Audio-To-Optical Conversion and Transmission

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Acknowledgements

I would like to thank Robert Fuchs and Jen Lumbres for assisting me with the construction of this experiment. I want to thank Professor Jin for helping me and answering all of my questions with this project. Thank you to my parents for supporting me. Last but not least, I would like to thank my girlfriend Korey for putting up with me when working on my project would make me just a bit insane.

ABSTRACT

The purpose of this project is to understand free-space optical transmission of signals in the application of transmitting an audio signal. An audio signal will be taken from the headphone output of a computer and used to modulate a current source driving an LED and a laser diode. The optical signal will then be transmitted through free space as well as two different focal length lenses and converted back to an audio signal to measure any attenuation or gain in the original signal. My experimental results showed that the LED was able to transmit up to 10 dB more power than the LD at all frequencies. However, the LD was able to transmit a more consistent power with respect to distance than the LED. The LED had higher average attenuation with respect to distance of 5.8dB/cm, compared to 5.2dB/cm for the LD. This could be because the LD transmits polarized light and the LED does not.

I. INTRODUCTION

The purpose of this project is to understand free-space optical transmission of signals in the application of transmitting an audio signal. I want to see if converting an audio signal to an optical signal and transmitting it through free space or a lens before converting it back to an audio signal has any effect on the received output. I will use the audio output from a computer to modulate an optical current source providing power to a Laser diode and a light emitting diode. The light emitted by those sources will then be propagated through free space and converted back to an audio signal by using a photodetector connected to an amplifier. The signal will then be reconnected to speakers to determine if any loss occurs at various frequencies.

With the knowledge gained from this experiment, a point to point communication system could be developed using an optical source rather than a high frequency RF signal. One problem that arises from using a radio signal is that it is not known if the signal is being detected by an unknown party. A free space optical signal has an advantage over a radio signal because if it is being intercepted, the signal is either cut off completely or there is significant power loss at the receiving end.

II. BACKGROUND

Wireless communication has become increasingly prevalent in the past few decades. Wireless communication is used by almost everyone, from using a television remote to calling a friend on a cellular phone and even to military communication applications. Two of the most important characteristics of this form of communication are the speed at which data can be relayed, and how far the signal can be propagated.

One example of a current use of wireless communications is a SwiftLink Deployable Com[3]. These portable SATCOMs are used in military operations and provide mobile communication for ground troops. They are small devices that are quick to set up and provide point to point communication. These devices can transmit data up to 6Mbps using an RF interface. However, a setback of this setup is that they must be placed in an open area to prevent interference with the signal. Because the signals may need to be relayed from a satellite as far as halfway around the world, the signal clarity is important. It can be difficult to establish a connection in a terrain with lots of mountains or trees. Another fallback of the SATCOMs is that the setup must remain stationary while communication is in progress. This is difficult to achieve in a warzone where active communication during combat is essential.

Free space optical transmission improves on RF and microwave frequency transmissions because a much higher data rate, up to 15 Gbps, is attainable. An experiment done by Hennes Henniger and Bernhard Epple attempted to attain high speed optical transmission on a mobile device[2]. In their experiment, they mounted a GPS and altitude and heading reference system (AHRS) onto a vehicle. The location of the receiving terminal was always known, so the GPS and AHRS could always point the transmitter in the correct direction, even if the line of sight of the signal had been broken. A camera was attached to the top of the vehicle, and the data being transmitted was the video being recorded. The laser being used was operating at 1500nm and a power of 180mW. The vehicle drove between distances of 1300 and 1900m away from the receiver up to speeds of 30km/hr. By using this setup, they were able to achieve data rates up to 1.5Gbps. The Henniger and Epple experiment improves upon the SwiftLink SATCOMs because the data rate is 250 times faster. Also, the system can be mounted to a vehicle, so mobile communication is possible. In the event of a disruption of the line of sight of the signal, a fast reconnection is possible due to the AHRS and GPS included in the system. A problem with this system is that it would not be usable in an urban environment because of too many obstacles.

III. REQUIREMENTS

The first requirement of this experiment is that it must take an audio signal as its input and produce the same audio signal at its output. The input will come from a male TRS connector and be converted using the system back to a male TRS connector so it can be output to speakers. All audio signals that are transmitted using a TRS connector do not exceed 5Vpp, so the output from the computer cannot exceed that limit. The input range of the laser diode current source is 10V, so audio input range is acceptable. The input current to the current source cannot exceed 5mA/V. The low bandwidth mode of the current source only accepts an input up to 15kHz. This can be a problem considering the audible range is 20Hz to 20kHz. However, this is acceptable because the musical range of frequencies is 20Hz to 10kHz which is within the range of inputs. Another requirement is that the gain of the photodetector and amplifier cannot be large enough to make the output signal exceed 5Vpp. If this were to happen, the audio signal would be clipped, which would result in the output sound making a crashing noise.

