Design of an Optical Wireless Communication System: Photophone

Mehmet Kurt (2443497) , Emirhan Yılmaz Güney (2443208)

***Abstract*—This paper provides the theoretical and literature research used in the construction of the optical wireless communication system, the photophone. The methodology used in the established circuits, the mathematical analysis of the sub-circuits, some previous simulation results, and how the whole system works properly are given in the subheadings. The methodologies of the circuits must be determined before the blocks required for the installation of the optical wireless communication system can be built. In general, the purpose of the overall system is to transmit the sound received from the microphone wirelessly by means of light. Besides, the amplitude of the audio signal to be transmitted can be measured by supplying the reference signal to an indicator circuit. The blocks that need to be installed sequentially will be shared with their detailed explanations under the headings and the simulation, together with the test results obtained.**

***Index Terms*—photo-phone, optical communication, wireless communication, analog electronics, infrared led modulation**

I. Introduction

OPTICAL wireless communication is a critical development in the invention of some crucial technologies which are widespread all around the world, such as the internet, mobile phones, etc. In this project, we will be setting up a complete optical wireless communication system, including the sound input, transmitter, receiver, and output blocks. Our main aim in constructing this system is to investigate the theoretical background of electrical modulation and transmission of light, which forms the basis of fiber optics and internet technology. The construction process of this electrical system includes also the filters, amplifications, and automatic gain control systems required for the conservation of the waveform for the transmission.

During the design of the circuits which will be used in the system, we utilized many of the concepts that we learned throughout the last term in EE313 laboratories. Since BJT's are used in many pieces of the circuit, the working principle of BJT's often utilized in the development process. In addition, the operational amplifier is another crucial component that is used to manipulate voltage waveforms and amplitudes. In summary, we set up an electrical circuit that gets the sound signal as an input and modulates the light of an infrared LED electrically accordingly with the input and outputs the amplified version of it in the sound form with the help of a speaker.

II. Theoretical Background

The main idea of the project is to modulate the light electrically and recover it using a photo-transistor. To establish this communication between transmitter and receiver blocks, the first requirement is to represent the audio signal electrically, by using a microphone. After this process, the working principle of LED, Photo-transistors, and Speaker will take place in addition to the electrical processing sub-systems.

To get the audio signal, we used an electret-condenser microphone. An electret is a stable dielectric material with a permanently embedded static electric dipole moment [1]. This type of microphone does not need voltage to charge them up, but they need an external bias voltage to work properly. This bias provides the required power to the built-in coming amplifier in the microphone, which is shown in "Figure 1". Utilizing the changing resistance of the microphone with the incoming audio signal, we first obtain a current signal which represents the audio signal. By using voltage division, we converted it to the voltage signal. To determine the voltage level that will be applied for bias, we checked the data sheet of the electret-condenser microphone and observed that the resistance on the microphone changes from 1kΩ to 10kΩ with input DC voltage varying between 4V-10V.

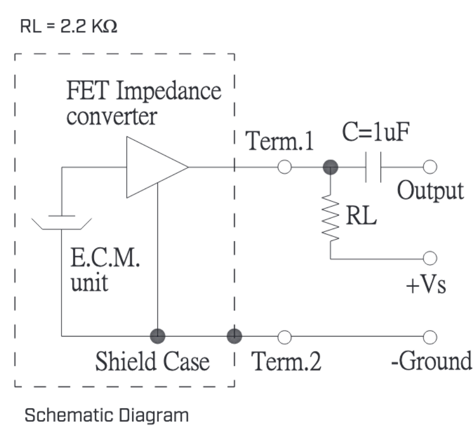


Fig. 1: Electrical equivalent circuit of the electret-condenser microphone.

For the conversion of electrical signal into light, we utilized an infrared LED, since infrared light is not in the range of visible light, which can cause distortions due to ambient light (see Figure 2).

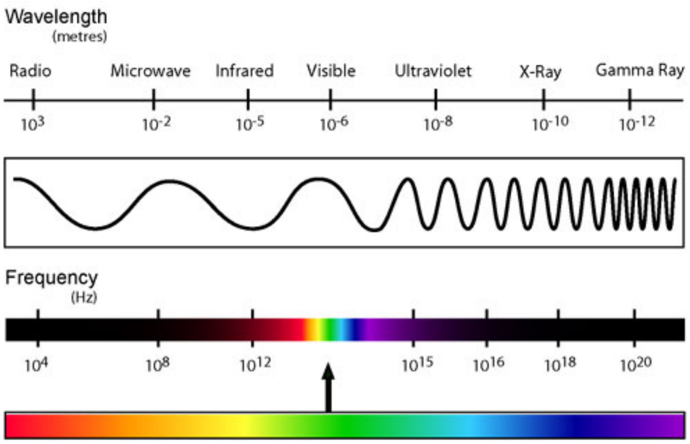


Fig. 2: Electromagnetic spectrum showing the visible and infrared light range.

