EE313 Analog Electronics Laboratory 2024-2025 Fall Term Project Photophone and Optical Wireless Communication

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***Abstract*—In this report, we explain the theoretical background of how to transmit data by using optical wireless communication (OWC) that utilizes infrared, visible, or ultraviolet light to transmit and receive data. Moreover, we also present the simulation and experiment results of the project. This project aims to design and implement an optical wireless communication system by using electronics methods and circuit topologies. In particular, a photophone structure was used to transmit data through the air, using visible light as the transmitter. It was seen that data really can be transferred over some distance with the use of light. However, it was also seen that when using visible range light, the outside sources of light such as ambient lamps will also greatly affect the output of the photophone. Therefore, it was concluded that perhaps the visible light range is not very suitable for this kind of operation, especially when transmitting data over a long distance.**

Keywords—Optical wireless communication, Free-space optical communication, Li-Fi, Photophone.

I. Introduction

In our world where we need to transfer large amounts of data in the smallest amount of time, light brings us a solution for fast data transmission. The photophone is a device that uses light to transfer data through air, without the need for cables. Therefore, in this project, we will bring a solution to this problem with the use of a photophone by using analog electronics and electronics based devices. This report will firstly dwell on the transmitter part and its components, then the receiver part and its components will be examined.

II. Transmitter

The transmitter is designed with separate blocks of circuits, each doing separate tasks. These blocks are used as specified in order in the block diagram in Fig. 1. As it can be seen from Fig. 1, op-amp buffers are used to isolate and enhance the signal quality before each stage and the usage reason of each will be covered in the related main part's explanation. The main components of the transmitter such as the microphone driver, AGC, active low-pass filters and transconductance amplifier for the laser LED driving will be examined in this part.

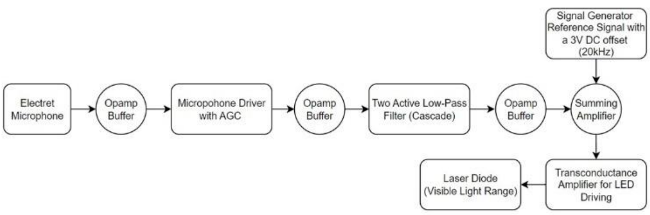

Fig. 1. Transmitter Block Diagram

A. Microphone Driver

An electret microphone was used in the circuit because of their ease of use and cheap cost. To drive it, the circuit in Fig. 2 was used. Here, the microphone is biased with 5V which creates a DC voltage across the microphone which then creates an electrical signal of the sound by changing the voltage across it when excited with an outer source of sound. The capacitor is used before the output to decouple the DC voltage from the sound signal. The 5.6kΩ resistor is a pull-up resistor to drive the microphone with according current in a proper range and prevent current sink. Moreover, an op-amp buffer is used to prevent any distortion in the sound signal caused by interactions and filtering effects between this and the AGC stage.

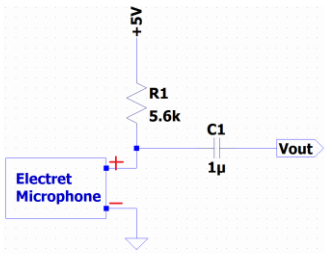

Fig. 2. Electret Microphone Driver Circuit

B. Automatic Gain Control (AGC)

The aim of the usage of this stage is to prevent clipping and provide a stable output voltage by adjusting the gain according to the amplitude of the input signal. When the amplitude of the input signal is low, the AGC adjusts the gain so that it is larger than one to keep the output voltage stable. However, when the input voltage level is too high and may cause clipping in the output signal if the gain is kept the same as in low input voltage case, which will cause loss of information, the AGC circuit decreases the gain so that there is no clipping of the output signal. The circuit used for AGC can be seen in Fig. 3, which was taken from [1].

