responsible group member for each and the status of the design process. In addition to the basic RoF system described previously with the WDM and switching systems, we have integrated an MCU to encrypt and decrypt signals as well as have a GUI to allow for easy control of the optical switching and encryption.
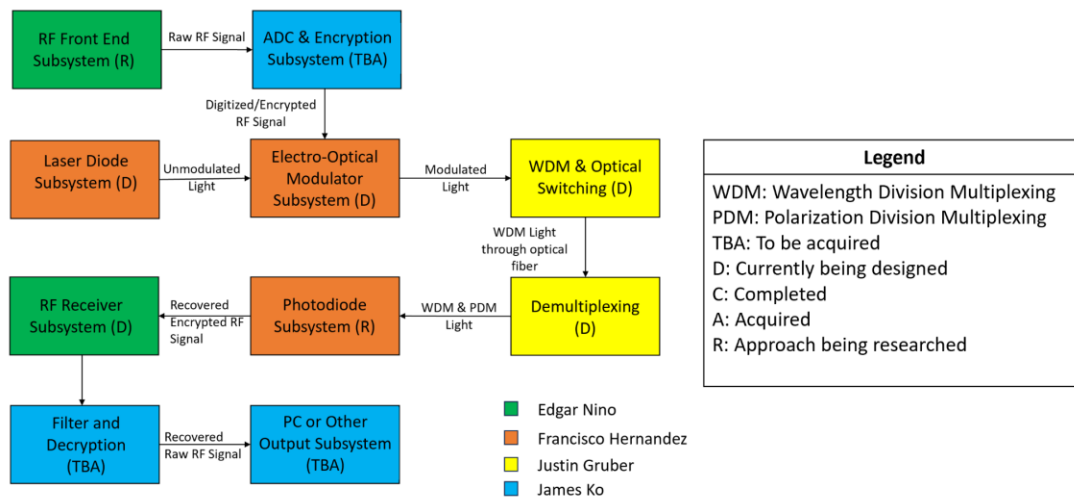
Figure 7: Divide & Conquer Hardware Block Diagram

2.7.3 Software Block Diagram

The software flowchart below shows the basic logic and organization of the software for the system that controls the switching and power saving. It starts with the system being turned on. As one can see in the diagram the solid lines are ones that the user will dictate, while the dotted lines will be automatic and will only be adjusted by a programmer to adjust timing or preferences. Thus the first thing the system will immediately do is switch the power saving mode on. This means that a clock will be set and running to see which lasers are needed. If a laser is needed it will be powered on and looped back to the checker. If the system is not used for a specified amount of time the laser will be turned off to conserve power.

After that, it will loop back to check when the laser is needed again or if another laser needs to be turned off. During this time, the user will modify the system to select which wave frequency it will be receiving and adjust for that. These changes will only be confirmed when the user saves the changes and returns to the main program. After that the user might also need to adjust where the destination for these signals will be directed towards. These will be running off the same microcontroller that will be placed relatively close to the center of the system so that signal delays are minimized and that the switches will react with relatively quick responses when signaled to redirect. Next the signal will be sent to the input end point to where it will be processed. The system will then loop back to the beginning where it will wait for its next signals to be sent. Logistically we should produce minimal errors as the only possible difficulty would be if we have difficulty modifying the signal sent in and it does not modify the signal properly or if it cannot adjust it so that it can be properly processed.

Another issue would be if we decide to encrypt the signal as we would then need to digitize the signal then encrypt that signal. The errors from this is not being able to decrypt the signal at the final location or not being able to digitize the signal clearly and it is unreadable either due to ambient noises or a signal that is fluctuating too much. Overall, this system should work as intended with the pseudocode imagined in Appendix D and E. The challenge will be understanding the microcontroller we choose and understanding the modified C language that is attached to it or if there is another language entirely. The code requires little depth of coding and requires just simple for loops, while loops, and binary checks.
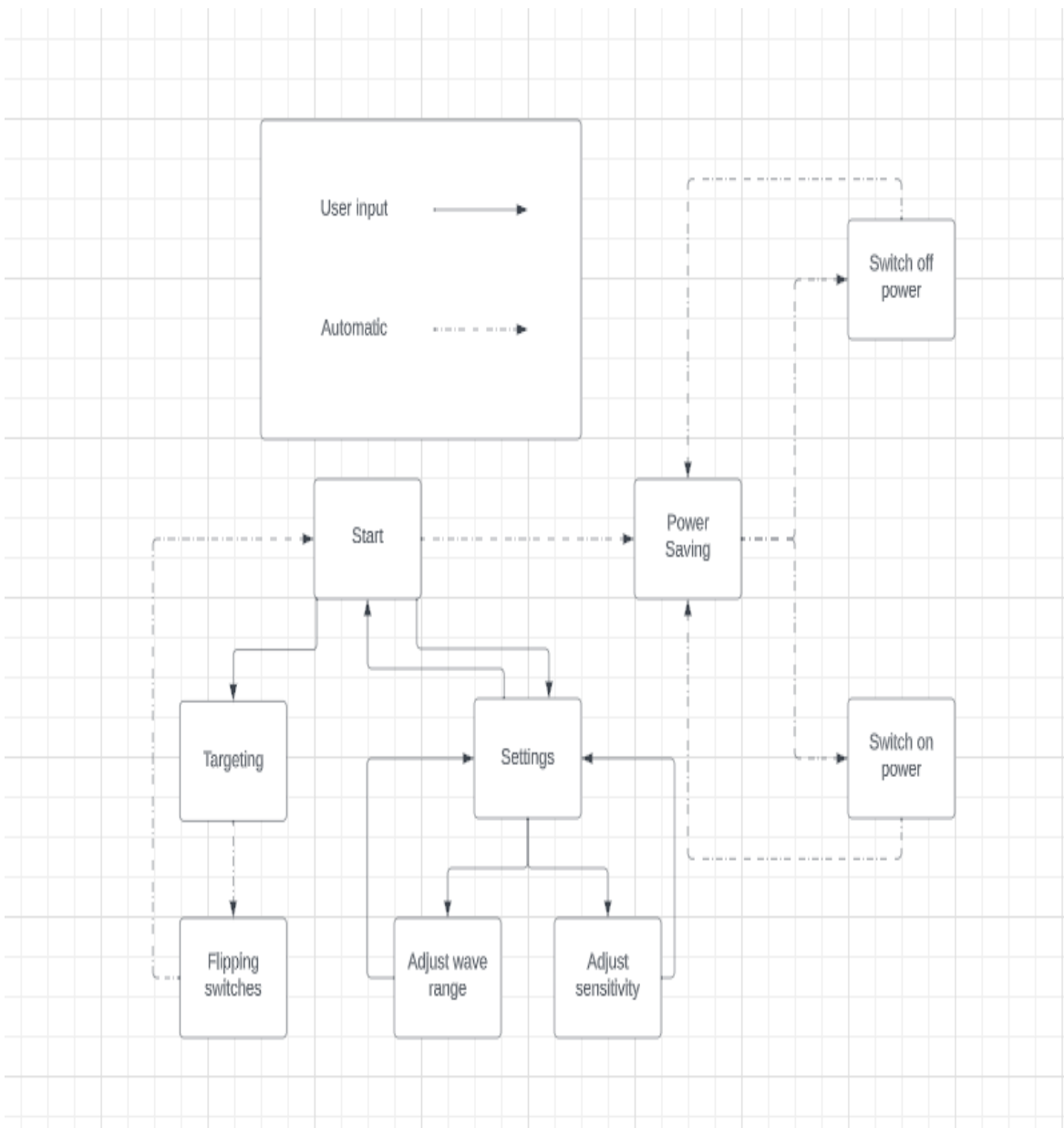
Figure 8: Divide & Conquer Software Block Diagram

3. Technology Investigation and Part Selection

3.1 Existing Projects and Products

3.1.1 Previous CFD Sponsored UCF Senior Design Project

Several companies produce commercial RF over fiber products currently. These companies include Advanced Photonics Integrated Circuits (APIC), Huber Suhner, ViaLite Communications, RFOptic, DEV System Technik GmbH, Emcore, Syntonics, and Foxcom. The available commercial RF over fiber systems span a

larger range of bandwidths, up to 20 GHz produced by APIC.[3] Additionally, several companies offer wavelength division multiplexed systems, including coarse and dense wavelength division multiplexing. As far as the members of this group are aware, a commercially available realization of an RF over fiber system with WDM and optical switching is not currently available. Although such systems have likely been created as custom systems, there are no products advertised publicly at this time.

The sponsor, Critical Frequency Design, has sponsored a senior design project at UCF in the past. This project also dealt with RF over Fiber systems, but the design and goals of the project were significantly different than those proposed for this project. This project was titled "Conceptualizing, Designing, and Building of an Electro-optic Modulator Bias Controller Proof of Concept" and had the goal of creating a Mach Zehnder Modulator with improved performance with a feedback loop based on a photodiode measurement. In contrast, our project is focused on creating an end-to-end RF over fiber communications link. While we have made use of an optical modulator, it is not the focus of our project as it was in the previous project. Instead, we are more focused on increasing the throughput of an entire RF over fiber system using optical multiplexing techniques, and utilizing optical switching to enable an asymmetric system in which there are more antennas than photodiodes.

3.1.2 Optical Zonu EIA 310-D 4-Channel RFoF Link

The Optical Zonu EIA 310-d is a fully integrated RFoF link that has 4 channels that each operate as a full duplex system, meaning they are bidirectional and can send data in either direction. Each of these channels operates using CWDM with 8 WDM channels allowing for a large amount of data to be transmitted. The system has a bandwidth extending from 30 MHz to 3GHz, covering a significant portion of the RF spectrum, but not the high-frequency bands used for satellite communications. There is also the option to extend this bandwidth to 6 GHz, but this will presumably come with an additional cost and will still not cover higher frequency ranges of satellite communications. The entire system is inside a metallic housing that can fit inside a standard 19-inch rack which measures 19x19x1.75 inches. The system is rated to function up to $60^{O}C$, which is high enough for most industry applications but not for many military applications which require high environmental qualification requirements.[4]

3.1.3 Huber Suhner RFoF 1-6 GHz (TX/RX)

Huber Suhner produces a range of RoF systems. The most comparable to our proposed system is the RFoF 1-6 GHz (TX/RX). This product is actually two products, as the transmitter and receiver are sold separately, but for simplicity, we have considered them as a single system in conjunction.[5] This system covers a very similar bandwidth to the previous product by Optical Zonu, with a bandwidth

of 100MHz to 6GHz. We now see a trend that most of the commercial systems available currently reach a maximum frequency of 6 GHz.

3.1.4 ViaLite Communications Rain Fade Diversity Link System

The ViaLite Communications Rain Fade Diversity Link System is a fully complete RoF system designed for a specific use case. This system is designed for use with Ka-band antennas for use in satellite communications. Ka-band signals are strongly attenuated by rain droplets, making the functioning of these antennas highly dependent on local weather conditions. In order to solve this problem, multiple antennas can be installed at a variety of locations. This reduces the risk of not having an antenna available with sufficiently good weather conditions. This then requires the transmission of a large amount of data from the remote antenna, as well as the ability to choose between the two antennas to select the antenna with the best weather conditions. To solve these issues, the system uses DWDM to transmit large amounts of data from the remote antenna, and a 2x2 switch to allow for switching between the local and remote antenna.[6]

This is a fundamentally different solution from the one we have presented. In ViaLite's system, the switching and WDM are independent systems. Each of the antennas uses 96 DWDM channels to transmit Ka-band data with a lower L-band frequency. The switching is then used independently to switch between the two antennas. In our system, the functioning of the switching is dependent on the wavelength of light from a given antenna, and the data is transmitted via a single channel that operates at the original frequency band of the antenna. Additionally, this system is designed to solve this issue of switching between antennas at different locations with the same frequency band, whereas our system is designed to switch between antennas of different frequency bands located at the same geographic location.

3.1.5 Comparison to Existing Products

Product	Bandwidth	Number of Transmitters	Number of Receivers	Switching Time	Optical Power	SNR
Optical Zonu EIA 310-D	30 MHz-6 GHz	4	4	N/A	4 mW	Not available
Huber Suhner RFoF 1-6	30 MHz-12.6 GHz	1	1	N/A	6 mW	Not available

GHz						
Rain Fade Diversity Link System	700 MHz-2.45 GHz	2	1	Not available	5 mW	23 dB
Our System	30 MHz-12.6 GHz	3	2	10ms	5 mW	25 dB

Table 2: Comparison of our system to existing products

3.2 Key components of RoF systems:

The development of a Radio over Fiber (RoF) system requires the integration of several key components. RF transmitters assume the responsibility of generating the initial radio frequency (RF) signals, whereas RF receivers are tasked with capturing and processing these signals at the receiving end.[7] Optionally, electro-optical modulators and demodulators can be incorporated into the system to accomplish the conversion of RF signals into optical signals, enabling transmission over optical fibers. The transmission medium of choice is the single-mode optical fiber, prominent for its attributes of minimal signal attenuation and extensive bandwidth. While antennas remain an optional inclusion, they serve as interfaces with wireless devices, further expanding the system's applicability.

To refine and enhance the quality of RF and optical signals, various components come into play, including MCUs, ADCs, and DACs. These components fulfill diverse roles such as signal filtering and error correction.[8] Critical to the RoF system's operation are laser diodes, pivotal for generating coherent optical signals capable of effectively transmitting modulated RF information over optical fibers. Complementing these are photodetectors, essential for capturing and processing optical signals at the system's receiving end.

For RoF systems operating in conditions with significant signal loss, optical amplifiers may be integrated, particularly erbium-doped fiber amplifiers (EDFAs), to bolster optical signal power and ensure signal integrity throughout transmission. Additionally, in systems employing wavelength division multiplexing (WDM) for channel separation and combination, MUX and DEMUX components equipped with diffraction gratings assume a central role. For the optical switching, we require fiber-based MEMS switches.

Ensuring seamless functionality and control are power supplies and control electronics, facilitating the distribution of power to various facets of the RoF system while managing the operation of lasers, modulators, and other critical constituents.

Moreover, the inclusion of signal sources and test equipment, including spectrum analyzers, oscilloscopes, and optical power meters, becomes indispensable for characterizing signals and facilitating the troubleshooting process. Finally, for RoF systems operating in varied environmental conditions, protective enclosures are a requisite, shielding system components from environmental factors. Additionally, cooling systems may be implemented to dissipate heat generated by specific elements, most notably lasers. The combination of these essential components collectively underpins the construction and operational efficiency of RoF systems, enabling their multifaceted applications in various domains.

3.3 Basic Electrical Hardware

This section will go over all the hardware components needed for this project. Each part will build off of each other as the desired specification of one part will impact the choices of the other parts. The voltage supply will need to generate enough power to empower the whole system and each part will need its own specified power. The filters will need to work with the chosen controllers. Converters will be needed to adjust the power lead to each part. Not only will this section go over the parts, but it will also explain why we have chosen specific parts.

Every choice in this hardware ensemble was made deliberately, considering the specific attributes of each component and its compatibility with the overarching goals of the project. The selected components not only fulfill the functional requirements but also align with principles of efficiency, compatibility, and futureproofing. This meticulous curation ensures a resilient and high-performance hardware foundation for the project, setting the stage for successful implementation and future scalability.

In the realm of RF system receivers, the market has an array of options. Websites like Digikey or Mouser Electronics present a variety of devices, each offering a wide spectrum of functionalities for the electrical front end of a project. There exists a gamut of chips, ranging from those encompassing the full suite of a transceiver's capabilities to specialized receivers, or a hybrid of both. Take, for instance, the CC113LRGPR, an example among these components. This chip can handle a range of different frequency bands while boasting high sensitivity.

This CC113LRGPR has a range of functionalities, supporting FSK modulation and GFSK modulation across various frequencies—315MHz, 433MHz, 868MHz, and 915MHz, to be precise.[9] Its ability to operate across this breadth of frequencies renders it remarkably versatile for non-licensed transmission below the 1GHz threshold. Such versatility marks it as an ideal choice for a senior design project due to its seamless integration into the system. Its SPI connection enables effortless communication with a microcontroller for programming and data reception.

3.3.1 Microcontroller

We have required a centralized microcontroller to facilitate the transmission of these signals to the designated receiver. To achieve an optimal and smooth functioning system, it is imperative that this microcontroller possesses the capability to receive numerous signals from a wide range of antennas. To ensure seamless operations, we must establish a dedicated microcontroller that can efficiently transmit signals to the specified receiver. However, it is crucial to note that this microcontroller must adhere to certain minimum specifications to guarantee its usability. Specifically, we require the microcontroller to be a 32-bit architecture, thereby enabling it to handle complex tasks and processes with enhanced efficiency and performance. Once we have established these basic requirements, we can then meticulously examine the available options to determine the most suitable microcontroller for our specific needs and objectives.

- Clock Speed: The clock speed determines how many inputs/outputs are allowed
- Storage Size: Preferably we get a microcontroller that has enough programming space to code efficiently
- Temperature: As heat can affect the optical components the system must not generate too much heat
- Cost: Cost which is our biggest limiter as our budget is being mostly utilized for the optic components

Supplier	Part Name	Clock Speed	Storage Size	Temperature	Cost
Meacon Embedded Works	DM37x	1 GHz	512MB	0 - 70C	$365.38
Octavo Systems LLC	OSD335x	1 GHz	4GB	0 - 85C	$70.96
iWave Systems	Arria 10	1.5 GHz	8GB	-40 - 85C	$1875.00
MYIR Tech Limited		1.5 GHz	8GB	-40 - 85C	$43.78
Texas Instrument	MSP430	16 MHz	128 KB	-40 - 85C	$26.59

Table 3: Summarized part selection for MCU

3.3.6 MSP430fr6989

The MSP430fr6989 was selected as the tool for coding the microcontroller. This was an easy choice as the MSP430 was easily the most familiar embed systems device we knew how to use. This was essential as we would like to limit the expansion of difficulty on the project as we were already going to have to figure out how to code the controller and figure out the configuration of the SDR systems.

The MSP430 was taught to us in the embedded systems lab. This lab taught us the fundamentals of coding small simpler devices with code that will work by itself and won't need constant user input to work. The lessons on how to find ports and how to call them, UART, and SPI will be utilized in this project.

Finding ports and how to call them will be essential to configuring the controllers' output ports and showing us the maximum endpoints that will be allowed. This will also make it so that we can orient the system so that there will not be a need for a messy loop of wires to the required switches.

The UART communication is widely used in various applications, such as connecting microcontrollers, sensors, and other embedded devices. It is known for its simplicity, ease of implementation, and reliability, especially for short-distance communication. Devices with UART interfaces can communicate with each other as long as they agree on parameters like baud rate, data frame format, and optional features like parity.[10]

SPI, or Serial Peripheral Interface, is a synchronous serial communication protocol commonly used for communication between microcontrollers, sensors, memory devices, and other peripheral devices. It is known for its simplicity, full-duplex communication, and high-speed data transfer capabilities. SPI typically involves a master device and one or more slave devices, and it utilizes a master-slave communication model.[11]

I2C or Inter-Integrated Circuit is a sort of mixture of UART and SPI. I2C also utilizes the master and slave communication method. However, it does something special with it and instead of just one master node and multiple slave nodes it will allow for multiple master nodes and multiple slave nodes.[12]

The uses case of I2C is quite useful when one considers the usefulness of being able to have multiple nodes to store data in a central spot. This allows for quick storage of information from different sources that will collect different information that may be used by those other sources to further their calculations or adjustments.

The MSP430 works off of a special language based of the C language that is designed for the controller. The MSP430 will work with the other controller chip to establish the switching of the switches and monitor the use of the lasers. There will be other switches that will signal to the controller how things will work and where the signal should be sent.

3.3.2 Digital Signal Processor

A digital signal processor is a specialized microprocessor that is specially designed for processing digital signals. A DSP would make the mathematical operations and manipulations to a digital signal. This is done so that a collected signal can be modified if needed as the signal connected could be weak and need amplifying or it could have a lot of noise along with it and needs to be cleared up to properly receive the intended signal. A DSP has a few parts including the programming memory, data memory, computing engine, and input/outputs. The programming memory of course will be used to store the programming needed to modify the signals in ways such as amplification, noise cancellation, and tuning. This programming memory is then used by the computing engine to put those functions into action. The data memory will hold any signals received so that it can be modified and sent to another location.[13]

3.3.3 ADC / DAC

ADC, also known as analog-to-digital conversion, is a critical process that plays a vital role in modern technology. Its counterpart, DAC, which stands for digital-to-analog conversion, is equally important. These two conversions will be indispensable when it comes to transmitting rf signals over optic wires, ensuring seamless data transfer and maintaining signal integrity.

ADC is responsible for the transformation of RF signals into a digital format, facilitating efficient processing and transmission. This conversion allows for precise and accurate representation of the analog signals in a digital form, resulting in enhanced signal quality and reliability. However, the journey of these digital representations does not end here. To complete the cycle and restore the original analog signal, a DAC steps in. By intelligently converting the digital representations back into their analog form, the DAC effectively bridges the gap between the digital and analog domains, allowing for seamless signal transmission and compatibility with analog devices.[14]

Now, it is worth mentioning the key element that comes into play here: the microcontroller. The microcontroller serves as a crucial component in managing and organizing the digital information obtained from the ADC. With its innate capability to process and manipulate data, the microcontroller ensures that the converted signals are directed to their designated receivers in a smooth and coordinated manner.

In summary, the integration of ADC and DAC is vital when transferring RF signals over optic wires. The ADC seamlessly converts analog signals into a digital representation, while the microcontroller diligently manages and directs this digital information to its designated receiver. Subsequently, the DAC expertly switches these digital representations back into their original analog signal, maintaining the integrity and accuracy of the transmitted information. It is through the diligent coordination of these components that the successful conversion and transmission of RF signals over fiber optics is ensured.

Supplier	Part Name	# bits	Input type	# inputs	Cost
Texas Instr.	ADC084S021 CIMM	8	Single	4	$2.75
Harris Corp.	HI3306JIB	6	Single	1	$300.84
Linear Tech.	LTC2391IUK	16	Differential	1	$310.60
Analog Devices Inc.	LTC2480CM S	16	Differential	1	$6.02
Texas Instr.	ADS7864Y	12	Differential	6	$16.38

Table 4: Summarized part selection for ADC

The input type of single and differential is that single inputs will all be based off ground or 0 to be simple. While differential is allowed to have negative reference points.

With that into account, I believe that the choice of ADS7864Y from Texas Instruments would be most ideal. The reason being that it has enough input bits to cover most applications and with 6 inputs allowed will allow for the schematic we imagined to be possible. We need multiple inputs to allow for multiple signals to be sent at the same time.

Supplier	Part Name	# bits	# of converters	Cost
Texas Instr.	DAC900E	10	1	$13.33
Harris Corp.	HI5760	10	1	$2.68
Rohm Semi-Conductor	BU2507FV-E2	10	6	$2.49
Analog Devices Inc.	AD5770RBC BZ-RL7	14	6	$37.38

Table 5: Summarized part selection for DAC

In turn of choosing a DAC after a ADC it would be best to match the amount of inputs with the out of converters needed, though if we ran a slower system we could choose to have less converters as they all won't be used at the same time. However, in this case we have chosen the AD5770RBCBZ-RL7 from Analog Devices Inc. as it has enough bits to cover the ADC's bits and has the matching 6 converters to match the ADC's ADS7864Y from Texas Instrument 6 inputs.

3.3.4 Software Defined Radio

A software-defined radio (SDR) is a radio communication system in which most of the traditional hardware components are replaced with software. The core functionality of an SDR is performed by software, running on a general-purpose computer or a specialized embedded system. This software handles the tasks of modulation, demodulation, encoding, decoding, filtering, and other signal processing operations that are typically performed by specialized hardware components in traditional radios.

The versatility of SDR lies in its ability to reconfigure and adapt to different communication protocols and frequencies through software updates. This flexibility allows SDR to support a wide range of applications, including wireless communication systems, radio astronomy, satellite communications, signals intelligence, amateur radio, and much more. SDR enables the development of multi-mode, multi-band systems that can rapidly switch between different frequency bands and modulation schemes.[15]

One of the key advantages of SDR is its ability to process and analyze large amounts of data. With the use of powerful processors and advanced signal processing algorithms, SDR can extract valuable information from the received signals, such as decoding specific protocols, identifying signals of interest, and even performing advanced signal analysis techniques. This makes SDR ideal for applications like spectrum monitoring, wireless security, and software-based modulation/demodulation research.

Overall, the flexibility, versatility, and data-processing capabilities of SDR make it a game-changer in the field of radio communication. Its ability to adapt to different standards and protocols through software updates makes it future proof, reducing the need to invest in new hardware for every new communication standard that emerges. SDR is empowering researchers, developers, and radio enthusiasts to explore and innovate in the realm of wireless communication systems.

When selecting a SDR, the most important specification is the bandwidth. In order to meet our system bandwidth requirement of 5 GHz, we require a SDR with a bandwidth exceeding 5GHz. The HackRF One is the only SDR we are comparing that meets this requirement, and thus we selected this component to use for the high frequency channels of the system.

Supplier	Part Name	Bandwidth	Configuration	Price
Airspy	Airspy HF+ Discovery SDR	260 MHz	Half duplex	$199.00

Great Scott Gadgets	HackRF One	6 GHz	Half duplex	$339.95
Seed Studio	KiwiSDR Kit	30 MHz	Full duplex	$332.99
Lime Microsystems	LimeSDR mini	3.5 GHz	Full duplex	$495.00

Table 6: Summarized part selection for SDR

3.3.5 Voltage Sources

A voltage source may also be required as we need a portable source of power to the microcontroller and the source of power to the antennas. Thus, we wanted to look at our options. We wanted to look for a voltage supply that followed enough power generated and was low cost.

There is also a need for voltage regulators that will take the voltage of the main voltage source and drop it down to an acceptable level for the electrical components needed in the system, and since there are two devices that require about the same voltage levels, further study must be made about the implementation of one or several voltage regulators.

Part Name	Cost	Power Generated
EG&G HFD	$229.93	+5V - -15V
New Focus Model 0901	$560	+15V - -15V
Leads & Northrup 9878	$99.96	+2V

Table 7: Summarized part selection for voltage sources

3.4 RF Filters

The RF filters are components that the RF front end of a system may or may not need based on the operation of the system. Filters are especially important if the device is operating in a highly used frequency band that makes high selectivity a need to accurately receive and process the signal. Nevertheless, since the use of filters is circumstantial on the surrounding frequency bands, they are not needed in all applications. One example is if the antenna receives a frequency band that includes the needed signal, but where the neighboring frequencies are practically negligible if it comes to interfering with the signal of interest.

These cases are specific to the application setup, and thus, the electrical systems can get away with not having to implement a bandpass filter. On the other hand, if

the power of the neighboring signals is too high, they may cause distortion in the receiving process of the system and do not allow the receiver to process the signal. In those cases, it is imperative to implement a filter that, depending on the frequency that causes the most interference, will need a specific frequency response to attenuate that interfering signal.

Furthermore, there are different types of filters for several scenarios such as low-pass, high-pass, band-pass, and band-reject filters. Each of them has a specific function that follows exactly their names. Low-pass filters reject high frequency, High-pass filters reject low frequency signals, the bandpass-filter allows signals of a specific range of frequencies to pass, and lastly, the band-stop filter stops signals with a specific frequency band.

3.4.1 Chebyshev Bandpass Filter

A Chebyshev bandpass filter is an analog filter that has a sharp roll-off rate and equiripple passband response. They are characterized by their ability to reject unwanted signals outside of the desired frequency band while maintaining a relatively flat response within the passband. This makes them ideal for applications such as RF transmitters and receivers, where it is important to filter out unwanted noise and interference. Chebyshev bandpass filters can be designed with different levels of passband ripple, depending on the desired performance and cost constraints. Higher levels of passband ripple will result in a sharper roll-off rate, but they will also require a more complex filter circuit. Chebyshev bandpass filters are widely used in a variety of applications, including RF communications, aerospace and defense, and test and measurement. Some of the advantages of using Chebyshev bandpass filters are a Sharp roll-off rate, good stopband attenuation, relatively flat passband response, and a wide range of design options. However, some of the disadvantages of using Chebyshev bandpass filters are the passband ripple, higher complexity than other types of filters, and higher cost.[16]

3.4.2 Butterworth Bandpass Filter

A Butterworth filter is an analog filter that has a maximally flat passband response and a monotonic roll-off in the stopband. Butterworth filters are characterized by their ability to maintain a constant gain across the desired frequency band while rejecting unwanted signals outside of the band. This makes them ideal for applications such as audio, video signal processing, telecommunications, and control systems where it is important to preserve the fidelity of the signal. Butterworth filters can be designed with different filter orders, depending on the desired performance and cost constraints. Higher filter orders will result in a sharper roll-off rate, but they will also require a more complex filter circuit. Some of the advantages of using Butterworth filters are maximally flat passband response, monotonic roll-off in the stopband, linear phase response, and ease of design and implementation. However, some of the disadvantages of using

Butterworth filters are a gradual roll-off rate compared to other types of filters, and a more complex filter circuit than other types of filters for a given filter order.[17]

3.4.3 Crystal Bandpass Filter

A crystal bandpass filter is a type of filter that uses quartz crystals to pass signals within a specific frequency band. It is known for its extremely high selectivity and good temperature stability. Crystal filters are typically used in high-performance RF transmitters and receivers, as well as in other applications such as satellite communication systems and military equipment. A crystal bandpass filter typically consists of a series of quartz crystals that are coupled together. The quartz crystals are tuned to resonate at the desired frequency band. When a signal is passed through the filter, it is only allowed to pass through the crystals that are resonant at the signal frequency. All other signals are attenuated. Crystal bandpass filters can be designed with different levels of selectivity and insertion loss. The selectivity of the filter is determined by the number of crystals used and the coupling between the crystals. The insertion loss of the filter is determined by the materials used to construct the filter and the design of the filter circuit. Some of the advantages of using crystal bandpass filters are extremely high selectivity, good temperature stability, long lifespan, and low insertion loss. However, some of the disadvantages of using crystal bandpass filters are high cost, complexity to design and manufacture, and limited power handling capability. Some examples of applications where crystal bandpass filters might be used are high-performance RF transmitters, high-performance RF receivers, satellite communication systems, military equipment, and test and measurement equipment.[18]

3.4.4 Surface Acoustic Wave (SAW) Filter

A surface acoustic wave (SAW) filter is a type of filter that uses the piezoelectric effect to convert electrical signals into surface acoustic waves and back again. SAW filters are known for their small size, low cost, and high performance. They are widely used in a variety of applications, including RF transmitters and receivers, cellular phones, satellite communication systems, and radar systems. A SAW filter typically consists of two interdigital transducers (IDTs) that are deposited on a piezoelectric substrate. The IDTs are spaced a certain distance apart, depending on the desired filter frequency. When an electrical signal is applied to the input IDT, it generates a surface acoustic wave. The surface acoustic wave travels across the piezoelectric substrate to the output IDT, where it is converted back into an electrical signal. The frequency of the filter is determined by the spacing of the IDTs and the speed of the surface acoustic wave. The selectivity of the filter is determined by the number of IDTs and the coupling between the IDTs. SAW filters can be designed with a wide range of selectivity, from a few percent to over 99%. Some of the advantages of using SAW filters are small size, low cost, high performance, wide range of selectivity, and good temperature stability However, some of the disadvantages of using SAW filters are

limited power handling capability and sensitivity to environmental factors such as vibration and humidity.[19]

3.4.5 Elliptic Filter

An elliptic filter is a type of electronic filter designed to have a very sharp transition between the passband and stopband, as well as to provide both a flat passband response and a very high degree of stopband attenuation. Elliptic filters are named after the elliptic functions that are used in their design. They are characterized by the unique feature of having ripple in both the passband and the stopband. The amount of ripple in each band is independently adjustable, and no other filter of equal order can have a faster transition in gain between the passband and the stopband, for the given values of ripple. Elliptic filters are designed using mathematical optimization techniques to minimize the filter order for a given set of ripple and transition band requirements. They are often used in applications where a very sharp transition between the passband and stopband is required, such as in communication systems and medical imaging equipment. Elliptic filters find applications in various fields, including RF and microwave engineering, where their steep roll-off and high selectivity are advantageous for filtering out unwanted signals and interference. However, their design can be more complex than that of Butterworth or Chebyshev filters due to the need to optimize multiple parameters.[20]

3.4.6 Filter Comparison

When selecting a bandpass filter for a project, there are several important characteristics and factors to consider when ensuring that the filter meets specific requirements. Some key considerations:

● **Center Frequency**: The frequency at which the filter allows maximum transmission of a signal. In other words, it's the frequency around which the filter is designed to pass or transmit signals with minimal attenuation or loss.
● **Bandwidth**: A measure of the range of frequencies that a bandpass filter allows to pass through with relatively little attenuation or loss. It is typically defined as the difference between the upper and lower -3dB cutoff frequencies of the filter.
● **Order**: The complexity of the filter design. A higher filter order indicates a more selective filter with a steeper roll-off in the frequency response. It's determined by the number of components used in the filter design and affects how quickly the filter attenuates frequencies outside its passband. Higher-order filters provide sharper transitions between the passband and stopband but are more complex to design and implement.
● **Passband Ripple**: The variation in amplitude (or gain) of signals within the specified passband of the filter. In other words, it refers to the fluctuations in signal amplitude that occur as you move across the frequencies allowed by the filter within its passband.[21]

- **Rejection in the Stopband**: A measure of a filter's ability to attenuate or block unwanted or undesired frequencies that lie outside its specified passband. In other words, it quantifies how effectively a filter suppresses signals at frequencies beyond its intended range.
- **Cost**: Depending on the budget constraints, we may need to balance filter performance with cost. More complex or specialized filters may be more expensive. Bandpass filters can range in price from a few dollars to several hundred dollars, depending on the type of filter and its specifications.

