ECE476: Electro-Optics
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Free-Space Optical System for Communication

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Abstract— This paper discusses a Free-Space Optical System for Communication. This is achieved through two circuits. The first circuit is a transmitter circuit made using a LM741 op-amp, a NE555P Timer, a LM313 Differential Comparator, and a laser diode along with some other miscellaneous resistors and capacitors. The receiver circuit is the second circuit which makes use of photodetectors of various types, a LM386, which is a low voltage audio power amplifier, a potentiometer, and a speaker, along with various resistors and capacitors. The function of each component will be explained in this paper to reveal the intertwined processes of each device in the overall circuit. In short, our transmitter circuit takes an AC voltage signal from an audio device, samples the signal through the use of a NE555P Timer and a LM313 Differential Comparator and transmits binary serial signal through a laser diode. This laser signal is then received by a photodetector, and this received signal is amplified by the LM386 into the speaker. This paper will also discuss some modifications to the described circuit above and elaborate on how these modifications affected the overall circuit's performance. Finally, we will discuss some limitations to the circuit, as well as potential improvements that can be applied moving forward.

Introduction

Free-Space Optical Systems are an attractive idea as they lend way to a large bandwidth, a low implementation cost, and are particularly robust to security breaches and electromagnetic interference [1]. This paper will discuss a simple system for optical wireless communication (OWC), which refers to the transmission of unguided propagation through optical caries, or light.

Today, OWC uses lasers or light emitting diodes to transmit light signals. This technology is not new, however. In 1962, MIT Lincoln Labs was able to build an experimental OWC link through a light emitting GaAs diode. In this experiment MIT Lincoln labs was able to transmit a TV light signal over a distance of 30 miles, demonstrating the potential of these systems [1]. The major limitation of these initial experiments was the large beam divergence of the laser beams, and this is the attraction of using an optical fiber where total internal reflection can be achieved, and beam divergence becomes irrelevant assuming that the angle of divergence is less than that of the acceptance angle.

Unfortunately, OWC has some major limitations. These limitations include pointing errors and atmospheric turbulence greatly hindering system performance and making them not truly practical on a large scale, but with future improvements and innovations, they may be more realistic systems in the near future [1]. These improvements must begin with a basic understanding of how to optimize these systems as well as understanding how these systems are affected by the environment. One obvious optimization, particularly important over longer distance OWC systems, is to operate said systems in primarily the IR range. IR light is less susceptible to light scattering in comparison to higher frequency wavelengths (why the sky is blue) and this is the rationale for using these longer wavelengths of light. In the area of autophoretic scattering and the turbulence phenomena, improvement in the area has recently been proposed [2]. It has been found that there is an inverse correlation between the level of attenuation and turbulence strength. Additionally, there has been recent exploration and modeling on the effects of atmospheric scattering due to several weather conditions, improving the predictability that the weather has on scattering events [3]. What this means for OWC as a technology is that in understanding the influences of the environment on a signal's transmission, we can better filter and predict signals, improving the efficiency and functional separation of transmitters and receivers in OWC technology.

Another limitation of OWC in general is background noise. Background noise limits the distance of signal transmission when the original signal is no longer distinguishable from the noise itself. This noise in OWC systems is largely attributed to atmospheric turbulence, as stated above, but can also be influenced by other environmental factors surrounding the system. Recently, in an attempt to combat this background noise, differential signaling techniques, such as pulse-position modulation has been used to some success [4], outlining a major improvement from the previous standard. Other research in the area of OWC has also demonstrated a massive reduction in the effect of background noise on signal transmission through pulse-amplitude modulation, which is similar to pulse-position modulation but largely varies in the receiver's detection capabilities [5].

Research and general knowledge about OWC tell that such systems can work particularly well on shorter distance applications, such as a wireless TV remote, or potentially even a building-to-building communication ecosystem within a city. There has also been discussion about using OWC for satellite-to-satellite communication [1], as the distance that the light can propagate is presumably much longer and more efficient given that satellites are approaching an environment that is a vacuum state, where we know the index of refraction would be a true 1; this would greatly limit the influences of weather and other environmental factors on the light propagation.

Background on Current Laser Communication Techniques

In understanding free-space OWCs, it is important to understand laser communication technologies as a whole. Laser communication can be mainly divided into three categories: fiber optic communication, laser atmospheric communication, and free-space laser communication.

Fiber optic communication is a common communication method with large transmission capacity and good confidentiality. This communication method converts electrical signals into optical signals and then transmits them through an optical fiber. The basic components of a fiber optic system are the optical transmitter, transceiver, the fiber optic line, as well as some passive components. Fiber optic communication is a widely used communication method.

Laser atmospheric communication is wireless communication, with a simple equipment structure and large information capacity, as the information carrier transmission of data has a code rate of up to 10Gb/s. While laser communication has relatively strong anti-electromagnetic interference capability, it is vulnerable to climate, especially in harsh climate environments that will cause information interruption.[6]

Free-space laser communication is mainly used in space. With the use of light waves with short wavelengths and high energies, the system's composition is similar to atmospheric communication. Since space is filled with complex electromagnetic waves, however, there is a need to enhance the receiver's sensitivity. This is achieved through high sensitivity anti-jamming optical signal receiving technology, and high gain transceiver antennas to help improve the accuracy of information transmission.[7]

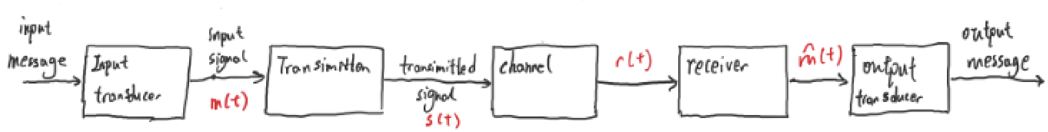

Figure 1: Standard communication system

Optical communication follows the standard communication system structure, as seen in Figure 1.