IV. DESIGN

When I first built the project, I did not include an amplifier between the photodetector and the speakers. With no gain, the sound coming from the speakers was almost completely noise. With the volume control on the speakers turned to the maximum, it was possible to make out the music being transmitted, but the noise was too loud to name it a successful transmission. Because of this, I introduced a non-inverting amplifier between the photodetector and speakers. The circuit layout can be found in Figure 1, below.

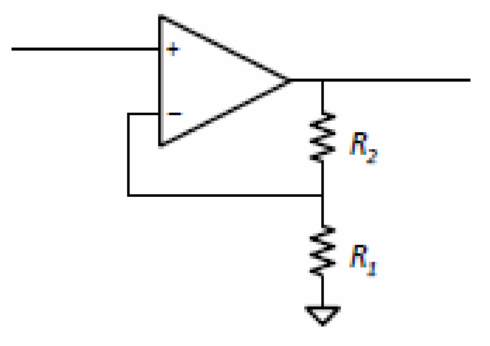

Figure 1: Non-inverting Amplifier Configuration

I changed the resistors until I found a desirable gain to give a large signal to noise ratio at the output. I used an LM741 op-amp with 10V rails and R2 = 51kΩ and R1 = 330Ω. This gives a nominal voltage gain of (51000 + 330) / 330 = 155.5. With this new gain I was able to successfully take my measurements.

V. CONSTRUCTION

The layout for the project can be found in Figure 2, below.

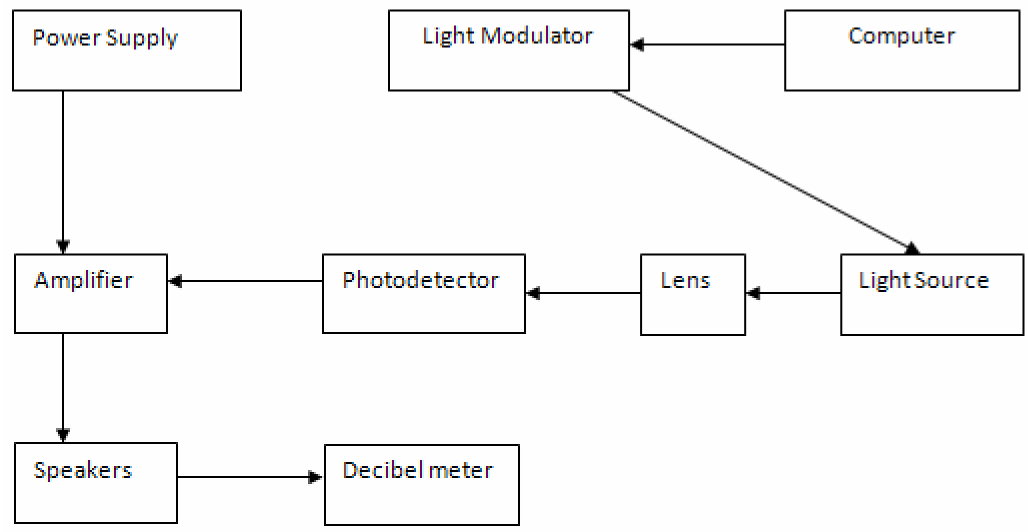

Figure 2: Project Layout

The initial signal comes from the audio out jack of the computer. It is connected to the light modulator using a male TRS to female RCA adapter, a 6 foot male to male RCA cable, and a female RCA to male BNC adapter. The light source is then connected to the modulator through the VGA connector. The light is then allowed to propagate either through free space or through a lens and is received by the photodetector. The photodetector output is connected to the amplifier using a BNC-to-grabber cable. Because the photodetector can only receive one channel, only one of the output speakers will produce any noise. This is acceptable because an RCA cable can only transmit one channel at a time as well, so it only receives the output intended for the left speaker. The amplifier receives its power from the power supply using three banana-to-grabber cables. The speakers receive their input from the amplifier using two banana-to-grabber cables and two alligator clips. The clips allow for a more secure connection between the cables and the TRS connector of the speaker. The TRS connector can be seen in Figure 3, below[6].

