High Frequency Open Air Optical Communication System

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Table of Contents

Appendices

List of Tables and Figures

Tables:

Figures:

Acknowledgements

I would like to thank my parents for all of their help and support they have provided for this project and my college career. I would like to thank Dr. Vladimir Prodanov, my project advisor, for his continual support and assistance with this entire project. I would also like to thank Dr. Dennis Derickson for his contributions to the beginning stages of the project helping develop ideas and defining how to approach the project.

Abstract

The goal of this project is to create a wireless optical communication system that operates at high frequencies (up to 3 GHz). The system will function by taking a digital electric input signal, converting it to a photonic signal, recovering the signal at the other end of a short distance (~1 foot) and converting it back into a digital signal. Unlike the more common fiber-optic data transmission systems, this system will transmit light through air, instead of fiber, as its medium. Doing so will have the benefits of a wireless system combined with the benefits from an optical system, including voltage isolation, no interference from electromagnetic waves, and no cross talk from other electrical signals.

Research for this project will consist of how to optimize an optical isolator system for high frequencies. This includes determining optimal wavelength of the light to be transmitted, the power necessary to successfully transmit the signal, and LED's and photo-detectors that are well suited for these requirements. Also, since these systems are useful in industry, cost of materials and production are important factors, and will be taken into consideration when selecting components.

Introduction

Transmitting signals at high frequencies is a daunting task. At high frequencies, parasitic elements, such as inductance and capacitance, become much more significant, and can affect circuit behavior in undesired ways. As such, components need to be kept as small as possible and traces as short as possible to minimize the parasitic elements in the components and traces. Also, a long stretch of a copper trace or wire can act as antenna, which may make the system susceptible to unwanted noise.

Optical communications help alleviate these problems. Optical communications work by using an electrical signal to modulate a light source, and then using a light receiver to reproduce the original electrical signal. Since light is unaffected by electromagnetic waves, this is very useful for sending signals over long distances or in areas with significant radio interference. Since there is no direct electrical connection between the input and output of an optical communication system, they can be used on a much smaller scale as optical isolators.

Optical Isolators, or optocouplers, are useful in circuits where there can be large voltage differences between two components, such as systems where creating a mutual ground is difficult to achieve. Having the components directly connected to one another can cause noise in a system, ground loops, distortion to the signal being transmitted, or even damage to the circuit. Optocouplers are a good solution to this problem: they convert the electrical signal to a photonic signal (typically using a Light Emitting Diode), and use an opto-detector to convert the light signal back into an electric signal.

Background

High speed communications have been around for many years, but the mode of transfer has changed drastically in recent history. Traditionally, wires and cables are used to transfer analog and digital data, but recently wireless communications have become much more popular due to their low cost, increased convenience and simplicity for users.

Table 1 shows the speeds of several types of wired and wireless communication, for a comparison to the targeted 2.97 Gbps Open Air Optical System. As the table shows, wired connections offer higher data transfer rates than wireless communication systems, because they do not have the same restrictions as wireless, and do not have as many problems with noise floor, signal interference, and low power efficiency. It is because of all these problems that wireless communications have lower speeds. Because of the limitations of wireless systems, an optical transmission system is preferred for high speed communication systems.

Connection	Connection Type	Max Speed
Wi-Fi		
802.11a/ 802.11g	Wireless	54Mb/s
802.11n	Wireless	300 Mb/s
Bluetooth	Wireless	3 Mb/s
Zigbee	Wireless	250 Kb/s
USB		
2.0	Wired	480Mb/s
3.0	Wired	625Mb/s
Ethernet		
Standard	Wired	1Gb/s
Wide Area Network (WAN)	Wired	10Gb/s
Coaxial	Wired	10Gb/s

Table 1: Speed Comparison Among Different Communication Types

Requirements

- System will receive an electrical signal, convert and transmit the signal optically, and recreate the electrical signal at the output
- System will be able to transmit high frequency signal; specifically 3G SDI Video signal, operating at 2.97 GHz
- System will have no physical or electrical connection between optical transmitter and receiver
- Successfully recover data at receiver end with no data loss and minimum delay
- Total system cost is low
- System is low power and does not create a safety hazard

Design Phase

After the requirements for the optical data transmission system were refined, parts needed to be selected to meet the specifications. This included selecting the necessary transmitting and receiving devices, as well as any necessary components needed to drive or recover the signal at either end of the system. The light source and receiver were selected at the same time, in order to ensure they could meet the project specifications and be compatible with one another.

One concern when selecting a light source was the output power of the transmitter. Lasers and LED's are rated on a scale of Maximum Permissible Exposure (MPE), which shows how potentially harmful the EM emissions can be. These are broken down into classes (See Table 2). In order to avoid potential eye damage if a mistake happened, low-power lasers and LEDs that would meet Class 1 or Class 1M requirements were under consideration. This required the device to have an Accessible Emission Limit (AEL) of approximately 40 μW. AEL is calculated based on several parameters, including power of the light, diameter of the source, diameter of the aperture (eye, ~7mm), wavelength, exposure time, duty cycle and angle of divergence of the light beam.

Lasers and LEDs are constructed entirely differently, leading to many differences in performance. Lasers produce a narrow beam of in-phase light at a given frequency (ex: 635 nm). LEDs emit light over a broader range of frequencies in a more dispersed beam (but can be very narrow depending on their construction). Lasers typically require higher power, but also have much shorter rise and fall times. Most LED's have slower rise/fall times, and thus only specialized ones are used for high speed optical communications (with cables or wireless).

Class	**Type of lasers**	**Meaning**	**Relationship to MPE**	**Hazard Area**	**Typical AEL for CW Lasers**
Class 1	Very low power lasers or encapsulated lasers	Safe	MPEs are not exceeded, even for long exposure duration (either 100 seconds or 30000 seconds), even with the use of optical instruments	No hazard area (NOHA)	40 µW for blue
Class 1M	Very low power lasers; either collimated with large beam diameter or highly divergent	Safe for the naked eye, potentially hazardous when optical instruments** are used	MPEs are not exceeded for the naked eye, even for long exposure durations, but maybe exceeded with the use of optical instruments**	No hazard area for the naked eye, but hazard area for the use of optical instruments** (extended NOHA)	Same as Class 1, distinction with measurement requirements
Class 2	Visible low power lasers	Safe for unintended exposure, prolonged staring should be avoided	Blink reflex limits exposure duration to nominally 0.25 seconds. MPE for 0.25 seconds not exceeded, even with the use of optical instruments.	No hazard area when based on unintended exposure (0.25 seconds exposure duration)	1 mW
Class 2M	Visible low power lasers; either collimated with large beam diameter or highly divergent	Same as Class 2, but potentially hazardous when optical instruments** are used	MPE for 0.25 seconds not exceeded for the naked eye, but maybe exceeded with the use of optical instruments**	No hazard area for the naked eye when based on accidental exposure (0.25 seconds exposure duration), but hazard area for the use of optical instruments** (extended NOHA)	Same as Class 2, distinction with measurement requirements
Class 3R	Low power lasers	Safe when handled carefully. Only small hazard potential for accidental exposure	MPE with naked eye and optical instruments may be exceeded up to 5 times	5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 in visible, i.e. 5 mW	5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 in visible, i.e. 5 mW
Class 3B	Medium power lasers	Hazardous when eye is exposed. Wear Eye Protection within NOHA. Usually no hazard to the skin. Diffuse reflections usually safe	Ocular MPE with naked eye and optical instruments may be exceeded more than 5 times. Skin MPE usually not exceeded.	Hazard area for the eye (NOHA), no hazard area for the skin	500 mW
Class 4	High power lasers	Hazardous to eye and skin, also diffuse reflection may be hazardous. Protect Eye and skin. Fire hazard.	Ocular and skin MPE exceeded, diffuse reflections exceed ocular MPE	Hazard area for the eye and skin, hazard area for diffuse reflections	No limit

Table 2: Laser Classifications, provided by Rockwell Laser Industries

Table 3 shows a comparison between lasers and LEDs, including the power and turn on/off times for each. Because this system was designed to operate at rates up to 3 GHz, short rise and fall times are necessary for successful signal transmission, and as such, lasers are much more desirable. Also, since lasers generally have higher power and have more focused beams (smaller angle of divergence), they are better suited for open-air communications. This table also demonstrates that lasers have a much more concentrated wavelength, as seen in the "Spectral Width" category. This means that lasers deviate from their nominal wavelength by a fraction of a percentage, whereas LED's have a much larger tolerance. The first entries in the table are from National Instruments, showing both Surface-Emitting LED's (SLED) and Edge-Emitting LED's (ELED); while the last entry is the Laser selected for this project.

Active Material	Type	Radiating wavelength λ (nm)	Spectral width $\Delta\lambda$ (nm)	Output power into fiber (µW)	Forward current (mA)	Rise/fall time (ns)
AIGaAs	SLED	660	20	190–1350	20(min)	13/10
	ELED	850	35–65	10–80	60–100	2/2–6.5/6.5
GaAs	SLED	850	40	80–140	100	—
	ELED	850	35	10–32	100	6.5/6.5
InGaAsP	SLED	1300	110	10–50	100	3/3
	ELED	1300	25	10–150	30–100	1.5/2.5
	ELED	1550	40–70	1000–7500	200–500	0.4/0.4–12/12
GaAs	VCSEL	850	0.65	400	1.5	.09/.09

Table 3: LED/Laser Characteristics, provided by National Instruments and Finisar

The Transmitter Optical Sub Array (TOSA) HFE4192-581 was selected as the laser for the system, while the Receiver Optical Sub Array (ROSA) HFD3180-203 was selected as the receiver portion of the system. Both parts are designed and manufactured by Finisar, and were purchased through Avnet Express. The components are designed to operate in a fiber-optic system, using a 50/125 or 62.5/125µm multi-mode fiber to connect them together.

The transmitter selected is a Vertical Cavity Surface Emitting Laser, or a VCSEL. VCSELs are commonly used on circuits for the purpose of optical communication. They are structurally different as regular lasers, but functionally the same. As the name suggests, instead of emitting photons parallel to surface they are mounted on, they emit photons perpendicular to the surface, or vertically. This has many applications for small scale electronics requiring optical data transfer because they take up less board space than traditional lasers. However, this does not affect the performance or results of this project.

The TOSA package has 4 pins, an anode and cathode for the laser, and an anode and cathode for a built-in photodiode. The laser operates as a diode, as such, there must be a positive voltage differential across the anode and cathode, but it does not regulate current. When implemented, a series resistance is needed to limit the current flowing through the laser. When the laser is turned on the photodiode activates, and a voltage differential can be measured across its anode and cathode. This can be used to regulate the output power of the laser by implementing a negative feedback loop. Due to the low frequency response of the diode, it will not be used in the final design of this project.