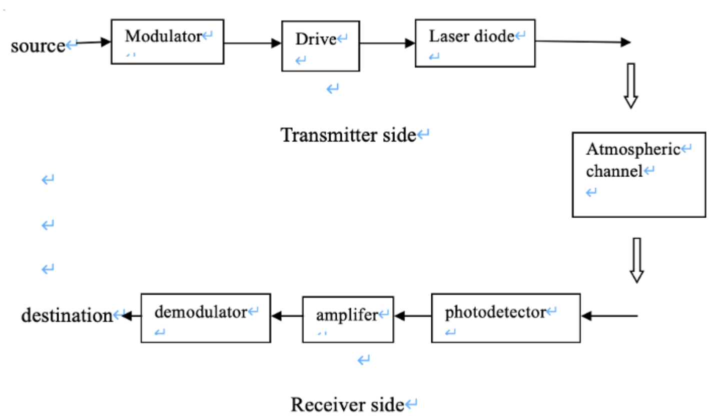

Figure 2: Free-space optical system for communication

Figure 2, is a more detailed example of free-space communication, where the electrical signal is modulated to the optical carrier generated by the laser through the modulator, and then the beam is shaped and launched into the atmosphere through the optical transmitting antenna. The optical signal is transmitted through the atmosphere and reaches the receiving end, where the optical antenna receives the optical signal focused to a photodetector to convert it into an electrical signal, which is amplified and filtered, and then demodulated. Comparing Figure 1 and Figure 2, we can see that basic communication principles apply to optical communication as well.[8]

Some Limitations of Free-Space Optical Systems
(1) High cost. Most of the research on systems based on atmospheric laser communication is concentrated in the military field, while in the civilian field it is usually limited to large companies. The main reason for this is the high cost of optoelectronic devices (semiconductor lasers, photodetectors, optical transceiver antennas, etc.). The quality of these devices largely determines the performance of the system.[9]

(2) Limited transmission power. Laser products have some safety restrictions due to the damage they can cause to the human eye. Laser emission power directly determines the transmission distance of the device however, and the laser emission power and modulation frequency are mutually constrained, that is, the modulation frequency of high-power lasers can not be very high. The cost of semiconductor lasers and the difficulty of temperature control will also increase as the increase in emitted power from a laser becomes higher and higher.[9]

Other Applications of Free-Space Optical Technology
Interstellar distance applications
Some space applications require the transmission of very large amounts of data. For example, data transmission between Earth-orbiting satellites was first demonstrated by ESA in 2001. Transmission rates of tens of megabits per second or higher over distances of several thousand kilometers are possible using moderately intense laser sources with an average power of a few watts.[10] Data can also be transmitted between spacecraft far away from Earth or between space stations near Earth. For example, planetary probes generate large amounts of virtual data, and the challenge is in how to transfer these large amounts of data to Earth. Currently, only radio communication lines working in the X-band or Ka-band can do this job. The spacecraft has a pulsed laser source (using pulse position modulation) and a medium-sized optical telescope aligned to the receiver. The latter can be a large ground-based telescope or a receiver in Earth orbit. The advantage of optical technology over radio communication lines is that optical waves have shorter wavelengths and can therefore send and receive information in a more directional manner, thus requiring lower power and higher data transmission rates. From a technical point of view, the antenna gain is higher. This is important for interstellar distance applications. However, optical links are also more sensitive to climatic conditions.[11]

Short-range free-space optical data links
In urban areas, data transmission between office buildings (LAN to LAN) is easier, as this is a short distance. The use of free-space laser data links for transmission over hundreds or thousands of meters is simpler and more cost effective than any other cable installation over long distance, however, especially if it is necessary to cross roads or other obstacles, or if a connection point is needed for a limited period of time. With this type of link you can get a very fast network connection, even though there may be only one link directly connected to the fiber network. Since almost all the emitted power reaches the receiver (photodiode), a moderate laser power is

required. Therefore there are also no laser safety concerns, especially when using a human eye safe laser, which radiates light in the 1500 nm spectral region. However, this technology is less effective than a cable service because the link is easily disturbed by air disturbances (heavy rain, fog, snow or strong wind, etc.) and flying objects. From this point of view, free-space transmission is more fragile than other wireless technologies, but it also has the potential to reach a large transmission capacity. It is resistant to electromagnetic interference and therefore one does not have to worry about electronic smog. In addition, there is no mutual interference between the different data links, there is also an advantage in terms of data security; since the laser beam is strictly aligned it is difficult to intercept information. As a final point, reliability can be enhanced by a number of methods, such as the use of multi-beam structures, larger power margins, auxiliary systems, and quantum coding techniques to improve security. Short-range optical data connections are also possible when no direct optical line of sight exists. When ultraviolet light is used, it is strongly scattered in the atmosphere and is only partially received. With the appearance of light-emitting diodes radiating deep ultraviolet (UV-C) and suitable semiconductor light detectors, the realization of this technology is possible. The main advantages of laser data links over radio or microwave links are the high data rates achieved, the low power requirements, the small size, and the lower chance of information interception. Moreover, there is no need to use government-assigned frequencies and there is no interference between different data links using this technology.[11][12]

Background our Free-Space Optical System Circuit Design

In this paper, we demonstrate an OWC system on a very small scale. We make use of various electronic devices to construct a simple transmitter circuit and likewise a simple receiver circuit. Here, we pass a serial voltage signal from transmitter to receiver through red light from an LED laser diode. The following will breakdown the inner workings of our circuit, as well as some of the interchangeable parts that were explored, with their theoretical pros and cons.