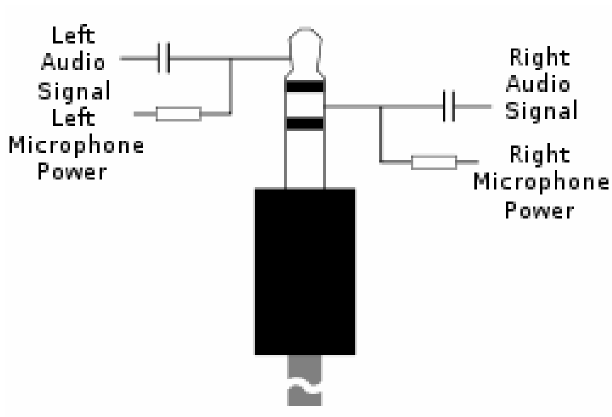

Figure 3: TRS Connector Diagram

As can be seen in Figure above, the output of the amplifier can be connected to either the right or left audio signal pins on the TRS connector. I chose the left speaker because the connection was easier to make without the alligator clips accidentally touching and shorting out the signal. The bottom pin of the TRS connector is reserved for the common ground of both signals if it is being used for headphones or speakers. A decibel meter is placed 1.5cm away from the left speaker to take measurements once the signal is received.

VI. TESTING

To ensure that my system met the requirements I set, I measured the voltage output at each stage of the system using an oscilloscope. I used the same volume output and cables for each measurement. I also took measurements at the same point in the song that was playing to ensure the voltage fluctuations were consistent for all measurements. The voltage measured directly from the output of the computer did not exceed 2Vpp. With the photodetector placed directly against the laser diode(LD), the voltage measured from the photodetector with the gain turned on did not exceed 1Vpp. The output voltage of the non-inverting amplifier was measured at 1.8Vpp. When the speaker was connected to the amplifier, the output coming from the external headphone jack was 2.5Vpp. All of these voltages were within the acceptable range given by the requirements. I then needed to ensure that the bandwidth range of the laser current source would not be exceeded. The average hearing range of a human is 20Hz to 20000Hz[4]. As most humans get older, they lose the ability to hear frequencies above 18kHz. According to the decibel meter manual, most music does not use frequencies above 10kHz. Also, a standard eight octave piano does not produce frequencies higher than 4.2kHz[5]. These frequencies are all within the bandwidth limitations of the current source.

When I first assembled the system, the music being produced did not sound the way it was intended. The higher frequency notes that were being played in the music would produce a crashing noise in the speakers. At that point, the laser diode current source had been set to 45mA. After reducing the current to 35mA, I was able to hear the music clearly.

VII. TEST RESULTS

Using a program named Audacity[1], I was able to transmit single frequencies through the system to measure any attenuation at several specific frequencies. I first measured the decibel level at various frequencies below 10kHz with the speakers directly connected to the computer to compare with my other data. After taking the measurements, I made sure that the volume adjuster on the speakers was in the same position for the rest of the measurements to ensure the internal gain of the speakers was constant. The data can be seen in TABLE I below.

TABLE I: Decibel Readings with Direct to Speaker Connection

f(Hz)	Direct to Speaker (dB)
60	80
80	86
100	95
250	113
500	109
750	109
1000	106
2500	95
5000	92
7500	100
9000	90
9250	90
9500	94
9750	90
10000	88

As can be seen in TABLE I, there appear to be two peak frequencies in the musical audible range. There is one maximum at 250Hz with a decibel level of 113dB, and another maximum at 7500Hz with a decibel level of 100dB.

After measuring the sound going directly to the speaker, I measured the audible levels using a Laser Diode and an LED to transmit the signal optically. The first measurement was taken with no distance between the light sources and the photodetector. The data for this can be found in TABLE II below.

TABLE II: Decibel Readings with No Gap

f(Hz)	LD(dB)	LED(dB)
60	70	81
80	79	89
100	87	97
250	103	110
500	100	107
750	100	107
1000	99	106
2500	92	100
5000	95	103
7500	93	103
9000	85	95
9250	86	93
9500	90	96
9750	90	93
10000	92	91

It is shown in TABLE II that at all frequencies except 10kHz, the LED is able to transmit more power to be detected by the photodetector. The peak decibel levels at 250Hz and 7.5kHz are present as well, so neither source has acted as a filter to change which frequencies are more present in the signal. In order to measure the attenuation of the system, I compared the no distance transmission data to the direct to speaker data. This is summarized in Figure 4 below.

