Switchable Radio over Fiber System for Low-Cost Operation of Multiple RF Inputs

Group 10

Team Members

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Project Motivation

- Problem statement from sponsor
    - High speed communications hardware is expensive
    - In typical systems, need a full communication link for each RF band
    - Inefficient use of hardware
    - Especially if not all bands needed simultaneously
- To solve this, we will implement optical switching in an RFoF link
    - MEMS fiber devices
    - Wavelength Division Multiplexing (WDM) used to selective direct signals
    - Asymmetric, 3 bands 2 receivers architecture

Project Goals

Basic	Advanced	Stretch
● Utilize a Mach-Zehnder modulator to modulate signals up to 25 MHz ● Have a low bit error rate to enable essentially error-free communication ● Design 3x2 non-blocking optical switching system ● Implement simple modulation schemes such as FSK or OOK	● Increase system bandwidth to 2.4 GHz ● Integrate the RF link with a software-defined radio interface ● Improve the signal-to-noise ratio in order to use higher-order modulation schemes ● Implement more advanced modulation schemes such as QPSK and QAM	● Increase system bandwidth beyond detector bandwidth with heterodyne detection ● Extend the frequency range up to 12.6 GHz ● Integrate phased-array antennas to enable beamforming and adaptive beam steering for enhanced communication performance and coverage. ● Incorporate RF or optical circulators to allow the communication link to be full or half duplex

Project Objectives

- Design/align
  - Diffraction grating-based wavelength division multiplexing system
  - 2x3 optical switching mechanism based on 1x2 fiber-optic-based switches
  - Laser diode system to generate and efficiently couple light from the laser diodes to the switches
  - Photodiode system capable of measuring frequencies up to the system bandwidth
- Use an optical modulator to modulate the intensity of light to carry an RF signal
- Run tests to measure the bit error rate, data throughput, and system bandwidth
- Obtain access to a lab with spectrum analyzers, signal generators, and power sensors to test and troubleshoot RF amplifiers, transmitters, and receivers
- Perform a link budget analysis to ensure that the transmitted RF signals can be adequately detected at the receiving end

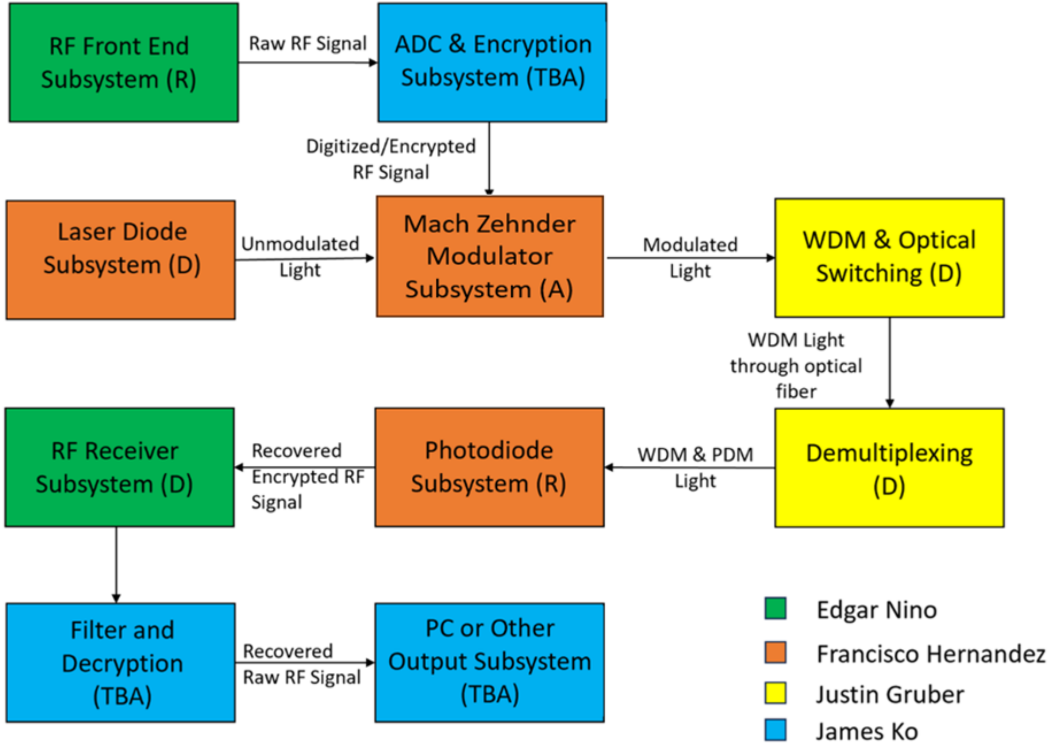
Engineering Specifications

Components	Specification	Values
Photodiode,Mach-Zehnder modulator, and RF filters	System Signal Bandwidth	30 MHz to 500 MHz
Mach-Zehnder modulator and fiber optic	Data Transfer Rate	1 GB/s
Link budget across all optical components	Optical Signal-to-Noise Ratio (SNR)	25 dB
RF filters and amplifiers	Spurious-Free Dynamic Range	60 dB
Fiber optic	Transmission Distance	2 km
Entire system	Bit Error Rate (BER)	$< 10^{-3}$
Laser diodes	Wavelength Channel Spacing	20 nm
Laser diodes	Optical Power Output	10 mW
Entire system	Total System Power Consumption	<50 W

Engineering Specification (Continued)

Components	Specification	Values
1x2 Fiber Switch	Switching Time	< 25 ms
Laser diodes	Number of WDM Channels	2
Diffraction Grating	WDM Free Spectral Range	750 nm
Fiber collimating/focusing lenses	Fiber coupling losses	<15 dB @ 30 cm separation
Photodiode	Optical bandwidth	1530-1625 nm (C+L bands)
Collimating lens	Collimated Beam Size	< 3 mm
Collimating lens	Coupling losses	< 1.5 dB
Multiplexing system	Size	10x10x10 cm
Entire System	Total system cost	< $15,000

Hardware Block Diagram



Legend

WDM: Wavelength Division Multiplexing
PDM: Polarization Division Multiplexing
TBA: To be acquired
D: Currently being designed
C: Completed
A: Acquired
R: Approach being researched

