Varying Optical Frequency Shifter

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Group B

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* Image Courtesy of UCF.edu

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1.0 Executive Summary

In recent years, optics and photonics has become an integral part of the communications world. The development and optimization of optical components such as lasers, photodetectors, modulators, fiber optic cables has allowed for unprecedented amounts of data sent at incredible speeds. Just as optical communications has become the backbone of the civilian communications network around the world, radio frequency photonics is becoming an increasingly used form of communication in the world of electronic warfare. By combining tried and true radio frequency technology with state of the art photonics components, sending larger and larger amounts of data at high speeds has become possible. This has led to the pursuit of radio frequency photonics as a way of ensuring reliable communications in an electronic warfare setting by many defense contractors -- such as Harris Corporation, the sponsor and customer for this project. The project discussed in this report is on the design and related investigations of a variable optical delay generator. Variable optical delays are of vital importance in the field of optical communications, particularly in regards to phased array antennas. The purpose of this project is to design a rapid and precise variable optical delay. While many variable optical delays exist on the market today, the specific, precise delay requirements for this project require a specific solution.

Two main approaches are considered for this project, and are discussed and compared in detail in this report. One approach involves the use of a variable free space optical cavity to generate optical delay based on the varied optical path length caused by the cavity. Proposed cavity designs include a Herriott cell design -- which involves the use of curved mirrors -- and a corner cube mirror design. By precisely varying the distance between mirrors, and therefore varying the optical path length of the signal as it propagates through the cavity, the delay of the signal can be varied. The electronics involved in this approach include designing and implementing the appropriate motor and motor control systems to precisely change the length of the cavity.

The other main approach considered in this report involves the implementation of serrodyne phase modulation. Serrodyne phase modulation involves shifting the frequency of an optical signal by phase modulating at a particular slope. Through the use of an appropriate dispersive media, specific delays can be implemented as different frequencies propagate at different distances through the dispersive media. Thus, many different phase modulation slopes would be necessary in order to generate the required delays. In addition to the central delay generation aspect of the serrodyne phase modulation approach, design additions are discussed in this report that will help mitigate the detrimental aspects of this method such as the generation of unwanted serrodyne spurs. The electronics involved in this approach include the biasing of both phase and intensity

modulators with the appropriate electrical signals so as to provide the appropriate phase shift with limited detrimental effects. However, with this approach, the sponsor and customer for this project (Harris Corporation) has stated that shifting the signal by the frequencies necessary to impart the required time delay with the appropriate dispersive media is a sufficient outcome of this project.

2.0 Project Description

In this section, the description of the project is detailed. This includes descriptions of the motivations for the project, the goals of the project, the involved personnel, the objectives and the requirement specifications for the project. Motivations detailed in this section include individual motivations of the group members, the sponsor motivation, as well as possible technical motivations for the project. The goal of this project is to design a rapidly swept optical time delay generator to be used in an overarching radio frequency photonics processing system. In the final system an RF signal is detected, processed optically by various elements of the system, and the processed signal is then converted back into RF and emitted. This information was given by our sponsor. Our task is to design this swept optical delay generator as one of these optical processing elements. The final goal of the project is to have a high degree of precision and control over the delay time, including the ability to specify and select discrete delay times at a rapid rate. Currently, there are two design approaches that are being reviewed and studied.

One design approach under consideration is to design an optical cavity with variable distance between the walls of the cavity such that the optical path length - and therefore the time delay - would increase. The cavity used would likely need to be folded multiple times in order to allow for a reasonable distance and number of components, as well as a feasible motor speed and precision. We have considered a few options that could possibly achieve. The first is a corner cube mirror approach. This would involve setting up a line of corner cube mirrors that reflect the light back and forth (tracing the light rays would show a square wave pattern) to create delay. This will give us great freedom with the intrinsic optical delay. In order to vary the delay, we would need a motor attached to one line of corner cube mirrors to translate the mirrors further away from the opposite line of corner cube mirrors thereby increasing the delay. This method is fairly simple, and has plenty of freedom, but the precision and speed of the motor is a very big limitation to this method. Another option with an optical cavity is making use of a Herriott cell. The basic concept of a Herriott cell is an optical cavity with two curved mirrors that has a single opening for the light to enter and exit. The light gets trapped in the cavity by getting reflected many times, and then finally leaves out the same opening by which it entered the cavity. To create a variable delay, we would have to change the location of one or both of the mirrors by using a motor. The main drawback to this method is there is limited resources available on this type of cavity, so it will be difficult to learn more about it without having access to a Herriott cell and performing extensive testing with it. Motor speed and precision are also a limitation with this method. Some objectives involved with this design approach include designing the cavity such that the delay can be adjusted appropriately, implementing and controlling a motor to precisely and rapidly manipulate the size of the cavity, and designing the appropriate lens systems to allow for efficient free space coupling into fiber after the optical cavity. If a design approach using multiple mirrors is chosen, cost becomes a significant factor for this design approach.

Another design approach under review is based on serrodyne frequency shifting. This serrodyne frequency shifting method is a well understood technique based on linear phase shifting. A phase modulator is implemented and driven in a linear fashion by a voltage source. The slope of this line determines the frequency shift of the incoming signal, so different slopes would result in different frequency shifts. A linearly Chirped Fiber Bragg Grating or some other dispersive media could then be implemented to generate a delay based on the frequency of the incoming signal. Thus, an approach similar to the Chirped Fiber Bragg Grating approach explored by the sponsor could be implemented while using a single wavelength source. Some objectives involved with this design approach include finding the appropriate voltage source and phase modulator for this system. There is a trade off to be made between the maximum Vpi of the phase modulator and the resolution of the voltage source that determines the slope of the phase modulation and therefore the frequency shift of the signal. Typically, phase modulators can be relatively expensive, and the cost of the voltage ramp may be high as well. Therefore, comparing the cost of the two approaches will be crucial.

2.1 Project Motivation and Goals

In this section, various motivations for the project are discussed. The individual group member will be discussed first. These will give a background on each group member, as well as the personal motivation from each. Then, the sponsor's motivation will be discussed. Lastly, the technological motivations will be detailed. After this section, there will be a clear understanding of the motivation behind our project from all parties involved.

2.1.1 Individual Group Member Motivation

Marcus Darby - Being the only member of the team who is not an optics major working on a primarily optics project allows me to gain more experience in the optics field, which is something that has interested me for some time. Being on this team will allow me to use what I have learned as an electrical engineer and apply it in a way I may not have otherwise done. This project also gives me the opportunity to understand how to design and use a microcontroller to fit the given requirements for our design. Previous courses have allowed me to understand just how to build and design circuits for a desired output signal. In the scope of this project, however, I need to understand how the microcontroller will work in tandem with the motors or any other connected parts. Thus I will need to first understand the properties of the signals that are desired and then figure out the best approach to implement such a signal. Overall this project is desirable for me by taking me outside of my comfort zone, allowing to learn and understand optics, a discipline that has similarities with yet is different than my own, while also working on an aspect of my own discipline I am not entirely experienced with. Being able to learn and adapt to these objectives will give me confidence that I can adapt to any situation and problem that I may have to face.

Kevin Gaj - With my majors being electrical engineering and photonic science, this project presents a great opportunity to apply my knowledge of both areas into one design. I will gain experience in both fields. Also, I am looking into a future career in the defense field, so this project could give me good experience in that area since it will most likely have some sort of military application. In addition to the above, this project will be a great opportunity to see how both of my majors can tie together in a final system. Usually my classes focus on just the electrical engineering aspects of a project or just the photonics/optics aspects of a project; however, now I can see how both sides are equally important in the design, development, and function of a final system. I have had an internship that was focused on electrical engineering design, but I have been wanting to also gain some industry experience in the field of optics. Although not directly in the industry, this project is funded by a major corporation, and it involves working with industry professionals. I feel this will be a good opportunity to give me some idea of what it is like to work in the field of optics in industry before I graduate from school.

Samuel Nunez - As an optics and photonics engineer, this project presents an opportunity to gain knowledge and experience in designing and perfecting an advanced fiber optic communications system. This project presents challenges from a theoretical geometric optics approach as well as real engineering issues regarding optical engineering components. Personally, fiber optics communication systems at photonics processing systems for electronic warfare and communication has been of great interest to me throughout my academic career. This project provides the opportunity to work on an exciting topic with some of the leaders in the field at Harris Corporation. Another personal motivation is the chance to learn and improve upon electrical engineering and coding skills. Due to the nature of the project it is likely that I will be able to gain experience with some of the topics I have learned in general electrical and computer engineering courses.

Caleb Stephan - With my major being Photonic Science and Engineering, I wanted to do a project that was heavily optics based. Every since taking geometric optics, the methods of directing, bending, and manipulating light has interested me very much. The applications of various optical systems have been very fascinating to me, and I want to learn what it is like to actually design an optical system. This project will give me an opportunity to apply concepts and principles I have learned from my academic studies to a real project. Personally, I learn best by doing, so working with optics and optical systems will aid me in learning more about my field of study. I am excited to see how things on paper meet real world application. Another motivation for me personally is that I am very interested in increasing my experience with research, design, and testing. I have very limited experience with these disciplines in the past, and this project will have me to engage in all three. I am motivated by this project because it gives me a taste of what industry will be like, since we are working with Harris to attempt to provide a system that will be of use to them. Overall, this project will stretch me in my knowledge and allow me to gain valuable skills that will be useful to my career in industry.

2.1.2 Sponsor Motivation

The sponsor is responsible for designing and constructing a complex RF photonics processing system comprised of multiple optical processing components. The optical delay generator discussed is one of these components. Initially, the sponsor had taken a different approach than what is suggested here, using a frequency swept source and Chirped Fiber Bragg Grating to generate the delay. This system, however, is not compatible with the overarching system due to the frequency swept nature of the source. The sponsor is interested in a continuous wave, frequency stable solution to this problem.

Another approach pursued by the sponsor was a circular multipass optical cell. The delay time of this system would be dependent upon the incident angle of the incoming light. However, the sponsor found that this approach yielded several issues regarding the total optical path length as a function of incident angle. Our project is to design a variable optical delay that overcomes the issues encountered by the sponsor while still meeting the requirement specifications of the system. The option for Harris Corporation to simply purchase a variable delay line off the market is not an option for this system. As discussed in the requirement specifications section below, the specifications of this system regarding delay resolution, maximum delay range, ramp time, and intrinsic delay are fundamental to this project’s future incorporation into the overarching photonics processing system designed by Harris. Typical variable optical delay generators on the market today provide delays of hundreds to thousands of picoseconds. The resolution of these delay generators is typically determined by a manual micrometer.

These metrics do not meet the requirement specifications detailed in the section below. Furthermore, most of these delay generators are manually operated. The requirement specifications given by Harris Corporation require the final system to operate within fractions of a second. Therefore, the final system must operate automatically and will likely require the use of microcontrollers to achieve the final goals for the project.

2.1.3 Technological Motivations

Due to the proprietary and classified nature of the overall photonics processing system in development by Harris, specific knowledge regarding the overarching photonics processing system and how this project would be used for it is unavailable to our group. However, in this section possible motivations and uses for variable optical delays are discussed. In terms of communications, variable optical delays are of high demand in regards to phased-array antennas. Phased array antennas are comprised of multiple, sometimes hundreds or thousands, of individual antenna elements. The maximum radiation in a particular direction is then controlled by the phase difference between the antenna elements [1]. This phase difference creates constructive or destructive interference, and depending on the degree of interference the direction of maximum radiation is changed. Optical fiber is being used more frequently in phased array antenna systems due to advantages such as its relatively lightweight and has low losses [2]. Selecting the precise phase shift based on wavelength selective time delay elements has been a topic of discussion in this field [2]. One possible use for this project could be to act as a wavelength selective time delay element in a phased array antenna.

2.2 Requirement Specifications

In this section, requirement specifications are discussed. These include any specific constraints provided by the sponsor. The main constraints for this project are related to the generated delays. The target delay range is from 1 to 2 nanoseconds, with step sizes of approximately 10 picoseconds. Harris Corporation has not given any requirement specifications in terms of an exact delay range. The only requirement in this area is that the final delay range of the system lie within the specified range. The target time spent at each step of the delay is approximately 50 microseconds or less. The total transition time is required to be 50% of the time spent at each delay step or less. The ramp period of the system is approximately 10 ms, and the target intrinsic delay is approximately 1 nanosecond. For the serrodyne phase modulation approach, which involves shifting the frequency of the optical signal to generate the optical delay, Harris has stated that a frequency shift of 100 MHz, the correct number of frequency shifts that corresponds to the required delay range, and the appropriate time for each frequency shift that corresponds to the required delay step duration will be a sufficient output of the system. This is because the design and purchase of the appropriate dispersive media required to generate the delay based on the frequency shift imparted by serrodyne phase modulation is expensive and beyond the scope of this project. The size of the system is a fairly flexible constraint. The customer has expressed interest in the system being confined to a 1 foot by 1 foot space, with the potential of reducing space required. Power is not a major concern of the sponsor, but a soft constraint of 30 Watts for the system, including the source and motor, was discussed. Table 1 and figure 1 detail these discussed requirement specifications.

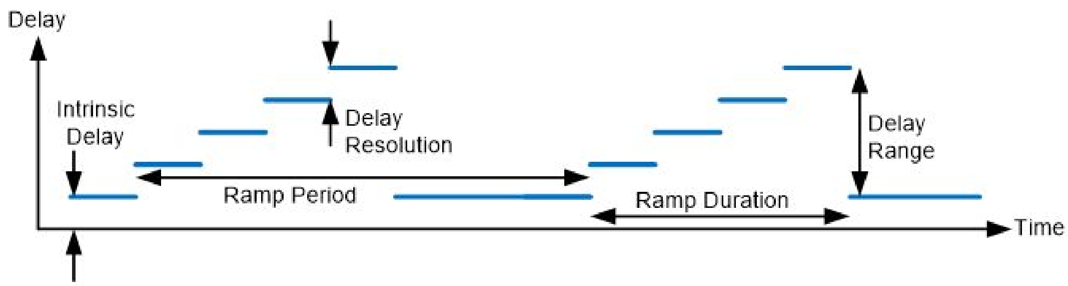


Figure 1: Model of Target Delay as a Function of Time (Provided by Harris)

Design Parameter	Target	Description/Notes
Max Delay Range	1-2 ns	This sets the total maximum path length of the system
Intrinsic Delay	1 ns (more if necessary)	Shortest possible delay through the entire system
Delay Step Size/Resolution	<10 ps	Maximum difference in delay time between steps
Delay Step Duration	<50 μs	Maximum allowable time spent at one delay. Derived assuming linear profile.
Max Delay Step Transition Time	Less than 50% of the Delay Step Duration	
Maximum Frequency Shift (Serrodyne Approach)	≈100 MHz	
Ramp Period	10 ms	
Ramp Duration	≤ Ramp Period	
Delay Ramp Sign	+ and -	
CFBG Dispersion	TBD	Only applicable with serrodyne approach
CFBG Apodization	Hanning	Only applicable with serrodyne approach

Table 1: Requirement Specifications

Traditionally, an optical delay line involves a single, long bundle of fiber optic cable in which the optical signal is allowed to travel for a given period of time to produce the delay signal. An RF signal will enter the unit and be converted to the optical domain through modulation. From here, the signal will travel through preselected delay fiber paths and produce the built in delay for the chosen path. The signal is then converted back to the RF domain. The problem with this approach for our design is that the intrinsic delay would be too high if running through a single, long fiber. In addition to this, the multiple steps of delays would require multiple fiber paths that each produce a greater delay than the previous fiber. In our design, it is possible that there could be hundreds of delay steps. It is not feasible or cost efficient to design a system that would require hundreds of separate fiber cable delay lines. Since the traditional methods of using an optical delay will not work, a new system must be developed that can delay an RF signal optically while still following the design parameters. Whatever method is used to achieve this must ensure that the intrinsic delay requirement is satisfied, otherwise traditional delay line methods could be achieved.

3.0 Research Related to Project Definition

In this section, all research related to the project definition is detailed. This includes research for a free space design approach with curved and un-curved mirrors, and research for a non-free space serrodyne approach. The details of the requirement specifications of the project are discussed in relation to the researched design approach.

3.1 Relevant Technologies and Potential Design Approaches

In this subsection, the relevant technologies that could be utilized for this project as well as potential design approaches are detailed and discussed. These technologies include those involving free space optical setups, as well as fiber-optic technologies. These different technologies will be analyzed to see whether or not they will be feasible to use given the design specifications of the project. There are various product options available for variable optical delays. However, there are none available on the market that can provide the precision and resolution in terms of delay time and follow the specific requirements for this project regarding ramp time of the system. There is, however, knowledge to be gained by researching the technologies and driving mechanisms behind some of these options. Therefore, this section is dedicated to researching, analyzing, and discussing any relevant technologies, existing products, and potential design approaches.

3.1.1 Optical Delay by Retroreflection

There are a few known methods for achieving optical delay. One of these methods uses the concept of retroreflection. Retroreflection is a simple process that happens when light from a source is reflected back in the direction of the source itself. This phenomenon is commonly used on road signs, pavement markings, and reflective clothing to name a few [3]. So retroreflection is quite useful to use in everyday life, but the point of researching this is to see if it can be used for the purposes of creating optical delay. Conveniently, generating an optical delay using retroreflection is fairly simple in nature. Now that the principles of retroreflection with corner-cube mirrors has been investigated, the existing products that use retroreflection to create an optical delay.

Retroreflection can be achieved with multiple methods, but one of the easiest is to use a corner-cube mirror. With a corner-cube mirror, the incident light will always be reflected back towards the source (see figure 2). This happens because each face of the corner cube is orthogonal to each other. There will be a varying displacement between the incident and reflected beam depending on where the light is incident on the corner-cube mirror. This is easily figured out by using some simple trigonometry, shown at the bottom of figure 2. Now that the principles of retroreflection with corner-cube mirrors has been investigated, the existing products that use retroreflection to create an optical delay.

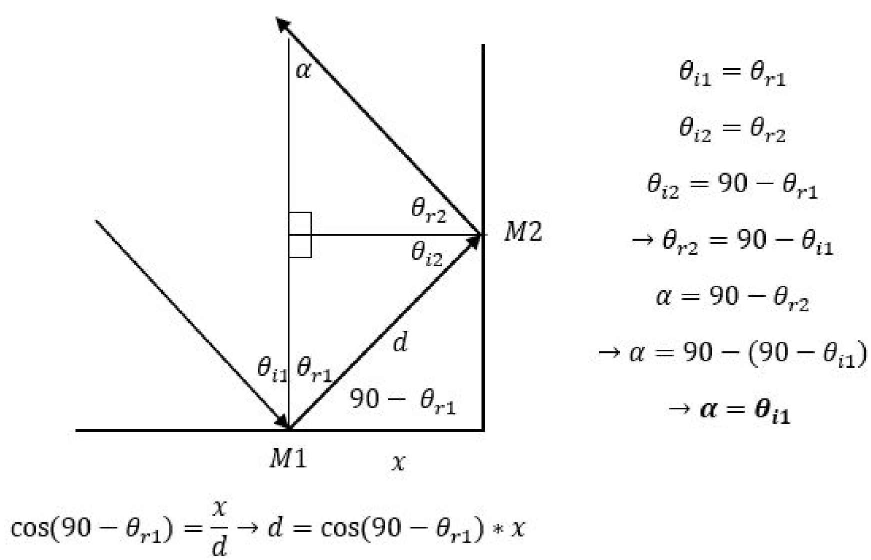


Figure 2: Sketch of a Two-Dimensional Corner-Cube Mirror.

In figure 2 above, M1 and M2 are mirrors that are orthogonal to each other. To the right of the sketch is a proof to show that the incident angle of the light ray is equal to the angle of the retro-reflected light ray. The distance between the incident light ray and the reflected light ray can be calculated using the equation at the bottom. All angles are in degrees. A few photonics/optics companies have developed ways to generate optical delay using retroreflection. A couple of these companies are General Photonics and Newport. General photonics has a product for generating a delay for optical fibers called VDL-001 – Optical Delay Line (shown below in figure 3) [4]. This is a manually operated, closed box optical delay line that utilizes the phenomena of retroreflection. Their models range in delay amounts from their single pass models with max delays from 330 ps – 600 ps to their double pass model with a max delay of 1200 ps [4]. The double pass model achieves the max delay needed, but the difficulty comes in creating a varying delay with a step size of less than 10 ps and a step duration of less than 50 μs. This would require an incredibly fast motor, and it would require the unit to be heavily modified in order to fit meet the requirement specifications of the project. For these reasons, other methods of achieving varying optical delay were investigated.

Figure 3: A Photo of the General Photonics VDL-001 – Optical Delay Line [4].

In figure 3 above, the unit itself, the fiber input and output, as well as the wheel used to adjust the optical delay is shown. Photo reprinted with permission from General photonics [4]. Another method involving corner-cube mirrors and retroreflection that was investigated was a free space setup. Newport sells a corner cube mirror mount for optical tables that can be used to create optical delay (shown below in figure 4) [5]. Generally, there is more freedom available to us with this method when compared with the previous method using an already made optical delay line, as it allows you to place the mirrors at any distance and use as many corner-cube mirrors as needed. This seems like the more realistic method of achieving what is needed in the requirement specifications of the project, because of all the freedom this allows. Figure 4 below shows several other parts in addition to the mirror mount. Photo reprinted with permission from Newport [5].

Figure 4: Photo of an Optical Delay Line Mirror Mount from Newport [5].

3.1.2 Corner-Cube Mirror Design Approach

By using corner-cube mirrors in free space, some of the requirement specifications are easily met. Since the max delay requirement specification is 1-2 ns, and the intrinsic delay is 1 ns, it is seen that this requirement is easily achievable because, considering the only thing that is changing is the distance between the corner cube mirror and the source and detector, the limitation is based only on the size constraint, of which there is none. For an intrinsic delay of 1 ns, the optical path length must be about 0.3 m (taking the approximation for the speed of light as $c = 3 * 10^8 \frac{m}{s}$). Also, for the max delay range from 1-2 ns, this corresponds to an optical path length of 0.3-0.6 m. Therefore, the max optical path length the cavity would need to provide is 0.9 m, which is fairly large considering the application, but entirely feasible. It is clear that the method of using a corner-cube mirror can easily achieve the requirement specifications of the max delay range and intrinsic delay, by having a large enough optical path length. Although these requirement specifications are easily met, other requirement specifications such as the delay step size/resolution and delay step duration are much more difficult to achieve.

The greatest hurdle needs to be overcome with this method involves the velocity at which the corner-cube mirror must travel at in order to vary the optical delay with the given step size and step duration. For the requirement specification of the step size (which is less than 10 ps) to be met, the amount of distance that the optical path length (OPL) would need to increase in order to achieve this step size is 0.003 m or 3 mm if the step size is at the maximum of 10 ps. Taking the step duration into account (which is to be less than 50 μs) and setting the time that the mirrors are at each individual step to be 30 μs, this allows a 10 μs transition time between steps.

These values chosen are only rough estimates for the sake of future calculations. They could very well be subject to change, but in order to simply test if this method is feasible, these values will be considered. Now that the change in optical path length and transition time is established, the delay generator design as well as the equations needed to determine how fast the corner-cube must move will be formulated.

The design using this corner-cube method is fairly simple and easy to formulate. First, a design that only involves one corner-cube mirror will be considered to see if this method is even possible. However, later a design with multiple corner-cube mirrors will be explored. For a design with a single corner-cube mirror, there will be an optical source lined up with the corner-cube mirror such that the light gets retro-reflected back into a receiver. Of course, the corner-cube mirror is mounted on a translation stage that is controlled by a motor to change the optical delay. A diagram of this setup is shown in figure 5.

In figure 5, it is shown that the light travels from the source in the positive z-direction, strikes the first mirror (M1) at an incident angle of 45-degrees, gets reflected in the positive x-direction, strikes the second mirror (M2) at an incident angle of 45-degrees, and gets reflected back in the negative z-direction towards the receiver. The distance d is a distance that varies with the translations stage. The distance h is a value that is dependent on where the light is incident on M1. The total optical path length that the light travels is the sum $2d$ and h. With this design formulated, the required speed that the corner-cube must travel can be calculated.

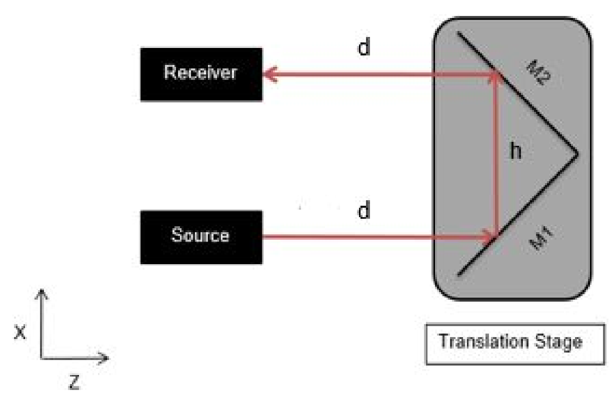


Figure 5: Optical Delay Generator with a Single Corner Cube Mirror.

In figure 5 above, M1 and M2 are mirrors at a 90-degree angle with each other, d is the distance traveled from the source and M1 as well as the distance traveled from M2 to the receiver, and h is the distance the light travels between each mirror. The light comes from the source traveling in the positive z-direction, gets reflected to travel in the x-direction M1, then gets reflected to travel in the negative z-direction by M2 to the receiver. The corner-cube mirror is on a translation stage that moves in the z-direction.

In order to calculate how fast the mirror must move, the relationship between the optical path length and the distance d must first be considered. For the sake of simplicity, h will be neglected as part of the optical path length since h will in actuality be much smaller than d. With this approximation, it is given that the relationship between optical path length and the distance d is given by equation 3.1.2.1.

$$OPL = 2d$$

Equation 3.1.2.1: Optical Path Length as a Function of Distance

And it follows that the relationship to the change in OPL to the change in d is given by equation 3.1.2.2.

$$\Delta OPL = 2\Delta d$$

Equation 3.1.2.2: Change in Optical Path Length as a Function of Change in Distance

Using this relationship, the velocity of the corner cube can be found. The expression for the velocity that the mirror must move in the z-direction (v) is given by equation 3.1.2.3.

$$v = \frac{\Delta d}{\Delta t} = \frac{\Delta OPL/2}{\Delta t}$$

Equation 3.1.2.3: Velocity of Corner-Cube Mirror

Where Δd is the distance the corner-cube mirror must travel, Δt is the transition time between steps, and ΔOPL is the change in optical path length. With the change in optical path length equal to 0.003 m and the transition time equal to 10 μs, the velocity is calculated to be 150 m/s. This velocity is incredibly fast and terribly unrealistic seeing as the max speed of an average motor is around 0.2 m/s. This is where the shortcomings and difficulties of this method were discovered. Given the current requirement specifications, using this design with only one corner-cube will not at all be possible. In the following few paragraphs, a system that utilizes many corner-cube mirrors to vary the optical delay will be discussed.

3.1.3 Multiple Corner-Cube Mirrors Design Approach

If more than just one corner-cube mirror is used, the equations used to calculate the velocity must be made more general. In the past example, only one corner cube mirror was used, resulting in the light traveling two distances d, with the distance h between mirrors. Since the distance between the mirrors is constant, it can be neglected when considering the change in the optical path length. If another corner-cube mirror was added where the receiver is, and the receiver was turned around and put just above the first corner-cube, it is evident that the light now travels three distances d and two distances h (assuming there is symmetry) between the mirrors of each corner-cube. This setup is shown below in figure 6. Seeing this trend, it can be concluded that the number of times the light travels the distance d is equal to the number of corner-cube mirrors plus one. The number of times the light travels the distance d will be referred to as N. Therefore, the new relationship between the change in optical path length and the change in the distance d is given by equation 3.1.3.1.

$$\Delta OPL = N\Delta d$$

Equation 3.1.3.1: Generalized Optical Path Length

Using this formula, the new formula for the speed that the distance must change is given by equation 3.1.3.2.

$$v = \frac{\Delta d}{\Delta t} = \frac{\Delta OPL/N}{\Delta t}$$

Equation 3.1.3.2: Generalized Velocity of Corner-Cube Mirrors

Know that there is a new term for the velocity with a variable amount of corner-cube mirrors, the number of varying distances can be calculated with a given velocity. The number of corner-cube mirrors needed given a max motor velocity will be calculated and discussed in the following paragraphs.

To calculate the number of varying distances d that are needed, and thereby the number of corner-cube mirrors needed, the max speed that the motor would be able to translate a set of mirrors must be known. Neglecting non-idealities such as acceleration time and the variance of speed and acceleration with a load on the motor, the max speed that a normal motor can travel (mentioned previously) is around 200 mm/s (0.2 m/s), or 600 mm/s (0.6 m/s) on a larger motor. Knowing this, the number of varying distances needed to have the translation stage move at this speed while still maintaining the correct delay step size and step duration can be calculated by solving for N in equation 5. Performing this algebra shows that N is given by equation 3.1.3.3.

$$N = \frac{\Delta OPL}{\Delta t * v}$$

Equation 3.1.3.3: Number of Varying Distances Needed

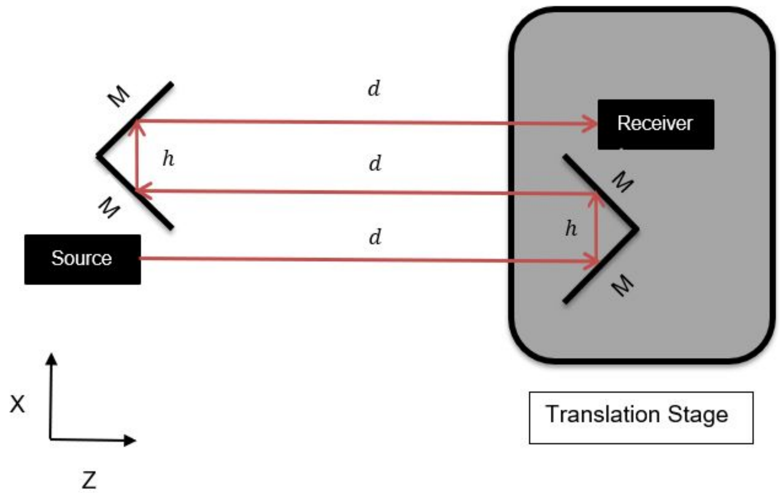


Figure 6: A Simplified Diagram of a Cavity with Two Corner-Cube Mirrors.

In figure 6 above, d is the varying distance, h is the distance traveled by the light between the mirrors, and M signifies a mirror. Adding an extra corner-cube mirror results in another varying distance d. By adding more corner-cubes, and thereby increasing the number of varying distances d, the velocity that the translation stage must traverse is decreased. Given that the velocity at max is 0.2 m/s, the transition time is 10 ps, and the change in optical path length is 0.003 m, N is calculated to be 1500. Therefore 1499 corner-cube mirrors would be needed to achieve this speed. This is a ludicrous amount of corner-cube mirrors. Even if the max speed was increased to the max speed for a large motor (0.6 m/s), 500 varying distances, resulting in 499 corner-cubes, would be needed. Although this is feasible, it would not be efficient, cost-effective, or compact enough to be useful. Knowing this, the multiple corner-cube approach is not compatible with the given requirement specifications.

3.1.4 Multi-Pass Corner-Cube Design Theory

While considering the corner-cube method, another idea that was entertained involved having the light travel multiple paths along a more realistic number of corner-cube mirrors before the signal was received. This would essentially multiply the varying distances by the number of different paths that were created, drastically decreasing the number of corner-cube mirrors. This was referred to as folding the cavity. For example, if three different paths were considered, two alternate, offsetting corner-cube mirrors would be needed. These corner-cube mirrors would need to be smaller than the normal corner-cube mirrors since the light beam needs to be reflected back onto the same corner-cube mirror. The light would travel through the initial path, then be retro-reflected by the first smaller corner-cube mirror back along a different path through the set of corner-cube mirrors. Once the light travels through a second time, another corner cube set very close to the source would retro-reflect the light again on a second alternate path, until finally being received. Refer to figure 7 for a graphical representation.

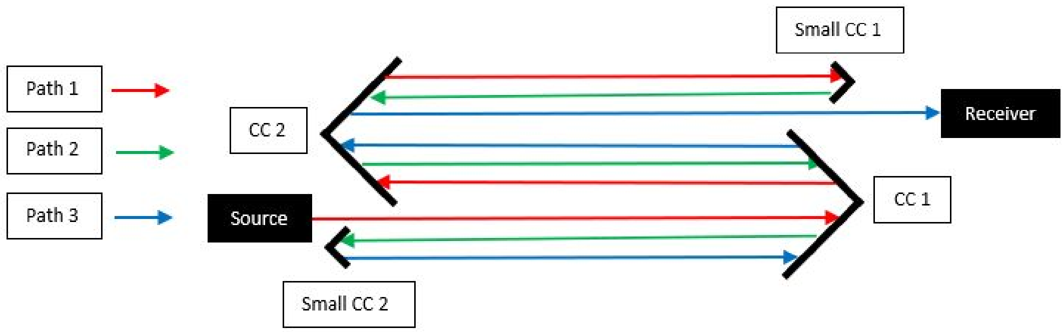


Figure 7: A Simplified Diagram of a System with Two Normal Corner-Cube Mirrors and Two Small Corner-Cube Mirrors

In figure 7 above, the two normal corner-cube mirrors (labeled as CC 1 and 2) and the two small corner-cube mirrors (labeled as Small CC 1 and 2) are used to redirect the light beam across a different path. The light is emitted from the source, gets reflected by CC 1 and CC 2 into Small CC 1, and then goes back through the system along a new path. This process is repeated, until finally reaching the receiver. Upon further investigating this theory, however, it was found that there are many spatial constraints that prohibit more than three paths. Since there needs to be one smaller corner-cube mirror per new path created, it would be very difficult spatially to include more than three paths because the small corner-cube mirrors need to be very close to each other while still being slightly displaced so as to make a discernible new path. To remedy this, the small corner-cube mirrors would need to be made very small so that the light beam could be continually retro-reflected to the same normal corner-cube mirror. However, reducing the size of the small corner-cube mirrors would make receiving the signal very difficult, since the alternate paths are very close together. In addition, this system would be very difficult to align and correct, with how tiny the small corner-cube mirrors would need to be. If this design were to succeed, a large number of alternate paths would be needed. If 19 normal corner-cube mirrors were used, resulting in 20 varying distances, 25 alternate paths—resulting in 25 small corner cube mirrors—would need to exist since 500 varying distances were needed with the fastest motor speed not taking acceleration and load variances into account (refer to section 3.2.2). This number of paths is not easily achievable. With these complications and difficulties in mind, the conclusion was to divert from the corner-cube mirror idea and continue researching different methods.

In conclusion, the design approach of utilizing retroreflection through corner-cube mirrors for achieving a varying optical delay was abandoned. Although the method would be possible for a slower optical delay generator, it would not be possible given the requirement specifications of this project. Obviously, if there is no need for an automatically varying optical delay, corner-cube mirrors prove to be an easy way to create an optical delay line, and that is why. Overall, this method is useful in some applications of telecommunications, but for this project, alternative methods must be explored.

3.1.5 Optical Delay Using 2D Array of MEMS Mirrors

This approach uses a series of programmable MEMS mirrors to physically deflect the beam to different paths [6]. The MEMS mirrors are set to either an on or off position electronically, allowing for an accurate programmable delay system [6].

In this system, the beam is deflected along a rectangular path by a series of mirrors, and is then finally reflected along the incident direction. By programming the individual mirrors, specified delay times can be chosen. For example, if the first and fourth mirror are moved out of the beam path, the three-stage system shown in the figure above becomes a two-stage system. By activating and deactivating these delay stages, the delay is chosen. An inherent "zero delay" is present in this approach, and is increased with the addition of multiple stages [6]. The developers of this technology boast as little as 10 picosecond resolution for this architecture [6].

This approach does satisfy the requirements of the project regarding delay resolution, and in fact could potentially be made finer by changing the length of the delay stages. However, using this approach in the final project would mean fabricating an unreasonable amount of stages in order to satisfy the requirements of the project regarding the range of delay. Namely, a delay resolution of 10 picoseconds were to be maintained, 100 stages would be required to reach a delay range of 1-2 nanoseconds.

3.1.6 Tunable Focus Lens-Based Variable Optical Delay Line

One suggested approach is to employ the use of multiple electronically controlled tunable lenses [7]. By electronically tuning a lens, the focal length of the lens can be controlled and set to a specific value [7]. If a system were then designed such that the focal length of the lens caused the free space propagating beam to travel through the system at a separate delay time, the delay of the system could be set by the tunability of the lens used.

In this system, the incident beam – propagating through free space or through optical fiber – is incident on the first lens and refracted upward. The angle at which the beam is refracted is dependent upon the focal length of that lens. As the angle of refraction of the initial lens is altered, the optical path length of the incoming ray is changed as well. This results in a variable optical delay in which the delay range of the system is limited by the tunability of the lenses used in terms of focal length. The focal lengths of each lens must be adjusted in order to satisfy the conditions regarding the distance between the lenses [7].

Positive aspects of this approach include a lack of mechanical movement and bulk as its driving technology operates within free space or within a fiber optic configuration, as opposed to approaches involving the mechanical movement of optical devices such as mirrors [7]. This approach has also been shown to achieve delay resolutions of approximately 2 femtoseconds, and has inherently high precision in terms of delay time through the use of digitally controlled applied voltage to adjust the focal lengths [7]. However, this approach is designed for relatively short optical delays – typically less than 100 picoseconds [7]. This project requires a delay range of 1-2 ns so the system of lenses would require a much higher degree of complexity, and likely more variability in terms of focal length than is reasonable.

3.1.7 Curved Mirror Approaches

Another potential design approach that was researched involved the use of an optical cavity created from curved mirrors. In the following subsections, the different types of curved optical mirrors will be discussed as well as their original uses. Calculations will be performed with a Harriett Cell design to analyze the feasibility of the method. The motor speeds will be considered in conjunction with of movement the curved mirrors must undergo. The limitations regarding this method will be considered and discussed as well. Throughout this section, an understanding of this curved mirror optical cavity design approach will be firmly established, as well as whether or not this approach will work for this project.

3.1.8 Two Mirror Multipass Absorption Cell or Herriott Cell

This approach uses a more direct method to alter the optical path length of the system. With this method, a multipass cell or cavity is constructed from two concave mirrors [8]. This approach is commonly known as a Herriott Cell, named after the one who originally described the theory behind this method [8]. The lateral position of one of these mirrors is then adjusted to a specified location, causing the incident beam to pass through the cell a different number of times than at its original position [8]. The beam enters and exits the multipass cell through a hole in the first mirror, and the location of the second mirror determines the number of passes through the cell [8]. However, there are discrete locations of the second mirror – and therefore the optical path lengths created by the multipass cell – that do not cause a change in the direction and location of the exit beam [8].

In the system described, there are a total of 6 contact points within the cell, with the 6th contact point directly coinciding with the entrance/exit point. As the distance of the second mirror from the first mirror is increased, the location of the 6th contact point is changed and therefore reflects within the cavity at this new point [8]. This results in a 7th contact point located on the second mirror, and therefore more reflection points within the cell. At another discrete distance, an N + 4 contact point is made – where N is the number of passes at the initial location (6 in this case) [8]. This contact point also coincides with the entrance/exit point and exits the cell at the same angle as the previous exit beam [8]. This is how multiple passes are generated within the cell, and the system continues in this manner as the number of passes approaches infinity as the distance between the two mirrors approaches twice the focal length [8]. When the distance reaches twice the focal length, the number of passes through the cell is set to 4 [8]. The distance between the two mirrors that relates to a specific number of passes within the cell N is given by equation 3.1.8.1.

$$d_N = 2f(1 - cos(\frac{N-2}{2N} * pi)$$

Equation 3.1.8.1: Discrete Distances for Multipass Cell [8]

The paper referenced uses the plot of an ellipse to visualize the reflections within the cavity, and the number of passes N is directly related to the number of passes around this ellipse [8]. As mentioned earlier in this section, the design discussed in the paper referenced has a total of 6 reflections at the initial position. The x and y axis of the ellipse shown are the x and y axis of the mirror planes themselves, showing that the entrance/exit point of the cavity is located directly on the x axis. For this system, the next time the ellipse closes is at the 10th contact point [8].