Characteristic	Chebyshev	Butterworth	Elliptic	Crystal	SAW
Center Frequency	Can be specified by designer	Can be specified by designer	Can be specified by designer	Fixed by the crystal	Fixed by the SAW device
Bandwidth	Can be specified by designer	Can be specified by designer	Can be specified by designer	Fixed by the crystal	Fixed by the SAW device
Filter Order/Complexity	≥ 3	≥ 4	≥ 2	≥ 4	≥ 4
Selectivity/Roll-off Characteristics	Steep roll-off	Gradual roll-off	Steep roll-off	Steep roll-off	Steep roll-off
Passband Ripple	Can be specified by the designer	Typically zero	Can be specified by the designer	Typically zero	Typically non-zero
Out-of-band Rejection	Typically good	Typically moderate	Typically excellent	Typically good	Typically excellent
Cost	Low to Moderate	Low to Moderate	Moderate to High	Moderate to High	Moderate to High

Table 8: Summarized technology investigation of RF filters

3.5 RF Amplifiers

Based on the requirements of the communication systems, ref amplifiers may be implemented. RF amplifiers are typically implemented in systems when a higher signal power is required for processing in the RF front-end module. Since one of the essential parameters for the wireless system is the signal to noise ratio, ideally, the signal would have a high power compared to the noise floor of the system,

which is the minimum power the system receives from its environment and that itself produces.

There are different topologies of amplifiers depending on what is intended to achieve with them. There are typically two types of amplifiers that will have a further explanation in the next sections discussing the advantages and disadvantages each present. These different types of amplifiers are used in combination to achieve the desired signal to noise ratio. However, combining amplifiers is not an easy task because they have other secondary effects such as the generation of harmonics, which would increase the nonlinearity effects in the system that in consequence may deteriorate the performance of the RF receiver.

3.5.1 Low Noise Amplifiers

An RF low noise amplifier (LNA) is an electronic device that amplifies a very low-power signal without significantly degrading its signal-to-noise ratio (SNR). Any electronic amplifier will increase the power of both the signal and the noise present at its input, but the amplifier will also introduce some additional noise. LNAs are designed to minimize that additional noise, by choosing special components, operating points, and circuit topologies. Minimizing additional noise must balance with other design goals such as power gain and impedance matching. LNAs are typically used at the beginning of a receiver chain to amplify a signal with minimal degradation due to noise. The specification that determines the noise in an LNA is called noise figure. So, the lower the noise figure of a LNA the better its performance. RF LNAs are used in a wide variety of applications, including cellular phones, Wi-Fi routers, satellite communication systems, radar systems, and test and measurement equipment.[22]

 Some of the key characteristics of RF LNAs are:

- **Noise figure**: A measure of how much additional noise the LNA introduces into the signal. The lower the noise figure, the better the performance of the LNA.
- **Gain**: A measure of how much the LNA amplifies the signal. The higher the gain, the more the signal is amplified.
- **Power handling capability**: A measure of how much power the LNA can handle without saturating. The higher the power handling capability, the more power the LNA can handle.
- **Impedance matching**: The impedance of an LNA must be matched to the impedance of the signal source and the load in order to achieve maximum power transfer.

3.5.2 RF Power Amplifiers

An RF power amplifier (PA) is an electronic device that amplifies a radio frequency (RF) signal to a higher power level. RF PAs are typically used in the final stage of a radio transmitter, their output driving the antenna. Design goals often include

gain, power output, bandwidth, power efficiency, linearity (low signal compression at rated output), input and output impedance matching, and heat dissipation. RF PAs are used in a wide variety of applications, including cellular phones, Wi-Fi routers, satellite communication systems, radar systems, broadcast radio and television, and test and measurement equipment. RF PAs are critical components for many RF systems, as they allow for the transmission of RF signals over long distances and through obstacles. Here are some of the key characteristics of RF PAs:

- **Gain**: A measure of how much a PA amplifies the signal. The higher the gain, the more the signal is amplified.
- **Power output**: A measure of the maximum power it can produce. The higher the power output, the more powerful the transmitted signal will be.
- **Bandwidth**: The range of frequencies that it can amplify. The wider the bandwidth, the more versatile the PA will be.
- **Power efficiency**: A measure of how efficiently it converts electrical power into RF power. The higher the power efficiency, the less heat the PA will generate.
- **Linearity**: The linearity of an RF PA is a measure of how accurately it amplifies the signal. The more linear the PA, the less distortion will be introduced into the signal.
- **Impedance matching**: The impedance of an RF PA must be matched to the impedance of the signal source and the load in order to achieve maximum power transfer.[23]

3.6 Multiplexing/Switching

3.6.1 Wavelength Division Multiplexing:

Wavelength division multiplexing is a method for increasing the data throughput of an optical fiber channel. This is done by propagating multiple wavelengths of light through the fiber core simultaneously. Each wavelength is modulated independently and thus carries an independent channel of information. As such, the data throughput scales as a multiple of the number of wavelength channels used. This allows for significantly larger throughput than single wavelength channels. Additionally, the different wavelengths propagate independently and there is very little crosstalk between channels. To integrate multiple wavelengths into a fiber optic communication system, the beams must be combined and coupled into the fiber. There are three approaches through which this separation of wavelengths can be achieved: diffractive optical elements, spectral filter-based, and interference-based.[24]

The simplest of these approaches is using a diffractive optical element such as a prism or diffraction grating. Each of the beams, corresponding to different WDM channels, are incident upon the diffractive element. The angle of incidence of each beam is varied such that the beams exit at the same angle. By aligning the laser

sources at these angles and to the same location on the diffractive element, the beams can be made to be coaligned. This has the advantage of only needing a single optical element to combine/separate a large number of WDM channels as diffraction gratings have free spectral ranges significantly larger than typical WDM channel spacing.[24]

Spectral filter-based approaches operate by using spectrally selective elements that either reflect or transmit light based on the wavelength, such as dichroic mirrors.[25] By transmitting one beam and reflecting another to match the angle of the transmitted beam, the beams are able to be combined. This can be repeated with n-1 spectral filters to combine n beams. Although this may be effective for small numbers of WDM channels, for systems with larger numbers of WDM channels you need increasingly larger numbers of spectral filters. Additionally, the specific wavelength cutoffs needed for WDM systems are not widely available and would likely need to be custom made. This approach also gets more difficult as the WDM channel separation shrinks, such as in a DWDM system, as the cutoff between transmission and reflection must occur over a very narrow wavelength range. This increases the cost of components, the size of the device, and the alignment time significantly.

Alternatively, an interference-based approach can be taken, such as in arrayed waveguide gratings (AWG). In this scheme, a single source is split into several channels in a waveguide. The light in the different waveguides experience different phase shifts. When these waveguide outputs interfere, they produce several outputs with varying frequencies. These devices are fabricated as photonic integrated circuits, typically on a silicon substrate. Commercial products are available that integrate these devices with fiber inputs and outputs to operate at fixed light frequency spacings. However, these devices do not support any form of optical switching and thus are not suitable for the multiplexing functionality required for this project. Although they could be used for the demultiplexing, they are not cost-competitive with the diffractive element method. Typical arrayed waveguide gratings are an order of magnitude more expensive than a diffraction grating.[24]

In each of these approaches, the coaligned beams of varying frequency are then coupled into the fiber and propagate over the length of the fiber. Since most optical receivers are wideband devices, they cannot distinguish between the wavelength-defined channels. To measure the signals independently, the component wavelengths of the signal must be separated. This creates a spatial separation of the WDM channels, allowing for each beam to be incident upon its own sensor, and each signal is measured separately. This is the demultiplexing step and is typically done in the same manner as the multiplexing but in reverse. For example, if the multiplexing was done using a diffraction grating to combine the beams, then the demultiplexing is achieved by using a second diffraction grating. However, since we are passing a beam with several component wavelengths coaligned through the grating, the grating now separates rather than combines. This will give us the necessary spatial separation of the WDM channels mentioned previously.

WDM can be broadly split into two types: dense wavelength division multiplexing (DWDM) and coarse wavelength division multiplexing (CWDM). The difference between these two methods is the spacing between adjacent channels, with CWDM having much larger spacing than DWDM. DWDM allows for a larger number of channels to be supported, and thus more data to be transmitted through a single fiber. However, this requires narrowband sources and more stringent multiplexing and demultiplexing requirements.[26, 27]

3.6.2 Dispersive Optical Elements (Prisms/Diffraction Gratings)

To perform WDM, we require a diffractive element that can combine/separate beams of different wavelengths. This can be done using either a prism or diffraction grating. A prism separates wavelengths through its inherent difference in index of refraction with wavelength, known as dispersion. When light enters the prism, different wavelengths are deflected at different angles according to the index of refraction they experience. This also occurs when exiting the prism, and results in an angular separation of component wavelengths of the initial beam. Prisms have the advantage of potentially having very low losses. If the entry and exit surfaces are coated with an appropriate ant-reflection (AR) coating, then the losses due to reflection can be reduced to a fraction of a percent. In addition, an appropriate material can be selected that has minimal absorption at the design wavelength. However, prisms do not produce as large of an angular dispersion as do diffraction gratings.[28]

In contrast, a diffraction grating separates wavelengths through diffraction. The grating possesses a periodic structure that causes light to be diffracted. Similar to the prism, each wavelength of light undergoes a different angular displacement. Prisms are limited in the angular separation of wavelengths they can produce according to the dispersion curve of the material they are made of. In contrast, diffraction gratings can produce a much larger separation of wavelengths by decreasing the period of the diffraction grating. As we wish to use closely spaced wavelengths for the WDM system, we desire a diffractive optic that can produce a large separation of similar wavelengths. For this reason, the large angular dispersion of diffraction gratings is advantageous. However, the tradeoff for this larger angular dispersion is increased power losses. While transmission gratings can be optimized for a specific wavelength and angle of incidence, they still cannot match the low power losses of a prism.[28] Both diffraction gratings and prisms have similar costs, with typical products of both products being approximately $100.

Technology	Angular Dispersion	Losses	Cost	Example Product

Prism	Low	Low	Moderate	ThorLabs PS851
Diffraction Grating	High	Moderate	Moderate	ThorLabs GR13-0616

Table 9: Summarized technology investigation of prisms vs. diffraction grating

When selecting a diffraction grating for the WDM system, the primary specifications we are interested in are dispersion, grating efficiency, and cost. We wish to have a large enough grating dispersion in order to make the separation of the channels of the WDM feasible. However, we don't want too large of an angular dispersion as it will limit the number of WDM channels that can be efficiently added to the system. We also look to maximize the grating efficiency to maintain a power-efficient system. However, these requirements must also be balanced against the cost of higher performance gratings. We must also ensure the size of the grating exceeds the beam size at the input and output of the fiber. At a minimum, we need to ensure that the diffraction grating has a free spectral range greater than the range of wavelengths we wish to use.

There are many different types of diffraction grating to consider. Firstly, there are transmissive diffraction gratings and reflective diffraction gratings, which transmit and reflect the diffractive light respectively. Also, there are differences in the geometry of the grooves between gratings. Grating grooves can be blazed, where the grooves are at an angle to the surface of the diffraction grating. This allows for the device to be optimized for minimum losses at a certain blaze angle and wavelength. Due to the angle of the grooves, the reflection from the surface is determined by the angled groove surface rather than the surface of the device's geometry. This is important as it allows for what is known as the Littrow configuration, in which the 1st order beam is diffracted at an angle equal to the incident angle. This is the configuration in which the diffraction grating has the highest efficiency, meaning the most power is concentrated in the first order. In contrast, holographic surface gratings are fabricated by means of the interference of two beams on a photosensitive material, and as such have a sinusoidal pattern. Compared to other gratings, this method produces less ghosting and scattering. However, holographic gratings are typically limited to the UV and visible spectrum.[29]

Supplier	Part Number	Angular Dispersion	Free Spectral Range	Grating Efficiency	Unit Cost
ThorLabs	GR13-0616	1.46 nm/mrad	800 nm	92.5%	$76.58

Spectrum Scientific Inc.	1200-1550-012-S-S	0.306 nm/mrad	775 nm	93%	$85.00
Optometrics	G600R1.6CEAS	1.46 nm.mrad	800 nm	90%	$76.00

Table 10: Summarized part selection for diffraction gratings

3.6.3 1x2 Optical Switches

To create our 2x3 optical switching subsystem, we need 1x2 optical switches as the basic building block. These switches are highly reliable MEMS-based systems that take in one fiber as an input and can output to either of the 2 output fibers. This switching mechanism can be triggered by a voltage pulse delivered to the device.[30] We must select a component that has the correct fibers to ensure single-mode operation at our operating wavelengths. This is done to minimize the insertion loss of the device at our operating wavelength. Additionally, we wish to have low insertion loss to decrease the overall loss of the system, which relaxes the power requirement of the laser diodes. We also look to have isolation between the channels significantly larger than the desired system signal-to-noise ratio. Most products have isolation values of 60-70 dB, so this should not be a difficult requirement. The optical switch must also be rated for a maximum power greater than our laser diode power, although again this requirement is satisfied for nearly all commercially available products.

The main difference between the commercially available options is the switching time. This limits how quickly the device can switch between different RF inputs. A long switching time is undesirable, as during this time no data can be transmitted. This will limit the total data throughput of the system, especially in use cases where frequent switching between channels is needed. Additionally, if precautions are not taken then any data received during the switching time is lost. This can be remedied by introducing a buffer that saves the information received during switching, and then transmits this information once switching is complete. This buffer must be large enough to handle the amount of data that would otherwise be transmitted during the switching time.

The other parameters are satisfactory for our needs across all of the components surveyed. Even the lowest isolation of 50 dB is well above our desired signal-to-noise ratio. Additionally, even the lowest maximum power rating exceeds the needs of our system. There are differences in the insertion loss of the devices. For example, the Agiltron SM28 has a smaller insertion loss than the Agiltron MISW-12B211333, however, even the larger loss is acceptable for our system. Thus, we choose the MISW-12B211333 as it meets the requirements at the lowest price point.

Supplier	Part Number	Isolation	Insertion Loss	Maximum Power	Switching Time	Unit Cost
Agiltron	SM28	70 dB	< 0.4 dB	1 W	< 0.9 ms	$265.00
Agiltron	MISW-12B211333	60 dB	< 1 dB	0.3 W	< 10 ms	$125.00
ThorLabs	OSW12-1310-SM	75 dB	<1.5 dB	0.3 W	< 1 ms	$1,126.20
Newport	MS-1315TT-12	50 dB	<0.7 dB	0.5 W	< 10 ms	$800

Table 11: Summarized part selection for 1x2 optical switches

3.6.4 Mirrors

To reduce the overall size of the device, we have used two mirrors in order to fold the optical path of the beams incident upon the diffraction grating in the multiplexing system. To do so with minimal losses, we require mirrors designed to have high reflectance over the range of wavelengths we are using. In general, there is a tradeoff between high reflectance and low cost, and these are the two main parameters we are concerned with. Additionally, the mirror must be large enough for the clear aperture to exceed the size of the beam, as well as contain the several passes needed to fold the beam path to an acceptable size. Mirrors can be split into two broad categories: dielectric and metallic. In this selection, we consider multiple options of each type as different materials offer different combinations of price and reflectance.

Supplier	Part Name	Clear Aperture	Reflectance (@1550m)	Unit Cost
Thorlabs	BB07-E04	16.15 mm	99.7%	$125.77
Thorlabs	PFSQ10-03-M01	22.86 mm	> 97%	$65.51
Edmund Optics	#34-390	18 mm	> 98%	$155.00
MKS Newport	05D20DM.8	10.16 mm	99.99%	$98.00

Table 12: Summarized part selection for mirrors

We have decided to choose part number PFSQ10-03-M01 from Thorlabs as it provides a large enough clear aperture, high reflectance, and low cost. The small difference in reflectance between this option and others does not justify the large increases in price. Even after 4 reflections off the mirror, the beam will undergo a loss of just 0.5 dB. Additionally, this is based on the average reflectance. The measured reflectance data provided by Thorlabs suggests that the reflectance at our wavelengths of interest will be closer to 98-99% meaning these losses will likely be lower.

3.7 Fiber Optic and Coupling

3.7.1 Fiber Optic

The fiber optic is the transmission medium in an RFoF system. The dispersion of the chosen fiber is of great importance, and the dispersion sets an upper limit on the bandwidth of the system. This is because as dispersion increases, closely spaced pulses will begin to overlap as they expand in the time domain. There are three main dispersion effects in fiber optic cable: material dispersion due to the difference in refractive index of the core material as a function of wavelength, waveguide dispersion due to the difference in effective refractive index experienced by different wavelengths, and modal dispersion due to the difference in effective refractive index experienced by different spatial modes. Modal dispersion is typically the strongest of these effects, setting the upper limit of the fiber's bandwidth. However, modal dispersion can be removed by utilizing a single-mode fiber in which only the fundamental mode can propagate.[31]

Fiber Type	Attenuation	Dispersion	Price/Meter
Single Mode	High	High	Low
Multi Mode	Low	Low	High

Table 13: Summarized technology investigation for SMF vs MMF

As we are trying to attain a system bandwidth in the GHz range, we have used a single mode fiber to avoid modal dispersion. Within single mode fibers, there are several different types we must consider. These include normal single mode fiber, dispersion-shifted fiber, polarization-maintaining fiber, and photonic crystal fiber. As our system does not have any polarization-specific optics or measurements, we do not have a need for polarization-maintaining fiber. While the large mode area of photonic crystal fibers does have advantages in ease of alignment, the cost is about two orders of magnitude higher making it economically unfeasible.[24]

As we are using wavelengths centered around 1550nm, we look for fiber optics optimized for this wavelength. This optimization means that the fiber optic will have low dispersion around this wavelength, with a flat dispersion curve across the range of wavelengths we plan to use. A low dispersion is optimal rather than zero

dispersion as the dispersion curve is typically steep at the zero-dispersion point. A flat dispersion curve is advantageous as it reduces the difference in dispersion between the wavelengths in the bandwidth of the laser. Additionally, at the zero dispersion point light will undergo stronger four-wave mixing effects. For these reasons, we don't wish to have the zero dispersion point at 1550 nm. Instead, we wish to have the zero dispersion point at a shorter wavelength.[32]

Supplier	Part Name	Attenuation	Dispersion	Price/Meter
Thorlabs	SM-28	< 0.18 dB/km	18 ps/nm/km	$0.61*
Thorlabs	DCF4	< 0.21 dB/km	-4 ps/nm/km	$3.00
Newport	F-SM1500-9/125	0.35 dB/km	N/A	$2.40

Table 14: Summarized part selection for fiber optic

* Price per meter for 100m of fiber

We have selected the SM-28 fiber as it has low attenuation and dispersion, along with a very cheap price. This cheap price is due to the large volumes of this fiber that are produced, as it is a very standard fiber for use in optical systems. Along with this is the fact that the optical switches and fiber couplers come standard with SM-28 fiber. This will allow for optimal coupling as using the same fibers ensures the NA and MFD of the fibers are the same.

3.7.2 1x2 Fiber Coupler

To combine light propagating in multiple fibers, we have required 1x2 beam combiners. These devices have two input fibers and one output fiber, or vice versa if used as a beamsplitter. These devices are composed of two fiber optic cables that are twisted, stretched, and then fused together. This results in coupling between the light fields of the two fibers. If the length of the distance over which the two fibers are fused together is varied, the relative amounts of power split into each of the two fibers can be varied. By optimizing for maximum power transmission into a single fiber, a beam splitter/combiner can be created. However, the device is still strictly speaking a 2x2 coupler with most power going into one of the outputs. In the 1x2 configuration here, one of the output fibers is terminated to prevent back reflections.

When choosing a 1x2 fiber coupler, we first must ensure that it covers the intended range of wavelengths over which we have been operating. In our case this is from 1530-1550 nm, however, we wish to consider scalability in this design up to larger numbers of WDM channels, which will require a larger bandwidth. In addition to

the bandwidth, there are also losses associated with fiber couplers. These losses are characterized by the insertion loss and the excess loss. The insertion loss is the ratio of the power transmitted to a single output compared to the input. The term loss here does not mean that this energy is truly lost, as even a lossless 1x2 coupler will have an insertion loss of 3.01 dB when the light is split evenly into the two outputs. The excess loss gives us a better idea of how much usable energy is actually lost in the system and is given as the ratio of the input light to the total output light across all outputs.[33]

In addition to these loss figures, we are also interested in the uniformity of the fiber coupler. The uniformity is a measurement of how much the insertion loss varies across the entire bandwidth of the system. It is calculated as the maximum insertion loss minus the minimum insertion loss experienced throughout the entire bandwidth. We wish to minimize this value, as we do not want larger differences in loss for different optical paths in the system. This is because the optical modulators are intensity-dependent, as the input signal must be tuned to the specific intensity of light being modulated.

Supplier	Part Name	Excess Loss	Insertion Loss	Uniformity	Bandwidth	Unit Cost
Thorlabs	TW1550R5F1	< 0.15 dB	< 3.7 dB	0.5 dB	1550 +- 100 nm	$333.08
Newport	F-CPL-S22155-FCAPC	0.06 dB	3.4 dB	0.5 dB	1300-1550 nm	$195
Agiltron	FCBB-11A481110	0.07 dB	3.4 dB	N/A	1260-1620 nm	$45

Table 15: Summarized part selection for fiber optic

While the Agiltron FCBB- 11A481110 has essentially the same performance as the Newport option, it comes at a lower cost, the Agiltron website estimates that this product has a minimum 5-week lead time. For these reasons we have used the Newport F-CPL-S22155-FCAPC fiber coupler in our project, as it has a low excess loss, low uniformity, covers our bandwidth, and has a lower cost than alternative options with an acceptable lead time.

3.7.3 Fiber Collimating/Focusing Lenses

Throughout our system we have instances in which we need the ability to efficiently couple light from a fiber to free space and then back to fiber. This includes when we are performing multiplexing and demultiplexing, as we require a free space beam to utilize the diffraction grating, but we need the beam in a fiber to perform

modulation and for reading the signal with the photodiodes. For this, we require a lens that can collimate or focus a beam to convert to and from free space and fiber. This lens must be capable of producing a very well-collimated beam, as we have suffered losses if the beam size expands quickly. Additionally, it must be capable of producing diffraction-limited spot sizes, as the beam must be focused to the size of the fiber core for high coupling efficiency. As we are using single mode fibers, the core size will be on the order of several microns. For these reasons, single spherical lenses are not sufficient as they have spot sizes typically in the hundreds of microns range.

There exist commercial products that are pre-aligned to collimate/focus a beam out of or into a fiber. These products have an FC/PC or FC/APC fiber mount in which the fiber is connected, and this results in proper alignment between the fiber tip and the lens. We have seen later that the focal length of this lens must be designed such that we get an acceptable beam spot size. We wish to have a collimating lens with a focal length of at least 8mm, as this will allow us to have a sufficiently collimated beam over the path length required by the multiplexing system.

Supplier	Part Name	Focal Length	Full-Angle Divergence	Waist Distance	Waist Diameter	Price
Thorlabs	F220APC-1550	11.32 mm	0.053^O	11.15 mm	2.15 mm	$177.45
Edmund Optics	#83-732	8.00 mm	N/A	N/A	N/A	$144.95
Thorlabs	50-1550A-FC	15 mm (WD)	0.25^O	15 mm (WD)	0.5 mm	$109.20

Table 16: Summarized part selection for collimating/focusing lenses

We have chosen the Thorlabs F220FC-1550 as it achieves the necessary small divergence angle and has an acceptable waist diameter, all with a manageable price point. In addition, we have required the FC/APC version of this component, however, the only difference is the connector type so we have used the same part but with the part number F220APC-1550 to denote the APC connector. This is necessary, as the fiber optic switches use FC/APC connectors while the fiber couplers use FC/PC couplers. The PC couplers are flat with rounded edges, while the FC/APC couplers are angled. Thus, if you try to couple one FC/PC coupler and one FC/APC coupler there is a mismatch of the face geometries and there will be large coupling losses. Additionally, trying to couple mismatched connector types can damage the fiber tips.[34]

3.7.4 Kinematic Mount for Collimating Lens

In order to precisely align the collimating lenses to achieve efficient coupling, we require the ability to finely align the angles of the lens-fiber assembly as even small positional and angular displacement can cause large losses.[35] To achieve this, we have made use of a tip/tilt mount for the collimating lens. This is a standard mounting scheme for optical components and allows for the angle of the optical element to be adjusted in two orthogonal directions. To allow for fine adjustments, this angular adjustment is performed via screws with a high thread count. Due to the size of the selected collimators, we have required a 12 mm or 1/2-inch mount. Additionally, we have required a fine adjustment with less than 1^O per screw rotation.

Supplier	Part Number	Degrees/Rotation	Mount Size	Unit Cost
Thorlabs	KM05	0.75^O	1/2 inch	$42.18
Newport	M1	0.38^O	1/2 inch	$38.82*
Edmund Optics	#58-850	N/A	1/2 inch	$86.00

Table 17: Summarized part selection for 1/2 inch kinematic mounts

*Also sold in packs of 10. This price is the average price of buying 11 when buying 1 pack of 10 and 1 individual.

We have chosen the Thorlabs KM05 as our kinematic mount, as it meets the requirements for fine adjustments and mount size. Although the Newport M1 is cheaper, due to the ubiquity of Thorlabs products and the wide-ranging uses of the KM05 mount it is available readily on second-hand goods markets such as eBay. This will allow us to acquire them for a greatly reduced price, while still maintaining the necessary performance.

3.8 Modulation

Modulation in wireless communications refers to methods of encoding the information in the signal. Some modulations are more efficient in terms of making the signal immune to a specific type of interference that may generate errors in the receiver once it gets the signal. Furthermore, depending on the desired modulation scheme, the wireless system would need a specific electrical module that modulates the signal for transmission.

One example is the frequency modulation scheme where the information of a signal is encoded by shifting the signal's frequency depending on what needs to be transmitted. A common example is audio transmission through frequency

modulation. This requires the use of a modulator section that modulates the information with frequency, and this can be achieved by using a voltage-controlled oscillator that varies its frequency based on the voltage controller input. This would make the frequency of the signal shift based on the voltage level of the voltage input controller. [36]

Furthermore, there are more complex and advanced modulation techniques for data transmission such as the BPSK (Binary Phase shift keying) in which data is encoded in binary values that will be represented by a 0 or 1 depending on the frequency of the signal. Also, this modulation scheme has more extensions to increase the data rate of this type of modulation by extending the symbols from 0 to 1, to more combinations.

Each modulation scheme has its trade off like everything in engineering, and this trade off is precisely what determines the choice of either one. For example, AM modulation is the easiest modulation scheme to implement, but it is also the most susceptible modulation scheme when it comes to noise due to the the fact that the information is transmitted with the amplitude of a signal that may encounter other signals or simply paths that can heavily attenuate it making so AM modulation unreliable for certain applications.

FM modulation for instance has a higher noise immunity because the frequency of a signal changes less easily than its amplitude, which makes the signal more resilient to noise, but one drawback of this modulation scheme is the complexity of the implementations. Meaning that in order to implement frequency modulation, extra hardware such as a Voltage controlled oscillator, which even though makes more resilient the signal, adds higher complexity to the system, and also increases the size of the transmitter and receiver.

The receiver also gets affected by the implemented modulation scheme because it needs to implement a specific electrical module able to demodulate the signal, which means that implementing a modulation scheme not only means that the data will be transmitted with a specific pattern, but it also means that the wireless system complexity, and potentially, cost is also going to increase.

3.8.1 RF Modulation Techniques

The two modulation techniques considered for this project are QPSK (quadrature phase shift keying) and BPSK (Binary Phase Shift Keying). Both schemes implement a carrier signal to transfer data, but they have different encoding schemes where the data is encoded and extracted from the phase change in the signal. If the signal changes its phase, it can be a 1 while if it does not change it phase it can be a zero. In BPSK, two different phases of the carrier signal are encoded where each signal represents either a zero or a 1, meaning that each symbol represents one bit of data. The QPSK differs in the bit encoding since it uses 4 different phases that allow the system to transmit two bits of data per

symbol allowing the system for higher data rate at the cost of complexity in the circuit for encoding and decoding.[36]

Since we are working on a satellite communication system, the standard for these communications is to use QPSK because it allows higher data rate and the signal is less vulnerable to noise. For this reason, we have used QPSK.

3.8.2 Mach Zehnder Modulator

A Mach-Zehnder modulator (MZM) is an optical device that is used to modulate the amplitude or phase of an optical signal. It is based on the Mach-Zehnder interferometer, which is a device that splits light into two beams, introduces a phase shift between the beams, and then recombines them. In an MZM, the two beams are separated by a beam splitter and then passed through two optical waveguides. One or both of the waveguides may contain an electro-optic material, such as lithium niobate (LiNbO3) or gallium arsenide (GaAs). When an electric field is applied to the electro-optic material, it causes a change in the refractive index of the material. This change in refractive index introduces a phase shift between the two beams. The two beams are then recombined by a second beam splitter. The phase shift between the two beams causes them to interfere with each other, resulting in a change in the intensity of the output signal. The amount of change in intensity depends on the phase shift between the two beams.[24]

Mach-Zehnder modulators (MZMs) can be used to modulate optical signals in a variety of ways.

- **BPSK**: a modulation scheme in which the optical signal is modulated with two different phases, 0 degrees and 180 degrees. This corresponds to two different binary values, 0 and 1.
- **QPSK:** a modulation scheme in which the optical signal is modulated with four different phases, 0 degrees, 90 degrees, 180 degrees, and 270 degrees. This corresponds to four different binary values, 00, 01, 10, and 11.
- **16-QAM**: This modulation scheme uses 16 different combinations of phases and amplitudes to represent four bits per symbol.
- **64-QAM**: This modulation scheme uses 64 different combinations of phases and amplitudes to represent six bits per symbol.
- **256-QAM**: This modulation scheme uses 256 different combinations of phases and amplitudes to represent eight bits per symbol.

Supplier	Part Name	Cost	Wavelength	Bandwidth	Data rate	Modulation Scheme
JDS Uniphase	10020 425	$599	1552 nm	11.1 GHz	10 Gbps	Intensity

Thorlabs	LN81S-FC	$2,728.89	1525 - 1605 nm	14 GHz	10 Gbps	Intensity
Fujitsu	FTM7937EZ	$980.00	1530-1610 nm	25 GHz	43 Gbps	DPSK
iXblue	LN-0.1-PD-P-P-FA-FA	Waiting for quote	1530-1580 nm	100-400 MHz	44 Gbps	Intensity
iXblue	LN-10-PD-P-P-FA-FA	Waiting for quote	1530-1625 nm	10-12 GHz	44 Gbps	Intensity
Fujitsu	FTM7977HQ	$860.00	1530-1610 nm	23 GHz	100 Gbps	QPSK
Fujitsu	FTM 7980 EDA	$769.00	1528-1612 nm	20 GHz	43 Gbps	BPSK
Sumicem	T.MXH1.5-40PD-ADC-LV	$249.99	1550 nm	20 GHz	40 Gbps	Intensity

Table 18: Summarized part selection for Mach Zehnder modulators

There are two main ways to demodulate a signal from an MZM:

Direct detection: the simplest and least expensive method, but it is also the least sensitive and least tolerant to fiber impairments. A method where the optical signal from the MZM is directly detected by a photodetector. The photodetector converts the optical signal into an electrical current that is proportional to the intensity of the optical signal. The electrical signal is then amplified and processed to recover the transmitted data. The amplified and filtered electrical signal is the demodulated signal.

