EE313 Fall 2022 Term Project Final Report

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***Abstract*— Subparts, details, and used components of our Analog Electronics Laboratory Term Project are presented in this report. The Project will be explained in two main sub-blocks which are transmitter and receiver.**

Keywords*— *Optical Wireless Communication, Low-pass Filter, Automatic Gain Control, RGB Indicator

I. INTRODUCTION

In this project, our purpose is designing an optical wireless communication system and implement it whose overall schematic is given in the figure 1. Electrical audio signal generated in micropone will be summed with carrier reference signal. This signal will be transmitted as a modulated light signal and then received. Afterwards, this signal is converted back to electrical signal in the receiver and speech signal is obtained by filtering the signal in the low-pass filter and reference signal is seperated by using the high-pass filter as well. Recovered speech signal will be amplified by power amplifier and it will be converted into the sound in the loudspeaker. Amplitude of the recovered reference signal will be determine signal strenght.

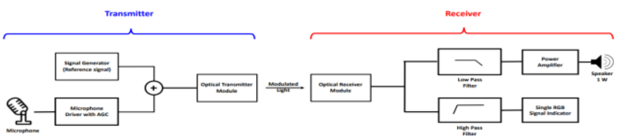

Figure 1 Overall Design Schematic

II. SPECIFICATIONS

- low-pass filter 3dB cut-off frequency: 3.7kHz
- high-pass filter 3dB cut-off frequency: 13kHz
- frequency of the reference signal: 20kHz

(since we need to filter the signals and don't risking for the switching rate we select a reference frequency that is in the middle of allowed band)

- Optical transmitter: IR LED
- Optical receiver: Phototransistor

III. TRANSMITTER

This sub-part enables us to drive the microphone together with the a sort of voltage stabilizer circuit and transmit the signal via the infrared light emitting diode.

A. Microphone Driver - Pre-Amplifier Stage

For this stage, a resistive type microphone is selected. To avoid environmental noise and obtain a desirable output signal amplitude we need to preamplify the signal and drive it. In order to do this we have used a common emitter amplifier in the forward active region by biasing it with 6 Volts using voltage divider. In figure 2 circuit schematic is shown where 0.1u capacitor is used to allow it only AC signal to pass through ,and R9 is used for DC biasing, R10 provides feedback to the circuit ,and R11 is for the gain ,and Vmic is the terminal where output is taken.

Furthermore, our experimental results were consistent with our expectations so driver part was working properly.

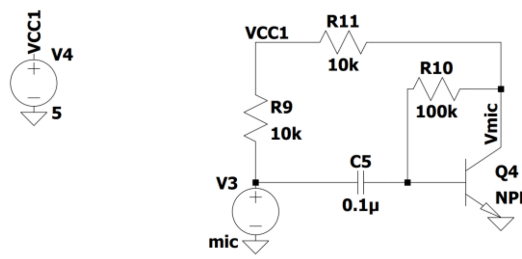

Figure 2 Microphone Preamplifier Circuit

B. Automatic Gain Controller Stage

Since the output of the microphone driver frequency and distance dependent we need to construct a circuit that provides us a relatively constant output signal in amplitude in order not to cause clipping or saturations at the following stages.

The circuit in figure 3 includes 3 stages. The Q1(Q1 is in saturation region) acts a variable resistance dependent on the output, Q2 is a common emitter with degeneration in forward active region which is made for the gain stage, and Q3 provides feedback to the circuit. D1 and D2 diodes rectifiy the

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signal and creates a voltage on C2 , this voltage is sampled and feds Q1. Therefore, the circuit has a series-shunt type negative feedback topology.

Following implications are based on the operation regions of the BFT transistor which is given in figure 4

When the voltage input is relatively high, voltage sampled on C2 is high so the voltage feds Q1 is high so the the base current is high as well as the collector current (i.e. β times I_B). Since Q1 is in linear region(SAT), as I_C increases V_{CE} increases linearly such as a resistor. If V_{CE} increases voltage input that goes into Q2(gain stage) decreases, so our output Vo_{agc} decreases.