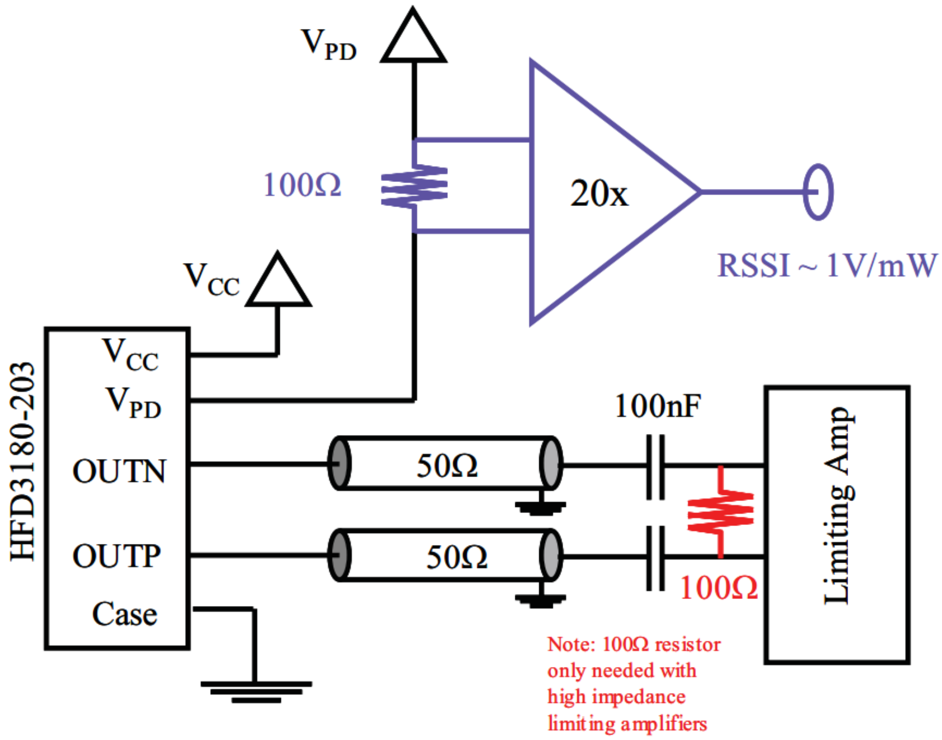
The ROSA selected was specifically designed to match up with the TOSA. One particularly appealing feature is the inclusion of a pre-amplifier built into the unit. This increases the output signal of the ROSA, simplifying the process of recovering the signal at the output and amplifying it to be read by other electronics. Another key feature is that it contains a differential output, Out+ and Out-, which can be used to further increase the signal integrity. Finally, the ROSA contains a Power Detection pin. If a resistor is placed between the supply voltage and the Power Detection pin, the power drawn by the resistor is proportional to the power received by the ROSA. This function is not used in the final design of the system.

Both devices operate at speeds up to 4.25 GHz, and are designed to send/receive photons with a wavelength of 850 nm. Since this is in the infrared light range, extra precautions must be taken around the system, since the light emitted from the TOSA is not visible with the naked eye. This also means that special equipment must be used to ensure the laser is operating.

Since open-air optical communications are not typically used in modern designs, there are no components available on the market specifically designed for that use. As mentioned previously, both components were designed to operate together in a system. As such, these components were selected because both are intended for use in a fiber-optical transmission line, which is similar to open-air communications, albeit aided by the use of a fiber. Many lasers designed for optical fibers, this TOSA included, have built in lenses that disperse the photons emitted from it so that the light couples more efficiently with the optical fiber. While this means that less optical power is received by the receiver in this project's open-air implementation, it proved very useful because the laser does not have to be pointed directly at the ROSA to successfully transmit the signal.

One concern with this particular VCSEL is that it is a Class 3B, which is significantly more powerful and dangerous than the desired Class 1. However, as mentioned above, the integrated lens in the TOSA disperses the light, making it less dangerous when viewed directly. Also, the laser can be driven with a range of currents from ~1 mA to 14 mA, making it possible to operate at lower power levels to make the system safer.

Figure 1 shows the recommended circuit configuration for the ROSA, taken from Finisar's datasheet for the component.



Optional RSSI implementation is shown in blue
Optional 100Ω differential termination for high impedance limiting amplifiers is shown in red.

Figure 1: Circuit Configuration for HFD3180-203 ROSA

Figure 2 shows the configuration for both the TOSA and the ROSA used in the final implementation of the project.

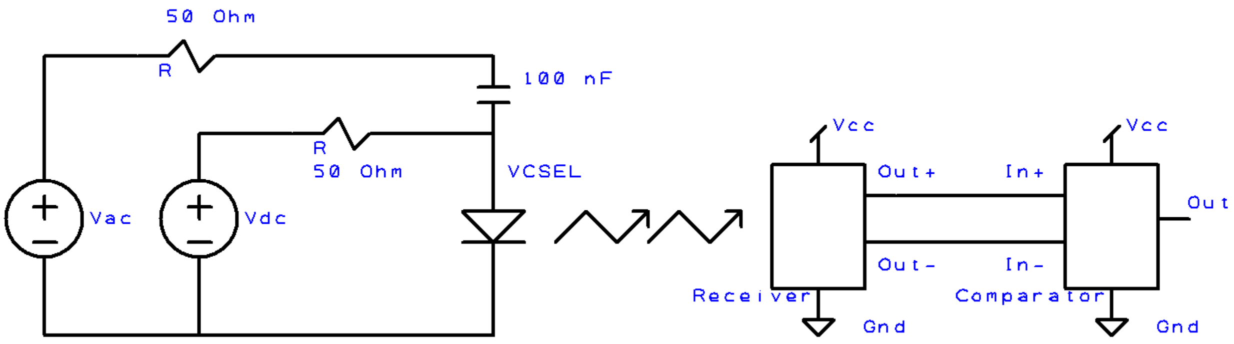


Figure 2: Final Circuit Implementation for Optical Open Air Communications System

For testing purposes, the DC and AC voltages applied to the VCSEL separated, and the AC voltage applied through a coupling capacitor. This is because on the test equipment available, there was no way to add a DC offset to the sinusoidal AC. As such, two separate sources were necessary.

On the receiving side of the system, coupling capacitors were connected to both output terminals of the ROSA, but not connected together through the 100 Ω resistor as mentioned in the datasheet in the final implementation. Also, the decoupling capacitor was placed between the supply voltage and circuit common to ensure a constant voltage between the two.

Testing and Implementation

TOSA Testing

After the components arrived, testing the VCSEL was the first priority. As mentioned previously, since the VCSEL operates at 850 nm, in the infrared range, it is not visible to the human eye. As such, special equipment needed to be used to ensure the laser was operating correctly.

The circuit in Figure 3 was constructed to test the operation of the TOSA. The resistor in series with the laser limits the current flowing through the circuit, and by measuring the voltage potential across the resistor, the current through the laser can be calculated.

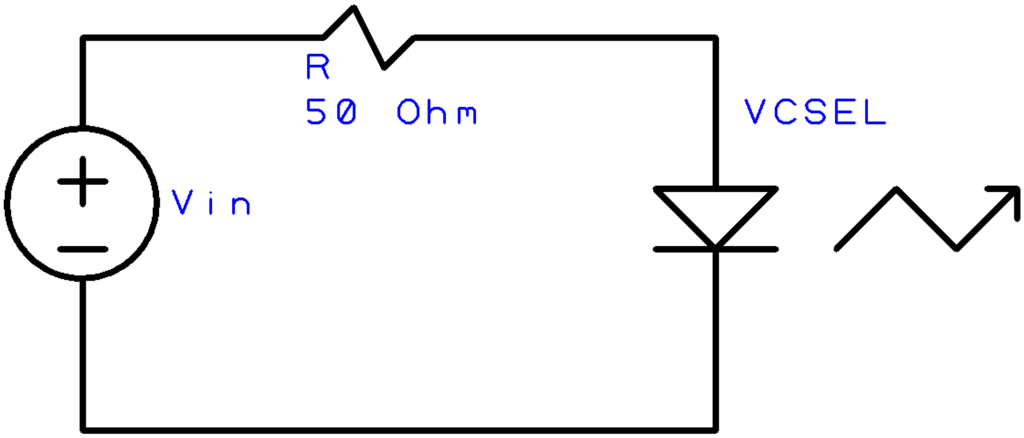


Figure 3: Circuit Used to Test VCSEL

This test proved that the VCSEL operates properly at the low frequencies tested. Table 4 and Figure 4 below show the data measured from the test, proving that the VCSEL operates as a diode with a finite turn-on voltage, and the current flowing through it is determined by the voltage across the series resistance.

V_{IN}	**$V_{Resistor}$**	**I_{OUT}**	**V_{LASER} (V)**
1.20 V	0.7 mV	0.01 mA	1.20 V
1.25 V	1.3 mV	0.03 mA	1.25 V
1.30 V	2.4 mV	0.05 mA	1.30 V
1.35 V	4.2 mV	0.08 mA	1.35 V
1.40 V	7.3 mV	0.14 mA	1.39 V
1.45 V	12.4 mV	0.24 mA	1.44 V
1.50 V	21.5 mV	0.42 mA	1.48 V
1.55 V	31.9 mV	0.63 mA	1.52 V
1.60 V	46.7 mV	0.92 mA	1.55 V
1.65 V	64.8 mV	1.27 mA	1.59 V
1.70 V	86.7 mV	1.70 mA	1.61 V
1.75 V	110.5 mV	2.17 mA	1.64 V
1.80 V	135.5 mV	2.66 mA	1.66 V
1.85 V	161.6 mV	3.17 mA	1.69 V
1.90 V	189.4 mV	3.71 mA	1.71 V
1.95 V	213.7 mV	4.19 mA	1.74 V
2.00 V	243.8 mV	4.78 mA	1.76 V
2.05 V	271.5 mV	5.32 mA	1.78 V
2.10 V	301.5 mV	5.91 mA	1.80 V
2.15 V	328.4 mV	6.44 mA	1.82 V
2.20 V	356.8 mV	7.00 mA	1.84 V
2.25 V	385.7 mV	7.56 mA	1.86 V

Table 4: Voltage/Current Characteristics of Laser

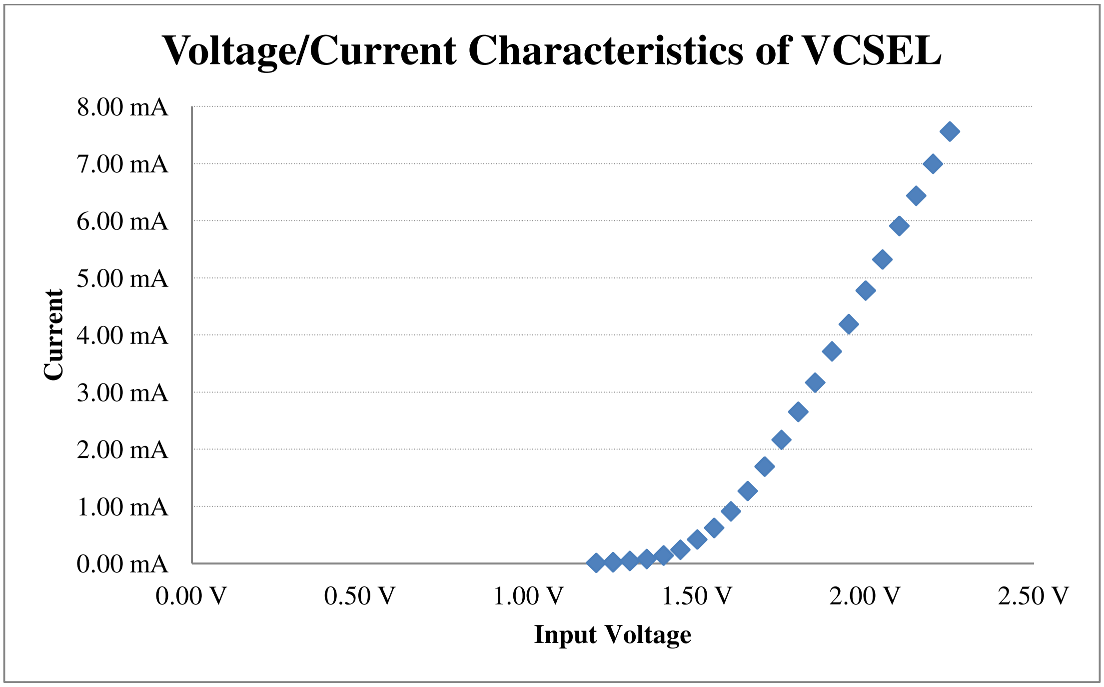


Figure 4: Input Voltage/Current Characteristics of Laser and Series Resistance

After ensuring that the laser was drawing the desired current, a method was needed to ensure light was being emitted from the laser when it was powered. Most digital cameras today have built-in Infrared-blocking lenses, which block out IR light to prevent distortions in the pictures they take. However, in many small, low-grade cameras, such as those used in computer webcams or in cell phone integrated cameras, these filters are omitted to save space and cost. As such, most standard cell phone cameras can be used to detect infrared light. Figure 5 below is a picture used with a cell phone camera, showing the Infrared light emitted from the laser as a bright purple light.