Coherent detection: This is a more complex and expensive method of receiving optical signals, but it is also more sensitive and more tolerant to fiber impairments. In coherent detection, the optical signal from the MZM is mixed with a reference optical signal. The mixed signal is then detected by a photodetector. The photodetector converts the mixed signal into an electrical signal, which contains information about the amplitude, phase, and polarization of the optical signal. The

electrical signal is then amplified and processed to recover the transmitted data. The amplified and filtered electrical signal is the demodulated signal.

Feature	Direct detection	Coherent detection
Principle	Detects the amplitude of the optical signal	Detects the amplitude, phase, and polarization of the optical signal
Sensitivity	Lower	Higher
Tolerance to fiber impairments	Lower	Higher
Cost	Lower	Higher
Complexity	Lower	Higher
Application	Short-reach applications, such as data center interconnects Applications where cost is a major concern	Long-reach applications, such as optical transport networks Applications where high performance is required, such as high-speed data networks and research applications

Table 19: Technology investigation summary for optical detection techniques

Because of the extreme complexity and cost of coherent detection, we have pursued direct detection.

3.9 Optical Detector

3.9.1 Photodiode Selection

PIN photodiodes and avalanche photodiodes (APDs) are both semiconductor devices that convert light into electrical signals. However, they differ in their internal structure and operating principles. PIN photodiodes have a simple structure with three layers: a p-type layer, an intrinsic layer, and an n-type layer. When light strikes the intrinsic layer, it generates electron-hole pairs. These electron-hole pairs are then collected by the p- and n-type layers, creating an electrical signal. PIN photodiodes are typically operated in reverse bias. This means that a positive voltage is applied to the p-type layer and a negative voltage is applied to the n-type layer. This creates an electric field across the intrinsic layer, which helps to collect the electron-hole pairs. PIN photodiodes are known for their high speed and low noise. They are also relatively inexpensive to manufacture.

APDs have a similar structure to PIN photodiodes, but they also have a high-field region. When light strikes the intrinsic layer of an APD, it generates electron-hole pairs. These electron-hole pairs are then accelerated by the high-field region, causing them to impact other atoms and generate additional electron-hole pairs. This process, called avalanche multiplication, can amplify the electrical signal by a factor of hundreds or even thousands. APDs are typically operated in reverse bias, just like PIN photodiodes. However, APDs require a higher reverse bias voltage than PIN photodiodes in order to achieve avalanche multiplication. APDs are known for their high sensitivity. However, they are also slower and noisier than PIN photodiodes. They are also more expensive to manufacture.[37]

Characteristic	PIN photodiode	APD photodiode
Internal Structure	Simple	Complex
Operating principle	Photoconduction	Avalanche multiplication
Gain	1	~100-1000
Sensitivity	Lower	Higher
Speed	Faster	Slower
Noise	Lower	Higher
Cost	Lower	Higher
Response time	~ 1-10 ns	~ 10-100 ns
Bandwidth	100 MHz - 50 GHz	~10 MHz - 2 GHz

Table 20: Summarized technology investigation for photodiodes

Saturation of the optical signal is also a factor in choosing which photodiode to use. Saturation occurs when the photodiode is receiving more light than it can handle. This can cause the photodiode to produce a non-linear output, which can distort the signal. PIN photodiodes are more resistant to saturation than APDs. This is because PIN photodiodes have a lower gain. As a result, PIN photodiodes can be used in systems with higher optical power levels without saturating.

Hence, because PIN photodiodes are resistant to saturation, have a higher operating bandwidth, faster response time, and lower cost it would be best to select them for the receiving subsystem.

Supplier	Part Name	Cost	Wavelength range	Response time	Bandwidth

Excelitas Technologies	C30641GH	$111.30	1300-1550 nm	10 ns	75 MHz
Thorlabs	FGA01	$67.55	800 - 1700 nm	0.6 ns	1.59 GHz
Thorlabs	FGA015	$63.00	800 - 1700 nm	0.6 ns	2.12 GHz
OSI Optoelectronics	FCI-InGaAs-75	$55–$62	900 -1700nm	0.4 ns	2.12 GHz
Optilab	PR-12-B-M	$1750	1250 - 1650 nm	29.13 ps	12 GHz
Emcore	2522 Microwave Packaged Photodiode	need to contact supplier	1280 - 1580 nm	15.9 ps	22 GHz
ThorLabs	DX20AF	$2310	1259-1650 nm	17.5 ps	20 GHz
Thorlabs	DET08CL	$325.49	800 - 1700 nm	70 ps	5 GHz

Table 21: Summarized part selection for PIN photodiode

3.9.2 Photodiode Driver

Photodiode driver circuits are used in optical communication systems to amplify the current generated by the photodiode in response to the incoming optical signal. The amplified current is then converted into a voltage, which is then processed by the receiver electronics to extract the data from the optical signal. Photodiode driver circuits are typically designed to maximize the signal-to-noise ratio (SNR) of the received signal. This is important because the SNR determines the bit error rate (BER) of the system. A higher SNR will result in a lower BER, which means that the system will be able to transmit data more reliably. In addition to maximizing the SNR, photodiode driver circuits are also designed to have a fast response time. This is important because the photodiode needs to be able to respond to changes in the optical signal quickly. A slow response time could result in data loss or corruption. Photodiode driver circuits are also designed to be linear. This means that the output voltage of the circuit should be proportional to the input current from the photodiode. This is important because the receiver electronics need to be able to accurately measure the amplitude of the received signal.

Photodiode driver circuits can be implemented using a variety of different circuit topologies. The most common topology is the transimpedance amplifier. A

transimpedance amplifier consists of a single transistor that is configured to convert the photodiode current into a voltage, which is then amplified and output to the next stage of the circuit. Other common topologies for photodiode driver circuits include the photoconductive mode circuit and the photovoltaic mode circuit. These two are the simplest types of driver circuit. They use only resistors and capacitors to bias the photodiode and provide a voltage output. However, a photovoltaic mode circuit is a circuit in which the photodiode is unbiased and connected to a high impedance load, whereas the photoconductive mode circuit is a circuit in which the photodiode is operated with a reverse bias and connected to a high impedance load. A photovoltaic amplifier is a logarithmic function of the incident power, which will not be ideal as this will result in slow response times to the optical signal.
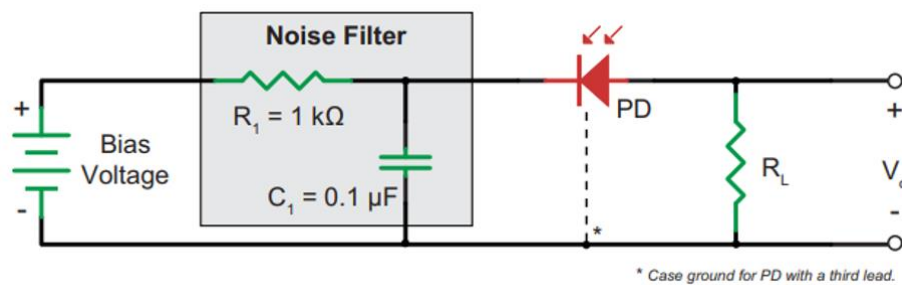
Figure 9: Recommended circuit from Thorlabs for FGA01 or FGA015 PIN photodiodes using a photoconductive mode topology
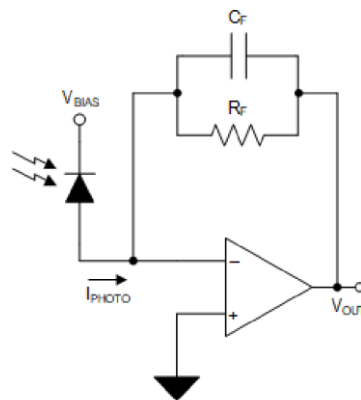
Figure 10: Possibly an alternative circuit for the PIN photodiodes using a Transimpedance Amplifier topology

The first design presented in figure 10, cascaded with a low-noise amplifier, is advantageous because:

1. It is the easiest circuit to design and build on a PCB.
2. It would also be able to work within the 5 MHz to 2.12 GHz frequency range.
3. Could amplify as high as 20dB.
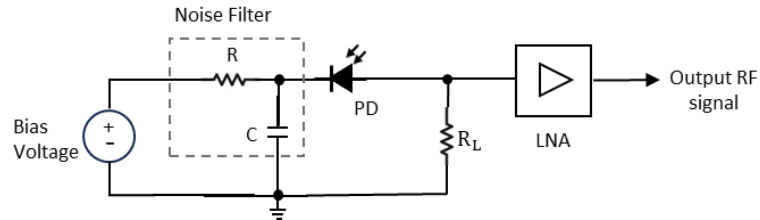
Figure 11: Selected photodiode driver circuit

Using the 2nd circuit design would not guarantee the same performance or benefits.

3.10 Optical Transmitter

3.10.1 Laser Diode selection

The following types of lasers are typically used in fiber optic communications:

- **Fabry-Perot laser (FP):** a common type of semiconductor laser used in fiber optic communication. It emits light over a wide range of wavelengths and is often used in short-haul communication systems.
- **Distributed Feedback (DFB) Laser**: a type of semiconductor laser that provides a single longitudinal mode of operation. They offer a narrower linewidth compared to Fabry-Perot lasers and are used in long-haul and high-speed communication systems.
- **Vertical-Cavity Surface-Emitting Laser (VCSEL)**: a type of semiconductor laser that emits light perpendicular to the surface of the chip. They are commonly used in short-haul communication applications, such as local area networks (LANs) and data centers.[38]

Type	Bandwidth	Spectral Purity	Cost	Typical applications
FP laser	Moderate	Moderate	Low	Short-distance communications
DFB laser	High	High	Moderate	Long-distance communications, high-speed data transmission
VCSEL	Moderate	Moderate	Low	Short-distance communications, optical interconnects

Table 22: Summarized technology investigation for laser diodes

For these reasons it would be best to work with DFB laser diodes as we have be doing long distance communications

Supplier	Part Name	Cost	Wavelength	Power
Thorlabs	L1550P5DFB	$90.55	1550 nm	5 mW
Thorlabs	L1510P5DFB	$90.55	1510 nm	5 mW
Thorlabs	L1530P5DFB	$90.55	1530 nm	5 mW
RPMC lasers	RWLD-1550S	$160	1550 nm	20 mW
Q-BAIHE	LSDLD1550-FC-MG	$66.88	1550 nm	4 mW
Laser Diode Source	LDI-1550-DFB-2.5G-20/70-B-2-SM1-FA-CW-0.5	$415.00	1550 nm	20 mW
Laser Diode Source	LDI-1530-FP-1.25G-15/50-B-2-SM1-FA-CW	$315.00	1530 nm	15 mW

Table 23: Summarized part selection for DFB laser diode

Given that our system requires two outputs, and we have used the CWDM standard spacing of 20 nm, we can use these two laser diodes that are commercially available at the correct wavelengths and require no customization.

3.10.2 Laser Driver

A laser driver is an electronic device that provides a stable, low-noise current source to a laser diode. Laser diodes are very sensitive devices, and their performance is highly dependent on the drive current. Any fluctuations in the drive current will be reflected in the laser diode's output power and wavelength. Laser drivers can be categorized into two main types:

- **Constant current drivers**: Provides a constant current to the laser diode, regardless of its voltage. This is the most common type of laser driver.
- **Pulsed current driver**: A pulsed current driver provides a pulsed current to the laser diode. This is typically used for applications where the laser diode needs to be turned on and off quickly. Ideal for direct laser modulation.
- **Constant power drivers**: Provides a constant optical power output from the laser diode. This is achieved by monitoring the laser diodes output power and adjusting the drive current accordingly. These are more complex and expensive than constant current drivers, but they can be useful for applications where a precise optical power output is required.
- **Buck converter driver**: This is a more complex laser driver circuit that is suitable for laser diodes. It uses a buck converter to regulate the voltage and current to the laser diode.
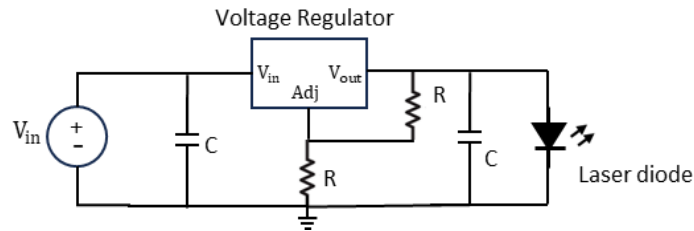
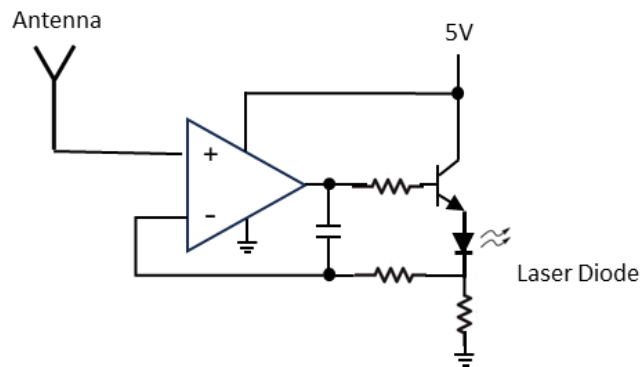*Figure 12: Potential design for a constant current laser driver*

Figure 13: Potential design for a pulsed current laser driver
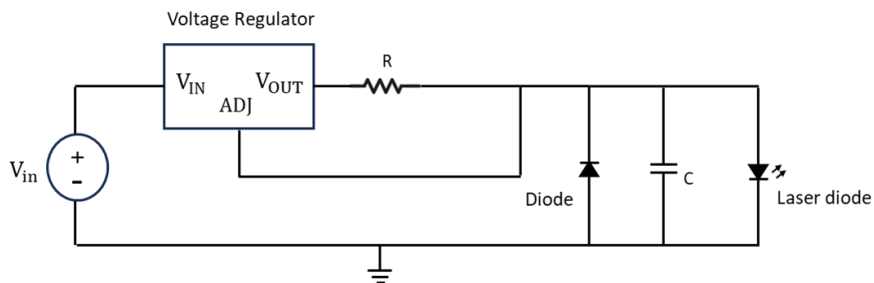

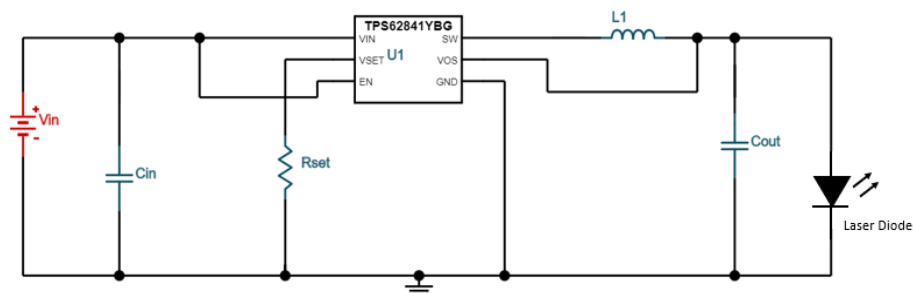*Figure 14: Alternative design for a constant current laser driver*

Figure 15: Potential design for a buck converter laser driver

Figure 14 or 15 is potentially the design we would like to use for the laser driver.

3.11 Software Technologies Comparison

3.11.1 Microcontroller Programming Language

The chosen programming language we have utilized for this task is a specifically designated C language in the context of UART. The chosen programming language is dependent upon the selection of MCU, and thus there is no need to compare selections here. The underlying concept behind the switching mechanism will revolve around the utilization of binary code, acting as a guiding framework for the microcontroller to determine the intended destination of the signal beam. This approach aims to streamline the entire process, enhancing the ease of programming and facilitating the debugging phase.

To facilitate simplicity, we have the capability to initially position all the switches in an identical starting configuration. Consequently, when encountering a 0, the switches will revert to their respective initial positions if they are not already placed there. Conversely, a value of 1 will trigger a switch to an alternative position, provided that the switch has not already reached that state. This systematic approach allows us to leverage the power of binary representation, wherein the number of required bits expands exponentially on a scale of 2 raised to the power of n.

Upon implementing this code, we have conducted a series of rigorous tests to scrutinize its effectiveness. By physically following the trajectory of the line, we have been able to discern whether the signal has inadvertently deviated from its intended destination, thereby enabling us to pinpoint the precise location of any errors that may have occurred.

3.11.2 SDR#

SDR# is a simple application that is accepted for most SDRs. It is a downloadable application. It says and appears to be intuitive with many of the functions readily available. It also has multiple useful functions such as digital noise reduction, offsetting, filtering, and automatic gain control.[39]

Digital noise control will be essential to what this project will be used for even though we have been generating the signal for this project, the intent is to receive a generic signal and be able to transfer it properly over fiber. An antenna will naturally pick up noise from signals other than the intended one, so having software that can reduce that from happening will be tremendous. This will make the signal clearer and be able to amplify such signals if they are weak.

Offsetting is a way to adjust weak signals. Offsetting helps to make a weak signal more visible as it accentuates the signal and makes it easier to spot what is needed.

Filtering is another useful function. The bandwidth of a radio can be very wide so having a built-in filtering system helps to adjust that range and helps to hone in on specific signals that one might favor. Filtering essentially allows for a system to restrict what is detected and narrow its field of range.

Automatic gain control will help in the other aspect of a signal, where if a signal is too strong, we can limit it. This will make it so that a stronger signal won't break the system in the sense that it will spike too much and not transfer the proper signal because of that. The gain control will make it so that it won't spike and return it to a normal signal.

3.11.3 GNU Radio

A GNU Radio is a free and open-source software development toolkit for building software-defined radio (SDR) systems. It provides a collection of signal processing blocks and a framework for creating radio applications. GNU Radio allows users to design and implement real-time signal processing systems by connecting these blocks together to create a flowgraph. At its core, GNU Radio consists of libraries, tools, and a comprehensive set of signal processing blocks for tasks like modulation, demodulation, filtering, data encoding, decoding, and more. These blocks can be combined through a graphical interface or written in Python code to create complex signal processing flowgraphs. GNU Radio also provides support for various hardware platforms, including popular SDR devices like the Universal Software Radio Peripheral , HackRF, and LimeSDR.[40]

One of the key features of GNU Radio is its flexibility. Users have the freedom to experiment with different algorithms, modulation schemes, and protocols, as well as create custom blocks to suit their specific needs. This allows for rapid prototyping and development of custom SDR applications.

GNU Radio supports various communication standards and protocols, making it applicable to a wide range of domains. It is widely used in academic and research institutions for exploring new radio technologies, implementing wireless communication systems, and conducting experiments in areas such as cognitive radio, wireless networking, and spectrum sensing.

Due to its open-source nature, GNU Radio is constantly evolving with new features and improvements contributed by the community. This makes it a powerful and cost-effective tool for educators, researchers, hobbyists, and professionals in the field of software-defined radio.

In summary, GNU Radio is a versatile and powerful software toolkit for building software-defined radio systems. Its extensive collection of signal processing blocks, support for diverse hardware platforms, flexibility, and active community make it a popular choice for exploring, prototyping, and implementing various wireless communication applications.

We can use GNU Radio's versatility and powerful software toolkit to build a radio for testing. We can thus simulate specific signals and test specific scenarios to ensure our design is working.

3.11.4 Radio Comparison

As the starting block of this project, we have needed a radio to provide a signal to the antennas. That's where the software defined radio and GNU radio come into place. Both choices are better than a traditional radio being able to adjust to the circumstance and issues that will inevitably occur in a project. The flexibility of both is pivotal to us as we are not as experienced and need something dynamic enough to be adjusted as we need it and not have to order another part when it doesn't quite work into our design. The SDR will work as a dedicated system that will process the signals. The GNU radio will supplement it as it provides additional functions we are looking for as it can provide filtering, modulation and demodulation, channel coding, and many more. This will simplify our process as we can condense the number of parts we need and be able to adjust everything in software instead of replacing hardware.

SDR technology provides a revolutionary approach to radio systems by enabling the majority of signal processing tasks to be handled in software rather than relying on fixed, hardware-specific components. This adaptability is particularly valuable for a project where circumstances and issues are likely to arise, as it allows us to adjust the radio's behavior without the need to replace or modify hardware components. SDR's ability to modify parameters in real-time and process signals dynamically aligns perfectly with our project's requirements.

Complementing the SDR, GNU Radio serves as a powerful software toolkit that extends the capabilities of our radio system. It adds a layer of functionality that goes beyond basic signal processing. With GNU Radio, we can implement various signal processing functions such as filtering, modulation, demodulation, channel coding, and more—all within the realm of software. This level of versatility is pivotal for our team, especially considering our level of experience. Instead of relying on a rigid, fixed hardware setup, we can make adjustments and optimizations directly in the software domain.

The synergy between SDR and GNU Radio streamlines our project significantly. The dedicated processing capabilities of the SDR are enhanced by the rich feature set provided by GNU Radio. This not only simplifies our overall system architecture by reducing the number of physical components required but also

empowers us to adapt and refine our radio system on-the-fly. As a result, we can iterate more efficiently and overcome challenges without the need for extensive hardware modifications.

In essence, the combination of SDR and GNU Radio marks a strategic choice at the project's outset, providing us with a flexible, software-driven solution that aligns seamlessly with our dynamic needs. This approach not only simplifies our design but also empowers our team to navigate the complexities of signal processing and radio communication with a versatile and adaptable toolkit.

3.11.5 Programming HackRF One

The coding of the HackRF will be quite simple as it is very intuitive. The device already has many functions set up in it and we have only had to learn how to configure the frequency that we want and send it as such. The drag a drop feature makes it so that the visual representation of what is happening is very clear. Adjusting values will be quite easy as well as each block will have its corresponding range and function. This will be used as a test source to make sure that the system is working as we know what is being sent and what is received is matching.
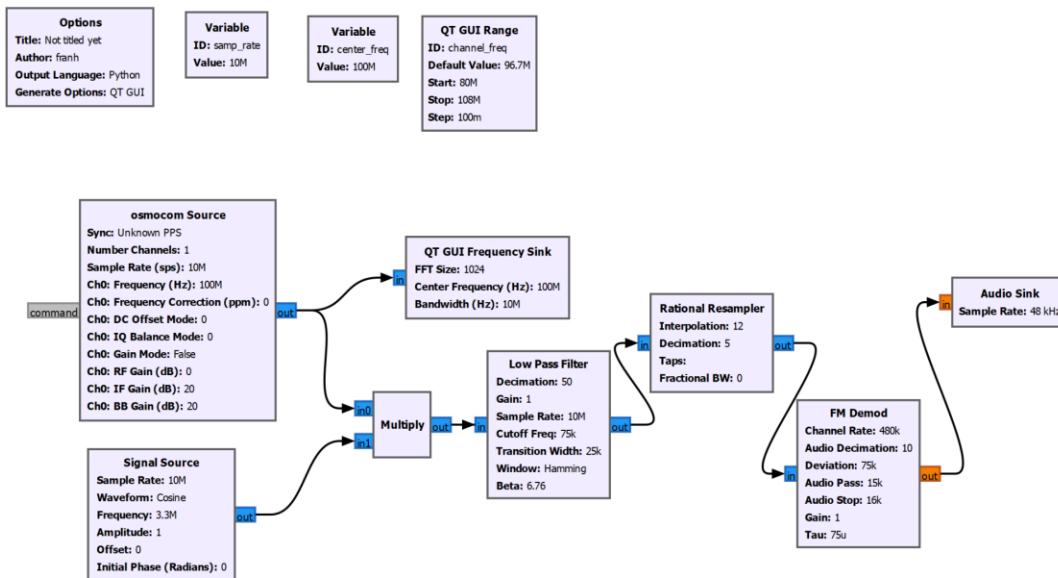

Figure 16: Example SDR design for receiving FM radio channels

This is a test of the device and the receiver. It is set up as a FM radio. It was set up to receive radio waves from 80M to 108M. It picks up a few channels but is not strong enough to clear through most noise in the air.

3.12 Encryption

3.12.1 Blowfish encryption

Blowfish encryption is a 64-bit cipher block that was designed by Bruce Schneier. It was intended as a fast alternative to the Data encryption standard. Blowfish is faster than the data encryption standard, not to mention it is free to use by the public. However, it was fair in a replacement to the data encryption standard due to the smaller block size that gave it its speed. Not only that but due to the small size of the block it was easier to attack the algorithm by hackers as it was easier to brute force the algorithm and mess with the encryption that way.

Blowfish is still used in practice today though. It can be utilized in applications such as bulk encryption, random bit generation, data backup, and much more.[41]

3.12.2 Twofish Encryption

Twofish is the successor to the Blowfish. The improvements came mainly from its change in block size as it doubled in size going from 64 bits to 128 bits. This allowed Twofish to be able to take on larger tasks that Blowfish could not handle and made it more secure in the process.

While Twofish may not see as much usage as its predecessor or some alternative encryption methods, it still finds application in scenarios where the emphasis is on robust security. Twofish's resilience against certain cryptographic attacks, combined with its larger block size, makes it suitable for specific use cases where the trade-off in speed is acceptable.

In summary, Twofish stands as a successor to Blowfish, implementing a significant improvement in security through the doubling of its block size to 128 bits. Despite its enhanced security features, its slower computational speed has impacted its widespread adoption, leading to its use in scenarios where security considerations outweigh the need for rapid processing.[41]

3.12.3 Data Encryption Standard

The data encryption standard is another encryption method that was created in the 1979s by IBM. This was the standard of encryption at the time. It is used for things such as electronic codebooks, cipher block chaining, and output feedback.

Data encryption standard uses a 56-bit key that does 16 rounds of processing to become encrypted. Each round would involve substitution, permutation, and mixed operations. This creates a tough encryption that is tough to crack.

Data encryption standard is significant to the progress of encryption but is now obsolete due to the fact that its cipher block is now considered too small and not as secure as its predecessor the Advanced encryption standard.[42]

3.12.4 Advanced Encryption Standard

The advanced encryption standard is currently the most widely used encryption method. It replaced the data encryption standard back in 2001 and has since been chosen as the standard of encryption by not only the United States government but also by many other private sectors.

Advanced encryption standard has three cipher blocks from 128 to 192 to 256. The 256-bit cipher block is the most robust of the three and would be considered the most secure. Though it is considerably slower and the fact that the other two cipher blocks haven't been decrypted and would provide the same level of security essentially.[43]

3.12.5 Feistel Cipher

Feistel Cipher is a symmetric structure used in the construction of block ciphers. Named after Horst Feistel, who designed it in 1973, and characterized by its iterative and reversible algorithm used to encrypt and decrypt information. It uses a round function which takes two inputs, the data block and a subkey, XORing the results repeatedly and returning half an output. This is done for an amount of time or rounds. In each round, the whole block is applied to the function but only half of it is kept. The side kept is switched per round.

3.12.6 Substitution-permutation

Substitution-permutation networks, commonly referred to as SP networks, represent a cryptographic structure used in block ciphers to achieve confusion and diffusion. The core idea involves employing substitution boxes (S-boxes) to perform non-linear substitutions on blocks of data, followed by permutation layers that rearrange the bits to introduce diffusion. This dual-layered approach enhances the security of the cipher by breaking the link between the statistical properties of the plaintext and ciphertext. The substitution step introduces non-linearity, making the relationship between input and output more complex and resistant to cryptanalysis, while the permutation step ensures that the influence of one input bit is spread across the entire block. Well-known block ciphers such as the Advanced Encryption Standard (AES) utilize substitution-permutation networks in their design, showcasing the effectiveness of this cryptographic concept in achieving a robust combination of confusion and diffusion for secure data encryption.

If we were to select an encryption method, we would probably go with the AES as it is one of the current stands of encryption. It has a more secure method of encryption as it mixes the message more and is hard to crack without the decryption key.

3.12.7 Encryption Comparison

To ensure the utmost security for our product, we have incorporated a robust encryption mechanism into the digital representation of our signals. Encryption, by definition, is a vital procedure that transforms digital information into an indecipherable format, thereby safeguarding it against unauthorized access. This formidable protective measure renders the information incomprehensible without the corresponding encryption key, reinforcing the overall security framework. In our pursuit of utmost diligence, we employ various common encryption algorithms such as Blowfish, Advanced Encryption Standard (AES), Data Encryption Standard (DES), and Twofish. These algorithms have been widely adopted and recognized for their effectiveness in preserving data integrity and confidentiality. Embracing these tested and trusted encryption techniques elevates the level of security we offer, ensuring the peace of mind of our valued audience.

1. Blowfish
    a. A symmetric-key block cipher with 64-bit block size.
    b. Designed by Bruce Schneir, it was designed to be a general-purpose algorithm and an alternative to Data Encryption Standard
2. Twofish
    a. A symmetric-key block cipher with 128-bit block size
    b. Designer by Bruce Schneir, it is a more modern form of the Blowfish
3. Data Encryption Standard
    a. A symmetric-key algorithm with 64-bit block size
    b. Designed by Horst Feistel, it was original designed for the National Bureau of Standards
4. Advanced Encryption Standard
    a. A symmetric-key algorithm with 128-bit block size
    b. Designed by Joan Daemen and Vincent Rijmen, the successor to the Data Encryption Standard and is designed based on the substitution-permutation network, which essentially is a series of linked mathematical operations to create the cipher block.

Name	Cipher Block	Structure	Shifting Rounds
Blowfish	64 bit	Feistel	16
Twofish	128 bit	Feistel	16
Data Encryption Standard	64 bit	Balanced Feistel	16
Advanced Encryption	128 bit	Substitution-permutation	10, 12, 14

Standard			

Figure 17: Summarized technology investigation for encryption

The choice in what to select is clear as the Advanced Encryption Standard is the standard of encryption for not only the U.S government but also many private sectors. The security provided by the Advanced Encryption Standard is unmatched. It is not the fastest encryption method but it does provide enough speed along with the size of it cipher block allowing for larger encryption schemes.

4. Related Standards and Design Constraints

4.1 Relevant Standards

As we have been working with various types of RF signals, it is important that our signals meet the standards of the intended application. These standards, and the organizations that create them, are dependent upon the signal type being transmitted. Additionally, there are standards that relate to the safe use of lasers that will be relevant to this project. We also must consider standards that relate to fiber optic communications, both generally and with respect to RF over fiber systems in particular.

4.1.1 ITU G 694.1/694.2

Wavelength division multiplexing is standardized by the International Telecommunications Union (ITU). The ITU publishes ITU G 964.1 and G 964.2 which deal with DWDM and CWDM respectively.[26, 27] These documents outline frequency grids for each type of WDM, which are sets of frequencies to be used for WDM communications. In addition to these nominal frequencies, these documents also detail the slot width, or how wide the frequency range of each signal can be. ITU G964.2 defines CWDM spacing of 20nm, with a reference wavelength of 1551 nm.

The use of 20 nm is designed such that CWDM can be performed by modern uncooled laser sources. According to the standard, modern uncooled lasers should be capable of producing a spectrum with a width of 6-7 nm. This gives a wavelength spacing of 20 nm, as it is desired to have WDM channel spacing of approximately three times the laser spectrum width. In contrast, ITU G964.1 defines the DWDM wavelengths in terms of frequency, with a reference frequency of 193.1 THz. The standard provides several options for the frequency spacing between adjacent signals. These include 100 GHz, 50 GHz, 25 GHz, and 12.5 GHz spacings. These small wavelength separations require the use of cooled lasers with smaller spectrums. In addition to the standard frequency slots defined according to the reference frequency of 193.1 THz and equal slot width, the standard allows for the use of a flexible grid of frequency windows. For our project,

we have been using CWDM and so the standard G 964.2 is the most relevant for us.

4.1.3 ITU G.9803

The ITU also publishes a standard detailing the operation of RF over Fiber links: ITU G.9803. This standard outlines the basic functioning of an RF over Fiber system. This includes the fundamental components of RFoF stated in the standard as:

- Electrical interface to put the waveform information into the RoF system
- Electrical-to-optical (E/O) conversion of the waveform information for generating the RoF signal
- Optical interface to transmit the RoF signal into an optical fiber
- Optical interface to receive the RoF signal from an optical fiber
- Optical-to-electrical (O/E) conversion of the waveform information for detecting the RoF signal
- Electrical interface to output the waveform information from the RoF system[44]

From this, we have developed our system to satisfy these requirements with the following components respectively:

- RF front end including antenna, filters, and amplifiers
- Mach-Zehnder Interferometers
- Collimating and focusing lenses to convert from free space to fiber-coupled light. This is included in the multiplexing subsystem.
- High-speed photodiode and RF downconverter to convert to electrical signal readable by MCU
- MCU is able to output the received RF signal

This standard also details several requirements to keep in mind when designing an RFOF system: radio signal quality, latency, eye safety, and interoperability. The standard does not provide exact quantities for these requirements but rather states that they will be unique to the application of the system and should be determined by relevant standards and requirements of the RF signal being transmitted.