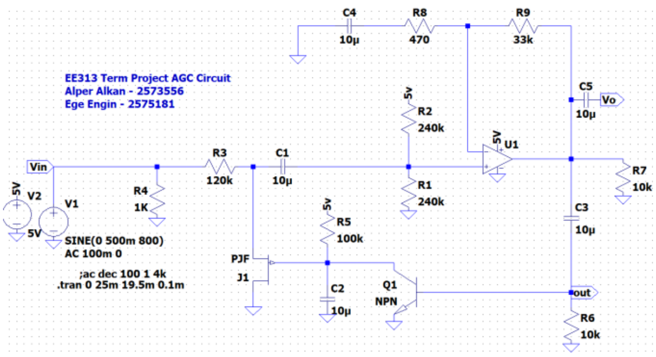

Fig. 3. Automatic Gain Control (AGC) Circuit

To examine the functionality of the components, the AGC circuit that is used is basically an op-amp voltage amplifier with feedback that changes the resistance of the p-channel JFET to control the gain of the circuit. Examining the circuit diagram in Fig. 3, a p-channel JFET coupled with R_3 and the equivalent resistance of the parallel connection of R_1 and R_2 form a voltage divider to the input signal. When the input signal amplitude level is below 40 mVp-p, the input is evenly divided between R_3 and $R_1//R_2$. The output amplitude of the LF353 op-amp isn't large enough to turn on the BC546 NPN BJT which acts as a positive peak detector. The gate of the JFET is pulled to +5 V, pinching its channel off and creating a very high resistance from drain to source. This essentially removes it from the circuit. In this case, the gain of the amplifier can be found as in (1), which is also verified using LTSpice with these components as in Fig. 3.

$$A_v = \frac{V_o}{V_{in}} = \frac{R_9}{R_8}\frac{R_1//R_2}{R_3 + R_1//R_2} = \frac{33k\Omega}{0.47k\Omega}\frac{120k\Omega}{240k\Omega} = 35.1(1)$$

As it can be seen from (1), the gain is pretty high and the output voltage is at about 1.4Vp-p. However, when the input voltage is above 40 mVp-p, the BJT is turned on at the positive peaks of the output of the op-amp, lowering the JFETs gate to source voltage. The channel resistance decreases and attenuates the input signal to maintain the output of the op-amp at approximately 1.4 Vp-p. As can be seen from Fig. 4., if the input voltage was 200mV the gain will be 6 [V/V] to provide stable output. Moreover, from Fig. 5., experimental results also show that if the input voltage was 1V the gain of the circuit would be 1.25 [V/V]. The output was the same for both inputs.

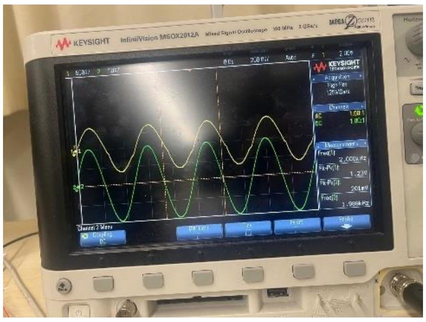

Fig. 4. AGC Circuit with 6 [V/V] Gain

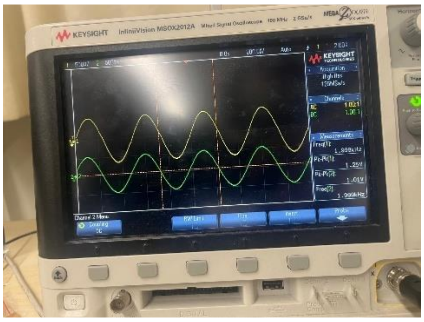

Fig. 5. AGC Circuit with 1.25 [V/V] Gain

After the AGC part, an op-amp buffer was used in order to prevent any unnecessary filtering effects, prevent any interaction between the circuits and to isolate the input voltage from the output voltage.

C. *Two Low-Pass Filters Cascaded*

In this part, we take the output from the AGC circuit and use a buffer between the two stages to have a non-distorted signal. The output of the AGC circuit is a stable output around 1.2V-1.3V between the operating range. After amplifying the sound signal, we need to filter out the coming signal so that the frequency range that passes through the filter is 300Hz-3.4kHz. First, we have designed a single stage low-pass filter as in Fig. 6., but the