Component selection

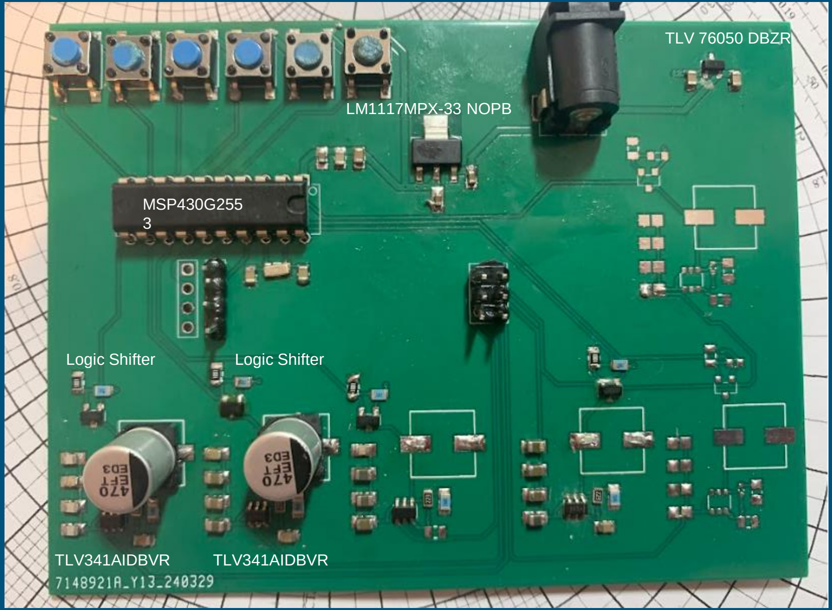
Feature	MSP430G 2553	ESP WROOM 32
Manufacturer	Texas Instrument	Espressif
GPIO	20	38
Operating Voltage	1.8V - 3.3V	3V
Development Tools	Code Composer Studio	Arduino IDE
Cost	$2 - $5	$3 - $10

LM1117MPX-33 NOPB	TLV 76050 DBZR	AMS1117
On Semiconductor	Texas Instrument	Advanced Monolithic Systems
3.3V output	5V output	3.3V output
800 mA output	100 mA	1A

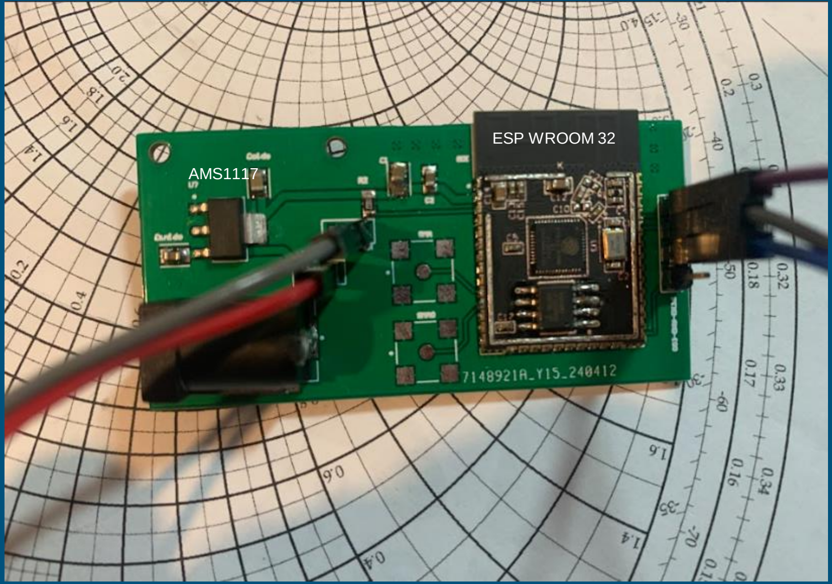
TLV341AIDB VR
Texas Instrument
Operational amplifier
Suggested by MEMS switch manufacturer

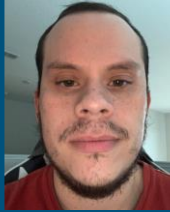
Printed Circuit Boards

Switch Driver



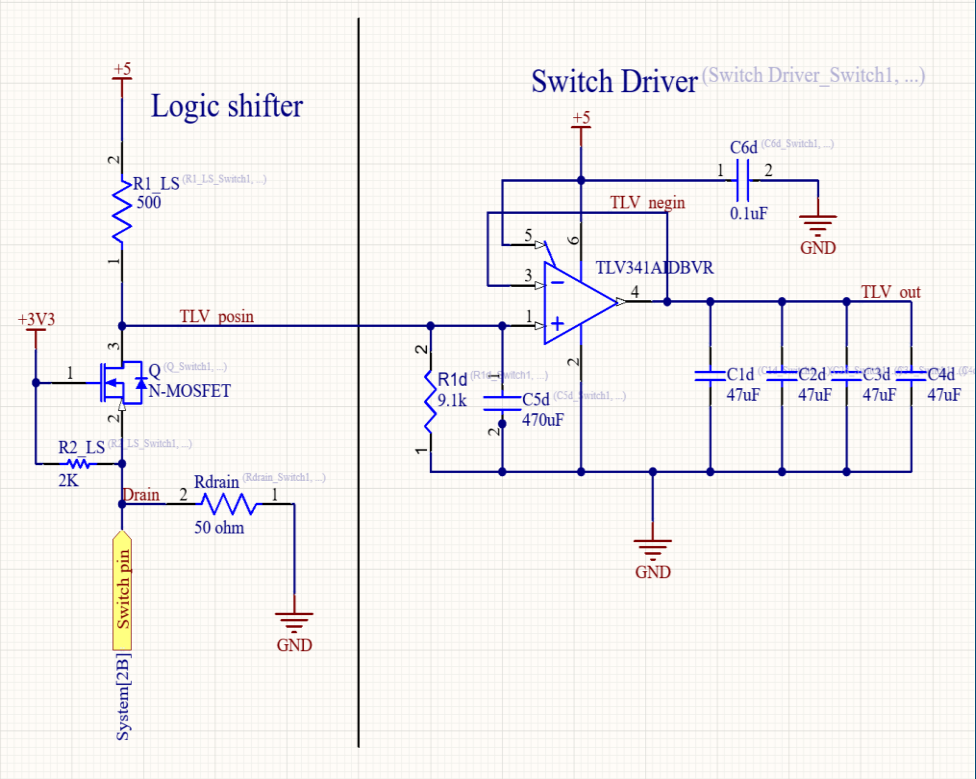
RF receiver





Switch driver

- Logic shifter needed to convert 3.3V to 5V
- MCU is programmed to output 3.3V and select which switch to activate.
- When 3.3V are applied, the MOSFET is off (Vgs = 0), then the TLV sees 5 Volts with a voltage division