4.1.3 IEC 60825-1

The IEC 60825-1 is an international standard published by the International Electrotechnical Commission that deals with the classification and safety of lasers.[45] Of particular importance to us is the definition of laser classes, as this determines the safety features deemed necessary by the next standard, ANSI Z136. This standard, unlike Z136, quantifies the definitions of the laser classes. The standard defines the laser classes as follows,

- Class 1: Safe for viewing, even with optical instruments. This is quantified based on the accessible emission limit (AEL).
- Class 1M: Safe for viewing, except with some optical elements under conditions detailed in the standard
- Class 2: Lasers emitting at a wavelength between 400-700 nm, where the blink reflex is able to prevent damage from occurring.
- Class 2M: Where the requirements of class 2 are met, except when using optical instruments to view the beam under certain conditions.
- Class 3R: Lasers with an AEL less than 5 times that of a class 2 laser within 400-700 nm, and less than 5 times that of a class 1 laser outside of this wavelength range.
- Class 4: Laser capable of producing diffuse reflections that are dangerous. These lasers exceed the AEL requirements of class 3R lasers. Federal regulations dictate that class 4 lasers have a keyed interlock system integrated into them.

4.1.4 ANSI Z136 Standards

The ANSI Z136 standard details how to safely handle lasers and laser systems. This standard was created by the Laser Institute of America in partnership with the Occupational Safety and Health Administration as it deals with the safety regulation of lasers in a workplace.[46] In addition, the standard is certified by the American National Standards Institute. The standard details a rating system that organizes lasers into several classes based on wavelength, power, and safety features. It then details the proper procedures for personal protective equipment, engineering safety features, and operating procedures for lasers. The document is organized into several sections, numbered ANSI Z136.X.

The first document, ANSI Z136.1, is an overview of laser safety across industry and academia. This document lays out the definitions of the classes of lasers as well as general best practices when handling lasers of different classes. This includes both beam hazards and non-beam hazards such as electrical shock. It then describes the many different methods through which safe laser operation can be achieved, including PPE, warning labels, and proper operating procedures. The document defines the roles of a laser safety officer, as well as their responsibilities and duties. These include cataloging and classifying an organization's lasers, ensuring proper safety measures are in place, and educating personnel on laser safety.

The remaining 8 documents in the ANSI Z136 series cover laser safety considerations in specific use cases and environments. This includes standards specific to fiber optical communications, health care, hazard evaluations, educational institutions, outdoors, testing/labeling of lasers, use in research in development, and use in manufacturing. For this project, we are primarily interested in ANSI Z136.2 - Safe Use of Optical Fiber Communication Systems

Utilizing Laser Diode and LED Sources, and ANSI Z136.8 - Safe Use of Lasers in Research, Development, or Testing.

ANSI Z136.2 Deals with the eye safety considerations of light exiting the fiber of an optical fiber system. The standard details calculations for the safe distances at which the highly divergent beams from fiber optics can be viewed. These calculations determine the accessible emission limit, which is calculated based on the beam divergence, the distance from which it would reasonably be viewed, and the aperture size of the human eye. This method of determining the class of laser considers if the system will be in a controlled environment such as a locked room in which telecommunication equipment is installed. By restricting the distance from which these beams can be viewed, the risk of eye damage drops dramatically due to the divergence of the beam resulting in a reduction in the amount of energy that enters the eye.

In contrast, ANSI Z136.8 deals specifically with laser safety in the context of R&D and testing. It states that in these environments, it is common for standard safety procedures such as interlocks and housing to be disabled or not present. This increases the risk, and thus effective class, of the laser as the accessible emission limit may be increased due to the laser being operated without critical safety features. This is a necessary part of the R&D process, as these safety features must be developed during the process, meaning at some point they must be tested without them. There is a larger risk of laser injuries during optical alignment as the beam path is not yet fixed and must be accessible by the engineer. This can result in unintended changes in the beam path, and thus risk of laser injuries. In addition, during the assembly of the product, there is not yet protective housing, increasing the electrical as well as optical risks of the laser system.

4.1.5 Coding standards

The standards of coding can have several nuances going from person to person but generally they do not differ too critically. The goal of coding standards is to increase coding efficiency and to minimize errors or bugs from the code. A code that follows standards will be more readable and easier to look back at.

One of the most important standards of coding is to make clear variable names so that you know exactly what that variable should be used for. This allows for better transactions when altering values and when trying to find that variable later down the code.

Next is to have as few lines as possible. Not every code can be 50 lines, but reducing redundancy and simplifying the process will allow for the code to be more readable. A good standard in coding is when you repeat a line of code to do a calculation, one should instead create a function in the code that can be called on so that those lines of code do not repeat as often.

Another good standard of coding is making comments as you code about what a code should be doing. Countless times I have coded something wrong and had no clue what my code was doing because I did not comment anywhere. Since I started with comments to indicate what sequence I wanted my code to follow and allowed me to code more efficiently.

The standards are not just a suggestion, but necessary when working in groups to not create a cluttered mess as we all do not think the same, but having the same methods will create an easier workspace.

4.1.6 Encryption standards

Encryption standards and policies change depending on the circumstance. What is being encrypted plays a role in what should be done. The amount of people who need access to such information and what is contain can change the encryption method used. Common use and low classification will generally use a public as it is a cipher that is generated by an algorithm and produces a private key to decrypt it. While a private key is a single key created and is usually passed with the file, thus it is harder to hack into.

Though some encryption methods have not been cracked it is never too safe to have extra security, thus I would use at least a double encryption method which implements two encryption schemes onto the same text to allow for another layer of protection.

4.2 Design Impacts of Relevant Standards

4.2.1 Design Impact of ITU G 694.1/694.2

The standard ITU G641.2 imposes significant design restraints on the device. By standardizing the wavelength spacing for communications systems to 20 nm, this standard dictates the design of the multiplexing and demultiplexing systems. This is because the wavelength spacing between CWDM channels dictates the angular spacing between channels being combined/split with a diffraction grating.

For this reason, the selection of our diffraction grating is heavily influenced by this wavelength spacing set by the standard. We see in the design section that the separation angle between adjacent WDM channels is dependent on both the wavelength separation of the channels and the angular dispersion of the diffraction grating. We wish to find a grating that along with the 20 nm spacing will produce an angular separation that is large enough to be achievable in a reasonably sized device. However, we do not wish to have an angular separation that is too large, as this will limit the total number of channels that can be integrated. This is because we can only physically align beams over a certain range of angles onto the grating. Obviously, a range of angles greater than 180° is not physically able to be incident on the diffraction grating.

Even more limiting than this is the fact that the efficiency of the diffraction grating drops as we move away from the blaze angle. As a result, we have a limited range of angles over which a high efficiency can be achieved. For these reasons, we see that this 20 nm spacing standard dictates the diffraction grating that we have selected. The largest angular dispersion that we were able to find was 0.306 nm/mrad, which corresponds to an angular separation of 3.745 degrees. This largest possible angular separation puts constraints on the size or cost of the device. This is because to achieve this small angular separation, along with the physical dimensions of collimating lenses, it will take a path length of nearly one-third of a meter for the beams to be coincident upon the diffraction grating. This could be solved by using a lens system to demagnify the angular separation. This would be prohibitively expensive, however, as we would require the use of diffraction-limited optics to achieve a high coupling efficiency into a fiber after the multiplexing. So, we see that this standard forces a tradeoff between cost and device size, as the wavelength spacing is not a variable to be changed.

This standard also dictates the types of lasers that we use. The wavelength spacing of 20 nm is chosen in the standard specifically to function with uncooled laser diodes. For this reason, we have used uncooled laser diodes in our system to keep costs down while still meeting the requirements of the standard. As was mentioned in the standard, this requires that the bandwidth of the laser source must be less than 6-7 nm to have sufficient separation between channels. Thus, we must ensure that our laser diode sources have bandwidths less than this amount. Due to our desired SNR, we require a bandwidth even narrower than suggested in the requirement.

Although using CWDM results in looser requirements on laser bandwidths than DWDM, it results in a large total bandwidth of wavelengths used in the system. For example, if we used DWDM with 0.8 nm spacings, then for two channels our system optical bandwidth is 1.6 nm. However, as we are doing CWDM it is 40 nm. As a result, the components we use must have consistent performance across this larger range of wavelengths. This includes all optical components that may encounter either of the two wavelengths including optical switches, fiber couplers, optical modulators, photodiodes, and optical fibers. This means that this standard will inform the selection of essentially all of the optical components in the system. This will increase the cost of the system, as components with higher bandwidths are typically more expensive. However, this moderate increase in cost is offset by the large cost savings of using uncooled lasers.

Additionally, this design decision limits the total number of WDM channels that the system can be scaled to. For CWDM this is 18 total channels within the range of 1271 to 1611 nm. Within these same limits, you could fit 498, 996, 1992, and 3985 channels when using DWDM spacing of 100, 50, 25, or 12.5 GHz respectively. This is significantly more channels than is practically achievable with modern technology, and thus the number of channels is essentially unlimited with regards

to the wavelength spacing. Instead, the number of channels is limited by other factors involved in the design of the MUX/DEMUX system design. So, we see that by using CWDM we are putting an upper limit to the number of WDM channels that our system could possibly support. However, this also means that we need only design the remainder of the components to handle 18 channels. For example, it would be useless to design a complex MUX system that could theoretically handle more than 18 channels.

4.2.2 Design Impact of ITU G.9803

We have already considered the eye safety and signal quality concerns in other sections, but we must consider the need for interoperability and latency. With regards to interoperability, the receiver should be designed such that it could be used with any WDM channel within the CWDM range. This requires that the detectors have a high efficiency across the entire range of wavelengths to be used for the CWDM channels. With regards to antenna and RF front-end interoperability, this is not of concern to this project. This is because we are designing the RF front ends to operate at different RF signal bands. As a result, we would not wish to have these RF receivers to be switchable as they are fundamentally different in order to meet the needs of the sponsor. This means that we do not wish to have modulators from different RF subsystems to be switchable. This would require each modulator to have a bandwidth equal to the largest bandwidth channel in the system. This would require the use of optical modulators that would have a much larger bandwidth than necessary for some of the RF subsystems. As a result, this is not a reasonable level of interoperability. However, the entire RF subsystem consisting of the antenna, modulator, filters, and amplifiers should be swappable within the system. This requires that each of the RF subsystems be nearly the same in size, weight, and power requirements.

4.2.3 Design Impact of IEC 60825-1

The design impact of this standard is considered later in the section "Ethical, Health, and Safety Constraints."

4.2.4 Design Impact of ANSI Z136 Standards

The design impact of this standard is considered later in the section "Ethical, Health, and Safety Constraints."

4.3 Design Constraints

For the receiver part, the primary constraints are size, performance, and cost. Since we have a sponsorship cost will not be a problem in this case. However, when it comes to size and performance, it is imperative to have a portable system that does not occupy more than 30 cubic centimeters.

Now, when it comes to the performance constraint, this is determined by the signal-to-noise ratio of the system in the receiver for an adequate BER. In communication systems, this is directly related to the link budget analysis because this determines the minimum signal strength for reliable communication which of course varies according to the application and modulation scheme.

Furthermore, the manufacturing of the PCB also has constraints, but these are notified by the manufacturing company nonetheless, where the constraints are cases such as limitations in the vias, or whether they have the capability of filling up the vias with a material such as copper or making a multilayered PCB.

4.3.1 Design Constraints Due to Modulation Scheme

As discussed previously, there are many different modulation schemes that can be employed for RF signals including QAM, PSK, and OOK. Within QAM and PSK there are different numbers of symbols that can be used, resulting in different rates of bits per symbol. By increasing the number of symbols used, we are able to increase the data rate of the communications link. However, this results in the symbols being closer together with regards to amplitude, phase, or both depending on the modulation technique being used. As a result, using larger numbers of signals requires a smaller noise figure in order to resolve adjacent symbols. The type of noise that is relevant depends on the characteristic of the wave being used as the symbol. For example, when doing PSK we need to minimize phase noise, and when using QAM we need to minimize both phase and amplitude noise.

Each of these types of modulation and number of symbols will have a characteristic relationship between the signal-to-noise ratio and the error rate. These plots are known as waterfall plots and are used to analyze which modulation method is best for a given system. This decision is made based on the signal-to-noise ratio achievable in the system, along with the highest tolerable bit error ratio. An example of such a waterfall plot is shown below.
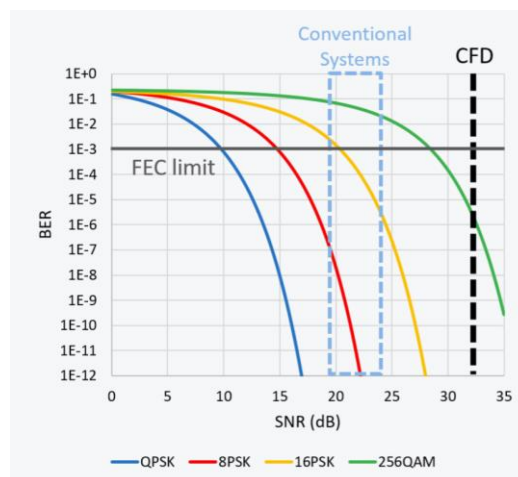
In the figure, we see a comparison of several different modulation schemes, and their associated BER vs SNR plots. The FEC limit corresponds to a bit error rate of 0.001. This is the error rate at which the use of forward error correction results in a final bit error rate that is essentially error free in the context of telecommunications applications. Of course, the system is not truly error free, but the errors are infrequent enough to make them negligible over a reasonable time frame. To achieve this essentially error free regime, we must operate with a signal to noise ratio equal to or greater than the intersection of the given modulation scheme's curve and the FEC limit. For example, if we wish to employ 256 QAM we would require a minimum SNR of about 28 dB, whereas for 16 PSK we would only require a minimum SNR of about 20. This presents a tradeoff between signal to noise ratio requirements and data throughput, with modulation schemes capable of transmitting higher data rates also having a higher SNR requirement.

We thus see that our selection of a modulation scheme dictates the SNR our system must achieve, which in turn puts a SNR on our individual components. The SNR of each component must be significantly lower than the required system SNR. This is because the noise of subsequent components in the system will add together. This includes both the optical and electrical components in the system. To achieve this SNR, we first needed to pick a laser that provides power several orders of magnitude larger than the noise floor of the photodiode plus the SNR. This is needed to account for losses that occur throughout the system. After this, we need to pick low-loss optical components. Additionally, we must carefully align the optical component to avoid unnecessary losses, especially the components involved in fiber coupling as even small misalignment can cause large losses. For these reasons, the system SNR will constrain the choices of nearly all components in the system, as well as the system architecture.

On top of the SNR ratio of the optical path, we also must ensure the SNR of the RF signal meets our requirements. To meet this requirement, we have needed to select RF components that have a low signal to noise ratio. This includes high quality filters, amplifiers with large gain, and making sure all components are impedance matched properly.

As a result of this high signal to noise ratio, we also require stringent testing of all noise sources in the system. Although many of the components include a nominal SNR as a specification, we must test that these components truly meet these requirements. Additionally, we must consider and test for external forms of noise. These include noise due to fluctuations in power supplied to components. Additionally, we must consider physical sources of noise in the system. Since we are using free-space optics, we must consider the impact of vibrations and air currents. For these reasons, we have required a well-constructed housing for the device to meet the large SNR required for the modulation schemes we wish to

employ in the system. This testing will need to be done at the individual component level, a subsystem level, as well as an entire system level.

To account for this design constraint, we have created a detailed link budget for the system. During the design phase, we have used nominal error values for each of the components to calculate the expected signal to noise ratio of the system. After testing of components, we have used the actual measured values in order to create an updated link budget.

4.3.2 Economic and Time Constraints

The economic considerations of this project primarily revolve around the cost of the system's components. Following an extensive investigation into the pricing of individual components, it was revealed that the optics segment accounts for the most significant portion of the budget. However, thanks to the generous sponsorship that has been secured for this project, the financial constraints have been substantially alleviated. With this sponsorship in place, a dedicated budget has been approved, ensuring that the necessary resources will be available for the successful execution of the project. We have received an upper limit to the budget of $15,000. However, the sponsor has expressed a desire to keep the budget below this maximum amount. The primary drivers of the cost are the photodiodes, laser diodes, and optical modulators. For all components, the price increases drastically as the bandwidth of the system increases. As a result, we have limited the bandwidth of our system to less than 5 GHz, as the cost of photodiodes increases rapidly beyond this point. Additionally, if we wish to implement DWDM rather than CWDM we would require temperature-controlled laser diodes in order to achieve narrow enough spectra. As a result of this constraint, we have chosen CWDM for our system.

Furthermore, the sponsorship has presented us with the invaluable opportunity to borrow certain components from the company's inventory. This strategic approach not only minimizes expenditure but also ensures that we have access to high-quality components without incurring additional costs.

Turning our attention to the electronics segment of the system, it's imperative to acknowledge that the cost dynamics are strongly contingent on the operational frequency. Particularly, if we aim to achieve the stretch goals set for this project, which involve attaining an operational frequency in the several gigahertz range, the expenses associated with numerous components can experience a significant surge. This underscores the importance of meticulous budget allocation and a strategic approach towards component selection to ensure that the project remains within financial boundaries while delivering optimal performance.

Both economic and time constraints limit the number of inputs and outputs that we can demonstrate. Each input requires a full RF front end, including an antenna, filter(s), and amplifier(s) as well as an optical modulator. These components are

very expensive and make demonstrating a larger number of inputs cost prohibitive. Additionally, each input will require the construction and integration of many components, so large numbers of inputs will greatly increase the time to construct and test the device. Increasing the number of outputs will increase the number of laser diodes and photodetectors needed, which both represent a significant portion of the total system cost. Also, we have required larger numbers of switches which can quickly add up in cost. For these reasons, we chose to make a 3-input 2-output system, as it demonstrates the switching capabilities of the design at the minimum cost. In addition, we have designed the system such that it can reasonably be scaled to larger numbers of inputs and outputs.

The time constraints of the project also limit the suppliers and products that we can consider. This is because some suppliers may have lead times on certain products of several weeks or even months. Due to the short time frame between finalizing our part selections and the end of the semester, we would not have time to wait for these lead times and then finish all necessary testing. For these reasons, we are limited in the components we may consider. This almost fully rules out the use of any custom optical products, as the lead times are typically longer than is feasible for our project.

Moreover, following extensive investigation into viable prototyping techniques for the receiver, we have arrived at the determination that the most advantageous approach is to prototype using the copper-clad PCBs readily accessible at UCF. These boards comprise a layered composition, with two copper layers flanking the dielectric substrate FR4 at the core. This choice stands out as the optimal solution due to the time constraints associated with obtaining a standard PCB, which typically entails a waiting period of approximately two weeks for shipment. By opting for prototyping with these copper-clad boards, we not only attain a higher degree of adaptability, but we also gain invaluable experience in design refinement, courtesy of the imperfections inherent to these boards.

4.3.3 Environmental, Social, and Political Constraints

The environmental, social, and political constraints of the project are minimal concerning the hardware. Regarding environmental constraints, our components do not contain any chemicals of special environmental concern. However, if any electrical components are to be broken and must be disposed of this must be done in accordance with environmental laws. If no components are broken, they will be the property of Critical Frequency Design after the project, and thus will not be disposed of.

However, when it comes to dealing with radio frequencies, the situation is not that simple because the radio frequencies are usually regulated by the government so that channels can be assigned for determined activities such as radio or television. Moreover, these radio frequencies are designated with a specific bandwidth,

meaning that they are limited to a frequency spectrum that can be used to transmit data.[47]

The Radio frequency (RF) side of the project is intended to operate in the Industrial, Scientific, and Medical (ISM) band, which is allocated from 433.05MHz to 434.79MHz. This band allows for the use of a bandwidth of 1.74MHz and a maximum power emission of 1 Watt. The designed system will operate within this frequency range and must not emit more than 1 Watt. If the operation range needs to be extended, modifications must be made on the receiver side to improve its sensitivity to pick up the signal from a further distance.

The ISM band is a license-free band, which means that devices operating in this band do not require a license from the Federal Communications Commission (FCC). This is because the ISM band is used for a variety of low-power applications, such as remote controls, wireless security systems, and garage door openers. The FCC regulations for the ISM band are designed to minimize interference between devices operating in this band.

One of the key regulations for the ISM band is the power output limit of 1 Watt. This limit is designed to prevent devices from interfering with each other. If a device were to emit more than 1 Watt of power, it could interfere with the operation of other devices in the ISM band.

Another key regulation for the ISM band is the bandwidth limit of 1.74MHz. This limit is designed to prevent devices from using up too much spectrum. If a device were to use more than 1.74MHz of bandwidth, it could interfere with the operation of other devices in the ISM band.

The ISM band regulations are important for ensuring that devices operating in this band can coexist without interfering with each other. By following the ISM band regulations, designers can help to ensure that their devices will operate reliably and will not interfere with the operation of other devices in the ISM band.

In addition to the ISM band regulations, there are also a number of design standards that apply to devices operating in this band. These design standards are intended to help ensure that devices are designed in a way that minimizes interference with other devices.

One of the key design standards for devices operating in the ISM band is the use of directional antennas. Directional antennas focus the signal in a specific direction, which helps to reduce interference with other devices.

Another key design standard for devices operating in the ISM band is the use of frequency hopping. Frequency hopping is a technique where the device changes its frequency periodically. This helps to reduce interference with other devices by

preventing the device from transmitting on the same frequency as another device for a prolonged period.

4.3.4 Ethical, Health, and Safety Constraints

Due to the nature of the wavelength of light being used, we must be careful to ensure proper safety constraints are met during the development and operation of the system. As discussed previously, the lasers we are using will fall into class 3R. As a result, they are potentially hazardous to the eye. Additionally, since we are operating in the NIR range, these lasers are not visible and as such the blink reflex does not serve to protect the eye from these lasers. As a result, we have required safety goggles rated for the appropriate wavelength range including 1530-1550 nm when working with these lasers. Although this will be satisfactory during development and testing, the final project will need to be demonstrated. As a result, we have required that these lasers be housed such that they are contained inside the device housing. Additionally, there should be a turnkey system set up such that the lasers can be removed from power. This will ensure that there is no accidental powering of the lasers, which could result in potential injuries. While not legally required as this is not a Class 4 laser, this is still a potential safety hazard that must be addressed.

In addition to this, there are other safety features that must be implemented into the device. We must include a label on the device warning that it produces potentially harmful radiation, along with the wavelength and power of light generated. Examples of these graphics are publicly available, and thus this should be easy to achieve. Additionally, when working with the lasers we must inform those occupying the lab space we are in and provide adequate eye protection for those in the lab. For these lasers, it is required that anyone operating the laser has taken a laser safety training course. For the two photonic science and engineering students, this requirement is already met as the completion of the University of Central Florida's laser safety training course was a requirement in order to obtain access to the CREOL senior design lab. In order for the remaining members of the team to operate the lasers, they must also complete this laser safety training course in order to properly understand the safe handling of lasers.

4.3.5 Manufacturability and Sustainability Constraints

The manufacturability constraints integral to this project, particularly concerning the RF receiver, primarily revolve around the PCB fabrication process. Our intention is to entrust this task to a reputable service provider like JLC or PCBway. This undertaking encompasses the intricate tasks of PCB design and layout, as well as the procurement of essential components, including pivotal elements like the antenna and amplifiers. These requisites will be conveniently sourced from reputable online electronic shops such as Digi-Key or Mouser Electronics. Depending on the level of service offered by the chosen PCB manufacturer, one plausible scenario entails us personally soldering the components onto the PCB.

The sustainability facet of this project introduces certain complexities, particularly since it contemplates the potential need to modify components of the PCB. This may inevitably lead us to acquire the components outright and undertake the soldering process ourselves, utilizing the available materials and equipment at UCF. This stems from the consideration that depending on the material used by a service provider for component soldering, the process of desoldering specific components may prove challenging. Therefore, the most judicious course of action would be for us to perform the soldering ourselves.

5.   Analysis of LLM for Senior Design

5.1 Analysis of ChatGPT for use in Senior Design

Large language models (LLMs) have recently gained immense popularity as a tool for generating text in many formats and for varied purposes. Given a text prompt, LLMs are able to generate responses to these questions that far exceed previous artificial intelligence systems in quality. LLMS function by generating words one at a time, each time predicting the next most likely word based on large databases of training data.[48] LLMs have been developed that can provide reasonable sounding answers to a wide variety of prompts, with perhaps the most popular of these being ChatGPT. ChatGPT has proven to be a valuable tool to many people for writing and learning, with ChatGPT commonly being used to output text that is to be published, or answer questions or provide explanations intended only for the user. In this section, we consider ChatGPT's ability to fulfill both roles in our senior design project.

Perhaps the most obvious potential use of ChatGPT is for writing sections of the paper that do not contain design work. This could include descriptions of background technologies. An example is given below of how this could be used in our paper to describe wavelength division multiplexing.

Prompt: Write a paragraph explaining the functioning of wavelength division multiplexing for fiber optic systems.

LLM Response: "Wavelength Division Multiplexing (WDM) is a crucial technology in fiber optic communication systems, enabling the simultaneous transmission of multiple data streams over a single optical fiber. It operates by dividing the optical spectrum of the fiber into multiple non-overlapping wavelength channels, each carrying a separate data signal. These wavelengths, often in the form of laser light, are combined at the sender's end and transmitted through the fiber optic cable. At the receiving end, a demultiplexer separates the combined wavelengths back into individual signals, allowing data to be transmitted and received independently. WDM significantly enhances the data transmission capacity of fiber optic systems, as it enables the parallel transmission of several signals over the same fiber,

thereby increasing bandwidth, reducing latency, and optimizing the utilization of the existing optical infrastructure. This technology is fundamental to meeting the ever-growing demand for high-speed and large-capacity communication networks in today's digital age."

This response from the LLM is largely well written and technically correct. However, it does not fully capture information that is relevant to the project, including how WDM can be performed. Another possible use of ChatGPT is to help explain concepts related to the product that may be confusing to us. An example is given below to explain how an optical modulator can change the intensity of a beam of light.

Prompt: How does a Mach-Zehnder Interferometer change the amplitude of light? I am confused how the phase shift can change the amplitude.

LLM Response: "A Mach-Zehnder interferometer (MZI) does not directly change the amplitude of light. Instead, it utilizes the interference of light waves to modulate the intensity of the output light. Here's how it works:

In an MZI, a single input light beam is split into two separate paths by a beamsplitter. These two paths travel different distances before being recombined at another beamsplitter to produce an interference pattern. When the two paths have the same length, the waves recombine either constructively or destructively, leading to either reinforcement or cancellation of the waves' amplitudes, respectively.

The key component that enables modulation of the interference pattern is a phase shifter. By introducing a phase shift to one of the paths (for example, by changing the refractive index of that path using an electro-optic modulator), the phase relationship between the two paths is altered. When the paths are recombined, the interference pattern changes, affecting the intensity of the output light. This change in intensity does not directly alter the amplitude of the light waves; rather, it results from the constructive or destructive interference of the waves.

In summary, the Mach-Zehnder interferometer utilizes phase shifts to modify the interference pattern of light waves, which, in turn, alters the intensity of the output light without directly changing the amplitude of the light waves."

The LLM provided a technical explanation that is concise, clear, and technically accurate. This seems to be a good tool for helping to explain technical concepts. However, the accuracy of these explanations must always be compared to trusted external sources. Next, we have seen how ChatGPT performs when given a specific design task.

Prompt: Design a multiplexing system for wavelength of 1530 and 1550 nm using a diffraction grating.

LLM Response: "In a Wavelength Division Multiplexing (WDM) system, a commercially available diffraction grating can be used to combine light from two lasers operating at 1530 nm and 1550 nm wavelengths. The diffraction grating would typically be specified by the manufacturer, and the necessary incident angles for the two wavelengths of light would also be provided in the product documentation.

Here is a general outline of the process without using equations:

Select a Diffraction Grating: Choose a diffraction grating with the appropriate specifications for your application. These specifications should include the groove density and blaze wavelength.

Consult Manufacturer Documentation: Refer to the manufacturer's documentation or specifications for the selected diffraction grating. The documentation will provide information on the recommended incident angles for specific wavelengths, including 1530 nm and 1550 nm.

Set Incident Angles: Configure the lasers to emit light at the incident angles specified by the diffraction grating manufacturer for 1530 nm and 1550 nm wavelengths. Proper alignment ensures that the diffracted beams overlap effectively on the output side, enabling WDM.

By following the manufacturer's guidelines, you can align the lasers at the correct incident angles without needing to calculate the angles using equations. It's important to rely on the provided specifications to ensure accurate and efficient wavelength multiplexing in your WDM system."

This response gives a good outline of how to go about the design and could be useful in helping an engineer to break down the task into smaller parts. However, it shows that ChatGPT is clearly not capable of doing design work or creating novel ideas. Next, we consider the use of ChatGPT as an aide for finding suppliers of components.

Prompt: What companies sell diffraction gratings at 1550 nm?

LLM Response: "As of my last update in January 2022, I don't have access to real-time data or specific product listings, including current availability or specific companies selling diffraction gratings at 1550 nm. However, I can mention that many optical component providers and distributors specialize in diffraction gratings.

To find diffraction gratings at 1550 nm, you can consider looking into well-known optics and photonics companies, such as:

- Thorlabs: Thorlabs is a reputable supplier of optics and photonics products. They offer a wide range of diffraction gratings suitable for various applications.
- Newport Corporation: Newport is another established company known for its optical components, including diffraction gratings.
- Edmund Optics: Edmund Optics is a global provider of optical components, including diffraction gratings designed for specific wavelengths.
- HORIBA Scientific: HORIBA offers diffraction gratings and spectroscopy solutions for scientific and industrial applications.
- Wasatch Photonics: Wasatch Photonics specializes in gratings and spectrometers for scientific and industrial applications.
- Kaiser Optical Systems: Kaiser Optical Systems is known for advanced diffraction gratings and spectrometer solutions."

Of the companies provided, several of them produce diffraction gratings at 1550 nm. However, not all of them produce the requested product. ChatGPT seems to be a useful tool to identify potential suppliers by narrowing your search down to a short list of options that are likely to have the product needed. However, it is not perfect, and it will still take manual searching to check each individual supplier.

Overall, ChatGPT is a valuable tool for aiding in writing, research, and design. We have seen through these examples that ChatGPT can produce writing on technical subjects that is descriptive and accurate. However, ChatGPT is limited to information available to it, which may not include more niche technical content or newer discoveries as it is limited to data from before 2022. Additionally, ChatGPT is not always 100% accurate, and as a result, any technical writing it produces must be fact checked. Depending on the content being produced, it may take just as long to fact check a ChatGPT response as it would to simply write the content yourself.

5.2 Summary of ChatGPT Analysis and Pros/Cons

ChatGPT can be a valuable tool to aid in understanding a topic by having ChatGPT explain things in a way that may be clearer to you. This is a valuable tool as you can ask ChatGPT your technical question in several different ways, and give additional prompts if the original explanation is not clear. However, this use case has the same problem as the previous one in that ChatGPT does not always produce accurate statements. For this reason, any understanding of a topic you gain from ChatGPT must be cross-referenced to a trusted source. However, this can still be valuable as hearing a topic explained in a different manner may help you to better understand the original source of the information. Additionally, ChatGPT struggles to accurately manipulate algebraic equations, and can often answer math problems incorrectly.

Pros	Cons
Can speed up the writing process	Can provide inaccurate information
Helps to identify potential suppliers	Limited with regards to recent information
Provides explanations of technical content	Cannot handle mathematical equations well
Can respond to follow-up questions dynamically, unlike static websites	Can only handle text inputs and outputs
Functionality can be extended with plugins	Certain features, such as plugins, require the paid version of the software

Table 24: Pros and cons of using ChatGPT for senior design projects

5.3 Alternatives to ChatGPT

There are many alternatives to ChatGPT that have been developed since its release, including Google Bard, Chatsonic, Claude 2, and more. While these are all general text based LLMs, there have always been more niche AI products developed with a specific use case in mind, such as GitHub Copilot which is an AI tool specifically designed to aid software developers in writing code. From our research into these tools, it seems that ChatGPT is the industry leader, with Google's Bard being a major competitor. For these reasons, we have compared these two tools for their usefulness to our project.

Bard functions very similarly to ChatGPT, but with some notable additional features. For one, Bard allows for images to be used as input by default whereas this is not a standard feature in the free version of ChatGPT. This has many uses, and in our case can be helpful for understanding diagrams related to our project. Additionally, Bard has a "Double-Check" button which allows you to easily use Google search in order to fact check the response generated by the LLM. Although you could use a search engineer independently with ChatGPT to achieve the same result, this feature speeds up the process, making it easier to fact check the LLM responses.