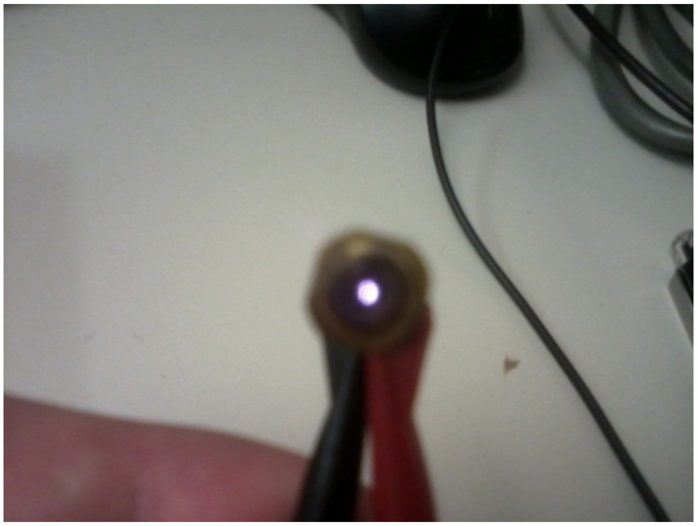


Figure 5: VCSEL Illuminated With Power Applied

The different voltages found in Table 4 were applied to the VCSEL while being monitored with the camera. As expected, when the input voltage passed 1.6 V, the laser turned on and the light was visible.

By shining the laser on a flat surface and looking at the light beam with a camera, it was confirmed that the laser does indeed disperse the light with approximately 15˚ of distribution. As noted, this means the laser does not have to point directly at the ROSA in the final implementation. This also simplifies testing, since a narrow laser beam is much more difficult to aim at a receiver than a diffused beam of light.

Next, a method had to be devised to ensure that the light transmitted by the TOSA could be detected by an arbitrary IR receiver. To do this, three separate test configurations were used: one with a phototransistor, and two with photodiodes (one of which was using the photodiode on a second TOSA). The two circuit implementations are shown in Figure 6.

The photodiode circuit is much simpler, since when it detects a light wave of 850 nm, it produces a voltage across its anode and cathode, which can be measured with a voltmeter. The phototransistor is slightly more complicated. When it detects the 850 nm wave, it switches the transistor into Saturation mode, drawing current from the Collector to the Emitter terminals. As such, a voltage source and current-monitoring resistor are necessary to measure if the transistor is activated or not.

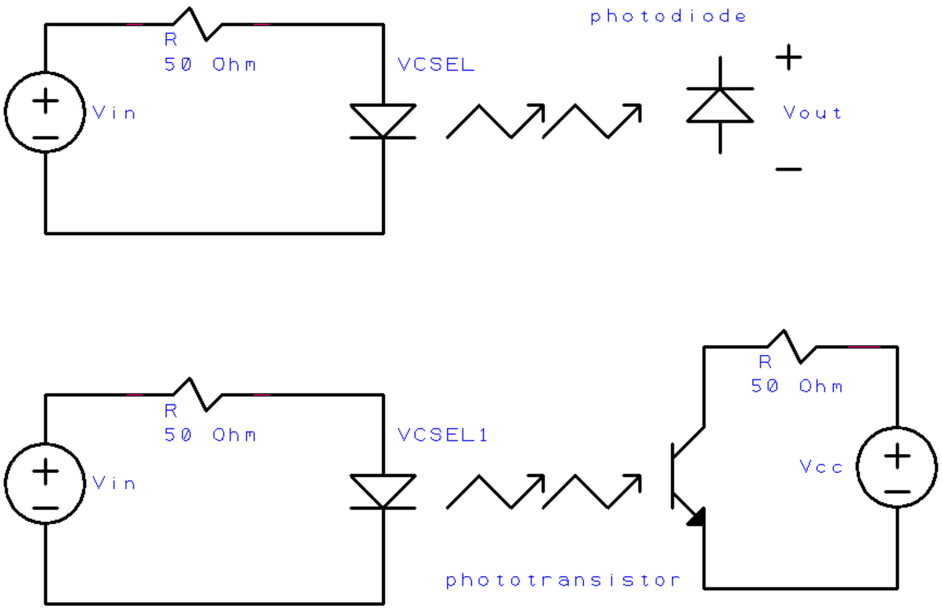
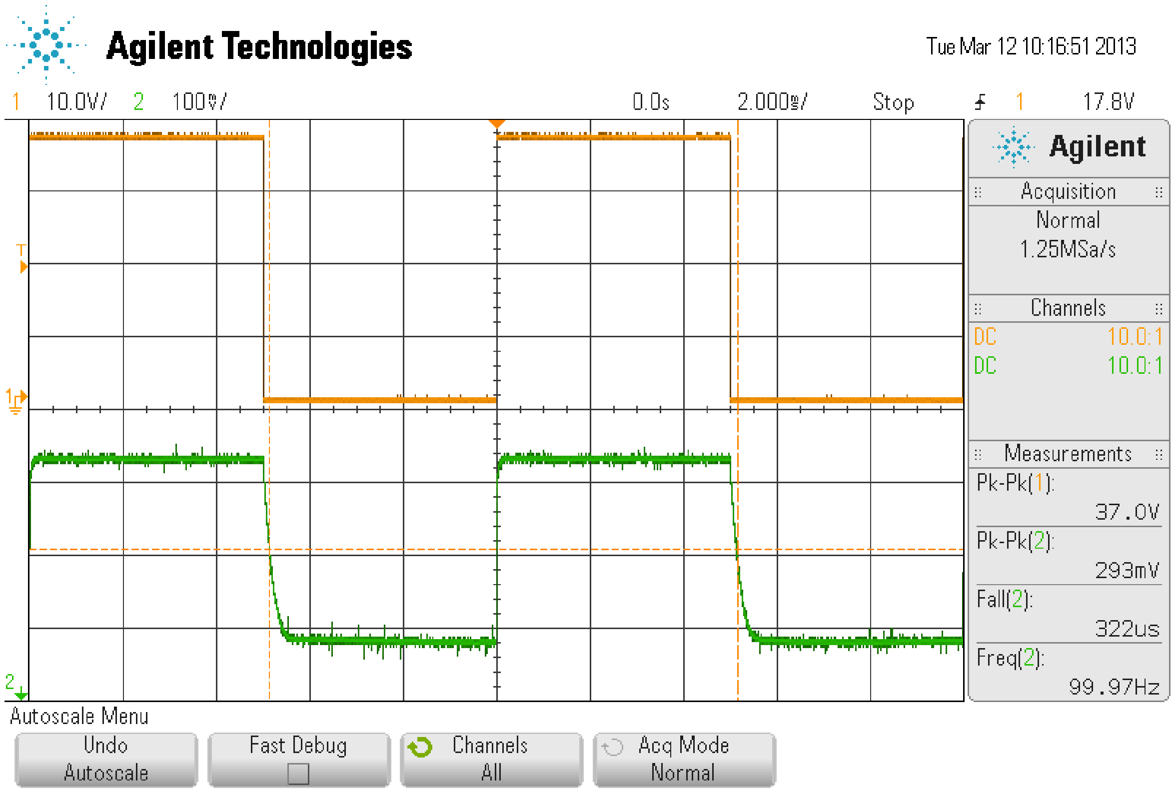


Figure 6: VCSEL Testing with Photodiode (Top) and Phototransistor (Bottom)

Figures 7-13 show the measured results of the testing with these different circuits. Figures 7-9 are measurements of the Photodiode, and Figures 10-13 are of the Phototransistor. The voltage waveform on top shows the input voltage applied to V_{IN} in Figure 6. In figures 7-9, the bottom waveform shows the voltage measured across the photodiode. In Figures 10-13, the bottom waveform shows the voltage drop across the 1000 Ω series resistor.



Tue Mar 12 10:16:51 2013

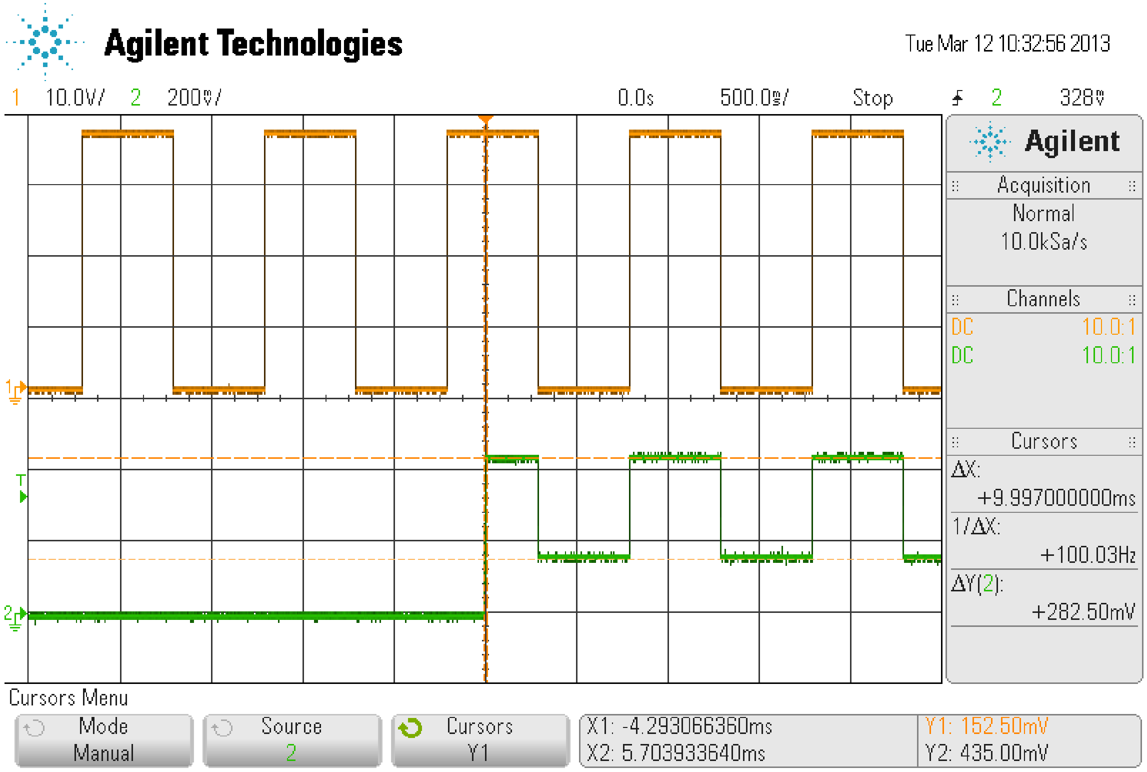
1 10.0V/ 2 100mV/ 0.0s 2.000ms/ Stop 1 17.8V