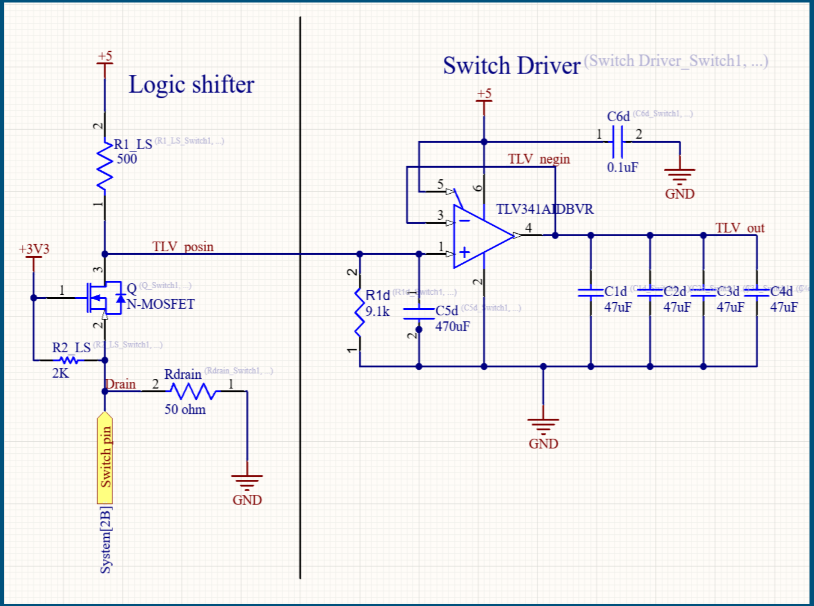


Issues and Troubleshooting

MSP430 Maximum current was exceeded with a 50 ohm voltage sink in the logic shifter (MSP outputs 6 mA, but with 50 ohms, it was drawing 66mA).

Resistors in logic shifter and voltage divider of the MEMS switch driver had to be scaled up. 50 ohms to 1K ohms, 500 to 22.1K ohms, 9.1K to 90K ohms to have the same logic shifter effect.

MEMS manufacturer mentioned later that the input to the switch driver should be 4V.



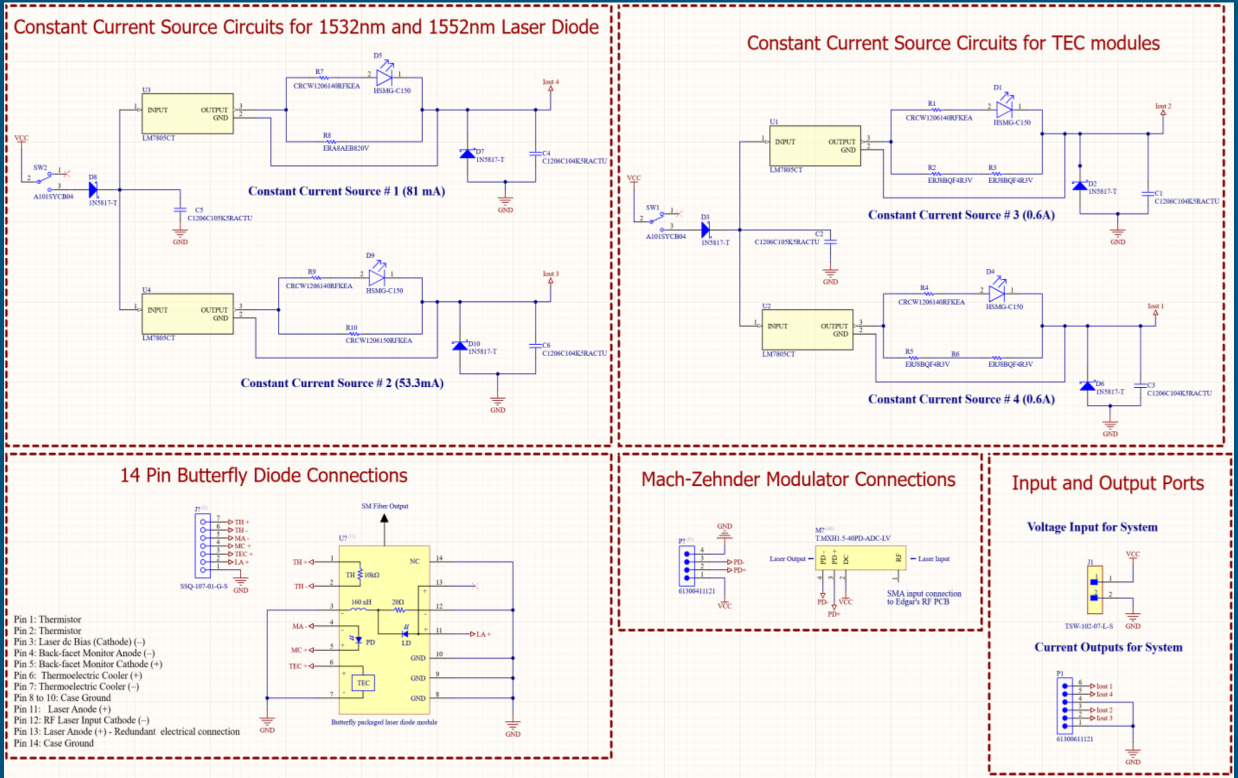
Optical Transmitter Design

A full system consisting of 3 crucial components to transmit signals over fiber optics:

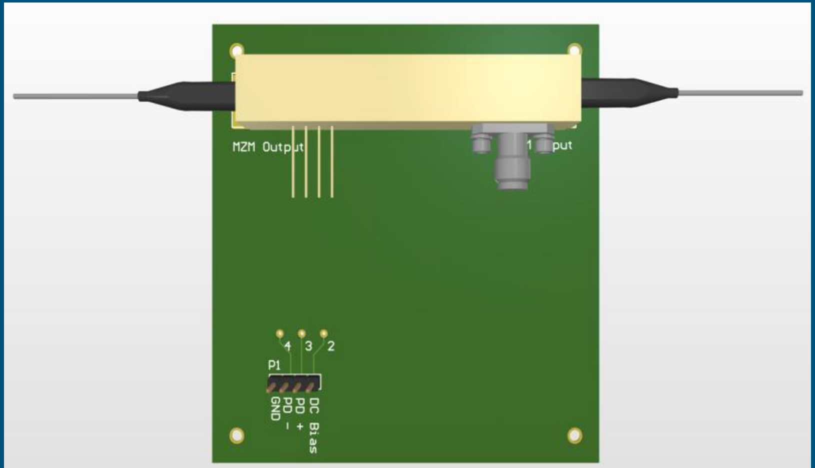
1. A constant current source to forward bias a laser diode in to operate in continuous wave mode

2. An MZM modulator takes in the RF signal as an input and modulates the CW laser

3. The information originally carried by the RF signal, is now transferred to an optical carrier signal, and will be transmitted into a fiber optic channel.