To test the image input feature of Bard, we input the following prompt to seek possible improvement to a block diagram of the optical systems included in the project.
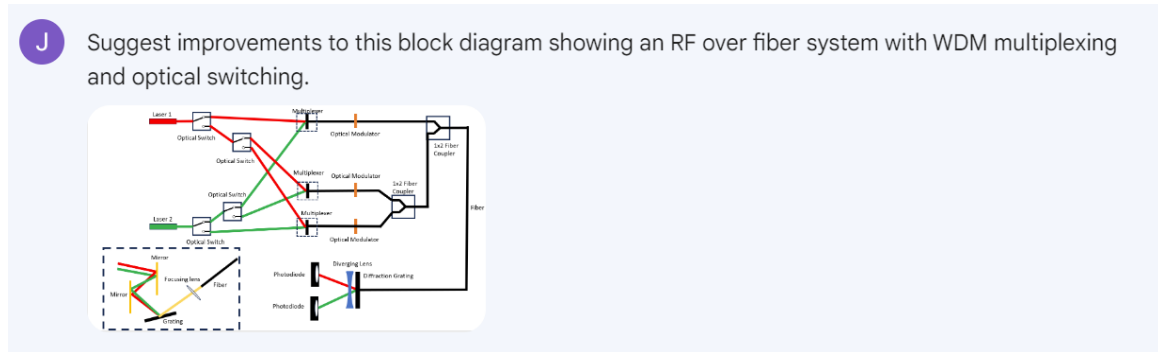
Prompt:

Figure 19: Example multimedia prompt for Google Bard LLM

LLM Response: Here are some suggestions for improvements to the block diagram showing an RF over fiber system with WDM multiplexing and optical switching:

- Add a circulator after the optical switch to prevent reflections from interfering with the signal.
- Add an optical amplifier after the circulator to boost the signal before it is transmitted over the fiber.
- Add a variable optical attenuator (VOA) after the optical amplifier to control the power level of the signal.
- Add a dispersion compensation module (DCM) after the VOA to compensate for dispersion in the fiber.
- Add a second optical switch at the receiver to select the desired RF signal.
- Add a second optical amplifier after the second optical switch to amplify the signal before it is demodulated.
- Add a bandpass filter after the optical amplifier to filter out unwanted noise.
- Add a low noise amplifier (LNA) after the bandpass filter to amplify the signal before it is demodulated.
- Add a demodulator to convert the optical signal back into an RF signal.
- Add an RF amplifier to amplify the demodulated RF signal before it is sent to the end device.

These suggestions are for the most part technically accurate and provide reasonable suggestions for potential hardware additions to the project. However, Bard suggests adding a second switching mechanism to select the desired RF signal. This does not make sense in the context of our project, as the combination of the wavelength selectivity of the WDM demultiplexer and the optical switching on the front end of the device already allows for the RF channel going to a given receiver to be selected. This shows that while Bard can interpret image inputs reasonably well and provide appropriate selections, it does seem to have trouble with concepts that require multiple steps of logical reasoning. While the suggestions it gives are in general good suggestions for most RF over fiber systems, the LLM is unable to truly understand the needs and purpose of our

system and as such seems to simply parrot responses typical of these types of systems, rather than be capable of making logical decisions based on the specific situation.

5.4 ChatGPT vs Google for Coding

ChatGPT has changed the field for coding. Coding has become more accessible and simple codes have been made easier. However, ChatGPT has yet to reach the level of coding more nuanced software. ChatGPT can create a solid floor to work off of allowing for redundancies to be reduced and coding remedial components quicker. It is getting better everyday at coding, however it does still make mistakes and is hard to catch if one does not at least have a little experience in coding.

Google in turn helps in those more niche situations but it does not have all the answers. If one is trying to code something of high difficulty, one is less likely to find a source explaining how to do it. Though Google does have resources that will teach one how to code.

Both resources are useful in their own right, but learning code is still the best idea today if one wants to be able to code for the industry.

6. Project Hardware Design Details

6.1 Multiplexing/Switching Design

For the optical switching subsystem, we require a subsystem that can take two beams as input and direct each beam to the desired output. For this system, it has been requested by the sponsor CFD that the system be designed to have 2 inputs and 3 antennas, or outputs. It has also been requested that the system be non-blocking, meaning that if desired the same input can be directed to multiple outputs.

In order to create an optical switching system, we require a component that can selectively steer beams down one of two optical paths. For this component we have chosen to use a fiber-based, MEMS optical switch. As described previously, this switch can direct an input to one of two outputs. Although they are MEMS-based, these devices are highly reliable and able to sustain the operation of lifetimes as long as 10^9 cycles.[30]

In order to operate these switches, we require a driving circuit that takes in a pulse from the MCU and outputs the necessary pulse to switch the fiber output. The manufacturer of the switches (Agiltron) provides a schematic for a recommended driving switch. This circuit takes a 5 V pulse as input, which allows for easy integration with the MCU as its output pins can produce 3.3 V pulses that can be

upconverted to 5V. As we are making use of several of these switches, we have required a PCB with a number of these driving circuits equal to the number of switches being used.
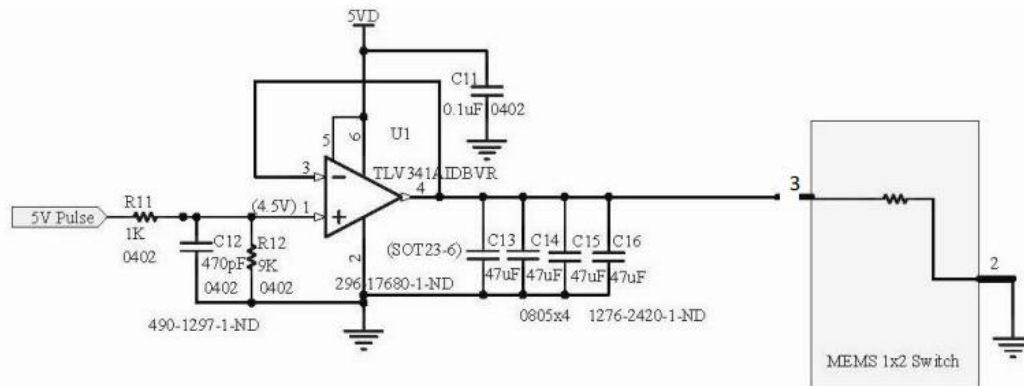

Figure 20: Recommended Switching Circuit from Agiltron (Reproduced with permission)

From this basic switching mechanism, we can design switching systems with larger numbers of inputs and outputs. To achieve the requested 2 input 3 output configuration, we have created two 1x3 switches. Each switch will direct a given WDM channel to one of three outputs. These 1x3 switches will be constructed using two 1x2 switches as shown in figure 21.
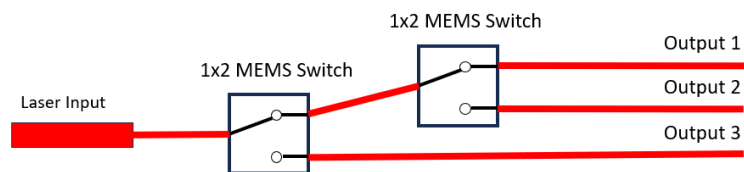

Figure 21: Design of a 1x3 switch from two 1x2 switches

This asymmetrical 1x3 slightly complicates the design of the switching system, as light directed to output 3 passes through only one switch while light directed to outputs 1 and 2 pass through two switches. As a result, outputs 1 and 2 will experience double the insertion loss of the 1x2 switches, while output 3 only undergoes a single insertion loss. As a result, the power transmitted through output 3 will be larger than the power transmitted through outputs 1 and 2. This is undesirable, as the optical modulation system will not properly modulate the signal if the power changes. However, this can be compensated for in the software by supplying different drive signals to the optical modulators with different powers. Additionally, there will be variation in the insertion loss of different units of the 1x2 MEMS switches. By testing and characterizing the losses of each switch, we can calculate the losses of each optical path. We can then feed this information to the software controlling the drive software and compensate for this variation in insertion loss by modifying the drive signal sent to each modulator.

To create a 2x3 switch, we have used two of these 1x3 switches. Output 1 of the two 1x3 switches need to be directed to modulator 1, output 2 to modulator 2, and output 3 to modulator 3. To combine the corresponding outputs of the two 1x3 switches, we have used a diffraction grating before each modulator. This could also be done with a beamsplitter cube or more fiber-based MEMS devices. However, the beam splitter cube would only work because we are using two wavelengths, and this solution would not scale. The MEMS beam combiner can scale, however, the number of these devices needed scales linear with the number of WDM channels. In contrast, a single diffraction grating can scale to larger numbers of WDM channels without needing additional components. Thus, for an mxn switch, where m is the number of inputs and n is the number of outputs, we require m 1xn switches and n diffraction gratings. Each 1xn switch requires 1-n of the 1x2 switches, for a total component requirement of m(1-n) 1x2 switches and n diffraction gratings.

For larger values of n, however, it may become economically advantageous to directly purchase the 1xn switches rather than building them from the 1x2 switches. For our case of a 1x3 switch, we see that two 1x2 switches are generally cheaper than a 1x4 switch. We compare our 1x3 switch design to a 1x4 switch rather than a 1x3 switch as MEMS optical fiber switches are not commonly available in a 1x3 configuration.
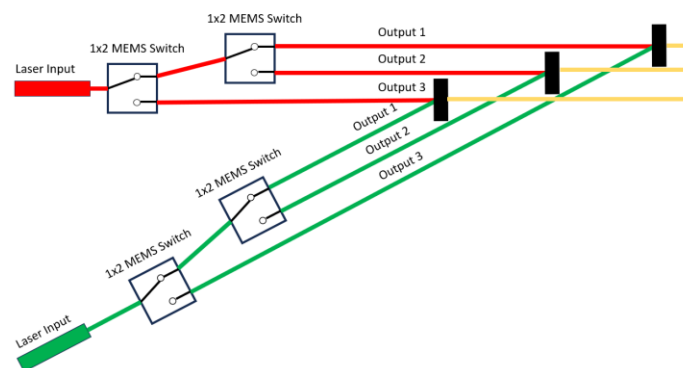

Figure 22: Design of a the 2x3 switching/multiplexing system

In order to combine the different spectral channels at each of the diffraction gratings, we must first collimate the beams from each of the fiber outputs of the 1x3 switching systems. This will require a short focal length collimating lens in order to minimize the beam size. After being collimated, the light from each output must be incident upon the correct diffraction grating at the correct angle. We can then solve for the necessary incident angles of the beams from the diffraction grating equation of $sin\ (\theta_m) = sin(\theta_i) + m\lambda f$ where θ_m is the angle of the mth diffracted beam, θ_i is the incident angle, λ is the wavelength, and f is the frequency of the diffraction pattern. As we are coaligning the beams, we wish for each beam to exit with the same angle θ_m. We have operated the system centered on the blaze angle in order to minimize power losses, so we set $\theta_m = 68.43^O$. We then solve for θ_i at each wavelength as $\theta_i = asin(sin(\theta_m) - m\lambda f))$. At the 20 nm

spacing of the WDM channels and the angular dispersion of 0.306 nm/mrad, we have an angular separation out of the diffraction grating of 65.36 mrad, or 3.745^O.

As the beams diverge upon exiting the fibers, they will grow until they reach the collimating lens. To collimate the beams, the lens must be placed at a distance from the fibers equal to the focal length of the lens. We can thus relate the beam size to the divergence angle of the fibers and the focal length of the collimating lens as $r = f \bullet tan(\frac{1}{2} * asin(NA))$ where r is the beam radius, f is the focal length of the collimating lens, and NA is the numerical aperture of the fiber. We have needed to collimate each of these beams and direct them to the same location on the diffraction grating.
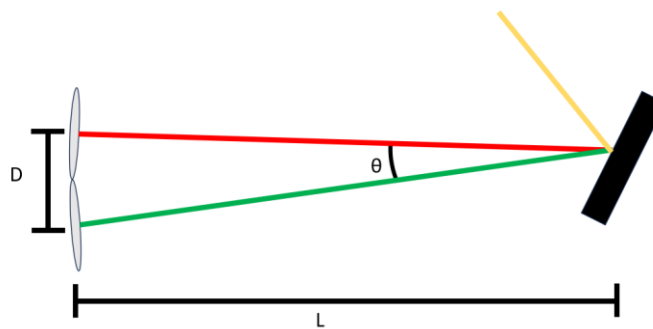

Figure 23: Geometry of angular separation of beams onto diffraction grating

For this setup, we see that the distance L can be found according to the equation

$$tan(\theta) = \frac{D}{L}$$

Due to the size of the collimating lens and mounts, the minimum distance between the beams is 25mm which will result in a value of L of 38.19 cm. This is undesirable, as it will dictate that the minimum device size in at least one dimension will exceed 38.19 cm. This is much larger than typical devices of this type. Additionally, this would result in either a very elongated shaped housing, or if a cubicle housing is used a large amount of empty space in the device. For this reason, we need to either shorten or fold these beam paths in order to fit them in smaller dimensions.

To solve this issue, we have used a multi-pass mirror system in order to shorten the largest dimension of the device. In order to achieve this, we have two parallel mirrors separated by a distance of 10 cm. The right mirror will have a lateral offset upward, allowing for the beams to enter the cavity from the left side. The beams will then be directed at an angle downwards such that they will make 3 one-way passes through the cavity before exiting to the right side once they have propagated below the right mirror. The beams will be separated by the necessary 3.745^O angle in the horizontal direction, while the surface of the mirrors will be oriented along the vertical direction. This allows for the separation angle to remain unaffected as the beams propagate through the cavity and incident upon the diffraction grating. Upon exiting the diffraction grating, the WDM channels will now be coaligned.

To design the cavity, we must consider the number of roundtrips in the cavity. More round trips shorten the distance between the mirrors, but at the cost of higher losses. The vertical distance traveled in a roundtrip, h, must also be greater than the size of the beam to allow the beam to exit the bottom of the cavity without clipping. We can relate L, h, and the vertical angle ϕ according to the equation $tan(\phi) = \frac{h/2}{L}$. In order to have a small device, we wish to have L < 5cm. We then require that 2.5*h > 25mm in order for the beam to exit the cavity. Additionally, we require 1.5*h < 23mm such that the last reflection from the right mirror does not clip off the mirror. As result, we see that 15.33 > h > 10 and we have set h to be the average of thse two extremes rounded to 12.5 mm. We now solve for $\phi = atan(\frac{h/2}{L}) = atan(\frac{1.25/2}{7.5}) = 4.764^O$. Each pass of the cavity has a path length of $\sqrt{(h/2)^2 + L^2} = 7.526\ cm$. So after 5 passes, we have an effective length of 37.63 cm. This gives us slightly less separation than the 38.19 cm needed, however this extra distance will occur both before and after the mirror cavity.
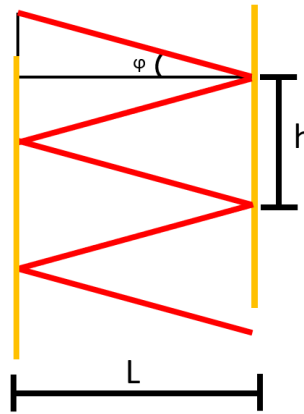

Figure 24: Diagram of mirror cavity geometry

This beam must then be focused on the primary fiber. To achieve maximum coupling, we must ensure that the beam is focused to a spot size no larger than the mode field diameter (MFD) of the fiber. Additionally, the focused beam must have a numerical aperture smaller than that of the fiber. Due to the requirement for a small spot size, we require an aspheric lens to perform the focusing of the beam. Specifically, we require a diffraction-limited aspheric lens. We then use the equation for the diffraction-limited spot size of a lens as $\emptyset < \frac{4\lambda f}{\pi D}$ where λ is the wavelength of light, *f* is the focal length of the lens, and *D* is the diameter of the input beam.[49] To achieve a small spot size a short focal length is desired and a large input beam diameter. However, for a single lens, the diameter of the lens can only be so small for a given focal length due to the required radius of curvature. Additionally, a single lens will suffer from a steep relationship between focal length and wavelength. From the given equation, the ratio of focal length to diameter must satisfy the following equation.

$$\frac{f}{D} > \frac{\emptyset\pi}{4\lambda}$$

In addition, we must satisfy the equation below.

$$NA_{lens} < NA_{fiber}$$

This is because any light outside of the numerical aperture of the fiber will not propagate into the fiber. So, in order to achieve high coupling efficiency we wish to have the NA of the focusing lens be smaller than the NA of the fiber.

We now see that the design of the collimation system and focusing lenses are inherently linked. This is because the diameter of the beam incident upon the focusing lens is dependent on the focal length of the collimating lens. We can relate the beam diameter to the collimating lens focal length according to the equation

$$D = 2 \cdot f_C \cdot tan(asin(NA_{fiber}))$$

If we use collimating and focusing lenses with the same focal length, then we can relate the two equations as $\frac{4\lambda}{2\pi*tan(asin(NA_{fiber}))} > \emptyset$. Thus, we see that the resulting focused spot size is independent of the selected collimating lens focal length. Additionally, the effective aperture of the focusing lens will be limited by the spot size of the collimated beam. Thus, the NA of the focused beam will be the same as the NA of the beam emitted by the fiber. For these reasons, we used the same lens for collimating and focusing as it greatly simplifies the design and ensures the NA is matched.

In addition, we must analyze how the focal length affects the full angle divergence of the beam. In general, a longer focal length will result in a smaller full-angle divergence of the beam. This allows for the beam to maintain a high collimation quality over a longer distance. This reduces the losses that the fiber-free space-fiber coupling will experience. For our system, we have a path length on the order of 10s of cm, and thus we wish to maintain low losses over this distance. The divergence angle can be estimated according to the equation $\theta = (\frac{D}{f}) * (\frac{180}{\pi})$. We see that the diverging angle is inversely proportional to the focal length. For these reasons, we wish for a collimating lens with a focal length of at least 10 mm in order to minimize the diverging angle and thus coupling losses. If we were to use a shorter focal length, the coupling efficiency as a function of the distance between the input and output fiber drops significantly. The chosen collimating lens has an NA 0f 0.24 and a focal length of 11.29 mm. This gives a beam size of 2.1 mm and a divergence angle of 0.053^O. This beam size is the beam waist size, but the beam size at the photodiode must be less than 3 mm. This is calculated using the path length of 38.1 cm and the divergence angle of 0.053^O to be $2.1\,mm + tan(0.053^O) * 38.1\,cm * 2 = 2.8\,mm$.

To predict the coupling efficiency achievable with the chosen collimating/focusing lens, we model the coupling in Zemax. To do so, we first import the Zemax lens file provided by Thorlabs and create two copies: one to collimate and one to focus.
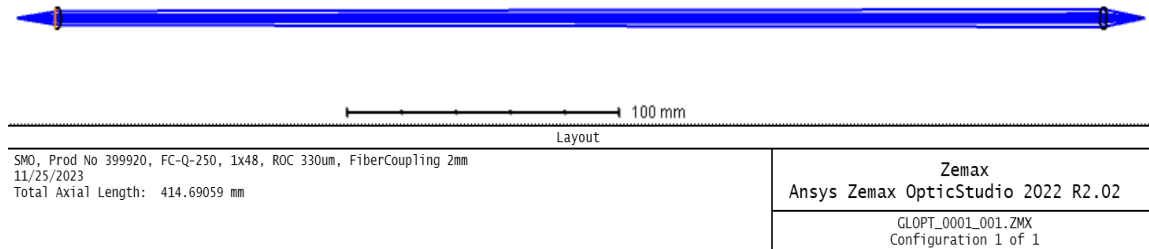


```
                                          |——————— 100 mm
                                          Layout
SMO, Prod No 399920, FC-Q-250, 1x48, ROC 330um, FiberCoupling 2mm          Zemax
11/25/2023                                        Ansys Zemax OpticStudio 2022 R2.02
Total Axial Length:  414.69059 mm
                                                          GLOPT_0001_001.ZMX
                                                          Configuration 1 of 1
```

Figure 25: ZEMAX setup of coupling efficiency between two fibers with collimating lenses

We then use the "Single-Mode Fiber Coupling calculation" tool in Zemax to calculate the coupling efficiency from one fiber to another. Also, we optimize the placement of the lenses relative to the fibers using the FICL operand and the "Optimize" function in Zemax. This is valid as the placement of the fiber connector is optimized by Throlabs during manufacturing. Based on these simulations, we should see an ideal coupling loss of -0.8541 dB when coupling from one fiber through free space to another fiber.

```
System Efficiency          :          0.870732

Receiver Efficiency        :          0.943430

Coupling Efficiency        :          0.821474  (-0.8541 dB)
```

Figure 26: Result of ZEMAX single mode fiber coupling efficiency measurements

6.2 Demultiplexing Design

The design of the demultiplexing system is very similar to the design of the multiplexing subsystem, but in reverse. In this case, we use the diffraction grating in order to separate the component WDM channels rather than combine them. The exit angles of the beams will again follow the diffraction grating equation given previously, with the exit angle separation being equal to the input angle separation derived in the multiplexing design.

The two WDM channels will now exit the diffraction grating with an angular separation of 3.745 degrees. We again have the issue of needing a long beam path in order to reach the necessary separation of the beams dictated by the size of the collimating lenses. We take the same approach as we did in the multiplexing system to solve this problem, using two mirrors in order to fold the optical path. The geometry of this design is essentially the same as in the multiplexer but with the beams separating rather than converging. After exiting the mirrors, the two beams will be incident upon their individual collimating lenses, which will couple them into a fiber or focus them onto the active area of the photodiode.
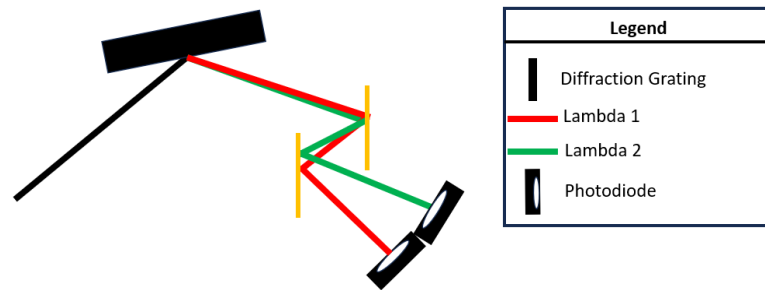
Figure 27: Design of the demultiplexing system

The separation required is determined by the size of the photodiodes. Since the photodiodes have a width of 20.3 mm, this is the distance we must separate the beams by. We again use the equation $tan(\theta) = \frac{D}{L}$ with an angular divergence of 3.745^O and now a separation of 20.3 mm to find a path length of 31.01 cm. To simplify the design, we have separated the photodiodes by 25 mm. This will allow us to reuse the multiplexer mirror cavity with minimal increase in device size.

6.3 Optical Link Budget

In order to ensure that we reach the desired system signal to noise ratio, we must create a detailed link budget for the optical path. This must include the signal to noise ratios of all optical components through which the laser will traverse. This includes the fiber optic, the Mach-Zehnder interferometer, the diffraction grating, mirrors, collimating/focusing lenses, and the photodiodes. Each of these components will either have a defined signal to noise ratio as is the case with the photodiode and Mach-Zehnder interferometer or will have a less well-defined noise source such as scattered light as is the case for the mirrors and lenses. These sources of error are harder to quantify and will require hardware testing to incorporate into the link budget. Additionally, there will be some amount of noise due to physical vibrations in the system as well as air currents, although these will also have to be determined via testing.

For most components in the link budget below, these losses and noise signals are printed as single numbers in the specification of the datasheet. However, for the photodiodes, the noise figure is given as a dark current. To be compared to the signal, we must convert this dark current to the equivalent optical power that would drive it. This can be done using the responsivity, which at 1550 nm is 0.9 A/W. Thus, we see that a dark current of 1.5 nA is equivalent to an optical power of $\frac{1.5\ nA}{0.9\ A/W} = 1.667\ nW = -57.79\ dBm.$.

We first create a nominal link budget based on the components for which signal to noise ratio specifications are available. The sum of these errors can be used to calculate a nominal signal to noise ratio for the signal. As this does not account for the previously mentioned additional noise sources that must be tested for, we wish

to add a safety factor to this signal to noise requirements. As our desired signal to noise ratio is 25 dB from all sources, we wish to have this nominal signal to noise ratio be greater than 35 dB in order to leave room for error regarding additional errors.

Power Losses	(dBm)		Noise Source	(dBm)		SNR
Input Power	13.01		Optical Switch Isolation	-58.801		55.455
Fiber-Fiber Coupling Loss	0.97		Photodiode Noise Floor	-57.78		
Optical Switch Insertion Losses	2		Total Noise	-55.25		
Diffraction Grating Losses	0.315					
Mirror Losses	0.397					
Fiber Losses	0.36					
Fiber-Fiber Coupling Loss	1.643					
Mach-Zehnder Modulator Loss	7					
1x2 Coupler Loss	0.12					
Output Power	0.205					

Figure 28: Nominal link budget of the optical subsystem

From this nominal link budget and SNR calculation, we see that the fiber-coupled devices have a significantly higher signal to noise ratio than is needed for the system. This means that these components will likely not be the limiting factors with regards to the signal to noise ratio, but rather we are limited by the free space optics portion of the system including the collimating/focusing lenses, mirrors, and diffraction grating. Reflections from these components will have a much harder to quantify impact on the system, and testing must be done once the system has been assembled in order to quantify their impact on the signal to noise ratio. However, we were able to estimate the losses that will result from these components based on published specifications for losses from the suppliers.

One source of power loss that will be difficult to know without testing is the losses due to the fiber-free space-fiber coupling. Although the collimating/focusing lenses are of high quality, the supplier does not provide information on the coupling losses as a function of the distance between the input and output fiber. Additionally, the exact losses will depend on the precision of the mounting hardware we use for the components. For these reasons, we obtain the hardware and perform testing regarding how efficient the coupling can be made as well as if this value drifts over time due to temperature fluctuations.

6.4 Passive Filters Design

The process of designing a bandpass filter is nowadays straightforward because it has been simplified to the extent that it is a matter of following an algorithm based on the requisites of the filter. For our case, the filter would ideally be a 3rd or 5th order, and either a Butterworth or a Chebyshev filter. However, the decision as to what filter type to use is determined by the designs. Once the type of filter is selected, based on basic parameters such as center frequency and bandwidth, one can start looking at different possibilities. Furthermore, since the component

values are given by an algorithmic computation that involves frequency and impedance scaling, fractional bandwidth, and the polynomial based on the filter type and order, one has to be sure first whether the values for the capacitors and inductors are realizable.

After simulating several designs for the bandpass filter with center frequency at 433MHz, we have chosen a 3rd order Chebyshev filter after 3 options because of the component values and filter performance.

The first filter design was a Butterworth bandpass filter model. This was devised because the Butterworth model is a standard filter we learn in basic filter designs at the university. However, one of its characteristics is the low insertion loss outside the bandpass frequency, which is not suitable for highly selective systems. Furthermore, the insertion loss in the passband was quite high compared to the second design, and this later presents a lower signal attenuation, which makes it more desirable.
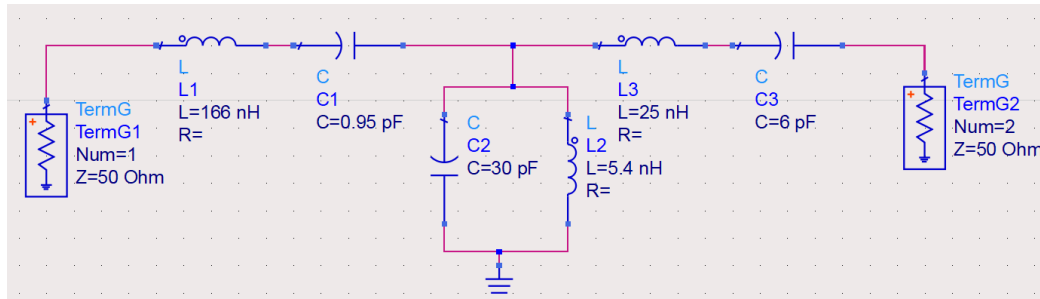

Figure 29: Circuit diagram of Butterworth bandpass filter for a 0.1db ripple

L1	C1	L2	C2	L3	C3
166 nH	0.95pF	5.4nH	30pF	25nH	6pF

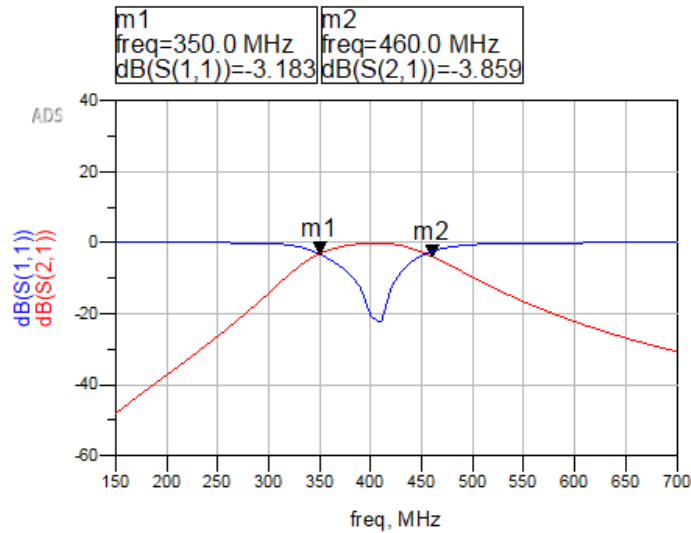*Table 25: Nth order element values for a 0.1db ripple*

Figure 30: S parameters for Butterworth bandpass filter

The second design in consideration is a 3rd order Chebyshev design. This design has a far better insertion loss outside the passband frequency and a superior insertion loss in the passband frequency. Overall, this design has way better performance than the previous Butterworth design. Furthermore, the components values were rounded to the closest nominal value, which makes the filter apt for integration in the system.
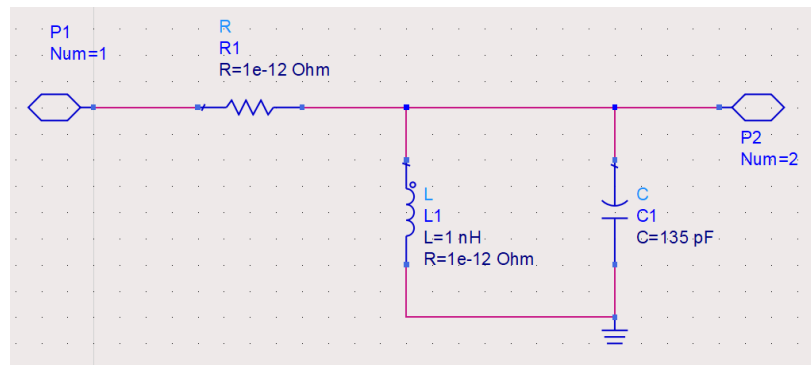

Figure 31: 1st order maximally flat circuit for 3rd order Chebyshev filter

L1	C1
82 nH	1.9pF

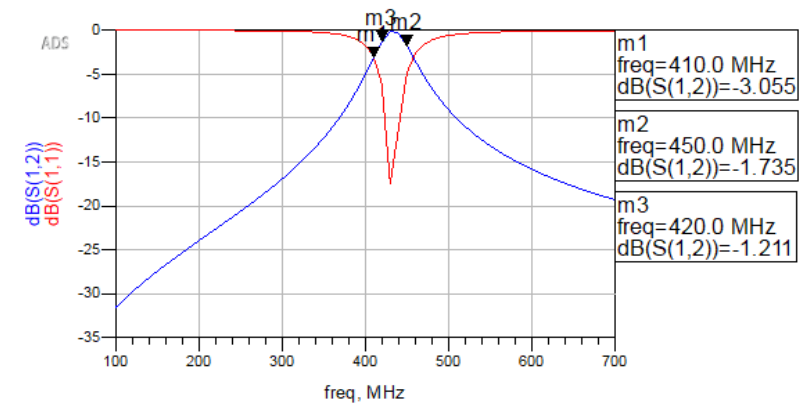*Table 26: 1st order maximally flat components value*

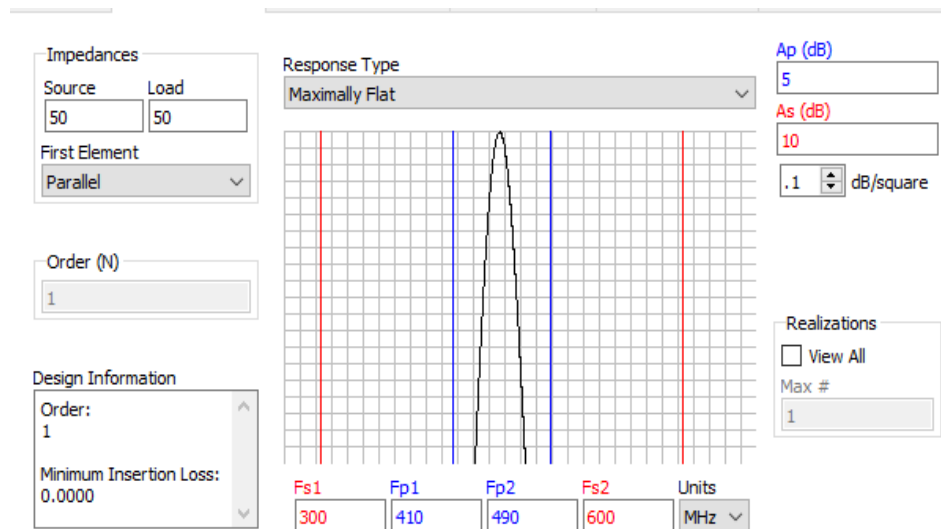Figure 32: 1st order maximally flat S parameters

Figure 33: Filter parameters

In the pursuit of designing and simulating the intricate bandpass filter, as well as conducting a comprehensive analysis of the system post-component integration, we've opted for the robust capabilities of Advanced Design System (ADS). This versatile software will serve as our cornerstone for plotting and dissecting the performance metrics.