Acquisition: Normal, 1.25MSa/s

Channels: DC 10.0:1; DC 10.0:1

Measurements:
Pk-Pk(1): 37.0V
Pk-Pk(2): 293mV
Fall(2): 322us
Freq(2): 99.97Hz

Figure 7: VCSEL Test Results with Photodiode at 100 Hz



Tue Mar 12 10:32:56 2013

1 10.0V/ 2 200mV/ 0.0s 500.0ms/ Stop 2 328mV

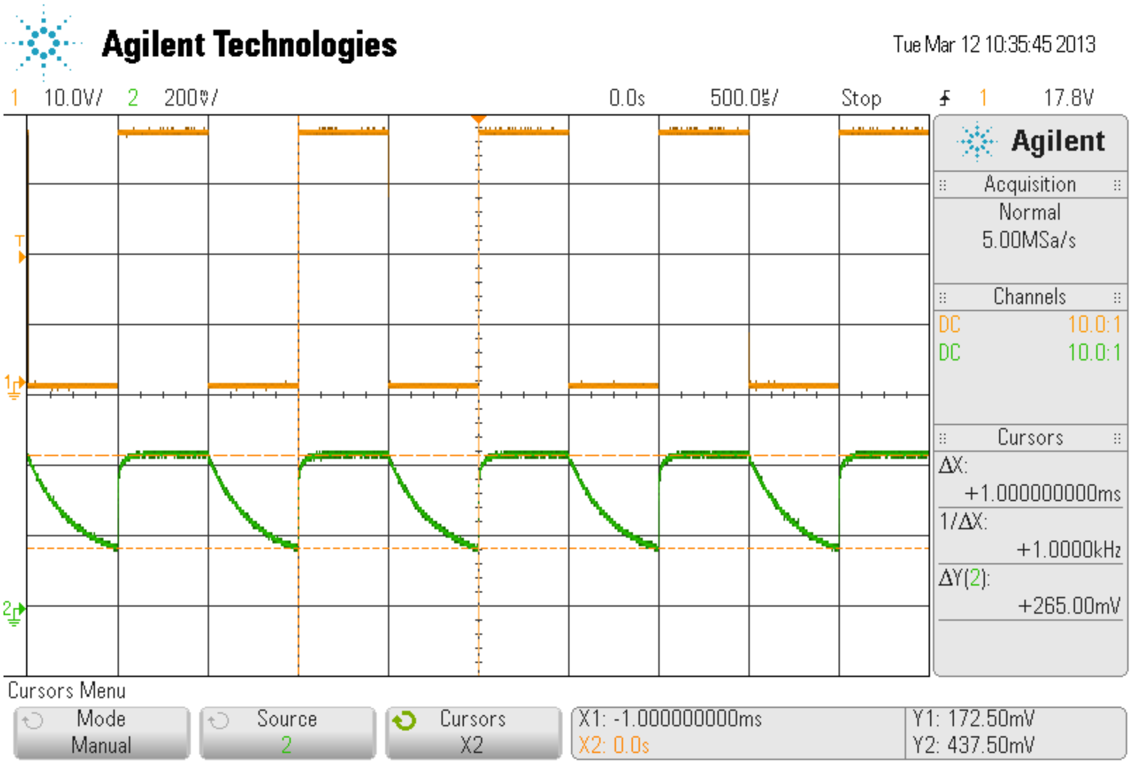
Acquisition: Normal, 10.0kSa/s

Channels: DC 10.0:1; DC 10.0:1

Cursors:
ΔX: +9.997000000ms
1/ΔX: +100.03Hz
ΔY(2): +282.50mV

X1: -4.293066360ms
X2: 5.703933640ms
Y1: 152.50mV
Y2: 435.00mV

Figure 8: VCSEL Test Results with Photodiode at 100 Hz (trigger on diode, note minimum "off" voltage)



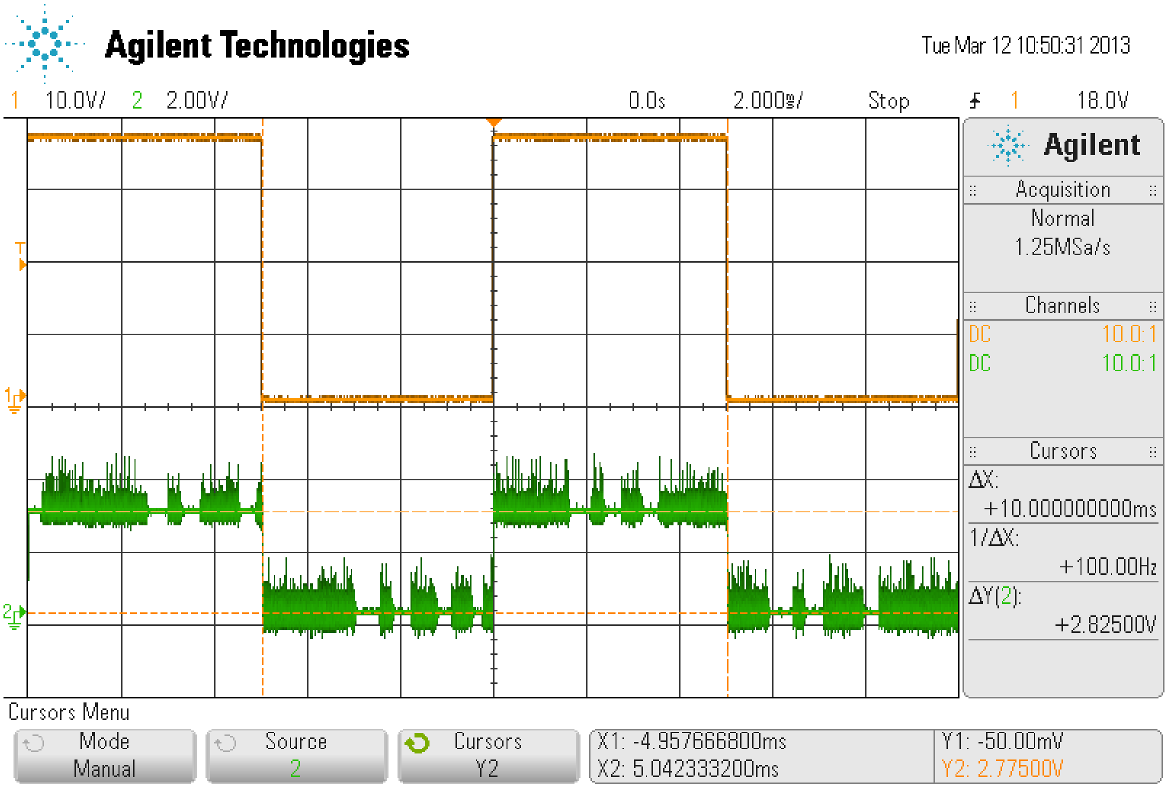
Acquisition
Normal
5.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Cursors
ΔX: +1.000000000ms
1/ΔX: +1.0000kHz
ΔY(2): +265.00mV

Mode: Manual
Source: 2
Cursors: X2
X1: -1.000000000ms
X2: 0.0s
Y1: 172.50mV
Y2: 437.50mV

Figure 9: VCSEL Test Results with Photodiode at 1 KHz (note fall time)



Acquisition
Normal
1.25MSa/s

Channels
DC 10.0:1
DC 10.0:1

Cursors
ΔX: +10.000000000ms
1/ΔX: +100.00Hz
ΔY(2): +2.82500V

Mode: Manual
Source: 2
Cursors: Y2
X1: -4.957666800ms
X2: 5.042333200ms
Y1: -50.00mV
Y2: 2.77500V

Figure 10: VCSEL Test Results with Phototransistor at 100 Hz, Voltage across R_C (note noise)

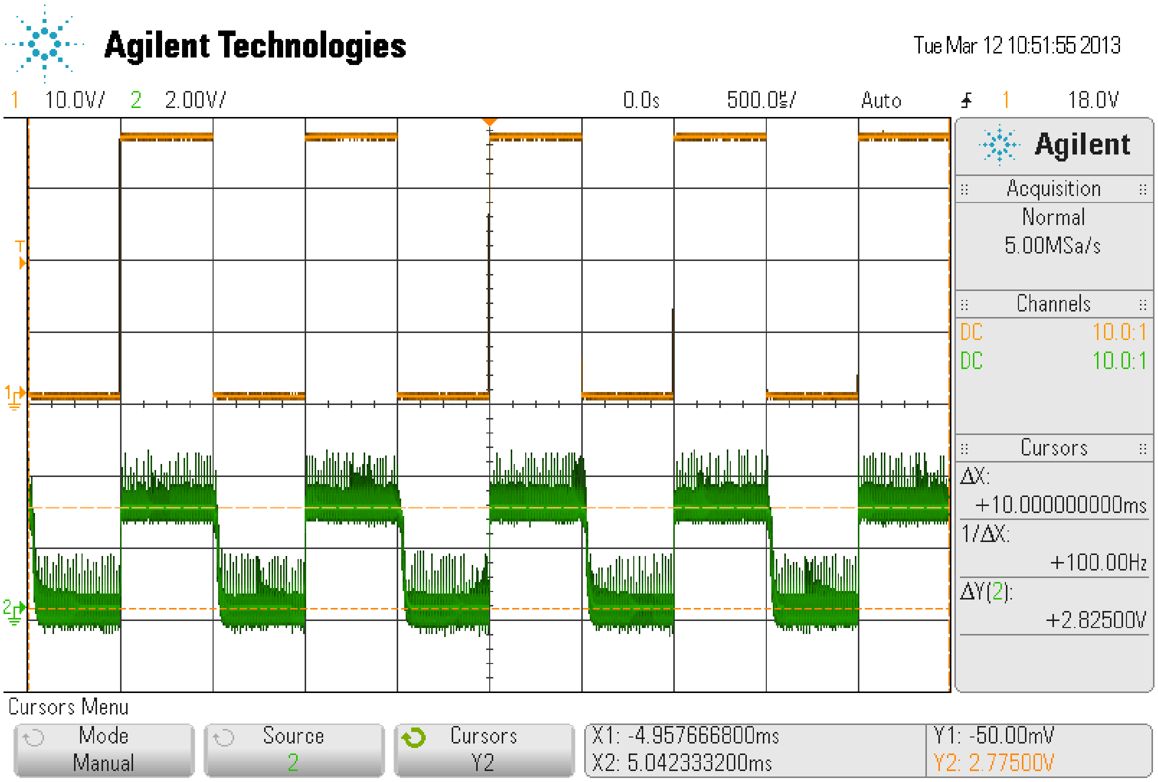


Figure 11: VCSEL Test Results with Phototransistor at 1 KHz, Voltage across R_C

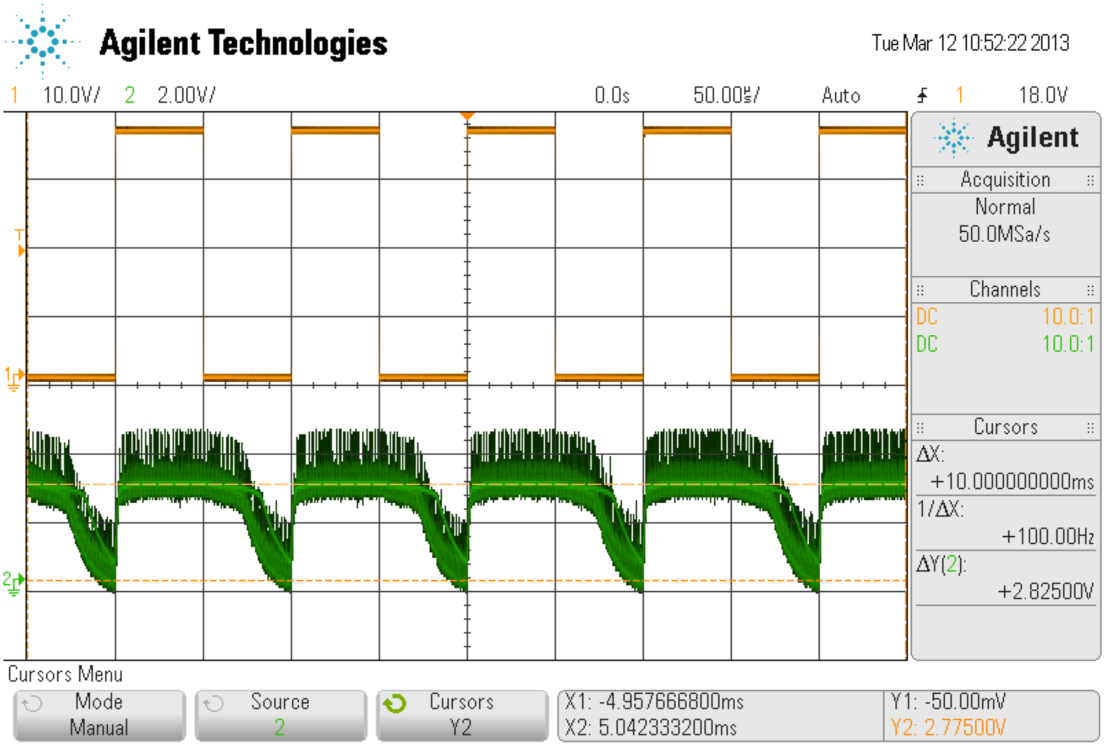


Figure 12: VCSEL Test Results with Phototransistor at 10 KHz, Voltage across R_C (note noise and fall time)