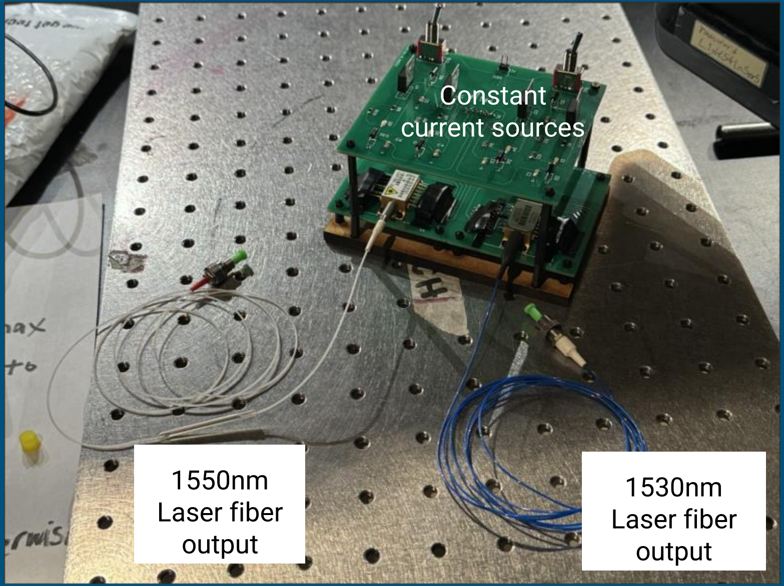


Prototype of Optical Transmitter



Mach zehnder modulators with jumper wires soldered onto the Anode ,Cathode, and DC pins

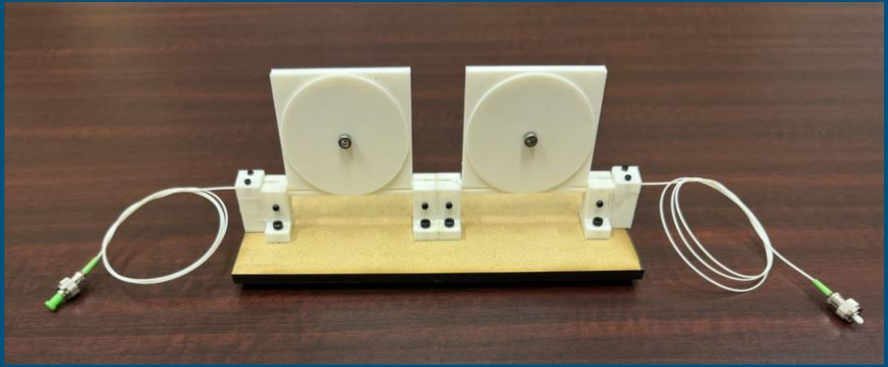
+



Laser diode and constant current source PCBs together

Fiber Polarization Controller

- A device that converts an arbitrary input polarization state to any desired output polarization state.



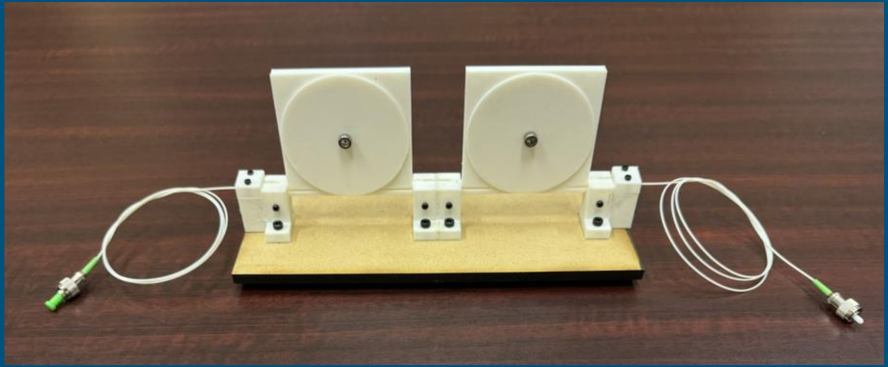
- Ensures that the maximum power from the laser diode is transferred to the modulator and fiber optic channel.

Polarization mismatch loss factor

$$L = \frac{P_{matched}}{P_{received}} = \cos^2(\theta) = \left(\frac{\hat{a}_{laser} \cdot \hat{a}_{modulator}}{|\hat{a}_{laser}| * |\hat{a}_{modulator}|} \right)^2$$

Fiber Polarization Controller (Continued)

- A device that converts an arbitrary input polarization state to any desired output polarization state.



- Ensures that the maximum power from the laser diode is transferred to the modulator and fiber optic channel.

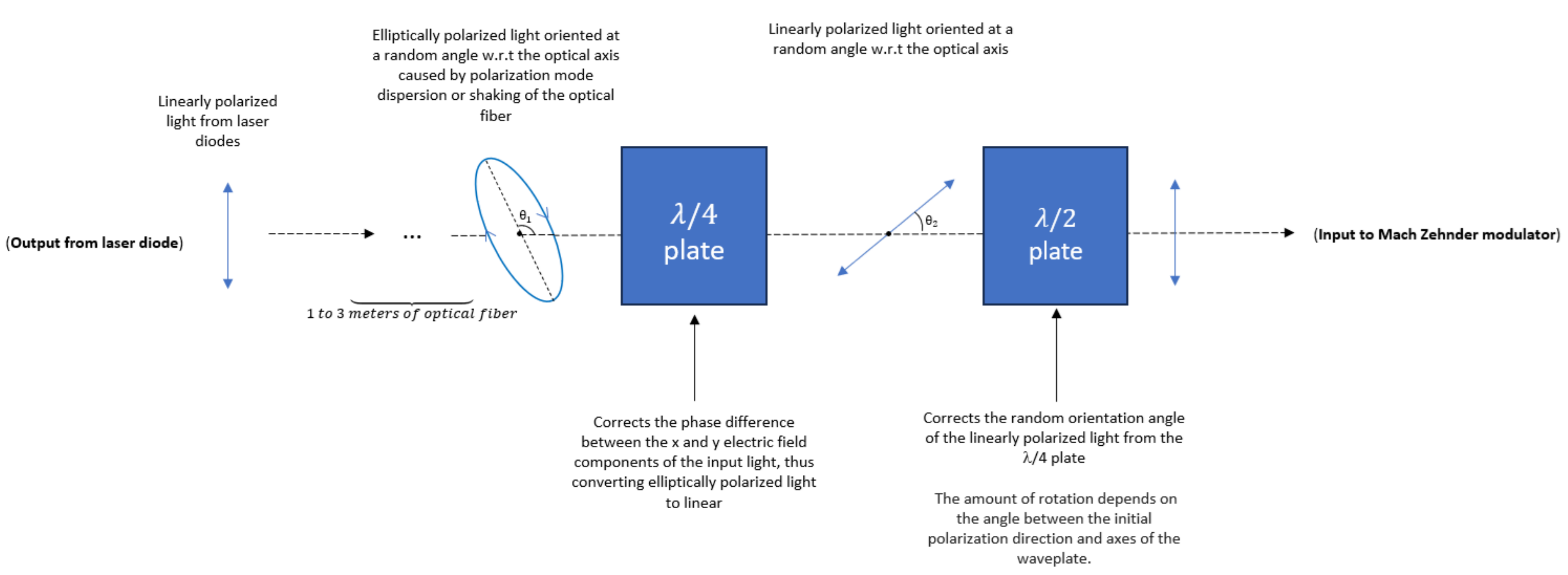
Jones Matrix To Describe the Input to Output Polarization Conversion from the 2 Paddle Fiber Polarization Controller for Polarization Matching