When it comes to the pivotal tasks of PCB routing, meticulous design, judicious part selection, and accurate modeling, our tool of choice has predominantly been KiCad. Its user-friendly interface and the added advantage of being cost-free make it an invaluable asset to our workflow. However, it's imperative to acknowledge that KiCad does have its limitations, particularly regarding seamlessly exporting PCB designs for further analysis in high-frequency software platforms like HFSS.

To address this, we're also exploring the potential of Autodesk's Fusion 360. This software package, with its accessible student version, emerges as an attractive

contender. Notably, it boasts a unique feature enabling us to effortlessly import the 3D model of the PCB into HFSS, a functionality that could potentially streamline our workflow and enhance our design iterations. This strategic consideration reflects our commitment to leveraging the most effective tools at our disposal to ensure the success of our project.

When deliberating on the selection of transmission lines to be implemented in the design, we find ourselves presented with two viable options. The first, and currently the most practical, is the implementation of the coplanar waveguide. This transmission line configuration features a central copper strip flanked by coplanar copper planes serving as the ground reference. However, it is worth noting that implementing this transmission line configuration necessitates an additional copper layer beneath the dielectric. In this scenario, the coplanar grounded transmission line structure emerges as a fitting alternative.
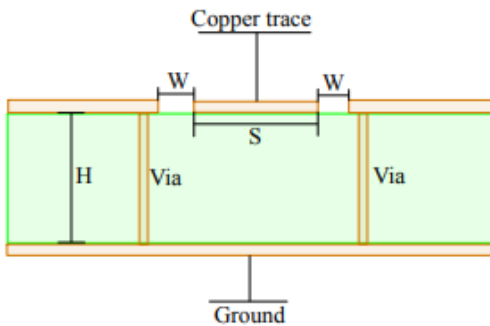
Figure 34: Grounded coplanar waveguide with vias

The difference between the coplanar waveguide and the coplanar grounded waveguide are the vias connecting the top layer of the copper that is not the signal conductor to the button layer by using vias. The other possible solution we are considering is to solder the top copper layer with the ground bottom layer to have them grounded without extensive use of vias or without vias at all. Moreover, these vias then may be filled with copper or other conductive material to provide a low impedance path.

Figure 35: Grounded coplanar waveguide without vias

Figure 36: Microstripline parameters

For the case of the microstrip line, it is also possible to implement the microstripline design by using the copper PCB clad boards, rout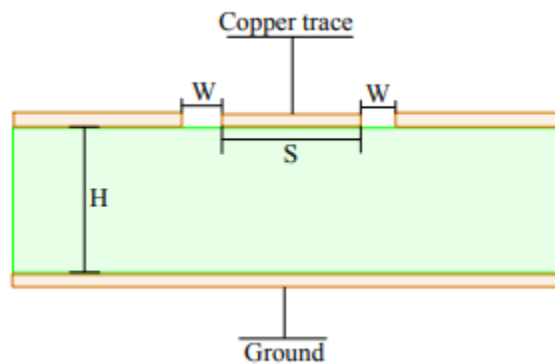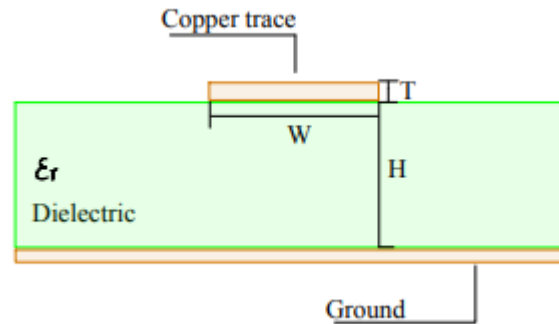ing with a milling machine the top layer using the parameters for a microstripline, and once the design is routed on the board, the coplanar copper layer can be etched away with a copper etchant so that we are left with a microstripline alone.

Once the prototype has been tested and integrated with the other parts of the circuit after a system analysis, we can then get the PCB manufactured for the final integration of the circuit, but in the meantime, we have more rudimentary methods for components testing that allow us to test the device components with higher levels of freedom.

Since we are going to build a communication system that receives a signal with a frequency of 400MHz, it is imperative that we proceed with caution, as this signal is at the lower end of the microwave realm, which ranges from 300MHz to 300GHz. As the frequency scales up, the challenges of working with high frequencies become increasingly notorious.

One of the most effective methods for predicting the performance of a high-frequency system is electromagnetic analysis, which involves simulating how the signal will propagate along the transmission line or waveguide in the system. There are several tools available for analyzing the performance of high-frequency circuits, but we have chosen to use Ansys HFSS in this case, as this is the software that we were trained on in our microwave class.

By carefully considering the challenges associated with working at high frequencies and using appropriate design tools, we can minimize the risk of unexpected problems and ensure that our communication system performs reliably.

Ansys HFSS (High-Frequency Structure Simulator) is a powerful software tool that is used to simulate the electromagnetic (EM) behavior of high-frequency structures

and devices. It is one of the most popular and widely used EM simulation tools on the market.

HFSS is based on the finite element method (FEM), a numerical technique for solving complex mathematical problems. FEM divides the structure or device being simulated into a mesh of small tetrahedral elements. HFSS then solves Maxwell's equations for each element in the mesh. This allows HFSS to accurately predict the EM behavior of the structure or device for a wide range of frequencies and materials. This software is useful for a wide variety of EM simulation applications, including:

● Antenna design: HFSS can be used to design and optimize antennas for a wide range of applications, such as wireless communication systems, radar systems, and satellite communication systems.
● Microwave circuit design: HFSS can be used to design and optimize microwave circuits, such as filters, amplifiers, and mixers.
● PCB design: HFSS can be used to design and optimize printed circuit boards (PCBs) for high-frequency applications.
● IC packaging design: HFSS can be used to design and optimize integrated circuit (IC) packages for high-frequency applications.
● EMC analysis: HFSS can be used to analyze the electromagnetic compatibility (EMC) of electronic devices and systems.

For the HFSS simulation, the transmission line is modeled by creating 3D objects with the HFSS project tool. The workflow basically consists of creating the geometric figures such as the ground plane, the coplanar plane, and the dielectric substrate. The separation from the transmission line to the coplanar ground plane can be achieved by using the Boolean function that allows the subtraction of the area, or volume of one shape to another. Moreover, since the design and modeling depend on parameters such as lengths and widths, it is highly convenient to make use of variables for the parametrization of the structures so that if some further modification of the structures are needed, one has a more efficient method to change dimensions and scale the project making use of parametrization.
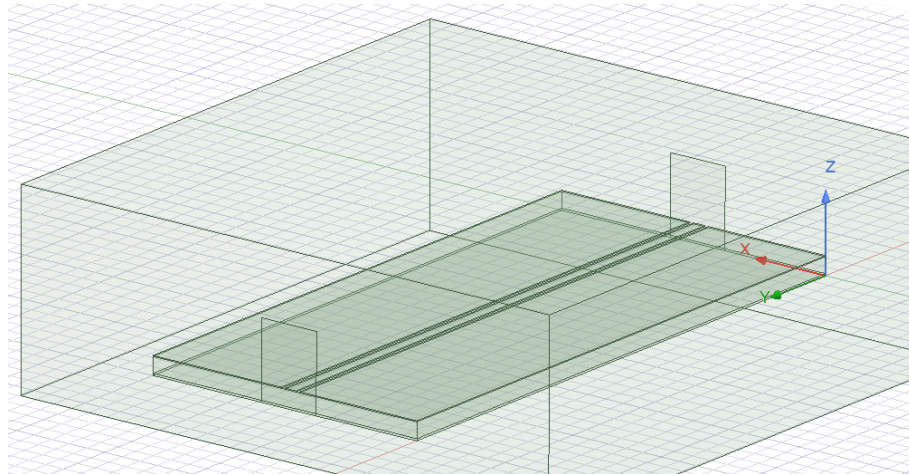
Figure 37: Coplanar waveguide simulation

Some of the most important measurements this simulation can do are the S parameters. What these parameters can tell us is how much power can be transferred through the transmission line and how much energy is reflected. This parameter is critical for the transmission line because based on the system requirements it will tell us whether that transmission line is suitable for our intended application.
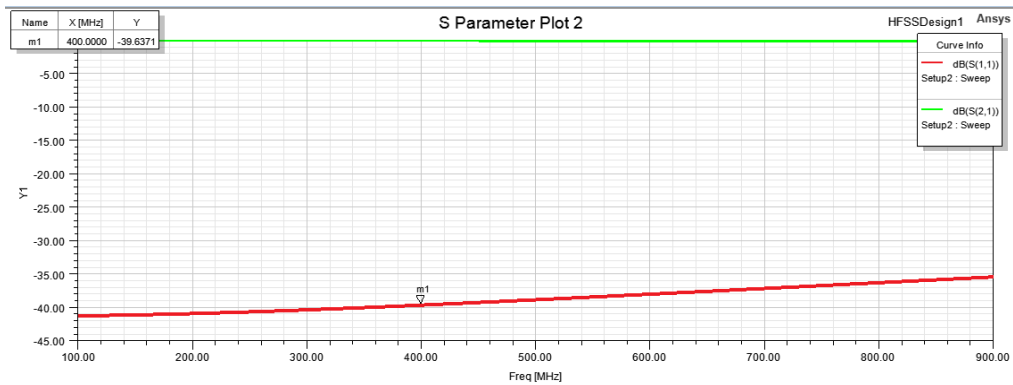
Figure 38: Thickness 1mm each copper layer for coplanar and ground plane. -39.63 dB S11

Figure 39: Thickness 2mm each copper layer for coplanar and ground plane. -37 dB S11

Since we have limited options when it comes to the manufacturability and prototyping of our electrical designs, I made two simulations where the copper thickness varies by 1 mm because the copper clad PCBs available in the labs are 1.6mm. However, there is no way to measure the thickness of the copper layers of the ground and the coplanar waver. Thus, I made two simulations to check whether the reflection coefficient is acceptable for these variations. After the simulations, the results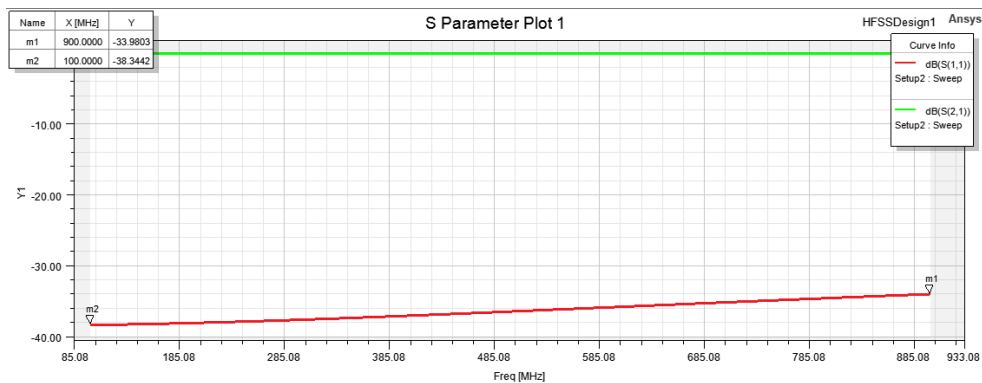 of the reflection coefficient are acceptable. A typical rule of thumb is that the reflection coefficient should be less than -10 dB, and in our case, we are obtaining a return loss of about -39 dB, which is a very encouraging result, especially since we are not using very high frequencies.
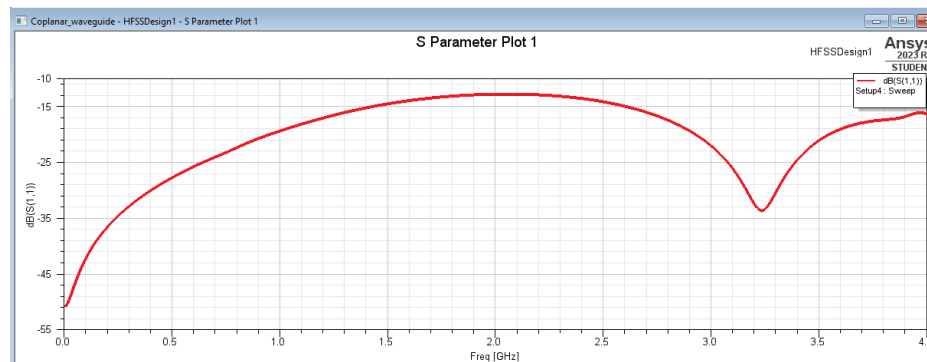
Figure 40: Return loss from 0.GHz to 4GHz

As we can appreciate from the simulation results, we obtain a good reflection coefficient because of the low frequency. However, if we were to operate at frequencies above 1 GHz, the reflection coefficient greatly increases peaking at 2GHz.

6.5 MCU System Design

There are multiple ideas for this project, one of which was signed between using multiple microcontrollers versus just a centralized microcontroller.

The use of multiple microcontrollers would involve Distributing the processing tests across several microcontrollers. The microcontroller can be responsible for specific functions or subsystems within a larger system, this approach allows for parallel processing which can improve overall system performance and response time. It also provides a failsafe as if one microcontroller fails or stops working, the rest of the system will still function. The idea for this was that we could write just one simple code for a single microcontroller then hand it off to the rest as it would function for all of them as they would just be working as switches and another would be used for a MUX for the others, along with a reverse for a DEMUX.

The idea for a centralized microcontroller was that it would consolidate all processing tasks into a single microcontroller. This approach offers simplicity and ease of management as there's only one point of control and can be more cost-effective as only one more control needs to be purchased and to maintain. While

a centralized microcontroller does simplify the system's design and reduces complexity, it may have limits in terms of processing power and scalability. Complex systems with high processing requirements may not be effectively handled by a single microcontroller, but as our system only requires just a simple switching and MUX/DEMUX that is not something to worry about.

The choice between both my controls and centralizers thus depends on the specifications of our application practice such as system complexity, process requirements, fail tolerance, scalability, and cost consideration would be evaluated to determine the most suitable approach. Thus, when we went through all those, we decided that a central microcontroller would be the best choice as the system complexity was very low, the fault tolerance was also very low, and the scalability was not a worry at the moment. The choice came down to the cost as we were limited with our budget and since a centralized system is less expensive, so we went with that decision.

Another concept that we contemplated was the incorporation of an additional microcontroller specifically designed to regulate a switch connection between the voltage sources and the lasers. By implementing this innovative solution, we would significantly enhance the level of control granted to the user, enabling them to effectively manage and restrict the energy consumption of lasers that are not being utilized. This ingenious approach ensures that substantial levels of power are not squandered unnecessarily, thereby promoting a more efficient and economical operation of the laser system. Ultimately, this proposal aligns with our overarching objective of maximizing resource utilization while minimizing wastage.

In the end, we decided to go with the centralized microcontroller idea. The idea was the better choice as it was less expensive and employed less complications. It only requires purchasing a single microcontroller which will control some physical switches and does not require immediate switching as we can delay the laser as all the switches are being performed. The reduction in complication comes from not needing to code or wire multiple microcontrollers and making sure that the master controller is communicating with the slave nodes properly and that all those slave nodes are activating the switches.

Architecture	Cost	Point of failure	Complexity
Master / Slave	More	Multiple	Same
Centralized	Less	One	Same

Table 27: Comparison of MCU architectures

6.6 Optical Transmitter Design

The optical transmitter shown in figure 41 enables the transmission of the high frequency RF signals over long distances with minimal loss through an optical fiber. It comprises a laser diode circuit, an intensity Mach-Zehnder modulator (MZM), and an RF source which will either be a software defined radio or a wave function generator. The laser diode circuit works by providing a constant current to the laser diode. The current driver is necessary to ensure that the laser diode emits a beam of light at a specific wavelength and with a desired output optical power. The circuit operates by providing a constant current to the laser diode through the current limiting resistor (R). The voltage regulator ensures that the current remains constant despite variations in the input voltage. The capacitor helps to reduce noise from the input voltage source assuming it is obtained from a wall plug. The 1N4007 diode serves a crucial role in protecting the laser diode from potential damage caused by reverse voltage transients, which can arise from unexpected power supply fluctuations or circuit interactions. The laser diode is a sensitive component that operates under precise current conditions. Exposing it to reverse voltage spikes can disrupt its operation and potentially lead to permanent damage. The 1N4007 diode acts as a protective barrier, ensuring that only the intended forward current reaches the laser diode, preventing any harmful reverse currents from flowing.
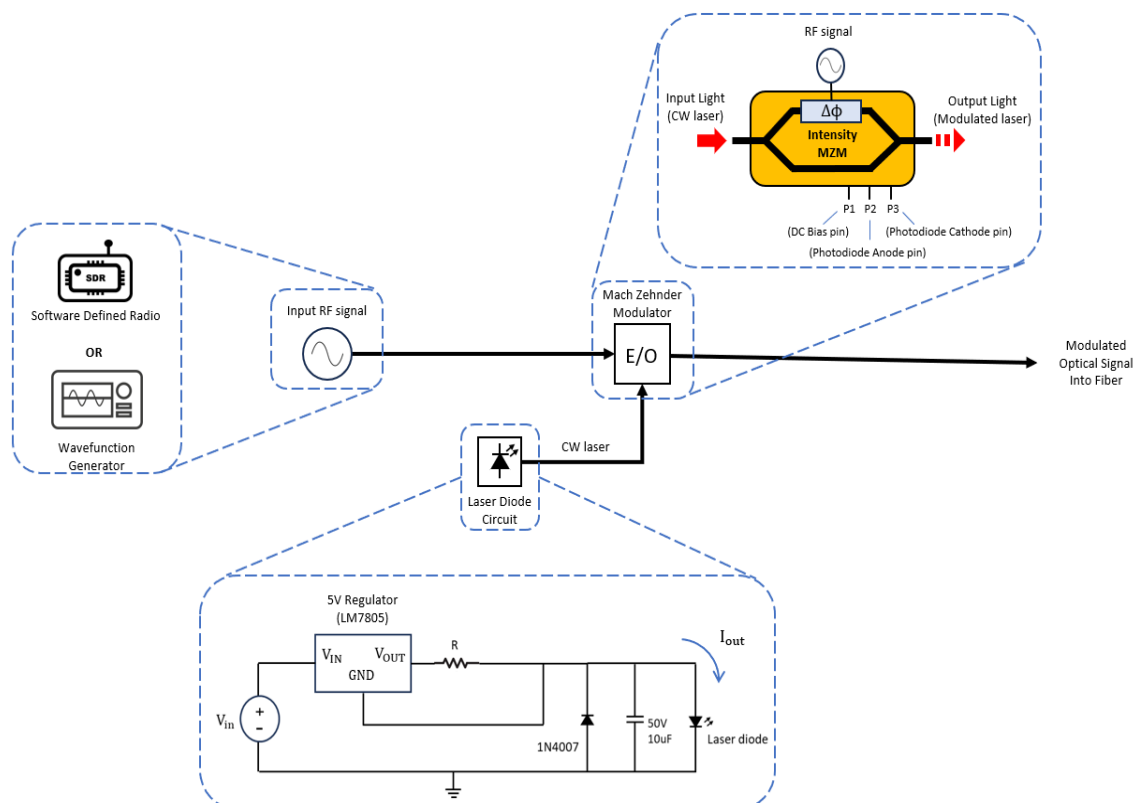

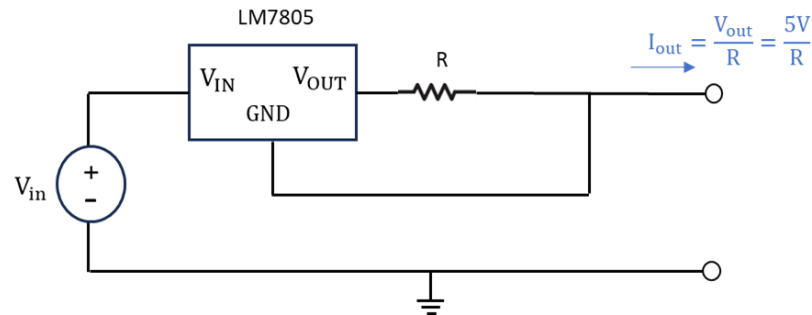*Figure 41: Optical transmitter design divided into 3 subsystems*

LM7805

Figure 42: Constant current source design for laser diode

As shown in figure 42, the LM7805, a 5V regulator is configured to create a constant current source, regardless of the input voltage. The current flowing through the laser diode is determined by the value of the resistor used and should be chosen to limit the current to a safe level for the laser diode. For the 1550 nm laser diode, an operating current of 100 mA is required to produce a continuous wave optical output power of 20 mW. For the 1530 nm laser diode, an operating current of 110 mA is required to produce a continuous wave optical output power of 15 mW. To obtain the required resistances, we must use the formula from figure 42, which is simply ohm's law as shown below.

$$R = \frac{V_{out}}{I_{out,1550nm}} = \frac{5V}{100\text{ mA}} = 50\Omega$$

$$R = \frac{V_{out}}{I_{out,1530nm}} = \frac{5V}{110\text{ mA}} \approx 45.45\Omega$$

6.7 Optical Modulator Design

The modulator we plan to use is the Sumicem 40Gbit/s Single Electrode Intensity LN Modulator T.MXH1.5-20PD-ADC-LV, which is a high-performance modulator designed for use in optical communication systems. It is based on a lithium niobate (LiNbO3) waveguide and can modulate a continuous-wave (CW) laser at 1550 nm. The modulator has a single electrode and can operate at data rates up to 40 Gbit/s. It has a low insertion loss and a high extinction ratio. The modulator is packaged in a compact module and is easy to operate.

Procedure to operate:

● Connect a polarization maintaining optical fiber with an FC connector to the input port of the modulator. This is where the CW laser will enter to be modulated.
● Verify that the input polarization is aligned to the slow axis of the polarization maintaining fiber before the maximum input power is inserted.
● Apply a voltage to the modulator electrode. The voltage will modulate the amplitude of the CW laser light.

- Apply an RF signal to the RF input port of the modulator. The RF signal should be at the frequency of the data that is being modulated.
- Monitor the output optical power to ensure that it is within the desired range using the built-in photodiode.
- Connect a single mode fiber with an LC connector at the output port of the modulator. This will enable the modulated optical signal to transmit through the communication channel, which is an additional fiber spanning a couple of kilometers.

Figure 43: Image of the sumicell intensity modulator

The equation shown below is for a Mach-Zehnder modulator (MZM) where only one branch is modulated by an electric field. This is known as a single-arm MZM. Pout is the output power, Pin is the input power, V_{input} is the voltage applied to the modulated arm, and V_π is the voltage at which the output power of a Mach-Zehnder modulator (MZM) goes to zero. This is because at this voltage, the phase shift in the modulator is π radians, which causes the two optical waves to interfere destructively and cancel out each other. The V_π voltage is the voltage required to produce a phase shift of π radians in the electro-optic crystal. The equation shows that the output power of the MZM is proportional to the input power and the cosine of the phase shift. The phase shift is controlled by the voltage applied to the modulated arm. If the voltage applied to the modulated arm is zero, then the phase shift will be zero and the output power will be maximum. If the voltage applied to the modulated arm is equal to the half-wave voltage, then the phase shift will be π radians and the output power will be zero. The single-arm MZM can be used to modulate the intensity of an optical signal by applying a voltage to the modulated arm. The voltage can be varied to produce different levels of modulation. The single-arm MZM can also be used to produce phase-shift keying (PSK) signals by applying a binary voltage to the modulated arm.

$$P_{out} = 0.5 * P_{in} \left[1 + \cos \left(\frac{\pi * V_{input}}{V_{\pi}} \right) \right]$$

To determine the half-wave voltage (V_{π}) at different frequencies, such as 5 GHz, we have needed to perform experimental measurements since the specification sheet of the sumicell modulator only specifies the V_{π} for 1kHz and 20 GHz. To determine the V_{π} at different frequencies, a Mach-Zehnder modulator (MZM) is employed, and its output power will be measured at various voltages and frequencies as shown in figure 44. This involves setting up a laser source, optical power meter, and signal generator. The signal generator frequency is set to 5 GHz, and a voltage sweep is applied to the MZM, recording the corresponding output power. The voltage at which the output power drops to zero, corresponding to the V_{π} at 5 GHz. This process can be repeated for different frequencies if we wish to obtain the V_{π} values for those frequencies. Alternatively, it may be easier to find the ($V_{\pi}/2$) voltage which is the voltage at which the output power drops to half of its maximum value, as it may be relatively easier to measure and can provide a good approximation of the true V_{π} value.
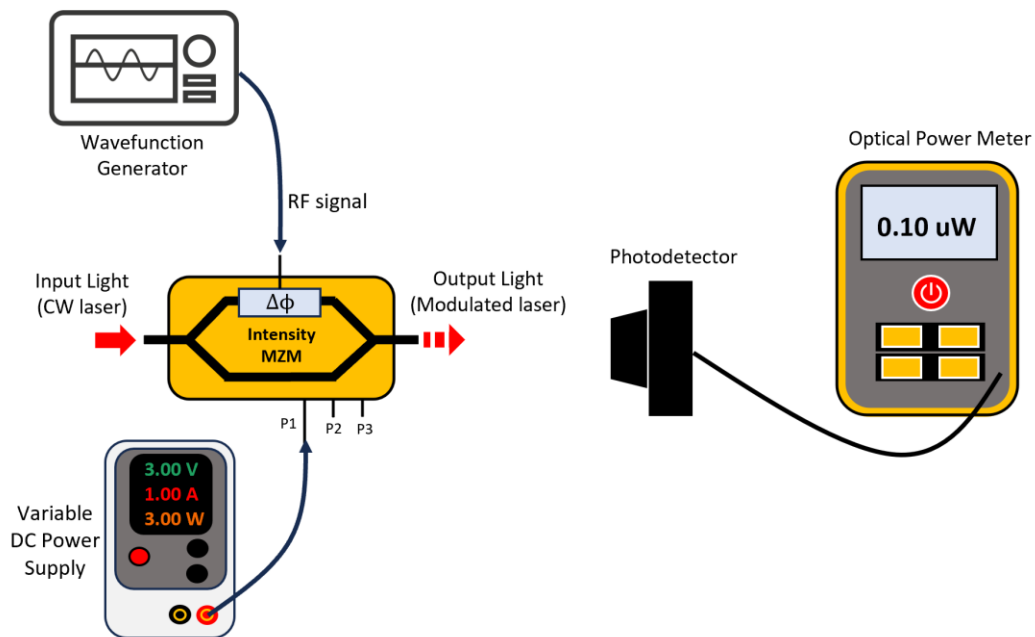
Figure 44: Experimental setup to determine the Vπ at certain RF frequencies

6.6 Optical Receiver Design

The optical receiver subsystem, depicted in Figure 44, plays a pivotal role in reconverting modulated optical signals into their original electrical counterparts, enabling the recovery of the encoded information transmitted over optical fiber. As the modulated optical signal reaches the receiver, it initially encounters a diffraction grating, a device specifically designed to split the incoming signal into a pattern of diffracted beams. These diffracted beams are subsequently directed towards a

collimating lens, which meticulously transforms them from diverging into parallel beams. This process ensures that the incoming light is properly aligned and focused onto the photodetectors.

Two sets of strategically positioned mirrors within the optical setup serve to direct the parallel diffracted beams onto corresponding focusing lenses. Each focusing lens efficiently concentrates the diffracted beam onto a dedicated photodetector. These photodetectors, the core of the receiving subsystem, meticulously transform the incoming optical signals into electrical signals, effectively converting the modulated light waves into corresponding electrical waveforms. The feeble electrical signals generated by the photodetectors are meticulously amplified using low-noise amplifiers. These devices carefully boost the signal strength, ensuring that the signals possess sufficient power for subsequent processing stages. However, the amplified electrical signals may still contain unwanted noise and interference. To address this challenge, two electrical filters are employed. These filters selectively remove unwanted frequencies and noise, meticulously refining the electrical signals and enhancing their overall quality.

The refined electrical signals then reach a measurement instrument. The signals can be displayed on an oscilloscope in the time domain, allowing users to observe their waveform characteristics, including amplitude, frequency, and rise time. This information can be used to assess the signal's quality and identify any potential issues with the optical receiver or the transmission link. Alternatively, the signals can be analyzed using a spectrum analyzer in the frequency domain, revealing the distribution of signal power across a range of frequencies. This information can be used to identify the modulation format used to transmit the information and extract the encoded data. Alternatively, the refined signals could reach a receiver circuit, responsible for demodulating the signals and decoding the information that was initially encoded at the transmitter.
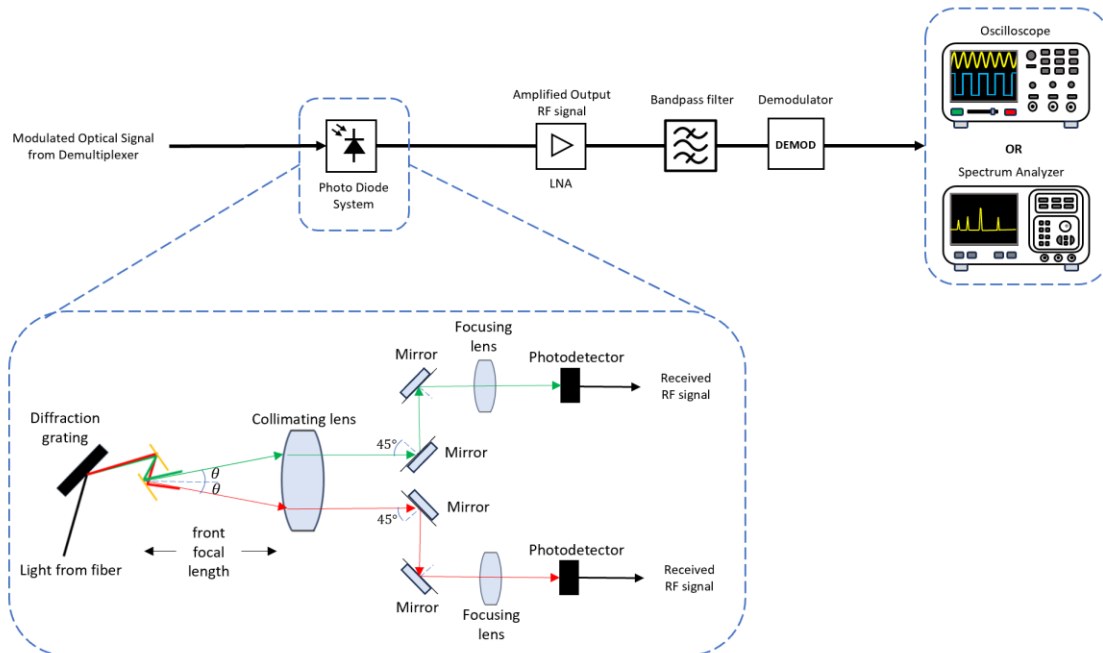
Figure 45: Direct detection optical receiver design

An alternative receiver design is shown in Figure 45, utilizing a balanced heterodyne optical receiver setup. This type of optical receiver employs two 50/50 beamsplitters, and 4 photodetectors to mix the received optical signals with a local oscillator (LO) signal, typically a narrow-linewidth laser. The two photodetectors at each branch are connected in a subtractor configuration, resulting in an output signal proportional to the difference in photocurrents between the two detectors. In optical heterodyne detection, a weak optical signal is mixed with a strong reference signal, or LO, to generate a beat signal. The beat signal is an electrical signal with a frequency equal to the difference in frequency between the optical signal and the LO. In heterodyne detection, the local oscillator frequency ω_{LO} is chosen to differ from the single-carrier frequency ω_o such that the beat frequency is in the microwave region. The beat signal is then amplified and filtered to eliminate noise and extract the desired information.