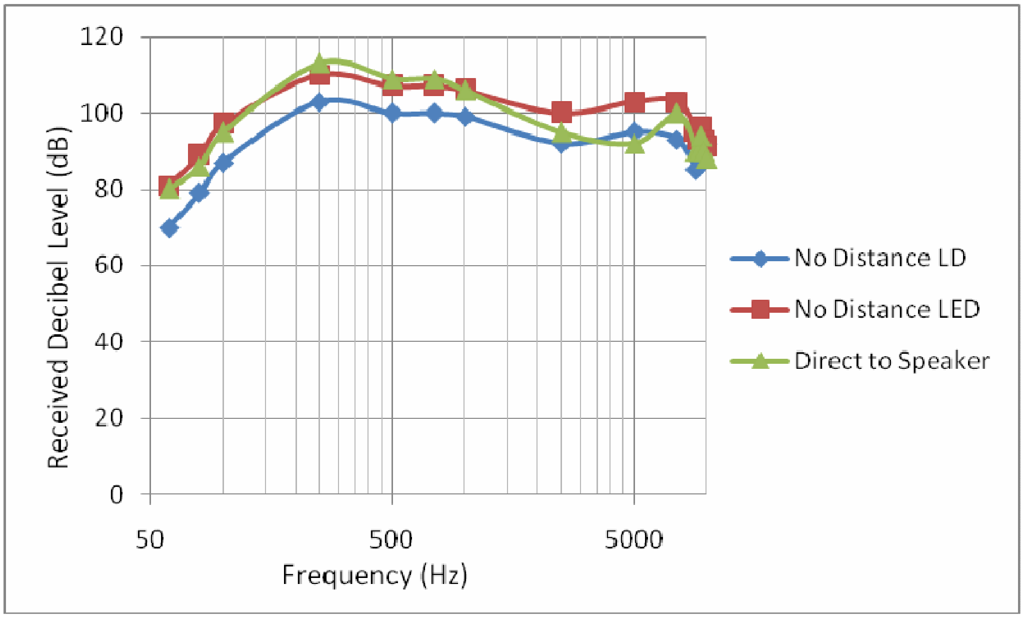

Figure 4: Comparison of transmission using light sources to direct speaker connection

From the graph in Figure 4, the LED source transmits more power at frequencies above 1kHz than the direct speaker connection. The LD also transmits higher power at 5kHz. The attenuation at each frequency is summarized in TABLE III.

TABLE III: Attenuation Between Direct Speaker Connection And Each Light Source

f(Hz)	LD Loss (dB)	LED Loss (dB)
60	10	-1
80	7	-3
100	8	-2
250	10	3
500	9	2
750	9	2
1000	7	0
2500	3	-5
5000	-3	-11
7500	7	-3
9000	5	-5
9250	4	-3
9500	4	-2
9750	0	-3
10000	-4	-3

As can be seen in TABLE III, the LD has a gain compared to the direct speaker connection of 3 and 4 dB at 5kHz and 10kHz respectively. The LED has a gain up to 11dB at frequencies below 250Hz and above 1kHz. This can be seen in the graph of Figure 5 on the next page.

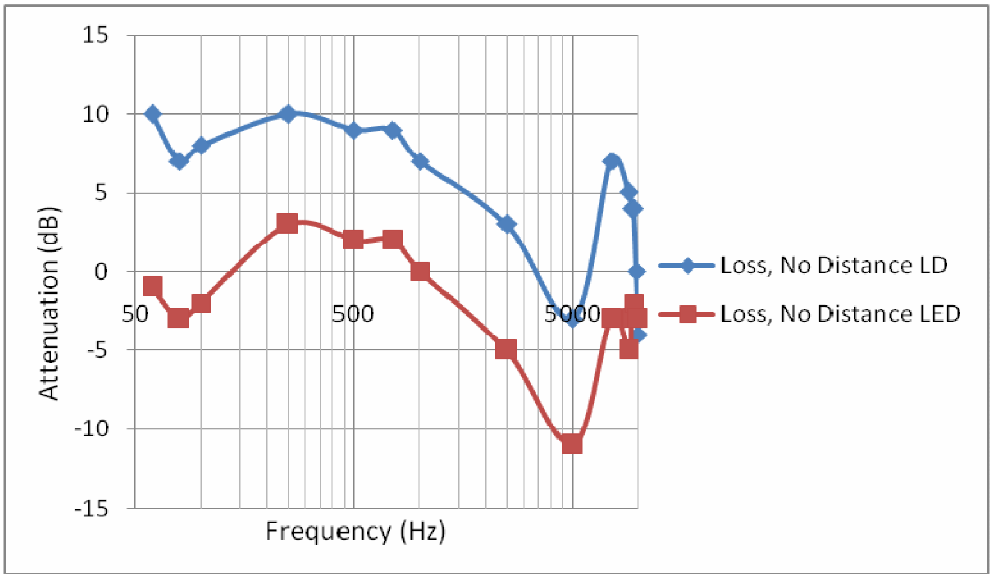

Figure 5: Attenuation of each source compared to direct speaker connection

From the graph of Figure 5, the region of highest attenuation for both sources occurs between 250Hz and 1kHz. This is also the region where the highest amount of power is received by the photodetector.