The slope of the exiting beam is independent of the number of passes within the cell [8]. This is another positive aspect of this technology, as it greatly simplifies the methods needed to ensure optimal free space coupling back into fiber. This technology also presents the possibility for a large range of varied delay lengths due to the possibility for multiple locations in which the input beam is able to exit the cavity. The maximum number of passes through the cell, however, is limited by the size of the entrance hole [8].

This relationship, which assumes that the the size of the beam at the various reflection points is limited by the diameter of the entrance hole, still allows for the possibility of several hundred passes [8]. The maximum number of passes directly correlates to the maximum optical delay achievable, as well as the fineness of the delay resolution. The delay resolution inherently increases with more passes in this technology, as an increase in the total number of passes causes an increase in the number of positions in which the beam is allowed to exit the cell.

This technology certainly contains many aspect which could prove useful for our project. Namely, the precision in the selection of delay times, the possibility for very fine delay resolution, the consistency in terms of position and direction of the exit beam, as well as the relative ineffectiveness of alignment error on the system are all useful parameters of this method.

The paper referenced describes a system comprised of two concave mirrors of focal length 500 millimeters and traverses a distance of one to two focal lengths, or 500 to 1000 millimeters [8]. These parameters result in a maximum length of 99.02 meters, and a delay length resolution of approximately 40 millimeters [8]. This results, approximating the refractive index of air to 1 and the speed of light in vacuum to 3 * 10^8 m/s, in a maximum delay time of 330 nanoseconds and a delay time resolution of 133.33 picoseconds.

Clearly, the approach described in this section contains many positive aspects which can be utilized for this project. However, the design described in the paper referenced does not meet the requirements of this project. Therefore, design changes regarding focal length of the mirrors, separation of the mirrors, start and stop locations, as well as the location of the beam entrance and exit locations must be examined.

Furthermore, the required speed of the motor used to move the second mirror is of great importance, as it is one of the limiting factors of the system in terms of ramp time and selection of specified delays. Specifically, according to the paper referenced, the motor speed must be fast enough to displace the second mirror from the first position to the second within the required amount of time. It is possible that, for this project, that speed may be unreasonable. In addition, even if the motor is able to displace the second mirror within the required time frame set by the ramp time and delay resolution requirement specifications at top speed, that does not necessarily mean it will be useful for this project. This is because the motor also needs to accelerate and decelerate within that time as well. That aspect alone proposes challenges with this design.

The final stages of movement could also pose an issue. It is possible that, in order to meet the requirement specifications of our project regarding ramp time and delay resolution, many intermittent steps in terms of the position of the second mirror would need to be taken. The paper referenced in this section mentions that as the second mirror approaches twice the focal length, The second mirror needs to traverse less distance between points at which the beam exits the cavity [8]. This could potentially mean that, as the final positions of the second mirror are met, the required displacement of the second mirror becomes unreasonably small. Further research and calculation is needed in order to discern this.

3.1.9 Compact Multipass Optical Cell

Another proposed technology for creating a variable cavity for the use of variable optical delays is described in this section. This approach involves the use of a single optical element, unlike the method described in section 3.1.3 which involves the use of two mirrors [9]. The single optical element used to create the delay is a circular cell with a reflective inner wall [9]. The input beam enters the cell and reflects within the cell a finite number of times until it exits through the same point as the entrance point [9].

In the system described, the beam is reflected multiple times within the cell, with each reflection being normal to the point of incidence. This allows for multiple reflections within the cell, causing a significant increase in the optical path length of the system, and thus a significant delay. With an increased number of passes within the cell, the total delay caused by the cell increases. Thus, varying the total number of passes within the cell is how the delay is varied using this technology. The total number of reflections within the cell is dependent upon the angle of incidence of the incoming beam [9]. By changing the angle of incidence, the reflections within the cell occur at different angles, thus resulting in discrete delay times for different angles of incidence.

The paper referenced reports path lengths ranging from 21 to 712 cm, corresponding to 3 and 89 reflections [9]. The resulting delay range is then given to be 700 picoseconds to 23.73 nanoseconds. The angle of incidence of the input beam was typically 2 to 3 degrees. This provides a relatively high range of delays. Furthermore, the ramp delay of the system is limited to the speed of the motors changing the angle of incidence of the incoming beam. As the angle of incidence only ranges from one degree or so, the speed of the motor required would likely need to be less than the speed required for a Herriott Cell.

However, this design is not without fault in terms of this project. Although the motor would not necessarily need to have as high RPM as the Herriott Cell method, it would likely need to have a higher degree of precision. The sponsor of this project has also expressed challenges regarding the relationship between angle of incidence and number of passes within the cell. It is therefore unlikely that this method will be pursued for this project.

3.1.10 Chirped Fiber Bragg Grating

In this approach, a Chirped Fiber Bragg Grating is employed to generate delay. A Fiber Bragg Grating uses Fourier Optics to reflect light based on the periodicity of the grating. The paper referenced in this section describes the use of N bandwidth tunable lasers and an optical combiner as the source for the system [2]. The output of the optical combiner is then sent to a circulator, which directs the signal to the Chirped Fiber Bragg Grating [2].

This Chirped Fiber Bragg Grating used is typically several centimeters long [2]. The reflection caused by the Fiber Bragg Grating is then reflected back into the optical circulator, which then directs the signal toward a Wave Division Demultiplexer [2]. The Wave Division Demultiplexer separates the signal into N wavelengths once again [2]. The N wavelengths are then detected by a photodiode [2]. The delay of a particular wavelength in the system is caused by the Chirped Fiber Bragg Grating [2]. Each wavelength has a slightly different resonance position within the Fiber Bragg Grating [2]. The paper referenced describes a Chirped Fiber Bragg Grating in which the reflection point for shorter wavelengths occurs at a shorter distance into the grating than for longer wavelengths [2]. As such, shorter wavelengths experience a shorter optical path length, while longer wavelengths experience a longer optical path length.

In order to incorporate this technology into our system, an approach using a single tunable laser source would need to be considered. The paper referenced describes an experiment in which the source used is a single wavelength tunable laser. In this experiment, an electro optical modulator is employed, and a network analyzer is used to supply the modulation frequency to the system [2]. The input port of the network analyzer is connected to the photodetector [2]. This allows for the measurement of delay for the different wavelengths.

The experiment using a single tunable laser employes a 40 centimeter long linearly Chirped Fiber Bragg Grating [2]. A linearly chirped grating allows for a linear relationship between the reflection position and input wavelength [2]. The period of the grating used was 4 nanometers [2]. For differences in wavelength of 1 nanometer, a delay of 824.1 picoseconds was measured in this experiment [2]. It is also notable that the delay time is independent of the modulated radio frequency [2]. This experiment also took into account the bandwidth of the different frequencies used, approximating a bandwidth of .5 nanometers [2].

Although the experiment described does not provide the necessary results in terms of delay resolution that is required by this project, it is likely that certain aspects could by adjusted in order to achieve these requirements. These factors would likely be the period of the Chirped Fiber Bragg Grating, the wavelength resolution of the laser source, or perhaps the refractive index of the fiber used. With the correct alterations, a suitable system could be designed using a similar technological approach.

However, this approach does have some negative aspects as well. For instance, the system is heavily dependent upon the stability of the source used in terms of frequency. A stable yet tunable laser source could have a significant impact on the budget for this project. The most difficult aspect of this approach is that it requires the use of a frequency swept source in order to generate a delay. The sponsor for this project has required that the final system must use a single wavelength source, as it is required for the communication of this project with other aspects of the overarching photonics processing system. Therefore, in order to use this technology in this project, design components would need to be added to allow for the use of a single wavelength source.

3.1.11 Piezoelectric Cylinder

In this section, the method of using a piezoelectric cylinder to create a cylinder of fiber optics cables that can vary in diameter. If the number of times the fiber wraps around the cylinder remains constant, then expanding or contracting the piezoelectric cylinder with various voltage changes would change the total length of fiber that travels around the tube. Piezoelectric material has the property, the piezoelectric effect, which relates its size to a voltage and electric field going through them. Placing these materials under tension or compression can create voltage proportional to the amount of stress the material is put under. Similarly, when the materials are exposed to an electric field, they lengthen or shorten depending on the polarity and magnitude of the applied field.
The Piezoelectric material varies with the voltage across it. For a piezoelectric cylinder, the way in which the cylinder changes shape depends on the resonant frequency of the cylinder. The resonant frequency can vary based on the size of the material used, thus it is convenient to consider the frequency, which relates the resonant frequency with the size. Symmetrically cylindrical tubes can be made to change shape radially, in length, or in thickness. In order to achieve circumferential changes in the short tubes with lengths equal to or less than the diameter, the frequency constant should be in a range of 100 to 120 kHz-cm (corresponding to 40 to 50 kHz for a tube with 2.5 cm diameter) [10].

The fundamental property of the piezoelectric material for this project is the ability to change the radius of a piezoelectric cylinder. In order to know how much material and fiber is necessary to create the desired delays, the amount that the material can expand must be known [11]. An example of how the cylinder can expand and compress is shown in figure 13 below.

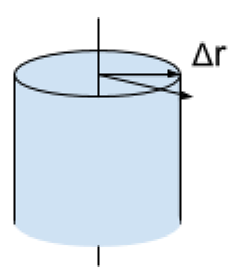


Figure 13: Piezoelectric Radial Expansion

In order to use piezoelectric material to create a difference in fiber length from stretching of just 4.5 mm, when using 20 meters of coiled fiber on a thin-walled disk [12]. This creates an intrinsic delay much greater than the change in delay created, which is too much for feasible use in this project.

3.1.12 Herriott Cell Design Methodologies

There are various technological options available for variable optical delays. However, there are none available on the market that can provide the precision and resolution in terms of delay time and follow the specific requirements for this project regarding ramp time of the system. There is, however, knowledge to be gained by researching the technologies and driving mechanisms behind some of these options.

The Herriott Cell design is one of the main areas of study for possible implementation of this project. In order to determine if this design is to be used, and if so which design parameters to follow, it must be known whether the translational mirror can physically be moved from location to location fast enough to meet the specifications. The original approach to the Herriott Cell design by our team was to control the movement of the translational mirror by a microcontroller-controlled motor. This option provides a simple enough design, but there were concerns about the speed and precision limitations in regards to the motor.

The design specifications state that the maximum delay range must be between one and two nanoseconds, the intrinsic delay is one nanosecond, delay resolution is less than ten picoseconds, each delay step duration is less than fifty microseconds, and the total ramp period is ten milliseconds (see Figure 14). In order to leave some room for error, some initial parameters were a max delay of 1.5 nanoseconds, a delay resolution of 8 picoseconds, a delay step duration of 44 microseconds, and 8 milliseconds of delayed signals with an additional 2 milliseconds of reset time for the translational mirror to return from its final position to its starting position.

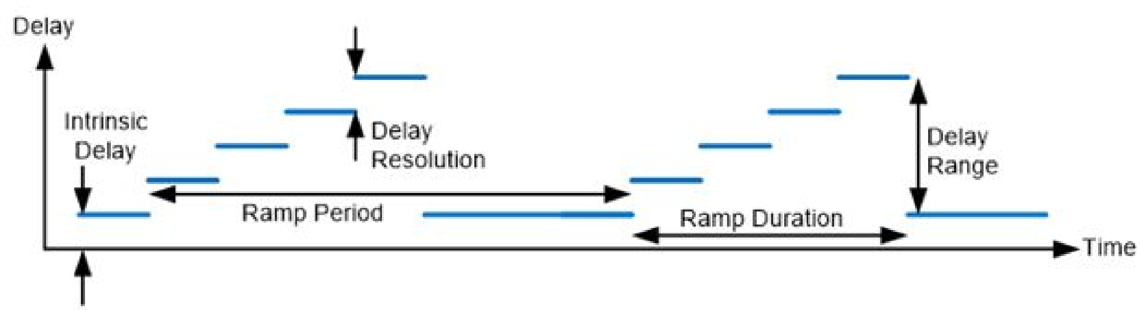


Figure 14: Model of Ideal Delay Generated

If the delay range in the vertical direction is set to be 1-1.5 nanoseconds, and the delay resolution is set to be 8 picoseconds, then the number of steps allowed will be or 125 to 187 steps. In the horizontal delay direction, if we allow 8 milliseconds for vertical delay signals, then there will be of time available for step-to-step period. If a delay range of 1 nanosecond is chosen, this will mean there are 125 steps, resulting in a step-to-step period of 64 microseconds. If each step duration is 44 microseconds, then there will be 20 microseconds available for transitions from one step to the next. In reality, this means there would need to be no more than 20 microseconds of time to shift the translational mirror from one location to the next. If the motor were to be used, this would leave 20 microseconds for the motor to accelerate and decelerate the translational mirror to its next position (also allowing for overshoot correction time). This may be possible, but a concern was that a fast-enough motor would not be achievable.

This led to investigating other means to accelerate the translational mirror from point to point. One possible solution investigated was the use of magnets in the optical cavity. The idea is that the translational mirror would rest on a magnetic-sensitive slab for support, and magnets in the sides of the optical cavity could be controlled to move the mirror. Although the motor method would also utilize magnetics, this method would remove the need for in-between parts from the motor to the translational mirror. Hopefully, this would increase the transitional speed between stages. This idea came from maglev train designs, such as those in Japan. These trains can achieve very high speeds, however the time to accelerate to these speeds was found to be too high for this project's application. In addition, it was later found that the Herriott Cell needs to reduce the distance travelled by the translational mirror between each step. By the final transition, the mirror would need to be shifted with nanometer precision. This is not feasible to do with magnetics.

3.1.13 Pockels Cell Approach

Another design approach considered for this project involved the use of a pockels cell. A pockels cell is a device which acts as a voltage controlled waveplate. Essentially, when no voltage is applied, light travels through the cell with one phase orientation (say zero phase shift for example), but when a voltage is applied the light travels with a different phase orientation (say now ninety degrees of phase shift), as demonstrated in figure 15. By placing a polarizer at the end of the pockels cell, the device can act as a switch dependent on when a voltage is applied. For example, if no voltage is applied, light will travel through the cell and out of the polarizer. When a voltage is applied, light travels through the cell, experiences a phase shift, and is then prevented from moving forward by the polarizer.

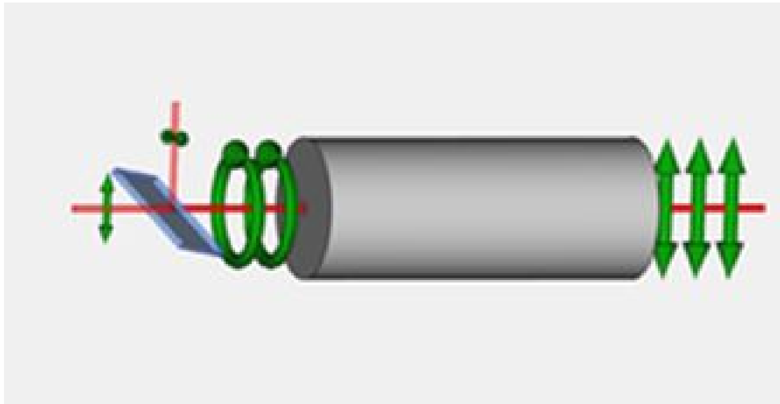


Figure 15: An Example of a Pockels Cell with the Addition of a Brewster Window to Convert Linearly Polarized Light to Circularly Polarized Light. Image obtained from Wikipedia (Author Ben Smith).

This method is often used with laser devices for Q-switching capabilities, but could possibly be used with our design to create the delayed signals required by the specifications. Our laser signal would travel through some cavity and through the pockels cell. The signal would be allowed to pass for the duration of our required step size, then an applied voltage could prevent light from passing for the ten picoseconds of delay between each step. From here, the voltage would be removed and the signal would be allowed to pass through the cell once more for the next step duration.

This approach seems simple and promising, but upon further researcher may not be possible for this design. Typical pockels cell have a responsivity on the order of a few nanoseconds, but we would need ours to function in the picosecond range for our specifications. There are specialty pockels cells that can be made, but it is likely that these will still be too slow. In addition to the slow speed, these specialty cells also tend to be very expensive (which would drain our budget more than we would like to allow) and may leave too much room for error with our extremely precise transition times. For these reasons, this approach is not feasible for our design.

3.1.14 Serrodyne Endless Phase Modulation

One approach considered involves the use of phase modulation as the generation of optical delay. Serrodyne phase modulation involves the use of linear phase modulation [13]. By linearly modulating the phase, the frequency of the signal is shifted [13]. This is due to the fact that the frequency of a signal is defined by the derivative of the phase of the signal with respect to time [13]. As such, linearly altering the phase has the ability to shift the frequency of the input signal.

However, this approach has limitations. Although in theory the endless modulation of phase with a single phase modulator should have 100% conversion efficiency, this is not the case in practical application [13]. Because it is not possible to drive an actual phase modulator from zero phase to infinite phase, serrodyne systems typically employ a sawtooth phase modulation format rather than a truly linear phase modulation format [13]. The sawtooth phase modulation function however -- due once again to the practical limitations of actual phase modulators -- has a finite fall time [13]. This fall time from the maximum phase modulation back to zero results in a discontinuity in the time domain [13]. As a direct result of this time domain discontinuity, unwanted harmonic spurs are generated in the frequency domain [13]. These spurs are known as serrodyne spurs [13].

In order to improve upon typical serrodyne phase modulation schemes to provide more truly endless phase modulation, the paper referenced in this section proposes two architectures to eliminate the time domain discontinuity -- and therefore the unwanted spurs in the frequency domain -- caused by the finite fall time of the sawtooth phase modulation format. Both of these approaches involve the use of time division multiplexing to achieve this goal.One approach proposed by the paper referenced in this section is referred to as the phase shift approach [13]. This approach incorporates the use of two phase modulators and an interferometric switch at the input port of each phase modulator [13].

These two phase modulators operate out of phase, and the interferometric switch ensures that no light enters a phase modulator as it resets its phase [13]. This effectively eliminates the time domain discontinuity experienced in typical serrodyne architectures. While one of the phase modulators is operating within the finite fall time of the sawtooth modulation function, no light is able to enter through the input port due to the interferometric switch. Meanwhile, the other phase modulator is able to continue operation as it operates out of phase with the resetting phase modulator. The paper referenced in this section reports significant suppression of serrodyne spurs (41 dB suppression at a carrier frequency of 100 MHz [13]). However, the paper also reports phase stability issues caused by temperature fluctuations in the fiber [13]. That being said, this method did achieve 41 dB suppression of unwanted serrodyne spurs, which is a significant suppression [13]. The other approach mentioned in the paper referenced is referred to as the time shift approach [13]. In this architecture, a single phase modulator is used [13]. The incoming signal is split into two by a one by two coupler. This split was done in order to create a heterodyne beat between the two branches, allowing for an accurate measurement of the added frequency shift [13]. One of the branches is then phase modulated, allowing for the frequency shift to take place [13]. Once again, this phase modulation is linear, to allow for a constant frequency shift [13]. The two branches are then combined again into a two by two coupler [13]. Both the arms of the coupler have seperate intensity modulators in line, and both modulate a simple on-off square wave function [13].

However, the two modulators operate with a pi phase shift, meaning while one of the modulators is set to the “on” position, the other is set to the “off” position [13]. In addition, a length of fiber is added to one of the branches, which adds a delay due to the increase in optical path length [13]. The branch with the added fiber length is referred to as Arm B, while the branch without the delay is referred to as Arm A [13]. This delay is equal to the amount of time the intensity modulator located in Arm A is modulating in the “off” configuration [13]. This added length of fiber allows for a quasi continuous increase in phase because as the intensity modulator in Arm A is in the “off” configuration, the intensity modulator in Arm B is just receiving the start of its phase ramp. In the experiment described in the paper referenced, this delay was 150 nanoseconds [13]. Photo detectors were placed in line after both of the intensity modulators in order to detect the output of both Arm A and Arm B [13]. Figure 16 depicts an example of the time shift architecture below.

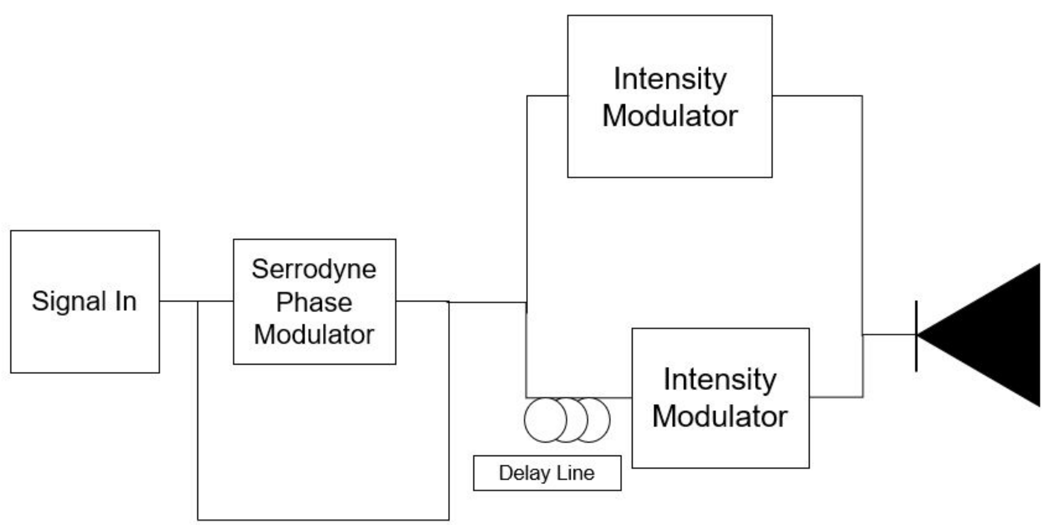


Figure 16: Time Shift Approach Architecture [13]

As the intensity modulator in Arm A modulates so as to block the phase discontinuity caused by the reset in the phase modulator, the intensity modulator in Arm B is biased to allow for the signal to pass through. With the added delay placed in Arm B, the combined signal experiences a continuous phase shift. The time shift architecture therefore allows for a continuous increase in phase, which as mentioned earlier in this section is unachievable with traditional serrodyne approaches.

The effects of the phase discontinuity are observable for both Arm A and Arm B. The graph on the right shows the signals after passing through the intensity modulators. As discussed, the two modulators essentially operate pi out of phase. Thus, when the two signals are recombined, a continuous phase shift is observed. This therefore greatly reduces the impact of serrodyne spurs. Using this approach, the paper referenced in this section reports 43 dB suppression of serrodyne spurs [13]. The suppression of serrodyne spurs is imperative to any system involving serrodyne phase shifting, as a surplus of high intensity serrodyne spurs can make signal detection extremely difficult.

This experiment showed a continuous frequency shift of 1 MHz for a 25 GHz carrier [13]. In terms of this project, a 1 MHz maximum frequency shift of the beat frequency caused by the two lasers would likely not be enough. This is because, due to requirement specifications involving delay resolution and range of delay, hundreds of frequency shifts would need to be implemented. As such, a higher maximum frequency shift would likely be necessary in order to allow for a reasonable resolution in terms of applied voltage.

It is important to note that this addition to serrodyne phase modulation in order to reduce the effect of unwanted serrodyne frequency spurs is patented by Dr. Delfyett, the author of the paper referenced in this section. However, as this project has no monetary goals, this is not an issue. Also, as an advisor for this project, Dr. Delfyett has supported our use of this method.

3.1.15 Serrodyne Approach Continued

As mentioned in the previous section, one possible solution to this project is to use a method called serrodyne phase modulation. This approach describes the need to split and recombine signals in order to create a shift between signal frequencies and then recombine them into a continuous signal. This section will describe three main parameters: the optical splitter, the optical combiner, and the Chirped Fiber Bragg Grating.

First, it is necessary to understand what an optical splitter/combiner is and how it functions in order to properly choose one suitable for this project. Simply put, an optical splitter takes a signal in at one end of a fiber optic cable and sends out two or more signals on the other end of the splitter into multiple output fibers. Splitters/combiners typically come in a 1x2, 1x8, 1x32, etc. configuration. For this project, only a 1x2 optical splitter and a 2x1 optical comber will be needed. Splitters are also typically designed for single-mode or multi-mode operation, which will correspond to specific wavelengths intended to propagate through the fiber. For multi-mode, fibers are generally fabricated for 850 nanometers and 1310 nanometers operation [14]. Single-mode fibers are typically fabricated for 1310 nanometers and 1550 nanometers operation [14].

Modern optical splitters have two popular types that are used: fused biconic tapered (FBT) splitters and planar lightwave circuit (PLC) splitters [14]. The differences between the two is determined in the manufacturing/fabrication stages of production. FBT designs use the traditional method of taking two fibers, intertwining them at a point, and applying heat during elongation to fuse them together. PLC splitters use lithography on a silica glass substrate that can easily produce different optical pathways with specific power ratios. If multiple splits are needed in an optical splitter, generally the PLC splitter is the best option. Table 2 shows a comparison.

	FBT splitter	PLC splitter
Operating wavelengths	850 nm	1260 nm ~ 1650 nm
	1310 nm	
	1550 nm	
Number of inputs	One or two	One or two
Splitter ratio	Customisable	Equal for all branches
Reliable splits	1:8 (can be larger with higher failture rate)	1:64
Maximum splits	1:32	1:64
Other	High failture rate	Low failture rate
	Lower price	Higher price

Table 2: FBT vs PLC Splitter Comparisons provided from Fiberbit.com

For this project, a single frequency laser source will be used as the input to the splitter. From here, the split signals will undergo phase modulation in the serrodyne process, and will later be recombined at different frequencies. It will be necessary to choose a splitter/combiner can support the frequencies used. The input wavelength in the final design will be 1550 nanometers, but a visible light source may be used for demonstration purposes. Also, since only a 1x2 splitter is needed, an FBT configuration will likely be selected. The combiner will need to support the range of frequencies produced during the serrodyne process. Assuming each signal is shifted by only one gigahertz per step (with 125 total steps), the maximum shift in wavelength from the initial source wavelength will only be about one nanometer. From the relation $c=\lambda v$ our initial frequency will be 19.4 petahertz. A maximum shift of 1 gigahertz will then correspond to a wavelength of 1549.99 nanometers. If step sizes on the order of megahertz are used, then it is likely the optical combiner could also be of the FBT type. If larger step sizes, such as gigahertz, are required then different combiners may be needed.

After the signals are properly split and recombined into a continuous signal of different frequencies, the step delay will be achieved by using a Chirped Fiber Bragg Grating. As mentioned previously, a Chirped Fiber Bragg Grating is a fiber that contains a core with multiple, varying refractive indices [16]. This will result in Fresnel reflections, where light traveling between different refractive indexes will both refract and reflect. At certain wavelengths, the bragg wavelengths, there will be a maximum in the reflectance at these surfaces where the refractive index changes. The spacing and periodicity of these refractive index changes can be manufactured in multiple fashions. In the Chirped Fiber Bragg Grating, the spacing and periodicity is in a linear fashion, such as that the wavelengths traveling through the fiber will be reflected back with a linear relationship (see figure 17). This means that if a Chirped Fiber Bragg Grating is produced correctly, our multiple-frequency signals could travel through this fiber and reflect back with linearly spaced delays between each frequency. This method would achieve our design specifications of nanosecond delay between each step of the 125 stepped signals.

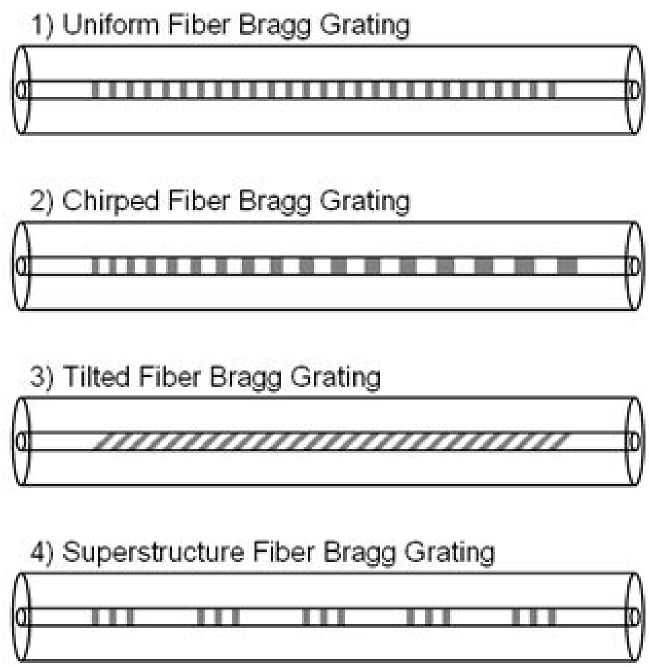


Figure 17: An example of multiple types of fiber bragg gratings. The dark areas represent changes in refractive index. Image obtained from Wikipedia with permissions under the GNU Free Documentation License.

The only concerns with this approach is developing a Chirped Fiber Bragg Grating with the correct delay response to our signals, and the assumption that the output of our signals can remain with different frequencies. If a single output frequency is desired for all delayed signals, then another component may need to be added to the system to convert the signals back to their original frequencies.

3.2 Strategic Components

This section discusses strategic components that are crucial to the various designs discussed in the earlier sections. This includes a discussion of free space fiber coupling, logistics with the motor, and information regarding the use of a microcontroller.

3.2.1 Free Space Fiber Coupling

When considering a free space optical delay design, there must be much consideration to how the light will be transmitted and coupled. In this project, the optical delay generator needs to be compatible with a fiber optic system. Therefore, the signal must be transmitted from a fiber optic cable. This is easy enough to accomplish, but the divergence of the light from the fiber must be taken into account. Likewise, the signal, after applying the delay, must be coupled back into an optical fiber. With the design of this project, single mode optical fiber must be used. Coupling light from free space into a single mode optical fiber is a very difficult and delicate task. The smallest adjustments will misalign the entire system, and the signal will be lost. Things to consider with free space fiber coupling include type of fiber, fiber size, beam divergence, beam diameter, optical path length, and focusing lens. In the following paragraphs, the nature light transmitted from a fiber based upon the fiber characteristics as well as how to couple the light back into the single mode optical fiber.

Important considerations with transmitting the signal from a single mode optical fiber include beam divergence. Optical fiber type and size directly affects this. If there is a large amount of beam divergence, it will be difficult to focus the light into an optical fiber with enough power for the signal to be recognized. Seeing as most of the free space approaches considered involve having the light travel a large distance before again entering the fiber, this is a very important consideration. To remedy this, the beam exiting the fiber must be collimated. The distance a lens must be placed can be accurately ascertained given the numerical aperture of the fiber and the focal length of the collimating lens.

In the methods that were considered in free space, the light would need to travel a large distance before being received by the optical receiver. The light would be transmitted from an optical fiber. Since an optical fiber is very small, the light exiting the fiber experiences a large amount of divergence. This creates a problem since the light must travel a large distance. The longer the distance, the more the light beam will diverge. This divergence must be remedied by collimation so that the light beam is not constantly diverging. Therefore, there must be a collimating lens placed in front of the transmitting fiber in order to collimate the light so as to keep the beam small and cut down on the beam divergence. This can be accomplished with a few different types of lenses. For telecommunication, graded refractive index (GRIN) lenses are predominantly used, but these are not to suitable when a larger (more than a few millimeters) beam diameter is needed [17]. The traditional singlet and doublet lenses can also be used when the collimated beam must have a larger beam diameter [17]. Whatever type of lens that is used must be placed about a focal length away from the fiber end so that the beam is collimated [17]. This can be done through a couple different methods, and these methods will be explored in the following paragraph.

To collimate a diverging beam emerging from an optical fiber, there are two different methods to achieve this. The first involves fixing the apparatus to a bare fiber [17]. This type of fiber-optic collimator is a very cheap and compact method to collimate the light beam, but it is a permanent connection [17]. The second type of fiber-optic collimator involves attaching the collimator via a mechanical interface to a fiber-optic connector [17]. An advantage of this method is that it makes it much easier to connect and disconnect the fiber collimator from the transmitting fiber [17]. The downside is that this method is that it cannot be used with bare fibers [17]. This would in turn make this method slightly more expensive. In choosing what type of fiber-optic collimator to use, the design and type of fiber must be taken into consideration. For the purposes of this project, it could be easier to use the connector collimator as the project will probably not be developed with bare fiber-optic cables. Although it would be slightly more expensive, it makes the whole process simpler and easier since it can be done with pre-made cables and connectors. The size of the collimated beam can be calculated with relative ease. The key parameters are the fiber radius, lens focal length, and the wavelength of the transmitted light. The radius of the collimated beam can be calculated by using the following equation:

$$w_{collimated} = f * \theta_{fiber} \approx f * \frac{\lambda}{\pi w_{fiber}}$$

Equation 3.2.1.1: Equation for the collimated beam radius [17]

where $w_{collimated}$ is the collimated beam radius, f is the focal length of the lens, θ_{fiber} is the half angle beam divergence of the optical fiber, λ is the wavelength of the light in the fiber, and w_{fiber} is the radius of the optical fiber [17]. This is assuming that the beam approximately has a Gaussian shape [17]. This is also assuming that the lens is placed at a distance relatively close to the focal length of the lens [17]. This can be especially challenging, especially with lenses that have small focal lengths [17]. Therefore, the larger the focal length of the lens, the less critical the longitudinal positioning will need to be [17]. As shown, the math involved with collimating a beam from an optical fiber is relatively simple. Coupling the transmitted, collimated light back into the fiber works much the same as transmitting the light. However, the alignment of such a task is very tricky and involved. A fiber-optic collimator would be needed, but there would be much alignment needed in order to redirect the light from free space back into the optical fiber. This is much easier said than done, and it requires many fine adjustments to focus the light into the fiber. This is where the main challenge of a free space system becomes apparent. Focusing the light back into an optical fiber is very difficult, and would require parts with almost no play. This difficulty is one of the main things that hindered the idea for a free space system. However, coupling the

In this section, the methods of transmitting light into free space from an optical fiber and receiving the light from free space were discussed. This research was necessary to investigate since some of the methods researched involved transmitting the light into free space cavities. Alignment is one of the most critical and delicate parts of any optical system, and the transmission and reception of an optical signal in free space is no exception. If our project were to utilize this, much care and patience would need to be attributed to the alignment of the system. The system would also need to be fixed down very well, so as to not throw off the alignment with any slight bumps or vibrations. Overall, this task is not an easy one, but it is doable.

3.2.2 Motor

In this section, research relevant to this project is discussed. Research topics discussed in this section include the mechanisms behind optical delay generators that are currently on the market, research regarding various proposed design approaches, technologies relevant to the product, and the selection of individual parts for the final product. For the design model using a two mirror multipass absorption cell or Herriott cell, one of the mirrors must be able to move a variable distance away from the other mirror. This is the only motion required for this design, thus keeping the need for motors low with one motor for this motion. In order to create the desired delays for the project, an understanding how the cell creates delays from this motion as well as how the motor will need to move is needed. The first consideration for the two mirror multipass design is the type of motor. The mirror that moves in this design is meant to have linear motion. In order to achieve linear motion, the main options include attaching the moving mirror to a motorized wheel that pushes and pulls the mirror with a belt pulley system or on a wheeled platform, using various types of linear actuators. When looking at these motor options, size, speed, acceleration, precision, and accuracy must be taken into consideration with the given load.

The project is desired to fit inside of a 1ft x 1ft x 1ft area. This means that the space between the mirrors, the mirrors themselves, the motor, the laser detector, and all connected devices must fit into this area. If the mirror is attached to a moving wheel, the wheel must have a diameter large enough to allow for appropriate velocities to reach the desired steps in the given time span, but also small enough to fit into the space. If the wheel used is larger, that also presents a larger mas that needs to be moved, which would mean the motor would need to apply more force in order to achieve a given rpm. Using a linear actuator would require less space depending on the size of the actuator chosen. Larger actuators would allow for greater displacement of the mirror, but could possibly lose precision of smaller movements. In order to determine the minimum size of the actuator, the maximum displacement between the first and final steps must be known.

An important aspect of this project is the speed at which transitions are made between each delay step. Even if the displacement of the mirrors that is needed to create the desired optical delay is very small, even in the range or microns, the max velocities needed to do so in the allotted period would be at least a few meters per second. With these max velocities needed in a short period of time, that means that the motors must also accelerate very quickly in order to obtain those maximum velocities and allow for enough time to reach the appropriate positions and then decelerate to a stop. Overall the motors must have high speed and acceleration. Considering the use of wheels to move the mirror, speed is a matter of the size of the wheel. Assuming that the motor will always maintain the same rpm, a simple change in the radius of the motor, which an attached wheel could accomplish, would change the circumference and thus the speed travelled by the outside of the wheel. This change in radius would similarly affect the acceleration, amplifying it as the radius increased. In reality the added mass and size to the wheel would create effects on the performance of the system. If a linear actuator were to be used, then the speed and acceleration would depend on the actuator itself. Looking at the smaller more compact actuators, up to 60 mm, they have max speeds up to 200 mm/s. Even the larger actuators, up to 300 mm, reach speeds up to 800 mm/s [18]. These speeds are significantly less than the few meters per second expected to move the mirrors in a sufficient amount of time.

When trying to decide which motors are best to use, the pros and cons must be weighed. The two main approaches discussed here are the wheeled platform approach and a wheeled belt-driven approach, both shown in Figure 18 below. For the wheeled method, the speeds and accelerations are theoretically achievable, but begin to lose reliability in the non-ideal case. Using larger wheels in addition to the mirror that would be attached means that there is a larger load, thus limiting how fast the motor would actually be able to move in both velocity and acceleration. Even when considering the case when appropriate velocities and accelerations are obtained, the wheels may be so large that they would become sensitive to slight changes. With this method, even the slightest of changes could cause the system to fail if the laser is unable to accurately and precisely exit out at the appropriate location.

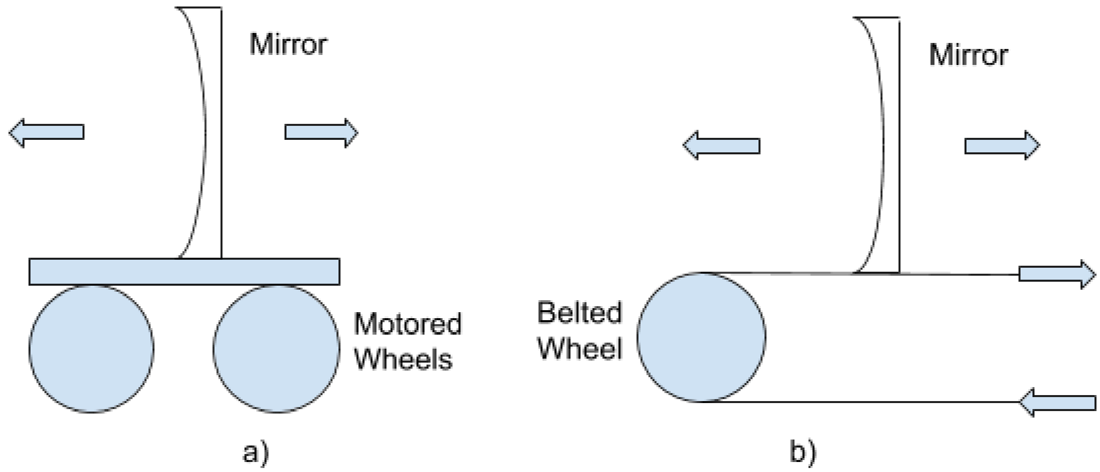


Figure 18: Two Mirror Multipass Absorption Cell Attached to a Platform on Motorized Wheels (a) or Belted Wheel (b)

When considering the wheeled or belt driven approach, stepper motors can be used to obtain more precise positioning. Stepper motors are motors designed to only move in certain angular increments, with steps as low as 0.9 degrees. These motors are also known for being highly accurate with stopping accuracy of 0.05 degrees, or ±1.4μm on a ball screw device. Stepper motors are also useful for their high responsivity, in sync with the received pulses, with minimal delay. This works out well for the project in which the system should be very responsive with the small times we are seeking to achieve. The down side to the stepper motor is that it works best with highest torque in the low to mid speed range. Generally the short distances between steps are small enough that to change steps requires such a small amount of time that the motor doesn't need to reach top speeds [19]. In the case of this project, however, the system must work within such a small period of time that the highest speeds possible are desired.