Light emitting diode is a semiconductor device that emits light when current flows through it [2]. In other words, the light intensity is dependent to the current. However, since it is a diode, current-voltage relation is highly non-linear. Since LED emits light in forward bias and the light intensity is current dependent, we used it with a current driving method with a bias current on top of it. The current bias required for emitting the light and their relation is provided in Figure 3. Thus, we modulated the light electrically using an infrared LED.

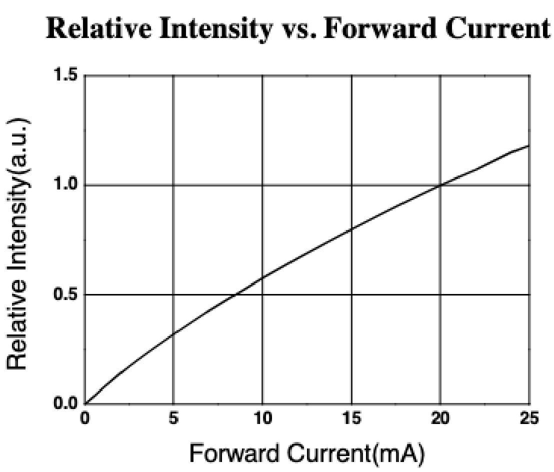


Fig. 3: Luminous light intensity versus current graph of a standard LED.

We utilized a phototransistor to recover the electrical signal representing the audio signal in the form of light to electrical form. In a phototransistor, the light incident to the photosensitive semiconductor base forms the base current. By biasing the collector pin of the phototransistor and placing a resistor on the emitter side, one can easily obtain the voltage signal carrying the light information. Compared to the photo-diodes, the photo-transistor provides a higher current, which makes it advantageous to use in the circuit. One can see the relationship between collector current and light intensity in the Figure 4.

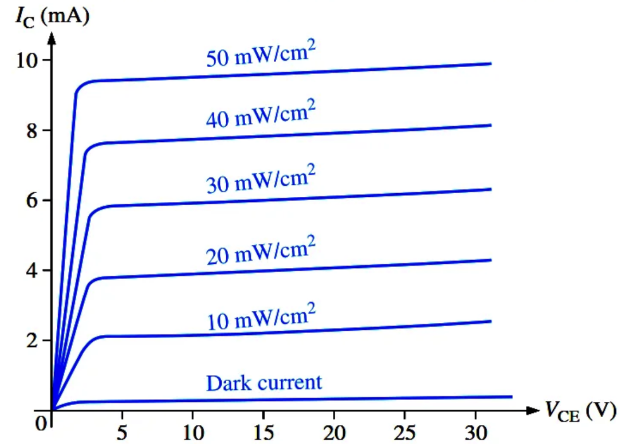


Fig. 4: Collector current versus collector emitter voltage plot with varying light intensities.

To determine the signal level, which lets one know how strong the transmission between the transmitter and receiver is, we used an RGB indicator circuit. However, it is not possible to make the transmission strength measurable without a reference signal, because the input sound has changing amplitude, which manipulates the amplitude of the transmitted audio signal. Therefore, we are using a reference signal added to the audio signal before the transmission block. The problem with using a reference signal added to the audio is the fact that we do not want to hear it from the speaker, as it will be only noise in the output. Therefore, we considered the audio and reference signals in the frequency domain, instead of the time domain. Considering the frequency domain, we chose a high-frequency reference signal, which is not in the range of the audio signal frequencies that humans can hear. After transmitting the summation of the low-frequency audio input and the high-frequency reference signal, we made use of a low pass filter on the receiver side to distinguish the two signals in the frequency domain and recover the audio signal. To extract the reference signal, we use a high-pass filter (see Figure 5).