After testing with no distance between the light source and detector, I increased the distance between them to 3cm to measure the effects of attenuation with respect to the distance traveled by the signal. The data taken for the received decibel level over a 3cm gap can be seen in TABLE IV below.

TABLE IV: Received Decibel Level with A 3cm Gap

f(Hz)	LD(dB)	LED(dB)
60	65	66
80	66	69
100	72	77
250	87	95
500	83	92
750	84	92
1000	82	91
2500	76	84
5000	77	86
7500	75	85
9000	70	78
9250	71	76
9500	73	79
9750	73	77
10000	74	73

The peak decibel level can be seen again at 250Hz for both the LD and LED. Something of note with this data is that both sources transmitted significantly less power due to the air gap. A graph of the received decibel level for both sources can be seen below in Figure 6.

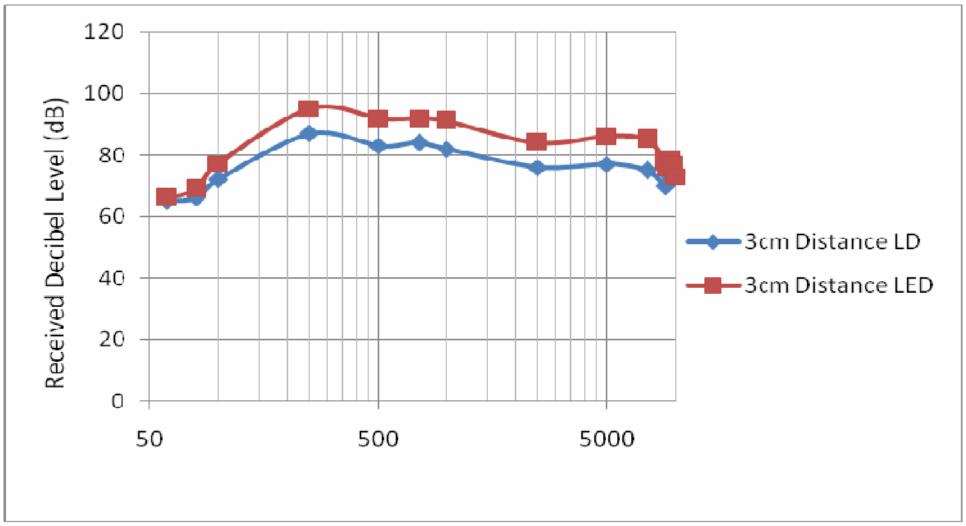

Figure 6: Graph of data transmission with 3cm air gap

Something to note from Figure 6 is that at the frequencies below 250Hz, the received power was much closer for both sources with the air gap than with no gap. Table V below shows the attenuation between having no gap and the 3cm air gap.

TABLE V: Attenuation with 3cm Air Gap

f(Hz)	LD Loss (dB)	LED Loss (dB)
60	15	14
80	20	17
100	23	18
250	26	18
500	26	17
750	25	17
1000	24	15
2500	19	11
5000	15	6
7500	25	15
9000	20	12
9250	19	14
9500	21	15
9750	17	13
10000	14	15

The average attenuation with respect to distance for the LD was 5.2dB/cm and the average attenuation per length of the LED was 5.8dB/cm. This calculation assumes a linear relationship between attenuation and distance. A graph showing the data of TABLE V can be found in Figure 7 on the next page.