When looking at the actuators, the speed and acceleration are significantly lower than desired, but the advantage that the actuators lies in their accuracy. The linear actuators are designed to have high precision and high efficiency. This means that the linear actuators would be reliable in making sure that the correct displacements are made in order to make sure that the laser reaches the output hole at the correct position. The linear actuators even have high-resolution motors that can reduce the error further.

When deciding the most appropriate motor for this project, the wheeled mirror is able to generate the desired speed and accelerations, while the linear actuators are able to generation reliable accuracy and precision. Ideally, a combination of these two aspects would be the best choice, but given the limitation of each, neither of these choices is particularly desirable. When considering which motors would be the most useful, it is important to look at the specific products available.

Looking at various products gives context as to the actual weight of characteristics and costs of the different options.

Looking at available linear actuators, Oriental Motor tends to have the best actuators with the most precision and speeds. They also have a good variety with different sizes and optional features. Some of the features are not necessary for the design of this project and can thus be excluded. This includes an electromagnetic braking system which helps to support loads when the the actuator is turned off. These brakes are mostly used when the actuator works with vertical motion and holding certain loads up [20]. Because the only load that needs to be supported would only be acted upon horizontally by the actuator, the system will not need the brake.

The mass of the load being transported by the actuators would only include that of the mirrors used as well as any platform that they may lay upon. When looking at the Herriott Cell approach, there would only need to be one small mirror that would need to be moved which would keep the transportable mass low. Using corner cubes would require the movement of multiple corner cuber. This would be more mass than the Herriott Cell approach. How much mass the corner cube approach would need to move depends on the type of corner cubes and how many would be needed. For now it will be assumed that the total load will be low.

The linear actuators are generally available with a built-in controller or a pulse-input driver. With the built-in controller, one is able to save data such as the positions into the driver. The built-in controller also allows for controllability via inputs and outputs or a network interface. The pulse-input driver requires the use of an external pulse card in order to send input pulses signals to the actuator [21]. The built-in controller will clearly be easier for the scope of this project with specific needs of precise positions and timing. When considering the type of screw used by the actuators, the two options are ground ball screw and round ball screw. When considering the two the main difference is that the rolled ball is cheaper, while the ground ball is much more accurate with a greater ability to produce repeatable results [22]. Because of the high precision and repeatability needed for this project, the ground ball screw is the best option. The following products are actuators available at Oriental Motor [19]:

Linear actuators with 24/48 VDC power supply, max transportable load of 15 kg and max speed of 600 mm/s:
EAS4X-D005-ARAK (50mm stroke): $999.00
EAS4X-D050-ARAK (500mm store): $1,130.00

Compact linear actuators with 24/48 VDC power supply, max transportable load, and no guide:
DRSM60-05A4AZAK / AZD-KD (built in microcontroller): $1,304.00

Compact linear actuators with 24/48 VDC power supply, max transportable load of 66 lbs, ground screw ball, and no guide:
DRL60-05B4M-KD (no adjusting knob, 0.00016 in. resolution): $1,298.00
DRL60-05B4MN-KD (adjusting knob, 0.00016 in. resolution): $1,341.00
DRL60-05B4P-KD (no adjusting knob, 0.00031 in. resolution): $1,237.00
DRL60-05B4PN-KD (adjusting knob, 0.00031 in. resolution): $1,280.00

Compact linear actuators with 24/48 VDC power supply, max transportable load of 66 lbs, ground screw ball, and guide:
DRL60G-05B4M-KD (no adjusting knob, 0.00016 in. resolution): $1,469.00
DRL60G-05B4MN-KD (adjusting knob, 0.00016 in. resolution): $1,512.00
DRL60G-05B4P-KD (no adjusting knob, 0.00031 in. resolution): $1,408.00
DRL60G-05B4PN-KD (adjusting knob, 0.00031 in. resolution): $1,451.00

Reasonable motors come up to around 18000 rpm. Depending on the radius used for a wheeled approach, the speed can vary.

3.2.3 Microcontroller

In this section, the needs and requirements for a microcontroller are explored. Given the project parameters, various movements and changes must happen within the system that is designed.

3.2.3.1 Herriott Cells / Corner Cubes

If the Herriott cell or corner cube method is chosen for the final design of this project, they will have their own parameters different than other approaches. They also have very similar parameters, requiring linear motion of one mirror or set of mirrors. Because of their similar designs, the microcontroller that each would require would be very similar. As such Microcontroller selection for both will be explored together.

In order to have an understand of what microcontrollers would work best for the design, it is first necessary to understand what physical hardware must connect to the microcontroller. It is important to know what kind of communication interfacing will be used and the necessary inputs and outputs needed. For the Herriott Cell and Corner Cube approaches, the hardware connections would simply include a power supply and a motor or linear actuator, which is minimal and good for simplicity. The Microcontroller will need some form or programming to ensure that it the motion of the motor or actuator is precisely what is desired. In this design, the main concern is the operating speed, which should be high enough to create the desired delay in the allotted time. The rest of the coding in the design would be relatively simple and straightforward, running the motor for a specified period of transition time between each delay step, holding for the remainder of the step duration, repeating until all steps have been completed when the motor must reset back to the original position.

When trying to determine the speed of the microcontroller, the clock rate must be considered as the microcontroller will not be able to operate faster than its internal clock will be able to run. The speed the step durations is set to be in the range of less than 50 microseconds, less than 50% of which should be spent on the transition time. This mean that the microcontroller should operate on the scale of microseconds at most. If the controller operates at no more than one microsecond intervals, that would correspond to a clock frequency of at least 1 MHz. For smaller intervals, the clock frequency must be increased.

3.2.3.2 Serrodyne

The serrodyne approach would require the control of a voltage ramp. This section explores what requirements would be necessary for a microcontroller to achieve this and any limitations that may pose a problem. Because of the way the serrodyne approach relies mostly on a variable voltage ramp to create various delays, the hardware is limited. The hardware is mostly in the circuit that will be used to create the voltage ramp. The software must be able to vary voltage at many precise levels. This can be done using a digital to analog converter (A/D).

3.3 Initial Possible Architectures and Related Diagrams

In this section, the initial block diagrams for both considered approaches are shown below. Figures 24 and 25 depict these initial block diagrams.

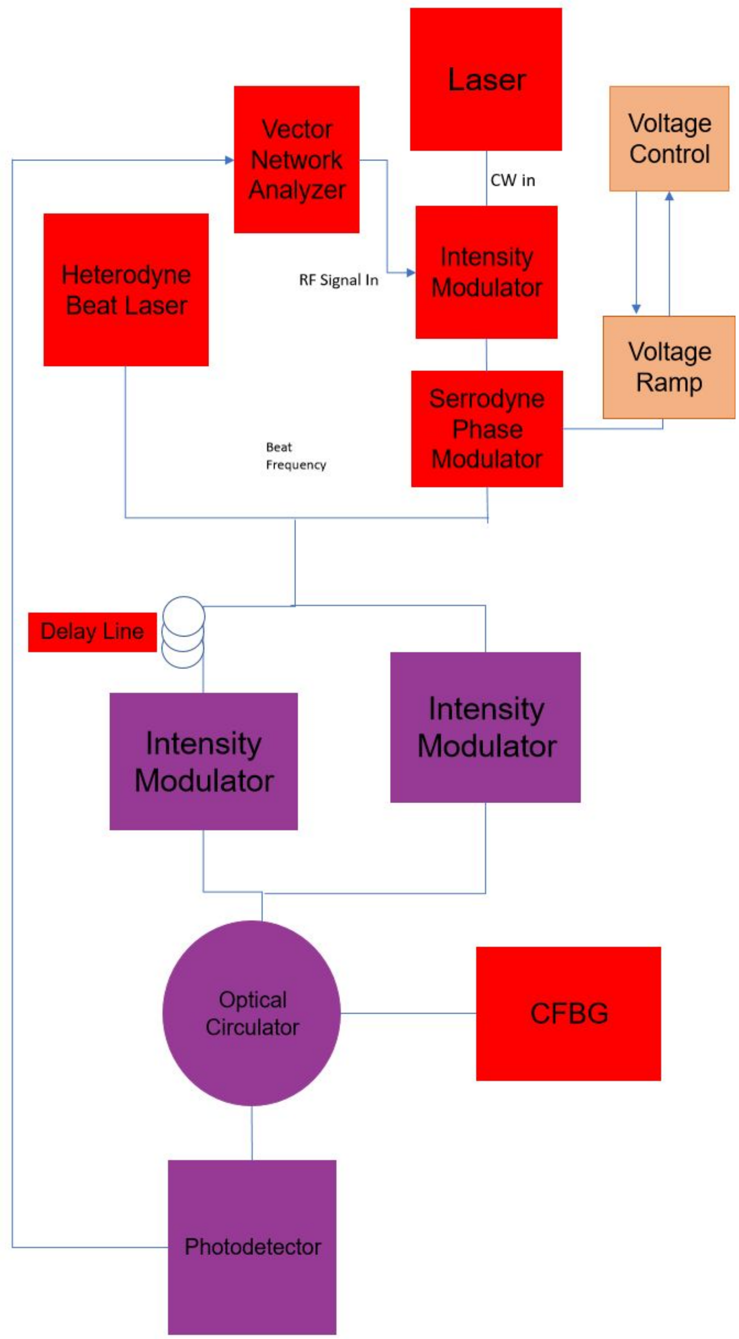


Figure 19: Initial Block Diagram for Serrodyne Approach

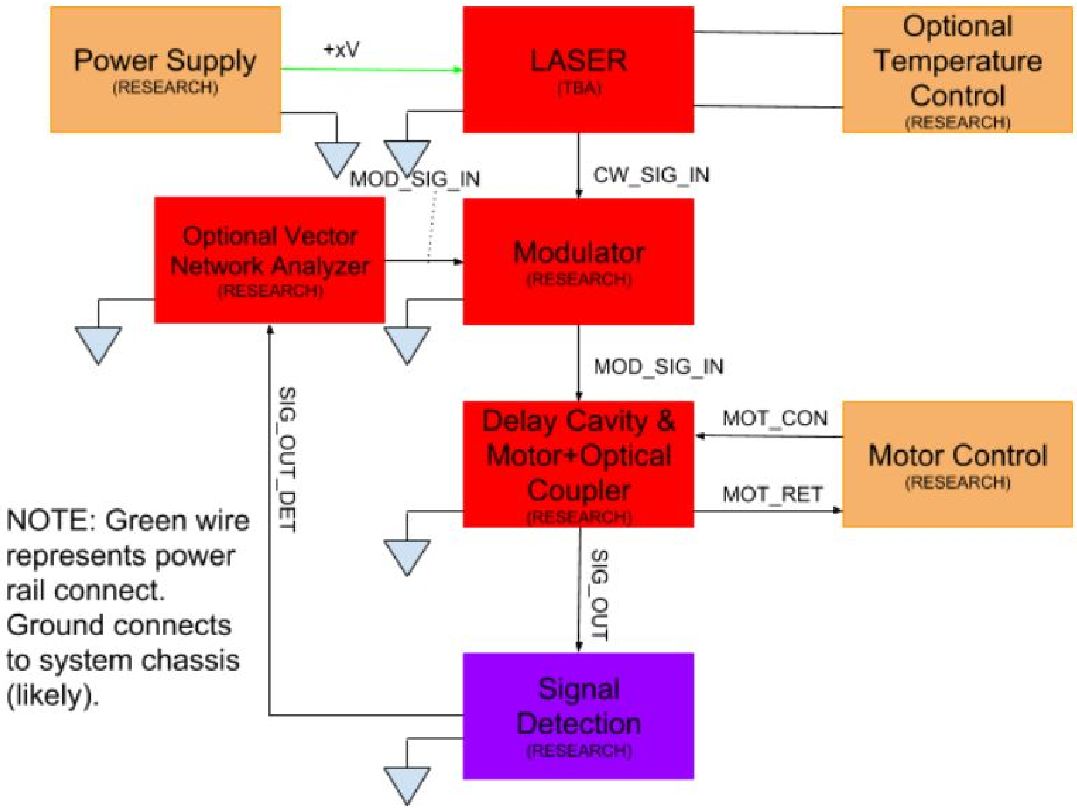


Figure 20: Initial Optical Cavity Block Diagram

3.4 Approach Comparison

This section will describe the main approaches considered for the final design following the research in the previous sections. The three main approaches will be compared: Herriott cell; corner cube; serrodyne method. The benefits and setbacks of each design will be discussed, and why the final design was selected. A backup design will also be mentioned in case of failure of our main approach.

The first design approach that was seriously considered was the Herriott cell. As mentioned, this involves two spherical/cylindrical mirrors that would reflect a beam of light for a set number of passes. By adjusting the spacing between the two mirrors, the beam path would change and produce the desired delay between signals. The convenience of this approach is that the geometry of the cell ensures that the input beam of light will exit the cavity in the same location if spacing requirements are met. This would be ideal for the placement of our detector, as there would be no need to move it to compensate beam shift. However, the primary problem with this design method was the response time of the motor used to adjust the cavity separation. Based on calculations, the motor would need to be able to move the second mirror in twenty microseconds and for a shorter distance with each step. This was not feasible because it required a motor with extreme speed and extreme accuracy. While some motors could accomplish one of these tasks, it was unlikely that we would find a motor that could accomplish both tasks together.

This led the team to investigate other approaches. One solution we looked into was highly folded optical cavities. This simply means that a cavity would contain multiple optical passes for a single cavity setup (similar to a fabry perot). With highly folded cavities, very slight changes in the separation distance between reflectors would produce much higher path length changes overall. This means we could reduce the required distance a motor would need to move a device to achieve the same optical path delay. If this could be achieved, the motor speed/precision requirements could be more easily obtained.

The second approach considered was the corner cube optical cavity. This system would involve two rows of corner cube reflectors. The first row would have a set position and the incident laser beam. The second row would have an equal number of corner cube reflectors on a uniform translation stage. The initial signal would go through the delay cavity with the separation distance between the rows at a minimum. With each consecutive delay step, a motor would move the uniform translation stage, increasing the separation between the two rows of corner cubes. The idea here is that the more corner cubes used, the smaller the translation distance between the rows of corner cubes to obtain the required optical delay.

While this approach seemed very promising at first, our team soon realized there were two major problems with this design. These two problems are related as well. In order to decrease the distance/speed requirements of the motor more corner cubes can be added to the system; however, with the addition of each corner cube to the uniform translation row, the motor requires more power to move the additional weight of each corner cube. This in itself solves one motor problem and adds another. The other issue that comes with this is that corner cube mirrors are expensive, and having multiple corner cubes would quickly eat away our budget. After some calculations, it was determined that a total of 600 corner cubes would be needed for this design to meet our requirement specifications. This could potentially cost upward of $60,000 for the mirrors alone. This was not feasible.

This leads us to our final design approach considered—the serrodyne method. This method takes a completely different approach than the other two designs. Rather than designing an optical delay cavity, the frequency of the signal will be shifted and then delayed by a dispersive media. A programmable voltage ramp would be used with multiple ramp slopes that correspond to a different frequency shift of our laser signal. Originally, the plan was to take these shifted signals and send them into a chirped fiber bragg grating, which would reflect different frequencies at different depths into the grating, thus creating the optical delay. It was soon discovered that chirped fiber bragg gratings can be very expensive if custom made, which ours would be. This, like the corner cube approach, would use up too much of our budget.

When discussing this issue with the project sponsor, they suggested that if we can prove the original signal has been appropriately frequency shifted in steps to a total of plus and minus 100 megahertz, then they could design a dispersive media to replace the chirped fiber bragg grating at a later time. This would help us achieve the requirements set by the sponsor without using up our entire budget on a single component.

There is one concern that with this approach, and without the dispersive media, this project has become more electrical based rather than optics based. To satisfy design requirements set by the university, we may need to introduce more optical design into the project with this approach. At this time, we are in talks with the sponsor to determine if there is a way we can follow through with this approach and still have enough optical design to meet the university requirements. Another consideration with this approach is whether to buy a voltage ramp that can be programmed for our purposes, or to have our team design a voltage ramp ourselves. This too is currently under careful consideration.

4.0 Related Standards

This section will discuss any relevant standards to individual components of this project, and the final project as a whole. This can include design standards and safety standards. Some slight background information is provided for each component and its relevant standards. Finally, it will be discussed how these standards impact the final design of the system.

4.1 Lasers

One main component to this project, regardless of delay design, is a laser source that transmits the received RF signal as an optical signal. Since the laser source is so crucial to this project, it is important to understand how a laser works in order to choose a proper source. It is also necessary to investigate standards on laser systems and any safety precautions that need to be recognized when assembling the system or handling the final product. The word laser is actually an acronym which stands for “light amplification by stimulated emission of radiation.” This gives an idea of how a laser physically functions. There are three necessary components for a laser to function correctly: a gain medium which will determine the wavelength of the emitted light; an energy pump that can provide a population inversion within the gain medium of the laser system; a resonator cavity that allows for optical feedback throughout the system.

How this actually works requires a look at the energy levels of the gain medium. It is known that atoms have electrons in multiple energy levels surrounding the nucleus. When an electron absorbs energy, it is able to jump to higher energy levels within the atom. This absorbed energy can come in the form of photons. Once an electron is in a higher energy state, over time it will drop to a lower energy level and emit a photon with energy corresponding to the difference in energy from the high state to the low state. However, there is another case where when an electron in a higher energy state encounters an incoming photon, the excited electron will drop in energy levels and emit a photon at the same energy as the initial, incoming photon. This is called stimulated emission.

In a laser the energy pump is used to create a population inversion (more electrons in the higher energy states than in the lower energy states) within the gain medium. Now when a photon enters the gain medium, these high energy electrons will emit photons with the same energy and phase as the initial photon. Due to the resonator cavity, many of these emitted photons will reflect through the gain medium for multiple passes, thus resulting in the emission of more photons of equal energy and phase. Since these emitted photons all share the same phase, they will add constructively, resulting in a beam of high energy photons. This is the basics of the laser.

4.1.1 Laser Standards and Laser Safety

In the United States, the main provider of laser standards is the American National Standards Institute (or ANSI). Laser standards are given in the ANSI Z136 series [23]. These standards include:

- ANSI Z136.1 Safe Use of Lasers
- ANSI Z136.2 Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources
- ANSI Z136.3 Safe Use of Lasers in Health Care
- ANSI Z136.4 Recommended Practice for Laser Safety Measurements
- ANSI Z136.5 Safe Use of Lasers in Educational Institutions
- ANSI Z136.6 Safe Use of Lasers Outdoors
- ANSI Z136.8 Safe Use of Lasers in Research, Development, or Testing
- ANSI Z136.9 Safe Use of Lasers in Manufacturing Environments

For this project, the pertinent standards would be ANSI Z136.1, ANSI Z136.2, and ANSI Z136.8. ANSI Z136.2 will be relevant when it comes time to test our optical fibers. This standard covers important safety information when testing optical fibers with lasers, such as the possibilities of hazards from laser light escaping from the fiber through cracks or defects. This can be especially dangerous when testing with lasers in the infrared range because the eye can not detect these wavelengths (someone could be blinded before they even realize it). The content of these standards is not freely available online, but some common safety standards include the use of proper personal protective equipment and lasers that are properly identified according to their hazard ratings. Two primary types of personal protective equipment for lasers are eye protection and skin protection. In extreme cases, respiratory protection may also be required for toxic plasmas and gases formed in the surrounding environment due to the laser and/or its system components.

Eye protection includes goggles, face shields, and prescription eyewear with proper reflection/absorption ratings [24]. No single piece of eyewear will protect against all laser wavelengths, so it is important to choose eyewear accordingly. Each set of eyewear should: be properly labeled for which wavelength it is intended to protect against; withstand peak powers emitted by the laser; allow enough visibility while maintaining eye safety [24]. Each laser should also be properly labeled for its associated hazard rating class. The following table provides the multiple classes of lasers and descriptions about the hazards incorporated with them. This table comes directly from the Occupational Safety and Health Administration "Laser Hazards" chapter.

	Applies to wavelength ranges				**Hazards**		
Class	**UV**	**VIS**	**NIR**	**IR**	**Direct ocular**	**Diffuse ocular**	**Fire**
I	X	X	X	X	No	No	No
IA	--	X†	--	--	Only after 1000 sec	No	No
II	--	X	--	--	Only after 0.25 sec	No	No
IIIA	X	X††	X	X	Yes	No	No
IIIB	X	X	X	X	Yes	Only when laser output is near Class IIIB limit of 0.5 Watt	No
IV	X	X	X	X	Yes	Yes	Yes

Key:

X = Indicates class applies in wavelength range.
† = Class **IA** applicable to lasers "not intended for viewing" *ONLY*.
†† = CDRH Standard assigns Class **IIIA** to visible wavelengths *ONLY*. ANSI Z 136.1 assigns Class IIIA to all wavelength ranges.

Table 3: OSHA Laser Classifications--Summary of Hazards (Provided by OSHA)

4.2 Optical Fibers and Fiber Standards

There are many standards when it comes to optical fiber manufacturing, testing, and specification, but since this project does not require us to design our own fibers, these standards are not of great concern to us. However, it is useful to know what certain standards are to assist in selecting the right fibers for this project.

In terms of this project, our main concerns regarding fibers is whether they are single-mode or multi-mode, the wavelength range that they are made to be operated with, the water index profile of the fiber core (in regards to attenuation), and the dispersion effects from the fiber. Another thing to keep in mind, but not as big of an issue, is the bending standards of the fiber used. Each fiber will have a certain angle of allowable bend before the fiber breaks.

With these areas of concerns in mind, these are the relevant standards that will help inform us of what fiber to choose [25]:

- ITU-T G.651 Characteristics of Multimode Fibers
- ITU-T G.652 Characteristics of Single Mode Fibers (4 types)
  - Type A
  - Type B
  - Type C
  - Type D
- ITU-T G.653 Characteristics of Dispersion-Shifted Single Mode Fibers
- ITU-T G.657 Characteristics of Bending Loss Insensitive Single Mode Fibers

Note that these standards listed are determined by the International Telecommunication Union (ITU), but similar standards exist under different organization titles, such as the International Organization for Standardization (ISO), International Electrotechnical Commision (IEC), and the Telecommunications Industry Association (TIA). These standards have different means of organization and identification, but generally follow the same principles [26]. When choosing a fiber for this project, first it should be decided if single-mode or multi-mode fiber should be selected. Multi-mode fibers allow for more data to be transmitted at once, but they suffer from higher dispersion. Single-mode still has some dispersion effects, but it is greatly reduced. Since we are only sending one signal at a time (with picosecond delay between each signal) any dispersion effects could be a real problem. Single-mode fiber would work best to reduce this problem. Also, only one data signal is being sent at a time, so there is no need for the higher data transmission given by the multi-mode fiber.

The next step is selecting a fiber that allows for the 1550 nanometer transmission of our laser source. A 1550 nanometer source will be used because it offers the lowest attenuation of our optical signal. In Figure 21 below, the attenuation of light at a given frequency traveling through a typical optical fiber can be seen. This information shows that for zero dispersion, 1300 nanometers is ideal, but for the lowest attenuation, 1550 nanometers is ideal. This is where a fiber based on the ITU-T G.653 standard is useful. Dispersion-shifted fibers use index profiles that lower the waveguide dispersion. By using fibers that utilize these standards, a signal can be transmitted in the 1550 nanometer, minimum attenuation, range while also having the benefits of zero-dispersion. So this project will benefit most if a fiber is used that satisfies these conditions.

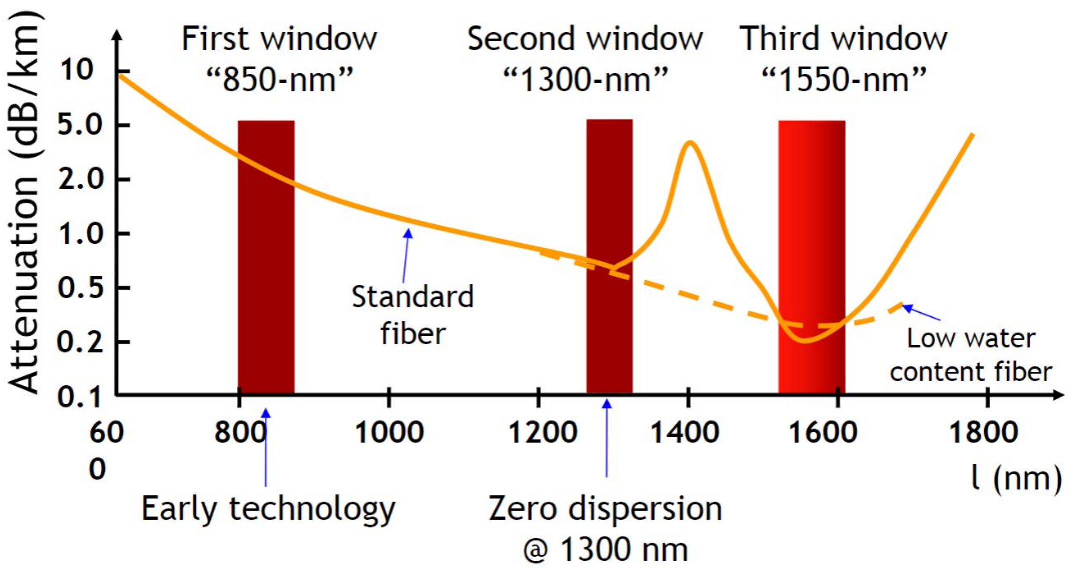


Figure 21: Optical fiber attenuation vs wavelength used.
Image provided by Dr. Rodrigo Amezcua Correa, CREOL UCF.

With the information mentioned above in mind, a good choice of optical fiber for this project would be SMF-28. This is a single-mode fiber that is " ITU-T Recommendation G.652.D compliant and also exceeds the requirements of the ITU-T G.657.A1 standard [27]." This means that this fiber has less than 0.3 dB/km attenuation when operated at 1550 nanometers and has excellent range of macrobending. This fiber is very standardized and quite cheap, at less than $60 for 100 meters of fiber. This project will only need around 0.3 meters of fiber if the serrodyne method is used, which would use a one nanosecond delay between the two intensity modulators. This would only cost $0.6 for a meter of SMF-28. However, it is unlikely that this fiber can be bought by the meter. Even so, this fiber is standard enough that there is a good possibility Harris will have some we can use, or we can just buy the 100 meters for $60 and still have plenty of budgeting for the rest of this project.

4.3 General Optical Communications Standards

In this section, standards regarding optical communications in general are discussed. A large amount of international optical communications standards are found on the International Telecommunications Union website, which is referenced in this section. Recommendation G.602 of the International

Telecommunications Union provides some general standards regarding optical communications [28]. According to this Recommendation, the necessary components of any transmission system include translating equipment, line terminal equipment, line intermediate equipment, cable, power feeding, primary power and standby power supplies [28]. A transmission system might also include the changeover equipment when automatic protection switching is provided [28].

A defining characteristic of optical transmission systems is the reliability of the transmission system [28]. The reliability of a transmission system is defined as the probability that the system can perform its required functions over a given time interval [28]. The parameter used to quantify this definition of reliability is the Mean Time Between Failures [28]. This section defines three instances when a system failure occurs. One is when there is complete and total loss of the signal [28]. Another is if the pilot level drops by 10 decibels below the nominal value [28]. The final definition of failure is when the total unweighted noise power integrated over a period of 5 milliseconds exceeds 1 million picoWatts on a hypothetical reference circuit described in Recommendation G.222 [28]. Finally, in order to be considered a failure, each individual instance of failure must occur over a period of at least 10 seconds [28].

Another defining characteristic of optical transmission systems is the availability in the transmission system [28]. Recommendation G.602 defines the availability of the system as the ability of the system to be in a operational state at a given instant or any instant in time over a given time interval [28]. According to this recommendation, the four factors that influence this characteristic of transmission systems are the reliability of the equipment, automatic protection switching, maintenance procedures and cable routing and protection [28]. Cable routing describes the route over which the cable runs, and can have a larger influence on the availability of the system if the route is along roads with heavy traffic [28].

Recommendation G.602 gives specific objectives in terms of availability. For the 2500 km hypothetical reference circuit described in Recommendation G.222, the objective availability should be greater than 99.6 % for one year of operation [28]. As described, this availability factor is dependent on the four factors described in the paragraph above. Recommendation G.602 states that the vast majority of unavailability time is caused by cable faults [28]. In fact, it is stated that the percentage of unavailability time caused by cable faults is on the order of 95% [28]. Thus, cable faults are significantly more dominant over equipment faults and cable routing [28].

4.3.1 Free Space Optical Communications Standards

If the approach used involves the use of a free space optical cavity, standards regarding free space optical communications must be understood and followed.

This section discusses general standards for free space optical transmission systems, particularly regarding co-located free space optical transmission systems. Ensuring that any optical signal occupying the same space within any sort of free space cavity used is important for the consideration of a cavity based approach, as it is likely that a multiple pass cavity would be implemented for that approach.

For any free space optical system, a receiver is of vital importance. In the scope of this project, the receiving portion of the free space system would be the fiber into which the light would be coupled. The acceptance angle of a free space optical receiver is defined by Recommendation G.640 of the International Telecommunications Union as the angle between the lines at which the power detected by the receiver falls to 1/e^2 [29]. According to this recommendation, this parameter is also called the field of view of the receiver, and is commonly defined as where the power density falls to a specific value [29]. The beam divergence is defined as the angle between the lines at which the power density of the free space optical beam falls to 1/e^2 [29]. Recommendation G.640 also notes that this parameter should be measured in the far field range from the free space optical transmitter [29].

Inter-channel crosstalk and interferometric crosstalk are defined as the ratio of the disturbing optical power to the wanted optical power detected by the receiver when the desired and disturbing signals are at different and the same wavelengths, respectively [29]. Recommendation G.640 provides the standardized procedure for ensuring the free space optical transmitter and receiver operate as designed in the presence of inter-channel and interferometric crosstalk. The first step described by Recommendation G.640 is to establish the maximum optical penalty due to crosstalk that the system can allow given the overall power budget of the system [29]. Next is to determine whether the experienced crosstalk is inter-channel or interferometric [29]. For the scope of this project, the crosstalk experienced would be due to the delayed optical signals potentially occupying the same space. As such, the crosstalk to be considered for this project would be Interferometric crosstalk. This is because the delayed signals would remain at the same wavelength regardless of changes to the cavity. The final step mentioned by Recommendation G.640 is to calculate the value of crosstalk required to generate the maximum optical penalty due to crosstalk [29]. For interferometric crosstalk, the equation for crosstalk ratio is shown below.

$$P_I = 10log_{10}\left(\frac{\frac{r-1}{r=1}}{\frac{r-1}{r+1} + 10^{\frac{C_I}{10}} - 4\sqrt{\frac{r}{r+1}10^{\frac{C_I}{10}}}}\right)$$

Equation 4.3.1: Interferometric Crosstalk Penalty [29]

4.4 Wires

This project involves the use of multiple components that must communicate data across the system via electrical signals. Although primarily optics based, a large portion of this project is also electrically based. This means it is necessary to find a way to connect these components with some type of interconnect. While the final design will use a PCB layout, a lot of the testing phases for this project will likely use free wires to connect each component. Therefore, this section will discuss wire standards, wire gauge, and wire specifications and how correct wires can be chosen for this project.

There are standards for wires chosen in North America by organizations such as the American Society for Testing and Materials, the National Electrical Manufacturers Association, and the Insulated Cable Engineers Association to name a few. These organizations create the standards for wires to be implemented nationwide. Some such standards include wire insulation coating, wire gauge, and wire material. In terms of information for this project, it is most important to understand the wire gauge and current ratings to perform proper testing. Test environments will be held in room temperature, so special insulation coatings are not needed. When selecting wires to perform testing, current ratings must be kept in mind to ensure safe test environments.

Electromagnetic Interference could also be of concern for this project if sensitive components are used. In this case it would be necessary to use proper shielding around wired signals to prevent leakage flux through the wire into surrounding components. This could also be partially negated by implementing twisted pairs or twisted triples for our interconnects. In the planning stages of this project these concerns were mentioned to the sponsor, but they have since informed us that these concerns will not be pertinent to this specific project. Likely, our only concern will be to select wires that can withstand our component current ratings.

Soldering could also be necessary for some testing, in which case we would need to obey soldering safety practices. However, it is likely that most testing for this project will be conducted in a standard breadboard environment with no need for soldering components or interconnects together. If any soldering is required in the final design of the project, it is necessary to find someone with soldering training, otherwise our system could fail to stand up against national soldering regulations. This would be of no concern in a test environment, but any final product must obey these rules and regulations.

4.5 Microcontrollers

Microcontrollers have standards. It is important to understand these standards in order to know the abilities and limitations of microcontrollers that may be used in builds of the project.

4.5.1 8051 Microcontroller

The standard for Microcontrollers was set in the 80s by the MCS 051, created by Intel. This microcontroller was able to use flexibility with a configuration that was able to satisfy a variety of needs that the user could design for. Because of the ease of having a microcontroller that already had a broad range of uses, other microcontrollers began to be built around this MCS 051 model, creating what is known as the 8051 standard. The 8051 is simple with no more and no less than a normal user would need. [30] In general the 8051 microcontrollers have a Vcc power supply, a ground, system inputs, control signals, and ports for external world interfacing. The power supply with a reference ground (GND) allows the entire system and electronics to operate. The system inputs are where clocks are where the system's clock are input as well as a reset, which is used to initialize the controller and restart it with default values. Control signals allow for memory interfacing [31].

4.5.2. How the Standards affect the Project

For this project, the electronics are not too complicated and the parts that need to be controlled are limited. Because of this, the microcontroller used for the project will not be complicated, so the standards that come with the 8051 based microcontroller should be enough to accomplish what is needed of the system. As the final system does not rely on free space optics as much as anticipated, we do not expect standards related to this dto have impacts on our design. Furthermore, any general optical communications standards can be met with our current approach.

5.0 Realistic Design Constraints

The following sections will outline realistic design constraints as they relate to this project and the given requirement specifications in the earlier parts of this paper. These constraints are influential in the design process of this project, as they are dependent upon various factors specified by the sponsor, project details, society, etc. Some of these factors mentioned within this section are as follows:

- Economic
- Time
- Environmental
- Social
- Political
- Ethical
- Health
- Safety
- Manufacturability

- Sustainability

Each constraint will be discussed in detail and will describe how these constraints were impactful to this project, resulting in the final design.

5.1 Economic and Time Constraints

Perhaps the two most influential design constraints to this project are the economic and time factors. This project is funded by the Harris Corporation, but as of this writing an exact amount of funding has not been determined/approved. Initial discussions have led us to believe that expected funds could be as much as $25,000, but this is still to be determined. With this in mind, it has been a goal to keep the overall cost of this project to a minimum. Even if the full funds of $25,000 are available, it is ideal to find a method of satisfying the project design constraints in a cheap manner while still producing quality results.

With some of our main design approaches, budget is one of the highest limiting factors. Our primary serrodyne approach would require the use of expensive phase modulators and Chirped Fiber Bragg Gratings. These two components alone can easily spend all of our budget money if custom designs would need to be ordered from the manufacturer (which is likely). The corner-cube approach, although simple, could also end up costing a lot of money. Optical devices in general tend to be expensive with current technologies in the market, and this approach would require the use of multiple reflectors (on the order of hundreds). A single reflector is in the range of costing $70-$200, which is obviously not feasible or affordable if hundreds of reflectors are needed. There is the possibility of using equipment provided by Harris, but even then many parts would still need to be acquired from other sources.

If we were to follow through with these design approaches and spend the majority of the project budget on these expensive components, it could result in other necessary components underperforming due to their cheaper nature. If the serrodyne approach continues to remain our main approach, then it will be ideal to find a way to implement the same effects without the need of the Chirped Fiber Bragg Grating. If this can be achieved, this will greatly reduce our spending and will nullify many of our budgeting concerns, as this is the most expensive part of this approach.

The other main design constraint to this project is the fact that there is a small amount of time to complete it. The project was assigned in January 2018 and the final design must be showcased in November of 2018. This gives us a little under a year to design, construct, and display the project; however, this project report is due by the end of April 2018, leaving only four months to develop a working design. After April, the next phase of the project will involve acquiring parts and assembling the actual final product.

The main challenge with this time window is that most of the project must be researched and designed in only a few months. This means that if any significant errors arise, we may need to scrap the project altogether due to lack of time to complete a secondary approach. It is crucial that we have backup designs ready to go in case of such a failure. Another problem is that if one design approach is good, but likely to go over our time constraint for whatever reason, it will be necessary to choose another approach that will instead satisfy the time window.

A concern our team has had with this project is that there is not a lot of readily available information in the public domain for an exact method of approach to this project. This has led our team to spend a majority of our time focusing on research into the best methods for achieving our goals. While this is a good thing to do to ensure we have the most successful final design, it has taken away from time that would otherwise be spent on other necessary parts of this project.

For example, many of our original design approaches involved the use of a motor to vary optical path lengths in very short time windows with high precision. Until the actual optical cavity was designed, it was undetermined what parameters would be needed for any selected motor components. This is also true for the control system utilizing any software related issues. Until the overall optical cavity design was determined, other aspects of the project were required to be put on hold.

This has resulted in our team falling slightly behind in terms of completed designs based on our initial time schedule. If we had been allocated more time than the four months of research provided, we could have met more realistic time schedule.

5.2 Ethical, Social, and Political Constraints

It is important to consider the ethical constraints of this project. Due to the scope of this project, there are few ethical constraints to consider. It is however, important to note that the running of this project should not be done in such a way that the laser used within the design is open to affect any bystanders and observers. It is also important to notify anyone nearby of the use of a laser in project and to disclose any effects that the laser could have on them, even if the laser is in a contained system that is not meant to reach observers. This project is primarily a proof-of-concept design to create the necessary delay steps for the sponsor of the project. Because of this aspect of the project, there are not really any social or political aspects and therefore no social or political constraints to consider.

5.3 Environmental, Health and Safety Constraints

With every engineering project, it is important to discuss any possible environmental, health and safety concerns. In this section, these three design constraints are discussed. Environmental concerns are not of major concern for this project. This is because any radio frequency radiation used in this project is relatively low power, and is fully confined within radio frequency waveguides. Therefore, we do not anticipate any environmental impact from this project. The most likely health and safety concerns are related to the laser used in the project. Although the wavelength of the laser (1550 nanometers) is outside of the visible range, it can still cause damage to the eyes. Further details regarding the standards that will be followed to limit any possible health and safety impacts caused by the laser are discussed in section 4.1.1. Another possible health and safety concern is related to the fiber optic cables used. Because fiber optic cables are made of glass, any breaking that is done can cause fiber optics to become a sharps hazard. Further details regarding the standards that will be followed in order to limit any possible health and safety impact related to fiber breakages is discussed in section 4.1.4. No other health and safety impacts are expected beyond this.

5.4 Manufacturability and Sustainability Constraints

Other constraints that must be considered include manufacturability and sustainability constraints. Manufacturability constraints refer to the constraints related to the actual manufacturing of the design, and the feasibility of putting the entire designed system together. This includes all parts that will be supplied and designed, and the parts necessary to construct them. This must be discussed in great detail as many of the parts that will be utilized in this project are difficult or very expensive to manufacture, and therefore difficult to obtain. Some of these parts include the potentially custom designed electrical function generator and the chirped fiber Bragg grating. The sustainability constraints refer to the constraints related to the actual upkeep needed to keep the designed system working as well as the longevity of the design itself. The parts that could potentially cause the output of the design to be faulty will be discussed, and any other problems that could arise from failing parts will be discussed as well. It is very important that this design has plenty of longevity due to the fact that it will be implemented into a fiber optic telecommunication system. It is crucial that all pieces in a system such as this are working at all times as the failure of one of these parts or pieces could cause the whole entire fiber optic telecommunication to fail, and it could be difficult to troubleshoot. Because of this, the sustainability constraints must be discussed in detail. First, the manufacturability constraints will be detailed and discussed, and then the sustainability constraints will be discussed after.