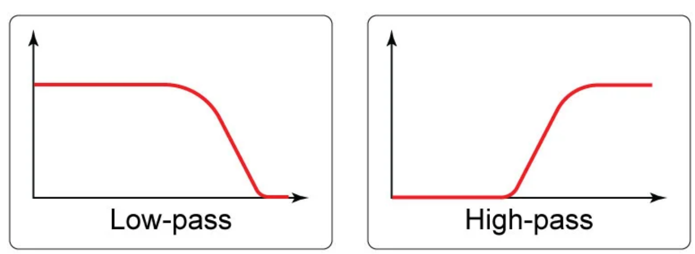


Fig. 5: Low pass and high pass filters that is used for distinguishing reference and audio signals.

For the determination of the cut-off frequency, we use the capacitor and resistor values used in the upper circuit (3). The cut-off value specifies the limit between the cut and passed frequency range.

$$f_c = \frac{1}{2\pi * R * C} \tag{1}$$

III. Mathematical Analysis of the Subsystems

In this section, we will be examining the designs of the circuits belonging to the sub-systems, and mathematical analysis of them, including the simulation results. One can see the block diagram of the overall system below (see Figure 6).

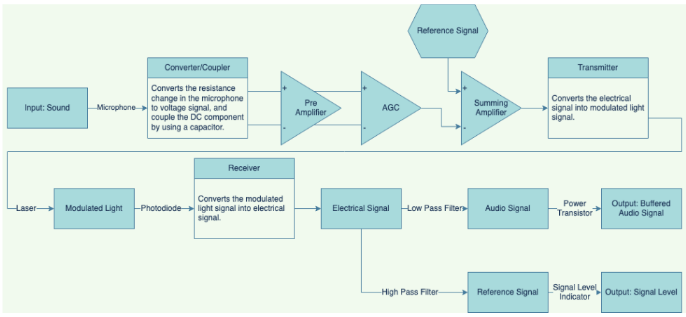


Fig. 6: Low pass and high pass filters that is used for distinguishing reference and audio signals.

A. Microphone Preamplifier

The first sub-block is constructed to first convert the current signal into voltage signal and amplify it since the current passing through the microphone has a small amplitude to use in the next blocks. Therefore, it needed to be amplified using a common emitter configuration. After the amplification, we put a low-pass filter to get rid of distorted signals. For the circuitry, see Figure 7

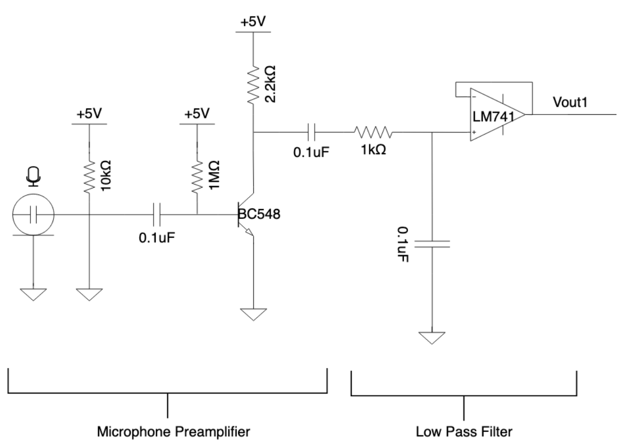


Fig. 7: Preamplifier and low-pass filter circuit diagram.

B. Automatic Gain Controller

This unit is used to eliminate the effect of varying distance between the microphone and the input audio source. By using this sub-system, we keep the output amplitude at a proper level over a wide range of input voltage levels. To achieve this, we constructed a circuit that is called Automatic Gain Controller, which is a closed circuit that uses a feedback loop to balance the output against varying input amplitude levels. This circuitry uses a shunt-shunt feedback loop, meaning that it mixes voltage and samples current. Thus, with the decreasing input amplitude, the feedback loop draws a smaller current to balance the output amplitude. In addition, two common emitter configurations are used for amplification and the common collector amplifier is used at the feedback part. For the circuitry, see Figure 8.