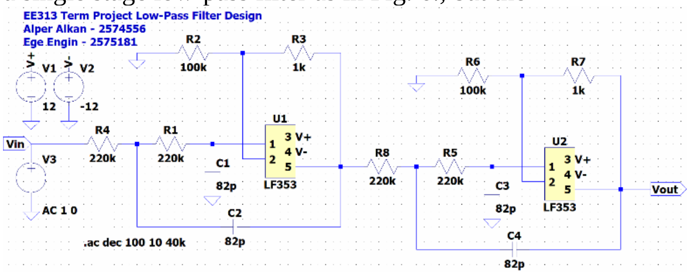

Fig. 6. Two Low-pass Filter Cascaded

suppression is not sufficient for us since the filter should suppress the higher frequencies around 10kHz range to approximately %10 of its upcoming amplitude. Hence, we have used the same filter configuration to have a better suppression for the higher frequencies. In Fig. 6, first stage filter gain is determined by the resistors R_2 and R_3, and for the second stage filter gain is determined by the resistors R_6 and R_7. The overall gain is determined by (2):

$$A_1 = \frac{R_2 + R_3}{R_2} = A_2 = \frac{R_6 + R_7}{R_6} = \frac{101k}{100k} = 1.01 \left[\frac{V}{V}\right]$$

$$A_{overall} = A_1 * A_2 \cong 1.02 \quad \left[\frac{V}{V}\right] \quad (2)$$

To determine the cut-off frequency of the low-pass filter, if the two resistors are equal (i.e. R_4 and R_1 are equal to 220kΩ), from the short circuit time constant method, the equivalent resistance seen by each capacitor is 440kΩ. Hence the cut-off frequency of the filter is determined by (3):

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2 \times \pi \times 440 \times 10^3 \times 82.10^{-12}} \cong 4411.2Hz \quad (3)$$

From Fig. 7, the cut-off frequency is obtained as 3.9kHz in LTspice. The difference occurred since LTspice added the unidealities to the circuit due to the usage of universal opamp3. The gain of the circuit is obtained as 164mdB which is approximately 1 [V/V] linear gain. Moreover, again to obtain a not distorted signal we have used buffer op-amp in between the low-pass filter stages.

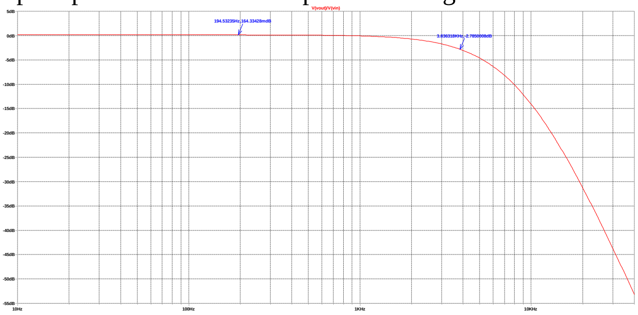

Fig. 7. Two Low-pass Filter Cascaded Frequency Response

As can be seen from the Fig. 8., the experimental results are also similar to the simulation results. In Fig. 8., the obtained data shows the midband region in which the output voltage is 1V and passes the signal in 1kHz.

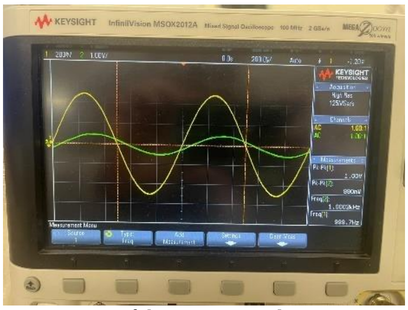

Fig. 8. Frequency Response of the Low-pass Filter

In Fig. 9., we have measured the cut-off frequency by finding the frequency which has the %70 of the maximum voltage, which is 3.910kHz. It is pretty close to the theoretical results that we have obtained, as expected.

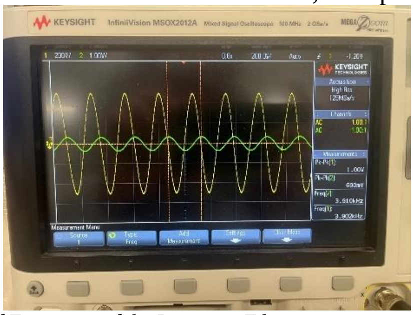

Fig. 9. Cut-off Frequency of the Low-pass Filter

D. *Summing Amplifier*

The reason for the usage of this stage is the need to determine the signal strength at the receiver side. By using the summing amplifier with the inputs as given in Fig. 10, we can sum a reference signal that is taken from the signal generator, with 20kHz frequency, 3V DC offset and 1.5Vp-p amplitude, together with the sound signal that is output from the cascade active low-pass filters stage. The output voltage can then be recovered at the receiver side which then allows us to determine the signal strength. The output of this system can be found as (4), which can be verified by the LTSpice simulation results given in Fig. 11.