As mentioned in the previous paragraph, the manufacturability constraints are a very crucial constraint to this project. There are several parts that are difficult and /or expensive to manufacture, and this section will discuss those parts and the constraints related to them. The first part, and perhaps the part with the most prevalent and strict manufacturability constraints attached to it, that will be discussed is the chirped fiber Bragg grating. Chirped fiber Bragg gratings are very detailed in the fabrication of them, and they are very difficult to manufacture. The reason for this is due to the periodically spaced refractive index changes throughout the fiber [16]. Seeing as the chirped fiber Bragg grating needs to be developed especially for the system designed in this senior design project, it is not an easily reproducible or manufacturable part. The reason this part will be developed after the completion of this project is due to the fact that the spacing of the varying refractive indices in the chirped fiber Bragg grating are directly related to the different frequency shifts that will be produced by the serrodyne phase modulator that this project aims to construct. The chirped fiber Bragg grating is just one of the parts that induce manufacturability constraints on this project. More of the other parts that contribute to the manufacturability constraints on this senior design project will be detailed and discussed in greater detail in the following paragraph.

Another piece of this project that contributes to the constraints of the manufacturability involves the usage of a custom electrical function generator. Although a decision regarding whether to buy an already made function generator for the voltage ramps and functions present in this project or to design a custom function generator has not been decided on yet, it is worth mentioning in this section as, if the custom function generator method is chosen, it will add a large contribution to the manufacturability constraints of this project. Using a custom-made function generator will make manufacturability harder as it will require the design and fabrication of another complex electronic component instead of just purchasing a pre-made electrical function generator. This constraint will depend entirely on whether a pre-made electrical function generator or a custom designed function generator is used in this project. Now that the manufacturability constraints have been discussed and detailed, the sustainability constraints related to this senior design project in terms of the lifetime and upkeep of the final designed system will be detailed and discussed in the following paragraph.

Another very large constraint present that applies to this senior design project design is the sustainability constraints related to it. As stated early, the sustainability of this optical telecommunication subsystem is crucial as it is a piece of the larger system. If the design will fail often or will need too much upkeep to keep it running, it will not be a very practical product. Therefore, the sustainability constraints must be discussed. There are many different factors that contribute to the overall sustainability constraints of this project. Some of these factors include the longevity of the fiber optic cables and connectors and the electrical components and wires to name a few. In the following paragraphs, the sustainability constraints related to these different factors will be discussed in detail, since the sustainability constraints are so prevalent to this project.

The first factor that contributes to the sustainability constraints of this project has to do with the longevity and upkeep of the fiber optic cables. Consideration of this factor has to do with the environment that the system will be utilized in. Provided that the environment that the fiber optic cables are exposed to is fairly clean and dust free, upkeep will be close to zero for the fiber optic cables. This is most likely the environment the final product will be in. However, there should always be an infrequent, periodic checking or testing of the fiber optic cables and connectors. For more info on testing fiber optic cables, refer to section 8.2.5. If there is any amount of dust in the environment, the fiber optic cable connectors should be cleaned periodically. In theory, fiber optic cables should last an incredibly long time. However, there should be at least some upkeep in order to prolong the life of the cables and connectors. If there is a power or signal loss that is affecting the desired data, the cables should be tested and cleaned. Now that the sustainability constraint inherent in the usage of fiber optic cables and connectors has been sufficiently discussed, other possible sustainability constraints related to this project will be discussed.

Some of the sustainability constraints that will apply to this senior design project cannot be fully ascertained as of yet. These include constraints related to the longevity of each part that is being used in this project. Seeing as more detailed information regarding some of the parts that Harris will be supplying to this project is currently not known to the team, the longevity and upkeep regarding these parts cannot be discussed. However, there will still be upkeep necessary in regard to these parts in order to keep the whole designed system working properly. A couple of the parts that would be included in this category would be the RF components and the chirped fiber Bragg grating. Since these parts will most likely not be handled by the individual group members when the design is implemented into the system, the upkeep and actions required to maintain the sustainability of the design will be up to Harris. This concludes the discussion regarding the manufacturability and sustainability constraints present in this senior design project.

6.0 Project Hardware and Software Design Details

In this section, the hardware and software design details regarding this project will be discussed in detail. The subsections in this section include the initial design architecture (shown through block diagrams and circuit diagrams), suppliers and supplied components, the optical subsystem, the electrical subsystem, details regarding the electro-optical integration, and the user's manual. All of these topics will be thoroughly discussed and detailed.

6.1 Initial Design Architectures and Related Diagrams

From the research done on relevant and existing technologies, the approaches under consideration have been narrowed down to two. The first general approach involves the use of a variable optical delay, such as the Herriott cell or variable corner cube delay described in previous sections. The second approach under consideration is based on serrodyne phase modulation described previously in this report. This approach would be based on the frequency shift caused by serrodyne modulation, and would likely involve a variable optical path length based on frequency of the incoming optical signal. In this section, the application of these technologies to this project is discussed.

6.1.1 Serrodyne Approach for Delay Generator

As mentioned in previous sections, serrodyne phase modulation is a well known method for shifting the frequency of an incoming optical signal by a certain amount. This shift is dependent on the slope of the phase modulation, which is defined by the amount of time taken to bias the phase modulator from negative to positive Vpi. For this project, the most basic form of this architecture begins with a laser source of approximately 1550 nm wavelength, a phase modulator to induce the serrodyne phase modulation and therefore the frequency shift, a voltage ramp capable of supplying voltage over a specified amount of time such that the slope of Vpi versus time provides the correct frequency shifts, and a frequency based optical delay component such as a Chirped Fiber Bragg Grating. The initial architecture of system is shown in figure 22 below. Figure 23 depicts the initial architecture for the electronics used in this approach.

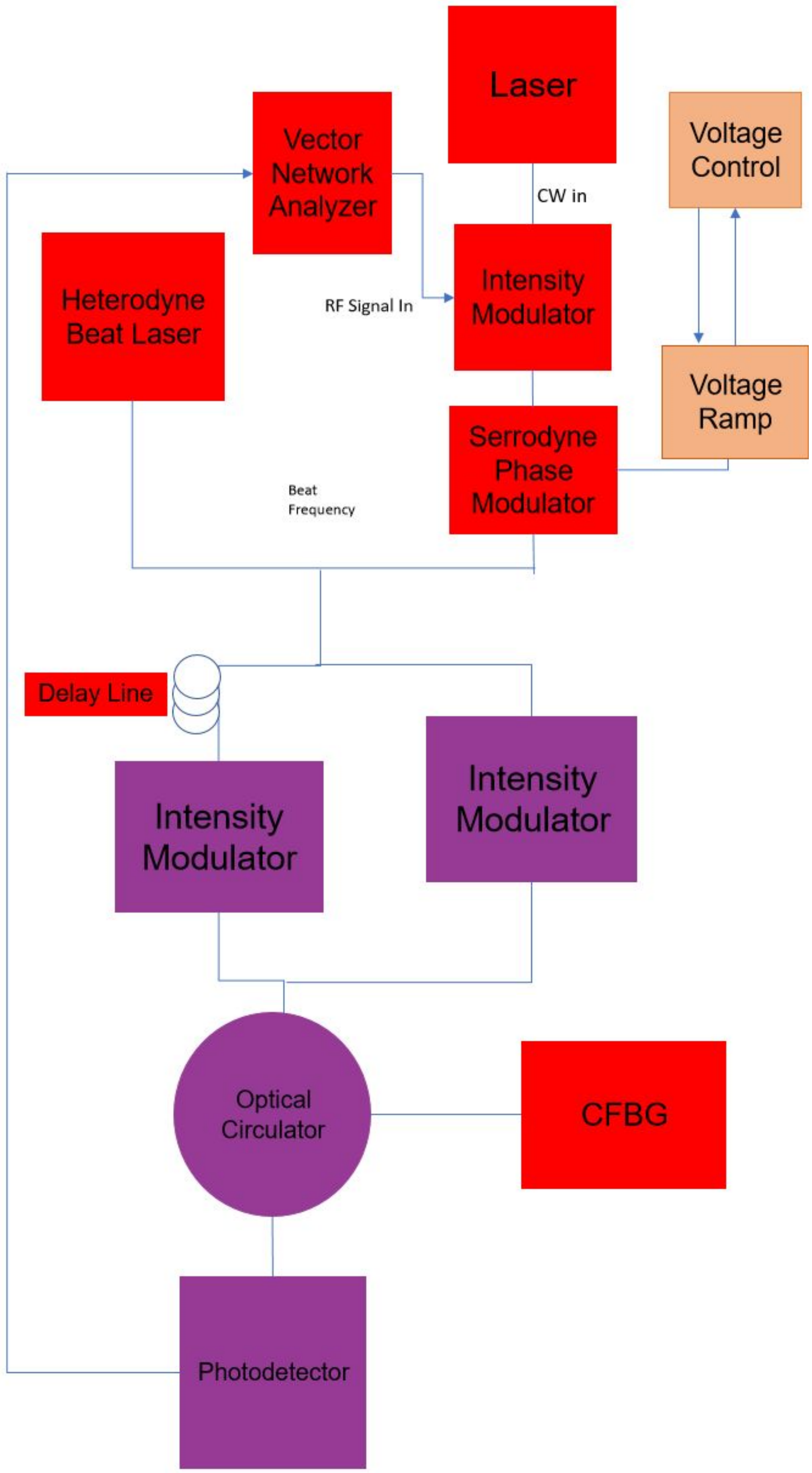


Figure 22: Initial Block Diagram for Serrodyne Approach

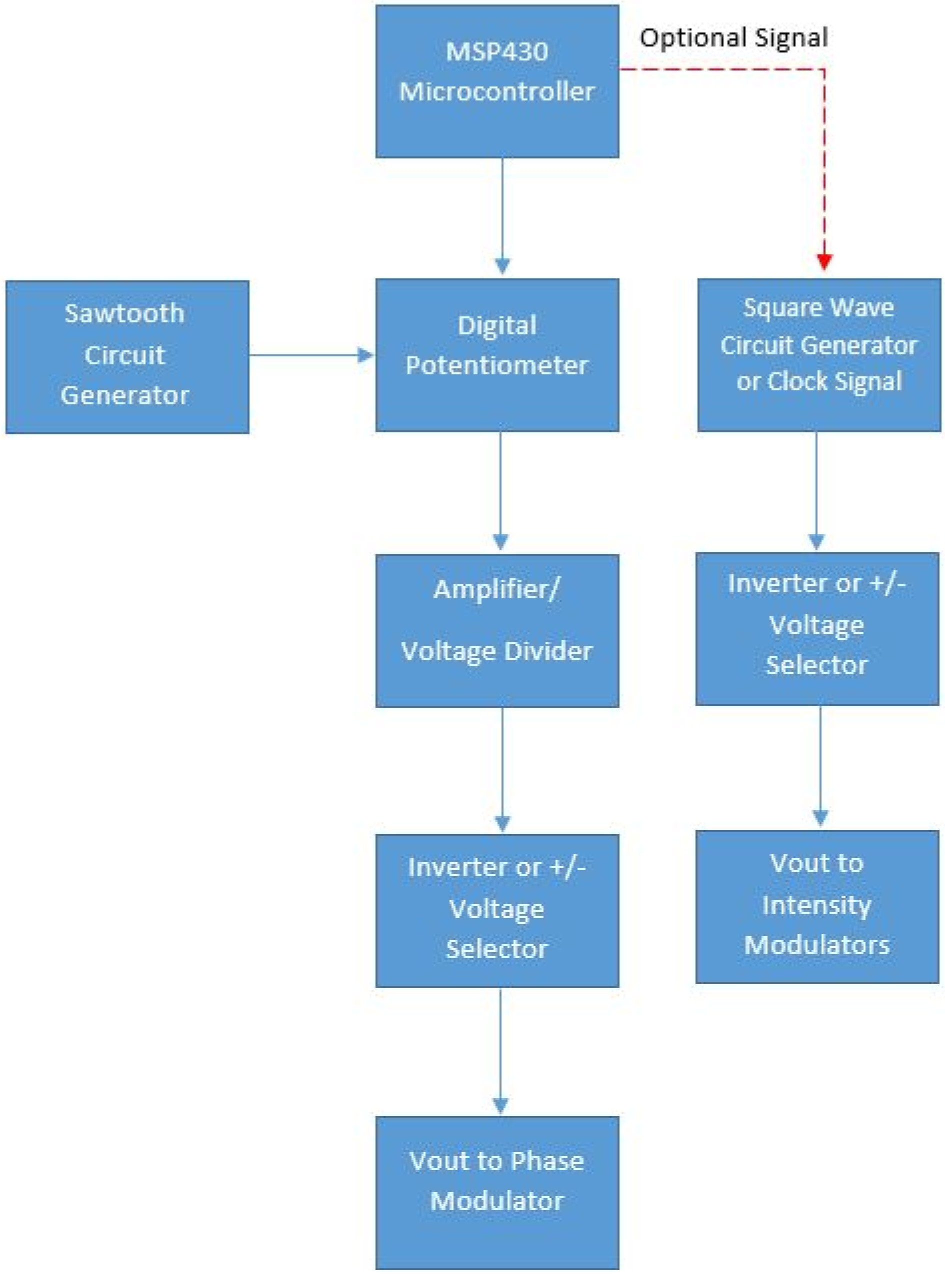


Figure 23: Block diagram for primary electronics.

6.1.1.1 Serrodyne Maximum Frequency Shift Considerations

From the initial calculations discussed in the initial calculations section, a total of 187 steps would be necessary for a max delay range of 1.5 nanoseconds. This figure is based on the requirement specifications involving delay resolution and time spent at each delay step.

As such, a large frequency shift of the incoming optical signal is preferable. This is because with a higher frequency shift, less precision would be required on the part of the voltage ramp and the Chirped Fiber Bragg Grating. As mentioned previously in this section and in the section detailing the technology of serrodyne phase shifting, the slope of the phase modulation determines the applied frequency shift. In order to allow for the hundred and eighty eight delay steps that corresponds to a delay range of 1.5 nanoseconds and delay resolution of 8 picoseconds, one hundred and eighty eight different phase modulation slopes would be required.

As such, the required resolution of the voltage ramp in terms of voltage supplied over a given period of time for this system is decreased with an increase in maximum frequency shift. With a larger frequency shift, the number of phase modulation slopes that need to fit within a certain range of voltages is decreased. For example, if the maximum frequency shift corresponded to a voltage ramp from positive to negative Vpi that occured over 5 nanoseconds, the maximum frequency shift applied would be .2 GHz. With this maximum frequency shift, the rest of the 186 voltage ramp slopes would lie relatively close together.

However, if the maximum frequency shift corresponded to a voltage ramp from positive to negative Vpi that occured over 1 nanosecond, the applied frequency shift would be 1 GHz. Therefore, the spacing between these slopes is decreased significantly. In terms of practicality regarding the actual voltage ramp used in the final system, a voltage ramp from positive to negative Vpi over 1 nanosecond is an idealistic goal for the purchased or designed voltage ramp for the final system. However, it is entertained here for conceptual purposes. Figure 24 depicts the slope spacing in these two scenarios below.

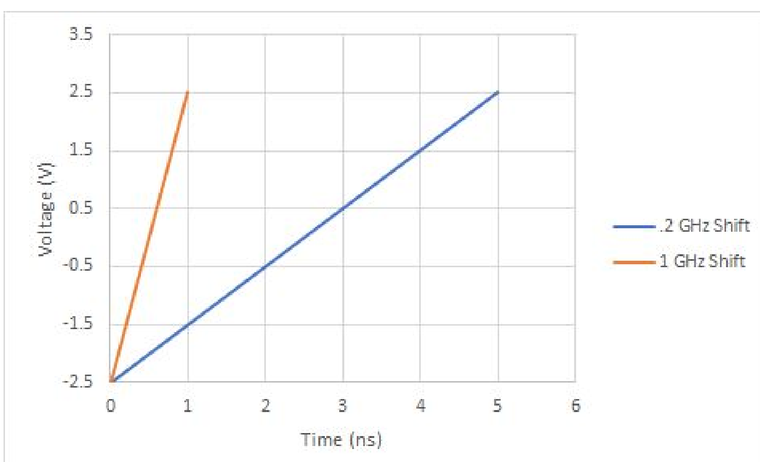


Figure 24: Depiction of Slope Differential for Higher Frequency Shifts

This figure was plotted by arbitrarily assuming a Vpi of 2.5 Volts for the serrodyne phase modulator. Clearly, the 1 GHz shift plot has a much steeper slope than the .2 GHz shift plot. It is obvious from this fact and the plot above that, with a total of 187 steps for a 1.5 nanosecond range of delay, the 1 GHz shift allows for a broader resolution between slopes as the slope approaches zero. This is important to consider because the tunability of the voltage source used in terms of voltage applied and the amount of time taken is limited. Therefore, if the differentiation between slopes is too small, the voltage ramp may not be precise enough to deliver the necessary frequency shifts.

Another important aspect to consider when discussing the slope differentiation is the effect on the frequency selective Chirped Fiber Bragg Grating in use. Regardless of the Fiber Bragg Grating used in the final system, the periodicity of the grating is limited in terms of resolution. This mean that if the frequency shift between coinciding delay steps is too small, the reflection point between these frequency shifts may not be large enough to create the desired delay. Therefore, a broader slope resolution is beneficial in this regard as well.

6.1.1.2 Serrodyne Phase Modulation Slope Considerations

One consideration to be made regarding the slope of the voltage ramp used is the sign of the slope. The frequency shift caused by serrodyne phase modulation is dependent on the slope of the voltage ramp applied to the phase modulator, and therefore is also dependent upon the sign of this voltage ramp. This means that if the maximum frequency shift achievable with the voltage ramp used is 1 GHz, the incoming optical frequency could be shifted by positive or negative 1 GHz.

This fact provides three possibilities in regards to the voltage ramp scheme. The first is to provide 187 positive voltage ramp slopes including a slope of zero, so as to generate 187 positively shifted frequencies. The second is to follow the same approach, but with 187 negative voltage ramp slopes including a slope of zero. The third is a culmination of the two. This would mean that a total of 93 positive slopes, a slope of zero, and 93 negative slopes would combine for a total of 187 shifted frequencies, centered around the incoming optical frequency. When considering these three approaches, it is clear that the third option provides the most advantages. To begin with, using half positive and half negative slopes means that the resolution between these slopes can be greater. As discussed previously in this section, broad slope resolution has many advantages with regards to the limited resolution of the voltage ramp source and the Chirped Fiber Bragg Grating.

In addition to the sign of the slope, another consideration to be made regarding the slope is related to how the slope is changed for different frequency shifts. As discussed in the section detailing the technology of serrodyne endless phase modulation, different phase modulation slopes result in different frequency shifts of the incoming optical frequency. For a 1.5 ns delay range approximately 187 delay steps are needed, which means that a total of 187 different slopes are required. This slope is defined by the amount of time taken to linearly increase the voltage from negative to positive (or positive to negative for negative voltage ramp slopes) Vpi. Therefore, this slope can be altered either by changing the value of the voltage supplied or by changing the amount of time it takes to reach the desired voltage level.

If the Voltage value were to be kept constant, that would mean the amount of time taken to reach Vpi would change. Assuming the approach involving both positive and negative frequency shifts is adopted and a maximum frequency shift of positive or negative 1 GHz is used, the maximum magnitude frequency shift would correspond to 1 nanosecond of time taken to bias the phase modulator from negative to positive Vpi. The intermittent 186 voltage ramp slopes would then occur with an increase in the amount of time taken to bias the phase modulator from negative to positive Vpi. Figure 25 depicts a slope change based on this principle.

The other option in regards to how the phase modulation slope is altered between different frequency shifts is to change the magnitude of the applied voltage. In this case, the amount of time taken would remain constant, but the starting and stopping point in terms of the voltage ramp would be altered. Assuming the same design parameters and an arbitrary phase modulator Vpi, the maximum frequency shift would occur over 1 nanosecond and would increase the bias voltage from negative to positive Vpi. The intermittent slopes would each have different voltage values but the time taken for each slope would remain at 1 nanosecond. Figure 25 depicts this type of slope change below.

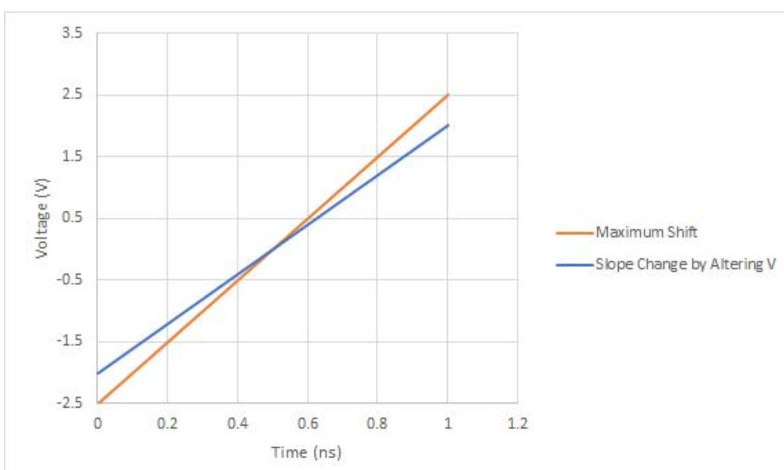


Figure 25: Slope Change by Altering Voltage

To decide which slope altering approach to consider, the required resolution for both approaches has been considered. Assuming once again that a maximum frequency shift of 1 GHz is achievable and a delay range of 1.5 nanoseconds is used, the differentiation between different frequency steps would be approximately 10.753 MHz. For the constant voltage, altered time approach, the time difference between coincident frequency shifts would be 10.8 picoseconds. This was found assuming a refractive index of 1.5 for the fiber used. For the constant time, altered voltage approach, the change in applied voltage is approximately 13.368 milliVolts in terms of the starting voltage. This was found using a theoretical Vpi of 2.5 Volts. The resolution in Voltage for the constant time, altered voltage approach requires significantly less precision than the constant voltage, altered time approach. There is also the option of considering an amalgamation of these two slope altering approaches. This would mean that less change in both voltage and time would be required. However, for this project, the limiting factor in this regard is the fineness of each individual slope change. Therefore, the altered voltage, constant time approach shows the most promise.

6.1.2 Circuit Designs

The primary circuits in the serrodyne approach involve multiple signals that are used for biasing elements in the optical setup, such as the phase modulator and intensity modulators. The phase modulator requires a voltage ramp over a set time period that goes from negative Vpi of the modulator to positive Vpi. To generate this ramp, we will need to design a circuit that generates a sawtooth waveform with variable slopes (up to 93 different slopes). These slopes must then go through an inverter stage to obtain the necessary positive and negative slopes to bias the phase modulator. In addition to the sawtooth waveform, two square waveforms must be generated. These square waveforms are used to bias the intensity modulators. This approach requires that one intensity modulator be turned on while the other is turned off, and then the two will cycle through at a constant rate of on and off states. To accomplish this, we need a square waveform that is high while the other one is low for the same duration of time. We can approach this in a few ways. One way is to take a clock signal generated by the microcontroller and use it to bias the intensity modulators. There would also need to be an inverting stage to put the square waveforms out of phase with each other. The other option is to build our own oscillator to generate a square waveform. We can either build two waveforms with the phase delay, or more practically, we can generate one waveform and pass it through an inverting stage. The latter option will ensure that the period of the two signals remains equal while offering the phase shift between the two waves. Figure 26 below depicts a model for the type of square wave required.

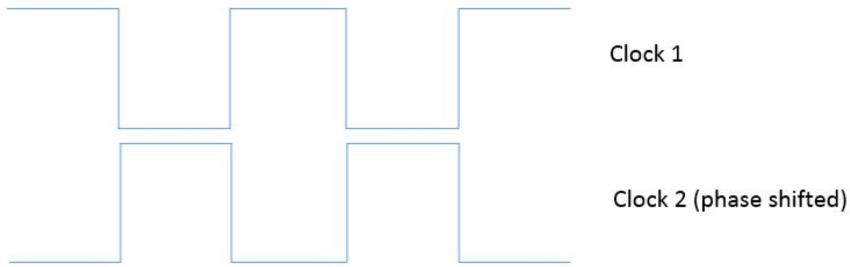


Figure 26: Clock Signals for Intensity Modulator Biasing.

The following figures will show schematic diagrams and simulations for possible approaches to generating the waveforms needed to bias the phase modulator and intensity modulators. Each design will be presented, analyzed, and discussed as to how it would accomplish our goals or why it needs to be altered. We will first present proposed designs for the phase modulator biasing and then designs for the intensity modulator biasing. Our primary approach is to design a sawtooth signal at the desired frequency (83.33 MHz, 10 ns rise time, 2 ns fall time) and then use other circuitry to modify the slope of the waveform. The first design approach for the sawtooth generator, shown in figure 27 below, uses three simple transistors, some resistors, a capacitor, and a DC bias. The left half of the circuit uses creates a bias at the base of the transistor and allows current to charge the capacitor. This generates the rise time for the sawtooth. The right half is used to discharge the capacitor and generate the fall time of the sawtooth. The base of the middle transistor is turned on by the right voltage divider. Once the capacitor reaches a certain voltage, the transistor conducts current and turns on the third transistor, which in turn pulls out current even faster from the capacitor [32].

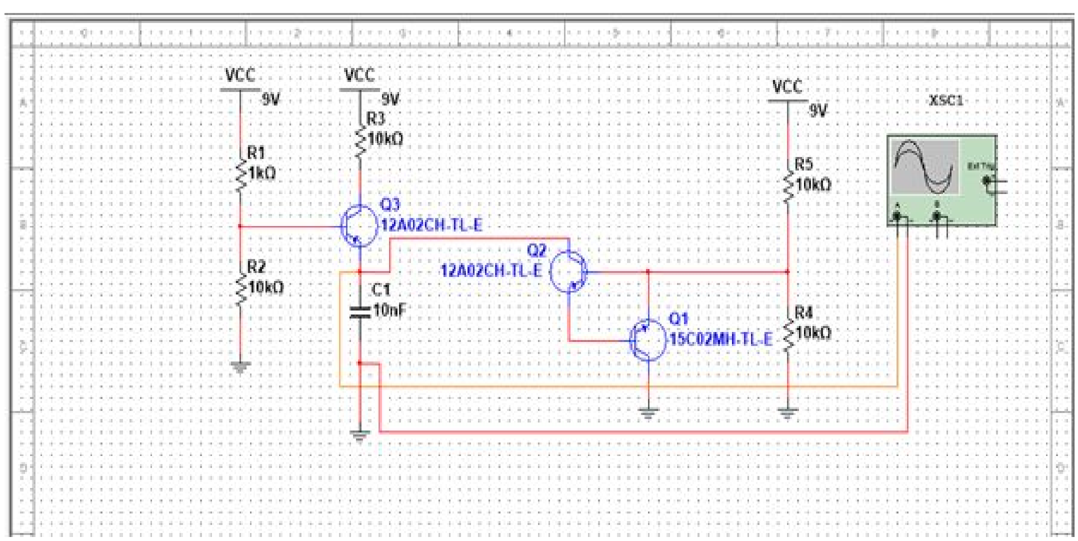


Figure 27: Sawtooth Generator Approach Number 1

The simulation for this approach just showed a flat output. This is likely due to Multisim (the simulation software used) treating the capacitor as an open circuit under the DC bias. In any case, this circuit may design a sawtooth waveform, but we need more control over our design. This approach does not provide much control in terms of setting the rise time and fall time of the waveform. For this reason other approaches were investigated.

Another possible design for the sawtooth is shown below. It is designed using a circuit that generates both square and triangle waves. While the circuit works well for lower frequencies, the design does not work so well under high frequencies, even when using high frequency op-amps as are used in the design below. As can be seen from the simulated waveforms, the square and triangle waves are both not very ideal and only at a fraction of the frequency desired (5 MHz versus a necessary 50 MHz minimum). See figure 28 below.

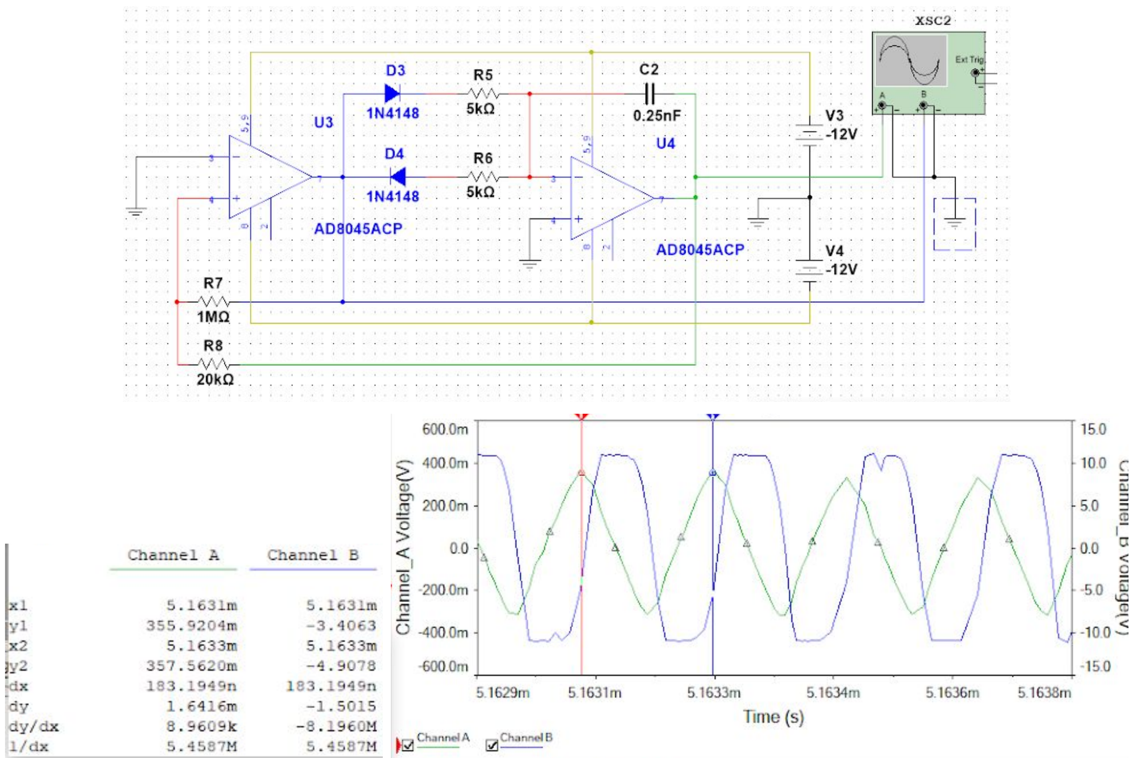


Figure 28: Sawtooth Generator Approach Number 2

One more sawtooth design that seems to work very well is shown below. The circuit already filters out any negative slopes, which is a design constraint that is desired for the serrodyning approach, in order to only keep one value of slope for a given period of time. It also outputs a ramp that appears to be very linear with a constant and reliable slope, even at high frequencies (20 MHz). The problem is that when its component values are adjusted to obtain the frequencies desired by the project (50 MHz), it either significantly loses linearity or fails completely.

Although it is nearly perfect for what it needed, it fails to be reliable at the frequencies needed. The final design for the triangle or sawtooth will be discussed later in this section when going over the final design. See figure 29 below.

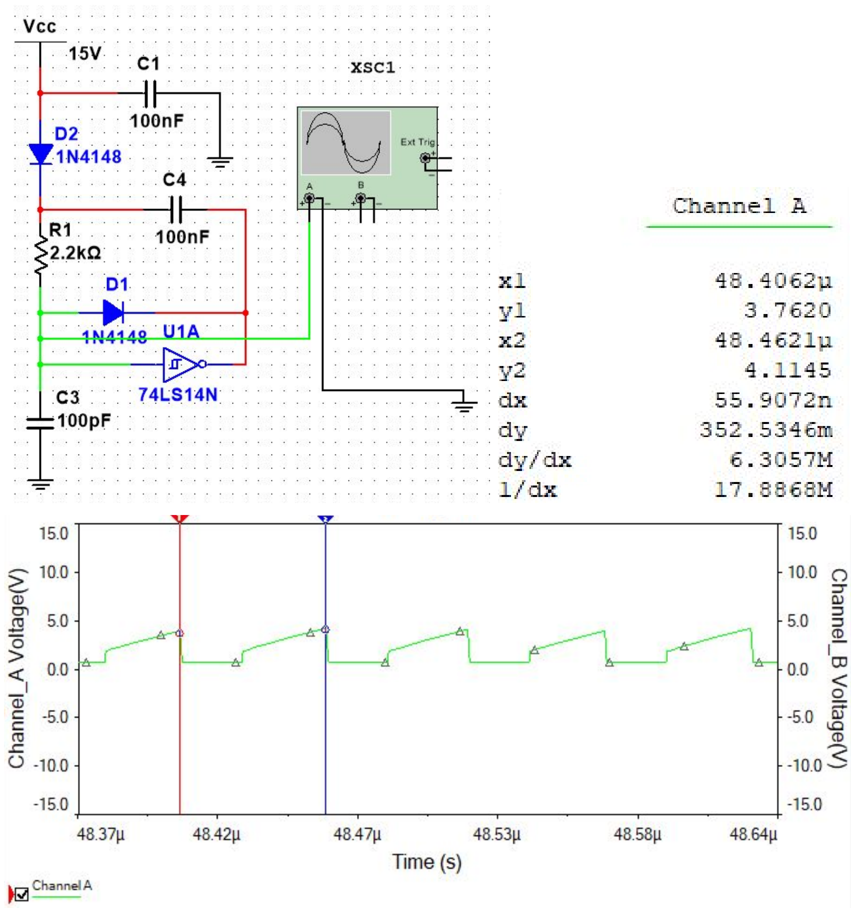


Figure 29: Sawtooth Generator Design Number 3

Once a sawtooth waveform is generated, next we plan to generate the various slopes for the phase modulator biasing by amplifying the sawtooth waveform. Our first thought to achieve this was to take our generated sawtooth waveform and run it through an inverting operational amplifier (opamp). The gain for an inverting opamp is the ratio between the two resistors across the opamp multiplied by a negative sign change. Figure 30 shows an example of this.

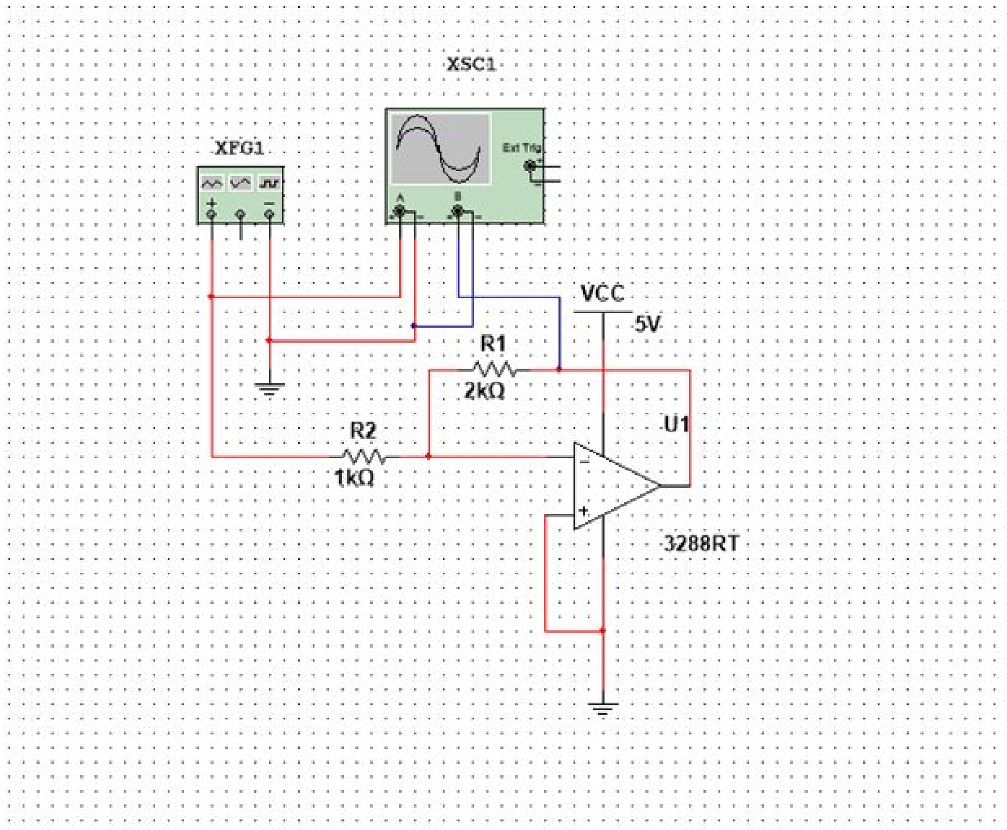


Figure 30: Inverting Opamp with a Gain of 2

To achieve different slopes, we will use a digitally controlled potentiometer to change the resistor values in the amplifier. A total of 93 positive slopes are needed, so 93 different resistances will be varied within the circuit. The resistors will be placed in such a way that the gain is always less than one. This means our initial sawtooth waveform will be the maximum voltage slope we need to bias the phase modulator, and each following slope will be smaller. A second opamp will be placed after the first to act as a unity gain inverting amplifier. By using a switch to change between this inverter and regular output, we can have our positive and negative voltage ramps. The sawtooth will start at its maximum positive slope. Then each consecutive slope will be scaled down until the minimum positive slope is reached. At this point, the inverter opamp will have its switch closed and the regular output will have its switch opened. The voltage slopes will then increase back to the maximum slope. Then the inverter switch opens and the regular output switch closes and the cycle repeats. Figure 31 shows an example of this circuit.

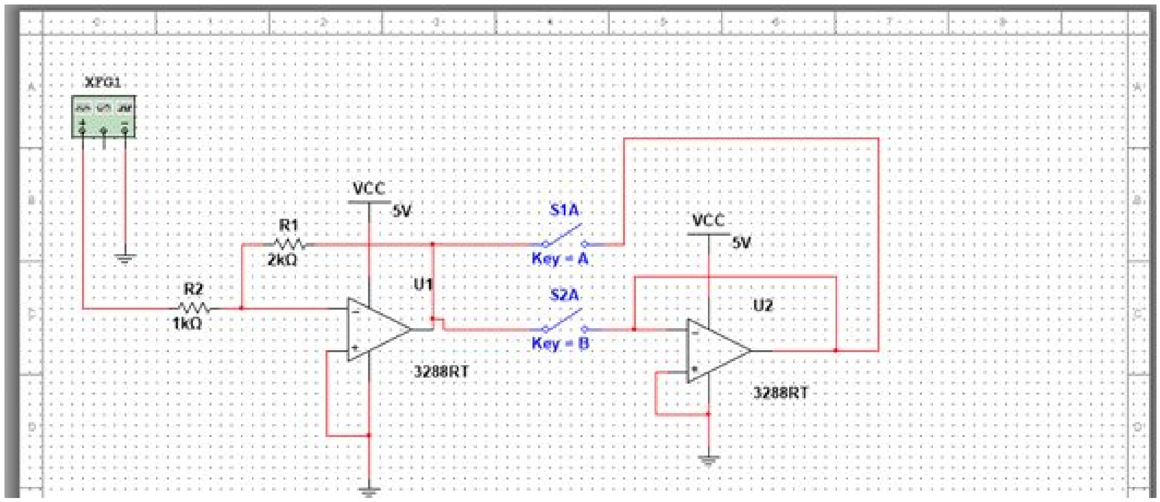


Figure 31: Sawtooth Amplifier Circuit Design Number 1

An initial test was run on the first stage of this circuit to show that a sawtooth could be scaled and inverted. If this works, then we know the second stage will simply invert our results. The initial conditions for the sawtooth waveform input are shown in Figure 33 (A) followed by the corresponding output waveform in Figure 33 (B). As expected, the circuit performs well and achieves inverting our input signal and scaling it by a factor of two. Now the input sawtooth had its frequency changed from kHz to MHz as shown in Figure 33 (C). The output this time shows a signal that seems scaled down rather than amplified by twice its voltage, and the signal also seems to have some capacitive charging and discharging distortions. Upon investigating this, we found that the gain bandwidth for this opamp was too low at this frequency, causing the signal distortion. See Figure 33 (D). Figure 32 demonstrates the gain-frequency relationship for an opamp.