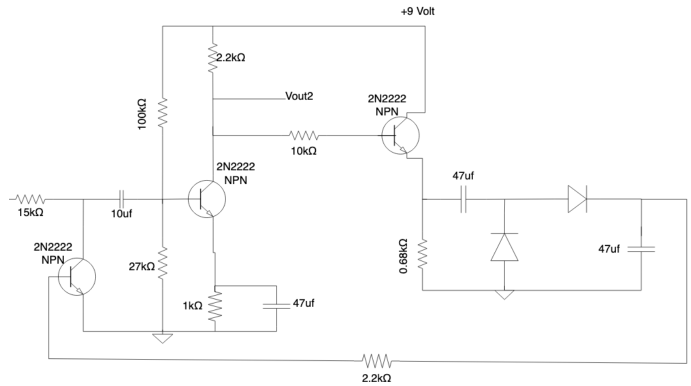
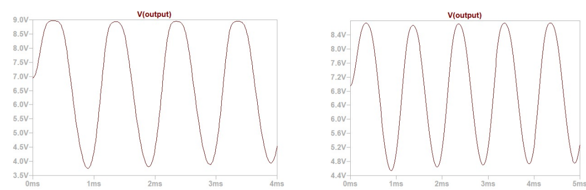


Fig. 8: Preamplifier and low-pass filter circuit diagram.

For the comparison of the output levels with different levels of input signal amplitudes, we made LTSpice simulations. We first give 10mV input instead of the microphone voltage and then make it 30mV to check if the AGC properly works. One can see the simulation results below (Figure 9)



(a) Input level 10mV (b) Input level 30mV

Fig. 9: Output levels with different input levels.

C. Addition of Reference Signal

As mentioned below, to determine the strength of the transmission, we use a high frequency reference signal. By using a summing amplifier constructed with an operational amplifier, we added up the AGC output carrying the audio information and the reference signal. One can see the circuitry in Figure 10.

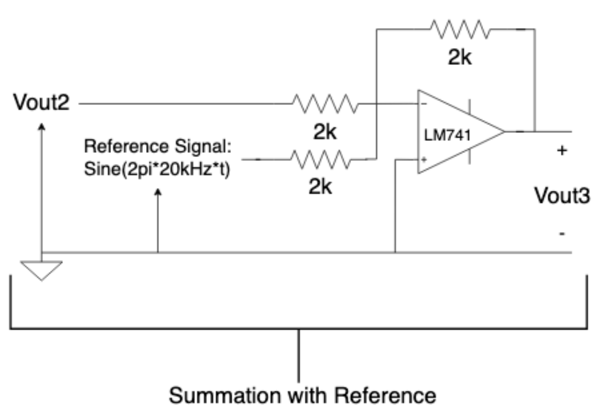


Fig. 10: Summing amplifier circuitry for adding the reference.

D. Modulation of Light: Transmitter

For the transmission, we use an infrared LED to convert electrical signal into a light beam, as mentioned in the theoretical background section. To make the LED emit a light that carries the input voltage signal, we needed to provide a bias current which makes the LED operate in its linear region. The LED driving circuit that provides this bias current could be obtained by using a current mirror circuitry that can be observed in Figure 11. As mentioned in the theoretical background section, we tried to obtain a bias current of 14mA which is required for the LED to operate in linear mode.

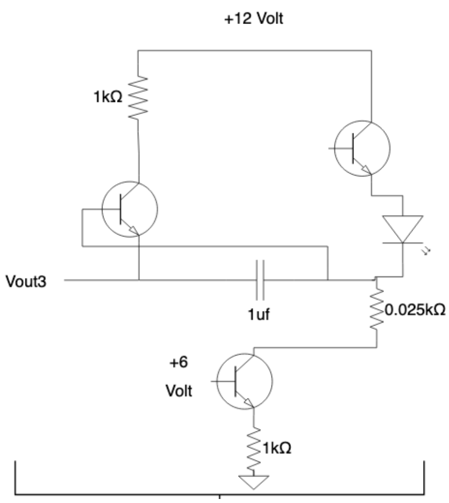


Fig. 11: LED driving circuit that includes a current mirror for biasing.

To validate the bias current level provided by the led driving circuit, we made a simulation in LTSpice, which one can observe in the Figure 12.

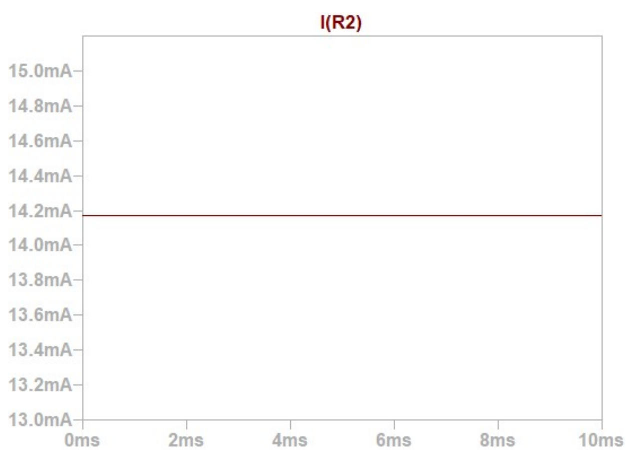


Fig. 12: LED driving circuit bias current output simulation result.