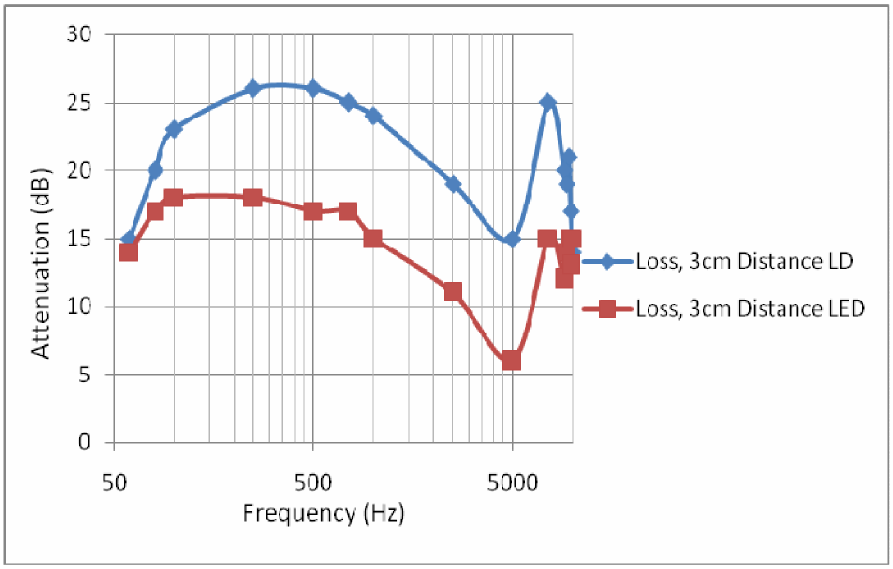

Figure 7: Attenuation for sources with 3cm air gap

From Figure 7, the highest attenuation occurs between 250Hz and 1kHz. There is also a peak in attenuation at 7.5kHz for both sources.

After measuring the system with an air gap between the sources and detector, I placed a lens in between to see how much focusing the intensity of the light would increase the power received. The first lens I used to measure was bi-convex and had a focal length of 50.2mm and was placed 8cm from the detector and 10cm away from the lens to focus the beam to a point on the detector. The data taken including the 50.2mm lens can be found in TABLE VI.

TABLE VI: Received Decibel Level with 50.2mm Lens

f(Hz)	LD(dB)	LED(dB)
60	66	69
80	73	74
100	81	83
250	96	101
500	93	98
750	93	98
1000	92	97
2500	85	90
5000	87	92
7500	86	90
9000	79	84
9250	80	82
9500	83	85
9750	82	82
10000	84	79

The peak transmitted power occurred at 250Hz for both sources when using the 50.2mm lens. The lens was also successful in increasing the received power by focusing the intensity on the detector. This data can be seen in the graph of Figure 8.

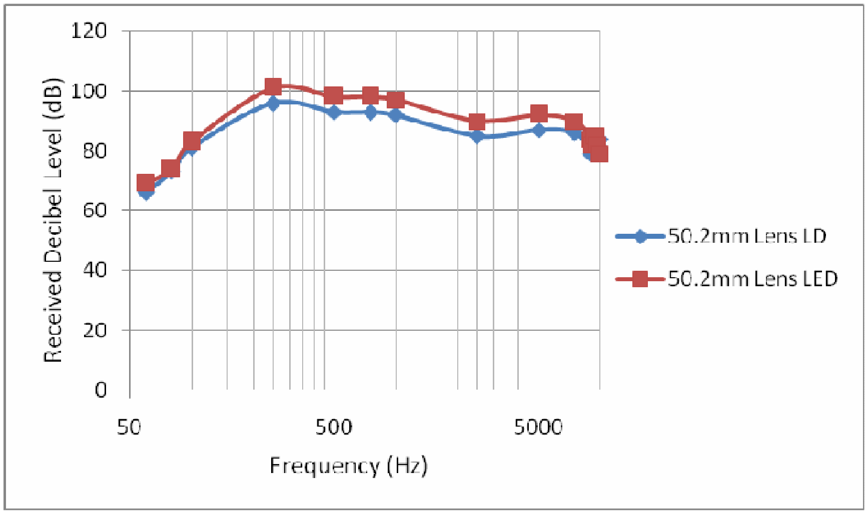

Figure 8: Graph of data transmission with 50.2mm lens

By comparing the graphs in Figures 6 and 8, the transmitted power was closer between both sources using the 50.smm lens than the 3cm gap. The loss of this system can be found in TABLE VII below.

TABLE VII: Attenuation with 50.2mm Lens

f(Hz)	LD Loss (dB)	LED Loss (dB)
60	14	11
80	13	12
100	14	12
250	17	12
500	16	11
750	16	11
1000	14	9
2500	10	5
5000	5	0
7500	14	10
9000	11	6
9250	10	8
9500	11	9
9750	8	8
10000	4	9

The attenuation using both sources was less than the 3cm air gap. Also, the difference between the LED and LD attenuation was less than the 3cm air gap. This could mean focusing the light beam using a lens has more of an effect for the LD than the LED. The graph of attenuation for the 50.2mm lens can be seen in Figure 9.