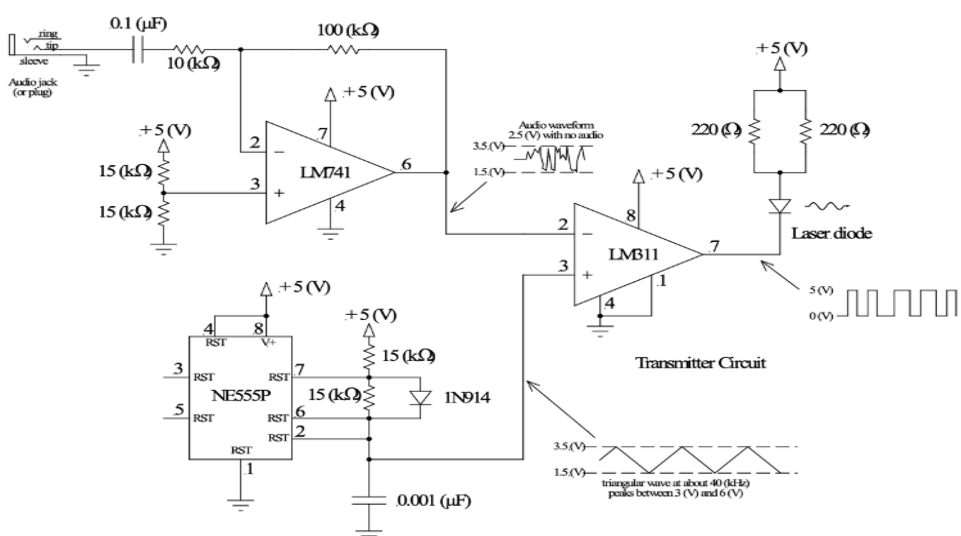

Figure 3: Transmitter circuit schematic

The transmitter circuit schematic can be seen in Figure 3. We can see that this circuit is broken down into the interconnections of 3 different devices, a LM741 op-amp, a NE555P timer, and a LM311 Differential Comparator. We will break down this circuit by exploring how each device works interdependently with its own configuration, and then merge these ideas to outline the transmissions of a signal. We will start our discussion with the LM741 op-amp and its relevant circuit components.

The LM741 op-amp configuration acts as a simple inverting amplifier. We can see that the voltage entering the positive terminal of the op-amp is 2.5 V when we Thevenise this voltage. From the diagram we know that for an inverting amplifier, the output voltage is $-(R_2/R_1)*V_s$ where V_s is the input voltage to the device. In our case, V_s is the AC voltage from the audio jack, as the capacitor between the audio jack and the 10 kΩ resistor limits the DC voltage, R_2 is our 100 kΩ resistor, and R_1 is our 10 kΩ. Therefore, we can see that in this part of the circuit, we have a negative gain of 10. This means that our output voltage from the LM741 op-amp is 10 times the voltage from the audio jack, that voltage is inverted, and also that voltage is summed with 2.5 V. This inversion is actually what we want, as the LM331 Differential Comparator inverts one input voltage, and this double inversion leads to a non-inverted, amplified, voltage. We will discuss more on that later on. We now understand how our voltage from the audio device is amplified and summed with 2.5 V, to be used later on in the circuit.

We now transition our discussion to the NE555P Timer. We used the NE555P Timer to create a triangular wave source to be used by the LM311 Differential Comparator. In order to understand how this triangular waveform is generated, we first must understand how the 555 timer works.

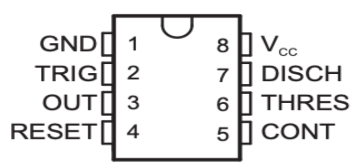

Figure 4: 555 timer pin configuration [13].

A screenshot of the 555 timer and pin configuration can be seen in Figure 4. This was obtained from a user manual for 555 precision timers from Texas Instruments [13].

We will start with a discussion of the simple connections. In our circuit, pin 1 connects to ground, corresponding with the ground pin. Pin 4 resets the timer when a low voltage is passed to it, hence, we connect pin 4 to a high voltage, as we never want to reset the timer. Pin 8 is connected to our 5-volt source and is our input supply voltage, or Vcc for the circuit. The manual states that the Vcc voltage must be between 4.5 to 16 V, so our 5 V source is sufficient. Pin 3 is the inverse of Pin 7, it is left open, as we simply don't need it. Likewise, we do not use pin 5. Pin

5 is a control voltage pin. When set to high, this pin can be used to control the frequency of the timer via an external source. As this is not desired, this pin is also left open.

This leaves only a discussion of pin 2, 6, and 7. Our timer works as a self-controlling system in a sense. To understand this, the three remaining pins need to be understood.

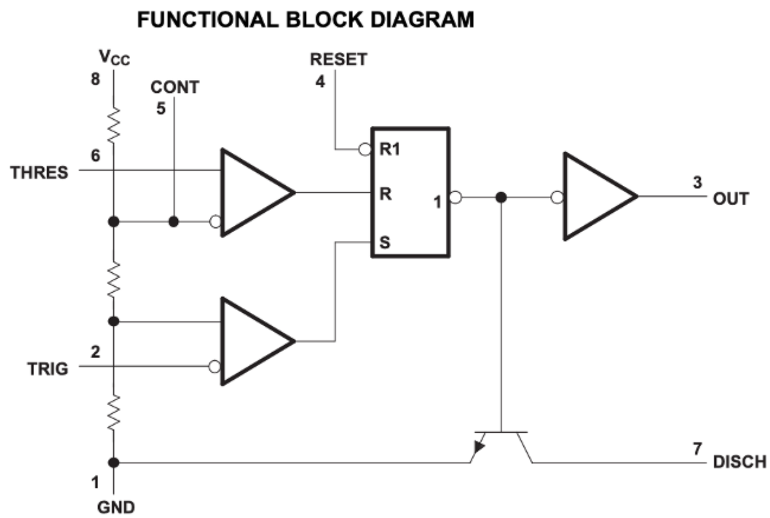

Figure 5: 555 functional block diagram [13].

Pin 2 is a trigger pin. This pin sets the internal flip flop to low, causing the switch to switch to a high voltage when a low voltage is passed [14]. This flip flop can be visualized in Figure 5.

Pin 6 is a threshold pin. This pin switches the internal flip flop to a low voltage when a high voltage is passed [14].

Pin 7 is the discharge pin. What that means is that this pin discharges the gathered charge when the timer switches from high to low. This discharge happens through an internal transistor on the device to the device's ground.

Now that we understand how the 555 timer works, we can now explain how it was used to generate a triangular waveform.

