Design of an Optical Wireless Communication System: Photophone

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***Abstract*— This research paper presents the design and implementation of a photophone, an optical wireless communication system that uses infrared light to transmit information. The design utilizes infrared LED for transmission, a photodiode for the receiver side, and other components for audio output and signal indication. The goal of this research is to demonstrate photophone in transmitting and receiving data wirelessly using light.**

Keywords—optical wireless communication, photophone

I. Introduction

In this report, design of an optical wireless communication system, also known as photophone, will be explained. Its theoretical design, real-life implementation, experimental results and comparison of simulation and experimental results will be given.

Optical wireless communication can be utilized with visible, infrared, or ultraviolet light to transmit the signal. In this design, the infrared LED is used for transmission. In addition to transmission part, the receiver side is designed with photodiode. Furthermore, a speaker with power amplifier and RGB signal level indicator are constructed. Each subblock of the photophone design will be discussed in detail. Literature research results will be given at each subblock explanation.

II. Theoretical Background

A. Optical Wireless Communication (OWC)

OWC is a way of transmitting and receiving information without wires by using visible light, infrared, or ultraviolet light. The first wireless telephone system, the photophone, which utilized light beam modulation to transmit speech is created by Alexander Graham Bell. In this report, a modified version of Bell's photophone, in which the transmitted light is modulated using analog electronics, will be designed.

B. Solution Path and Subblock Diagram

In Figure 1, the subblock diagram for project design can be seen. The first input signal comes from the microphone, which converts speech signal to electrical audio signal. This signal will be amplified and then by using a buffer, it will be delivered to the Automatic Gain Controller (AGC) circuit. The second input signal comes from the reference signal. This signal has higher frequency than the microphone's output. This signal will be used to understand the reception of the transmitted signal. Later two input will be summed with summing amplifier circuit, this operation is called as multiplexing.

Modulated light, which preserves this multiplexed signal information, will be sent to receiver side through air by the optical transmitter module. Here, optical information will be converted back into the reference signal and speech signal (demultiplexing) by using low pass (LP) and high pass (HP) filters. The audio signal will be put through the power amplifier circuit, and converted into sound by speaker. Reference signal will be used in RGB Led indicator to see the signal strength. During the transmission and receiving of the signal, and after the filters, signals lost some of their amplitudes. This resulted in usage of inverting amplifiers at different steps. Circuits designed for each step will be explained in detail.

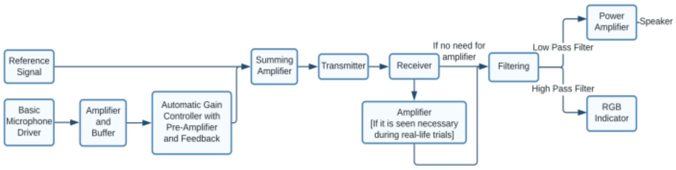

Fig. 1. Flowchart of subblock design

III. Circuit Designs, Mathematical Analysis and Simulation Results of Subsystems at Transmission

In this section of the report, for each subblock at transmitter side, circuit designs will be given, and they will be explained mathematically. Moreover, simulation results will be provided. Simulation results and theoretical designs are given at the same section to provide coherence and continuity in the report.

A. Microphone Driver

In Figure 2, the basic RC circuit used for electret microphone can be seen. In microphone circuits, resistor and capacitor are used to condition the electrical signal generated by the microphone element. The circuit's input impedance is determined by the resistor, and any undesired DC voltage that might be present in the signal is eliminated by the capacitor. The capacitor also has the ability to function as a low-pass filter. This helps to decrease signal noise. These circuit components help the microphone operate more effectively and reliably.

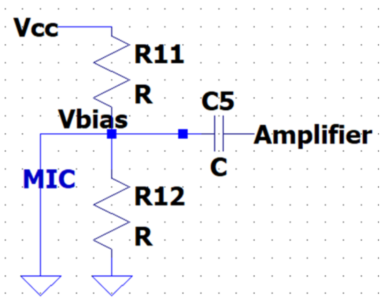

Fig. 2. Microphone driver circuit

Moreover, a voltage divider is used at the Vcc side of this circuit. The DC supply provides 12V, but microphone works with 6V; otherwise, it burns. Thus, voltage is divided to obtain 6V from 12V. The output of this voltage divider is connected to a buffer to isolate microphone circuit from another, while still allowing signals to pass through. Thus, loading effects are prevented.

B. *Automatic Gain Controller (AGC)*

Automatic gain controller helps to ensure that the amplifier isn't driving the signal too much or too little, resulting in output that is stable and predictable. To keep the output level consistent, an amplifier's gain is automatically adjusted. The AGC circuit keeps track of the output and modifies the amplifier's strength as necessary to keep the output level constant. [1]. It is crucial to use AGC for the signals coming from the microphone to obtain a relatively constant amplitude audio signal. The AGC circuit design can be seen in Figure 3 [3].