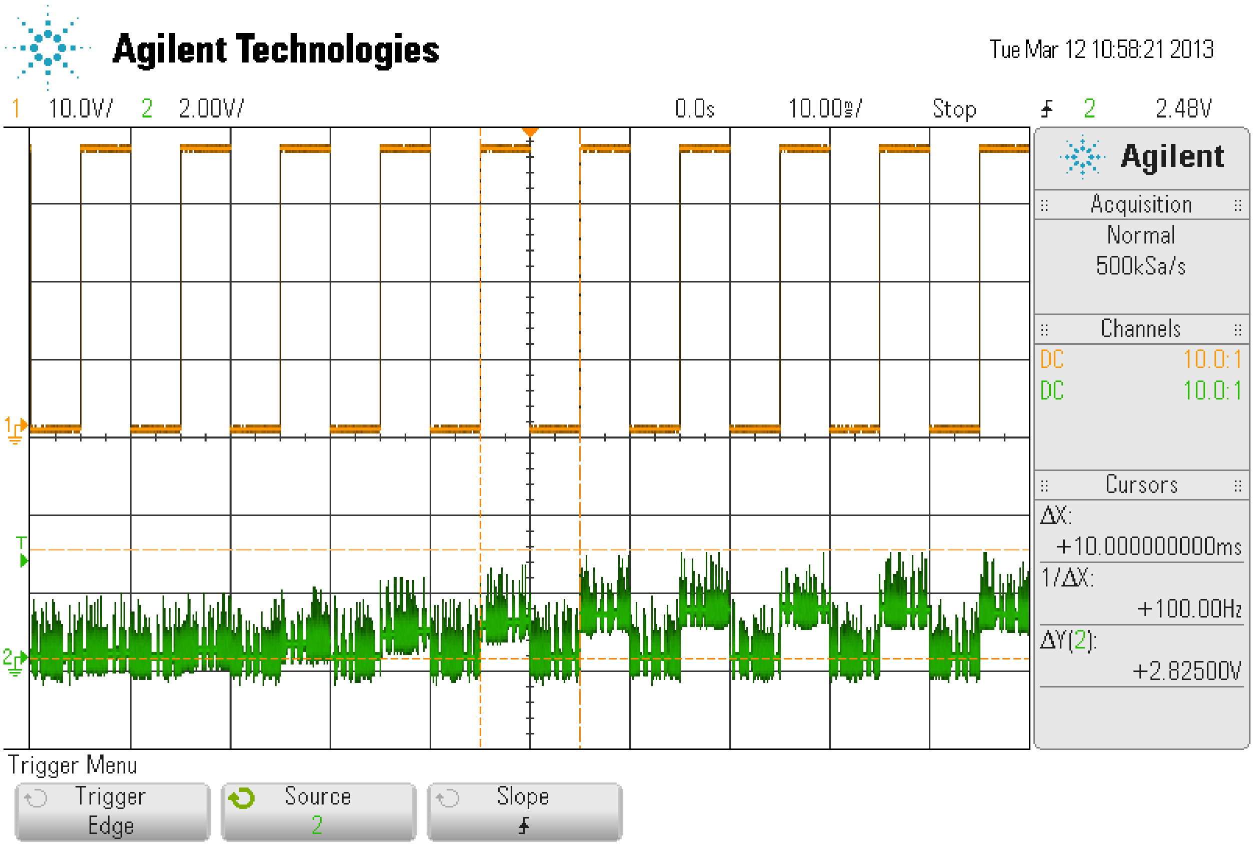

Agilent Technologies
Tue Mar 12 10:58:21 2013
1 10.0V/ 2 2.00V/ 0.0s 10.00ms/ Stop 2 2.48V
Acquisition
Normal
500kSa/s
Channels
DC 10.0:1
DC 10.0:1
Cursors
ΔX: +10.000000000ms
1/ΔX: +100.00Hz
ΔY(2): +2.82500V
Trigger Menu
Trigger Edge
Source 2
Slope

Figure 13: VCSEL Test Results with Phototransistor at 100 Hz, Voltage across R_C, Triggered on Transistor (note noise)

As seen in the figures above, both circuits functioned properly to a certain extent in the tests performed. The photodiode produced a voltage when light was detected, and the phototransistor drew current when light was detected, but each had a noticeable caveat. Both devices had significant fall times, which limit how high of a frequency they can operate at. In Figure 8, the TOSA is powered, but pointing away from the diode. The photodiode triggered the measurement when the laser was pointed at it. In this figure it can be seen that even after the laser fully shuts off, 152 mV is still measured across the anode and cathode. This is most likely due to some form of internal capacitance in the photodiode, which does not fully discharge because of the lack of a parallel load to discharge the diode.

As seen in the phototransistor testing, the device turned on and off when it detected the laser, but there was significant noise in both the saturation and cutoff modes of operation. As seen in Figure 13, this is a problem when the transistor does not conduct the full amount of current, and the noise is practically indistinguishable from the signal.

Given these issues, the photodiode tested is much more useful for optical communications, but its long fall-time prevents it from being useful at high speeds. This may be improved by adding a parallel load to the circuit, though that would also decrease the detectable peak-to-peak voltage. More testing and research is needed in a separate project for this to be used in an open-air optical communication system.

ROSA Testing

To test the ROSA, the circuit in Figure 14 was constructed. Both the TOSA and the ROSA were mounted on separate Printed Circuit Boards. This provided solid mechanical connections between the transmitter/receiver and any components, wires, or test probes that needed to be connected to them. A decoupling capacitor was connected between the V_{CC} pin of the ROSA and the Ground plane, to ensure any high frequency noise across the terminals would be filtered out. AC coupling capacitors were added to both positive and negative outputs of the ROSA, so that the differential signal could be more easily measured across the two terminals.

For testing, the TOSA was held approximately 1 cm away from the ROSA, to ensure most of the light emitted from the VCSEL could be transmitted to the receiver. Figure 15 shows a measurement of the system taken with an oscilloscope. As in previous measurements, the input applied to the TOSA is on top, while the output measured from the ROSA is on the bottom. The source powering the TOSA had a DC offset of 1.6V, with a separate source providing an AC signal with 0.75 V_{P-P}.

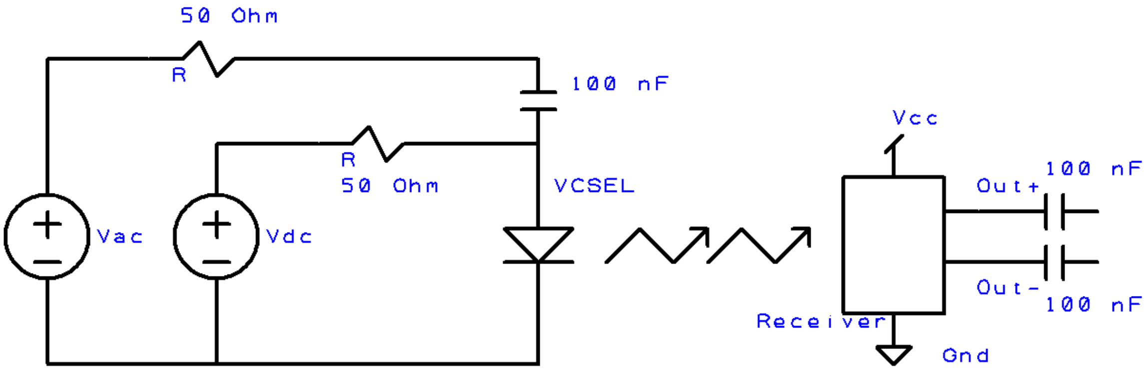


Figure 14: TOSA and ROSA Test Configuration

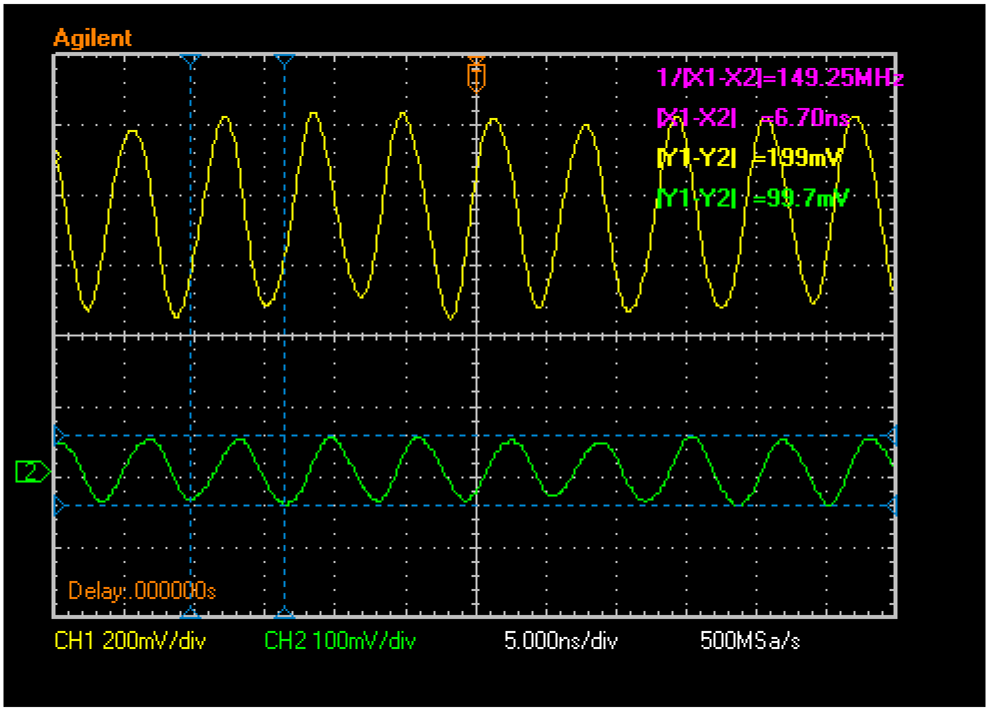


Figure 15: Initial Test Results of ROSA

This test proved that a voltage signal applied to the input of the TOSA can be transmitted optically to the ROSA and converted back into a usable electrical form. In this test, the AC differential across the output terminals of the ROSA was measured to be 99.7 mV, with a DC offset at both the terminals of approximately 3.12 V.

The next step was to find the optimal point of operation for the system. The input voltages, both AC and DC, were altered, and measurements of the input of the TOSA and the output of the ROSA were monitored and recorded: results are found in Table 5 and Figure 16.