When the voltage input is relatively low, voltage sampled on C2 is low so the voltage feds Q1 is low ,and so the the base current is low as well as the collector current (i.e. β times I_B). Since Q1 is in linear region(SAT) as I_C decreases V_{CE} decreases linearly like a resistor. If V_{CE} decreases voltage input that goes into Q2(gain stage) increases, so our output Vo_{agc} increases.

When 1V peak to peak voltage input is given to the AGC circuit, the output of AGC can be observed in in figure 5 as 9.8V peak to peak.

When 4V peak to peak voltage input is given to AGC, the output AGC can be observed in in figure 6 as 10V peak to peak.

From the simulations it can be seen that when input four times higher, output increases approximately %2 which is a great result. Also in practically, AGC circuit performs similar behaviours with the simulations.

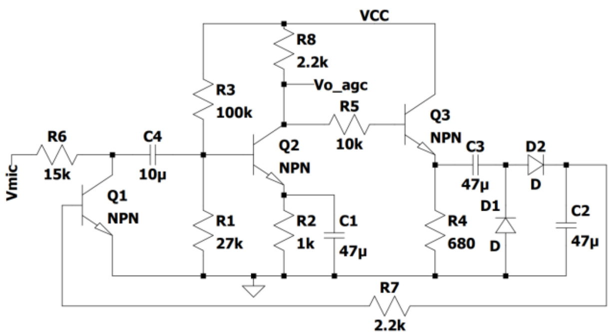

Figure 3 Automatic Gain Controller Circuit

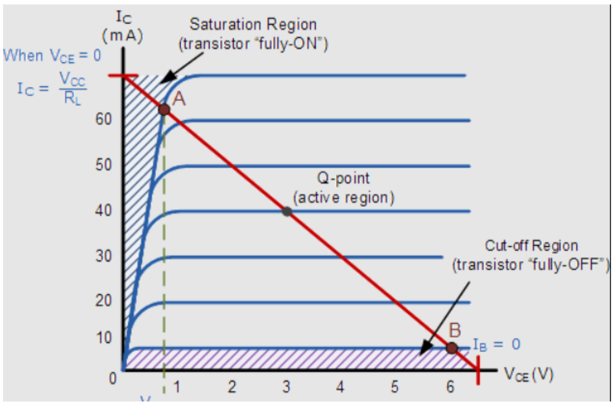

Figure 4 BJT Transistor Operation Regions

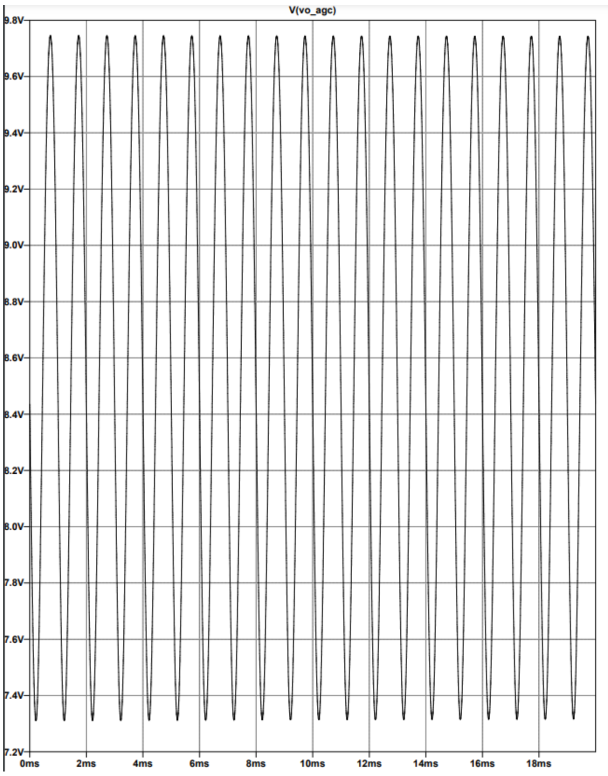

Figure 5 AGC Output When 1V Applied

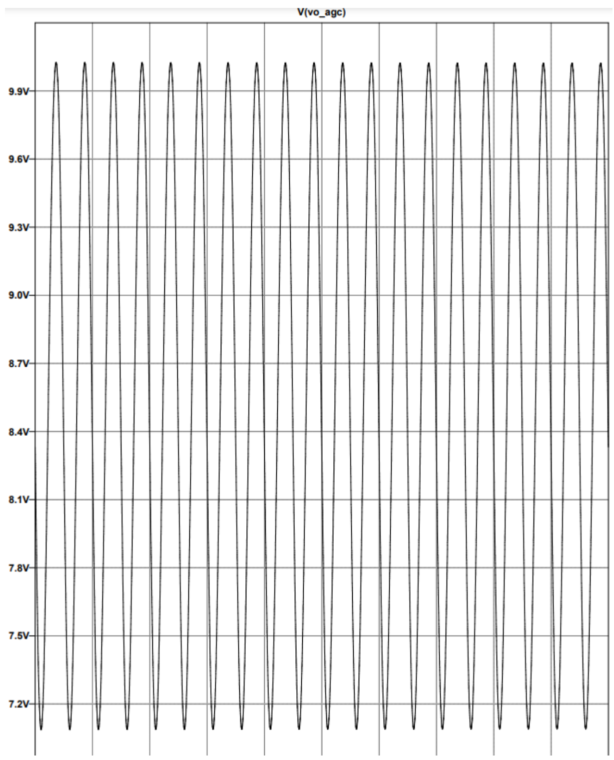

Figure 6 AGC Output When 3V Applied