The fundamental principle of this detection technique is to amplify the incoming signal by combining, or mixing it, with a locally generated continuous-wave (CW) optical field. The term "mixing" refers to the phenomenon where two optical waves with frequencies ω_1 and ω_2, when combined, produce additional waves with frequencies equal to $2\omega_1$, $2\omega_2$, and $\omega_1 \pm \omega_2$. All frequency components except $\omega 1 - \omega 2$ are filtered out at the receiver. The result of this mixing process is that the predominant noise in the receiver is the shot noise originating from the local oscillator. This allows the receiver to achieve shot-noise-limited sensitivity. Achieving shot-noise-limited sensitivity is highly desired in heterodyne detection due to its significant impact on the receiver's overall performance. When a receiver operates at shot-noise-limited sensitivity, it means that the shot noise generated by the local oscillator is the dominant noise source. This is advantageous because the LO is a controlled and well-characterized source of noise, making it easier to

mitigate compared to other noise sources such as thermal noise or background radiation.

The output current at receiver would be equal to

$$i_{received} = \underbrace{i_{dc}}_{dc\ term} + \underbrace{i_{IF}(t)}_{time-varying\ term} = \frac{\eta q}{h\nu}P_{LO} + \frac{2\eta q}{h\nu}\sqrt{P_S P_{LO}}\cos(\omega_{IF} + \phi(t))\cos(\theta(t))$$

where ω_{IF} is the intermediate frequency which is typically a few tens or hundreds of megahertz, $\Phi(t)$ is the relative phase difference between the incoming information bearing signal and the local oscillator, Ps is the optical power of the incoming signal, PLO is the optical power of the local oscillator, and $\cos(\theta(t))$ is the polarization misalignment factor between the signal wave and the local-oscillator wave.

$$\cos(\theta(t)) = \frac{E_s \cdot E_{LO}}{|E_s|\,|E_{LO}|}$$

The dc term is normally filtered out in the receiver, and the IF current gets amplified. One then recovers the information from the amplified current using conventional RF demodulation techniques.
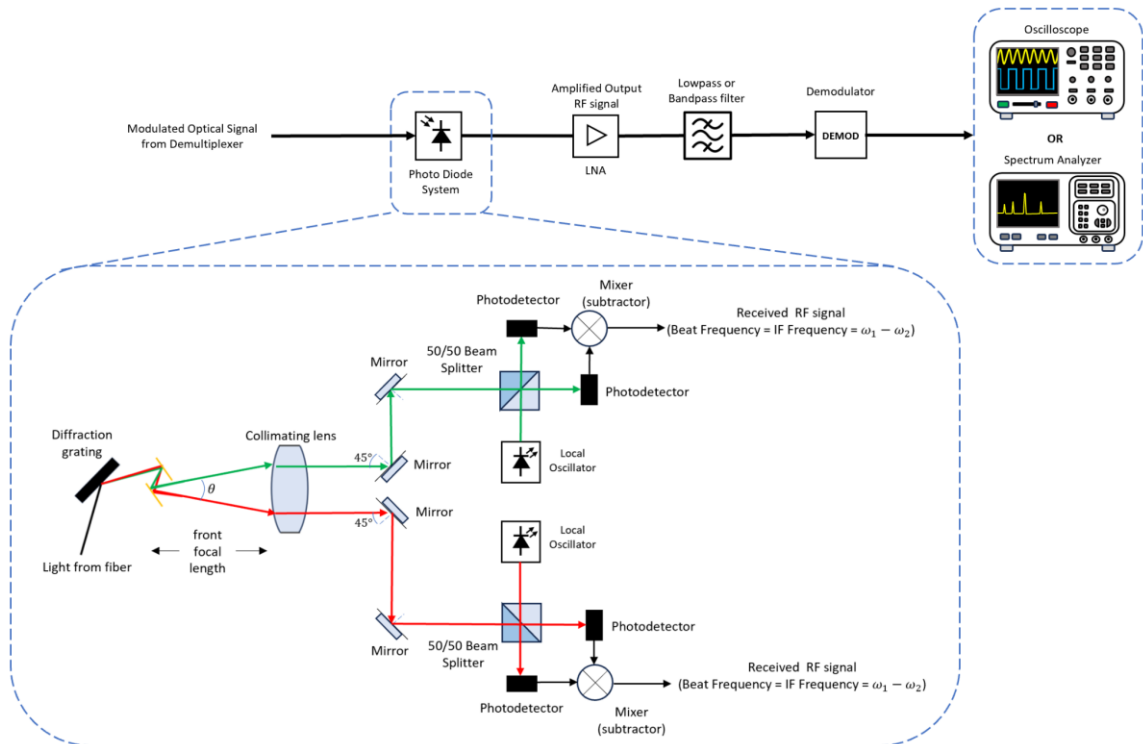

Figure 46: Balanced heterodyne detection optical receiver design

The optical receiver would work as follows:

1. The received 1530 nm and 1550 nm optical signals are separated using a diffraction grating.
2. The separated signals are then collimated by a lens and redirected by mirrors to facilitate directing the beams onto photodetectors.
3. The optical signals are mixed with local oscillator (LO) signals using a 50/50 beam splitter. For the branch containing the 1550 nm signal, the LO will have a wavelength close to 1550 nm. Similarly, for the branch containing the 1530 nm signal, the LO will have a wavelength near 1530 nm.
4. The mixer generates an intermediate frequency (IF) signal, which is equal to the difference in frequency between the received optical signal and the LO signal.
5. The IF signal is amplified, filtered, and demodulated to recover the original information encoded on the optical signal.

6.8 Electrical Design

The electrical design of an RF system with a microcontroller included involves several intricacies that deal with several difficulties ranging from basic layout challenges that may seem to be trivial at first, but as the PCB is routed and more components are integrated into it, it proves to be a challenge by itself where the PCB layout could substantially increase in difficulty to the point of needing multiple layers, which again, also increases the difficulty of the PCB design because adding another layer to it implies considering impedance changes when designing an RF system.

In the case of our project, the PCB layout consists of the RF receiver section with the high frequency signal on one side of the board with empty space around it so that it does not interfere with other nearby traces. These high frequency traces have a controlled impedance of 50 ohms that is achieved by controlling the dimensions of the board such as the dielectric thickness, the copper thickness and the spacing between the signal trace and the coplanar ground. This section will be shielded with vias to further enhance the noise immunity and possible radiation to other traces.

As more traces are done on the PCB, the more complicated the design gets because they then start to block possible paths for the other traces, and then it is necessary to make traces underneath components or to implement another layer in order to get other signal traces to their design connection. This is achieved by pouring another polygon forming another layer, but this also requires planification in order to be consistent with the design and keep parasitics controlled to ensure the proper functioning of the circuits.

In the case of our PCB, it is very likely that we are going to need at least one extra layer to connect the traces of the SPI signals (SIMO, SOMI, CHIP SELECT, and SERIAL CLOCK), because they were blocked by a power signal trace, and also because of the pin arrangement of the MCU and the receiver that in some cases,

will be so unfortunate to have them cross. For instance, pin 1 is on top of pin 2 in the MCU while the pin connection of pin 1 is underneath the pin connection of pin 2, which in a direct connection means having to cross the traces, which is not possible. Therefore, the trace has to do something like surrounding both pin one and two to leave from under pin 2, but if there is a power ground underneath the MCU it is not possible.

In these cases, vias are used to connect that pin of a component that cannot be connected to the pin of another component. This via connects the pin to a buried layer inside the PCB, and that layer contains the connected signal that can then take it underneath the traces that were blocking it so that in the end, there is another via connecting that buried layer to the destiny pin of the other component. That is the case for 3 pins of the receiver that will be likely grounded and not used, otherwise an extra layer would have to be included.

The electrical design includes switch drivers that require a 5 volt input. However, the microcontroller pins can output a maximum of 3.3 volts, which means that they will not be able to input the required voltage to the switch drivers by themselves. This problem is addressed by implementing a logic shifter circuit implementing an N channel MOSFET. The way this circuit works is that it takes 5 volts as input in the source terminal, and this terminal is connected with a resistor to the switch driver positive input terminal. Now, when the MOSFET is not conducting (V_{gs} < $V_{gs,active}$) it acts as a voltage divider where depending on the resistance value chosen for the resistor connecting the source and the positive input terminal of the op-amp, can consume up to 99 percent of the input voltage so long the MOSFET is not conducting.

On the other hand, if the MOSFET is conducting current, meaning that V_{gs} > $V_{gs,active}$, which would be the case if the gate of the MOSFET is at the potential of 3.3 volts, then it would present a path by fairly less resistance through its channel all the way to tis drain that is connected to the pin driver of the MCU. In this case, the current passes through the MCU pin and most of the voltage drop happens in the MCU, which in consequence leaves the input of the switch driver at a voltage less than 5 volts if this is properly designed.

However, after reading in the MCU data sheet, I found out that the input impedance of the MCU pins is in the order of 10^{12} ohms. That presents a problem because then the voltage division due to the impedances of the resistor from the source to the N channel added with the channel resistance in series turns out to be ineffective for the purpose of having a voltage drop of less than 4.8 volts from the channel resistance in series with the MCU, meaning that most of the voltage drop occurs in the MCU that in consequence, will present a voltage potential of about 5 volts at the input of the switch driver keeping it in this way high even if the MCU pin at the drain is at ground potential. The solution for this problem is more or less simple because we can simply add a resistor with a relatively small resistance compared to the source resistor. In this way, the voltage drop across the source

resistance is going to be significantly higher compared to the previous option with no resistor to ground.
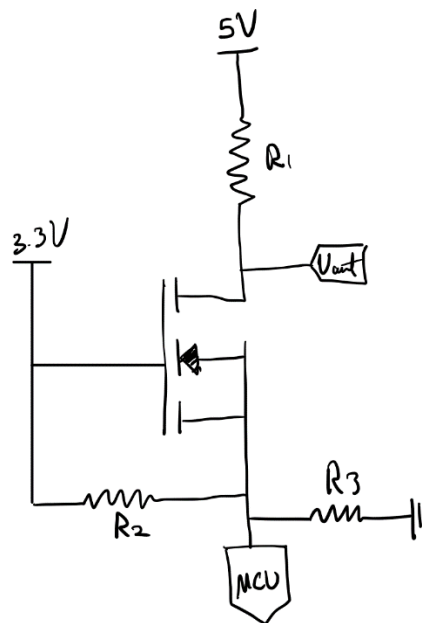
Figure 47: Circuit design to convert 3.3V MCU pin output to 5V

For the switch drivers, they were group the 6 underneath most of the circuitry involving the RF receiver on top of them and to the right, and also the MCU circuitry right on top of them, it was chosen to be this way because each individual switch driver requires a pulse from the pins of the MCU to switch, and since there is 6 of them, it means the care must be taken as where to place them with respect to the MCU so that their traces can make it to the switch drivers. However, these traces block the power traces needed for the logic shifters that in consequence require a buried power plane for power distribution of both voltage levels required, the 3.3 and 5 volts.

Another option to avoid the implementation of a multilayered PCB is making the power traces of 5 volts circumvent all the switches by routing this power trace o. The left side of the switches, and then connecting them from the bottom up. This has the tradeoff nonetheless of blocking the switches drivers output so that they won't be able to reach the board edge. Albeit this seems to be an issue, the switch drivers are connected to the switches with wires because they will not be in the PCB, which leaves the option of following this power routing approach and put a jumper or some connector right on the output of the Switch drivers so that the wires will not present any issue for the routing.

7. Project Software Design Details

7.1 Pseudocode for Power Saving

The code is designed for a scenario where lasers are used intermittently, and power conservation is not a priority but a necessary function to reduce overall power consumption and reduce the heating to the system.

The embedded system utilizes a sophisticated power management strategy to optimize energy usage in the chip. When a laser is not actively in use, the associated voltage source is temporarily turned off to conserve power. This is achieved through a meticulous implementation of an internal clock and a timer mechanism.

The code is structured to create an internal clock that acts as a reference for tracking the duration during which a laser remains inactive. A timer is initiated each time the laser is turned off, and this timer runs in the background as part of a while loop. The loop continuously checks the status of the laser, ensuring that the timer only proceeds if the laser remains inactive. This real-time monitoring mechanism prevents premature power cutoffs in case the laser is reactivated before the specified time threshold is reached.

Visually, the code's impact on laser power management can be observed by referring to the image below, which likely contains graphical representations or charts illustrating the relationship between laser usage, the timer, and the corresponding voltage source states. This visual aid provides insights into the temporal aspects of the power management system, showcasing how the timer interacts with laser activity and power conservation.

It's crucial to note that the code structure is designed with flexibility in mind. The reference to adjustment indicates that the code can be fine-tuned to accommodate specific requirements or changes in the embedded system's functionality. This adaptability ensures that the power management logic can be tailored to the unique characteristics and demands of the application, making it a robust and customizable solution for laser power optimization in the chip.

Figure 48: State diagram for power saving code

This state diagram shows how the code should be flowing. It will start with the controller being powered by the voltage source. This will kick off two things, the variables needed and the clock. The variables needed will be all the out pins needed. This amount will be the number of lasers. The clock will also be initialized to a specific amount of time, 5 minutes. If the clock loops back to 0 it will trip a sign to pulse a 5V charge to the tripped laser and turn off its voltage source or laser. After which it will clear the timer and proceed to scan for other signals. The other situation will be if the laser turns back on, in that case a counter signal will be sent ahead of time which will turn off the clock and resume checking for other signals. This system will be able to handle multiple trips at the same time, allowing for

seamless transitions. The key to this is making sure that the queue is large enough so that it can handle the situation of every laser turning off at the same time.

7.2 Pseudocode for Switching the Laser Endpoints

This code is for the switching of where the laser is going to end up. This will adjust the reflector to make the light reflect to the correct endpoint to be read. The idea for the code will be to set up the number ports needed for the specific use case. The number of ports will be determined by $x <= 2^n$ where x is the number of end points and n will be the number of switches needed to make it functional. The number of switches needed, n, will also be the number of ports needed and enabled to make the system functional. This can be seen visually by looking at Appendix E. This visual will showcase how each switch will be configured.

In summary, the code is designed for simplicity and adaptability in the laser endpoint switching. The code will be adjusted if the simplicity becomes a hindrance to its functionality and no longer becomes useful. Though coding such a simplistic code means that anyone can adjust it if the number of endpoints increases or decreases.
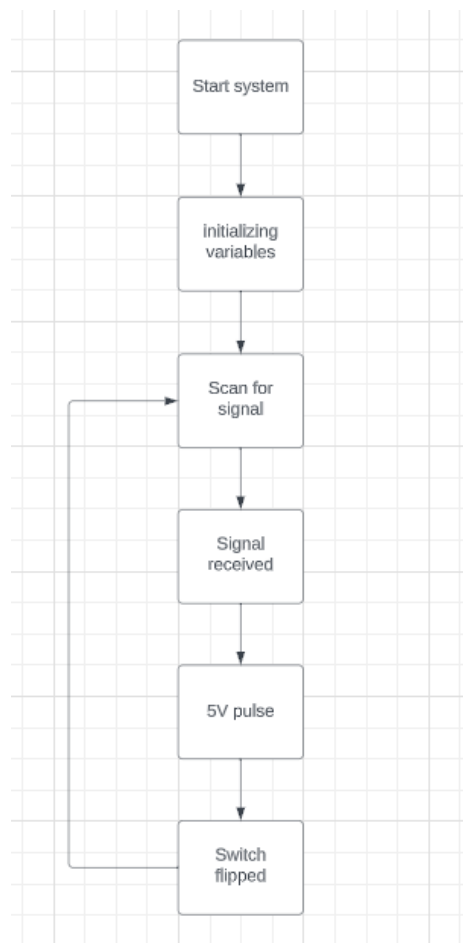

Figure 49: State diagram for switching code

This code is simple code that has no diverging lines. The code flows linearly once the trigger signal is sent. If an error is made, the user only needs to resend the signal to correct the mistake. The critical part of this is making sure that the 5V pulse has a pulse long enough for the switch to register the pulse and that the 5V sent to the switch is constant there before and after.

7.3 Master / Slave Nodes

One way to code a large-scale system with multiple moving parts is to have a single controlling node that will take charge of several simple units that will do repetitive actions. This method will require a trigger from the master node that will then make the slave node perform its purpose. The code for this method will be simplified as it separates the requirements from the action required thus making the purpose of a code clearer. This method however will cost more to implement as it requires more parts. The master node will have to be able to have enough storage to maintain the slave nodes. Another issue would be points of failure as there could be a failure of the master node not conveying the signal to perform the action. This could be due to an error in the code or a miss read about the status of the system. However, the issue could also be the slave node. The slave node could be faulty and is not performing its action properly.

7.4 Single Centralized MCU

Another way to code a large-scale system is to have a hefty, centralized microcontroller to maintain everything. This will make it wholly responsible for any failure in the system. The controller will also of course need to have even larger memory storage to hold not only the programming language that now contains the parameters, but also perform the action that needs to be done if said parameters are met. The controller will also now have to also hold the data memory of the signal that is being sent. The controller will also now have to hold the memory to alter the data if it needs modifying.

7.5 Software Design Summary

To summarize, the concept of the coding design is quite simple as there was not much to code and the coding that was required was very simple and needed little research as the concept was already a prerequisite to the class. The codes needed for the project were codes that are going to be implemented into the microcontroller.

The microcontroller will have two sets of code implemented into it. The main concern was if the controller had a clock speed big enough for our purposes as we were going to have to divide the time down to have multiple out ports. This will be used in both sets of code.

One of the codes, the power saving one, is the most tactful of the two as it will be running the clock continuously as it will be checking for lower power usage in a laser and will thus then register a time of said lower power and see if it extends for a period of time after which it would switch off that lasers power as it was not being utilized but instead held on standby so it will be turned off for standby and will be turned back on when it is required again. If the power of the laser goes low but does get used again quickly the laser will not be turned off and the clock register will be cleared and it will proceed as so, checking to see if any laser goes low in power.

The other code will work with the actual signal being sent. The code is done so in an iterative style as it will probably be more problematic to do the code recursively. We are not low on memory space and the computation time will be relatively quick with the code that is written and that it will be based in a C language, which does not slow down with iterative code but instead has an issue with code taking on too much information and not storing it properly. This will not be an issue as the code is just a series of if statements that will switch the physical switches of the reflectors to guide the laser to the desired end point.

8. System Fabrication/Prototype Construction

8.1 Circuit Schematics

The software we are going to use for the circuit schematic is Altium Designer and Fusion 360 because they are widely used in the common electronics and the RF industry. Eagle is widely used because it is easy-to-use, and its integrated tools for automating the design process. The workflow of how we are designing the schematics is basically importing the components needed for the design from outside libraries if they are not already included in the libraries, which is the case for generic elements. After importing them into the project, a separate schematic is done with each device for ease of design, and then they are integrated in a PCB later on.

The process of design consists in designing each module individually in their own schematic making use of the ports function in the schematic to then be connected with a multi schematic connection function integrated in the software. After each individual module schematic development, a system schematic is created where a sheet representing each individual module generates the ports that correspond to each connection in the schematic to be connected to the other schematics to their corresponding ports.

8.1.1 Fiber Switching System

The circuit schematic for the 1x2 Fiber Switch driving circuit is shown below in figure 50. This PCB is made up of 6 of the recommended driving circuits shown previously in figure 20.
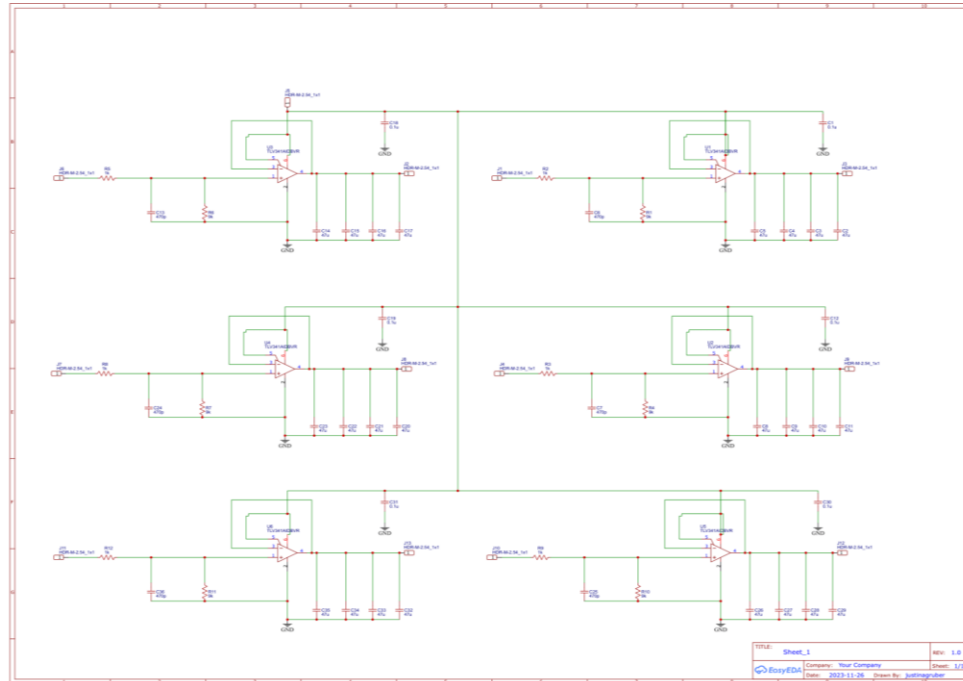
Figure 50: Circuit diagram of fiber switch driving circuit

8.1.2 CW Laser Driver Circuit

The circuit schematic in figure 51 shows the constant current driver for the two laser diodes (1550nm, 1530nm) which provide a constant current of 100 mA and 110 mA respectively.
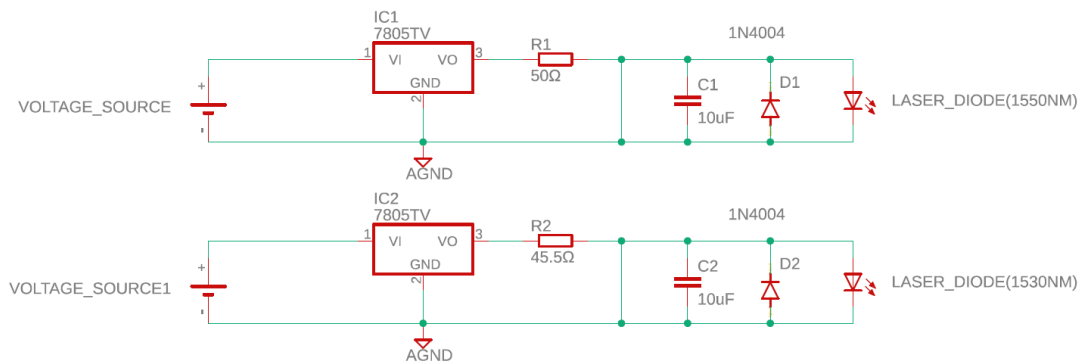
Figure 51: Circuit diagram for supplying constant current to the laser diodes

8.1.3 MSP430 Circuit
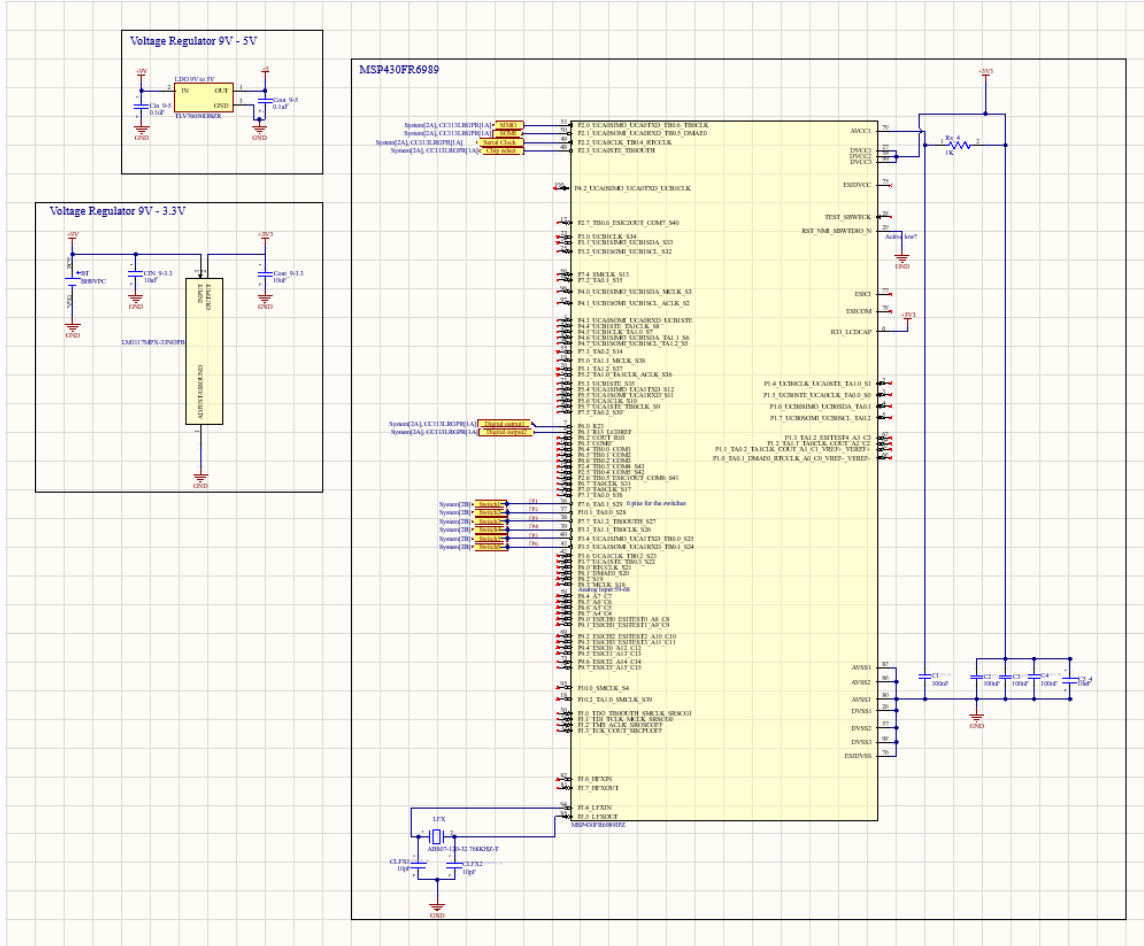
Figure 52: Circuit schematics for MSP430FR6989, TLV76050DBZR, and LM1117MPX-33NOPB voltage regulators
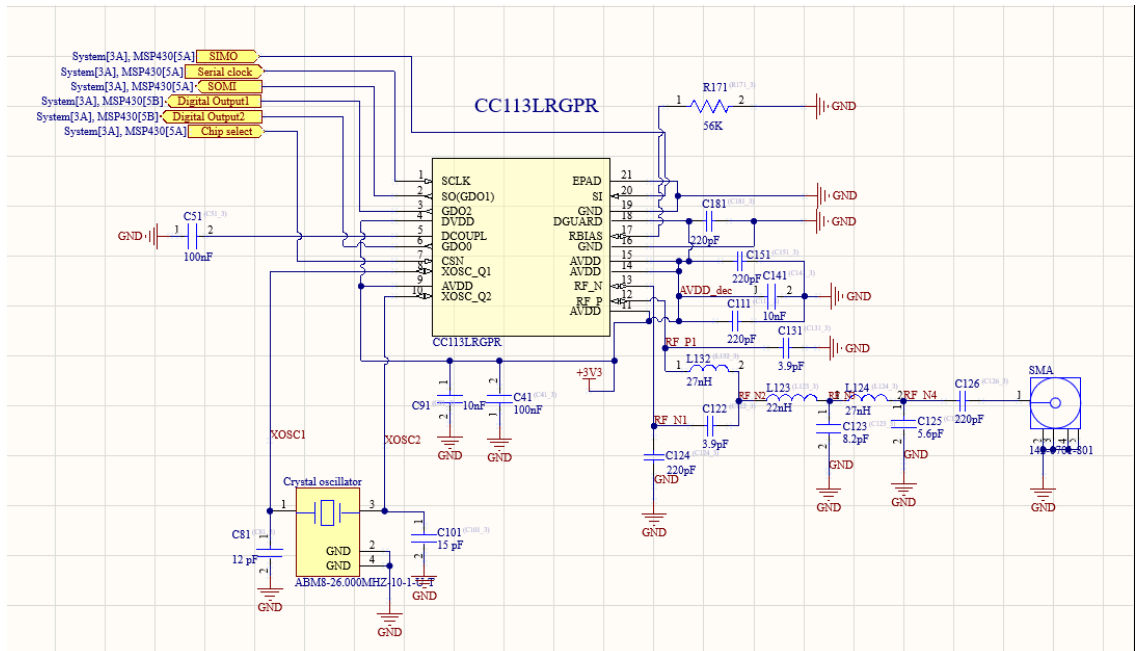
Figure 53: Circuit schematic for the receiver module
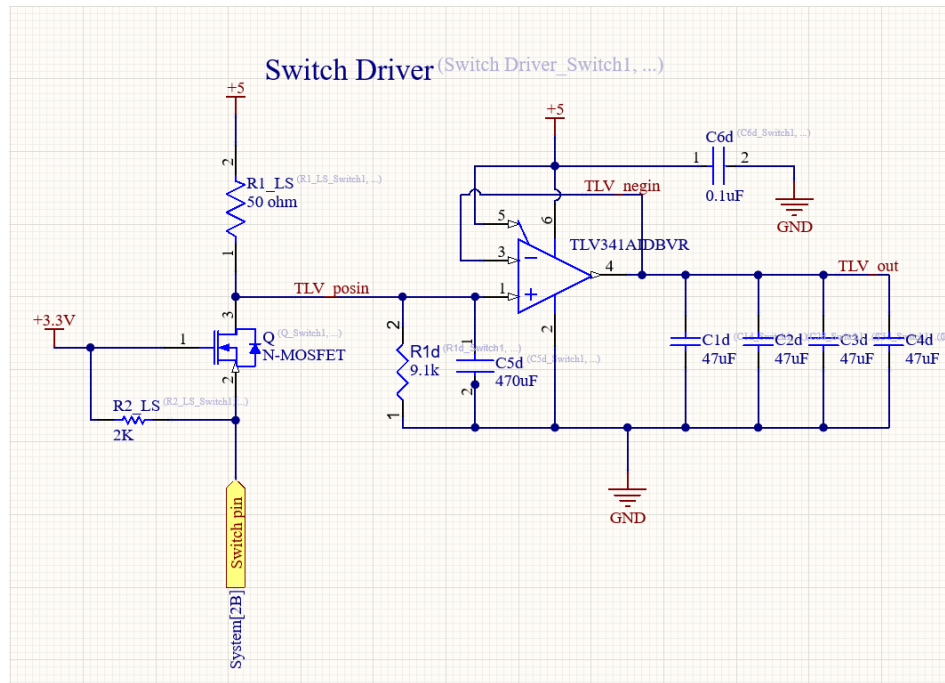
Figure 54: Circuit schematic for switch driver and voltage upconverter

8.2 Overall Schematic
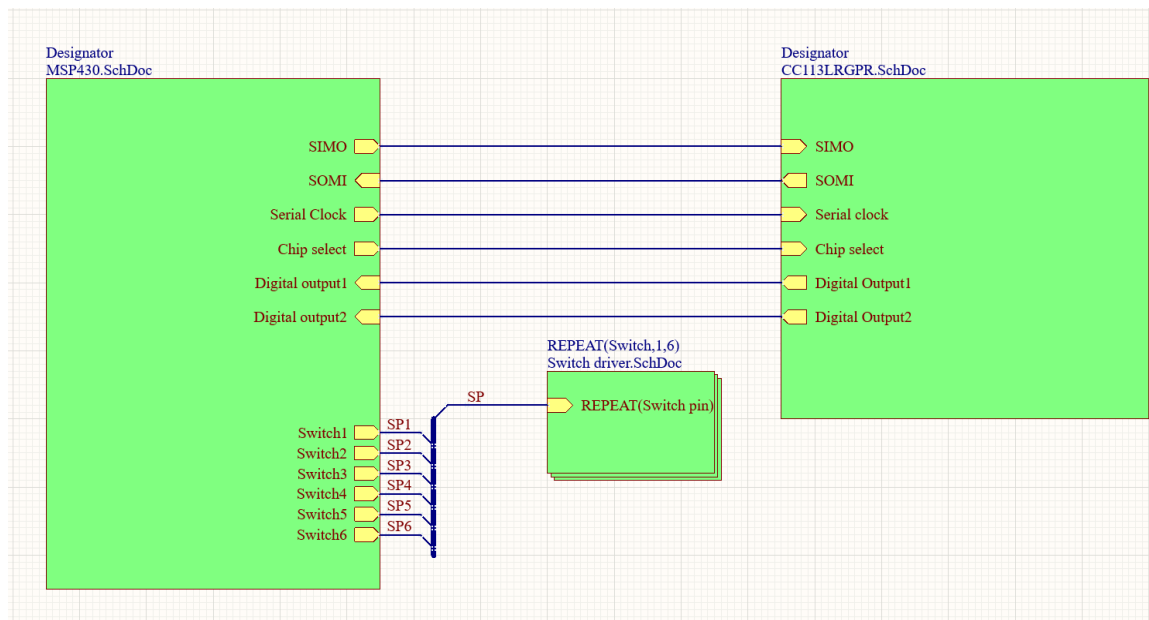
Figure 55: Overall circuit schematic for MCU, Receiver, and MSP430FR6989 connected with ports

8.3 PCB Vendor/Fabrication

The PCBs in this project were designed using the Altium design software. They were ordered from the manufacturer JLCPCB. These PCBs come with traces and vias, but we had to solder the components onto the PCB after receiving the PCB.