$V_{DC\ Bias}$	$V_{AMP(Displayed)}$	$V_{AMP(measured)}$	$V_{OUT(P-P)}$
1.45 V	200 mV	176 mV	30 mV
1.45 V	300 mV	252 mV	36 mV
1.45 V	400 mV	332 mV	48 mV
1.45 V	500 mV	412 mV	60 mV
1.45 V	600 mV	484 mV	70 mV
1.55 V	200 mV	164 mV	36 mV
1.55 V	300 mV	240 mV	52 mV
1.55 V	400 mV	290 mV	66 mV
1.55 V	500 mV	350 mV	78 mV
1.55 V	600 mV	472 mV	94 mV
1.65 V	200 mV	136 mV	42 mV
1.65 V	300 mV	204 mV	54 mV
1.65 V	400 mV	268 mV	72 mV
1.65 V	500 mV	320 mV	88 mV
1.65 V	600 mV	436 mV	100 mV
1.75 V	200 mV	130 mV	48 mV
1.75 V	300 mV	192 mV	66 mV
1.75 V	400 mV	254 mV	74 mV
1.75 V	500 mV	308 mV	92 mV
1.75 V	600 mV	420 mV	106 mV
1.75 V	700 mV	472 mV	124 mV
1.75 V	800 mV	528 mV	156 mV
1.75 V	900 mV	596 mV	160 mV
1.75 V	1000 mV	656 mV	176 mV
1.75 V	1100 mV	736 mV	192 mV
1.75 V	1200 mV	808 mV	202 mV
1.85 V	200 mV	124 mV	40 mV
1.85 V	300 mV	180 mV	52 mV
1.85 V	400 mV	240 mV	66 mV
1.85 V	500 mV	300 mV	80 mV
1.85 V	600 mV	330 mV	106 mV
1.85 V	700 mV	460 mV	98 mV

Table 5: V_{OUT} Measurements and Optimization of Optical Transmission System with Variable Input DC and AC Input Voltages

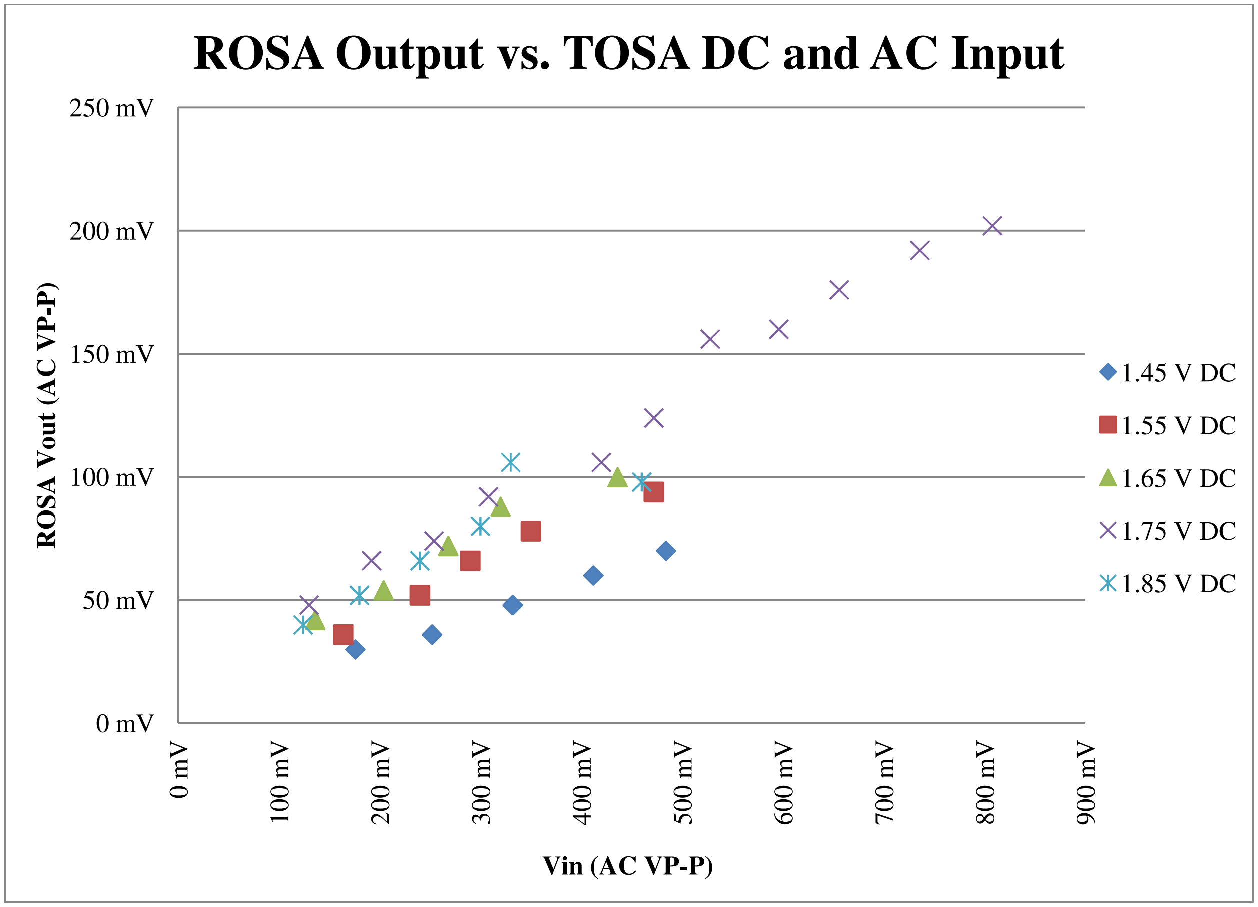


Figure 16: Voltage Transfer Characteristics of Optical Communication System

As seen from the table and graph, there is a positive correlation between the AC amplitude of the input signal to the amplitude of the signal at the output of the ROSA. This was expected, since as the amplitude increases at the input, the laser receives more current at the peak voltage, and has a lower minimum voltage.

The system performed the best (i.e. had the highest output voltage) when the DC offset applied to the TOSA was 1.75V. Because of this, more tests were performed at this voltage, showing that the output of the ROSA is capable of outputting a 200 mV_{P-P} signal.

Table 6 and Figure 17 show the results of a test comparing the input to output voltages of the system while changing the distance between the TOSA and the ROSA. The input at the TOSA was a constant 1.65 V DC with a 450 mV AC signal operating at 150 MHz coupled to it. As shown in the graph, as the distance increases, the output decreases, due to the low detectable signal strength. After the peak-to-peak voltage of the output drops below 30 mV, it becomes indistinguishable, and the signal is unreadable.

In the test performed at the stated input voltages, after the two components are separated by approximately 15 cm, the waveform becomes too small to differentiate the signal from small distortions and noise.

Distance	$V_{OUT(P-P)}$
1 cm	76 mV
3 cm	66 mV
5 cm	58 mV
7 cm	52 mV
9 cm	48 mV
11 cm	44 mV
13 cm	38 mV
15 cm	38 mV
17 cm	34 mV
19 cm	28 mV
21 cm	28 mV
25 cm	30 mV
29 cm	28 mV

Table 6: Output of Optical System with varying distance

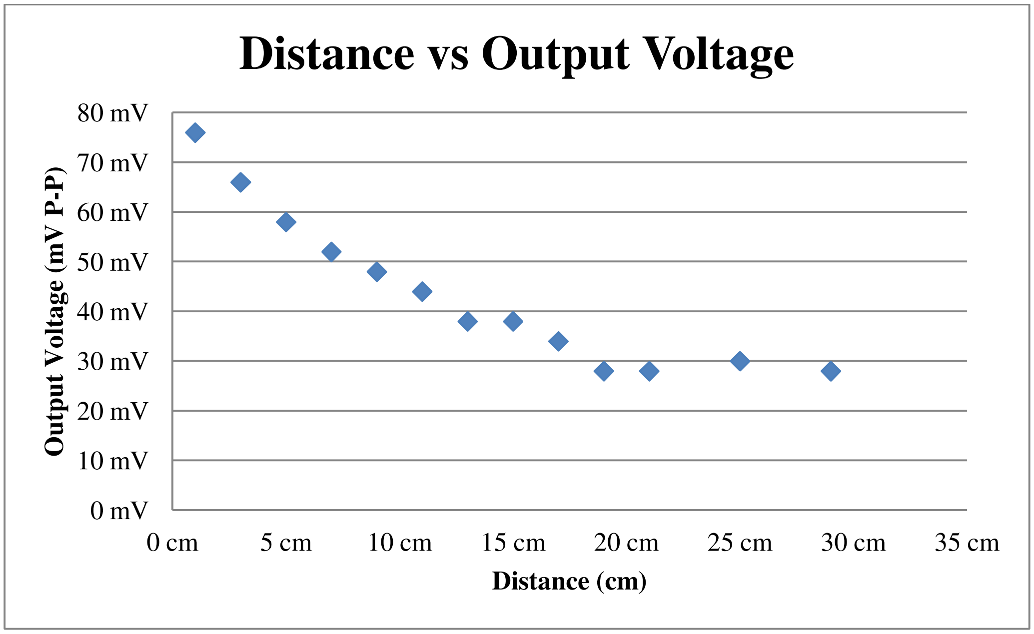


Figure 17: Distance vs. Voltage Characteristic of Optical Communication System

Figures 18 and 19 show two different scope measurements of the system, the former with the TOSA and ROSA separated by 1cm, the latter with them separated by 10 cm. As seen in these scope captures, as the distance between the two devices increases, the phase delay in the system also increases. The free air transmission of the optical system should be causing a delay of approximately 0.33 ns, instead of the measured 2.14 ns. This extra phase change is therefore attributable to stray inductive and capacitive elements in the system.