C. Optical Transmitter Stage (Transconductance Amplifier)

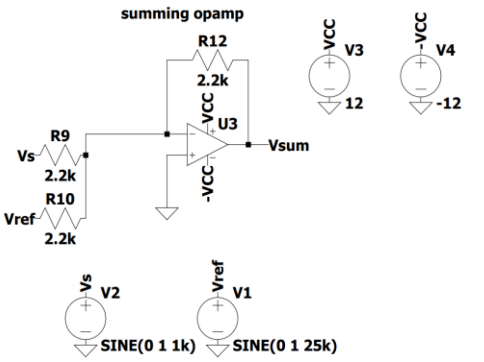

Figure 7 Inverting Summing Op-amp

Before this stage, an inverting summing op amp shown in figure 7 is used for summing the high frequency reference signal having negative offset (for opening the LED i.e. to be able to transmit the whole sine wave otherwise output signal would include only the positive part not the negative part of the sine wave) with the low frequency speech signal. The reason behind using negative offset voltage is for obtaining a positive offset after the inverting summing op-amp stage. Summed output then, is sent to the transmitter circuit.

In transmitter module, hence environmental noise would be much larger in the case of visible light LED usage, infrared led is selected for the sake of noise reduction. Using laser would be an another choice ,nevertheless cost concerns lead us to use ir LED. Then, we needed to decide whether we drive the circuit with an op-amp or transistor. Since op-amp output may cause non-linear distortion ,and BJT transistor has a better linear operation, transmitter circuit is decided to be used.