The device starts low. The 5V source passes current through the 15 kΩ Resistor. When the node connecting to pin 2 and 6 is low, most of the current passes through the diode. This current charges the .001 µF capacitor. As this capacitor charges, the voltage at the node increases with the voltage across the capacitor. Once this voltage achieves 2/3*Vcc, which in our case is 3.33 V, pin 6 is activated, turning the timer to a low voltage. The charge stored in the capacitor is then discharged through pin 7 until the voltage across the capacitor is equal to 1/3*Vcc, which in our case is 1.66 V. Once this voltage is achieved, pin 2 sets the timer's voltage to high, and the charge can no longer discharge through pin 7, hence, the capacitor starts charging again. It should be noted that because the diode is in our circuit and current flows from a high to low voltage, we know that almost all current discharges through pin 7 to ground or propagates onward in our circuit. This cyclical process explains how the timer toggles between 1.66 V and 3.33 V.

We still have to explain why this output voltage across the capacitor is triangular, however. This can be explained via the RC time constant. We know that capacitors charge in accordance with an RC time constant. In our circuit here, our capacitor is very small (.001 μF) and our resistance is also relatively small (maximum of 30 kΩ). When solving for our RC constant, we see that a worst-case scenario RC constant would be $3*10^5$ (s). Since our RC time instant is so small, our change in voltage across the capacitor approaches a linear pattern, and this is the reason that we can achieve a triangular waveform using the 555 timer. It should be noted that our experimental RC constant for this timer was on the magnitude of microseconds, so we can confirm that our change in voltage for this timer configuration is essentially linear. More on this will be discussed later.

The frequency at which this timer oscillates can be calculated as well and relates to the switching time and the RC time constant of this portion of the circuit. Given our circuit, we know that this operating clock-like frequency is quite high, so we know that aliasing should not occur until very high frequencies are achieved. Since we will be using this circuit for music, we can assume that most music will be within frequencies that can successfully be sampled by this relatively fast timer. We will explore the idea of aliasing in our analysis section below, and also in our analysis section.

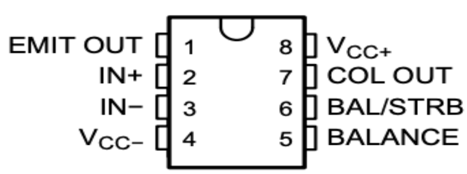

Figure 6: LM331 Differential Comparator pin configuration [15].

The next portion of the transmitter circuit to understand is the functionality of the LM311 Differential Comparator. We start by examining again the pin configurations of the device which can be seen in Figure 6. Pin 1 is the output pin of the internal transistor. Pin 2 is the non-inverting pin of the comparator, while pin 3 is the inverting pin of the comparator. This inversion refers to the input voltage being inverted or not with respect to the supply voltage. Pin 4 is the device ground pin. Pin 5 turns off DC-offset voltage, but we do not use it here, so it is left open. Pin 6 can be used to turn off the output stage, but again, we do not use it here, so it too is left open. Pin 7 is the collector output pin of the internal transistor. Lastly, pin 8 is the Vcc pin, or operating voltage pin of the device [15].

As our voltages do not exceed 5 V, a Vcc of 5V is sufficient for device operation. We ground pin 4, the ground pin, and pin 1. Pin 1 is the emitter portion of the device's internal transistor. We want this excess charge to flow to ground, hence, this pin is connected to ground. With this in mind, pin 7, the collector pin of the internal transistor, is used as an output transistor. How this device works is that it compares the voltages at pin 2 and to the inverted voltage at pin 3. When the inverted voltage at pin 3 is higher than voltage at pin 2, the output is high, and inversely, when the non-inverted voltage at pin 2 is higher than the inverted voltage at pin 3, the output is low.

Knowing that our amplified audio voltage is being compared to our triangular periodic wave and knowing that our triangular wave, at its peak, is always greater than the amplified audio voltage, we can see how this LM311 portion of the circuit is used as an analog to digital sampler [15]. When the sampling process occurs, we see that a binary encoding occurs. This binary coding turns on and off the laser diode, and we understand that this encoded signal can be decoded by the sister circuit in this project, smoothed, and finally amplified to a speaker.

We also know that our sampling frequency is set by the triangular waveform from the 555 timer; knowing this frequency, we can solve for the highest frequency signal that we can sample without aliasing. We will also be able to determine if this sampling frequency is high enough that humans cannot detect the discontinuity, or if this circuit would in fact negatively affect the perceived quality of sound once the sample signal is decoded by the receiver circuit.

This concludes our discussion of the transmitter circuit seen in Figure 3.