E. Recovering the Audio Signal: Receiver

To recover the audio signal from the light form into electrical form, we use a component which is called Phototransistor, as mentioned in the theoretical background section. To drive the phototransistor, we connected a resistor to the emitter pin and convert the current output coming from the transistor, named collector current into a voltage waveform. To make the transistor work in the correct mode, we also applied a DC bias current from the collector side. In addition to the common collector design, we added a common emitter amplifier to the output to amplify the voltage on the resistor connected to the phototransistor. One can see the circuitry in the Figure 13.

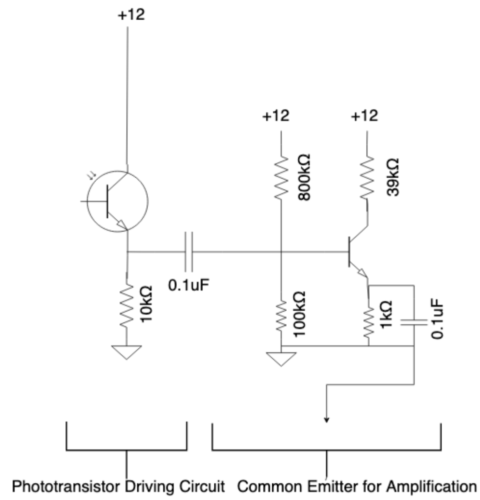


Fig. 13: Phototransistor driving circuitry.

F. Recovering the Audio and Reference Signals: Filtering

After receiving the audio signal from the light beam and converting it to the voltage waveform using the receiver circuitry, we needed to distinguish the low-frequency and high-frequency components of this signal. As mentioned in the theoretical background part, we utilized the frequency domain to achieve this. Therefore, we used two filters, namely active high-pass and low-pass filters. From the low pass filter, we obtain the audio signal which typically is in the range 1KHz-3KHz, whereas from the high pass filter, we obtain the high-frequency reference signal. We used active filters to eliminate the frequency noises and any kind of distortion. The circuit schematics are provided below (Figure 14).

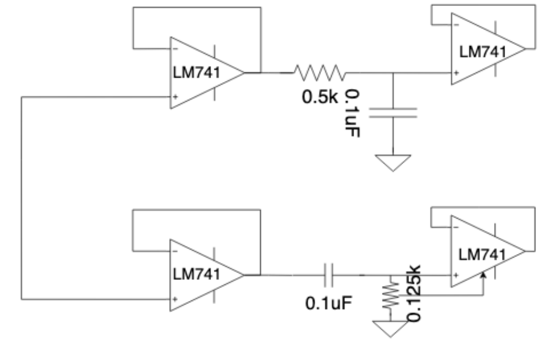


Fig. 14: Filtering circuitry.

G. Hearing the Sound: Power Amplification

After we eliminate the high-frequency band from the input signal, we get an input voltage that has a small amplitude, around 25-50 millivolts, which is not enough for the speaker to output a sound that has enough strength to hear. The main function of the power amplifier, which is also known as a "large signal amplifier" is to deliver power [3]. Therefore, we used a power amplifier at the output, which provides high switching currents, which we will need because the speaker we used is 16Ω, since power is resistance multiplied by the square of the current. To eliminate the distortion and have a highly stable waveform, we used a class AB power amplifier, which includes diodes to achieve. The class AB power amplifier is shown below (Figure 15).

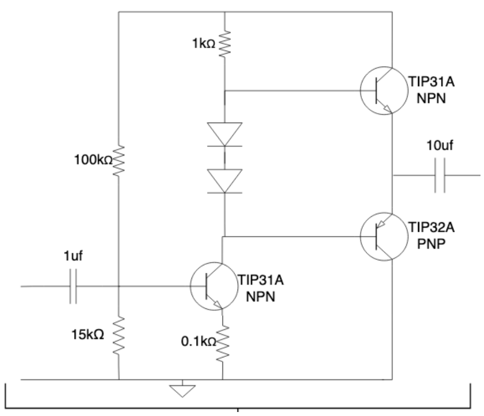


Fig. 15: Class AB power amplifier circuitry.