$$I_1 + I_2 = 0\ (KCL)$$

$$\frac{V_1 - V_+}{R_3} + \frac{V_2 - V_+}{R_4} = 0$$

$$V_+ = \frac{V_1 + V_2}{2}$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_+} = 1 + \frac{R_2}{R_1} = 2$$

$$V_{out} = A_v V_+ = 2 \times \frac{V_1 + V_2}{2} = V_1 + V_2 \quad (4)$$

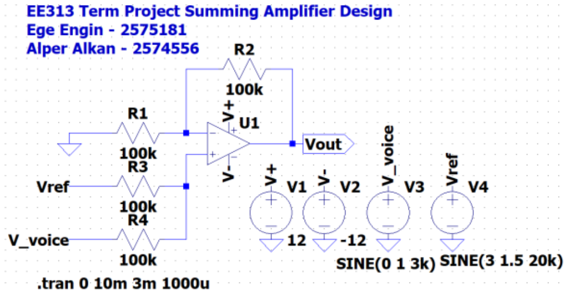

Fig. 10. Summing Amplifier Design Circuit

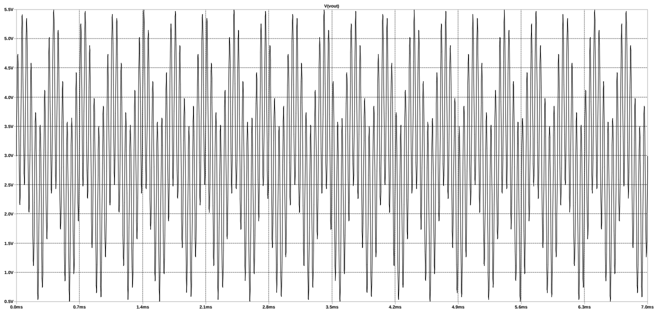
Fig. 11. Summing Amplifier Design Circuit Transient Response

Finally, the experimental results are also shown in Fig. 12., which are quite similar to the simulations. In this result, the given signal to the microphone is 3kHz, and the output is measured from the output of the summing amplifier circuit.

Fig. 12. Summing Amplifier Experimental Result

E. *Transconductance Amplifier*

The aim of this stage is to convert the voltage to an output current for LED driving. In this project, we drive the laser diode for the light transmission with current, since the voltage vs. brightness characteristics are not linearly dependent, but the brightness linearly depends on the current. Hence, we choose to use transconductance amplifier as in Fig. 13. for laser diode driving.

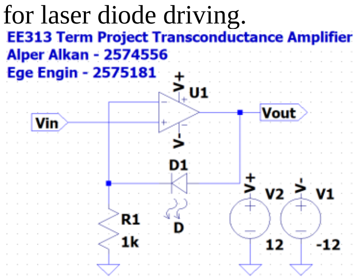

Fig. 13. Transconductance Amplifier Circuit

III. RECEIVER

The receiver is also designed with separate blocks of circuits, each specialized for a certain purpose. The general structure of the receiver is as in Fig. 14, in order. The main parts of the receiver are the transimpedance amplifier, pre-amplifier for voltage amplification, low and high pass filters, power amplifier and comparator for signal strength detection.

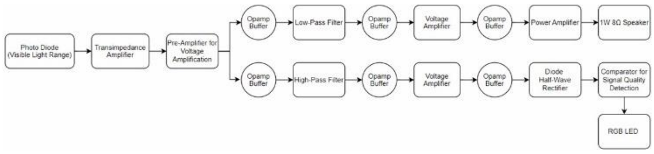

Fig. 14. Receiver Block Diagram

A. *Transimpedance Amplifier*

We decided to use a transimpedance amplifier to get the output signal as a voltage rather than the supplied current output of the photodiode. Therefore, we have driven the photo diode with a transimpedance amplifier with a 3.3kΩ resistor as in Fig. 15. The output of this amplifier was connected to a buffer to minimize the interaction between this and the next part of the receiver circuitry. In this part, since we used a visible range light to transmit the data, the 100Hz lights in the lab would create a quite high voltage on the photodiode which should be considered during the design. We have solved this problem by putting some solid objects over the diode to provide some shade from the laboratory's lights.