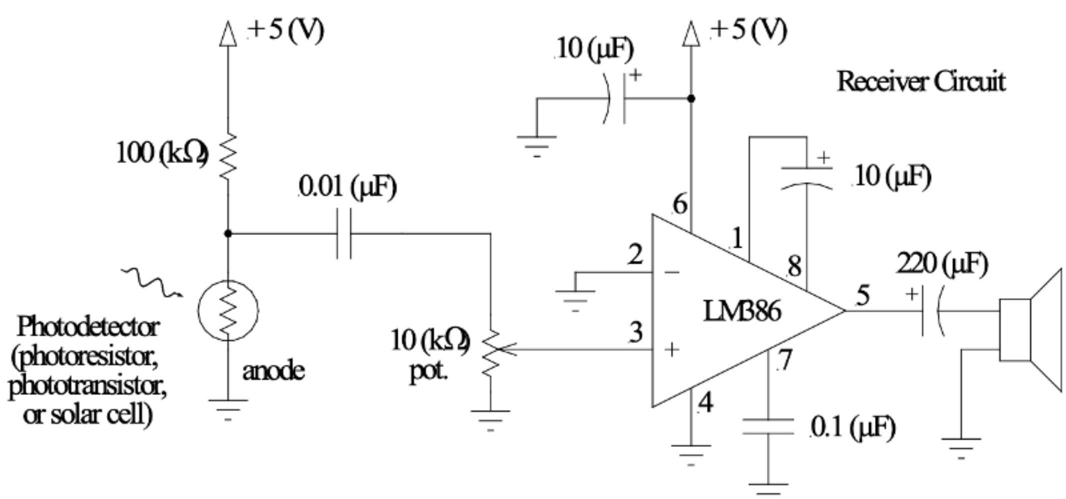

Figure 7: Receiver circuit schematic

We will now discuss our receiver circuit as seen in Figure 7. As we can see, the propagating light signal from the transmitter circuit hits our photodetector. In the case of the photoresistor, the resistance varies, in the case of a phototransistor, the current across the resistor varies, making the voltage across the resistor vary, and in the case of the solar cell, the voltage varies. All three of these variations lead to a change in voltage that occurs at the node between the 100 kΩ resistor, the photodetector device, and the .01 µF capacitor. This change in voltage is slightly smoothed by the .01 µF capacitor, applying the ideas of an RC time constant as outlined above. It also limits any DC voltage from propagating. As the photodetector device does not instantaneously change, this latency also contributes to a smoothing of the voltage signal propagating through the circuit. This change in voltage is applied across the potentiometer in the circuit. Changing the resistance of the potentiometer would change the voltage drop across the node internally of the potentiometer and ground. This potentiometer is the essential component in the voltage divider between it and the 100 kΩ resistor. In other words, increasing the resistance of the potentiometer increases the amplitude of the voltage at the internal node, making the eventual sound from the speaker louder, and likewise, decreasing the resistance of the potentiometer makes the sound softer. It should also be noted that changing the resistance of the potentiometer also changes the RC time constant of this part of the circuit. This RC time constant is also heavily dependent on the internal resistance and capacitance of the photodetector that we used; obviously, this can change quite a bit between different photodetectors; we will explore this idea in the analysis section of this report.

Moving forward with the discussion of the receiver circuit, the voltage across the potentiometer is passed to the LM386, a low voltage audio power amplifier. In short, our positive signal voltage is passed to pin 3. Pin 7 is connected to ground. This is because pin 7 is a bypass pin that bypasses the 1.35 kΩ internal resistor between pins 1 and 8 when set to high, and we do not want to make use of this functionality in our circuit, hence, we ground this pin. Pins 1 and 8 can modify the gain of the amplifier. We elect to put a 10 µF capacitor in series between pins 1 and 8, as this gives us a gain factor of about 46 dB, compared to about 26 dB. A capacitor is inserted between pins pin 7 and ground to limit noise. Pin 3, the input pin, is connected to our changing voltage, and this changing voltage is amplified.

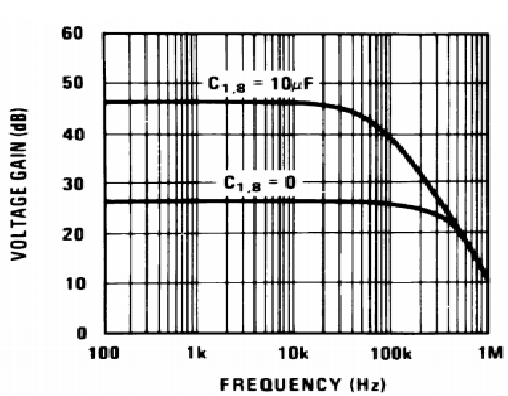

Figure 8: LM386 graph of voltage gain vs frequency [16]

On our data sheet, we see that the amplification is dependent on frequency. As the LM386 is a low pass filter, lower frequencies are amplified more than higher frequencies, but all lower frequencies are amplified about the same, as seen in Figure 8. Assuming that musical frequencies fall into the range of 0 Hz to 12 kHz, triangulating this to our data sheet, we can see that our frequency dependent gain factor would be relatively constant. Again, this gain is about 46 dB based on the capacitor connected between pins 1 and 8.

This entire circuit ultimately takes our digital serial input and smooths the rigid AC signal using capacitors. This smoothed signal is eventually amplified by the LM386. This amplified signal is then passed to the speaker, and we can hear our music. The capacitor in between the output of the LM387 limits the DC current from being too large and killing the speaker. It can also limit the amplitude of sound that the speaker produces, as we know that the change in voltage across a capacitor is frequency dependent. This concludes our discussion of the receiver circuit seen in figure 7. Hopefully this explanation of some of the logistical inner workings of the circuits above can be a helpful tool in understanding the free-space optical communication system that will be shared in this report.

Method

In this project, we built a transmitter circuit and a receiver circuit and tested it under three separated conditions where the way the receiver circuit was changed by using a photoresistor, phototransistor, and a solar cell. In this section, the methods for each experiment will be explained.

Figure 9: Photodetectors (from left to right) - A Photoresistor, Phototransistor, and Solar Cell

Experiment #1: Transmitter circuit with the photoresistor

The first step was to gather up all the materials to build the circuit which can be seen in Figure 9 and Figure 10. It should be noted that for this first experiment the photodetector used was the photoresistor. The transmitter circuit's power source was the RedBoard, while the receiver circuit was powered by your standard 9V battery that was connected to an adapter which connected to the circuit, dropped down to 5V. The next step was to mount the laser to a stand and then shine the laser beam onto the photoresistor. Once the beam was lined up, music was played on the laptop which was then channeled through the RedBoard into the transmitter circuit. This amplified signal was then was shot out through the laser into the receiver circuit with the photoresistor.

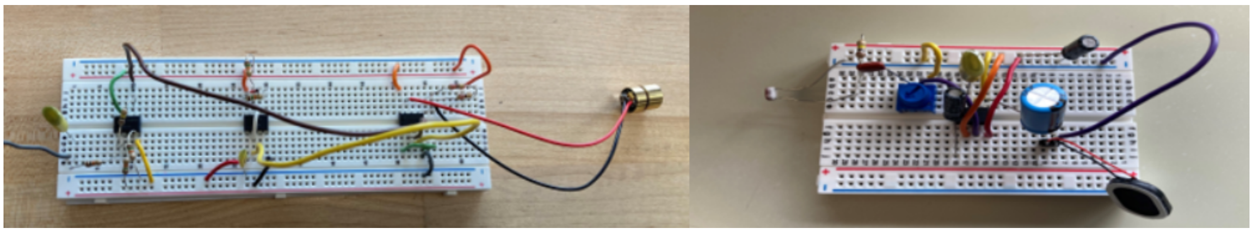

Figure 10: Transmitter Circuit (upper left) and Receiver Circuit (upper right)