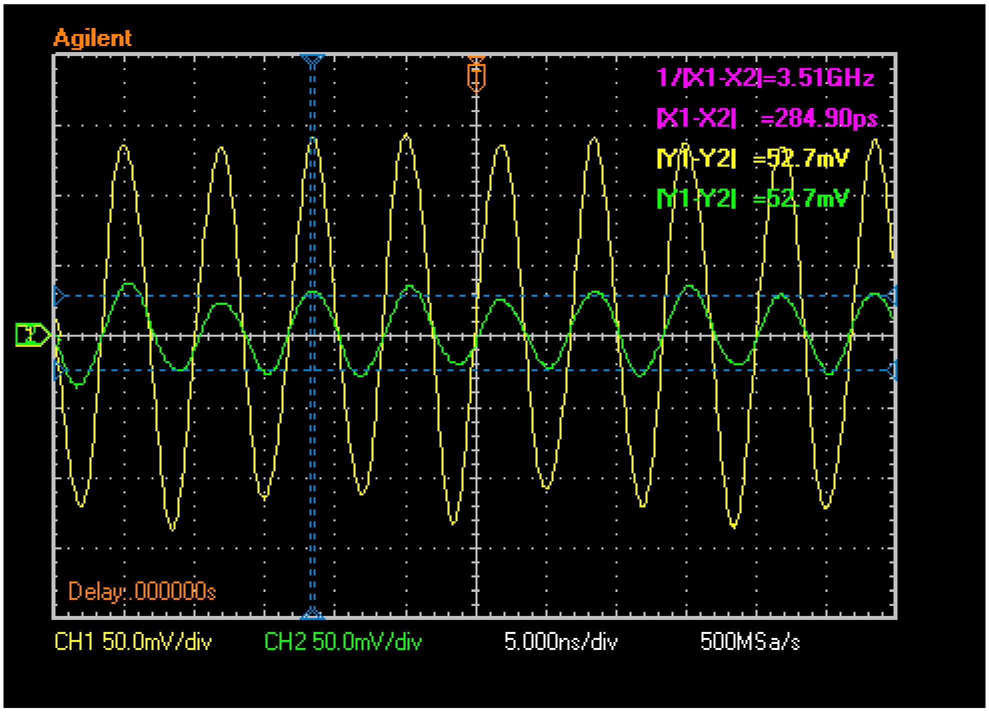


Figure 18: ROSA and TOSA Separated by 1 cm

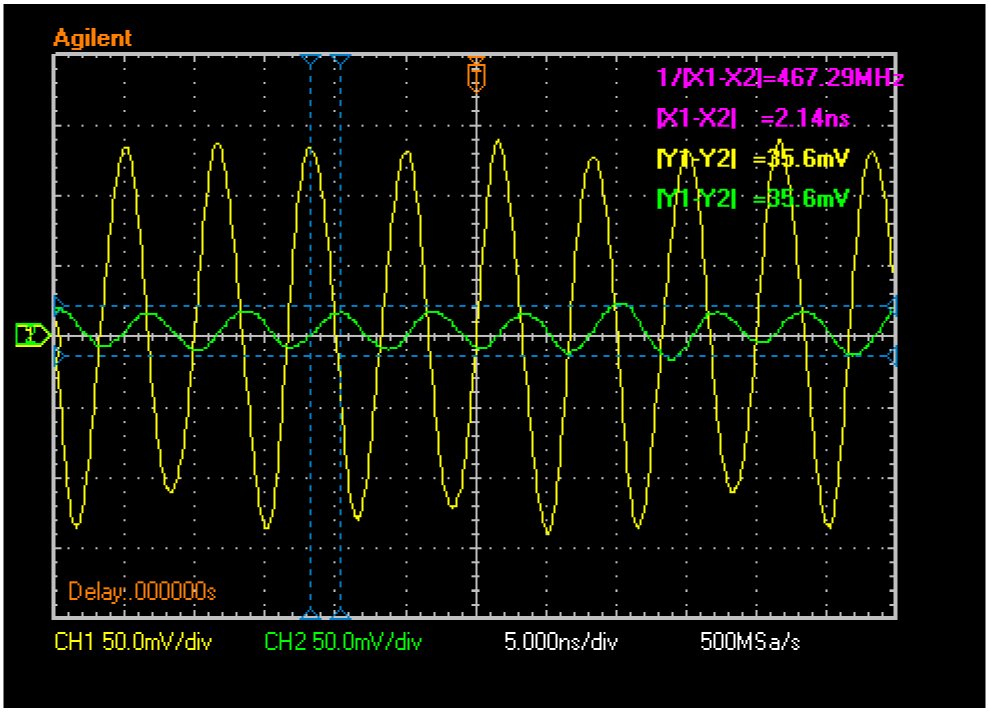


Figure 19: ROSA and TOSA Separated by 10 cm

A similar test was performed, but instead measured the change in output response when the input frequency to the TOSA was monitored. The results are found below in Table 7. The DC offset of the TOSA was set to 1.65V, with an AC voltage of 250 mV$_{P-P}$.

The results from this test show that the ROSA can operate below the rated minimum frequency of 155 MHz, albeit unreliably. There are peaks in operation at 140 MHz and at 100 MHz, but very poor operation at other frequencies. At 110 MHz and below 100 MHz, the signals are too distorted from the original to be recognizable. The peaks in operation at 140 MHz and 100 MHz are unexplained, and would require further research to determine why the ROSA still operates at these frequencies.

Frequency	$V_{OUT(P-P)}$
150 MHz	82 mV
140 MHz	128 mV
130 MHz	98 mV
120 MHz	28 mV
110 MHz	52 mV
100 MHz	96 mV
90 MHz	30 mV
80 MHz	18 mV
70 MHz	30 mV
60 MHz	22 mV

Table 7: Input Frequency of TOSA vs. Output Voltage of ROSA

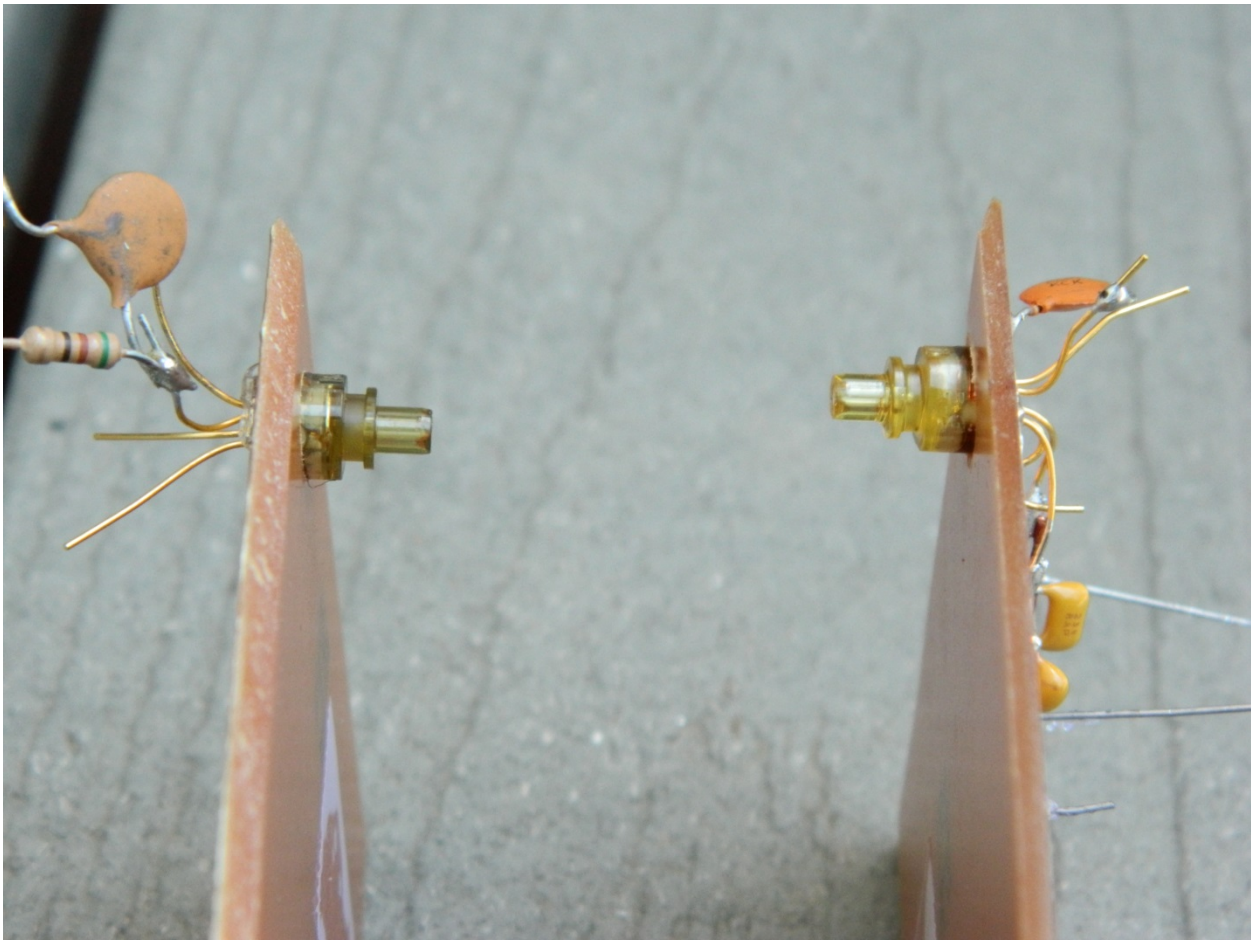


Figure 20: Picture of ROSA and TOSA when Transmitting

Final Circuit Testing

The circuit in Figure 20 was constructed as the final implementation of the optical communication system. An amplifier was added after the output of the ROSA to boost the signal so that it could be more easily used and monitored in a real system. The amplifier selected was a MAX999 EUK Comparator.

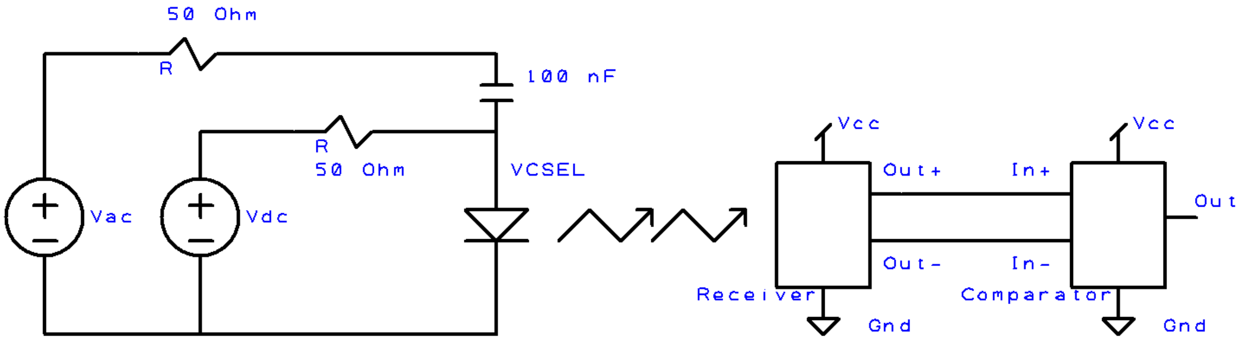


Figure 21: Final Optical System Circuit Test Configuration

Figure 21 shows a picture of the physical implementation of the final test circuit. In previous tests, AC coupling capacitors were connected to the outputs of the ROSA to filter out the ~3.1V DC at the terminals. However, for the comparator to sense the voltages properly, the signal at the input terminals need to be within the range of the voltage rails (0-3.3V). Instead of removing the capacitors for this test, they were shorted out, so that they could still be used in future tests if necessary. Hot glue was added to the comparator after the components and wires were soldered together to give it significantly more physical support, so that when test equipment would not damage it when connected.

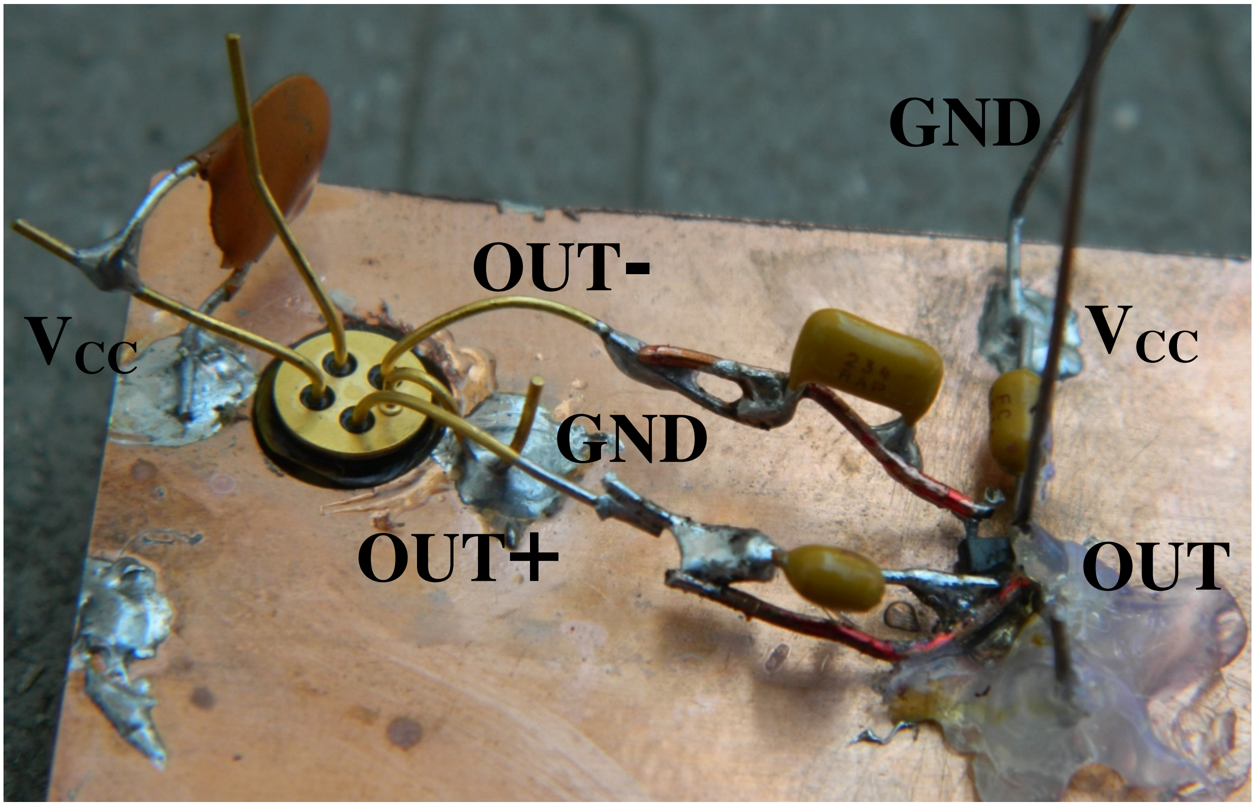


Figure 22: Picture of ROSA and Comparator mounted on a Printed Circuit Board

Because the comparator has a rise and fall time of 2.3 ns with propagation delay of 4.5 ns, it has a maximum frequency of approximately 100 MHz. As seen previously in Table 7, even though the ROSA has a rated minimum frequency of 155 MHz, it still operates at100 MHz. Any testing with the circuit above 100 MHz caused problems with interfacing with the comparator, and testing at lower frequencies resulted in too small of an output signal from the ROSA.