9. System Integration and Testing

Due to the large number of subsystems and components in the project, we have required extensive testing at the component, subsystem, and full system levels. First, we must ensure that each individual component meets the relevant specifications. Although we have designed the system to operate with the nominal specs available from the suppliers, we must ensure that under our actual operating conditions, these specifications are met. Next, we must ensure that when these components are integrated, they work together as designed to form functioning subsystems. After this, we have integrated the subsystems and performed final testing to ensure the system meets the engineering specifications. Due to the combination of RF hardware, PCBs, optical hardware, and software, we have split this testing into various sections.

9.1 RF Testing

The primary parameters used to characterize the RF performance of the optical link are the gain, noise figure, and spur-free dynamic range (SFDR). The link gain G is defined as the ratio of the RF power P_{out} generated in the photodetector load resistor to the RF power P_{in} to the laser transmitter. Thus, for a directly modulated link, the gain is

$$G = \frac{P_{out}}{P_{in}} = S_M^2 \eta_{LF}^2 T_F^2 \eta_{FD}^2 \mathcal{R}^2 \frac{R_{load}}{R_M}$$

where S_M is the slope efficiency (given in watts per ampere) of the modulation device, η_{LF} is the laser to-fiber coupling efficiency, T_F is the fiber transmission efficiency, η_{FD} is the fiber-to-detector coupling efficiency, R is the photodetector responsivity (given in amperes per watt), R_{load} is the detector load resistance, and R_M is the modulator resistance. The two major contributors to the maximum value of the gain are the limits of the modulator slope efficiency and the photodetector responsivity since the values of the other parameters do not vary significantly.

The noise figure (NF) represents a measure of the degradation in the signal-to-noise ratio (SNR) between the input and the output of the link. It is defined in decibels by

$$NF = 10 \log \frac{SNR_{in}}{SNR_{out}} = 10 \log \frac{\overline{N}_{out}/B_e}{k_B TG} = 10 \log \frac{N_{out}}{k_B TG}$$

where the input noise is the thermal noise power generated by a matched resistive load kBT held at T = 290°K. The parameter kB is Boltzmann's constant and Be is the noise bandwidth of the electronic receiver.

The spur-free dynamic range (SFDR) is defined as the ratio between the powers in the fundamental carrier and the third-order intermodulation (designated by IMD3) at that power level where the IMD3 is equal to the noise floor. This means that the SFDR is the usable dynamic range before spurious noise interferes with or distorts the fundamental signal.

$$SFDR = \frac{2}{3} 10 \log \left(\frac{IP_3}{N_{out} R_{load}} \right)$$

The point IP3 designates the input power at which the IMD3 is equal to the output carrier power. The SFDR is measured in units of dB · Hz$^{2/3}$.

Regarding the electrical part of the RF side of the project, the testing to be done here is a small part of the complete system because the RF front end ends with the Texas Instruments receiver module CC113LRGPR. Therefore, the testing required in this RF front end section is the balun network that converts the one signal input from the antenna to a two-input differential signal into the device.

9.2 General Electrical Testing

The electrical testing of the receiver will be done by parts to find possible problems in the design or components easier. The plan is to make a PCB for the receiver with pin headers that will be connected to 5 pins of the receiver that include SIMO, SOMI, Chip select, Serial Clock, and two digital outputs. For the purpose of testing the information being transmitted, we can use a digital analyzer and a predefined data package to make it easier to read with the analyzer. Then this PCB will be jumped to a MSP430fr6989 development board to program the receiver so that once we are going to test the receiver, our only concern will be the receiver and not also the microcontroller.

The receiver PCB will include the receiver itself CC113L GPR with the components found in the application note for the PCB design to include an antenna. Therefore, the second area of interest is the antenna matching network connected to the SMA connector where an antenna or a function generator can be plugged in to test whether the antenna and the receiver are matched.

Following the same testing modularity, we have also made a PCB prototype to test the MCU and that it works well in order to verify the designs of the schematics. Once everything is tested with the testing PCB boards and the development ones, then the final PCB can be sent to manufacturing for the full integration.

9.3 Optical Testing

9.3.1 Optical Switch Testing

To ensure proper operation of the optical switches, we have tested the switching mechanism using the provided circuit design from Agiltron. We have input the

beam from the 1550nm laser into the switch, and measure both outputs using the photodiodes. This includes both the steady state to measure the insertion loss and isolation between the channels, as well as transient measurements to determine the switching time. Switching time is typically characterized as the 10% to 90% time, which is the time it takes for the power in the chosen channel to increase from 10% of its final value to 90% of its final value. For our application, we need to have more stringent requirements as even at 90% power the remaining 10% will be coupled into the other output. This will result in a very low SNR for the system as that 10% of power is modulated with an undesired signal.

For this reason, we have instead measured the switching time as the time taken to reach a -25 dB power difference between the two channels, as we can only make use of the channel once we reach the necessary SNR of the system. Characterizing the insertion losses of each switch will allow us to balance the losses experienced by each beam. For example, if we have two switches with lower insertion losses and two with higher insertion losses, we have used one of each for both of the 2x3 switches to ensure more equal losses of both.

9.3.2 Fiber Coupling Testing

To ensure high-efficiency coupling, we must characterize the maximum coupling using the lasers, fiber, and collimating/focusing lenses we are using in the project. We first must measure the maximum possible efficiency, which will be done using 6-axis stages for each of the fiber collimating lenses. These stages will be made up of multiple 2-axis stages, which will be borrowed from the undergraduate teaching lab at the University of Central Florida. Careful alignment with these stages allows us to achieve maximum coupling with the two collimating lenses separated at the distance they will be in the final system.

We have measured the power out of the first fiber, and then the power that is coupled into and out of the second fiber to find the losses. Then, we have mounted the collimating lenses and fibers to the KM05 mounts to be used in the final system. With these mounts at the same separation distance as before, we have measured the maximum coupling possible with this less ideal mounting configuration. Ideally, this value should be within about 0.5 dB of the ideal coupling figure measured previously.

9.3.3 Diffraction Grating Testing

Regarding the diffraction grating, we wish to characterize both the losses incurred by the diffracted beam as well as the angular separation of the two wavelengths. To measure the power losses, we have first collimated the beam from each laser and measure the power using the photodiode or a power meter. Then, we have aligned the laser in the Littrow configuration such that the 0th order beam is reflected into the laser cavity. This is done as it is the configuration in which the highest efficiency is achieved. After this, we have measured the power of the 1st

order diffracted beam and calculate the losses. We have repeated this for both lasers independently. Next, we have co-aligned the two lasers using a two-mirror setup for both. To ensure a very close coalignment, we have observed the overlap of the spots in the near field and the far field. We have then directed the coaligned beams onto the diffraction grating, and observed the separation of the spots at a distance of 50 cm. From the distance and separation, we can calculate the angular separation of the two beams. The power of each diffracted beam is also measured to determine the losses of the diffraction grating for the two beams.

9.3.4 Mirror Cavity Testing

The multi-pass mirror cavity will require testing to ensure acceptable power losses and sufficiently aligned beams. Firstly, we have aligned each of the lasers to make the necessary number of passes through the system by orienting the zenith angle. We have then measured the power of the beam before and after the cavity to determine the power losses due to the multiple reflections. Then, we have aligned the azimuth angles of the two beams such that their paths intersect after exiting the mirror cavity at roughly the needed separation angle. We have then introduced the diffraction grating and observe the two spots of the diffracted beams in the near field and far field. We have need to determine how well the two beams can be coaligned using this mounting setup. This will be quantified by coupling the combined beams into a fiber and then measuring the relative powers of each beam. Ideally, we should be able to match the coupling efficiency of the collimating/focusing lens previously for both beams simultaneously. This will be measured by maximizing the total power through the fiber with both lasers on. Then, we have turned on only one laser and measure the power, then repeat the measurement with the other laser.

9.3.5 Laser Diode Testing

To ensure proper operation of the driving circuit, such that the laser diodes produce a CW laser at 1550 nm and 1530 nm, a series of tests should be performed. First, we have verified the power supply voltage. The 5V regulator should provide a stable 5V output voltage. To measure the voltage, we have used a multimeter connected to the V_{out} pin of the LM7805 regulator with respect to ground. Next, to test the input operating current to the laser diode, we have measured using a multimeter connected in series with the laser diode, ensuring that we are supplying the right amount of current, which should be around 100 mA for the 1550 nm diode and 110 mA for the 1530 nm diode.

Furthermore, check the laser diode voltage drop. The laser diode voltage should be within the range specified in the laser diode datasheet. Measure the diode voltage drop using a voltmeter connected across the laser diode. Finally, test the laser diode output power using an optical power meter. The laser diode output power should be equal to or greater than the desired output power.

In addition to these tests, visually inspect the circuit for any signs of damage or overheating issues. Monitor the temperature of the LM7805 regulator and the laser diode using a non-contact infrared thermometer or thermocouple, ensuring that the temperature remains within the specified range. If necessary, add heat sinks for Peltier coolers to the driving circuit design. If the driving circuit passes all of these tests, it is likely operating correctly.

9.3.6 Photodiode Testing

Testing photodiodes involves evaluating its performance parameters such as responsivity, dark current, noise equivalent power (NEP), and linearity. Responsivity measures the ratio of the photocurrent's output current to the incident optical power. To measure the responsivity, we have needed a calibrated light source, a power meter, and maybe a current amplifier. We should set-up the light source to emit a known power at the desired wavelength (1530-1550nm) and measure the output current of the photodiode. Then we have calculated the responsibility by dividing the output current by the incident optical power. The dark current is a small current that flows through the photodiode even in the absence of light. To measure the dark current, we must place the photodiode in a completely dark environment and measure its output current using a sensitive multimeter. The dark current should be very low, typically in the picoampere range for the DET08CL photodiode.

The Noise equivalent power (NEP) represents the minimum detectable optical power that the photodiode can distinguish from the background noise. To measure NEP, we have needed a low noise amplifier, a bandpass filter, and a spectrum analyzer. Connect the photodiode to the amplifier and filter the output to a specific bandwidth. Measure the noise power desist using the spectrum analyzer and calculate NEP using the formula: $NEP = \frac{\sqrt{4kTBF}}{R}$, where k is Boltzmann's constant, T is the temperature in Kelvin, B is the bandwidth, and R is the photodiode's responsivity.[50] Linearity is the photodiode's ability to produce an output current proportional to the incident optical power over a wide range of input powers. To test linearity, we have needed a variable-intensity light source and a power meter. We can measure the photodiode's output current at different incident optical power levels and plot output current versus input power. The graph should show a linear relationship.

9.3.7 Optical Modulator Testing

To test the optical modulator, we should first measure the output optical power. This can be done by connecting an optical power meter to the modulator's output and a light source to the input. The output power should fall within a specified range of -6 to -9 dBm when the pi-voltage is applied, which occurs when an applied bias voltage of 3.5V is applied to the RF GPPO connector of the modulator.

Next, we should test the on/off extinction ratio, which is a measure of the modulator's ability to suppress unwanted light. A high extinction ratio is desirable because it means that the device can efficiently modulate the optical signal without interference from unwanted light. To test the extinction ratio, connect the modulator's output to a power meter and measure the amount of light coming out when the pi voltage is applied and not applied, signifying the on and off states. The extinction ratio should be greater than or equal to 20 dB.

Thirdly, we should measure the insertion loss, which is the amount of signal loss introduced by the modulator. This is done by connecting an optical power meter to both the input and output of the modulator. Without applying bias voltage, measure the optical power output (reference level). Then, apply a bias voltage of 3.5V and measure the modulated output power. Calculate the insertion loss by subtracting the modulated power from the reference power. The insertion loss should be less than or equal to 7 dB.

Fourthly, we should test the frequency response of the modulator. This is done by connecting the modulator to a vector network analyzer (VNA) and applying a bias voltage of 3.5V. Sweep the modulation frequency from 1 GHz to 20 GHz and monitor the modulator's response on the VNA display. The frequency response should be flat within the specified range of 1 to 20 GHz.

Finally, we can test to verify the photodiode characteristics. This is done by connecting a current meter to the PD anode and cathode pins, applying an optical signal to the modulator, and measuring the photodetector sensitivity. The photodetector current should be within the specified range of 0.01 to 0.4 mA/mW. If all tests are passed, then the modulator is ready for use.

9.4 Software Testing

9.4.1 Switch Software Testing

The switch testing will be tested with the software to ensure that the code is working correctly. I will implement a pseudocode that will work on the MSP430 to demonstrate the idea of what needs to be done when we get the microcontroller chip to operate it. The goal is to just implement the pseudocode and ensure we have an idea of how to implement it into the project. To make sure the code works as intended, we have selected each possible combination of inputs and outputs and monitor the voltages of the 6 MCU pins being utilized. We have then compared the actual voltages output to the necessary combination of high voltage and low voltage needed.

9.4.1 Voltage Testing

The next test that needs to be done is that the controller also needs to be able to be able to pulse a 5 volt pulse to activate the switch and to be able to turn off the source. In this testing we have made sure the voltage supplied is the correct 5V pulse, as well as ensure that the duration of the pulses is acceptable. This will test the consistency of the work and if what we have envisioned can be put into practice.

9.5 System Testing

After all of the subsystems have been integrated, we must test that the different parts of the project function together as anticipated. The main points of integration are between the RF system and the optical system, in which the RF signals must properly modulate the optical carrier. This testing will involve generating an RF signal and measuring the output from the Mach-Zehnder modulator. This testing may be an iterative process, in which the conditioning of the RF signals is modified to attain the maximum performance of the Mach-Zehnder modulator. Additionally, we must ensure that the laser system, photodiode system, and optical modulator systems are integrated with the multiplexing system, switching system, and fiber coupling systems in order to propagate a signal through the entire system. Care must be taken to ensure proper alignment and connection of all of these optical systems to minimize losses.

9.5.1 Optical Integration

Integration of the optical subsystems should be a straightforward process, as all of the completed subsystems are fiber-coupled with either FC/APC or FC/UPC connectors. The connections between these fiber connectors are achieved using mating sleeves in which each fiber connector is aligned via a key and slot configuration and secured by tightening onto the threads of the connector. The only point of integration that does not connect via this method is the integration of the demultiplexer and the optical receiver system. Since the demultiplexer outputs two free-space beams, they must be carefully aligned relative to the optical receiver system. After aligning these systems, we have launched a CW optical signal through the system and measure the output power incident upon the photodiode. This will allow us to measure the optical loss of the system and compare it to our predicted link budget.

9.5.2 Optical-RF Integration

Testing must also be done to ensure that the RF systems properly interface with the Mach-Zehnder modulator. For the CW laser signal to be modulated to carry the signal, the voltage applied to the Mach-Zehnder modulator must meet specific values detailed previously. This testing will be performed after the optical integration, as it requires a full optical link. To test the signal generation of the RF system and modulator, we have modulated each laser with a known signal and measured the output at the photodiodes. We have then compared the input and

output waveforms and measure the frequency, signal to noise ratio, and variance between the signals.

9.5.3 Software Integration and Overall Signal Testing

After the optical and RF systems are properly integrated, the software must be integrated to allow control over the system. The first step of this process is testing the software control over the switches. To do this, we have monitor the output of the two photodiodes while we cycle through all possible combinations of input-output mappings of the channels. For each combination, the crosstalk must be measured to ensure allowable noise is added to other channels, and that the correct signal is directed to the correct photodiode. For this reason, each laser will be modulated with a distinct frequency. The Fourier transform of each output signal will then reveal the relative power of each signal on each photodiode.

To test the overall signal quality of the system, we have then performed a series of measurements over the full frequency range of RF signal to determine the bandwidth of the system as the -3dB frequency point for each of the three RF subsystems. Additionally, the testing mentioned previously in the RF testing section will be repeated, but now with the signal being sent through the entire system before being recovered and tested.

An eye diagram is a standard method of measuring the quality of a digital communications link. To create an eye diagram, a sequence of bits is sent through the system and the measured output waveform of many sequences of three bits is measured. This results in an opening at the center of the diagram that resembles an eye, hence the name eye diagram. From this eye diagram, we have calculated the time over which a measurement of a 1 or 0 can be made, as well as the acceptable level of noise in the signal below which a 0 and 1 are distinguishable. Also from this data, we have calculated the output current from the photodiode for a 0 and 1, including the average and standard deviation. From these values, the bit error rate can be extracted.

10. Failure Modes, Effects, & Criticality

The failures are rated on a critical Scale from 1 – 10, with 1 being a minor annoyance and 10 being a pivotal part of the project. This will allow us to manage risk while completing the project by first performing testing on failures that could result in long delays due to long lead times for replacement parts.

10.1 Laser Failure

If the laser diodes in the system where to malfunction it would make it so that the system would not function as intended. If the laser's output is not stable the wavelength of the intended signal will not be interpreted as intended and the

message will not be correct. Due to the long lead time this would be extremely detrimental to the project.
Critical scale: 9

Another error that can occur is if we do not align the receiver properly or if the spacing of the diodes are to great, as too great of an error will cause inaccurate measurements of the laser. As a form of light the signal will become weak as it gets farther from its source. If expanded too far it will cause the signal or output to falter.
Critical scale: 3

However, both of these errors are easily fixable. The weak laser can be replaced or recalibrated so that it has a stable wavelength. The error of alignment will be check constant and should not occur as we check for proper output.[51]

10.2 Fiber Optic Failure

Fiber optics has greatly improved communication as it has improved high-speed data over long distances. However, it is not without its flaws. When working with fiber optics it is important to check for losses. As fiber optics work with light going through fiber the loss of signal can be caused by anything that would affect that light. This could be the absorption, bending, or scattering of the light so that the signal is weakened to the point it is not received properly. The fiber optic we are using is widely available, and easy and cheap to replace.
Critical scale: 2

Another problem is that if the fiber is contaminated with dust, dirt, or other particles that would halt the light passing through would also cause a problem as the signal will be weakened or completely stopped from reaching the source.
Critical scale: 4

Another issue would be if the connection to the receiver is not done properly. Improper connection to the receiver can cause alignment issues or signal losses.
Critical scale: 3

These errors can mostly be solved. Improper connection can be fixed by adjusting the connection to the receiver. Contamination of the wire can be corrected by cleaning it along with the receiver. However, if the fiber is causing a loss and the fiber and receiver have been cleaned and are aligned correctly, then there is a issue with the fiber wire itself and should be replaced in this instance.[52]

10.3 Filters Failure

The RF filters are used to filter the frequencies being considered. It limits the range of what should be received. However, if the filter is not working correctly the filtered frequencies may be out of the range of what the receiver is anticipating and will

not be picked up. This could be caused by a few issues. One is that the filter is not set up properly. The filter could have the wrong resister values or missing wiring of the circuit causing the filter to not work as intended.
Critical scale: 3

Another issue could be that the filter is not being grounded so there is not an actual limitation to the frequencies being pass through.
Critical scale: 3

These issues can be resolved from clean circuit making and assuring that everything is flowing correct and double checking values as we go.

10.4 Switching Failure

Switches are being implemented to redirect signals to different endpoints. A failure in the switches can be caused from either the switch itself or the microcontroller. The switch itself could be faulty and is not working as intended. Either partially or entirely not performing the switching of circuits. The switch could also not be performing the switch quickly enough and part of the signal is loss due to the delay.
Critical scale: 4

The microcontroller could also be the issue as it could not be programmed correctly. It could be switching too late or switching the wrong tracks and sending the signal to the wrong receiver. This can be from poor programming or from misconnected pins.
Critical scale: 3

These issues can be fixed relatively easily. We have extra switches ordered in the event that we discover a faulty switch. In the event that the switch is not the issue than we would have to check the microcontroller and the code to see if the pins are connected correctly and if the code is signaling the right pins.

10.5 Microcontroller Failure

The microcontroller is in charge of making sure that the switches are taking place when needed and that the voltage sources are not running for too long unused. Errors can come in the form of poor coding or faulty pins. In the result of poor coding, the system can be functioning below optimal output. This could cause delays in switching and in turn cause signals to be lost or misinterpreted. The system can be overflowed with commands and cannot complete all the task immediately.
Critical scale: 4

If the microcontroller were to have a faulty pin this could cause switching to not occur properly or a signal to be lost.
Critical scale: 2

These errors can be fixed quickly by rechecking the code and deeper research into the pin layout of the controller. These controllers will not be working at full capacity most of the time but they should be coded to be capable of working under such a load.

10.6 Voltage Supply Failure

The voltage supply is consequential to this project. A voltage supply that does not have enough output or cannot withstand the usage can prove an issue to this project.

If the voltage supply cannot provide the needed energy for the system than errors can occur more often. Say the lasers are not supplied optimal power, than the signal of the laser will be weakened causing the signal to be weakened or loss power. If the microcontroller is not supplied enough power, than switching can be delayed or will not happen at all.
Critical scale: 8

If the voltage supply is not producing enough output we have replaced the supply as quickly as possible.

11. Administrative Content

11.1 Milestone Discussion

Task	Deadline	Status	Responsible
Project Selection	9/15/2023	Complete	Group 10
Initial Divide and Conquer	9/15/2023	Complete	Group 10
Obtain Optical Components for Demo	10/05/2023	Complete	Justin/Francisco
Updated Divide and Conquer	10/06/2023	Complete	Group 10
Construct Optical Mid-term Demo	10/08/2023	Complete	Justin/Francisco
Mid-term Demo (Optics)	10/12/2023	Complete	Justin/Francisco

Finalize Component Selection	10/30/2023	Complete	Group 10
Initial PCB Design/Prototyping	10/30/2023	In Progress	Edgar/James
60 Page Draft	11/03/2023	Complete	Team 10
Updated 60 Page Draft	11/17/2023	Complete	Team 10
Construct Final Demo	11/28/2023	Complete	Justin/Francisco
Final-demo (Optics)	11/30/2023	Complete	Justin/Francisco
PCB Designs Finalized and Ordered	11/30/2023	In Progress	Edgar/James
120 Page Final Report	12/5/2023	Complete	Team 10
Conduct tests to ensure RF functionality and communication.	1/30/2024	Pending	Edgar
Conduct Testing of Lasers, Photodiodes, and Optical Modulators	1/30/2024	Pending	Francisco
Conduct Testing of Power Supplies, Optical Switch PCB, and Software	1/30/2024	Pending	James
Conduct Testing of Diffraction Gratings, Optical Switches, and Fiber Coupling	1/30/2024	In Progress	Justin
Design of Optical Bench/Housing	01/30/2024	Pending	Team 10
Machining of Optical Bench/Housing	2/29/2024	Pending	Team 10
Final Alignment of Optical Components, and troubleshooting of RF subsystems	3/30/2024	Pending	Team 10

| Final Signal Quality Testing | 4/15/2024 | Pending | Team 10 |
| Final Demo | TBD | Pending | Team 10 |

Table 28: Major milestones for senior design 1 and 2

11.2 Budget and Finance Discussion

The funding for our project will be provided by our sponsor CFD. We have received a budget limitation from CFD of $15,000 for all materials required for the project. In addition to this financial budget, CFD has expressed the ability to loan us certain equipment that may include optical modulators or other components. Below we detail the approximate budget of the planned components for the project.

Estimated Budget and Financing:

Item	Supplier	Part Number	Unit Price	Quantity	Estimated Price
Mach-Zehnder Modulator	Sumicem	T.MXH1.5-40PD-ADC-LV	$249.99	3	$749.97
Single Mode Optical Fiber	Thorlabs	SM-28	$0.6144/m	100 m	$61.44
Laser Diodes	Laser Diode Source	LDI-1550-DFB-2.5G-20/70-B-2-SM1-FA-CW-0.5	$415.00	1	$415.00
	Laser Diode Source	LDI-1530-FP-1.25G-15/50-B-2-SM1-FA-CW	$315.00	1	$315.00
Photodiodes	Thorlabs	DET08CL	$319.11	2	$638.22
Diffraction Grating	Spectrum Scientific Inc.	1200-1550-012-S-S	$85.00	4	$340.00
Collimating Lens UPC	Thorlabs	F260FC-1550	$177.45	4	$532.35
Collimating Lens APC	Thorlabs	F260APC-1550	$240.45	6	$1442.7
Kinematic Mount	Thorlabs	KM05	$42.18	11	$463.98

Mirror	Thorlabs	PF10-03-M01	$56.26	6	$337.56
Fiber Coupler	Newport	F-CPL-S22155-FCAPC	$195.00	2	$390.00
Optical Switch	Agiltron	MISW-12B211333	$125.00	4	$500.00
RF Transceiver Options	Great Scott Gadgets	HackRF one	$344.95	1	$344.95
	Texas Instruments	CC113LRGPR	$1.8	3	$5.4
RF Filter	UCF Dielectric Labs	Fabricated at UCF B096QC2S	$0 (free) $133.78	1 1	$0.00 $133.78
Microcontroller Development Board	STMicroelectronics	STM32 Nucleo Development Board	$22.81	2	$ 45.62
	Texas Instruments	msp430fr6989	$20	1	$20.00
PCB Fabrication	JLCPCB	TBD	$42.50	3	$42.50
Housing Materials		TBD	TBD	TBD	TBD
Total Budget:		TBD (< $15,000)			

Table 29: Bill of materials and budget

11.3 Work Delegation

Subsystem	Task	Assignee	Secondary
Optical Switching	Hardware Selection	Justin	Francisco
	PCB Design	James	Edgar
	PCB Test	James	Justin
	Software Design	James	Justin

	Software Test	James	Justin
MUX/DEMUX	Hardware Design	Justin	Francisco
	Alignment	Justin	Francisco
	Testing	Justin	Francisco
Fiber	Hardware Selection	Justin	Francisco
	Testing	Justin	Francisco
RF	Antenna Selection	Edgar	Francisco
	Receiver Implementation	Edgar	Francisco
	RF Testing	Edgar	Francisco
Laser Diodes	Hardware Selection	Francisco	Justin
	Hardware Design	Francisco	Justin
	Testing	Francisco	Justin
Photodiodes	Hardware Selection	Francisco	Justin
	Hardware Design	Francisco	Justin
	Testing	Francisco	Justin
Encryption	Software Design	James	Francisco
	Testing	James	Francisco

Table 30: Work delegations

12. Conclusion

So far, we have presented a detailed design for a system that incorporates fiber optic switches to realize a unique asymmetrical design in which a small number of recovers can be switched to any of many RF inputs. We have designed a series of three RF receivers optimized to operate at 3 different RF frequencies. In order to modulate light to carry these RF signals, we have designed an optical transmitted consisting of two lasers at 1530 nm and 1550nm, an optical modulation system enabled by a Mach-Zehnder interferometer, and an optical receiver that

consists of a photodiode and associated circuits. To enable the switching mechanism, we have designed two 2x3 switches that can direct each of the two laser diode wavelengths to any of the three optical modulators. The two wavelengths are then combined prior to the modulators via a wavelength division multiplexer in which the multiplexing is performed by a diffraction grating. The combined beams are transmitted through a fiber optic and are then demultiplexed prior to the optical receiver via another diffraction grating.

Throughout the design process, our system has undergone several large changes in the basics of the project. Initially, the project was imagined as a high data throughput system, in which we would utilize wavelength division multiplexing as well as polarization division multiplexing in order to construct an RF over fiber system with a large number of channels per fiber. However, at the recommendation of our sponsor Dr. Charles Middleton at Critical Frequency Design, this original design was abandoned as there are commercially available systems that achieve these goals using integrated photonic solutions that far exceed the capabilities we could create using free space optics. Instead, we decided in collaboration with the sponsor that we would pursue the asymmetrical switch-based design presented in this document. Even after this major design change, we underwent several smaller changes, including changing the target RF bandwidth, changing the switching mechanism, and choosing to input signals via coaxial cable rather than from antennas. Through this, we learned that the design process is highly fluid, and often requires many changes throughout the early period of design. Additionally, we learned that it is necessary to be in constant communication with the customer in order to better understand their needs and design a project to meet them.

In addition, we have learned that communication within an engineering group is vital. Each of us has unique skills and backgrounds and may not have a full understanding of what the rest of the group is working on. This is especially true considering that the 4 of us each have different majors or combinations of majors. This presented challenges in making sure we understood how each of our sections of the project would function together to form a cohesive device. Through this, we have learned the necessary communication skills for working across engineering disciplines.

Overall, we feel that this project has been a challenging but rewarding experience. The large budget has provided us with extensive resources to create a complex project, however with this comes a large workload as there are many part selections that need to be considered carefully, as well as extensive testing for each of these components. However, this work has provided us with exposure to a wide array of hardware and software that is widely used throughout the industry including Mach-Zehnder interferometers, software defined radios, wavelength division multiplexing, and much more. This equipment would typically be cost-prohibitive for undergraduate students to gain experience with, and we are thankful for our sponsorship from Critical Frequency Design for this opportunity.

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RE: Request to Republish Circuit Schematic

Jim <jzhao@photonwares.com>
Thu 11/9/2023 12:28 PM
To:Justin Gruber <Justin.Gruber@ucf.edu>;Sales <sales@photonwares.com>

Ok, you can do it

Thanks

Dr. Jim Zhao
Photonwares Corporation
Office:781-935-1200x2600
Cell: 781-583-8068
15 Presidential Way, Woburn, MA 01801

From: Justin Gruber <Justin.Gruber@ucf.edu>
Sent: Thursday, November 9, 2023 12:25 PM
To: Sales <sales@photonwares.com>
Subject: Request to Republish Circuit Schematic

Hello,

I am a student at the University of Central Florida, and I am currently taking a Senior Desing course in which we plan on using your product "MEMS Ultra-Mini 1x2, 2x2 Fiber Optical Switch." For this project we are required to write a detailed report of our design, and I would like to get your permission to use the image of the recommended driving circuit from the datasheet of the aforementioned product. This report will be published publicly by the university, and the image would be properly cited to your company. Would you be able to grant permission to republish this schematic?

Thank you,
Justin Gruber

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RE: Permission to use images from CFD website

Charles Middleton <cmiddleton@Criticalfrequency.com>
Mon 12/4/2023 9:14 AM
To: Justin Gruber <Justin.Gruber@ucf.edu>

Hi Justin,

Yes, you may use images from our website.

Thanks,
Charles

From: Justin Gruber <Justin.Gruber@ucf.edu>
Sent: Sunday, December 3, 2023 2:54 PM
To: Charles Middleton <cmiddleton@Criticalfrequency.com>
Subject: Permission to use images from CFD website

Hello Charles,

For our report we need explicit, written permission to use copyrighted images. Can we use images from the Critical Frequency Design website in our report?

Thank you,
Jusitn Gruber

Appendix C: ChatGPT Statement

We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for summarizing and proofreading purposes.

Appendix D: Pseudo Code Power Saving

```c
1  #include <stdio.h>
2
3  int main(void)
4  {
5    // power saving mode
6
7    // set a timer
8
9    // detectior for  voltage from source
10
11   while (/* source voltage is less than (amount) */)
12   {
13     //start timer
14     if (/* timer reaches # minutes */)
15     {
16       // turn off voltage source
17       // stop timer
18     }
19   }
20
21   // repeat for # of sources
22  }
```

Appendix E: Pseudo Code Switching

```c
1  #include <stdio.h>
2
3  int main(void)
4  {
5    // enable switches / ports ( with switches all sent from the same position)
6
7    if (/* switch is flipped */)
8    {
9      // send change reflector
10   }
11
12   // repeat for x <= 2^n with x being the number of endpoints and n being the amount of swicthes needed
13  }
```