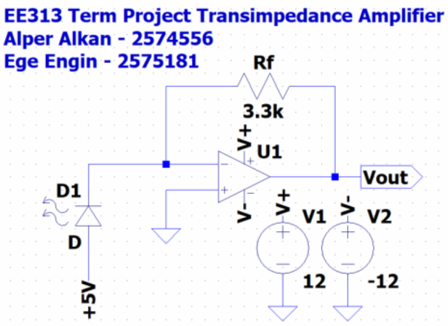

Fig. 15. Transimpedance Amplifier Circuit

B. *Pre-amplifier for Voltage Amplification*

We used a basic op-amp voltage amplifier to amplify the voltage signal obtained from the transimpedance amplifier. Its purpose is to amplify the very low input signal that we obtain from the transimpedance amplifier. The topology used for this amplifier and equation for the gain of this amplifier is as in Fig. 16 [2].

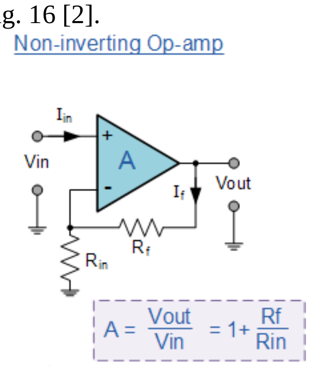

Fig. 16. Non-Inverting Amplifier Circuit

C. *Low-Pass Filter*

In this part, we need to use a low-pass filter to filter out the sound signal from the high frequency reference signal that is supplied from the signal generator as in Fig.5. However, for this filter unity gain filter is not sufficient since the amplitude of the signal is too low. Due to the transmission of the light, we lost the amplification at the transmitter side. Therefore, we use a filter which has 1.7 [V/V] linear gain.

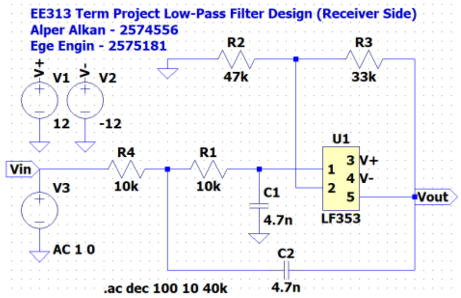

Fig. 17. Low-pass Filter for the Receiver Side

To calculate the gain of the filter we will use the same formula as in eq.1 and obtain the (5):

$$A_1 = \frac{R_2 + R_3}{R_2} = \frac{47k + 33k}{47k} \cong 1.7 \left[\frac{V}{V}\right] \quad (5)$$

The gain of the circuit is also around 1.07 [V/V] in the Ltspice simulation as in Fig. 6. Moreover, since the resistors are equal to each other the cut-off frequency can be determined by the (6):

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2 \times \pi \times 10 \times 10^3 \times 4.7.10^{-9}} \cong 3.4kHz \quad (6)$$

Moreover, the simulation results for the low-pass filter are as in Fig. 18., as it can be seen from the frequency response, the 3dB cut-off frequency is 3.65kHz, which is close to the theoretical value.

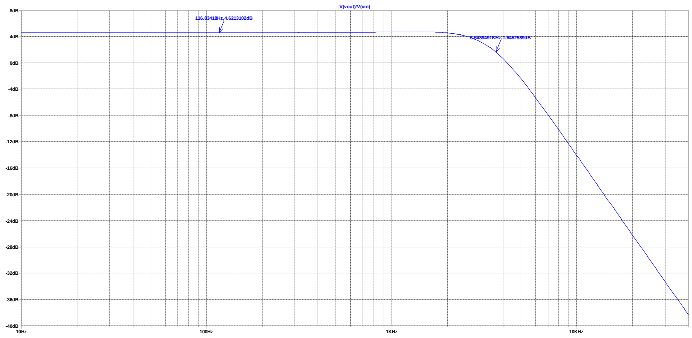

Fig. 18. Frequency Response of the Low-pass Filter

D. *High-Pass Filter*

In this part, we take the input from the pre-amplifier circuit after connecting the buffer op-amp to not have any distorted signal. The reason why we use a high-pass filter with a gain is having a low amplitude signal after transmitting the light. The purpose of this active high-pass filter, which is in Fig.19, is to filter out the low-pass signal and keep the high frequency reference signal for classifying the quality of the signal by using the comparator circuit. Same gain and cut-off frequency formula applies for this filter as in (7) and (8) respectively:

$$A_1 = \frac{R_1 + R_2}{R_1} = \frac{47k + 33k}{47k} \cong 1.7 \left[\frac{V}{V}\right] \quad (7)$$

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2 \times \pi \times 22 \times 10^3 \times 10^{-9}} \cong 7.2kHz \quad (8)$$

In Fig. 17, the 3dB cut-off frequency of the high-pass filter

Measured as 6.6kHz from the LTspice, and the gain of the filter is measured as 4.56dB which is approximately 1.7 [V/V]. The discrepancies are because of the non-idealities of the op-amp since we use the universal opamp3 model from LTSpice.