The circuit was tested using the same method as before. The TOSA and ROSA were placed 1 cm apart, and the input of the TOSA was set to 1.65 V DC with an 800 mV_{P-P} AC voltage. The output of the comparator was a 3.05V AC signal. The input to the TOSA and output of the comparator were monitored and the results can be seen in Figure 22.

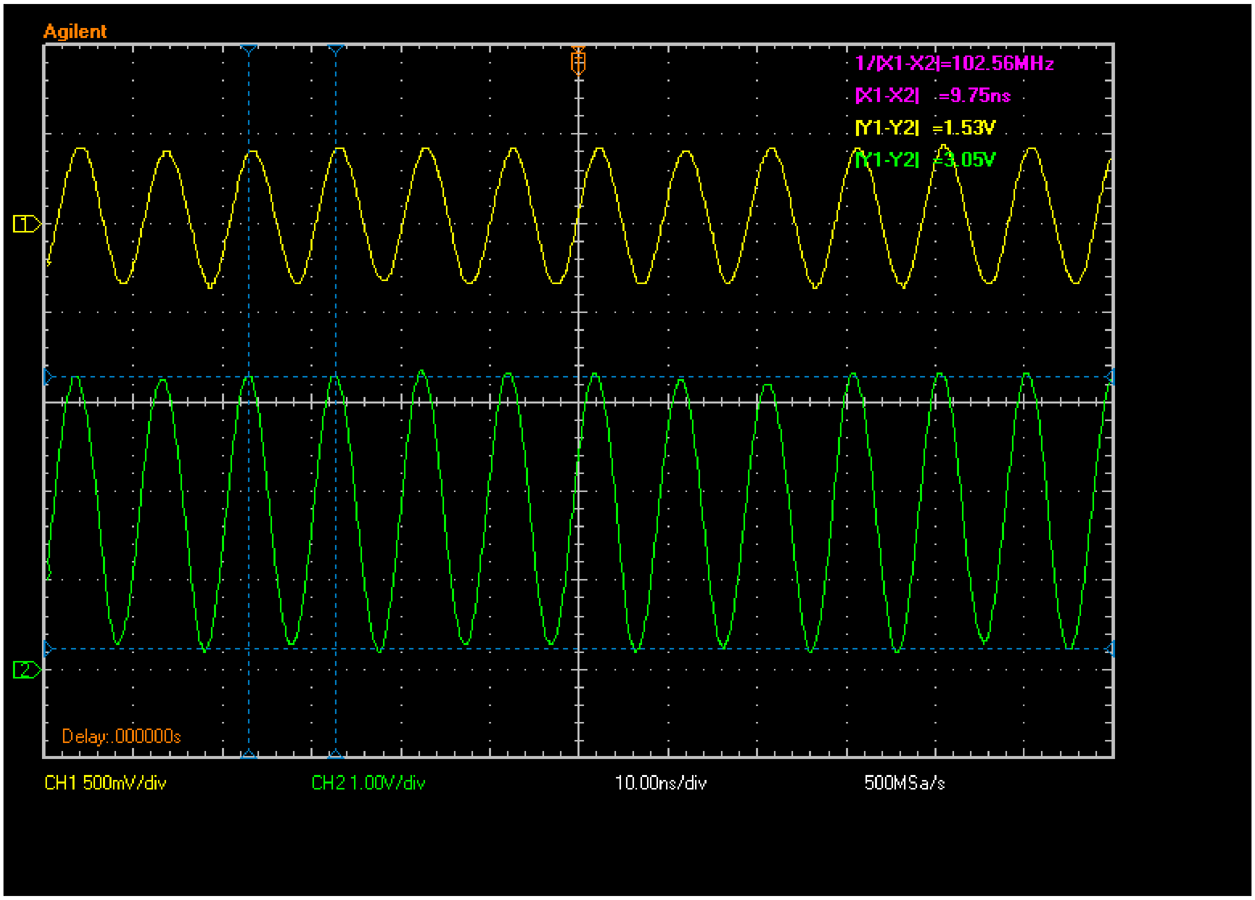


Figure 23: Input and Output of Optical Communication System

This proves that the optical communication system is working properly. The TOSA and ROSA are successfully transmitting and receiving the signal, and the amplifier is amplifying the signal to a 3.3 V level, useful for RTL (Resistor-Transistor Logic) or CMOS circuits. Although the system is tested using an analog sinusoidal signal, the system should still work properly using a high-frequency digital signal. The only modification to the system to do this is to change the amplifier to a component that operates at higher frequencies.

Conclusion

The Open Air Optical Communication system was a success. The three main components of the system, the optical transmitter, optical receiver, and the signal amplifier, worked together cohesively to effectively transmit an electric signal across the system. This was made possible by careful part selection to ensure the components, which were designed for operation with optical fibers, would still transmit and receive light waves sufficiently in an open-air system. This system also showed that when using lasers in open air optical communications, the laser and receiver do not have to be directly aimed at each other to ensure an optical communication link, making the system easier to implement and more reliable when used outside of a laboratory environment. The system in its current state could not be tested to transmit data at the highest theoretical frequency because the necessary test equipment was not available in the laboratory. It was proven that the system could operate at the lower-bound of the frequency range, and could be tested at the higher end given more time and higher bandwidth equipment.

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Appendix A: Analysis of Senior Project Design

The Optical Data Transmission system receives a high frequency (100 MHz-4.25 GHz) digital electric input signal and converts it into an optical signal. The signal is then sent across a short length of open air and is converted back into an electrical signal by a receiver. The signal is then amplified such that has the same properties as the original signal with minimal distortion. This system allows for high voltage potential differences across the input and output, as well as transmission of data immune to electromagnetic interference.

The significant challenges in this project were the implementation of the optical devices communicating via open air and designing the high speed electrical components. Using the components to communicate without the use of an optical cable proved challenging, but was vital to the success of the project. Designing the electronics so that they would function at high speeds was a difficult design challenge, and care had to be taken to ensure that the signal was not lost or distorted during transmission. The main challenge in this project was determining which components should be used that will meet the desired specifications.

Techniques learned over the course of this project include research and selection of high speed components, including receiver, amplifier, transmitter and optical transmission media; layout of high speed circuits, and terminating optical cable properly.

There are several different costs for the research and development of this project. In terms of human capital, time needs to be spent to learn about the techniques for fiber, research and components, and layout the circuit. Financial costs include the price of materials and tooling. Manufactured Capital required for this project includes equipment and materials for soldering, high speed oscilloscope and other test equipment. This project has physical components, which use natural capital, including gold, tantalum, silicon, Gallium Arsenide, and copper.

The optical data transmission system includes materials such as lead, Gallium Arsenide, epoxy, gold and tantalum. Lead and Ga As can be dangerous to the user and to the environment if not handled properly. Fumes from epoxy and the soldering process can be harmful if inhaled. Gold and Tantalum are both rare materials, which can be expensive to obtain.

The use of rare materials like tantalum (in capacitors) and gold (in plating of components), does raise some ethical issues. In some foreign countries where these materials are abundant, political issues and wars sometimes arise over the control of them.

If manufactured as a product, these optical data transmitters would be sold soon after the design project is completed, and would have an expected life cycle of 10 years. There will be no maintenance required. The estimated initial cost of the system is $50. After the project is complete, the next step is to contact companies and organizations in potential fields where the high-speed optical system could be useful, such as in medical, manufacturing or military applications.

Several issues need to be addressed when designing and manufacturing the system: stray capacitances, variations in impedance, impedance matching and cable termination. Manufacturing tolerances also need to be noted, so that there is no overall change in consistency among the manufactured products

Care needs to be taken when the system is manufactured because the components are very fragile, they can be damaged by ESD, and they could be contaminated by dirt, dust or debris. Special care needs to be taken when packaging the system for shipping, selecting packaging that is resistant to ESD, shock, or contamination. System may need cleaning over time due to dust or debris getting on the components.

Care was taken when the system was designed and tested, so that the system does not produce unsafe levels of optical radiation. The system contains a high intensity laser, and as such, protective glasses are necessary when constructing and testing.

Appendix B: Specifications

- Transmits data at speeds up to 4.25 Gb/s (gigabits per second)
- Transmit optical data through open air up to 15 cm away
- Input logic low: 0-1.0V
- Input logic high: 1.7-2.0V
- Output voltage level: 0.14-3.1V nom
- Input resistance of TOSA = 50 Ω
- Output resistance of ROSA = 45 Ω
- Output resistance of Comparator = 50 Ω
- Laser meets Class 2M specifications

Appendix C: Bill of Materials

Component	Manufacturer	Qty	Cost
HFE4192-581 (TOSA)	Finisar	1	$22.16
HFD3180-203 (ROSA)	Finisar	1	$14.79
MAX999EUK (Comparator)	Maxim Integrated	1	$7.84
Resistors	n/a	2	$0.10
Capacitors	n/a	4	$0.25
Circuit Card Material	n/a	1	$5.00

Appendix D: Schedule

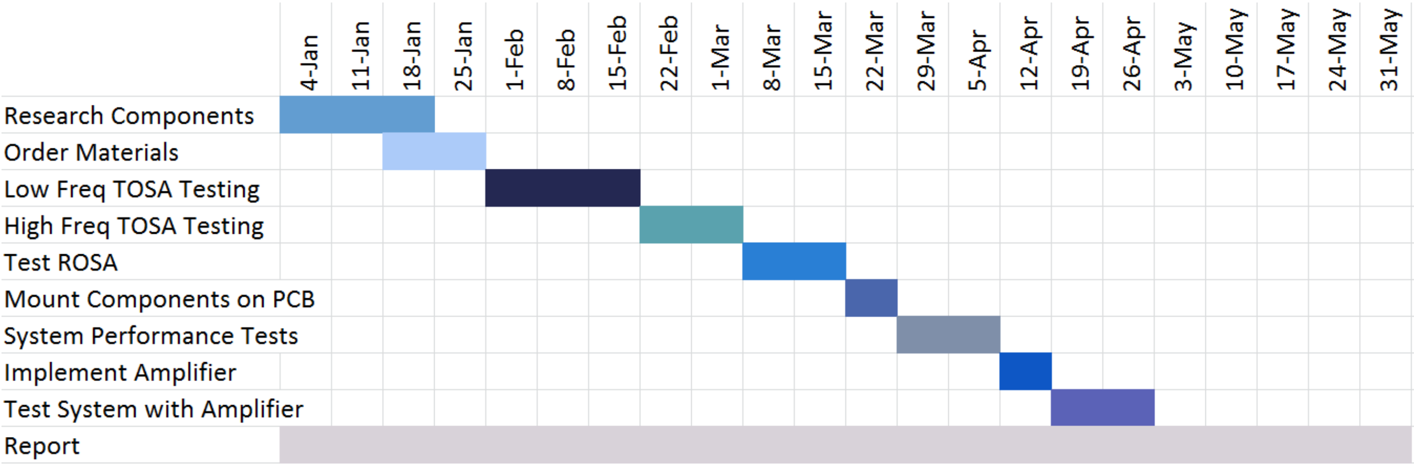

Figure 24: Gantt Chart