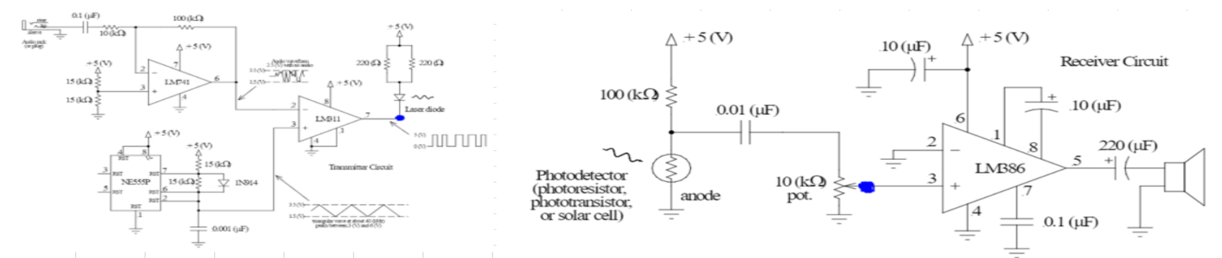

Figure 11: Diagrams Showing Placement of Scope Probes

At that point, music would play out of the speaker on the circuit. It was noted that the noise was a bit fuzzy. At this point we decided to mount a lens to a stand that focused the beam on the photoresistor even more acutely, improving sound quality. The next step of the experiment was to measure the RC time constant value which was done by using scope probes that were hooked up to the oscilloscope. The locations on the transmitter and receiver where the scope probes were hooked up are denoted by the blue dots in Figure 11 above.

It should be noted that experiment 1 was then repeated to see how far we could transmit the light and still have good audio. We ran out of room to test because of the size of the room, but we still got satisfactory results at 18 ft between the transmitter and receiver circuits.

Experiment #2: Transmitter circuit with the phototransistor

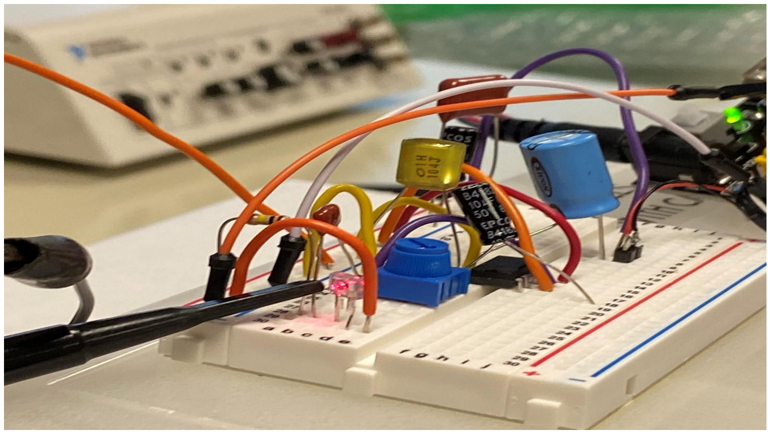

Figure 12: Receiver Circuit with Phototransistor

In the next experiment, the previous photoresistor in the receiver circuit was replaced with a phototransistor. Then, same as before, the beam was trained onto the phototransistor with the help of the mounted lens to focus the beam. A picture of our experiment layout for the phototransistor can be seen below in Figure 12 above.

The next step in the experiment was to hook up the scope probes to the same parts of the circuit as before and then calculate the RC time constant. The value of which can be found below in the analysis section.

Experiment #3: Transmitter circuit with the solar Cell

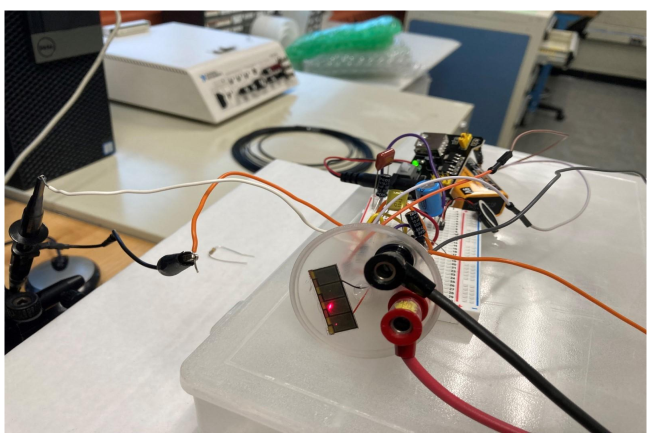

Figure 13: Receiver Circuit with Solar Cell as Photodetector

In this experiment, a solar cell was used as the photodetector for the receiver circuit. The first step was to connect the solar cell to banana cables and then thread wires through the end of the banana cables, connecting them to the breadboard. From there, the 5mW laser beam was focused on the solar cell and music was played. This can be seen in Figure 13.

It should be noted that while music played there was some static coming through on the speaker. Our way of reducing this noise was to change the 100 kΩ resistor to a significantly larger 1 MΩ resistor. This resulted in cleaner music being played over the speaker, although there was still nominal static coming through, as this larger resistance increased the RC time constant of the receiver circuit. The circuits were then hooked up to the oscilloscope and the RC time constant was calculated, as done previously, and the results can be found in our analysis section.

Analysis and Conclusion

Mechanical Challenges

The purpose of this section is to explore some of the challenges faced while conducting the experiments done in this project. The first challenge faced was the construction of the two circuits. Originally, due to poor planning, we had to rebuild the transmitter circuit to get all the components to all fit properly on the board. The most prevalent challenge throughout all the experiments was keeping the laser stationary. This was because the mount we used to hold the laser was very poorly put together. We tried several times to fix that by adding various parts available to us in the lab to pinch the laser in place, however, in the end, we found that the best way to correct this was to use excessive amounts of tape to hold the laser steady.