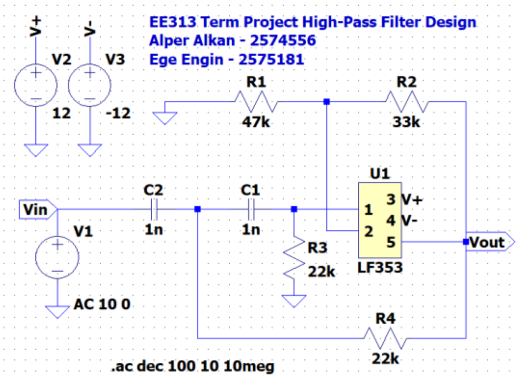

Fig. 19. High-pass Filter Circuit

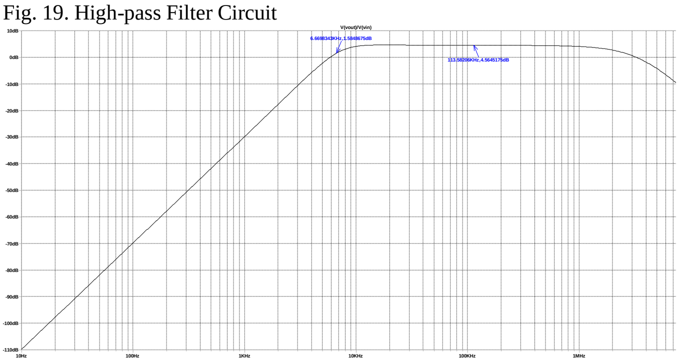

Fig. 20. Frequency Response of the High-pass Filter

E. *Diode Half Wave Rectifier and Peak Detector Circuit*

Before inputting the signal into the diode half wave rectifier, a voltage amplifier is applied to amplify the small input voltage to higher levels since we will be losing a 0.7V to bias the diode when using the diode half wave rectifier as a peak detector for the comparator part. The general half wave rectifier topology in Fig. 21 was used where a 100kΩ resistor and 100nF capacitor was used to rectify and detect the amplitude of the input signal.

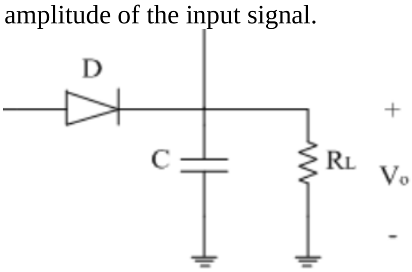

Fig. 21. Diode Half Wave Rectifier

F. *Comparator*

Op-amp comparators were used to determine the voltage level at the receiver side. A singular comparator works such that when the input reference voltage is lower than the DC signal that it is compared to, which is obtained by a simple resistor voltage division of the +12 DC supply, the comparator gives out a -SAT output, therefore, as it can be seen from Fig. 22, we used diodes to prevent this from affecting the +SAT working comparators. When the input reference voltage is higher than the DC signal that it is compared to, it will output a +SAT response; therefore, forward biasing the diode at its output and the part of the RGB led that it is connected to. Here, it can be seen that when the input reference voltage is higher than the DC comparison signal, that comparator is always on. Therefore, we have used lower resistances for comparators that work when the voltage level is higher such that when the amplifier works in different areas of operation, we get distinct colors from the RGB led for all 5 signal strength conditions, low signal to high signal. It should also be noted that the op-amps used in this part are LM324 op-amps since they have 4 op-amps in one package, which is very space-efficient for this usage in particular. When doing real tests to see if the comparator is working, only the opening voltage of diodes used was different than the expected 0.7V and everything else was the same, which is in accord with out theoretical expectations.