In figure 8 transmitter circuit is shown where vcc equals to 12V and D1 is an ir LED. According to the datasheet our ir led needs approximately 20mA forward current and corresponding voltage is found 1V from datasheet. DC analysis for Q2 to be in forward active region and LED to be open is made below:

$$\mathrm{Vsum}(\mathrm{V_{base}}) = \mathrm{vcc} * \frac{\mathrm{R14}}{\mathrm{R14+R13}} + 4.3(offset)$$

$$\mathrm{V_{base}} = 11.5V$$

$$\mathrm{V_{emitter}} = \mathrm{V_{base}} - 0.7 = 10.8V$$

$$\mathrm{V_{collector}} = \mathrm{V_{emitter}} + 0.2 = 11V$$

$$\mathrm{I}_E = \frac{\mathrm{V_{emitter}}}{500\ ohm} = 22mA$$

$$\mathrm{I_C} = 22mA$$

Also, experimental results showed us that theoretical calculations above were close enough to transmitter circuit be fully functioned in the experiments.

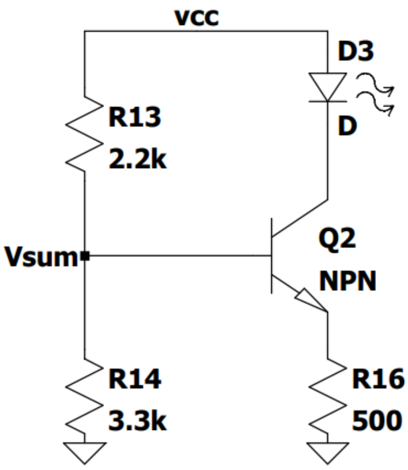

Figure 8 Optical Transmitter Circuit

IV. RECEIVER

To catch the transmitted light which contains the audio signal and high frequency reference signal, there must be some sort of light sensor. In this sub-part this sensor is drived and some low-pass and high-pass filters are used to separate necessary signals for their corresponding operations.

A. Optical Receiver Stage (Transresistance Amplifier)

A Phototransistor is used at the optical receiver module whose schematic is given in figure 9. It has a resistor between its collector and 12V Vcc supply. Phototransistor is preferred over photodiode since it has a better quantum efficiency which means that the ratio of absorbed photon over the emitted photon is larger. Because of the following reasons phototransistor is selected to be used.

- Photodiode needs an op-amp and two resistors to drive it
- Op-amp has a some non-linear operation
- Phototransistor is more sensitive than photodiode
- Phototransistor has a higher gain in amplitude
- Phototransistor operation is linear i.e. I_C depends linearly on I_B ($\beta * I_C$).

Phototransistor's base current is caused of absorption of light and this leads to a large output current at the emitter. Thus, when the phototransistor is used at the receiver module later amplification (like in photodiode) is not needed. These are the reasons that phototransistor is used at the optical receiver module. By using a resistor R42 in figure 9 ,we convert the current into voltage and take the output from here. In terms of this operation(i.e. converting current to the voltage), that circuit operates as a transresistance amplifier.

In the experiments, we observed that our design methodology was correct and our transresistance amplifier is working well functioned.

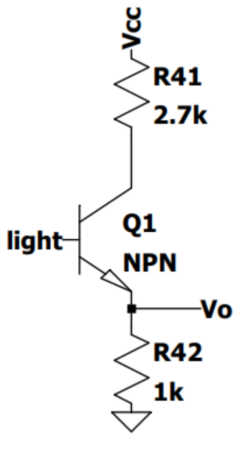

Figure 9 Optical Receiver Circuit

B. Low-pass Filter Stage

Before this stage a voltage buffer op-amp is used to buffer the signal in order the receiver not to affect the frequency response and the operation of the filter.

A 4th order low-pass filter is designed and used to extract the voice signal from the 20kHz reference signal in figure 10. This filter has a cut-off frequency of 3.7kHz which is sufficient for the purpose of this filter is used in this project(using Short Circuit Time Constant method required dominant pole i.e., 3.7kHz can be found approximately). It has a 20dB gain at the pass-band and since this voltage will be buffered to the speaker 10V/V gain is enough to hear the sound from the speaker. A Butterworth filter is used to have as flat frequency response as possible in the pass-band to achieve a better-quality sound. The slope of the transition is 60dB/decade. Also, frequency response of the filter can be seen in figure 11.