Influence of Light Intensity and Spot Size on Performance

It is important to understand how the intensity of the laser source and the beam divergence affects signal transmission. The intensity of the laser beam emitted by the light source of the atmospheric laser communication system obeys a Gaussian distribution, and according to the probability density function of the Gaussian distribution, it is known that the intensity of the light intensity at the center of the laser beam is the strongest, and then the intensity of the light intensity from the center to the periphery will show an exponential decrease. Establishing the Z-axis along the direction of laser beam transmission, it is known that the amplitude distribution of the light field intensity of the Gaussian beam can be described by Equation (1), and the center of the beam waist is the origin of the Z-axis:

$$E(r,z) = \frac{A_0}{\omega(z)} e^{\frac{-r^2}{\omega^2(z)}} \quad (1)$$

Equation (1) in w denotes the spot radius of the Gaussian laser beam at the z-point, where z is the distance of the Gaussian laser beam propagation along the z-axis and r is the vertical distance from a point on the laser cross-section to the z-axis. Based on the propagation form of the Gaussian laser beam, the following equation for its spot radius can be obtained

$$\omega(z) = \omega_0 \sqrt{1 + (\frac{z\lambda}{\pi\omega_0^2})^2} \quad (2)$$

The communication distance here is the far-field case for a Gaussian beam.

$$\theta = \frac{\lambda}{\pi\omega_0} \quad (3)$$

Under the far-field condition, for a Gaussian laser beam, the laser divergence angle and the spot diameter of the final Gaussian beam can be calculated after the laser is emitted through the optical transmitting antenna and converged at the receiving end by the optical receiving antenna, respectively:

$$\theta = \frac{2\lambda}{\pi\omega_0} \quad (4)$$

$$\bar{\omega} = 2\omega(z) = \frac{2\lambda z}{\pi\omega_0} \quad (5)$$

Assuming that the transmitting power and receiving sensitivity of the free-space laser communication system has been determined, the communication capability and communication quality of the whole system are largely determined by the laser transmission effect. It can be seen from Equation (1) that the laser transmit power density is inversely proportional to the spot diameter of the Gaussian laser beam, so under the condition that the receiving antenna receives the same aperture, the smaller the spot diameter of the laser transmit beam, the higher the laser transmit power density, and the longer the laser transmission distance. From Equation (4) and Equation (5), we can see that to reduce the spot diameter of the Gaussian laser beam, we can use the method of collimated beam expansion, that is by increasing the spot radius of the emitted laser beam and thus reducing the laser divergence angle, the laser transmission distance is increased.

We saw this effect in our experimentation through swapping the between a .39 mW and a 5 mW laser diode. The .39 mW laser diode had a very large beam divergence; this coupled with its low power meant that using it we were not able to achieve free-space optical communication over a very long distance. Using the 5 mW laser diode with a smaller beam divergence and a higher output power, we were easily able to transmit a signal over 18 ft, and could have probably extended this signal transmission even further if space was not a constraint.

RC Time Constant of the Receiver Circuit Results and Discussion

Solving for the RC time constant of each device can provide some insight into how the receiver circuit smooths the transmitted rigid voltage. For this calculation, we will assume that the resistance and capacitance of the photodetectors used in the circuit is negligible. This is perhaps an invalid assumption, so experimentation is necessary to validate this calculation. If the experimental data does not match that of the computation here, we know that we can adjust the capacitors and resistors in the circuit until the desired time constant can be shown. Ideally, we would be sure that our circuit has a flexible time constant where some variation does not negatively affect the circuit's performance. This is in no way an absolute science, however, and ideal values may come down to preference of sound.

With our above assumption that the internal resistance and capacitance of the photodetector is zero, we can solve for our theoretical time constant. If the resistance across the potentiometer is zero, our time constant would be 0.01 μF * 100 kΩ. = $1*10^{-3}$ (s). If the resistance of the potentiometer is 10 kΩ, our time constant would be 0.01 μF * (100 kΩ + 10 kΩ) = $1.1*10^{-3}$ (s).

These calculations also assume that our listed resistances and capacitances are correct; variations in their actual value can also contribute to inconsistencies in our calculated and measured RC time constants.

Given our calculations we assume that our time constant therefore falls near 1 ms in value. Our real-world experiments found that the photodetector that we used heavily impacted this RC constant, so we know our assumption is invalid, but it is a reasonable starting point. Below we will discuss our measured RC time constants for each device.

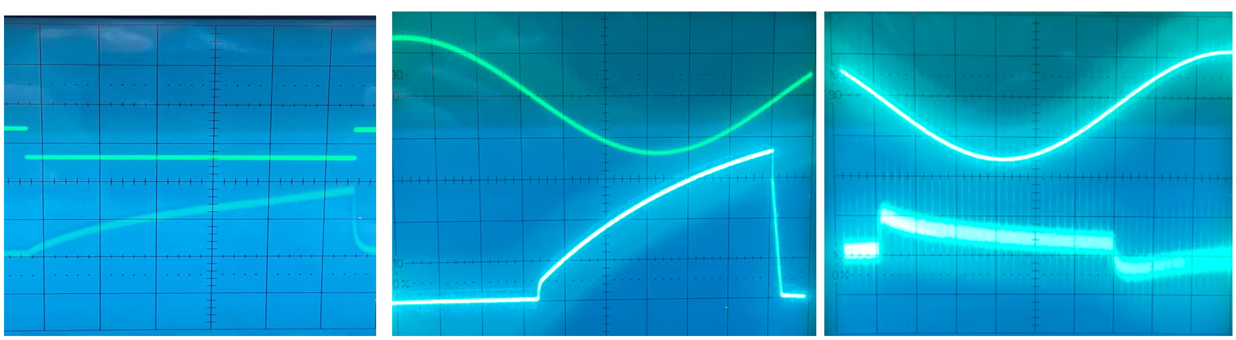

Figure 14: Oscilloscope output for photoresistor, phototransistor, and solar cell, in that order

In this section of the report the time constants will be calculated for each experiment using the data collected from the oscilloscope. We will compare these calculations to the theoretical calculations detailed above. The first RC time constant that was measured was for the photoresistor. In Figure 14, the top line represents the output from the transmitter while the lower line represents the input to the receiver.

We know that the RC time constant can be measured by seeing where the increasing voltage is 63% of its maximum value [17]. In Figure 14, we can see that the lower line approaches about 63% of its maximum value near 3 divisions. Given that the oscilloscopes horizontal divisions are 1 ms per division, we can see that the RC time constant receiver circuit before being fed into the power amplifier is about 3 ms.