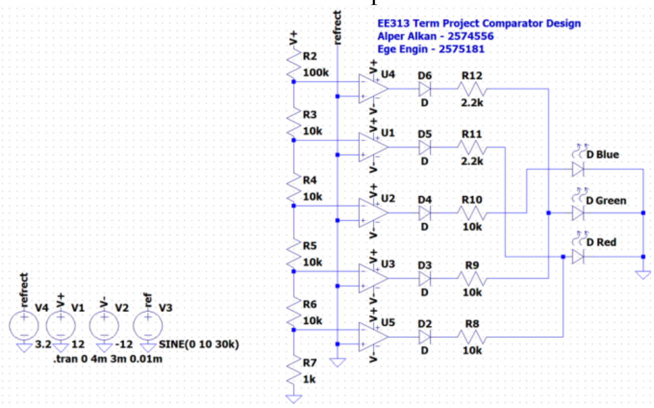

Fig. 22. Comparator Circuit Diagram

G. *Power Amplifier*

We use a power amplifier which is called as a class AB amplifier, since there are two transistors. We have one npn TIP41C on the high voltage side and a pnp TIP42C on the low voltage side. In this topology as in Fig. 23. Which we have taken from [2], npn transistor supplies the positive output voltages while pnp supplies the negative voltages. In this project, according to the requirements, we need to have at max. 1W power for our power amplifier. This requirement limits us in designing. Hence, we used the power BJTs and resistors for the other circuit components. The simulation results are given in Fig. 24. According to the results, we could not supply that much current from the power BJTs. Since the current is too high we could not manage to control the circuit.

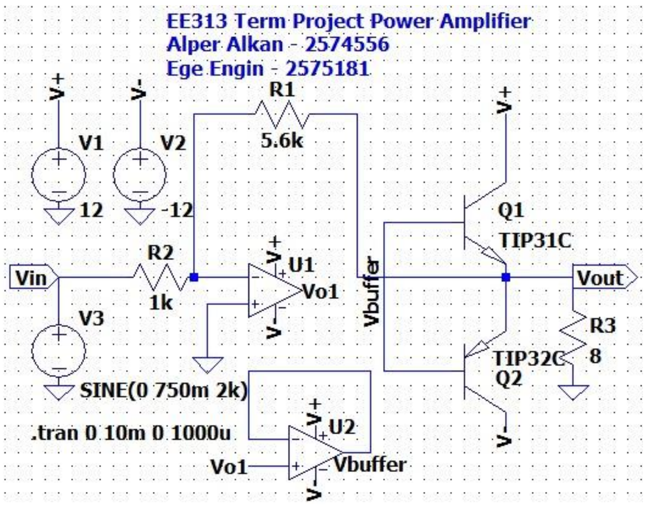

Fig. 23. Power Amplifier Circuit

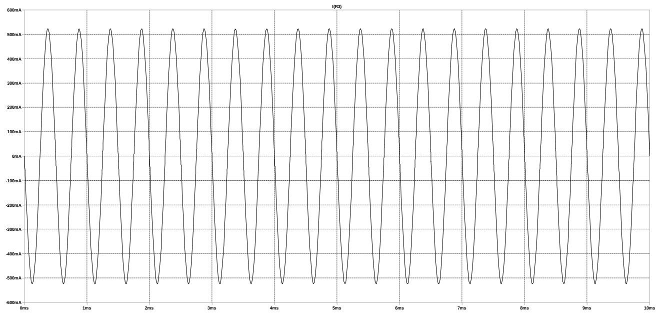

Fig. 24. Power Amplifier Circuit Output Current

IV. CONCLUSION

To conclude, we have seen that light can be used to transfer data wirelessly, without the need for cables. However, there are still problems such as ambient lighting like the laboratory's lamps affecting the output of the photodiode, the problem of clipping and others, which make it much harder to get good results. Therefore, it was found out that using light that is outside of the visible range and using more specialized circuitry that work within predefined margins and frequency ranges has a lot of importance and should be considered. Also, using digital signals instead of analog signal would help a lot with noise and other problems that are encountered a lot with analog circuits. Our work sheds light on ways to transmit data wirelessly, and the shortcomings of analog data transfer using visible light. It also enlightens some of the prominent problems that are to be encountered with analog data transfers, for which people should keep a watch for. In the future; using digital signals, using infrared light and receivers instead of the visible range will improve the results of this project and definitely will be considered.

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