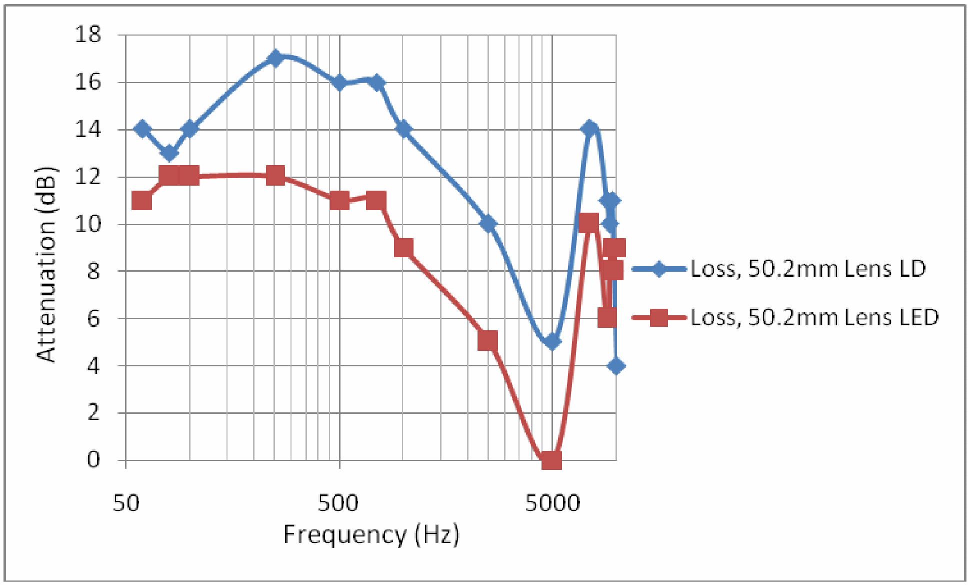

Figure 9: Attenuation for sources with 50.2mm lens

For both sources, the highest attenuation occurred at 250Hz. There was up to 11dB less attenuation when using the lens to focus the intensity for the LD. There was up to 6dB less attenuation for the LED. This means the lens was more effective at reducing loss for the LD than the LED.

Next, I used a bi-convex lens with a focal length of 75.6mm placed 14 cm from the detector and 14cm from the light source. The data for this setup can be found in TABLE VIII.

TABLE VIII: Received Decibel Level with 75.6mm Lens

f(Hz)	LD(dB)	LED(dB)
60	66	66
80	70	69
100	76	76
250	91	95
500	89	91
750	88	91
1000	87	90
2500	81	84
5000	82	85
7500	83	83
9000	77	77
9250	76	76
9500	81	78
9750	81	76
10000	84	72

TABLE VIII shows that using the 75.6mm lens is not as effective as using the 50.2mm lens to focus the beam for either source. At all frequencies the transmitted power is lower. This is shown in Figure 10.

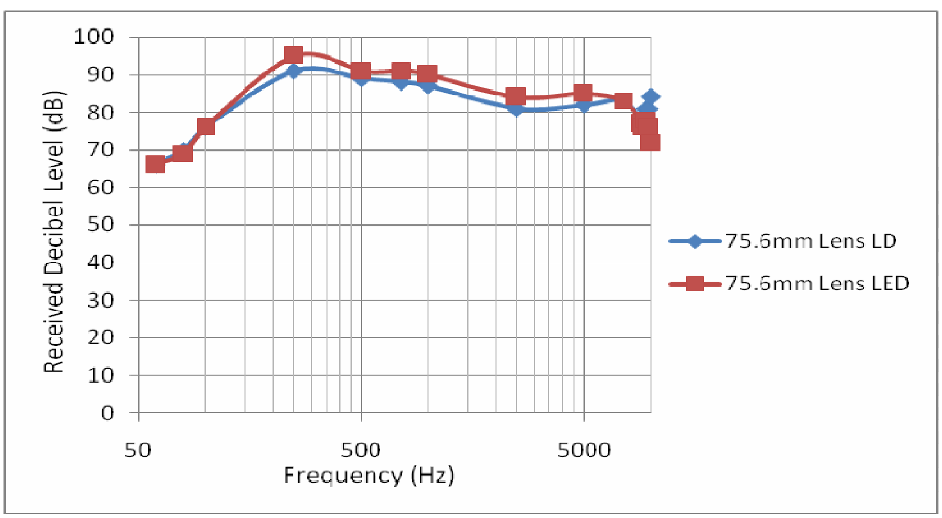

Figure 10: Graph of data transmission with 75.6mm lens

It can be seen in Figure 10 that using a lens is more effective at helping the transmission of light from an LD. In the graph, the difference in power of transmitted data is even more close together than with the 50.2mm lens. In fact, the frequencies above 9250Hz are transmitted with higher power for the LD than the LED. The table of data showing attenuation for the 75.6mm lens can be seen in TABLE IX.