$$\begin{bmatrix} E_y \\ E_x \end{bmatrix}_{out} = POL_Y * HWP(\psi_2) * QWP(\psi_1) \begin{bmatrix} E_y \\ E_x \end{bmatrix}_{in}$$

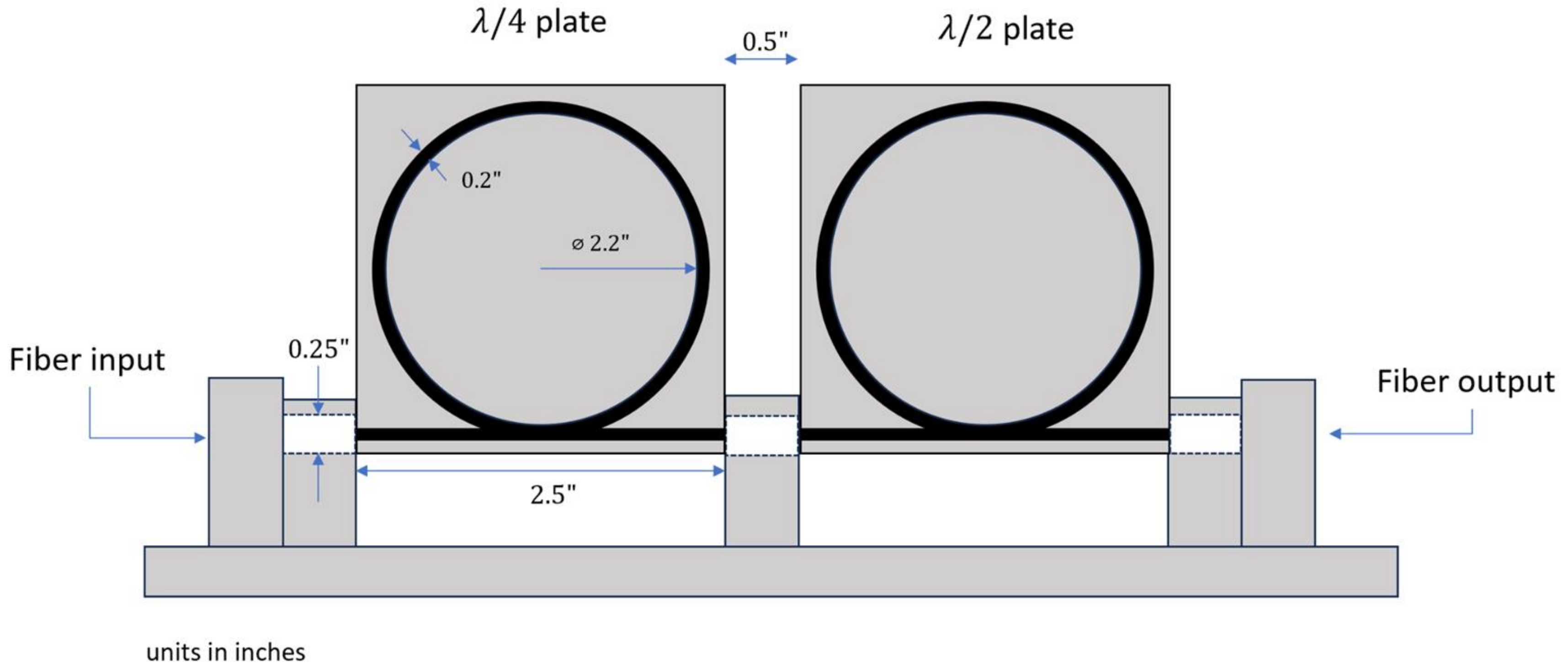
$$\begin{bmatrix} E_y \\ E_x \end{bmatrix}_{out} = \left(\underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}}_{\substack{\text{Jones matrix for a} \\ \text{linear polarizer oriented} \\ \text{in the} +y \text{ direction}}} \right) \times \left(\underbrace{-j \begin{bmatrix} \cos(2\psi_2) & \sin(2\psi_2) \\ \sin(2\psi_2) & -\cos(2\psi_2) \end{bmatrix}}_{\substack{\text{Jones matrix for a} \\ \text{half wave plate}}} \right) \times \left(\underbrace{\frac{1}{\sqrt{2}} \begin{bmatrix} 1 - j\cos(2\psi_1) & -j\sin(2\psi_1) \\ -j\sin(2\psi_1) & 1 + j\cos(2\psi_1) \end{bmatrix}}_{\substack{\text{Jones matrix for a} \\ \text{quarter wave plate}}} \right) \begin{bmatrix} E_y \\ E_x \end{bmatrix}_{in}$$

$$\begin{bmatrix} E_y \\ E_x \end{bmatrix}_{out} = \left(\underbrace{\frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 \\ \sin(2(\psi_1 - \psi_2)) - j\sin(2\psi_2) & -\cos(2(\psi_1 - \psi_2)) + j\cos(2\psi_2) \end{bmatrix}}_{\text{Jones matrix for a 2 paddle fiber polarization controller}} \right) \begin{bmatrix} E_y \\ E_x \end{bmatrix}_{in}$$