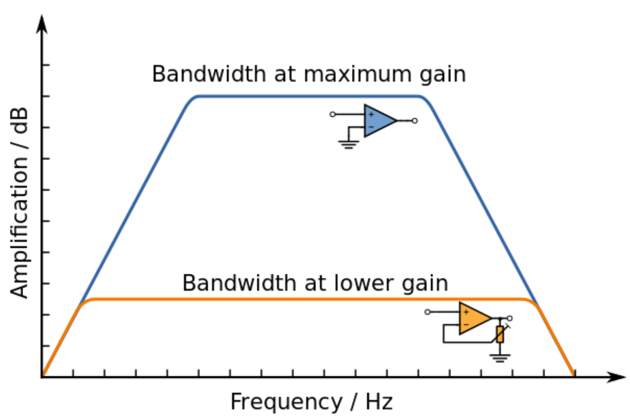


Figure 32: Gain-Frequency Curve for Opamp.
Image provided by Wikipedia (released to public domain by author).

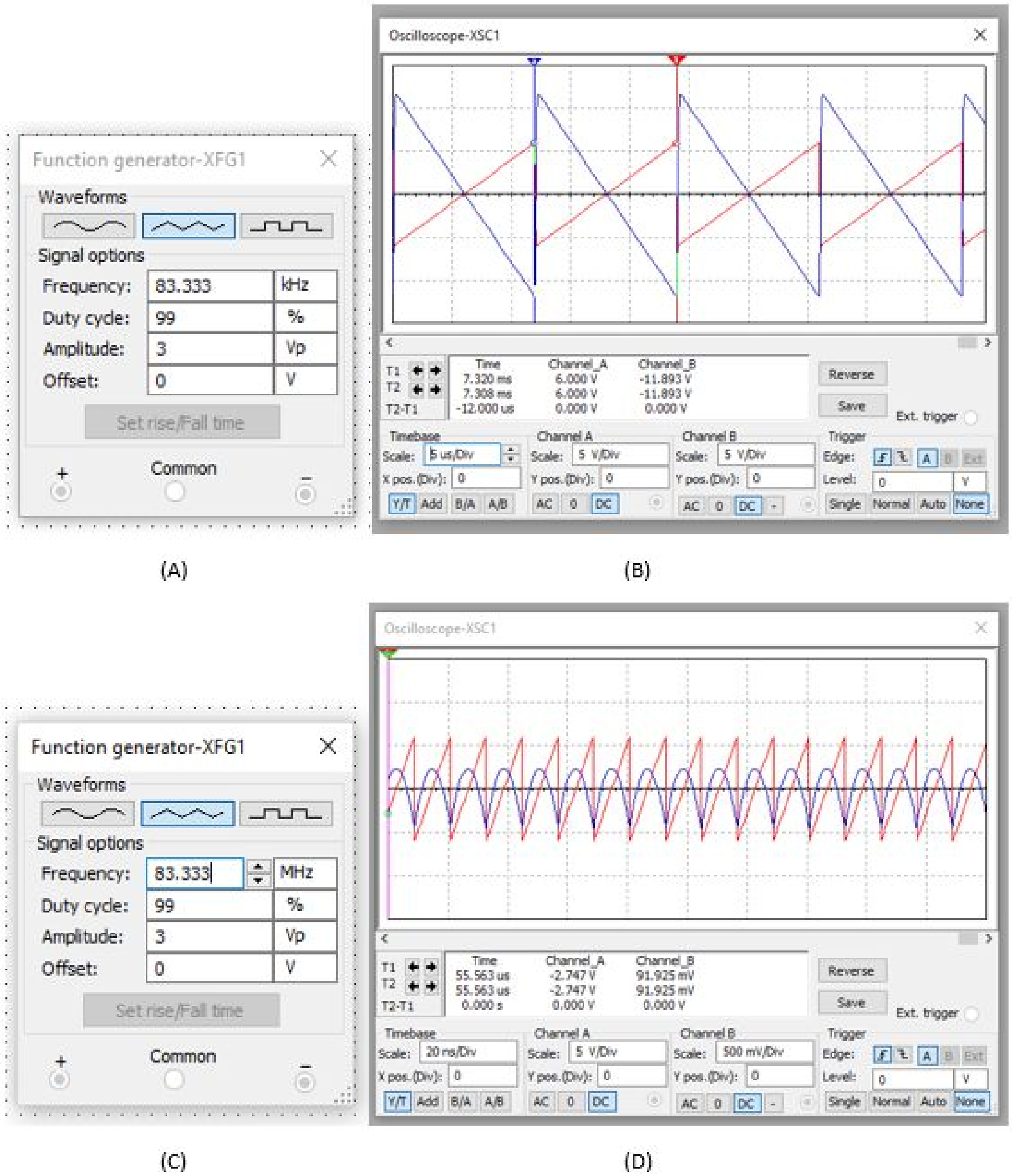
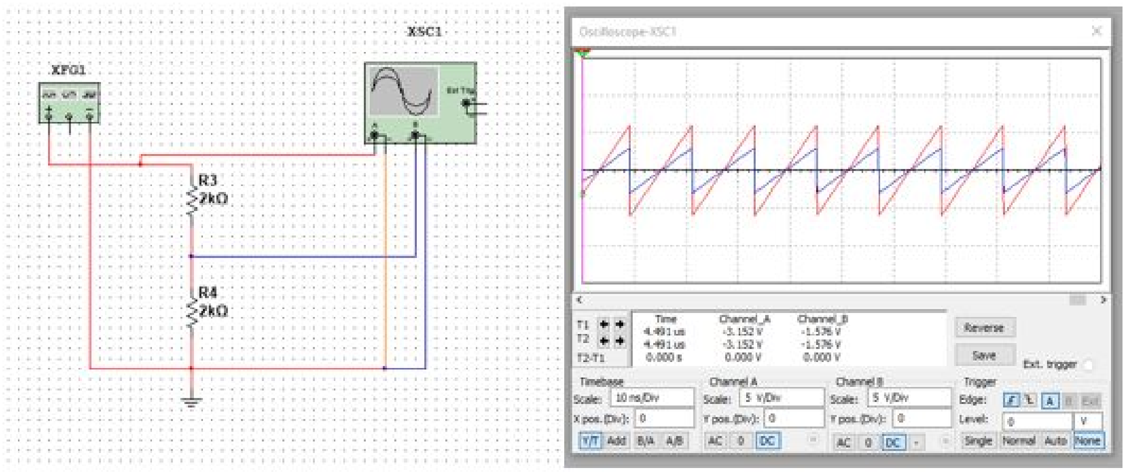


Figure 33: Sawtooth Input-Output Comparison for Opamp Amplification Stage

It became clear after investigating some more that likely all opamps would yield this output distortion for frequency ranges above a few megahertz. This was a problem since our sawtooth needed to have a rise-time-fall-time total period of 12 nanoseconds (or 83.33 MHz). This brought our team to consider using a simple voltage divider to scale our sawtooth waveform. The input would remain unchanged, and the digital potentiometer (two in total) would still be used. To obtain the positive and negative ramp slopes, switches will be used to select between a positive sawtooth and a negative sawtooth. The initial sawtooth (maximum voltage slope) will need to pass through the circuit unaltered. This will correspond to the top potentiometer (where the signal is coming from) to short, and the bottom potentiometer to open. All other voltage ramps will be scaled by a change in resistance for these two potentiometers. Figure 34 (A) shows a test case to see if the voltage divider will scale correctly. In this case, each potentiometer is set to a resistance of 2k-Ohms which should cut the input signal voltage in half. Figure 34 (B) shows the corresponding output which has successfully scaled our input signal. The final design would look the same as in Figure 34 (A), but would have the two inputs for the positive and negative cases. The output would then go directly to the phase modulator.



(A) (B)

Figure 34: Voltage Divider for Sawtooth Waveform Amplification and Test Case Output Signal.

The following table will provide a list of possible R1 and R2 combinations to achieve the desired output slopes (where R1 is the first resistor to see the signal and R2 is the resistor connected to ground). To ensure distinguishable signals, each slope must be spaced by at least 32 mV. The phase modulator we are using has a Vpi of 3 volts, meaning our slope must go from -3 volts to +3 volts in the designated time period. Table 4 will have a maximum voltage of 3.008 volts and a minimum of 32 mV. The zero voltage case requires would correspond to an open circuit for both potentiometers, the maximum voltage would be a short across R1 and an open across R2. Potentiometer values were selected to ensure a change in resistance between each voltage slope will always be 500 ohms. Since the initial voltage ramp is linear, we will only consider a scaling factor on the maximum voltage, and all other voltages for the ramp will scale linearly. This means a potentiometer with a maximum resistance of 50 kOhm is needed. This was chosen based on minimum wiper resistance and cheapest in cost.

Vin (Volt-max)	R1 (Ohm)	R2 (Ohm)	VOUT (Volt-max)	delta R1 (Ohm)	delta R2 (Ohm)
3.008	SHORT	OPEN	3.008		
	500	46500	2.976		
	1000	46000	2.944	500	500
	1500	45500	2.912	500	500
	2000	45000	2.88	500	500
	2500	44500	2.848	500	500
	3000	44000	2.816	500	500
	3500	43500	2.784	500	500
	4000	43000	2.752	500	500
	4500	42500	2.72	500	500
	5000	42000	2.688	500	500
	5500	41500	2.656	500	500
	6000	41000	2.624	500	500
	6500	40500	2.592	500	500
	7000	40000	2.56	500	500
	7500	39500	2.528	500	500
	8000	39000	2.496	500	500
	8500	38500	2.464	500	500
	9000	38000	2.432	500	500
	9500	37500	2.4	500	500
	10000	37000	2.368	500	500
	10500	36500	2.336	500	500
	11000	36000	2.304	500	500
	11500	35500	2.272	500	500
	12000	35000	2.24	500	500
	12500	34500	2.208	500	500
	13000	34000	2.176	500	500
	13500	33500	2.144	500	500
	14000	33000	2.112	500	500
	14500	32500	2.08	500	500
	15000	32000	2.048	500	500
	15500	31500	2.016	500	500
	16000	31000	1.984	500	500
	16500	30500	1.952	500	500

	17000	30000	1.92	500	500
	17500	29500	1.888	500	500
	18000	29000	1.856	500	500
	18500	28500	1.824	500	500
	19000	28000	1.792	500	500
	19500	27500	1.76	500	500
	20000	27000	1.728	500	500
	20500	26500	1.696	500	500
	21000	26000	1.664	500	500
	21500	25500	1.632	500	500
	22000	25000	1.6	500	500
	22500	24500	1.568	500	500
	23000	24000	1.536	500	500
	23500	23500	1.504	500	500
	24000	23000	1.472	500	500
	24500	22500	1.44	500	500
	25000	22000	1.408	500	500
	25500	21500	1.376	500	500
	26000	21000	1.344	500	500
	26500	20500	1.312	500	500
	27000	20000	1.28	500	500
	27500	19500	1.248	500	500
	28000	19000	1.216	500	500
	28500	18500	1.184	500	500
	29000	18000	1.152	500	500
	29500	17500	1.12	500	500
	30000	17000	1.088	500	500
	30500	16500	1.056	500	500
	31000	16000	1.024	500	500
	31500	15500	0.992	500	500
	32000	15000	0.96	500	500
	32500	14500	0.928	500	500
	33000	14000	0.896	500	500
	33500	13500	0.864	500	500
	34000	13000	0.832	500	500
	34500	12500	0.8	500	500
	35000	12000	0.768	500	500

	35500	11500	0.736	500	500
	36000	11000	0.704	500	500
	36500	10500	0.672	500	500
	37000	10000	0.64	500	500
	37500	9500	0.608	500	500
	38000	9000	0.576	500	500
	38500	8500	0.544	500	500
	39000	8000	0.512	500	500
	39500	7500	0.48	500	500
	40000	7000	0.448	500	500
	40500	6500	0.416	500	500
	41000	6000	0.384	500	500
	41500	5500	0.352	500	500
	42000	5000	0.32	500	500
	42500	4500	0.288	500	500
	43000	4000	0.256	500	500
	43500	3500	0.224	500	500
	44000	3000	0.192	500	500
	44500	2500	0.16	500	500
	45000	2000	0.128	500	500
	45500	1500	0.096	500	500
	46000	1000	0.064	500	500
	46500	500	0.032	500	500
	OPEN	OPEN	0		

Table 4: Sawtooth Amplification Voltage Divider Resistance Values.

For the final design of the electronic system for this project, the first step of the circuit design will be to design a sine wave oscillator that creates a frequency of 50 MHz. In order to do so a colpitts oscillator will be used. To create this, the design is shown in the figure below. As shown by the output waveform, the design creates a clean sinusoidal waveform which is ideal for this project. From this, we can use the sinusoid with a comparator to obtain a square wave. See figure 35 below.

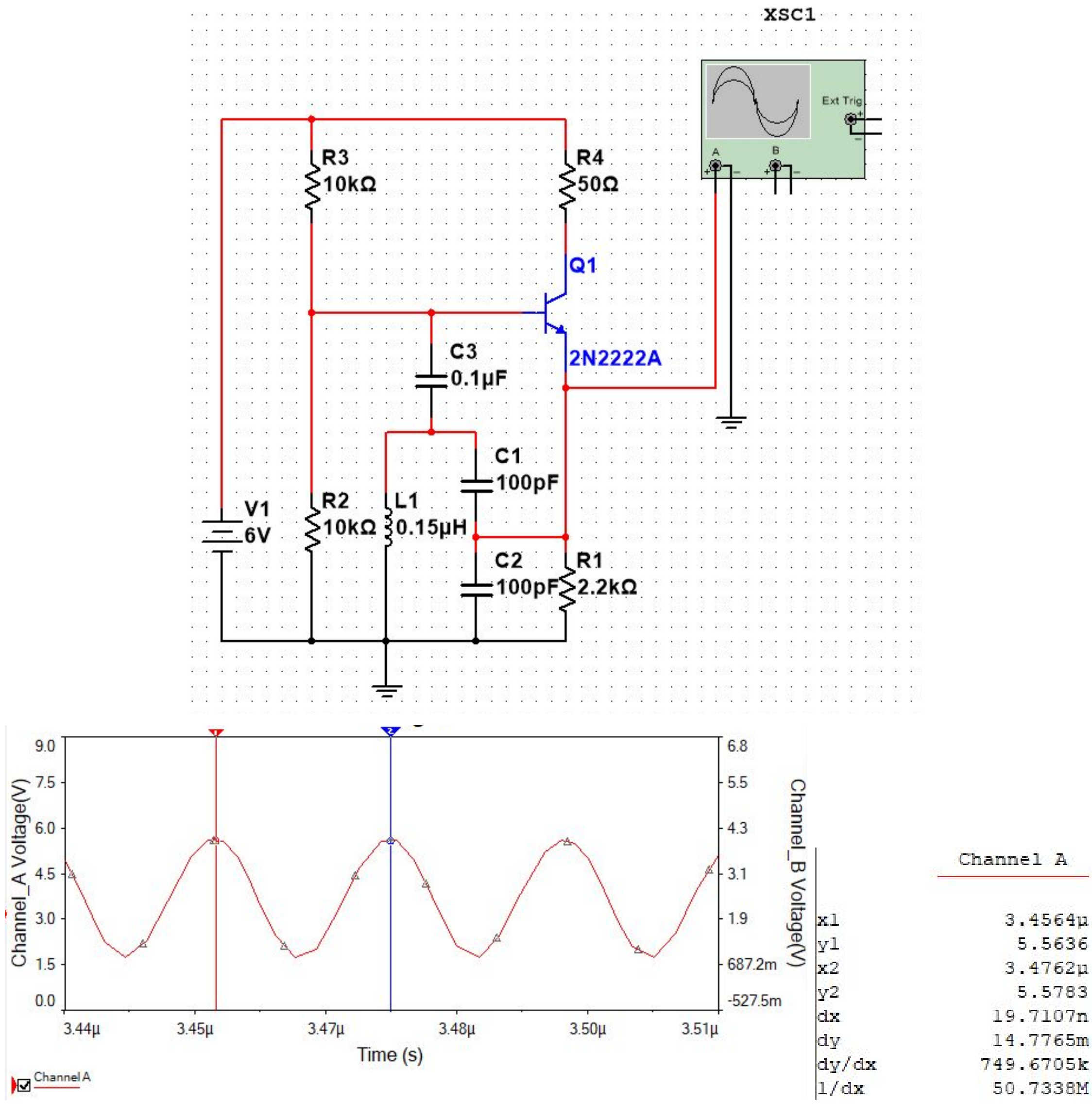


Figure 35: Colpitts Oscillator Circuit for 50 MHz

When using a comparator on the sine wave that outputs from the colpitts oscillator, it is important to note that high frequency signal that is going through the comparator and the high frequency square wave that needs to output from the comparator. This is important when choosing comparators because not all comparators will be able to properly operate at such high frequencies. Because of this, only high speed / high frequency comparators are considered. For the design chosen, the LT1715 is used as the comparator. The design of the comparator taking a sinusoidal input is shown in the figure below. As can be seen in figure 36 below, the square wave is not perfect. However, for the sake of this project, it will be sufficient enough to filter out the downward slopes of a generated triangle wave.

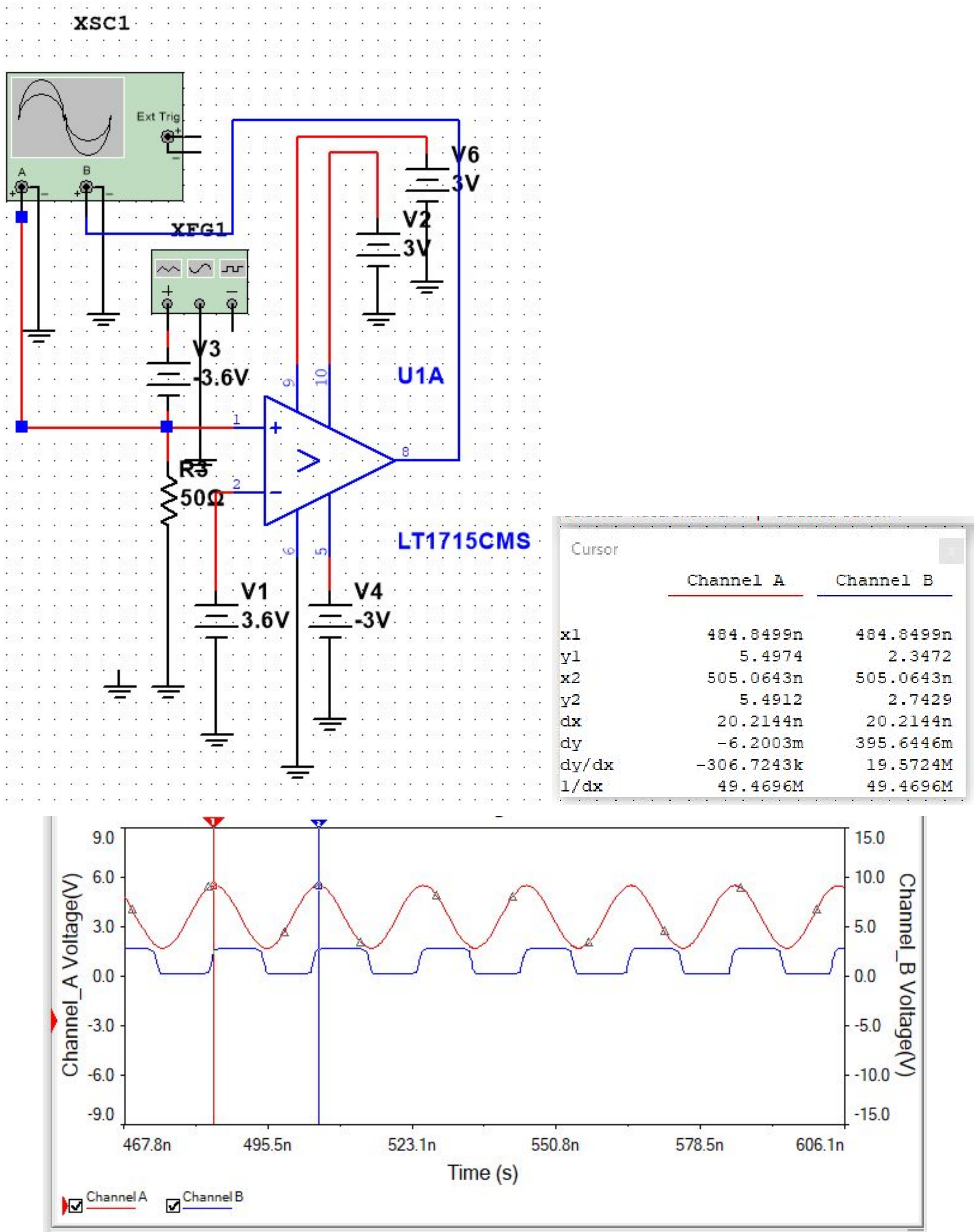
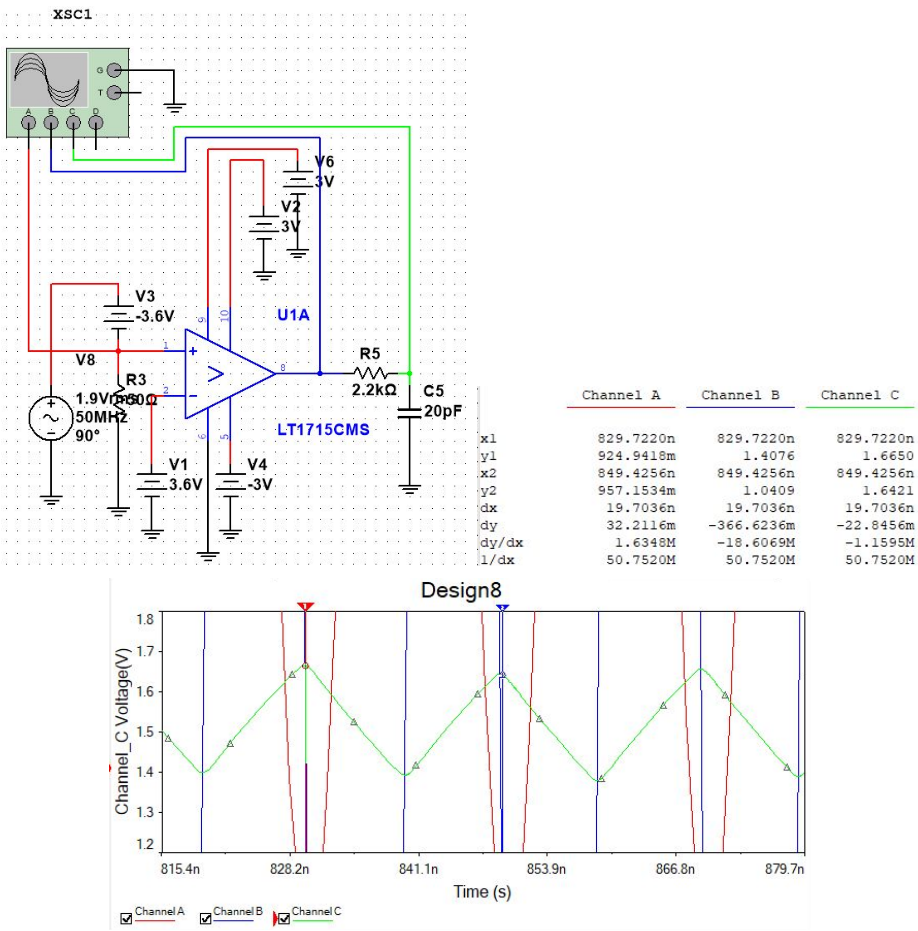


Figure 36: Comparator Circuit Design

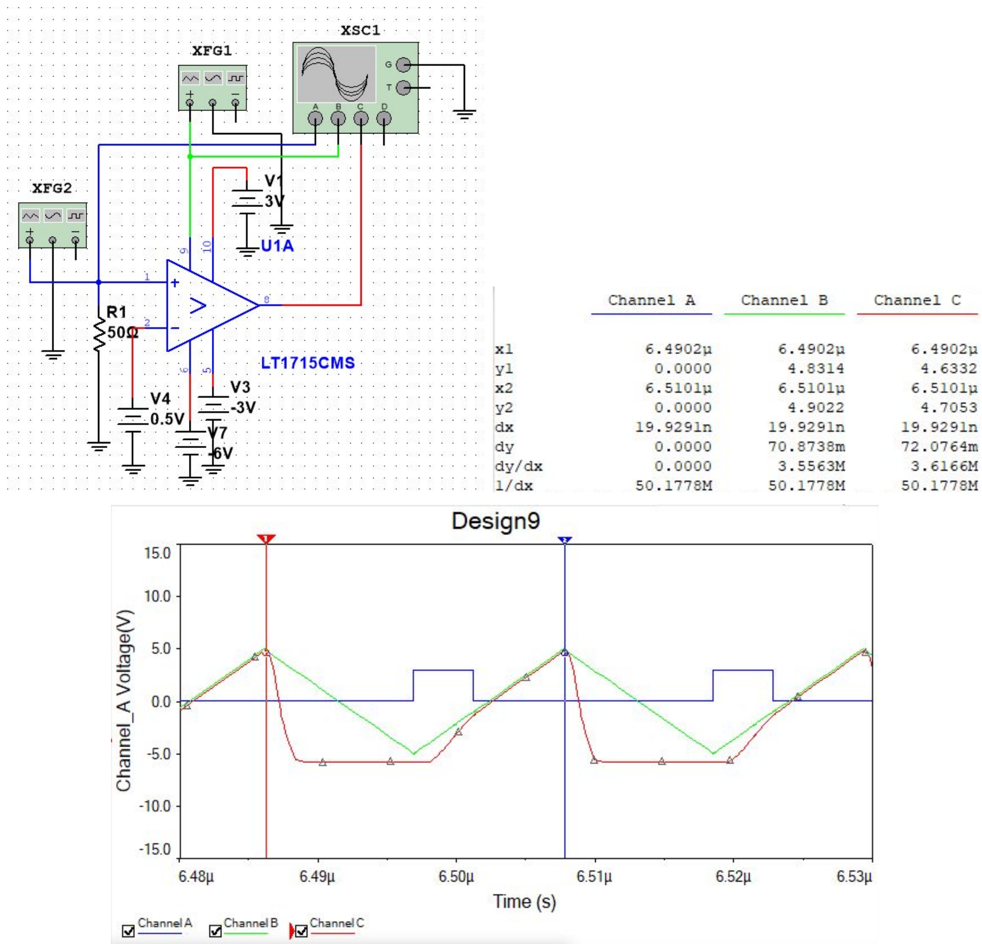
The final step in the design is to obtain a triangle, or ramp, waveform to create the slopes used for the serrodyne approach. This again used a separate colpitts oscillator and a comparator to create a square wave. From that square, simply add a resistor and a capacitor to create simple integrator circuit, as shown in figure 37 below.



	Channel A	Channel B	Channel C
x1	829.7220n	829.7220n	829.7220n
y1	924.9418m	1.4076	1.6650
x2	849.4256n	849.4256n	849.4256n
y2	957.1534m	1.0409	1.6421
dx	19.7036n	19.7036n	19.7036n
dy	32.2116m	-366.6236m	-22.8456m
dy/dx	1.6348M	-18.6069M	-1.1595M
1/dx	50.7520M	50.7520M	50.7520M

Figure 37: Triangle Waveform from a Colpitts Oscillator.

After adjusting a few of the DC values used in the circuit and with adding a high frequency amplifier, the triangle wave can reflect the necessary amplitude and offset necessary for the ramp that goes into the serrodyne approach. Although the triangle is not quite perfect and does not change from positive to negative slope as fast as would be ideal, it seems to be the best options available for the that is easily obtainable for this project. In order to use the square wave with the triangle wave to only obtain the positive slopes of the triangle wave and filter out the negative slopes, another comparator will be used. Because the two options for the output voltage are given as inputs to the comparator, the upper output can be defined at the triangle wave that was just designed. The square wave can then be used as the main input, referenced with some voltage value between the two values of the square wave to determine when the triangle wave is output. Because of the high frequency of the system, there are slight delays, so the square wave can be adjusted so that the triangle wave is output for the appropriate amount of time. This setup is shown in figure 38 below, using simple function generator to represent the generated square and triangle waves for sake of simplifying the circuit.



	Channel A	Channel B	Channel C
x1	6.4902µ	6.4902µ	6.4902µ
y1	0.0000	4.8314	4.6332
x2	6.5101µ	6.5101µ	6.5101µ
y2	0.0000	4.9022	4.7053
dx	19.9291n	19.9291n	19.9291n
dy	0.0000	70.8738m	72.0764m
dy/dx	0.0000	3.5563M	3.6166M
1/dx	50.1778M	50.1778M	50.1778M

Figure 38: The General Final Setup for the Voltage Ramp

With the voltage ramp obtained, another can be built to work in parallel but out of phase by 180 degrees with each other. This will allow a circuit that outputs what would be essentially a sawtooth with constant positive slope, so the serrodyne only reads the positive slope value. From there the voltage divider is the only thing necessary for the final design to vary the slope for each delay step. Other than simple DC voltage sources (batteries), resistors, capacitors, and inductors, the only major parts are the transistor for the colpitts oscillator, the comparators, and the operational amplifier. For the colpitts oscillator, a 2N2222A is sufficient enough to create the desired sinusoid output. An LT1715 comparator is able to operate at high frequencies and is therefore a good choice for this project. As seen in previous simulation waveforms, it is not able to obtain square waves with ideal rise and fall times, but they are sufficient for this project. An AD8045 operation amplifier works for similar reasons, being able to operate at high frequencies.

6.2 Suppliers and Supplied Components

This section will cover the supplied components and their suppliers. Since this project is being developed with Harris Corporation as the sponsor, not all of the parts necessary to this project had to be bought or developed by the group members. The necessary parts that were not developed or bought were provided by Harris. These supplied parts will be detailed and discussed in this section. These parts include the photodetector, any RF related components and sources (including a vector network analyzer), an intensity modulator for the RF signal, and the chirped fiber Bragg grating (which will be developed or investigated at a later time by Harris). In this section, the details regarding all of the parts listed above will be discussed, including their use in the project and why the parts are necessary and relevant to the project.

To start off, the supplied parts that currently do not have much information regarding the specific part will be discussed. As mentioned previously, Harris will be responsible for providing the RF components and sources. One of these components is a vector network analyzer. The vector network analyzer will be used to analyze the optical delay after it has passed through the entire system. In addition to this, another piece of technology that Harris will be providing to the project is an RF signal generator. This is an incredibly crucial part to this project, as it is responsible for generating the actual signal that will be modulated in order to be frequency shifted. Another component that will be supplied for the project by Harris is an intensity modulator for the incoming RF signal. For more details on how the intensity modulator works, please see section 6.5. Although these RF components are not being designed or purchased using the provided funding, they are an integral part to the final system. The design that this project aims to complete is only a part of the entire system that is used for RF communication. Again, though there is not very much information provided at this point on the RF components, it is necessary to mention the components as well as their purpose for this project.

Another crucial piece that will need to be used after the finished design of this product is the chirped fiber Bragg grating. This is a part that will need to be manufactured by Harris after the final design of this project. This is due to the fact that the fabrication of the chirped fiber Bragg grating will depend upon the frequency shift induced by the ramped phase modulator. The chirped fiber Bragg grating is where the actual optical delay is generated. The different frequencies that are generated from the serrodyne approach are routed into the chirped fiber Bragg grating, and specific frequencies are reflected back through Fresnel reflection at different distances [2]. These reflections at different distances along the chirped fiber Bragg grating account for the delay steps that are necessary as per the requirement specifications of this project [2]. For more detail on how the chirped fiber Bragg grating functions, see section 3.1.10.

Now, the photodetector that will be supplied will be discussed. The photodetector that Harris will be providing for use in the optical delay generator is an InGaAs photodiode developed by Discovery Semiconductors. The specific photodiode model from Discovery Semiconductors that will be used is the DSC100S [33]. This is a high-speed photodiode that is used for RF applications [33]. This will be the receiver used to collect the RF signal. This photodiode is hermetically sealed, and are said to have low harmonic distortion according to Discovery Semiconductors website [33]. They are designed for applications that involve systems with high optical power that operate within a bandwidth of 6 GHz [33]. See figure 39 for a graph of the frequency response of the DSC-100S photodiode, which will be used for this project. The photodetector is an important part of our project as it is needed to convert the optical signal to an electrical signal. The frequency response of the photodiode shown in figure 39 is used to detect RF signals from around 0 to 6 GHz [34].

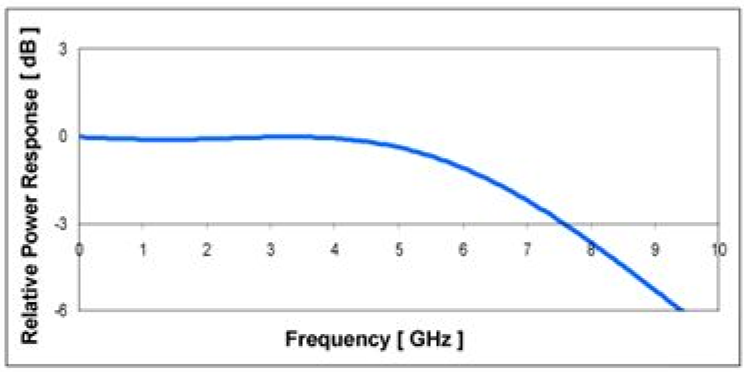


Figure 39: Frequency Response of the DSC-100S Photodiode
Reprinted with permission from Discovery Semiconductors

In conclusion, there a several very integral parts of the final system that will not be designed by the team that was tasked with the development of this senior design project. The different RF components, the chirped fiber Bragg grating, and the photodiode have all been addressed in this section. These are the parts of the project that are supplied, and they will not be designed. Our sponsor, Harris Corporation, will be providing these parts. This project is dedicated to enabling the possibility of creating an optical delay generator by frequency shifting an inputted signal. The other parts that are supplied by Harris will be integral to creating an optical delay. The chirped fiber Bragg grating is especially essential to generating an optical delay as it reflects the frequency shifted incoming light signal at different points along the fiber Bragg grating therefore creating a stepped optical delay. Overall, this project mainly focuses on the electro-optical integration that shifts the frequency of the light so as to create an optical delay. For more information on the electro-optical processes and integration present in this project, please refer to section 6.5.

6.3 Optical Subsystem

In this section, the details of the optical subsystem are discussed. This includes the discussion of any and all optical components used in the system. The approach considered primarily in this section is the serrodyne approach discussed in previous sections -- namely the approach comparison section in which the serrodyne approach was shown to be the superior method . This is because, due to details described in the previous sections of this report, the serrodyne approach offers a relatively cost effective solution with a minimization of problematic variables such as free space optical alignment and motor speed, acceleration and precision. As such, the details of the optical subsystem regarding the serrodyne approach are discussed here.

As described in the section on serrodyne frequency shifting, serrodyne frequency shifting is the process of changing the frequency of an incoming optical signal by means of phase modulation. In theory, the optical signal enters the phase modulator -- which alters the phase of the signal by the varying of the modulator's refractive index -- and is shifted by a certain frequency. The frequency shift imposed by the phase modulator onto the optical signal is dependent upon the slope of the phase modulation used. This means that the inverse of the amount of time taken to bias the modulator from negative to positive Vpi (or in the reverse order) is the frequency shift applied to the optical signal. The initial discussions regarding serrodyne frequency shifting mention that a large frequency shift would be preferable, as the required precision of the voltage ramp used to bias the phase modulator used is inversely proportional to the frequency shift applied. Specifically, a theoretical frequency shift of 1 GHz was discussed.

However, the system is also limited by the voltage ramp in terms of the voltage ramp's ability to bias the modulator from negative to positive Vpi in a very short amount of time. While the voltage ramp component is discussed more thoroughly in the section regarding the electrical subsystem of the final design, the maximum frequency shift applied by the serrodyne phase modulator is approximately 100 MHz. This value was given by the sponsor as requirement specification for this particular method of delaying the optical signal.

In addition, the initial design section describes implementing intensity modulators in order to suppress the intensity of unwanted serrodyne spurs. These spurs are the result of a finite reset time when biasing the phase modulator. This design addition essentially removes the finite reset time by allowing for two branches of the optical circuit, one of which is delayed by the reset time described, to continue the progression of the signal in an interleaved manner. This is accomplished through the use of intensity modulators, where the two intensity modulators operate under on and off conditions at separate times.

However, the use of two intensity modulators adds a high degree of cost to the final system. After discussing with the sponsor for the project, this addition was originally chosen to be a stretch goal for the final system. That being said, after further deliberation with the sponsors and advisors for this project, it was determined that the implementation of these intensity modulators provides the project with a necessary degree of optics and photonics design. With that in mind, the initial block diagram implementing the use of the two intensity modulators in order to decrease the intensity and therefore the effect of serrodyne spurs is shown below. Note that figure 40 shown below only considers the serrodyne frequency shifting component of the system.

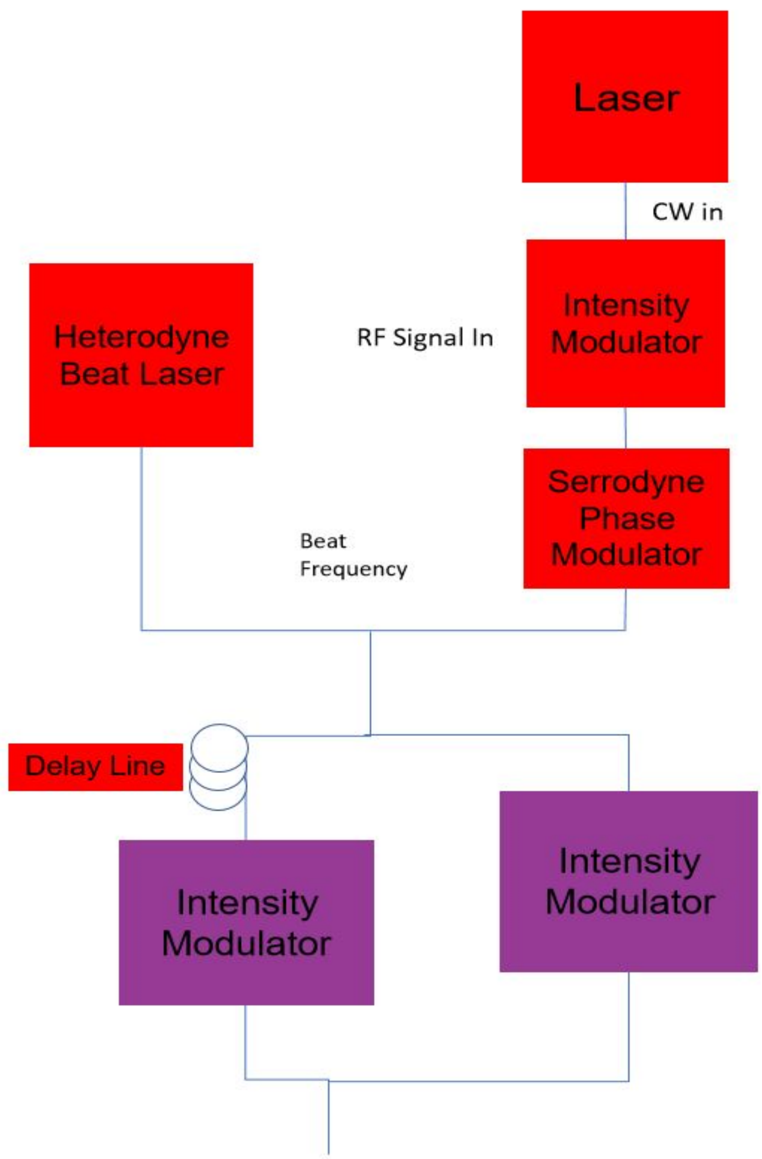


Figure 40: Serrodyne Component of Initial Block Diagram

As discussed in greater detail in the subsection on the electrical subsystem of this design, the voltage ramp and voltage control are used to bias the phase modulator by generating a sawtooth output function. For the maximum positive frequency shift -- this value would be approximately 100 MHz -- the sawtooth function would need to range from negative to positive Vpi of the phase modulator. The value of Vpi for the phase modulator has been determined to be approximately 3 Volts. This voltage ramp would need to occur over a time period of 10 nanoseconds.