TABLE IX: Attenuation with 75.6mm Lens

f(Hz)	LD (dB)	LED(dB)
60	14	14
80	16	17
100	19	19
250	22	18
500	20	18
750	21	18
1000	19	16
2500	14	11
5000	10	7
7500	17	17
9000	13	13
9250	14	14
9500	13	16
9750	9	14
10000	4	16

Something to note from TABLE IX is that the attenuation for the LED has its peak at 100Hz rather than 250Hz in each other measurement. The attenuation for the system with the 75.6mm lens can be found in Figure 11.

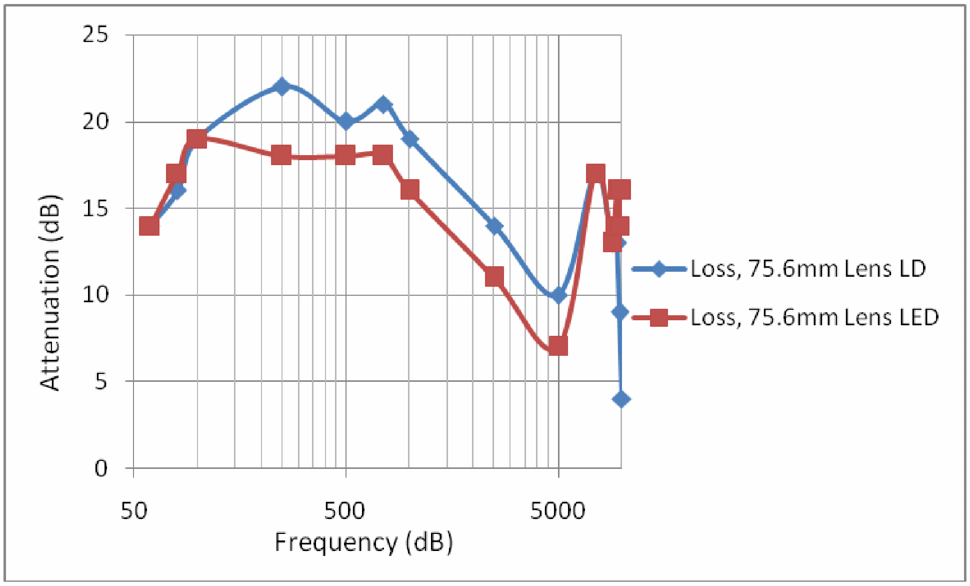

Figure 11: Attenuation for sources with 50.2mm lens

From the graph of Figure 11, it is apparent that there is less attenuation for the LD at frequencies below 100Hz and above 7.5kHz. This could be because the lens is more effective at focusing the LD light. It could also be because the LED has a higher attenuation with respect to distance, so there is less power to focus once the light has propagated to the surface of the lens than with the LD.

VIII. CONCLUSIONS

After testing the differences between the two sources, I have concluded that the laser diode would be a better light source for any point-to-point communication systems than the LED. Although the LED is capable of transmitting a higher power than the LD at the transmitter, not many communications systems would require a light source to propagate over no distance. The LD has a lower attenuation with respect to distance, so it would require less power to transmit the data the same distance as an LED.

Another conclusion is that using a lens to focus the transmitted beam is more effective for a laser diode than an LED. This could be due to the wavelength that each source operates at. The LED operates at 850nm and the LD operates at 650nm. The most common wavelength used in optical fibers is 1550nm because it provides a lower attenuation; perhaps the lowest attenuation for the lens is at 650nm. Another possibility is that the lens helps focus the LD light more efficiently because the LD source provides polarized light, while the LED does not. Using the lens to focus the beam also allows the source to use less power to transmit data than just having a direct point-to-point connection.

Many communications systems that are built for point-to-point communication are built at high elevations to ensure a constant line of sight for their transmissions. For long distance transmissions, it would not be possible to use a lens at a significant distance between the transmitter and receiver to reduce any attenuation in free space. For that purpose, an LED and an LD would not be sufficient light sources for propagation further than a few meters. A laser would be more effective for long distance or mobile transmission.

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[6] Wikipedia. TRS Connector. 7 May 2011. 10 May 2011. <http://en.wikipedia.org/wiki/ TRS_connector#Audio>

Appendix A

Parts and Cost List

Part	Cost
Topward Electric Instruments Co. Dual Tracking DC Power Supply	N/A
ILX Lightwave LDX-3210 Laser Diode Current Source	N/A
Radioshack Digital Sound Level Meter	$49.99
Logitech LS-21 Speakers	N/A
5x Banana to grabber cables	N/A
1x BNC to grabber cable	N/A
1x BNC to BNC cable	N/A
1x Scope probe	N/A
2x Alligator clips	N/A
1x BNC to RCA connector	$6.79
1x 6.6’ RCA to RCA cable	$11.99
1x RCA to TRS connector	$3.99
Total	$72.76