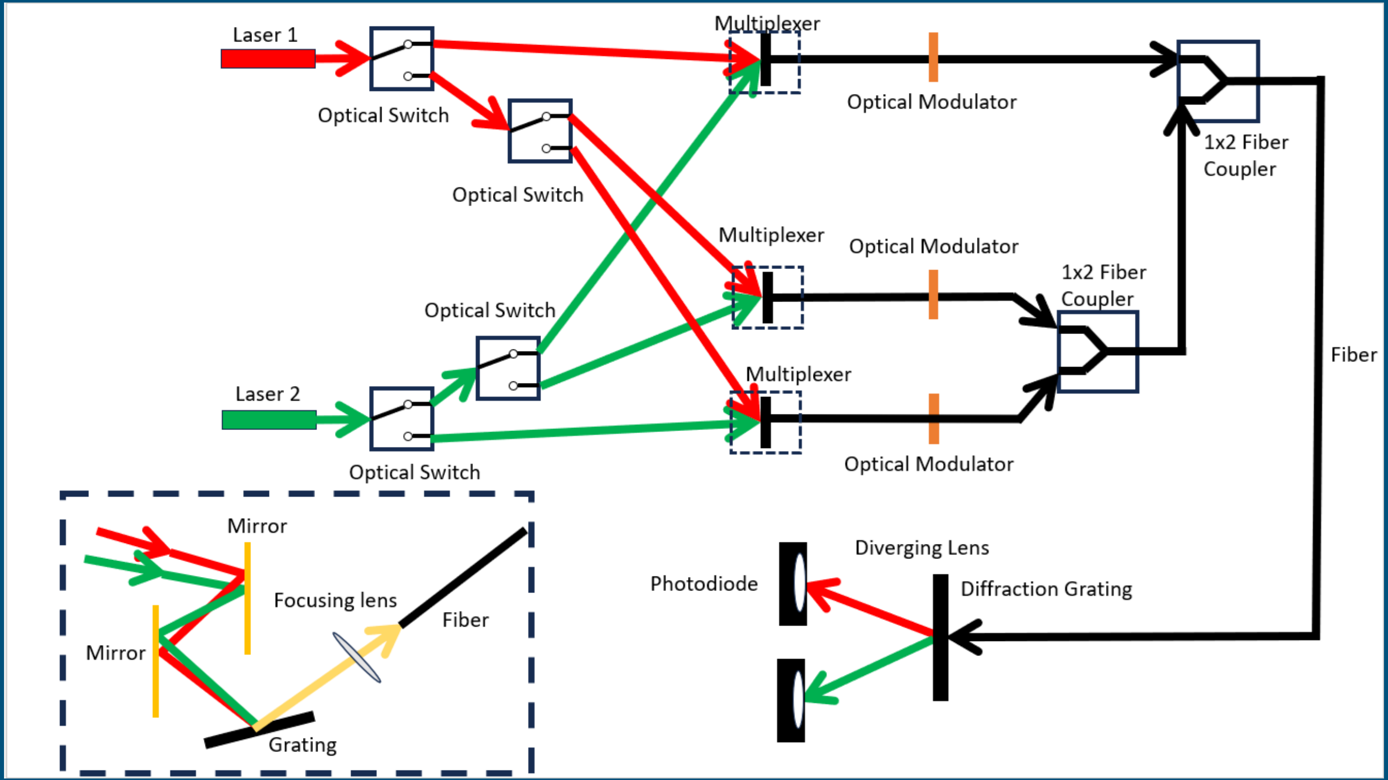
Fiber Polarization Controller (Continued)



Fiber Polarization Controller (continued)



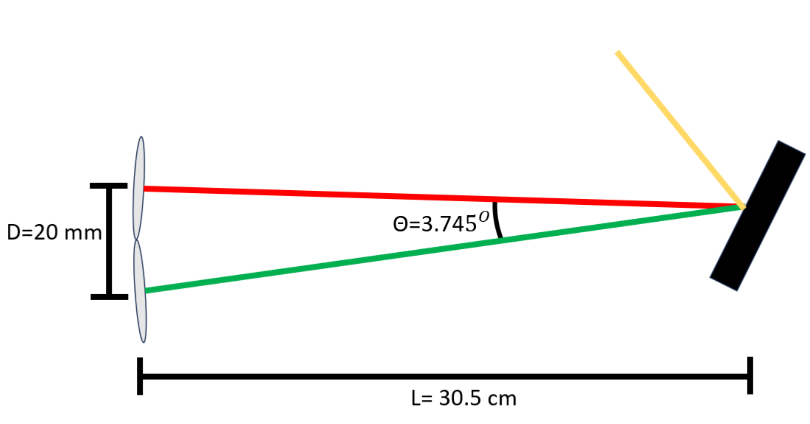
Optics Block Diagram



De/multiplexing Design

$$atan\left(\frac{1.25/2}{7.5}\right) = 4.764^{o}$$

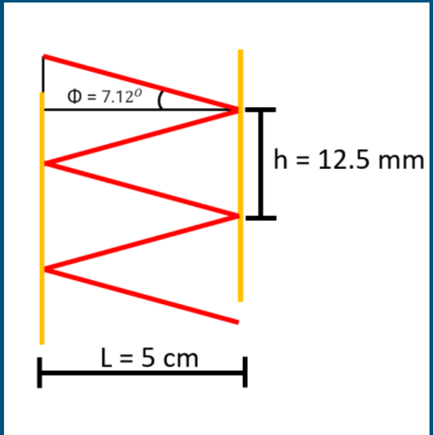
- Multiplexing is combination of different wavelengths of light
- Different wavelengths experience different angles of diffraction
- Even with large dispersion, angle difference is small (~3.4°)
- Use mirror cavity to get long path length, but small device size



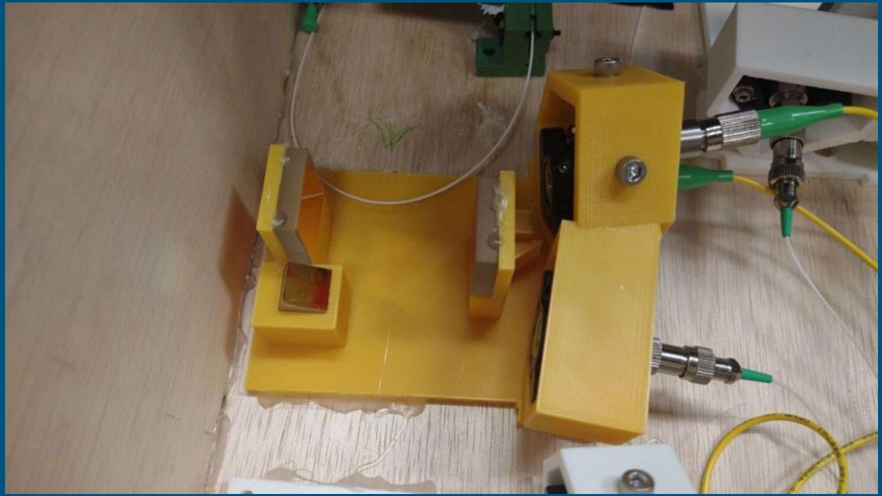
$$\sin(\theta_m) = \sin(\theta_i) + m\lambda f$$