To see the output power waveform plots obtained from the LTSpice simulations, one can observe the figure given below (Figure 16).

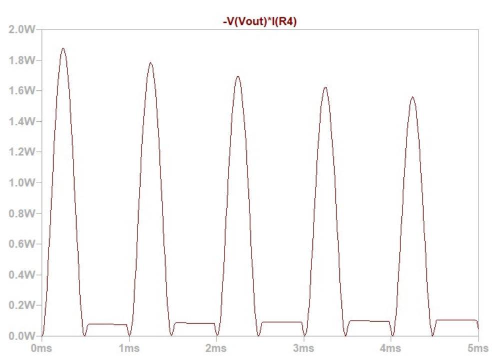


Fig. 16: Power output obtained by the class AB power amplifier.

H. Signal Level Indicator

To measure the amplitude of the incoming signal at the output side, we use a comparator circuit that compares the output voltage coming from the high pass filter with a reference DC signal given to it. To be able to compare the DC reference signal with the output voltage, we first needed the convert the AC waveform into a DC form. To achieve this, we used a peak detector circuit, which detects the peak value of a signal thanks to a capacitor charging mechanism. One can see the peak detector circuitry and the LTSpice simulation results of it in Figure 17 and Figure 18.

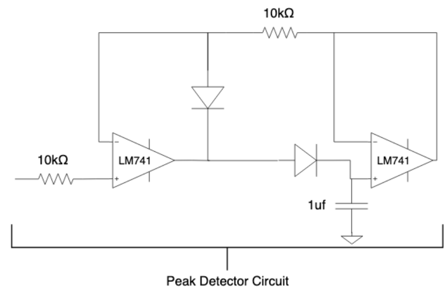


Fig. 17: Peak detector circuit schematic.

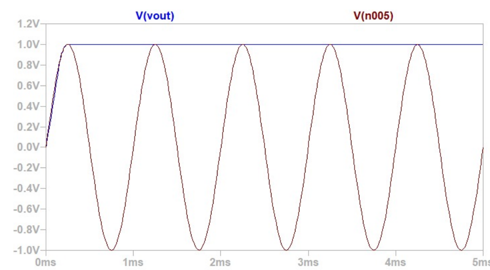


Fig. 18: DC output obtained by the peak detector with 1V peak-to-peak sinusoidal AC input.

For the comparator circuitry, we used a couple of operational amplifiers which are working in saturation mode to operate as a comparator, with using voltage division between the non-inverting inputs of them. In addition, we have used an RGB LED at the output to make it emit a light of a color depending on the output of the comparator circuit which determines and classifies the amplitude voltage coming from the high pass filter of the optical wireless transmission receiver block. For the circuitry, see Figure 19.

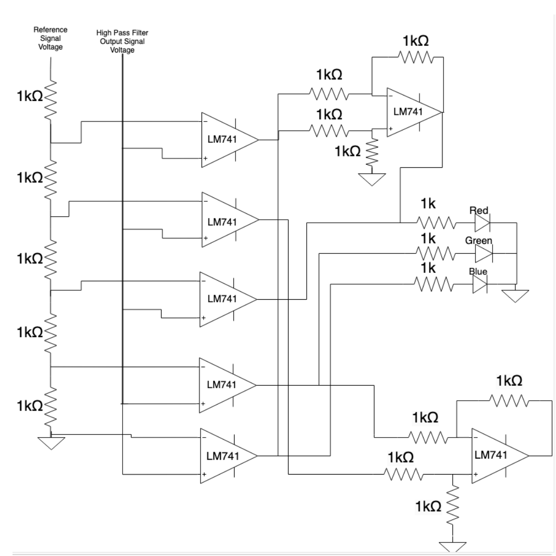


Fig. 19: RGB indicator circuit schematic.

To observe the comparison performance of our indicator circuitry, we made LTSpice simulation. One can see the output of the simulation in Figure 20.

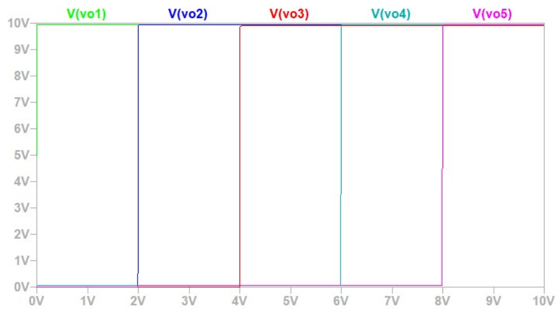


Fig. 20: RGB indicator simulation results.