For the phototransistor, the horizontal divisions are .2 ms, and 63% of the maximum value is achieved at around 2 divisions, so the RC time constant here with the phototransistor is only .4 ms, significantly smaller than the photoresistor.

While measuring the value for the solar cell, the RC constant was too small to measure with our original circuit. We therefore decided to change the 100 kΩ to 1 MΩ to calculate the time constant. The horizontal divisions are 50 µs, and it seems that 63% of the maximum value is achieved at around .1 of a division. This gives an RC time constant of 5 µs. Using this to solve for the original RC time constant gives a RC time constant of .5 µs, so it makes sense that we couldn't read this one the oscilloscope. This is by far the smallest time constant of all 3 devices tested.

We predict the increase in the RC time constant of the photoresistor is because the photoresistor obviously adds an increased resistance to the circuit, increasing the RC time constant. This RC time constant is also likely frequency dependent, but about 3 ms is a reasonable average. The phototransistor has a much smaller RC time constant and this is likely due to the low resistance of the transistor when light is incident on it. Looking at our circuit in Figure 7, we see that if the resistance of the transistor is low, the thevenin resistance is also low, and our RC constant is likewise low. A similar phenomenon must occur with the solar cell. The solar cell can be pictured as a voltage source in many ways. This means that the node between the solar cell and the 100 kΩ has it's voltage set from the solar cell directly. This basically eliminates the 100 kΩ resistor from the RC calculation, and the RC time constant is therefore only between the .01 µF capacitor, the potentiometer, and the internal capacitance and resistance of the solar cell (see Figure 7). As the 100 kΩ resistor dominates our RC time constant and is essentially omitted, we can see why the RC time constant of the solar cell is so small.

The relative performance of each photodetector is most likely based on these RC time constants. The phototransistor performed the best, indicating that its RC time constant of .4 ms may be ideal in reconstructing the smoothness of the audio signal. The photoresistor performed poorly, probably because its RC constant was too large and hence was not responsive to large changes in voltages, distorting the music. Finally, the solar cells time constant was perhaps too small, as it responded too quickly and the audio signal signals therefore sounded rigid and poor. This poor audio for the solar cell also most likely stemmed from the noise in the solar cell from the environment as the solar cell is much more responsive to ambient light compared to the other photodetectors. From this exploration we can see the importance of having an ideal RC time constant in our receiver circuit, and we can also see the importance of tuning our RC time constant to what works best for the desired application of the circuit.

Limitations of the 5V Source Voltage

During our experimentation, we originally had the transmitter circuit and the receiver circuit connected to the same 5 V source. What we found, however, was that this caused audio to be output from the speaker without the light signal being transmitted. After some investigation, we decided that this is because the change in current at the laser diode changed the voltage of the source voltage slightly. When this source voltage for the transmitter circuit was the same as the source voltage for the receiver circuit, this change in voltage was amplified in the receiver circuit across the 100 kΩ resistor. This is the reason for the unwanted audio being produced from the speaker.

We thought that if we used a better source than the 5V source pin of the Arduino, perhaps a source with a higher max current, that the source voltage would be more stable, so we experimented with one of the voltage sources in the lab. The problem persisted, however, and we decided that it was best to simply separate the two circuits, using two separate voltage sources. When we did this, there was no leakage voltage into the receiver circuit, and the speaker only produced audio when the laser source transmitted a signal to the photodetector, as we desired.

Limitations of Sampling Rate and Aliasing

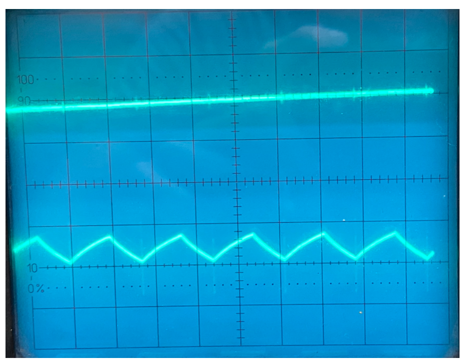

Figure 15: Triangular waveform of the NE555P timer.

We can see in Figure 15 the triangular waveform of the NE555P timer. The divisions on the oscilloscope here are 10 µs, and we can see that the difference between peaks is above 1.5 divisions. We therefore can conclude that our sampling rate is 15 µs, and our sampling frequency is therefore about 66 kHz. To avoid aliasing, the sampled waveform must be at least half of the frequency of the sampling frequency. This gives a maximum waveform frequency of about 33 kHz. This is well outside of the detectable frequency range for human hearing, so we verify that our circuit can successfully sample all the frequencies that can be heard in traditional music.

We were able to achieve aliasing when higher frequency waveforms were input into our receiver circuit. This could be a limitation if there is any high frequency noise in the circuit and emphasises that high frequency filtering can improve the circuit, ensuring a more pure sound. Regarding the circuit general performance, however, we can conclude that our sampling rate of the NE555P timer is appropriate for this application.

Future Improvements and Finals Remarks

Our simple circuits proved quite effective in demonstrating signal transmission capabilities in a free-space optical system. Easy improvements to the system would surround using stronger, more focused lasers, better photodetectors, and also a better speaker. We also demonstrated how playing with the RC time constant of the circuit can improve performance. Other filtering techniques to filter out noise can also further improve our system - both electrical noise and optical noise.

Our system was tested in a very controlled lab setting. Future experimentation will be necessary to see how the system performs over longer distances, as well as under various environmental conditions. Furthermore, lensing techniques can be used to improve system efficiency and the achievable distance of a clean signal transmission. It would also be interesting to explore some sort of amplification circuit that would add to the complexity of the circuit, but also add to the distance that a signal can be transmitted in free-space in our setup. We also believe that improvements to the reduction of ambient light in the system can improve performance, especially for the solar cell. This can possibly be achieved through simply covering the system and limiting the light passing into the receiver. It can also maybe be achieved through different light filtering techniques, where we can be more selective on which wavelengths of wavelength of light enter our receiver.

Ultimately, our experiments can be a success as we were able to demonstrate the potential of free-space optical communication systems in real-world applications.

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