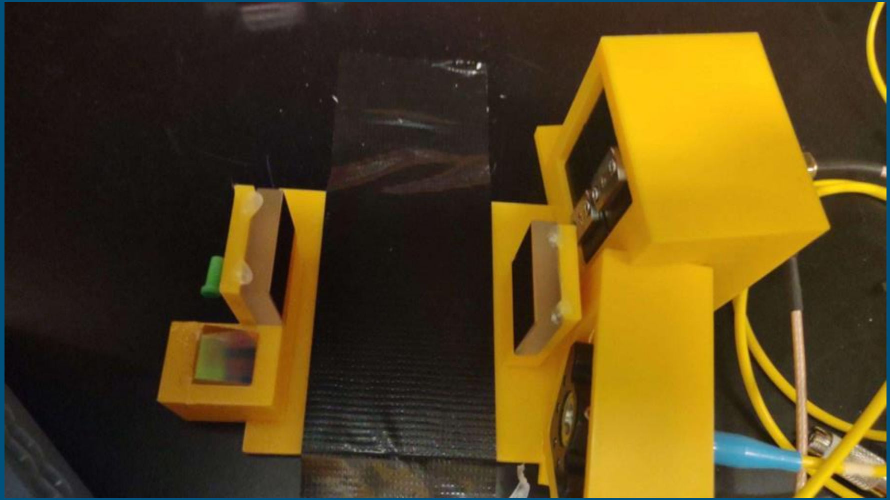
$$\theta_m = 68.43^{o}$$

$$\theta_i = asin(\sin(\theta_m) - m\lambda f)$$



De/multiplexing Design





Diffractive Element Part Selection

$$\sin(\theta_m) = \sin(\theta_i) + m\lambda f$$

$$\theta_m = 68.43^o, 64.685^o$$

- Need to separate ~20 nm (1550-1530 nm)
- Detector housing size is a design constraint
- Requires strong dispersion
  - Use diffraction grating rather than prism
- Designed a diffraction grating + mirror cavity system

Supplier	Part Number	Angular Dispersion	Free Spectral Range	Grating Efficiency	Unit Cost
ThorLabs	GR13-0616	1.46 nm/mrad	800 nm	92.5%	$76.58
Spectrum Scientific Inc.	1200-1550-012-S-S	0.306 nm/mrad	775 nm	93%	$85.00
Optometrics	G600R1.6CEAS	1.46 nm.mrad	800 nm	90%	$76.00

Mirror Part Selection

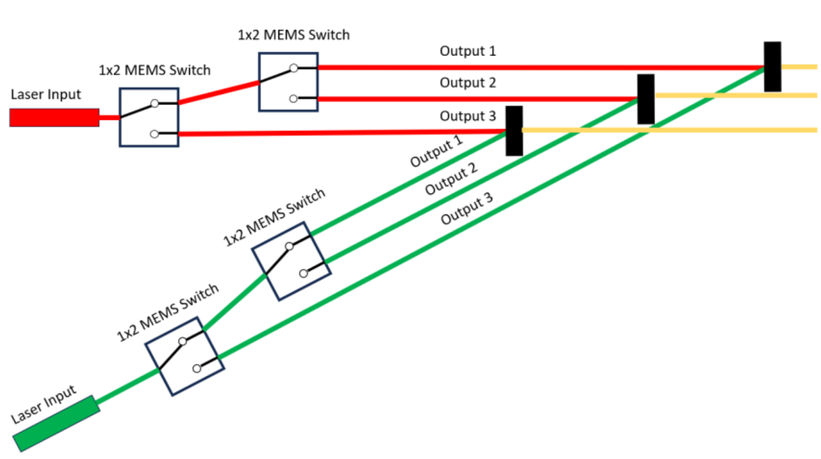
- Require low losses
- Must be balanced with cost
- Clear aperture must be large enough to fit both beams

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

$$10 * log10(0.97\text{^}5) = -0.66\ db$$

MEMS Optical Switch Part Selection

- MEMS device switches fiber to 1 of 2 output ports
- Will combine 1x2 switches to create switching subsystem
- Need two 1x3 switches, one for each laser
- Need high isolation to minimize crosstalk



Supplier	Part Number	Isolation	Insertion Loss	Maximum Power	Switching Time	Unit Cost
Agiltron	SM28	70 dB	< 0.4 dB	1 W	< 0.9 ms	$265.00
Agiltron	MISW-12 B211333	60 dB	< 1 dB	0.3 W	< 10 ms	$125.00
ThorLabs	OSW12-1 310-SM	75 dB	<1.5 dB	0.3 W	< 1 ms	$1,126.20
Newport	MS-1315 TT-12	50 dB	<0.7 dB	0.5 W	< 10 ms	$800

2x1 Fiber Coupler Part Selection

- Need to combine outputs of all three modulators
- All signal propagate through transmission fiber together
- Requires fiber couplers
- Need low loss coupling
    - Excess loss is true “loss”
    - Insertion loss is not truly lost
    - Uniformity unimportant, calibration
- Agiltron has >6 week lead time

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

Fiber Collimator/Focusing Lens Selection

- Diffraction gratings are free space components
- Require fiber-free space-fiber coupling
- Waist diameter must be smaller than detector size (3mm)
- Must balance loss and spot size
- Simulated in Zemax
- < 1 dB loss