It is important to note that this is a significantly more reasonable voltage ramp time period, as the time required is an order of magnitude slower. This is helpful in terms of voltage ramp time. However, this does cause the need for precise voltage amplitudes as these values are closer to each other. Once again, for a delay range of 1.5 nanoseconds, the total number of slopes has been calculated to be approximately 187 slopes.

As the voltage ramp and voltage control are used to supply the sawtooth function, the phase modulator imparts a frequency shift that corresponds to the slope of the biasing sawtooth function that is generated by the electrical subsystem. However, as mentioned in the theoretical section on serrodyne phase shifting, due to the realistic nature of the electrical components that comprise the voltage ramp and voltage control there is a finite reset time for the biasing sawtooth function. As shown in figure 40 above, two intensity modulators can be implemented in order to manage the negative effects of this reset time, which manifests itself in unwanted serrodyne spurs in the output signal. As shown in the figure, a delay line is implemented in one of the intensity modulator branches. This delay line causes an optical delay in that branch equal to the reset time of the voltage ramp. This allows the two intensity modulators to operate out of phase with each other, allowing for a reduction in serrodyne spurs. As shown in figure 40 above, the block diagram depicts the use of a heterodyne beat laser. The frequency of this beat laser would need to be an arbitrary, but relatively low, frequency difference from the continuous wave laser. This allows for the two frequencies to beat at the location where they are joined together by an optical splitter. The point of this is to be able to detect the frequency shift imparted by the serrodyne phase shifter. For a typical telecommunications wavelength of 1550 nanometers, the corresponding frequency is over 193 THz. Therefore, a shift of plus or minus 100 MHz may not be easy to detect. With the use of a heterodyne beat laser, the detected frequency is the frequency difference between the beat laser and the continuous wave laser. If the two lasers were to be separated by a frequency of 5 GHz, this change would be much easier to observe.

That being noted, the use of a heterodyne beat laser would not necessarily need to be used in the final implementation of the system. With the correct dispersive media -- such as the Chirped Fiber Bragg Grating discussed in previous sections -- in line with the system after the serrodyning portion of the system, a lower beat frequency would not need to be generated using a heterodyne beat laser. This removes a slight degree of complexity when considering the final use of the system, while also decreasing the required cost of the system. However, for breadboard testing and for demonstration of the shifted frequencies, the possible use of a Heterodyne beat laser was discussed. As discussed previously in the paragraph above, the initial block diagrams incorporate the use of a seperate laser in order to observe the serrodyne frequency shift more easily. However, after further deliberation and discussion, it has been found that this is entirely unnecessary. Instead, an optical splitter -- the functionality of which is discussed in previous sections of this report -- can be used to split the signal before the phase modulator used to shift the signal by serrodyne phase shifting. These two branches are then recombined after the phase modulator, allowing for the detection of the beat frequency, and therefore the frequency difference, between the original optical signal and the frequency shifted optical signal. A block diagram depicting the optical subsystem discussed is shown in figure 41 below.

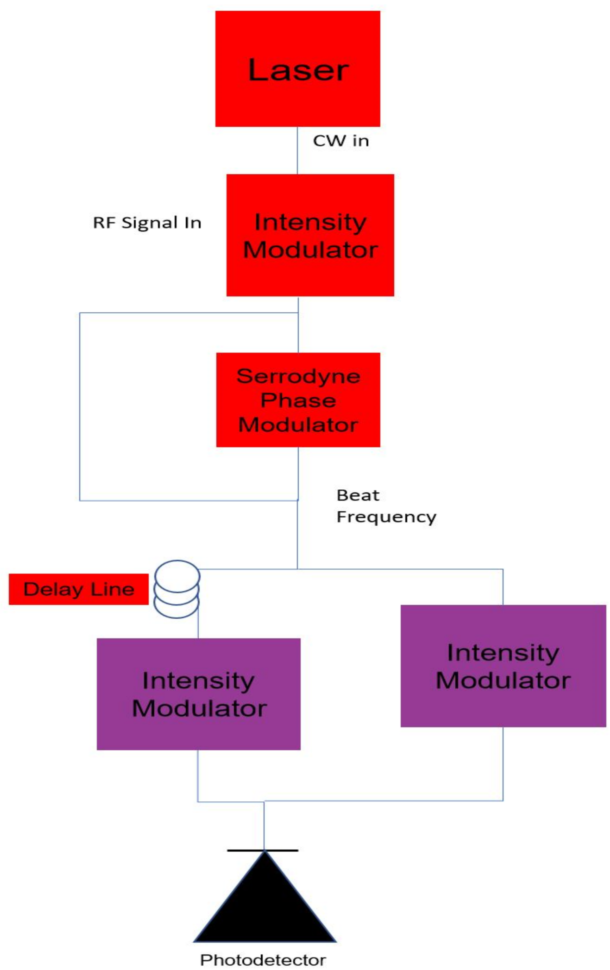


Figure 41: Optical Subsystem

As can be seen above, figure 41 depicts the optical subsystem of the overall frequency shifting system. This means that all electrical components were left out. However, it is important to note that each of the modulators shown in the figure require a voltage bias of some sort. Specifically, the phase modulator is biased with a voltage ramp slope corresponding to the correct frequency shift, and the intensity modulators are each biased with an appropriate square separated by a pi phase shift. These voltage ramps and their generation and control are discussed in greater detail in the electrical subsystem section of this report.

Another important component regarding the optical subsystem of this project is the dispersive media used in the final system. The dispersive media element is what will be used to delay the incoming optical signal based on the frequency shift imparted by the serrodyne phase shifting portion of the system. As discussed in previous sections, it is likely that the dispersive media element used would likely be a Chirped Fiber Bragg Grating.

Assuming that a Chirped Fiber Bragg Grating refractive index of 1.5 is used, the necessary optical path length of the Chirped Fiber Bragg Grating to allow for a 1.5 nanosecond delay for the highest frequency signal sent in by the serrodyne phase shifting portion of the system would be approximately 33.75 centimeters. As such, this implies that the linear grating period would need to allow the 100 MHz blue shifted frequency to travel along the full length of the Chirped Fiber Bragg Grating and then be reflected. This causes a round trip delay of approximately 1.5 nanoseconds when compared to the uninterrupted propagation time of the same signal. This is the target maximum delay of the system. The 100 MHz red shifted optical signal sent in by the serrodyne phase shifting portion of the system would need to be reflected at the entrance of the Chirped Fiber Bragg Grating. This would allow for the 1.5 nanosecond delay between the most positively frequency shifted signal and the most negatively frequency shifted signal, as the -100 MHz shifted signal essentially propagates through the system uninterrupted. In order for the target maximum delay of 1.5 nanoseconds to be met along with the other requirement specifications regarding delay range and delay step duration, each frequency shift would need to be separated by approximately 1.0695 MHz.

However, the use of a Chirped Fiber Bragg Grating or some other dispersive media presents some debilitating consequences. One negative aspect that this brings to the system is a certain degree of complexity. The details regarding the specifics of the dispersive media would likely be enough to allow the design and fabrication of this dispersive media to be the goals of a separate, individual senior design project. In addition, the cost of fabricating this dispersive media would require a significantly large budget. A quote received from a Chirped Fiber

Bragg Grating manufacturer gave an approximate cost of $5000 to $6000, with an added fee od $5000 for NRE design.
For these reasons, the sponsors have determined that the design, fabrication and implementation of a dispersive media would be beyond the scope of this project. We have agreed that demonstrating the appropriate frequency shifts as discussed previously in this section would be sufficient results for this project. However, in order to include sufficient optics and photonics design for the project, we have agreed with the sponsor to pursue the use of interleaving intensity modulators to decrease the intensity of serrodyne spurs.

Another key element of the optical subsystem is the delay line, which is used to separate the signals entering the two different intensity modulators by a specified amount of time. The purpose of this delay line is so that the two intensity modulators can operate as interferometric switches in an interleaving periodic manner. That is to say, when one intensity modulator is biased such that it is in the "on" position, the other intensity modulator is biased in the "off" position. As such, with an appropriate delay length implemented in one of the intensity modulator arms, the signal associated with the fall time (or rise time for negative frequency shifts) of the voltage ramp used to bias the phase modulator is stopped from passing through the system. This is because while one of the intensity modulators is set to the "off" configuration and blocks the signal associated with the fall time (or rise time for negative frequency shifts), the other intensity modulator is set to the "on" configuration. However, because this second intensity modulator is delayed, the signal passing through this intensity modulator is associated with the desired slope of the voltage ramp, and therefore the desired frequency shift.

Calculating the appropriate optical path length resulting with the appropriate time delay for the optical subsystem is critical. If this delay is not correct, the signal associated with the fall time (or rise time for negative frequency shifts) may be allowed to pass through at variable moments. As such, it is important that the delay length discussed allows for a seemingly endless serrodyne phase modulation. For this to occur, the delay length needs to be equal to the fall time fall time (or rise time for negative frequency shifts) of the voltage ramp used to bias the phase modulator.

The length of this delay in terms of time has been determined to be 10 nanoseconds, corresponding to half of the period of the triangle wave used to bias the phase modulator. The corresponding half period of the square waves used to bias the intensity modulators has been determined to be 10 nanoseconds as well. The only difference between the two waves being the pi phase difference between them. This allows for the undelayed intensity modulator branch to operate in the "on" configuration for 10 nanoseconds and in the "off" configuration for 10 nanoseconds as well. Meanwhile, the delayed intensity modulator branch is then allowed to operate in the "off" configuration for

10 nanoseconds while the undelayed intensity modulator branch operates in the “on” configuration, and in the “on” configuration while the undelayed intensity modulator branch operates in the “off” configuration. This cycle is then repeated after 20 nanoseconds. This would mean that a 10 nanosecond delay is required in the second intensity modulator branch. The refractive index of the single mode fiber used is approximately 1.45, which means that the length of the delay line will be 2.069 m to allow for a 10 nanosecond delay length in the second intensity modulator branch.

This process allows for the system to essentially disregard the unwanted fall time (or rise time for negative frequency shifts) associated with serrodyne phase shifting. As discussed in the section detailing the theory of serrodyne phase shifting, the reset time of the voltage ramp causes serrodyne spurs. These serrodyne spurs make it difficult to discern the desired signal. This method helps to reduce the intensity, and therefore the effect, of these serrodyne spurs.

Another important aspect of the optical subsystem is the modulation of the radio frequency signal onto the optical carrier. This is accomplished through the use of the first in line intensity modulator shown in figure 41 above. The signal will be created by a radio frequency signal generator provided by Harris Corporation. The frequency of this signal is essentially irrelevant for this project, as the actual radio frequency signals used are unknown for proprietary reasons. As long as the frequency chosen is within the radio frequency domain, it can be shown that similar modulated frequencies will experience the same phenomena as the signal propagates through the system. It is also important to note that this first intensity modulator will be provided by Harris.

6.4 Opto-Electrical Integration

In this section, the details regarding the electro-optical integration will be discussed. Electro-optical integration is what the project mainly revolves around. Since the serrodyne endless phase modulation approach was chosen for this project, the electro-optical integration is a crucial and essential part to the development of the optical delay generator. The information regarding the use of a voltage ramp for the phase modulator, as well as the use of input voltages to intensity modulators present in the design of this project will be explained and detailed in this section. To begin, the details of how the voltage ramp for the phase modulator mentioned above in section 6.1 will affect the incoming optical signal will be explained. After this, the relationship between the input voltage signal to the two intensity modulators will be discussed and detailed.

The voltage ramp signal that will be configured as an input to the phase modulator is a very important and crucial piece as to how an optical delay will be achieved. The reason for this is that the method of phase modulation that is used in this project is what causes a frequency shift in the optical signal, which—after the signal passes through the configuration of intensity modulators that remove the spurs—causes the signal to be reflected with linear spaced delays between each signal, therefore achieving optical delay. It is very important to first understand what a phase modulator is and how different electrical signals affect the phase modulation before moving forward. This will be one of the main focal points of all design put into this project, so it is necessary to further explore the details of phase modulation and how it is related to the electro-optical integration. Therefore, the next topic explored will be the phase modulator and its function.

The phase modulator is a type of electro-optic modulator that controls the optical phase of a light signal [34]. Phase modulators usually include have a Pockels cell (discussed briefly in section 3.1.13) and a polarizer to align the polarization of the beam of light with one of the optical axes of the nonlinear crystal of the Pockels cell [34]. As discussed in the aforementioned section, a Pockels cell, simply put, shifts the phase of the incoming light beam by using an applied voltage. This occurs by changing the refractive index of the nonlinear crystal of the Pockels cell by applying a voltage and thereby an electric field [34]. This change in refractive index is proportional to how strong the electric field is [34]. By changing the refractive index, the phase of the incoming light beam will be delayed [34]. For each type of Pockels cell, there is a certain voltage that causes a phase change of π [35]. For the purposes of this project, the frequency of the incident light beam must be shifted. This is done through phase modulation by different voltage slopes since the frequency of a light signal is defined as the derivative of the phase [13]. Now that the details of the logistics of the phase modulator have been explained, the details of how the different voltage ramps affect the frequency of the signal will be discussed.

As mentioned previously, the Pockels cell has a specific voltage (called Vpi) that corresponds to a π phase shift [35]. Therefore, there must be a certain amount of voltage ramps that are generated between negative Vpi and positive Vpi that provide the proper number of linear frequency shifts that are needed to produce the optical delay. As mentioned in section 6.1.1.1, there are one hundred and eighty seven steps corresponding to one hundred and eighty seven slopes for a delay range of 1.5 nanoseconds per the requirement specifications of the project. This is because each voltage slope corresponds to a different frequency shift which in turn corresponds to a different delay time. Per the discussion in the aforementioned section, the slope change is altered by the starting and ending voltage, with a constant time range for the slope. The one hundred and eighty seven steps will include ninety three positive slopes (with the max positive slope going from negative Vpi to positive Vpi), a slope of zero, and ninety three negative slopes (with the max negative slope going from positive Vpi to negative Vpi). For this project, the phase modulator considered is an EOSPACE Low Vpi Modulator [36]. This modulator has an ultra-low loss max value of Vpi of five volts at one Gigahertz [36]. Therefore, the slopes would be contained between the values of negative five and positive five volts. The change in applied voltage would then be approximately 26.74 milliVolts. Now that the electrical properties that affect the phase modulation have been discussed, the consequential optical affects and integration will be discussed.

The optical phenomenon that happens inside of a Pockels cell is fairly complex, so this will not be detailed in this paper. However, the optical consequence of applying a sloped voltage source to the phase modulator will be explored and discussed. As discussed a few paragraphs earlier, the phase of the light beam that travels through the Pockels cell is changed with an applied voltage. The frequency is then changed by applying a sloped voltage to the Pockels cell (part of the phase modulator). This frequency shift corresponds to different delay times by the use of a chirped fiber Bragg grating. This chirped fiber Bragg grating will reflect back certain frequencies at certain distances along the grating. For this project, the chirped fiber Bragg grating will not be fabricated. The frequency shift is the only thing that will be developed and integrated. However, though it will not be developed in this project, the chirped fiber Bragg grating is a crucial piece of the entire system. A discussion of what a chirped fiber Bragg grating is and how it works is found in section 3.1.10 in this paper. It is through the sloped phase modulation that a frequency shift is created, and it is through the chirped fiber Bragg grating correctly reflecting (by Fresnel reflection) the different frequency values that a stepped delay is achieved. A block diagram of how the electrical and optical components fit together in the entire system is shown below in figure 42. As discussed previously, the sloped phase modulation is one of the main focuses of this project. Now that this has been discussed and detailed, the electro-optical integration involving the intensity modulators will be explored.

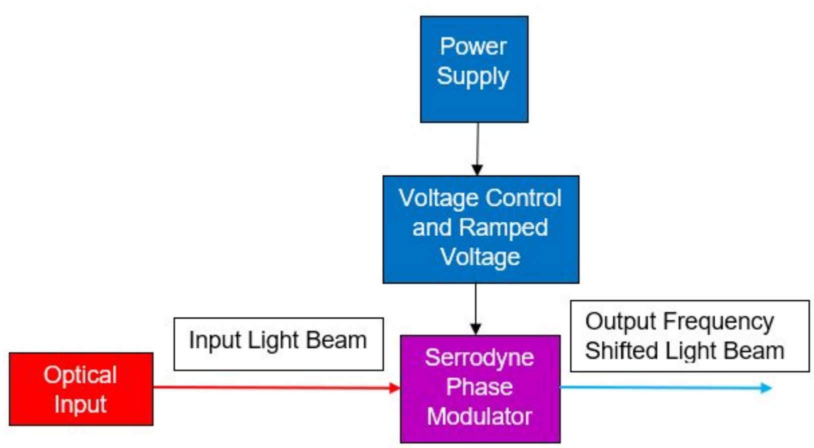


Figure 42: Simplified Block Diagram of the Electro-Optical Integration for the Phase Modulator.

In figure 42 above, the block labeled “Optical Input” includes a continuous wave laser and a vector network analyzer (for the RF signal) connected to an intensity modulator. The blue blocks represent the electrical components, the red block represents the optical components, and the purple box represents where the electro-optical integration takes place. The voltage control and ramp (powered by a power supply) are input to the phase modulator, and the initial light beam is propagated through the phase modulator. It is necessary to mention that the fiber optic cables that the input light beam and output frequency shifted light beam reside in are not shown in this diagram, but they do exist in the design. The change of the light beam from red to blue is to signify a frequency shift but is not representative of the actual frequency shift. The actual frequency shift is much smaller than the frequency shift between red and blue light. Now that the electro-optical integration of the phase modulator has been sufficiently discussed, the details regarding the electro-optical integration of the two intensity modulators as well as the delay introduced from the optical fiber will be explained. Though the most crucial part of the electro-optical integration is with the ramped phase modulation that introduces a frequency shift, the use of two intensity modulators in the design is also very important. The reason that two intensity modulators are being used is because of the fact that the ramped phase modulator will have a finite fall time [13]. This produces unwanted frequency spurs in the output [13]. The details of this are explained in greater depth in section 3.1.14. Because of this, the direction decided on for this project involves splitting the frequency shifted signal into two different paths, and then delaying one of the paths by a certain amount, and then using an intensity modulator for each path to eliminate the harmonic spurs. In the next paragraph, the information regarding the introduction of an optical delay to one of the arms and its relation to the timing of the electrically driven phase modulation slope will be discussed.

The relationship between the introduced optical delay line and the voltage ramp for the phase modulator is crucial to the design of this project using the serrodyne continuous phase shifting technique [13]. The optical delay line introduced to one of the lines split from the phase modulator (called Arm B) is introduced in order for there to be a quasi-continuous phase ramp to the signal [13]. The phase modulated signal gets split into Arm A and Arm B, and it is first transmitted through Arm A [13]. Once the phase modulation ramp reaches the top of the ramp, it must fall back down and start again. During this time, the signal going through Arm B is delayed so that it is only starting its phase modulation ramp [13]. Therefore, the added delay—in conjunction with the two intensity modulators for Arm A and Arm B (discussed next)—creates the quasi-continuous phase shift [13]. The added optical delay is dependent on the size of the period of the voltage ramp that is input to the phase modulator. Now that the connection between the optical delay and the electrical input voltage ramp has been discussed, the electro-optical relationship and logistics as well as use of intensity modulators and their connection to the electro-optical integration will be investigated.

Before the details of how intensity modulators are used in the project, the electro-optical relationship present in an intensity modulator will be briefly explained. Intensity modulators (also called amplitude modulators) alter the amplitude of the input light beam [34]. This is possible due to the use of a Pockels cell and polarizers [34]. Figure 43 below shows a typical configuration of an amplitude modulator. The incoming light gets polarized linearly, and then passed through a Pockels cell set at a specific voltage, and then passed again through the other linear polarizer (at an angle of ninety degrees to the first polarizer) to alter the amplitude of the optical signal [34]. The Pockels cell is used to alter the polarization state of the light after it passes through the first polarizer. Depending on the voltage applied to the Pockels cell, an amplitude value anywhere from the amplitude value of the input to essentially zero amplitude can be obtained [34]. For the purposes of this project, the amplitude modulator must be used as an optical switch. Therefore, the voltages applied must be switched to correspond from full transmission to essentially zero transmission. The details of how this is done is discussed in the following paragraph.

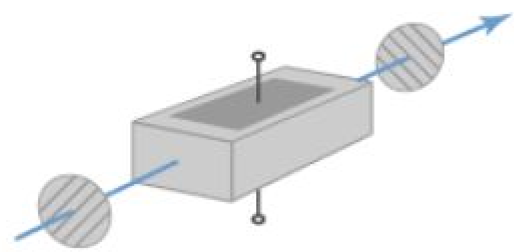


Figure 43: A Typical Configuration of an Amplitude Modulator.
Figure reprinted with permission from author, Dr. Paschotta of RP Photonics, and publisher of physical encyclopedia, Wiley-VCH.

The amplitude modulator shown in figure 43 above consists of a linear polarizer, a pockels cell, and then another linear polarizer that is at an angle of ninety degrees to the first polarizer [34]. From the information in the previous paragraph, there are two separate signals after having one of them delayed by a certain amount. In order to have a fully quasi-continuous phase modulation ramp, separate intensity modulators for both Arm A and Arm B must be used [13]. The purpose of the intensity modulators is to act as optical switches for Arm A and Arm B [13]. First, the intensity modulator in Arm A is set to be “on,” meaning it allows the frequency shifted signal to pass through Arm A, during the entire duration of the phase modulation ramp [13]. Once the ramp finishes, the intensity modulator in Arm A will be set to minimize the signal completely so as to provide no output from Arm A and therefore avoid the frequency domain spur from the fall time of the phase modulation ramp [13]. At the same time, the intensity modulator in Arm B (previously set to minimize the signal through it) is set to allow its signal (which is just at the beginning of the phase modulation ramp) through during the entire duration of the frequency ramp [13]. This allows for a quasi-continuous phase modulation ramp, and therefore a continuous frequency shift [13]. For this to take place, the intensity modulator for Arm A must be π out of phase with the intensity modulator in Arm B [13]. In other words, the input voltage signals to the separate intensity modulators are square waves that are π out of phase with each other. This is how the quasi-continuous phase modulation exists, and it would not be possible without it. According to the cited paper, these separate optical signals are received by a photodetector separately and then combined in the electrical domain so as to avoid the unwanted effects of optical interference [13]. See figure 44 below for a simplified block diagram of the electro-optical integration of the delay line and intensity modulators. As in figure 42, the red boxes represent optical components/processes, the blue boxes represent electrical components, and the purple boxes represent where the electro-optical integration takes place. Also as in figure 42, each arrow connecting the box is a fiber optic cable containing the signal. After the signal is frequency shifted, the signal is split into two paths (Arm A and Arm B), and one of the signals is delayed [13]. The intensity modulator for Arm A is on when the intensity modulator for Arm B is off, and vice versa [13]. This is due to the fact that the square wave voltage sources are out of phase with each other. Finally, the properties of electro-optical integration that is pertinent to this project, including the ramped phase modulation, delay line, and intensity modulators, has been discussed and detailed.

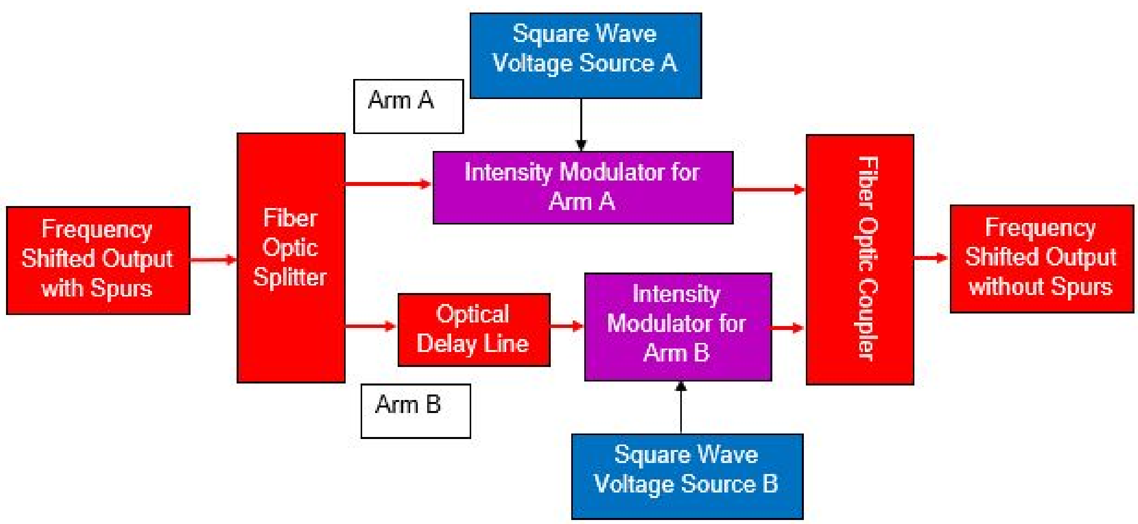


Figure 44: A Block Diagram of Electro-Optical Integration after Frequency Shift

In conclusion, the electro-optical integration is a very key and crucial element to this project. The fact that the members of this project consist of only electrical and optical engineering students explains why the project needs to have this element be a part of it. In this section, all the electro-optical integrations pertinent to this project were discussed. This includes the method of inputting a ramped voltage source to the phase modulator in order to create a frequency shift in the light signal, as well as using a delay line and two intensity modulators to increase reduce the frequency spurs and increase the signal quality. Also, the details regarding the logistics of phase modulators and intensity modulators was briefly discussed. This includes the function of the modulators, as well as what parts are used. The use of Pockels cell in each of the modulators was also detailed and discussed. Although there are other areas of electro-optical integration relevant to this project that are not mentioned in this section, all of the information pertinent to the group members' contributions was discussed. This is due to the fact that Harris is providing some of the other key electro-optical components. Since these components are supplied and not designed, they are not discussed in detail in this section. For more info on the supplied parts to this project and the suppliers of them, refer to section 6.2 Suppliers and Supplied Components. Figure 45 below shows the final block diagram for the system, including both electrical and optical components.

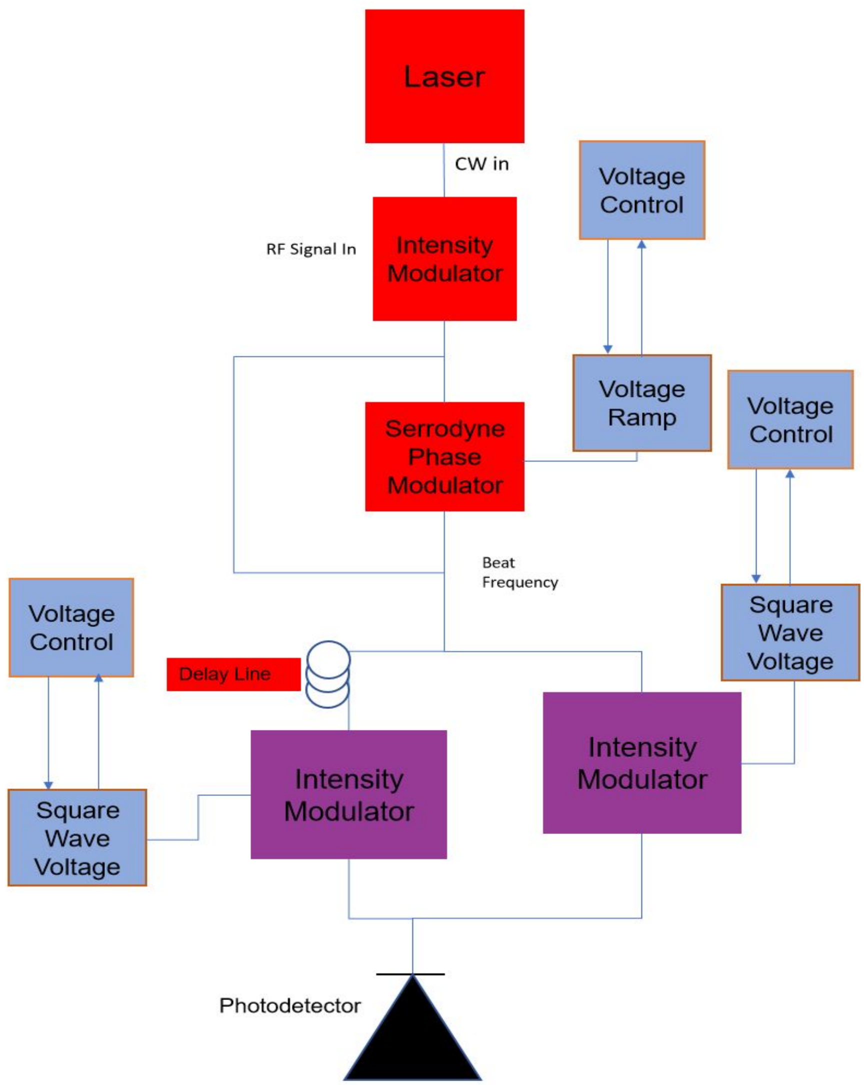


Figure 45: Final System Block Diagram as of Senior Design 1

6.5 User's Manual

To start the system, these are the following steps that should be followed to ensure safe and accurate use/data. First, start by powering on the receiver circuit detector. This will involve a spectrometer and an oscilloscope (for showcase purposes; in the actual product this receiver circuit will receive the delayed signals and interface to another part of the system that this project gets integrated into). The oscilloscope will be plugged into a standard wall outlet for power. The spectrometer will be powered via USB-to-laptop connection. Do a test to make sure the spectrometer is receiving data. This could involve waving the hand in front of the receiver to interfere with ambient lighting. Set the oscilloscope to detect signals with nanosecond precision. Once the receivers are properly initialized, then the next step is to apply power to the laser. The laser will be plugged into a wall outlet as well, but note that the actual design will have control and power from the overall system. Next turn on the RF modulator to control the modulation of the laser to output a desired signal. From here the microcontroller and oscillator circuits will be turned on, starting with the oscillator. A switch will be designated for each circuit that, when flipped, will supply power. The microcontroller will be set to run its code upon activation, so it is important to have the the sawtooth and laser already powered up. Wait a moment for the oscillator to arrive at steady state. At this point, the receiver should detect the original modulated signal as well as a single frequency shift. Once the microcontroller is powered up, the sawtooth bias will begin the change in its amplitude, and the frequency shift will continue through multiple steps. From here, the system should be fully functioning. The output should show multiple signals with different frequencies of the original modulated RF signal. These signals can then be sent into a dispersive media to add the desired delay between each frequency signal. Upon completion of its use, power down the system. It is recommended that the oscillator circuits be powered off first, then the microcontroller, followed by RF modulator, laser, and receivers.

7.0 Project Prototype Construction and Coding

In this section, the construction and coding related to the prototype of the project is discussed. First, the bill of materials of the project and a brief description of the function of each item within the project will be detailed. Then, the plastic circuit board vendor and assembly related to the prototype will be discussed. Finally, the final coding plan for the project will be detailed.

7.1 Parts Acquisition and Bill of Materials

In this section, the bill of materials that are needed for this project as well as a few short descriptions of each part will be detailed. Seen below, table 5 lists each part needed, the amount of the part needed, and the cost to acquire the part can be found. The purpose that each of the parts listed will have in the project will be explained in this section.

Item	Quantity	Part Number	Cost
Thorlabs low Vpi Phase Modulator	1	LN53S-FC	$2k
Thorlabs Intensity Modulators	2	LN81S-FC	$4.4k
2X2 Optical Coupler (FC/APC)	3	10202A-50-APC	$578.34
PM Fiber Optic Connector (FC/APC)	1	P3-1550PM-FC-2	$192.78
FC/PC to FC/APC Patch Cables	3	P5-SMF28E-FC-1	$153
1550 nm SMF (20 m) (FC/PC)	2	P1-SMF28E-FC-1	$81.10
MSP430	1	MSP-EXP430G2	$10.37
MUX/DEMUX	2	MUX507IDWR, DG333ADW-T1-E3	$8.69
Comparator	6	LT1715CMS	$7.05
Operational Amplifier	8	AD8045ACP	$34.56
Other Electrical Components for Voltage Ramp (resistors, capacitors, inductors, DC voltage sources)			$73.64
Total (Rounded up slightly to allow for any extra unplanned costs)			~$9k

Table 5: A Table Detailing for Each Part the Name, Quantity, Part Number, and Price for the Given Quantity.

First, the optical components will be detailed. The first part that will be discussed is a low Vpi Phase Modulator that is developed and manufactured by Eospace. This part changes the phase of the incoming light when a voltage is applied to it. For the purpose of this project, it will be combined with a ramped voltage source so as to change the frequency of the incoming light beam. Please refer to section 6.5 for more information regarding the use of phase modulators. This phase modulator was chosen because of the low Vpi characteristic. The Vpi of this modulator is 3 Volts, as compared to 5 Volts of typical phase modulators. Other optical components include intensity modulators. The intensity modulators that will be used with this project are manufactured by Thorlabs. These intensity modulators will be responsible for turning on and off Arm A and Arm B as mentioned in preceding sections (see sections 3.1.14 and 6.5 for more details regarding the use of these intensity modulators. These components were chosen in part due to the favorable cost in comparison with other similar intensity modulators -- which can cost up to $5000 -- and in part because they were recommended by Harris. The 1x2 and 2x2 optical splitters/couplers that this project will utilize are manufactured by Thorlabs. The 1x2 splitter splits the single frequency input source into two signals. Once one of the signals is frequency shifted, the 2x2 then takes these two signals, combines them, and then splits them again to be put through the two alternating intensity modulators. Of course, when working with fiber optic cables, connectors for them are needed. This project will require a total of six connectors. In order to create the delay for Arm B (see section 6.5), a certain amount of fiber optic cable must be connected to it to create the delay [13]. This explains the need for the 1550 nm single-mode fiber. Some of the electrical components for the design of the voltage ramp are still being researched, and this is still to be determined. For the project, there will also be a need for two digital potentiometers. These fiber optic components were chosen to be purchased from Thorlabs due to the favorable prices and recommendations from Harris. The total for all of these parts adds up to (rounding up) about $9,000. This is only a current estimate for all the parts this project will need, and it is subject to change. In conclusion, this section covered all of the materials projected to be needed in the development of this project and gave brief descriptions of their uses within the project. As stated early, this is not the final bill of materials, and it is subject to change.

7.2 PCB Vendor and Assembly

One of the strictest requirements for this project is the timing constraints involved with delaying each signal. An issue that was brought to our attention is that long wires can add to system function times as current travels through the wire. Although this time is very small, it could present some error in our final system where timing needs to be kept miniscule. A workaround to this problem is the use of printed circuit boards (PCB) for most, if not all, of our electrical components and subsystems. PCB designs will limit the length of conductive interconnects and will help ensure accurate results with minimum error. This will require extensive testing of both the breadboard predesign and the final PCB circuit to see that desired outputs can be achieved properly.

Printed circuit boards are used in nearly all electronic devices today. They are relatively cheap and easy to mass produce. PCBs use multiple layers of nonconducting substrates that are each etched with conductive layers, such as copper, to connect the circuit to each component. These layers can be stacked and laminated together to form a three-dimensional circuit that is capable of minimizing space while incorporating a higher density of components. These components are typically soldered onto pins or exposed conductive layers on the PCB. Each PCB can be simple with only a single layer, dual-layered with components on both the top and bottom of the board, or multi-layered with components and connections on up to forty layers. Manufacturers will offer to solder the components onto the board or we can solder on the components ourselves. The problem is many of these connections require precise soldering and follow soldering regulations, so it would be ideal to have the manufacturer solder our components for us. However, manufacturers will also typically charge a fee per component soldered. This can range anywhere from a few cents to a few dollars per component soldered onto the PCB. This will be an important consideration in choosing a PCB vendor and what the final cost will be. Alternatives to PCB include wire wraps and point-to-point construction, but these are rarely used anymore. This often involved wrapping the wire connection directly onto the pin to secure it in place, or screwing/nailing the wire into place. For obvious reasons, this is not a suitable method for this project where connections need to be maintained in short distances and with little room for error (such as a loose wire wrap that could cause an open circuit or even short circuits to other parts of the system).

When choosing a vendor, our two main concerns are cost to buy the PCB and time to manufacture and receive the PCB. This project is on a limited time schedule, but thankfully we have until the end of Fall to showcase our final design. This means if we can design our PCB by the summer, then we should have plenty of time to receive our PCB and conduct any necessary testing. This will also leave sufficient time to order any backups in case our initial PCB design does not work or experiences some error along the way. The added benefit to this time is that if we can manage to wait longer to receive our PCB, then the cost of the board will likely go down. Generally, PCB vendors will give discounted prices when bought in bulk, but we only need a single board for our purposes, maybe three maximum (for testing purposes and for the final design). This generally leads to more fees. The tradeoff is usually a cheaper PCB with longer manufacturing time, or a PCB that costs a little more, but you will receive it sooner. Table 6 below shows a price comparison for some common online PCB vendors. These prices are generated for a single-layered board with six square-inch dimensions.

Vendor	Quantity	Price	Days	Country
Bay Area Circuits	1	$47.52	10	USA
PCBWay	5	$53.25	49	China
Advanced Circuits	3	$113.48	10	USA
BasicPCB	3	$117.00	11	USA
PCBCART	5	$86.25	12	China
Eurocircuits	1	$80.22	9	Belgium

Table 6: PCB Vendor Price Comparison for a Generic 6-Square-Inch Board

It can be seen from these price comparisons that the price will typically be lower for overseas PCBs, but they will also take longer to arrive. However, it also seems that for a lower price we can buy more boards in the same shipping delivery. This could be useful if we need to run multiple tests at the same time, or if a board becomes lost or destroyed. This does lead us to question the quality of the PCB vendor, but this may not be an issue. The European PCB actually is cheaper than the USA counterpart and arrives in the same time period. This is something that needs to be looked into.

The actual design of the PCB will be done by our team in a readily available, free software. There are many options online to choose from when it comes to PCB design and simulation software. Some of these softwares include Protel, OrCAD, and Eagle. Although some paid softwares will offer additional perks, for our purposes this will not be necessary. We will likely be conducting our design in Eagle (easily applicable graphical layout editor) because it is free and is similar to other softwares our team has used in the past. Eagle allows us to place parts from large, extended libraries and create each connection as we want it on the board. Each pin must be named and labeled appropriately, which will tell the manufacturer where to solder on components and any other necessary connections. Eagle also offers a downloadable extension that runs circuit simulations. This can be used to test our connections and circuit performance before we send out our final designs to the vendor.

It is also important to note that some boards may have specific regulations to follow, such as board-end clearance. This means we may have to leave some space at the end of the board, and thus have less space for our components. Spacing concerns could require us to purchase larger boards, which in turn will eat into our budget even more. Another space concern is how the etched conductive layers can be spaced appropriately to avoid any electromagnetic interference between signals (EMI) or crosstalk. This interference could degrade signal quality and alter the performance of our components in the system. With traditional wiring, this problem can be somewhat eased with the use of twisted pairs and/or twisted triples, but since the board uses metal etchings instead of wiring, this is not a possibility. A similar concept can be used, however, when laying out the design of the conductive etches. The twisted pair works in wires by having two wires intertwined together, each carrying equal currents in opposite directions. From electromagnetics, we know that long wires will produce a magnetic field that circulates in rings around the wire. If the currents are equal and in opposite directions, these ring components will almost completely cancel out any produced magnetic fields. In the PCB design, we can not intertwine conductive etches, but we can place signals and their returns close together to cancel any magnetic fields. This will help to minimize error, but it should also be noted that our sponsor said EMI concerns are minimal for this project. In any case, we will take all precautions to minimize the chances of any errors developing in our final system.