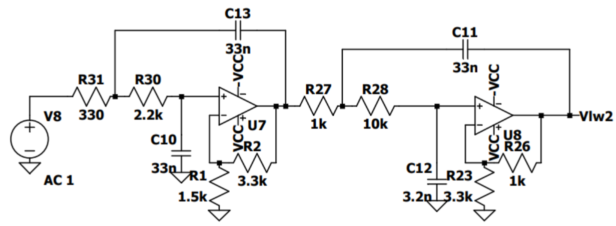

Figure 10 4th Order Low-Pass Filter Circuit

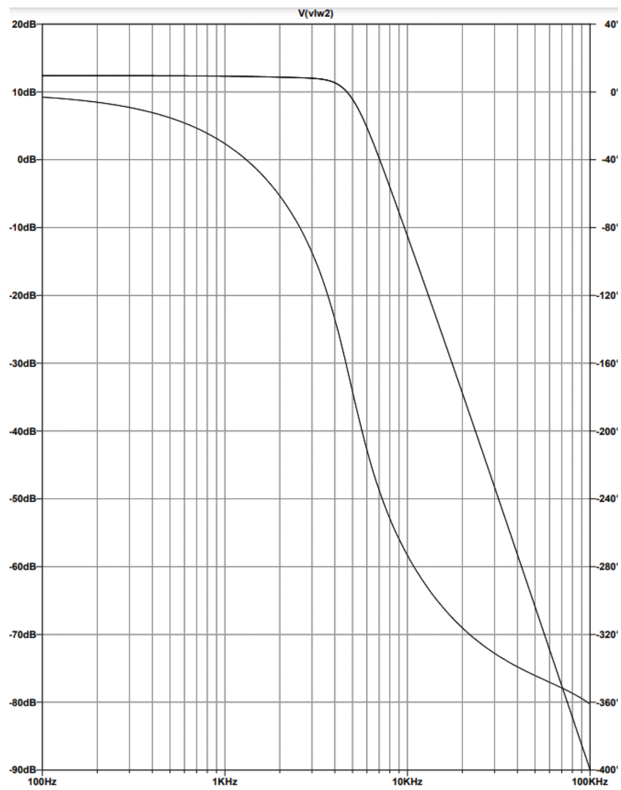

Figure 11 Low-Pass Filter Frequency Response

It is observed that our filter design is very well functioned in practic. Nevertheless, at the experimental results our cut-off frequency was slightly lesser. Therefore, we have decreased some capacitors a bit to obtain a little bit higher dominant pole and changed resistors so that our operation would stay stable(for stable gain and no ripples).

C. Power Amplifier Stage and Speaker

We take the recovered the speech signal at low-pass filtering stage as an input at this stage, and to hear speech sound we need to drive the loudspeaker.

In order to do this, we need at least 1W power which determines necessary current needed:

$$1W = I^2 * R$$

Since our speaker is 16Ω, we need at least 250mA current output. Because current output of the op-amp is low, and BJT transistors would be burned at that much current we used BJT power transistors and even power resistors to avoid burning components.

Another purpose of this circuit is to buffer the voltage output of the low-pass filter to drive the speaker by transferring a significant amount of power.

For that purposes we needed to decide which class of amplifier we will use. Therefore, my making a search, we reached following information:

- The primary benefit of Class A is the minimized distortion while it suffers from low efficiency because of biasing needs.
- Class B is more power-efficient than Class A, but it experiences cross-over distortion, which distorts the output signal's shape.
- Due to their low crossover distortion, high linearity, so the combination of an acceptably high efficiency and high-quality output, Class AB type is mostly used type of amplifier for our needs.

By looking these results, we decided to use Class AB type amplifier in figure 12.

In schematic in figure 12, diodes are used between the two transistors' bases for the biasing. When current flows through the diode, there will be a forward bias voltage drop which is nearly 0.7V and this voltage drop keeps the keeps the BJT's in forward active mode. Also, transistors operates in a way that allows the opposite half-cycles of the signal to pass through.