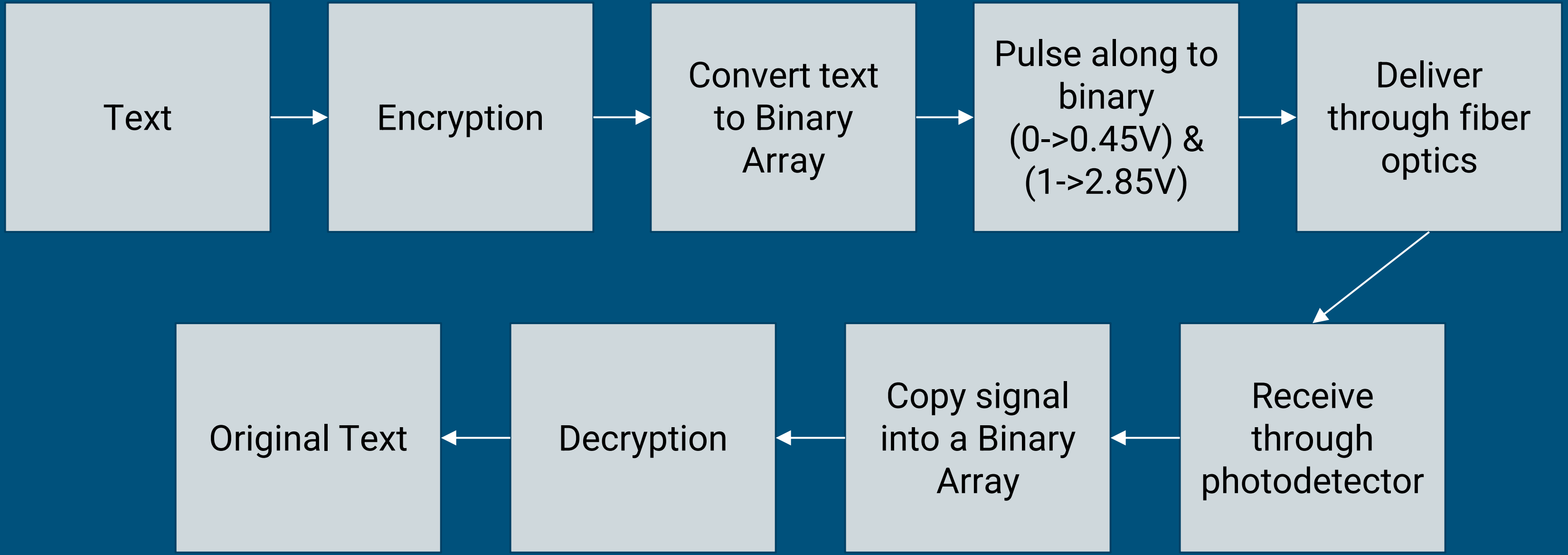
$$NA_{lens} < NA_{fiber}$$

$$\frac{4\lambda}{2\pi * \tan(\operatorname{asin}(NA_{fiber}))} > \emptyset$$

System Efficiency	0.870732
Receiver Efficiency	0.943430
Coupling Efficiency	0.821474 (-0.8541 dB)

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

Software Flow State Diagram



Text To Binary Conversion

To change a letter or string of letters into a binary array one must first convert the letters into a numerical value specifically the its equivalent ASCII value

Then with that ASCII value of the letter one will convert that into binary with increase bits

Next we will continue for the rest of the string of letters after.

Finally we will do these things in reverse to get the original message back.

Encryption

Encryption involves the use of a ciphergraph. This is essentially a mathematical algorithm that will shift the values of the message being encrypted into a line of text that is unreadable to the human eye.

Encrypting a message requires a key to do show as to mix up the encryption algorithm and that key is the only way the message can be decrypted.

If the key is not identical to the key used to encrypt it then when trying to decrypt a message that message will become even jumbled and is still unreadable.

Standards

- ITU G 694.1/694.2 (CWDM and DWDM standards)
  - 20 nm spacing (1530 & 1550 nm)
- ITU G.9803 (RFoF)
- IEC 60825-1 (Laser safety classes)
  - Class 3 laser
  - Eye hazard
- ANSI Z136 (Laser safety precautions)
  - Proper safety precautions
- Coding Standards
- Encryption Standards
  - Method of encryption
  - Encryption keys must match

Issues and Troubleshooting

- MEMS Switches failing
  - After a few days of running
  - Significantly less than stated lifetime
  - Under maximum voltage
  - Could not locate issue, removed from system
- Alignment is very sensitive
  - Temperature dependent
    - Wavelength changes
  - Vibration dependent
    - Minimal- see video for vibration test
  - Polarization dependent
- Electrical amplifier not working
  - Needed transimpedance amplifier
  - Replaced with optical amplifier
  - Spectral broadening

Design Constraints

- Time
  - Our design was too big for the time allocated and with the team size
- Economic
  - Though we have the funding of “Critical Frequency Design”, we did not have those funds readily available to us to use. Along with a deadline we would not be able to grab parts necessary
- Safety
  - As we are using lasers, we could get eye damage and we could set fire to the housing

Bill of Materials/Budget

Item	Supplier	Part Number	Unit Price	Quantity	Estimated Price
Mach-Zehnder Modulator	Sumicem	T.MXH1.5-40PD-ADC-LV	$249.99	3	$749.97
Single Mode Optical Fiber	Thorlabs	SM-28	$0.6144/m	100 m	$61.44
Laser Diodes	Laser Diode Source Laser Diode Source	OSC-LDS-C-039C LC25W5172BAX-J34	$240.00 $310.00	1 1	$240.00 $310.00
Photodiodes	Thorlabs	DET08CL	$319.11	2	$638.22

Bill of Materials/Budget Cont.

Diffraction Grating	Spectrum Scientific Inc.	1200-1550-012-S-S	$85.00	4	$340.00
Collimating Lens UPC	Thorlabs	F260FC-1550	$177.45	4	$532.35
Collimating Lens APC	Thorlabs	F260APC-1550	$240.45	6	$1442.7
Kinematic Mount	Thorlabs	KM05	$42.18	11	$463.98
Mirror	Thorlabs	PF10-03-M01	$56.26	6	$337.56
Fiber Coupler	Newport	F-CPL-S22155-FCAPC	$195.00	2	$390.00
Optical Switch	Agiltron	MISW-12B211333	$125.00	4	$500.00
RF Transceiver Options	Great Scott Gadgets Espressif	HackRF one ESP WROOM 32	$344.95 $2.5	1 3	$344.95 $7.5

Bill of Materials/Budget Cont.

Microcontroller Development Board	Texas Instruments	msp430g2553	$2.68	3	$8.04
PCB Fabrication	JLCPCB	-	$42	2	$83.59
Housing Materials	TBD	TBD	TBD	TBD	TBD
Total Budget:		TBD			

Work Distribution

Subsystem	Task	Assignee	Secondary
Optical Switching	Hardware Selection	Justin	Francisco
	PCB Design	Edgar	Francisco
	PCB Test	Edgar	Justin
	Software Design	Edgar / James	Justin
	Software Test	James	Justin
MUX/DEMUX	Hardware Design	Justin	Francisco
	Alignment	Justin	Francisco
	Testing	Justin	Francisco
Fiber	Hardware Selection	Justin	Francisco
	Testing	Justin	Francisco
RF and MCU	Receiver Implementation	Edgar	Francisco
Laser Diodes	Hardware Selection	Francisco	Justin
	Hardware Design	Francisco	Justin
	Testing	Francisco	Justin
Photodiodes	Hardware Selection	Francisco	Justin
	Hardware Design	Francisco	Justin
	Testing	Francisco	Justin
Encryption	Software Design	James	Francisco
	Testing	James	Francisco