7.3 Final Coding Plan

The code used will only be used to update the values of the potentiometers in order to vary the slope of the sawtooth waveforms for the serrodyning. The clock speed will need to be initialized to ensure everything occurs in the proper time periods. A loop will output bit sequencing to vary the potentiometer. The code will wait a certain period of time before updating for the slope remains constant for long enough for the proper measurements to be made. Refer to figure 46 below.

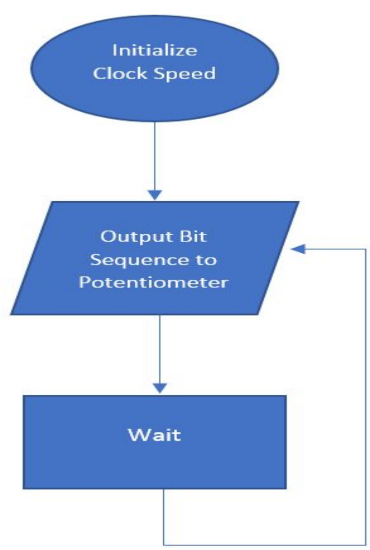


Figure 46: Code Flowchart

8.0 Initial Project Prototype Testing Plan

This section will describe the multiple testing and test environments required for this project. Hardware and software testing will both be discussed, and any data concerns from these environment ambient settings will be discussed. Analysis will also include testing of individual components and the procedures taken to do so.

8.1 Hardware Testing Environment

Section 8.1 specifically talks about each individual test environment for all design tests and troubleshoots. This will include our three main facilities: CREOL, Harris, and the UCF engineering lab. An additional section will also discuss temperature concerns for this project and these environments.

8.1.1 CREOL Testing

Most testing for this project will take place within the University of Central Florida's CREOL labs. CREOL, which stands for 'center for research and education in optics and lasers', is the college of optics and photonics at the university. The second floor senior design lab is equipped with standard optical tables and computers, so optical components can be securely fastened, and any software needed for this project can be run within the lab. The site is also secured and requires a key to enter. This lowers the likelihood of any equipment being stolen and the likelihood of anyone entering the lab and tampering with our test equipment. The site also has protective equipment that may be provided upon request for dealing with lasers and any laser related hazards. If for some reason this lab becomes ill-suited for our needs, there are other labs around CREOL that contain more space and even more equipment capabilities. These other labs are also equipped with laser safety warning signs that will light up when a laser is in use, and all other standard safety protocols that need to be followed when conducting these experiments. The site is maintained at room temperature, and ambient lighting consists of typical fluorescent lighting. These are important considerations when thinking about the nature of our experiment and how these external factors play a role in the performance of our system.

The building has after-hours access which gives us the ability to work on our project at all hours of the day. This is convenient when considering normal site may close down for the evening. If any late night testing is required, we will be able to do this. It is also likely that most of our equipment will be stored here when we are not using it. This is why the security of the site is ideal. Testing itself will involve stabilizing the optical equipment on the optical tables, aligning the laser with alignment tools within the lab, and using the onsite power meters to do most of our power readings. The labs also come equipped with their own spectrometers that have software analysis capabilities. Since we need to measure multiple frequency shifts, we will use these devices to our advantage. The lighting in the room is also adjustable, so we have the ability to remove most ambient lighting to reduce the error due to noise. Of course, there will always be some noise present. The lasers typically used in the undergraduate lab are Helium-Neon lasers in the visible range. We will likely use these for testing purposes for proof of concept for this design, and then use the sponsor's lab with the actual laser to be used in the final system. Oscilloscopes are also readily available if needed for receiver measurements, but this will likely be done at the sponsor's lab.

8.1.2 Harris Testing Environment

As mentioned previously in this report, this project is sponsored by Harris Corporation. Harris has offered assistance from and advising point of view, as well as a monetary point of view. Harris has offered funding for any materials and components that need to be purchased for this project, up to an amount further detailed in the section on the budget of the project. Any materials or components currently owned by Harris have been offered for use at the location of Harris. As such, this includes using the lab space at Harris as a testing environment. In this section, details regarding the testing environment at Harris are discussed.

One important factor regarding the Harris testing location is the location of the company itself. All group members on this project are full time students at the University of Central Florida. While Senior Design and therefore this project are a major concern for all group members, we all have other courses that occupy a considerable amount of time. Harris is located in Melbourne Florida, which is approximately 1 hour and 30 minutes from the University of Central Florida in Orlando. With that in mind, the location and the scheduling necessary to account for that location are key aspects regarding the Harris testing environment. The limited time for all group members to commute to Harris from Orlando and each group member's limited time due to other academic commitments means the time spent at the Harris testing environment needs to be optimized. This requires that any testing done at the Harris testing location needs to be fully planned out. Further details regarding testing is discussed in the section on testing in this report.

Aside from time constraints regarding the Harris testing environment on behalf of the group members for this project, using Harris as a testing location means taking up space and equipment used by the company for whatever amount of time we are testing. As Harris is an active professional engineering company, any lab space is likely to be in use. As such, this is yet another reason for time spent at the Harris testing environment to be optimized.

Another key factor regarding the Harris testing location is the equipment at this location. As mentioned previously in this section, Harris has offered the use of equipment already owned by Harris. The details regarding the equipment are discussed in the section detailing parts acquisition. However, it is important to note in this section that various vital pieces of equipment will only be able to be used at the Harris testing location.

In addition, various environmental factors at the Harris testing location will likely be different from the actual environment in which the system will be employed. While the actual environmental conditions for the final system are not known due to the proprietary nature of the final system in development at Harris, it is unlikely that the environmental conditions will be exactly the same as the conditions at the Harris testing location. These variable environmental conditions could include temperature, temperature stability, vibrational stability, moisture control and various other conditions that could impact the operation of the system. Testing for this system will not involve any kind of mechanical packaging to minimize these fluctuations in environmental variables, so it is important to note them here.

8.1.3 Temperature Sensitivity

A large concern when running testing for this project is the temperature of the components and the temperature of the ambient setting. This is especially of concern for the laser source used to carry our signals. Laser performance is highly sensitive to temperature variations. The center wavelength emitted by the laser will shift with a change in temperature, which could completely ruin our results. Our final design involves a dispersive media that delays signals of different frequencies. Any frequency shifts would ruin this data and likely cause project failure. Not only is center wavelength shifted with temperature, but the bandwidth is also widened, which will lower the performance and reliability of the laser. Lasers are usually used when a small bandwidth is desired. A third temperature problem for the laser is the output current-voltage curve. A temperature change will shift this current-voltage relationship and alter the efficiency of the system. For these reasons, it is important that all test environments share similar temperature conditions with what the final system will be exposed to. If this becomes a concern, temperature regulators may need to be used. Thankfully, the CREOL labs have temperature regulators available, and most lasers can be purchased with temperature controls preinstalled.

Temperature is also of concern with any fiber optic cables used, as the temperature change will cause the fiber to expand and contract. This will be a very small change, but over long distances this could severely alter the total path length of any beam propagating within the fiber. In terms of our desire to shift the frequency of our incoming laser signal, this is not a huge concern, so long as the path length of the dispersive media used is not significantly altered. Similar to fiber optic cables, any lenses used in the system will also experience a temperature expansion coefficient. This impact in lens focusing and aberrations is miniscule and likely of no concern.

Electronic devices within the system could also have their performances altered by any extreme temperature changes. For the lab settings we are using, this is probably not a concern, but it is important to make sure heat can easily escape from the final system. Any heat buildup could cause components to fail or become destroyed. As of now, there are no heating concerns with the project, but if our sponsor decides the final system could have heating issues, we will need to add a heat sink to our PCB and/or any other components that are temperature sensitive and release a lot of heat.

8.1.4 UCF Engineering Lab

The UCF engineering lab is located on the fourth floor of the Engineering I building. This lab includes multiple countertops with breadboards, function generators, oscilloscopes, wires, and other necessary components/test equipment. The majority of this project's electrical components and electrical subsystems will be tested within this facility. This will include the voltage ramp generation, the square wave generation, and the voltage ramp amplification stage. This facility offers plenty of electrical outlets, so computers running any software for the microcontroller can also be tested here. The lab is kept at room temperature, so any temperature concerns should be alleviated. This lab, like CREOL, is also under secure lockdown, and requires a keycard to gain access. This will ensure some safety if equipment is left here for storage, but all senior design students will have access. CREOL on the other hand only allows a select few students to enter, so this would be a safer location for storage. This lab also tends to become overcrowded toward the due date of senior design projects, so it will be important to conduct all testing before this overcrowding occurs.

8.2 Hardware Specific Testing

This section will describe the specific testing for individual components and individual subsystems within this project design. Once these subsystems have been discussed, the final system testing procedure will be briefly discussed as well.

8.2.1 Microcontroller Testing

The microcontroller used with this design will be the MSP430 produced by Texas Instruments. This part was selected because it is what we are familiar with from previous UCF electrical engineering courses. The microcontroller is used in this design to control the change of resistor values in the voltage ramp amplification stage. This is done using two digital potentiometers that act as a resistor tree.

When a certain address of bits is sent to the potentiometer, designated switches will close and vary the resistance across the device as a whole. This change needs to happen between step sizes of each frequency signal. The time period between frequency steps can be less than or equal to forty microseconds with a time of less than or equal to ten microseconds for the actual transition. This means a clock frequency of 100 kHz should suffice to vary each resistor with the specified transition period, assuming a single line of code is used to create this transition. The MSP430 can reach these clock speeds with the attachment of a crystal oscillator. Testing this microcontroller will first involve ensuring this clock signal is running at the proper frequency. A line of code can be written to test this for us within the software. Once this clock frequency is confirmed, the microcontroller will be attached to the digital potentiometer. A probe will be used to measure the resistance across the potentiometer, and an oscilloscope will measure the voltage change across the potentiometer with time. A single line of code corresponding to a change in the potentiometer's resistance will execute, and the time between voltage shifts on the oscilloscope will be measured. This will be compared with our theoretical speed of ten microseconds. If this succeeds, then we will run multiple lines of code corresponding to multiple resistance changes. Each time period between each transition will be measured and compared. If the frequency and speed are correct, then we will know the microcontroller is working properly.

8.2.2 Laser/Spectroscopy Testing

When testing our laser source, these steps should be followed to ensure accurate readings of our laser system. First, the laser itself should be tested on its own for accurate data readings. There are three primary readings that should be tested: the laser peak and average power, the laser emitted frequency, and the beam spot size/dispersion. These values will help us to determine our initial reference frequency (which should be 1550 nm) and will help us ensure that we have enough energy to send the beam through the entire system and still be detected. This energy will determine how much loss we can afford to have throughout other components in the system.

The laser will be provided by the project sponsor. Depending on if the sponsor allows us to take the laser to the university labs for testing, our testing equipment/test environment could change. In any case, both locations will have stable temperature conditions, which is necessary to have good measurements of laser power. If testing is conducted at the sponsor's lab, then we will use any power meters and spectrometers they have on location to measure the emitted frequency and power of the laser. If we are allowed to test the laser at the university lab, then we will use the CREOL power meters to measure peak and average powers. This is typically a Newport 1918-R power meter. The laser will be aligned on an optical table and then the power readings will be taken. This will involve mounting the power meter to the end of the laser output (with the power meter settings corrected for the desired frequency range). Peak and average power will be recorded. A secondary reading will be taken at a distance equivalent to where any fiber coupling may occur. For this, the power meter will be secured by optical posts at the location of the fiber entrance and will remeasure the peak and average powers. These values will also be recorded.

From this location, the beam spot size and dispersion value will also be determined. One method of measuring the beam divergence and spot size is to use a knife edge and “cut” the beam. This knife edge is mounted to a translation stage and slowly adjusted across the front end of the power meter detector. As the knife travels in front of the detector, more and more of the beam will be clocked. By plotting the measured intensity with respect to the distance translated by the knife, a Gaussian profile should result (assuming a Gaussian laser source). The beam width at this location is considered to be the distance between the ($1/e^2$)(Emax) points. Emax is considered to be the maximum irradiance measured. Figure 47 shows this.

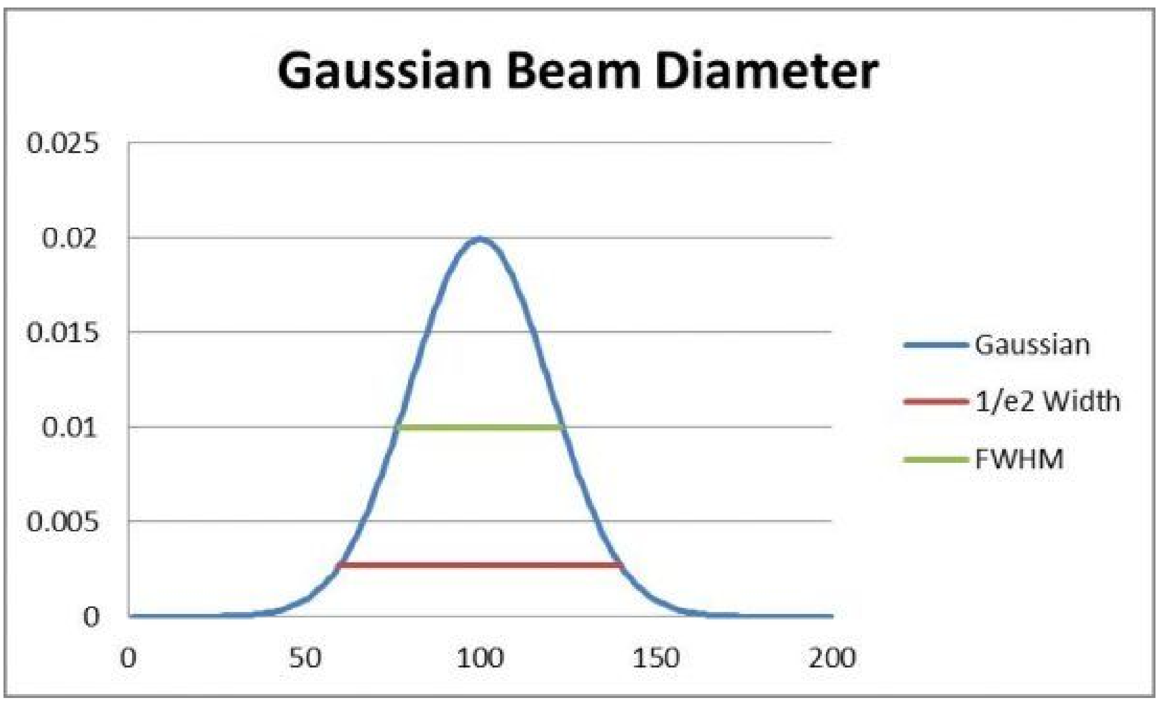


Figure 47: Measuring a Laser Spot Size Using Plotted Irradiance Pattern
Image Provided by Ophir-Spiricon

This knife experiment can be conducted at multiple distances away from the laser emitter. By comparing how the beam spot changes over a given distance, the divergence of the beam can be calculated. Once this is known, we can know where to place our fiber optic coupling cable to ensure the highest transfer of beam power.

For confirming the frequency of the laser a spectrometer will be used. The lab spectrometers (StellarNet Blue-Wave spectrometer) have fiber receiver ends that can be used to couple the laser beam into the spectrometer. From here a wire connects the spectrometer to a software that can analyze the laser spectrum. This software will show intensity of the beam detected by the spectrometer, as well as any frequency components detected. Ambient lighting could cause some unwanted frequency spikes on the software, but since our laser is out of the visible range, it should be clear which frequency is from our source. To be safe, the ambient lighting could be dimmed or even removed to ensure as accurate of a reading as possible.

8.2.3 Receiver Testing

Another component in this senior design project that can be tested is the photodiode used as a receiver. As discussed in section 6.2, the specific photodiode that will be utilized in this project is an InGaAs photodiode developed by Discover Photonics. This part will be provided to us by Harris Corporation. In order to test this photodiode, there must be a working RF source used to test it since this photodiode is used to receive light signals in the RF frequency range. To test it and see if it is working properly, the optical source will need to be coupled into a known, working fiber optic cable. To make sure there is power coming through the fiber optic cable, there should be a power meter attached to the end of the fiber optic cable to ensure that power from the source is coupled into it. Once that is tested, the fiber optic cable should be hooked up to the photodiode. Once the fiber optic cable is connected to the photodiode, the photodiode can be verified by measuring the current produced by the optical signal. Once the receiver photodiode is successfully, it is ready to be implemented into the system.

8.2.4 RF Intensity Modulator

As mentioned in previous sections of this report, the final system will include the use of three separate radio frequency intensity modulators. As such, it is important to discuss the necessary testing procedures in order to ensure that each radio frequency intensity modulator is operating correctly. In this section, the specific testing procedures for the intensity modulators used in the system are discussed.

The three intensity modulators that will be used in the final system each are responsible for different roles. The first intensity modulator in terms of system order is used to impart the radio frequency signal onto the optical carrier. This is accomplished by using a radio frequency signal generator as the bias for the intensity modulator discussed. This allows for the signal to propagate through the optical system as sidebands to the optical carrier. Therefore, the testing procedures for this intensity modulator should ensure that the radio frequency signal is successfully modulated onto the optical carrier, which is the laser in this scenario. The best way to test this is by using a spectrometer to view the signal after it passes through the intensity modulator discussed. This allows for the signal to be viewed in the frequency domain.

The radio frequency modulated onto the optical carrier simulates the signal being sent or received in the final system. However, the information regarding the actual signals is proprietary information. With that in mind, an arbitrary radio frequency can be chosen for the purposes of this project, as long as it remains within the radio frequency domain. If a radio frequency of 2.5 GHz is chosen, the modulation sidebands will be located 2.5 GHz above and below the optical carrier frequency in the frequency domain. Therefore, a sufficient test for the first intensity modulator would be to place the modulator in line directly after the laser and modulate a 2.5 GHz tone onto the optical carrier. Then, the signal can be detected by using the photodetector provided by Harris and viewed using the provided spectrometer. If the correct optical carrier frequency and sidebands are observed, then the intensity modulator is operating correctly

The two other intensity modulators essentially act as interferometric switches in the final system. Both of these intensity modulators are biased by square wave voltage sources. When biased at positive Vpi, they allow the signal to pass through. When biased at negative Vpi, the prevent the signal from passing through. Therefore, an appropriate test to ensure these two intensity modulators would be to bias them separately and make sure that each intensity modulator operates correctly in both the “on” and “off” configurations. This can be done by placing each individual intensity modulator in line directly after the laser, separately of course, and biasing the modulator so that it is in the “on” configuration. Then, by placing the photodetector after the intensity modulator, the correct or incorrect operation can be ascertained by whether or not the signal can be detected by the photodetector. A similar test can be done with the “off” configuration, only in this case correct operation would mean little to no signal detection at the photodetector.

8.2.5 Fiber Fault/Defect Testing

This project will need to utilize fiber optic cables. Therefore, there must be sufficient testing and evaluating of the fiber optic cables to ensure that they are working properly and that there are no defects. Although it will be Harris’ responsibility to test the telecommunication cables that a will be hooked up to the optical delay generator, there must be proper testing of the fiber optic cables that are used in the project. This section will cover the various methods to test fiber optic cables to discern any defects or faults in the cables themselves that will be necessary to this project.

To test the optical fibers, special fiber optic cable testing tools must be utilized. There are a variety of tools that can be used to test fiber optic cables. These tools include a powerful microscope (100 to 200X), light source for the fiber, power meter, optical loss test set (denoted OLTS), working fiber optic cables to be used as references, optical fiber connectors, and a visual fault locator [37]. Once these tools are acquired, the methods and logistics to using these tools must be investigated and understood. Without proper understanding of some of these tools and how to use them, the testing will not be accurate, and some faults in the fiber optic cables can be missed. This could have dire consequences to our project, as a faulty fiber optic cable could severely skew our desired results. In the following paragraphs, the details regarding how to use this test equipment will be explained.

One of the ways to test optical fibers is to test them visually. This involves using a microscope or/and a visual fault locator to physically see any faults or discontinuities in the fiber optic cables [37]. This is a very logical way to test fibers and should most likely be the first method used to test the fiber optic cables as it ensures that the fiber optic cables are not broken [37]. As mentioned earlier, there are a few different ways to visually test the fiber optic cables. To begin this discussion, the uses of the microscope and logistics on how to use it will be investigated. Then the logistics of using a visual fault locator will be discussed.

The microscope is used to visually inspect the fiber connectors [37]. With the microscope, faults like scratches, unwanted debris, and defects due to polishing can be identified and addressed [37]. Some microscopes that are specially made to be used to test fiber optic cables have an adapter to easily connect a fiber connector to aid in inspection [37]. Also, some fiber optic inspection microscopes have a way to tilt the connector or have various illumination angles so as to get a better view of the fiber optic cable connector [37]. While using the microscope, the method is to inspect, check for dirt or anything that is cleanable, clean any affected areas, and then reinspect the fiber optic cable connector [37]. As a safety precaution, a power meter should be used to ensure that there is no light coming through the fiber optic cable attached to the connector [37]. Of course, this is a non-issue if the fiber is not connected to any type of source. CREOL has a simple video microscope that could most likely be utilized to test any fiber optic cables that would be used in the design of our project. If, for whatever reason, the microscope is not available for use, there are a few other ways to test the cables used that could make up for the lack of a visual testing with a microscope. Now that the methods and details regarding testing optical fiber connectors visually by using a microscope have been investigated, other methods of visual testing will be explored.

Another couple of tools used to visually test fiber optic cables include a visual tracer or a visual fault locator [37]. Both tools basically have the same function, that is, to visually check the fiber for any discontinuities. The visual fiber optic tracer is, simply put, a small, pen shaped light source with a low output power that has a connector on the end of it for fiber optic cables [37]. Fiber optic cables are connected to it, and the light source is turned on to allow light to propagate through the cable [37]. The opposite end of the fiber is observed to see if the light is getting all the way through the fiber [37]. If there is no light seen at the end of the cable, there is a fault in it, and the cable should be replaced [37]. However, this tool is used for multimode fibers, and this project requires the use of single mode fibers [38]. Therefore, this tool will not be used to test the fiber optic cables used in this project. However, the visual fault locator can be used with single mode fibers [38]. Therefore, the visual fault locator will be detailed next as to its use and how to use it.

The visual fault locator is an advanced tool used to check for discontinuities or breaks in fiber optic cables [38]. This differs from the tool mentioned previously (the visual tracer) in that it involves the use of a high-powered laser instead of a low intensity light source to check for faults [38]. The visual fault locator uses powerful visible light, like that of a red Helium-Neon laser or a laser diode that emits visible light (usually in the 635-650 nm range) to inject into the fiber optic cable that is being tested [38]. Once the light is successfully coupled into the fiber optic cable, the light is bright enough to reveal breaks or areas of discontinuity in the fiber optic cable [38]. The feasibility of testing the fiber optic cable with this method depends on the type and jacket color of the cable being tested [38]. For example, the high-power laser light will usually pass through a single-mode optical fiber that was a yellow jacket and will also usually pass through a multi-mode optical fiber with an orange jacket [38]. This allows any big areas of loss to be easily identified, even if the jacket of the fiber optic cable is somewhat opaque [38]. However, if the jacket of the fiber optic cable is any other, darker color, the breaks or discontinuities will not be visible by using the high-powered laser source [38]. The visual fault locator generally has a range of about 3-5 kilometers due to the high loss at visible wavelengths in fiber optic cables [38]. Although this is a fairly short distance for most telecommunications applications, this is a sufficient distance for the testing purposes of this project, as the fiber optic cables needed for the development of this project are generally much shorter than 3-5 kilometers. Although some of the tools for visually testing fiber optic cables have been discussed, there is one more visual method of testing optical fibers.

Another, much simpler way of visually testing fiber optic cables is to simply look at the cable itself [38]. Although it may seem obvious, it is worth mentioning. Observing and looking at the cable to check for kinks or bends should precede any other form of visual fiber optic cable testing [38]. It can be easily identified if one of the fiber optic cables are clearly broken. Therefore, before performing any visual fault tests with either a visual fault locator or a visual tracer, the fiber optic cable itself should be properly examined for any breaks, kinks, or bends first. It should also be noted that, when using this method to visually find fiber optic cable faults or defects, there should be no optical power coupled into the fiber so as to avoid any eye damage. This method of visually testing fiber optic cables can also be used to detect bad patch cords or splices [38]. Again, this is the simplest way to visually check a fiber optic cable for faults and should not be overlooked. Now that the methods for visually testing fiber optic cables have been sufficiently explained and detailed, the other methods of testing a fiber optic cable for faults or defects will be investigated.

Another way to test fiber optic cables is by checking and measuring optical power [37]. In fiber optic cables and telecommunications, the unit of power used in the measurement of optical power is dB [37]. It is worth mentioning that there are two different types of dB units: the first is dBm, which is a direct power measurement, the other is dB which is a relative power measurement (used when measuring the power lost in a fiber optic cable) [37]. Measuring the power present in a fiber optic cable requires a few tools. There must be a transmitter to couple a certain amount of optical power into the fiber optic cable, a known working fiber optic cable for reference (this is in addition to the fiber optic cable that needs testing), and a fiber optic cable power meter (meaning it has a screw on coupler for a fiber optic cable attached to it) [37]. The power meter must be set to the proper wavelength of the transmitted light and to dBm when measuring optical power [37]. To test the cable of interest, first attach the known working cable to the transmitter and the power meter. Turn on the transmitter and the power meter, take note of the optical power that is measured. Then, swap the cable from the know working cable to the cable that needs testing. Repeat the same procedure with the cable needing testing. If the optical power measured is less than the previous optical power, there is a problem with the fiber optic cable, and it must be addressed. The discussion on measuring optical power in fiber optic cables as a way to test them will be continued with a discussion on measuring loss in fiber optic cables.

Continuing from the previous paragraph, there is another type of power measurement that can be used to test a fiber optic cable. This method involves measuring a relative loss in dB [37]. The process of this measurement is similar to the process for measuring the optical power in a fiber optic cable. This time, instead of hooking up the fiber optic cable that needs to be tested directly to the transmitter and power meter, the known working reference cable is connected to the transmitter, and the power meter is set to measure the proper wavelength and is set to dB (for optical power loss measurements) [37]. This is to get the "zero dB" value as a reference for the loss in the fiber optic cable to be tested [37]. Now that the "zero dB" reference loss is calibrated, the fiber optic cable that needs to be tested is connected to the known working reference cable, and then finally connected to the power meter [37]. This will then give the optical power loss in dB. It is important, when using this method to measure loss, that the connector used is clean so that the measurement is accurate [37]. This method of testing is used to test both the connectors and the fiber optic cable for faults [37]. There is one other method of measuring loss in a fiber optic cable. This method involves the use two known and working reference cables, and it will be discussed in detail in the next paragraph [37].

Another method of testing fiber optic cables by measuring optical power loss involves the use of a transmitter, two known and working reference cables (one as a launch reference, one as a receiver reference), the cable that needs to be tested, and a fiber optic power meter [37]. This method of testing is to simulate connecting the fiber optic cable to a fiber optic plant [37]. This is called double-ended testing (as opposed to the single-ended testing detailed in the previous paragraph) [37]. The start this method of testing a fiber optic cable, the zero reference loss must to calibrated [37]. This is done in a similar manner to the single-ended testing method, as the power meter is simply connected to the first reference cable that is connected to the optical transmitter [37]. Then, the test cable is connected to the first (launch) reference cable, and then the other end is connected to the second (receiver) reference cable [37]. This receiver reference cable is then connected to the power meter [37]. This method is “the standard test for loss in an installed cable plant” [37]. Although it is similar to the previous method, it has slight differences. The double-ended method tests the loss present in two connectors and all the fiber optic cables involved [37]. This is most likely the test that will be used in this project as our system will be connected to a larger fiber optic system. Now that the methods of measuring optical power and optical power loss in a fiber optic cable as a method of testing it has been discussed, one last fiber optic cable fault/defect testing method will be detailed and discussed.

The last fiber optic testing method that will be talked about involves the use of an optical time domain reflectometer [37]. This is perhaps the most complex tool used out of all the tools that were previously discussed. Optical time domain reflectometers are used to “locate faults, measure cable length and verify splice loss” [37]. This tool cannot, however, measure the optical power from the transmitter or at the receiver [37]. Simply put, optical time domain reflectometers act as RADAR for fiber optic cables [37]. A signal is input, and then the optical time domain reflectometer looks for reflected return signals from the interfaces of connectors or splices [37]. Although optical time domain reflectometers are useful tools for testing long lengths of fiber optic cables, they are not very useful when testing short distances of cables [37]. For this reason, optical time domain reflectometers will not be very useful to our project.

This concludes the discussion on the topic of fiber optic cable fault/defect testing. In this section, the various ways of testing fiber optic cables and connectors have been discussed. These methods include using a microscope to check for cleanliness of fiber faces and connectors, various visual methods for checking fiber optic cables for discontinuities or faults, optical power and optical power loss measurements, and the use of an optical time domain reflectometer. Although all of these methods and tools may not be used in the actual testing of the fiber optic cables used in this project, it was still worth discussing in order to understand the various ways fiber optic cables can be tested in both a test design environment as well as a working cable plant environment. The methods discussed in this section will be useful to the design, development, and testing of this senior design project.

8.2.6 Final System Testing

Testing the final system will depend on the parameters of the final design set by the sponsor. Currently, we are designing a method to produce a frequency shift of up to 187 steps from our initial beat frequency. From here, the some type of dispersive media will delay each frequency at separate intervals. It has yet to be determined whether the sponsor will require us to just produce the frequency shifting or if we need to provide the dispersive media as well.

If the dispersive media is included in the final system, then we will likely test the system as a whole by connecting the receiver to an oscilloscope capable of measuring in the picosecond range. If such an oscilloscope can not be found, then likely what we will do is run a block of code on our voltage ramp that corresponds to longer time periods between voltage ramp slope changes. This will give us more time between signals that can then be detected by the oscilloscope. This slower delay could then be run on each frequency shift step to show the corresponding delay would result in the desired values in the real-time final system.

If the dispersive media is not included in the final system, the approach will be very similar, but rather than an oscilloscope a spectrometer will be used. The spectrometer will need to confirm that there is a correct frequency shift corresponding to the voltage ramp slope biasing the phase modulator. If we can show that our voltage ramp slopes correspond to the correct frequency shifts, then we can conclude that a dispersive media with the right parameters could produce the necessary delay between frequencies. This method will also be more flexible for demonstration purposes because it allows us to use a visible laser source for demonstration purposes. As long as we show the frequency shift is the same amount of change as it would be in the final system, it does not matter if we use a visible source rather than infrared, as the concept will be the same in the real system. The only component where this would matter is in the dispersive media, because this delay is a function of the frequency. Since in this case no dispersive media is present, any frequency source can be used as long as the frequency shift is guaranteed.

The above case would be ideal for showcasing our design, but it would not provide a true picture of how the actual system will perform. The correct 1550 nm source could be used, it would just mean that the demonstration would have to be completely on the spectrometer software.

8.3 Software Test Environment

In order to ensure that the software works properly with the hardware used in this project, it is important to test the specific software that is used. In this section, the various external needs and requirements of the software will be explained in order to understand what type of software testing environment will be necessary in order to properly test the codes used and make appropriate observations and tests. Various options for the software language will be explored in order to make a decision on which language is best suited for the needs of this project. Then the types of programs and systems used to test and troubleshoot will be discussed.

8.3.1 Language Used and Why

There are various options for the language that can be used for this project. It is important to understand the benefits and drawbacks of each language. These benefits and drawbacks include the capabilities of the language itself, as well as the capability of the project team to understand how to efficiently and effectively create and run the necessary codes for this project. For this project design, the timing is important to monitor and adjust to very fine precisions. Because of this, it is important to use a coding language that allows for measuring or calculating the time it takes to go through each line of code. This includes being able to iterate through certain lines of code one at a time, tracking certain variables to observe when and how they change, and seeing the clock timings. Ideally, the best way to observe these details of the code used for this project, the programming language would have assembly capability so that it is easy to read and understand the step-by-step process involved in each line of code and understand the time it takes to go through each line. It is also important that the the language used is familiar and easy to work with for the ones designing the actual software.

The two main languages that are options for being used with the MSP430 are C/C++ with Code Composer Studio and the Energia language with Arduino. Code Composer Studio is an integrated development environment, or IDE, that works with Texas Instruments MSP microcontrollers, such as the one that will be used for this project [39]. The IDE has a compiler for C/C++ that optimizes both code size and performance for the these microcontrollers [39]. Code Composer Studio also has a scripting designed to allow the automation of repetitive tasks that work for testing and benchmarking as well as a processor that is capable of advanced hardware debugging [39]. These features allow for various breakpoints and watchpoints in both the software and the hardware [39]. When looking at these features, Code Composer Studio allows for great flexibility in testing, including when testing should occur, and various ways to debug. This IDE also has the option to create assembly codes and run them step by step [40]. This is a very important detail for running codes down to a level of specificity that allows for reading the clock timing for each step.

Energia is much more simplified and easy to use IDE for microcontrollers [41]. It is much more limited in capability with greater focus on the basic and core fundamentals of functionality [41]. While this makes it easier to create the software necessary, it is not ideal for a good testing environment. The members of the team with the most programming experience who will be primarily working on the code are also more familiar with using the Code Composer Studio and the C programming language. Although using Arduino would make the coding itself much simpler and easier with minimal lines of code, the project scope requires much more precision and accuracy in the small details of the coding, which makes Energia with Arduino less suitable. Meanwhile Code Composer Studio allows for the necessary observations to be made when going through software testing for this project. A summary of the benefits and drawbacks of each language and program are presented in the table below. Because Code Composer Studio is better suited for testing, that is what will be used for this project, mainly working in C, but testing with the assembly provided by Code Composer Studio.

Feature	Code Composer Studio (C/C++)	Arduino (Energia)
Simple	No	Yes
Ability to track variable values	Yes	No
Assembly Option	Yes	No
Clock Timing	Yes	No
Can Run One Line at a Time	Yes	No
Familiarity	Yes	No

Table 7: A Summary of the Pros and Cons of Using Code Composer Studio with C/C++ and Arduino with Energia

8.3.2 Programs/Systems used to Test/Troubleshoot

When considering the specific programs and systems used for testing a troubleshooting the project, the available systems within Code Composer Studio should be explored. The basics of the programs and systems used were briefly discussed in the previous section, which mentions that Code Composer Studio has the options to view and create codes in assembly. This will be the main way in which we test the software part of the project. With the strong significance of precise and accurate timing, it is important to use the features that allow for step by step assembly run codes to observe how the project code will run in real time when taking into account the clock speed of the microcontroller and the runtime of the code itself. If the code is able to run each step in a sufficient time period, that is the most important aspect of the software. If the code ends up taking too long of a time period to run, than the assembly code will allow us to view which lines of code take up the most time and the compiler and intuition will allow for more optimized code to be created to adjust the size and timing of the code. In the case of this project, even if we only save a few steps of coding, that will make a difference in ensuring that the code timing is within an appropriate time range. Code Composer Studio is also able to to certain hardware debugging for the microcontroller, which will allow for observing how the software directly interacts with the hardware. This allows for any appropriate adjustments to be made to the software should they affect the hardware in any significant way. The actual functionality of the code will simply be tested in the hardware, the MSP430 microcontroller. Running the code step by step will allow for measurements and observations to be made which should correspond to the specific lines of code.

9.0 Administrative Content

9.1 Milestones

Number	Task	Start	End	Status	Responsible
Spring 2018					
1	**Assign Rolls**	1/16/2018	2/2/2018	Completed	Group
	Project Report				
2	Initial Divide & Conquer	1/16/2018	1/28/2018	Completed	Group
3	Second Divide & Conquer	2/27/2018	3/8/2018	Completed	Group
4	Table of Contents	3/8/2018	3/22/2018	Completed	Group
5	First Draft	2/9/2018	4/13/2018	Completed	Group
6	Final Document	3/30/2018	4/26/2018	Completed	Group
	Research, Document, and Design				
7	Initial Calculations	2/2/2018	2/16/2018	Completed	Group
8	Cavity Options	2/9/2018	3/22/2018	Completed	Group
9	Free-Space Fiber Coupling	3/1/2018	3/23/2018	Completed	C, K, S
10	Serrodyne Approach	3/1/2018	3/23/2018	Completed	K, S
11	Herriott and Corner Cube Approach	2/16/2018	3/23/2018	Completed	C
12	Simulations	3/9/2018	3/30/2018	Completed	C, K, S
13	Motor	2/16/2018	3/23/2018	Completed	M
14	Microcontroller	3/2/2018	4/6/2018	Completed	M
15	Power Supply	3/16/2018	4/6/2018	Completed	K, M
16	Laser	3/9/2018	3/30/2018	Completed	C, K, S
17	Modulator	3/1/2018	4/6/2018	Completed	C, S
18	VNA	3/1/2018	4/6/2018	Completed	C, K, S
19	Signal Detection	3/1/2018	4/6/2018	Completed	C, S
20	Final Design	3/30/2018	4/13/2018	Completed	Group
21	**Order Parts & Prototype Design**	3/30/2018	8/20/2018	Researced	Group
Fall 2018					
22	**Build & Test Prototype**	8/20/2018	9/7/2018	Completed	Group
23	**Order Initial PCB & Parts**	8/27/2018	9/21/2018	Completed	Group
24	**Test &Troubleshoot First Design**	9/14/2018	10/26/2018	Completed	Group
25	**Optical Testing with Sponsor**	10/19/2018	11/27/2018	Completed	Group
26	**CDR Presentation**	8/24/2018	9/14/2018	Completed	Group
27	**Order Second PCB & Parts**	10/12/2018	10/26/2018	Completed	Group
28	**Test &Troubleshoot Second Design**	10/19/2018	11/16/2018	Completed	Group
29	**Midterm Demo**	10/26/2018	10/30/2018	Completed	Group
30	**Final Adjustments to Design**	11/9/2018	11/27/2018	Completed	Group
31	**Full Design Testing with Sponsor**	11/13/2018	11/27/2018	Completed	Group
32	**Final Presentation**	11/13/2018	11/28/2018	Completed	Group
33	**Final Documentation**	8/27/2018	12/4/2018	Completed	Group

Table 8: Projected Project Schedule

MILESTONES KEY:

C = Caleb
K = Kevin
S = Sam
M = Marcus

9.2 Budget and Financing

As discussed in section 7.1, the total budget that is projected to be needed for this project is around $9,000 dollars. Harris has agreed to provide for this budget with their own funds, and they have expressed continued financial support if the budget for the project exceeds $9,000. This will allow us some flexibility if a complication arises or a new, unplanned part is needed for the project. We plan on cooperating with Harris to utilize some of their equipment which will reduce the amount of funds required. Harris has been cooperative in this regard. For more information regarding the equipment that will be provided for the use of this project by Harris, see the below paragraph and section 7.1 Parts Acquisition and Bill of Materials.

Some of the equipment provided by Harris will include high speed photodetectors for signal detection, a vector network analyzer for analysis of the delay, a radio frequency signal generator, and an intensity modulator for modulating on the radio frequency signal. Other equipment that may be provided by Harris includes phase and intensity modulators necessary for serrodyne phase shifting approach and chirped fiber Bragg grating. Any equipment not provided by Harris Corporation would need to be purchased with funds from the provided budget. Therefore, these pieces of equipment, although vital to the successful performance of the designed system, will not be considered in regards to the budget needed for this senior design project.

9.3 House of Quality

The House of Quality on this page summarizes the project's requirements and specification, and how they each relate to one another. The quantitative values associated with the engineering specifications are displayed at the bottom of the House of Quality.