Since we cannot bias the amplifier correctly, our experimental results were not as expected as theoretical results.

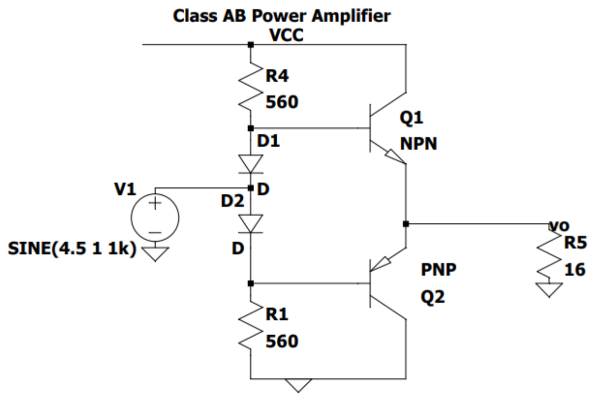

Figure 12 Class AB Power Amplifier

D. High-pass Filter Stage

A 4th order Sallen-key active high pass is used to separate the reference signal (with a frequency of 20kHz) from the voice signal to examine the level of signal at the next subblock. In theory, the 3dB cut-off frequency of this circuit is approximately 13kHz, the slope of transition is 60dB/decade and the pass-band gain is 0dB which is equal to the 1V/V. This filter's gain is adjusted this way to inhibit the op-amp's from saturation region. Even though, the observed data from LTSpice were this, experimental outcome has varied from LTSpice results. The output voltage has dropped significantly, the reason behind that result is the internal capacitors in op-amp. After that, a new filter is designed to diminish that effect filter which is shown in figure 13. This filter has an 18dB gain at the pass-band and frequency response can be seen from figure 14, and even though this design has performed better in practice yet still poorly. The reason of this, is again the internal capacitors of op-amps.

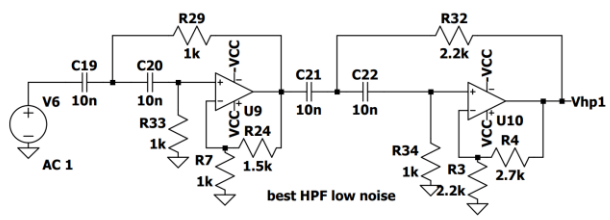

Figure 13 4th Order High-Pass Filter Circuit

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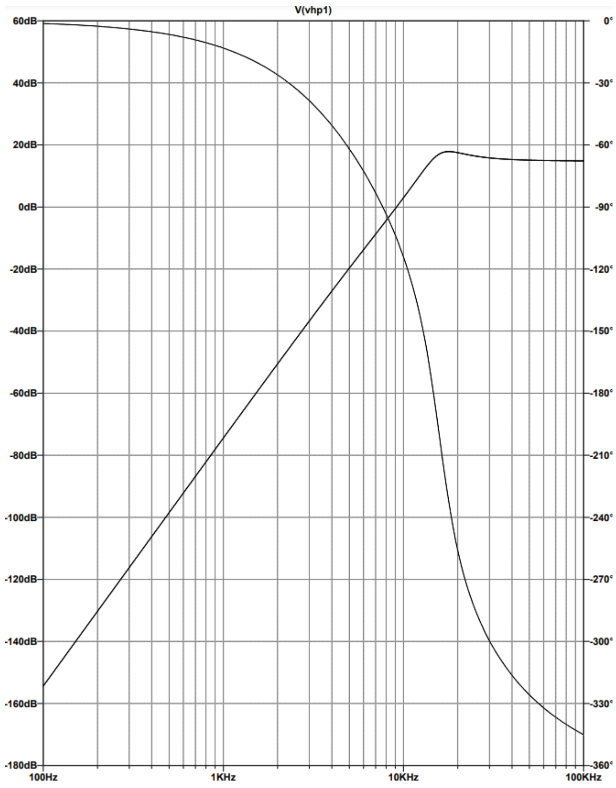