IV. Experimental Results

After analysing the sub-blocks of the overall system and making the required simulations to make sure they are working suitable with the calculations, we made some experiments to examine the system in the real world.

On the input side, we gave various audio signals which have different strengths for testing. In our tests, we observed that our automatic gain controller unit works in a specific range of input amplitudes. Thus, we concluded that our automatic gain control unit fails over approximately 20 cm distance to the microphone from the sound source. This limitation is stemmed from the characteristics of the microphone we are using, which is mentioned in the theoretical background section.

To test our transmitter, we examined the voltage waveform over the LED's positive and negative pins. After we tried various methods for applying the bias current required for the linear operation of LED, we reached the solution we provided in the subsystems section, which is a current mirror circuitry in general. Then, we observed the same voltage waveform with the same frequency over the infrared LED.

After ensuring that we can completely carry the audio signal in a light beam, we started to test the receiver unit, which consists of a phototransistor and a resistor basically. In our tests, we firstly fail to capture the light due to the difference between the frequency range of incoming light and the biasing of the phototransistor. Then, we provided the correct bias and made the phototransistor work in the frequency range that includes the infrared light frequency level. Then, we see the same voltage waveform with a serious decrease in the amplitude level.

For the test of the filters we constructed, we used Fast Fourier Transform analysis which shows the frequency spectrum of the incoming signal. Since we have used first order filters, we encountered a problematic situation because our filters were not be able to fully eliminate the unwanted signals, depending on the filter type. For instance, we observed a high frequency component with a very low amplitude in the output of the low pass filters in our tests. This was due to the low level of decay in the cut-off region of the filters.

To observe the difference between a first-order and a second-order filter, we can examine the cut-off value formulas of both configurations.

For a first order filter, as mentioned in the theoretical background:

$$f_c = \frac{1}{2\pi * R * C} \tag{2}$$

On the other hand, for a second order filter, the cut-off frequency is:

$$f_c = \frac{1}{2\pi * \sqrt{R_1 * R_2 * C_1 * C_2}} \tag{3}$$

The circuit schematics for a second order low pass filter is shown in Figure 21.

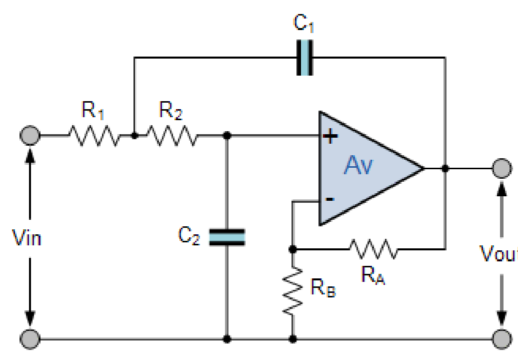


Fig. 21: Second order low pass filter circuit schematic.

The frequency response difference can be seen in Figure 26.

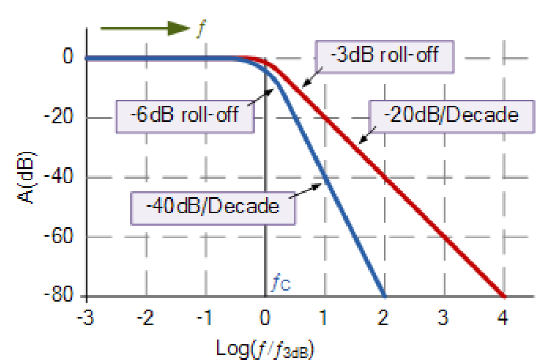
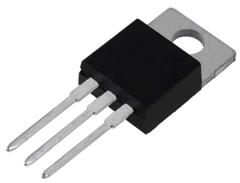


Fig. 22: Second order low pass filter frequency response.

In the power amplifier circuitry, after we constructed the circuit with the commonly used BJT's such as BC548 and BC557 etc., we have observed that circuit fails to operate with the high level of current passing through them. Then, we checked the datasheet of these BJT's and observed that their maximum current values were much smaller than our power amplifier circuitry generates, which is given in the subsystems section. Then, we constructed our circuit again with power transistors such as TIP31A and TIP32 etc. At the end, we have the amplified output and we can successfully hear the sound output produced by the speaker. The difference between the appearances of a standard BJT and a power transistor is visualized below (Figure 23).