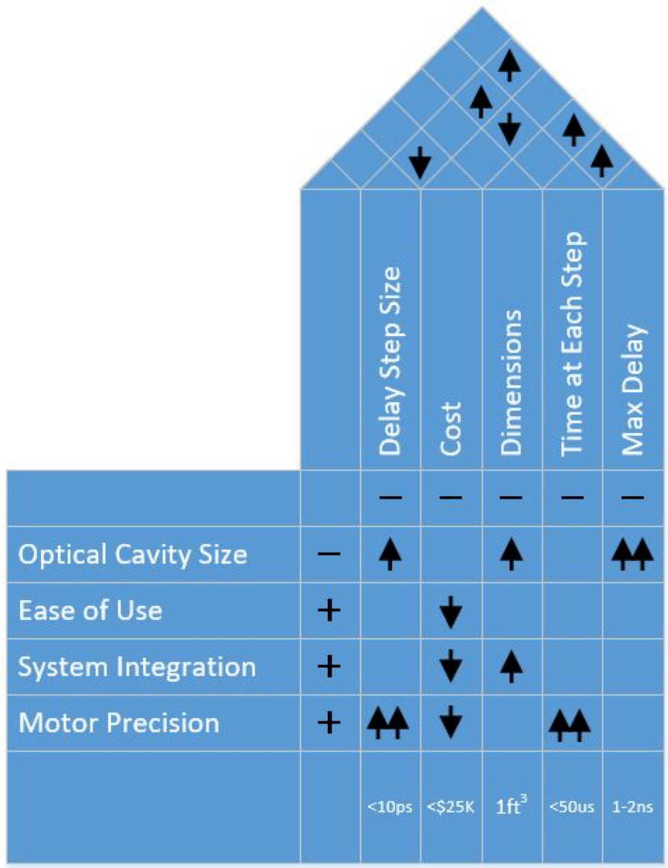


Figure 48: House of Quality

House of Quality Legend

↑= Positive correlation
↑↑= Strong positive correlation
↓= Negative correlation
↓↓= Strong negative correlation
+ = Increases the requirements
- = Decreases the requirement

9.4 Project Summary and Conclusions

In this report, the design of a variable optical delay generator for a radio frequency photonics system is discussed. In a radio frequency photonics system, an intensity modulator is used to modulate a radio frequency tone onto an optical carrier signal, typically generated by a laser. Because of the unique and precise requirement specifications regarding the generated delay, the approach used would need to allow for accurate and rapid changes between specific delays. After sufficient research two main approaches were considered for this project, and have been discussed thoroughly in this report. The first approach considered involves the use of a variable optical cavity. Cavity designs discussed include corner cube mirror and curved mirror cavities. By precisely varying the size of the cavity through the use of electrically controlled motors or linear actuators, the total distance travelled by the optical signal as it propagates through the system is increased. Thus, the total time for the optical signal to propagate through the system is varied with the variable cavity. By accurately controlling the cavity size and its corresponding relationship to the delay generated, the required delays could theoretically be met. However, after further research and calculations, it was found that this approach was not practical.

The other approach discussed in detail in this report, which was chosen as the main approach for the project, involves the use of serrodyne phase modulation. This is a method used to shift the frequency of an optical signal based on the slope of phase modulation. Then, by altering the slope by specific amounts, specific frequency shifts can be achieved. With the appropriate dispersive media, the required delays can be achieved. In order to incorporate this method into this project, the number of frequency shifts corresponds to the required number of delay steps discussed in this report. However, due to the expensive and detailed nature of designing and purchasing an appropriate dispersive media to cause the correct delays based on the frequency shifts imparted by serrodyne phase modulation, the sponsor and customer for this project, Harris Corporation, has stated that a demonstration of the appropriate frequency shifts discussed would be a sufficient output of this system.

In addition to the primary frequency shifting function of this serrodyne phase modulation approach, design additions were included in order do reduce the negative effects of this approach, primarily the generation of serrodyne frequency spurs. This was accomplished by implementing two parallel intensity modulators, one of which is separated by a specified constant delay, and biasing them such that frequency spurs are limited. The phase modulator used to cause the frequency shift is biased by a voltage ramp, the slope of which determines the frequency shift. The two parallel intensity modulators are biased by square waves with the same period as the voltage ramp, allowing them to operate as interferometric switches.

Research regarding this approach is detailed in this report, along with research regarding the materials needed and the cost. Real world design constraints such as ethical, environmental, health and safety constraints are also discussed. The standards related to this project have also been detailed in this report. The testing environments as well as initial testing procedures are also discussed in detail. After researching for the project in great detail and planning for the purchase and testing of components, the necessary electronics and coding involved, as well as the final operation of the system, this project is ready to enter the construction and testing phase. With the finished project, we hope to meet all of the design specifications requested by the sponsor.

10. Testing and Results

In this section, the results obtained from testing are discussed. These include results from testing the individual photonics and electronics subsystems, as well as results from the final system in which the two are combined.

10.1 Photonics Subsystem

In this section, the results obtained from testing the optical subsystem are shown. These include individual results from testing the phase and intensity modulators. The first test performed was a measurement of the optical output of the intensity modulator as a function of DC bias. The results from the test are shown below.

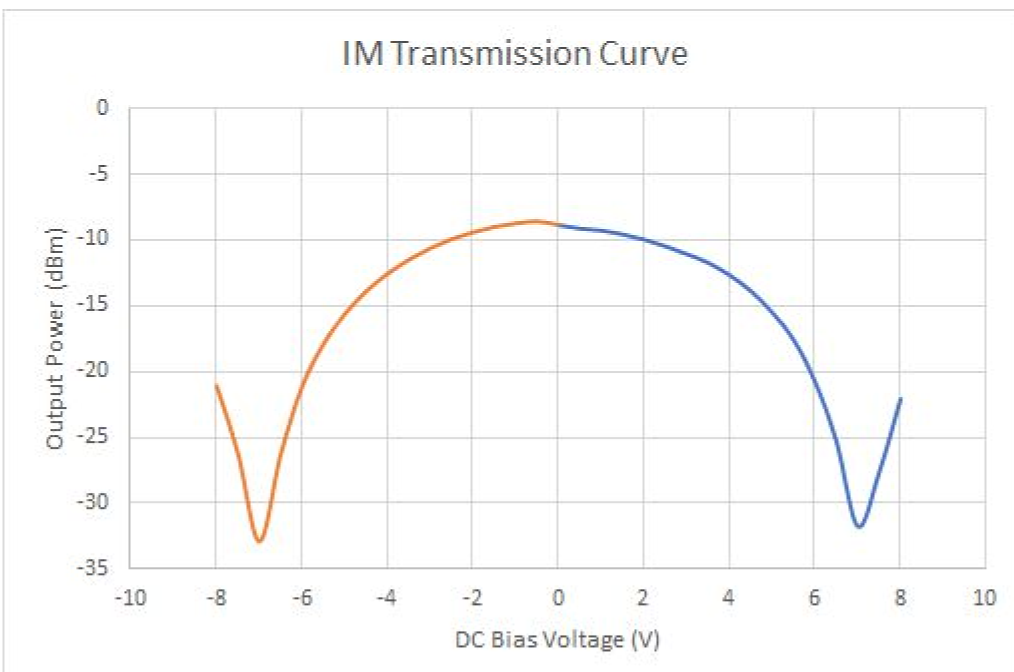


Figure 49: Intensity Modulator TRansmission as a Function of DC Bias

As expected, the optical power output varies with DC bias. This measurement is vital to the operation of the final system, because the DC bias point that is chosen for the intensity modulators will directly affect the degree to which the intensity modulators are able to “block” the unwanted sections of our serrodyne modulation ramps. Specifically, the electric square wave signal driving the intensity modulators will need to allow the modulator to “swing” from maximum to minimum output. Our electronic square waves are currently designed to operate from 0V to +/- 6V for the two intensity modulators, respectively. As such, the appropriate bias point would be either 0V or Vpi (7V), which would allow for the driving square wave to bias the modulator appropriately for our purposes. However, separate bias points could be used when adjusting RF phase to correctly window the electrical phase ramp. The effect on the optical output while biasing the intensity modulator with a 6 Vpp square wave voltage signal is shown in the figure below.

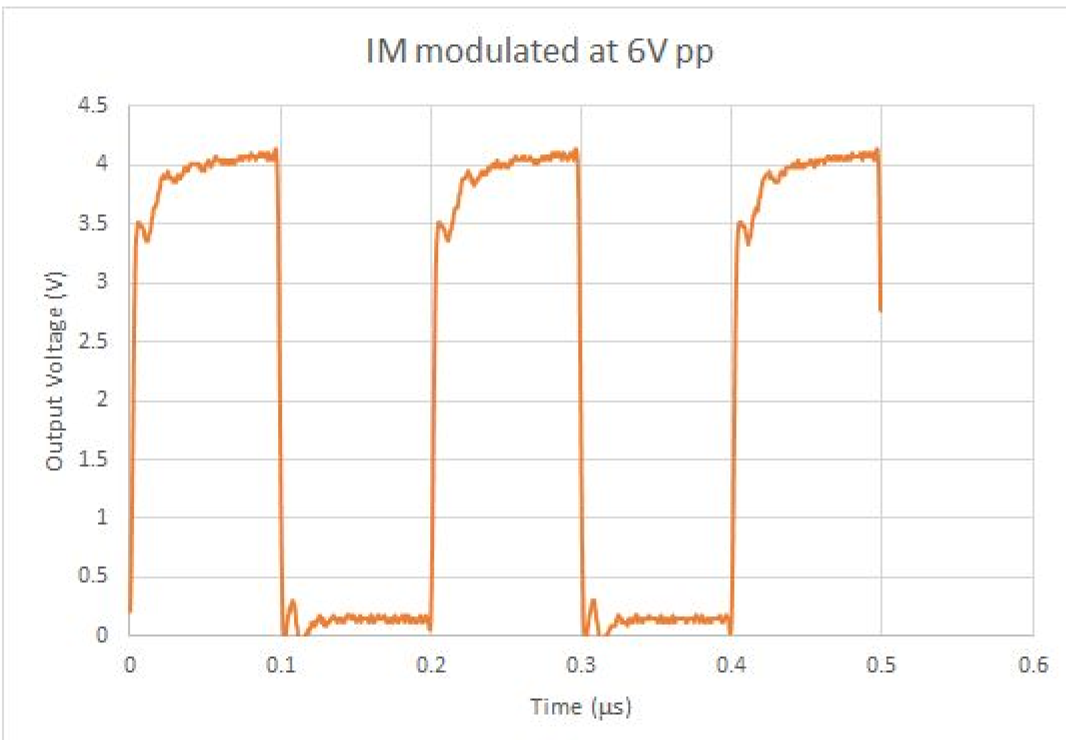


Figure 50: Optical transmission of square wave intensity modulation

The figure shown above shows that the modulation scheme designed is capable of suppressing optical amplitude sufficiently, and is thus capable of suppressing unwanted frequency components in the electrical ramp as expected.

Results from testing the serrodyne components of the photonics subsystem were also obtained. As discussed previously, in order to detect the frequency shifts imparted by our system it is necessary to optically down-convert through heterodyne detection. Initially, the system was designed using a single laser source which would be split into two branches. The serrodyne shift was to be imparted on one branch while the original frequency was maintained in the other, resulting in a heterodyne beat when combining these two branches. However, this led to significant amplitude instability when tested due to the interferometric nature of this design. This meant that any slight temperature change or perturbation of the optical fiber in either of the branches would result in a change in the interference of the signals, resulting in amplitude instability. In addition, centering the down-converted signal at 0 Hz resulted in overlap of the positive and negative frequency terms, which introduced further amplitude instability. The initial solution to this issue was to include two separate lasers with some frequency difference as opposed to a single laser, thereby suppressing coherent interference effects. However, the results obtained from testing this configuration showed an introduction of significant frequency instability caused by the inherent frequency fluctuations of the two lasers with respect to each other.

To satisfy both the frequency and amplitude stability issues, an optical frequency comb generated through electro-optical modulation of a single laser is used as the source for the system. This was accomplished by placing another phase modulator immediately after the laser and modulating with a microwave signal of sufficient power so as to generate a frequency comb from the corresponding modulation sidebands. For this system, the separation of the comb teeth was 10 GHz. The phase modulator used to generate the comb was an Eospace phase modulator provided by the sponsor. A customizable optical demultiplexer was then used to isolate two of the comb teeth into separate branches, thus allowing the selected comb teeth to function as two sources with offset frequency and therefore stable amplitude as well as relative frequency stability with respect to each other. The demultiplexer used was a Finisar Waveshaper 4000s and was also provided by the sponsor. Therefore, two sources were essentially used to optically downconvert as shown in Figure 53. The spectrum of this source and the block diagram for the source generation are shown in the following figures.

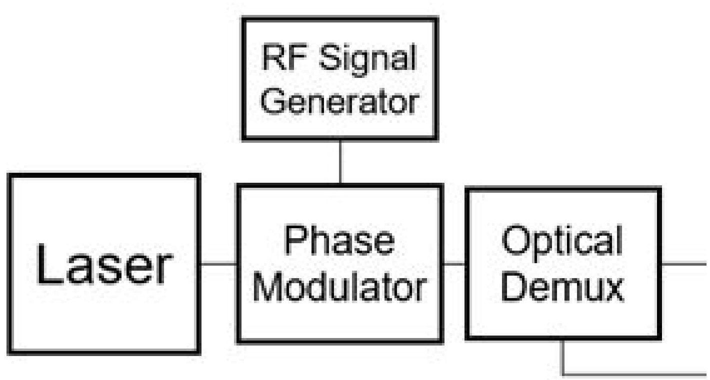


Figure 51: Source Block Diagram

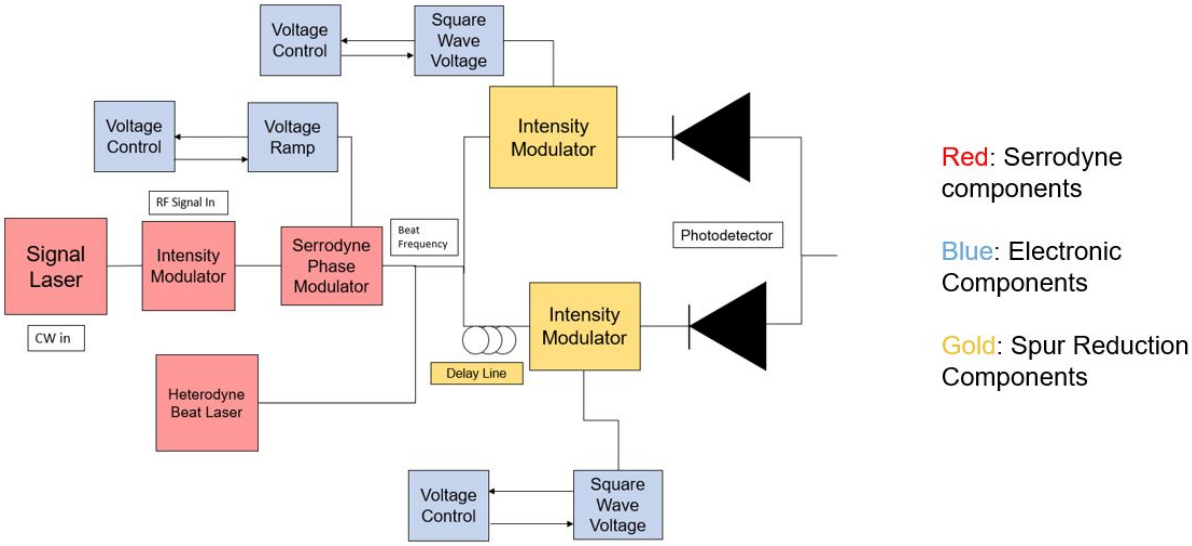


Figure 52: Final Block Diagram

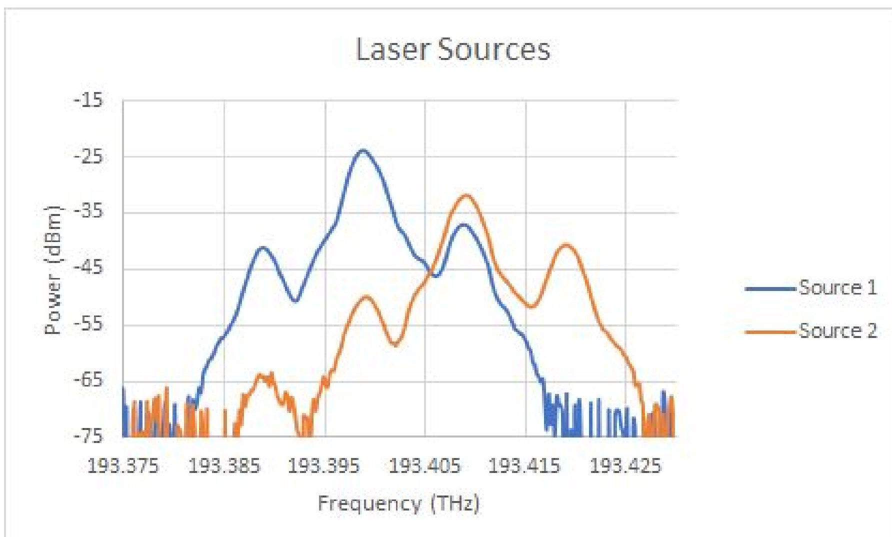


Figure 53: Spectrum of Optical Sources

The serrodyne subsystem as a whole was also tested. A 2.75 MHz sawtooth function was generated using a function generator, and was used to modulate one source as shown in Figure 53. The results were viewed using an RF spectrum analyzer and are shown below. Note that the boxed tone is the desired 2.75 MHz tone.

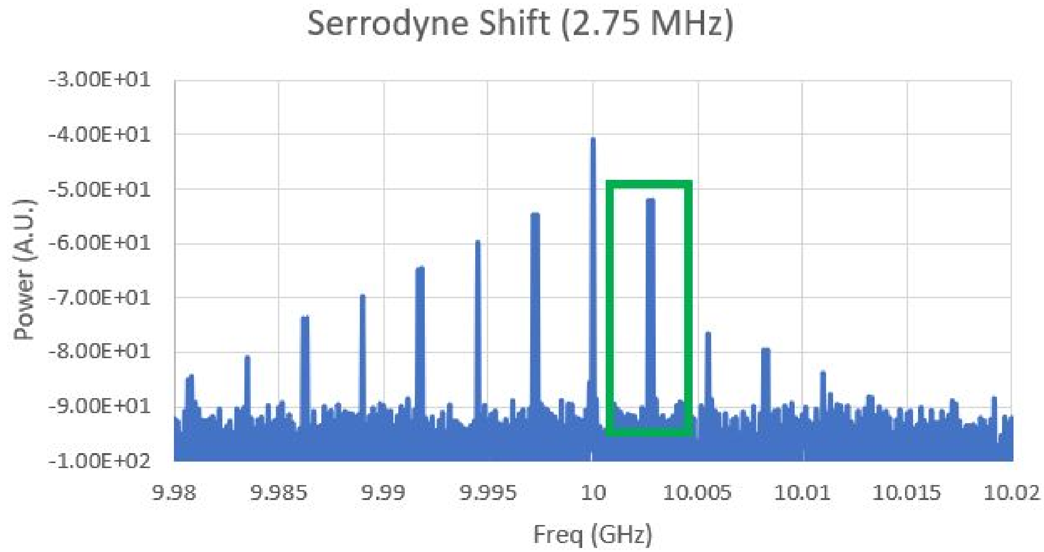


Figure 54: Serrodyne Shifted Optical Signal

The figure shown above depicts a 2.75 MHz shift, however there are several undesirable aspects. The frequency boxed in green depicts the 2.75 MHz shift that is desired. The other frequency components shown are the unwanted serrodyne spurs that are primarily a factor of the sawtooth electrical signal fall time. However, with the introduction of the spur reduction components, those will hopefully be reduced in amplitude. Another issue is the strong 10 GHz peak that still appears when applying serrodyne modulation. This peak corresponds to the 10 GHz spacing of the sources used. In an ideal system, this peak would drop in amplitude significantly. However, due to the complicated spectrum of our sources (see figure 53s), we see a strong 10 GHz peak corresponding to the 10 GHz spacing of the nearby comb lines in each source. Therefore, the inclusion of this peak is a factor of the functionally limited optical demultiplexer provided. Further testing was performed with different ramp frequencies ranging from 500 kHz to 2.5 MHz, which showed a direct correlation with the shifted signal that was detected. This shows that the optical subsystem of this project is capable of supplying a range of frequency shifts which satisfy the requirement specifications set by the sponsor, with shift resolution directly related to the electrical signals used. Overall, the initial results are promising, and begin to show the frequency shifting capabilities required by the optical subsystems of this project.

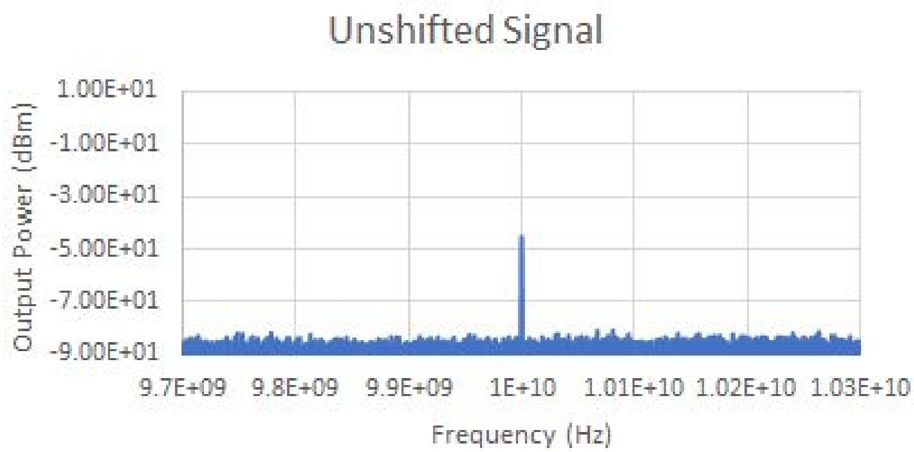


Figure 55: Unshifted Optical Signal

Figure 55 (shown above) shows the initial frequency tone created by the two sources that were generated by the optical frequency comb (see figure 53). The frequency difference between the peaks of the two sources was equal to 10 Ghz, thereby resulting in the tone shown above. This is the signal that will be shifted by implementing the serrodyne frequency shift. The frequency of the triangle wave applied to the phase modulator was 100 MHz.

The triangle waveform at 100 MHz that is applied to the phase modulator results in a close to ideal sawtooth waveform with the use of the two intensity modulators. This results in a sawtooth waveform with a frequency of 200 MHz. Therefore, the frequency shift induced onto the original signal is 200 Mhz. Figure 56, shown below, shows the shifted signal after it has passed through the phase modulator. As is evident in figure 56, there are obvious spurs that occur. These were anticipated, and expected. In the next paragraph, the frequency spur reduction implementation will be shown.

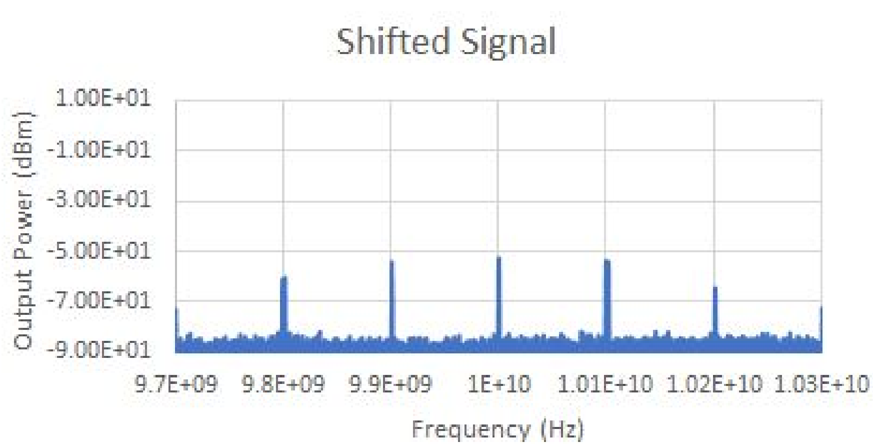


Figure 56: Shifted Optical Signal with 100 MHz Triangle Wave

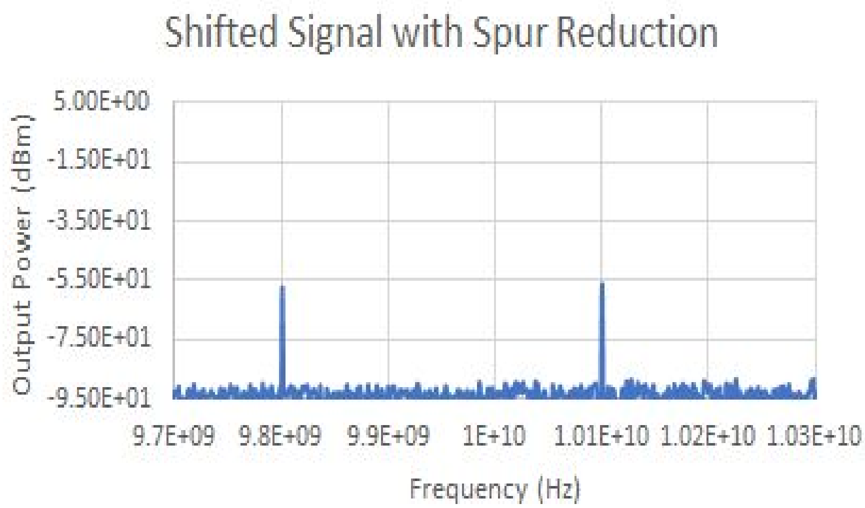


Figure 57: 200 MHz Red-Shifted Signal with Spur Reduction (2 Averages)

After the spur reduction was implemented (using the two intensity modulators and the delay line), the resultant frequency spectrum (after just two averages) is shown above in figure 57. It is apparent that the frequency spurs have been drastically reduced, and they are now below the noise floor. The peak power has been, for the most part, maintained with minimal loss introduced. The shifted signal is the 200 MHz tone on the left. Again, this resultant trace is after just two averages. This shows that the spurs in the shifted signal have been successfully reduced. However, there is still a single tone (shown on the right) that is unwanted. The details of why this occurs is discussed in the next paragraph.

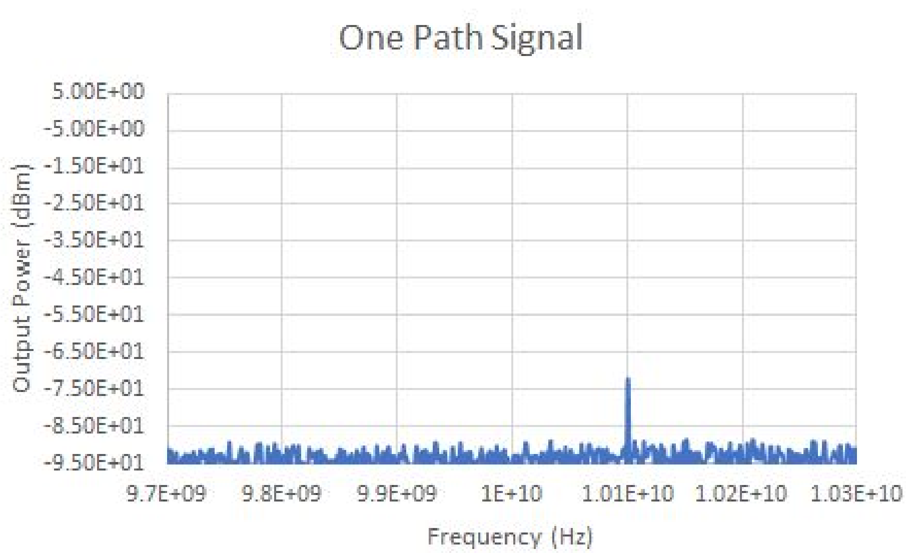


Figure 58: One Path Signal to Diagnose Unwanted Spur

The single unwanted frequency tone, shown on the right of figure 57, was investigated. It was found by troubleshooting that this unwanted frequency tone is a byproduct of the imperfect sources that were used. This was found by disconnecting one of the sources, and observing that the frequency tone was still present, even though the other laser that should be beating with it was removed (see figure 58 above). If the sources had a better linewidth, this unwanted tone would disappear. Due to the nature of the sources and the demultiplexer that was available at the time, this tone could not be removed. Nevertheless, the spur reduction proved to be successful.

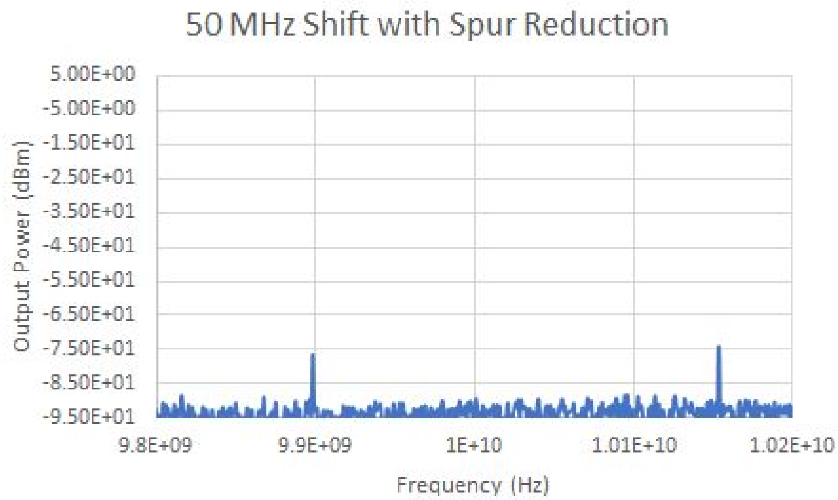


Figure 59: Repeated Experiment with 50 MHz Triangle (100 MHz Red-Shift)

Because the system needs to cause multiple frequency shifts, a 50 MHz triangle wave was input to the phase modulator to induce a 100 MHz red-shift. The resultant trace is shown above in figure 59. It is apparent that the frequency of interest (on the left) has shifted 100 MHz. Again, this trace is done with only two averages. The unwanted frequency tone due to the nature of the sources is still present, but this is to be expected.

Overall, the optical subsystem worked as predicted. Successful frequency shifts were produced, and the spurs resulting from the reset time of the sawtooth function were also successfully reduced. Although it was not perfect spur reduction due to having an unwanted frequency tone, if there were more ideal sources available, the unwanted tone would disappear. Also, although only two frequency shifts were shown, many more would be able to be created with the proper electrical signals. This system will be able to reach the number of frequency shifts needed. The sponsor of this project will be able to take this work and further modify and optimize it to meet their needs.

10.2 Electronics Subsystem

This section shows the final results for the electronics portion of this system. The final design used dual power supply rails of positive and negative 6 Volts. The oscillator portion of the circuit was replaced by a surface mount oscillator package due to complications from the original oscillator built from scratch. This output went into the comparator where the square wave was generated. The square wave was amplified into the triangle wave portion of the circuit. Originally the positive and negative triangle waves were selected using two transistors biased via the microcontroller. It was found that the negative portion of the triangle wave was destroyed due to the transistors becoming reverse biased. To remedy this, a multiplexer was used that allowed current flow in both directions. The software selected which line of the multiplexer to use for the positive or negative triangle waveform. These triangle waveforms were then supposed to pass through the digipot to scale the peak voltages in a voltage divider format. It was later found that the digipot could not operate at the desired frequency of 50 MHz due to internal capacitance filtering away the signal. A secondary multiplexer/demultiplexer was used in place of the digipot. Each output line of the multiplexer connected to a unique voltage divider. The line used was also selected by the microcontroller. For the purposes of demonstration, only four voltage dividers were used, but the circuitry could be upscaled to accommodate more signal steps. However, it was suggested that moving forward it would be better to vary the frequency of the triangle wave rather than the peak-to-peak voltage. A future design could implement a digitally-controlled oscillator to do this. Each output connected to SMA jacks to interface between the electronics and optics.

The code for this design was simplified for demo purposes to account for fewer delay steps. The code needed to control the two multiplexers. Table 9 shows a truth table for these multiplexers, and figure 60 shows an oscilloscope trace of the code running for a step duration of roughly 1 second. The variable ‘i’ is a global counter that determines when the software interrupt triggers and when it resets.

Counter i	A2 select	A1 select	A0 select	Enable	+/- triangle
0	0	1	1	1	1
1	0	0	1	1	1
2	X (0)	X (0)	X (1)	0	X (0)
3	0	0	1	1	0
4	0	1	1	1	0

Table 9: Multiplexer truth table for 5 delay steps

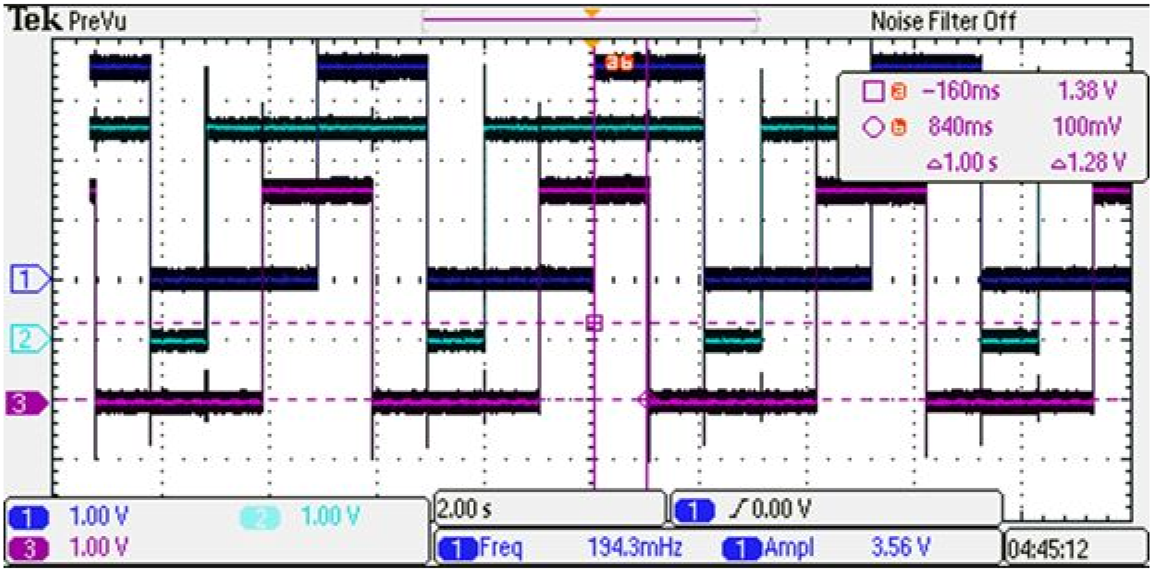


Figure 60: Microcontroller software shown via oscilloscope traces

Figures 61-63 show the outputs of our desired waveforms. The square wave was having some stability issues, but due to time constraints could not be resolved. In the future it is recommended that some external hysteresis be added along with some decoupling capacitors on all reference voltages. This should hopefully clean up the signal. It could also just be that the oscilloscope used to measure the waveform could not capture all harmonics of the signal. The signal itself is 50 MHz and the oscilloscope is rated for 200 MHz. The voltages are not entirely what was desired, but some external amplification stages may be added to correct this. The oscillator outputs a clipped sinusoid, but the comparator should clean this up when converting to the square wave.

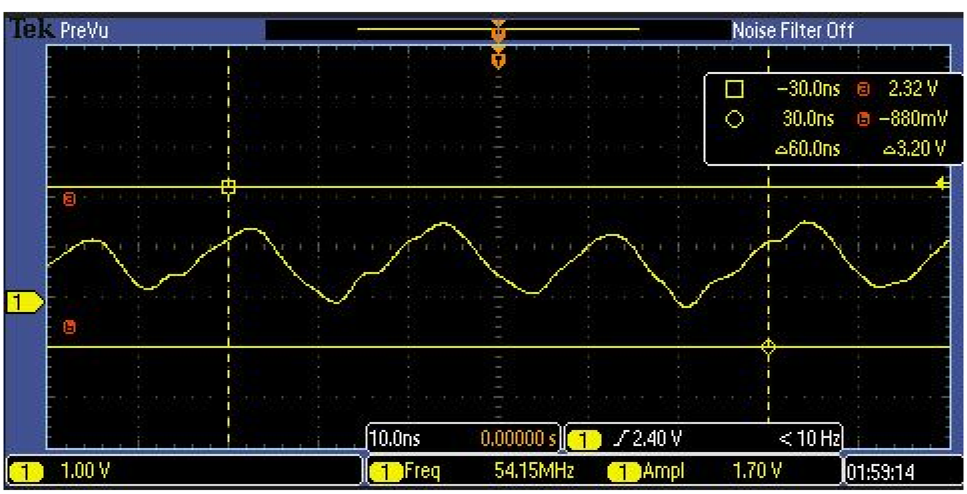


Figure 61: Positive triangle output waveform from printed circuit board.

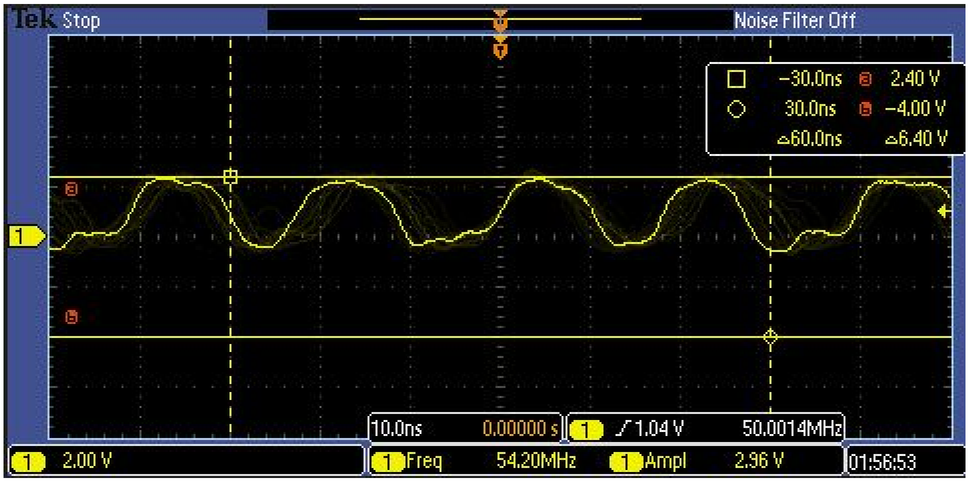


Figure 62: Positive square output waveform from printed circuit board.

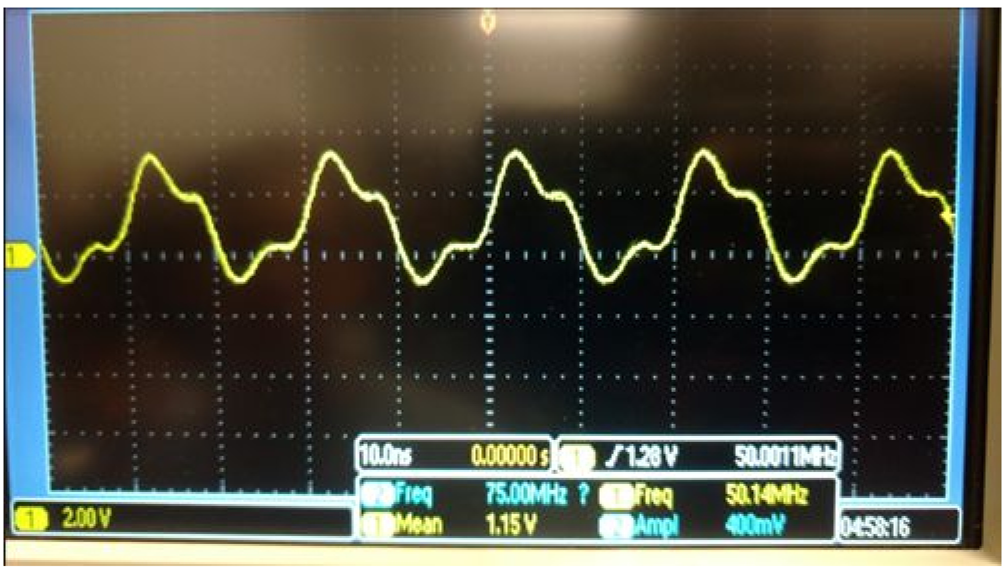


Figure 63: Oscillator clipped sinusoidal output waveform from printed circuit board.

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