Figure 14 High-Pass Filter Frequency Response

E. RGB Signal Indicator Stage

After the separation of reference signal from voice signal, signal level indicator will give an information about the signal's strength with the color of the light that RGB led emits. The circuit designed for this purpose consists of two stages which can be seen from the figure 15. First stage is composed of a diode, 100nF capacitor and 150kΩ resistor. Diode is connected in series with the output of the high-pass filter and by using this, negative side of the waveform is eliminated since we should have a DC voltage at the comparator input. 100nF and 150kΩ are connected parallel to each other and connected to the common ground. Since, τ=RC=150Hz this RC part of the circuit acts like a 150Hz filter and convert the 20kHz reference signal to DC which is compatible for the second stage of the signal level indicator which consists of four comparator circuits. At the second stage the output of the first stage is connected to the non-inverting input, boundary voltages(1V,2V,3V,4V) are divided by voltage divider and connected to inverting input ports and 1kΩ resistors and a RGB led pins are connected to the output of the OPAMPs (UA741). Cathode RGB led is used and the cathode pin is connected to –12V DC supply. RGB led can emit three distinct colors: Blue, red and green. However, by mixing two or three of these colors distinct colors for different strength cases can be achieved. In theory, there should be five different colors for five different stages of strength. Red is for no signal, green is for low signal, yellow is for moderate signal, blue is for good signal and white is for excellent signal. However, in our project we've achieved to emit four distinct colors for different voltage intervals. The nonideality of the elements caused the change between blue to white continuous.

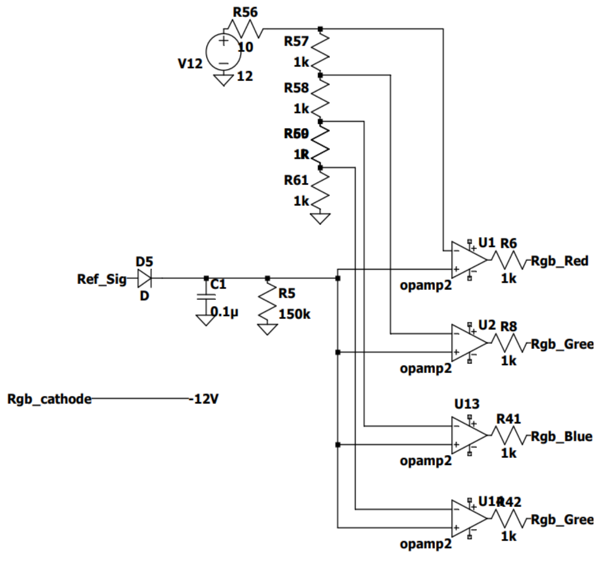

Figure 15 RGB Signal Indicator Circuit

V. Conclusion

In this project, a photophone:optical wireless communication device is built by using not only the theoretical knowledge from analog electronics class which includes transistors, feedback amplifiers and filters but also the all circuit theory classes and even semiconductor class. We gained a deeper understanding of designing, using, and debugging analog circuits practically. We came across new circuit topologies and learned different driving methods which have different pros, cons and superiorities over others while compromising some features .

Basically, an audio signal and a reference signal are transmitted via photons by using an IR led and received from a phototransistor. After some processes like filtering and amplification the purposes of the project are met together until this stage.

Nonetheless, we have indicated the levels of the signal with the reference signal mostly ,but not completely. Although our design idea was not wrong, we cannot drive the power amplifier properly. Since we cannot drive the last stage, we can manage only one time to convert the low frequency signal to the audio signal and hear it from the speaker.

In closing, since we had a great chance to put our knowledge and learning abilities to work in the design and implementation this experience will be extremely beneficial to our future engineering careers.

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