(a) Power transistor

(b) BC548 BJT

Fig. 23: Power transistor and BJT appeareances.

After examining all the sub-blocks and experimental results, one can see the real circuitries which are constructed to the breadboards.

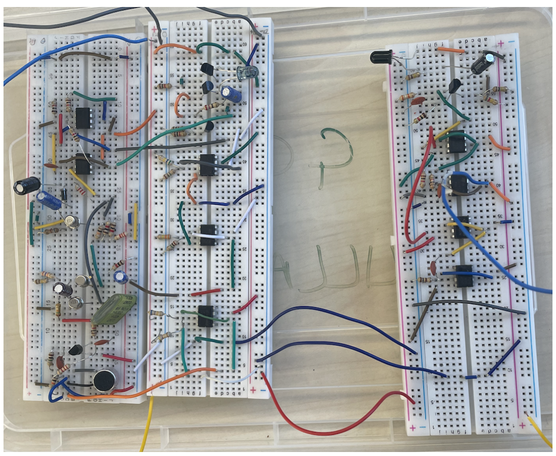


Fig. 24: The circuit of transmitter and receiver blocks. Left to right: Microphone and AGC, Transmitter, Receiver

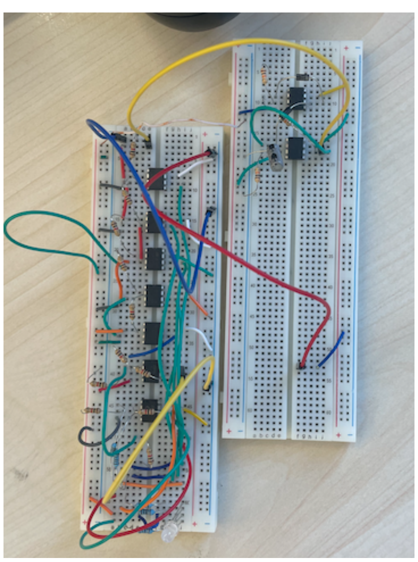


Fig. 25: The circuit of signal level RGB indicator.

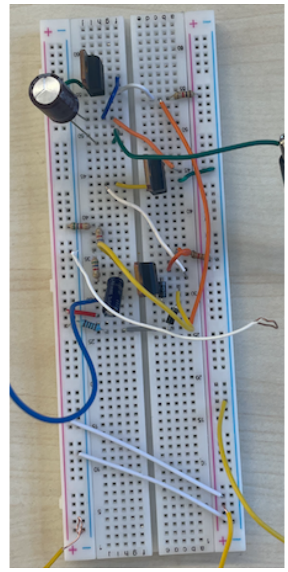


Fig. 26: The circuit of power amplifier.

V. Conclusion

In this project, we aimed to construct an optical wireless communication system, by using the concepts we learned in the Analog Electronics Laboratory sessions. To achieve this, we utilized various types of amplifier topologies, operational amplifier circuitries, feedback loops, etc. In addition, we dealt with the modulation of light electrically and capturing the light beam using a phototransistor. In these processes, we additionally encountered various problems such as loss of information due to various components, demultiplexing problems, and noise and distortion stemming from the real-world effects.

By solving the problem of optical wireless communication, we have learned the concept that forms the basis of fiber optics and internet technology. In addition, we gained knowledge on the implementation of specific topologies, feedback networks, and filters such as AGC, power amplifiers and second-order filters, etc. Thus, we accomplished our goal, which is to completely construct the whole optical wireless communication system, and tested and inspected the characteristics of our circuits in the presence of the lab assistants.

References

[1] Wikipedia contributors, *Electret microphone — Wikipedia, the free encyclopedia*, https://en.wikipedia.org/w/index.php?title=Electret_microphone&oldid=1119017031, [Onlineß; accessed 25-January-2023], 2022.

[2] Wikipedia contributors, *Light-emitting diode — Wikipedia, the free encyclopedia*, https://en.wikipedia.org/w/index.php?title=Light-emitting_diode&oldid=1134927809, [Online; accessed 25-January-2023], 2023.

[3] W. Storr, *Class ab amplifier design and class ab biasing*, Aug. 2022. [Online]. Available: https://www.electronics-tutorials.ws/amplifier/class-ab-amplifier.html.