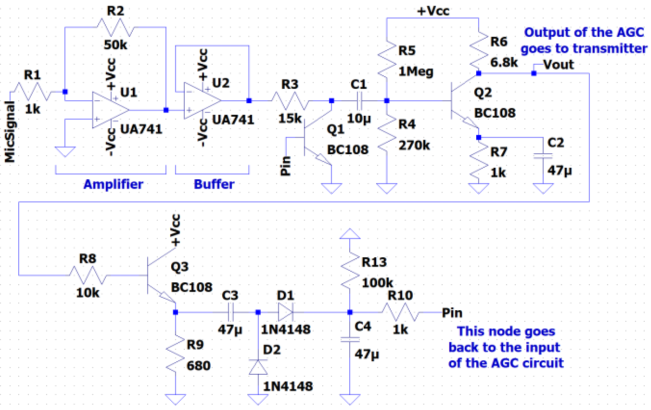

Fig. 3. Automatic gain controller circuit

The output from the microphone circuit is amplified at the first step to decrease the noises. With the usage of buffer, the AGC circuit is isolated from the amplifier. Then the AGC circuit starts to operate. Here the first BJT is used to adjust input resistance.

$$r_o = |V_A| / I_c \tag{1}$$

r_o resistance of the BJT depends on its I_c collector current by the relation (1). This BJT is biased thanks to 1N4148 diodes, C4 capacitor and R13 resistor. The diodes converts AC signal to DC and creates a DC bias. The voltage at that node changes the collector current. This results in change at r_o resistance. Input resistance also changes. Since the gain depends directly at input resistance, circuit manages to modify its gain for different input signals. As the input signal increases, gain decreases and vice versa.

The simulation results for this circuit can be seen in Figure 4. Input signal is changed between 0 to 100mV with 10mV steps. Slight increases are observed when input signal increases, but these differences are negligible. During experimental results, it is expected to obtain slight changes with the changes in the amplitude of the input signal.

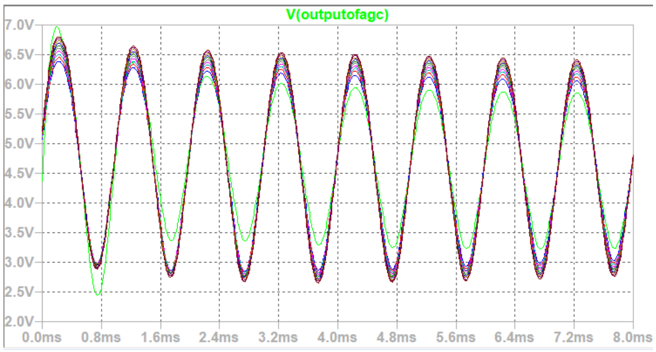

Fig. 4. Simulation results for AGC circuit

C. *Low Pass Filter*

After AGC circuit, a passive low pass filter is implemented to filter frequencies which are higher than the 5 kHz, which means cut-off frequency f_c is equal to 5 kHz. This filter is required to prevent frequency spectrum overlap between the audio source and the reference signal. The required resistance and capacitance values are calculated with the (2) formula.

$$f_c = 1 / 2\pi RC \tag{2}$$

The filter circuit can be seen in Figure 5.

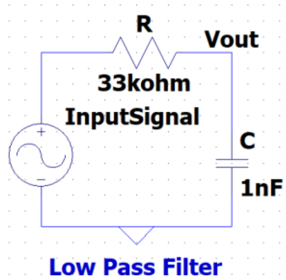

Fig. 5. Passive Low Pass Filter Circuit

Moreover, the simulation results for the low pass filter are in Figure 6. the 5 kHz cut-off frequency is obtained which is consistent with mathematical calculations.

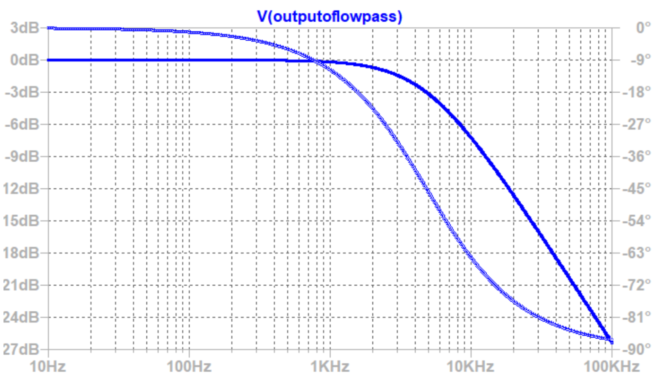

Fig. 6. Simulation results for low pass filter

D. *Summing Amplifier*

After low pass, summing amplifier comes to combine reference signal and input signal from the microphone. Aim of using reference signal is to understand how well the receiver receives the transmitted signal.

To combine the two signals, a noninverting summing amplifier is used. The circuit diagram is in Figure 7.

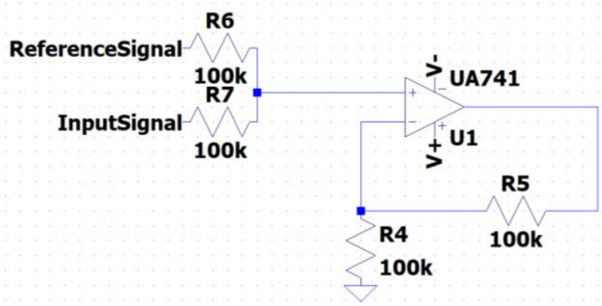

Fig. 7. Passive Low Pass Filter Circuit

The resistance values are kept equal in the circuit. The noninverting amplifier increases the amplitudes of the input signals by a factor of two, which can be understood from the equation (3).

$$A_v = 1 + R_5 / R_4 \quad (2)$$

The output waveform of summing amplifier is in Figure 8.

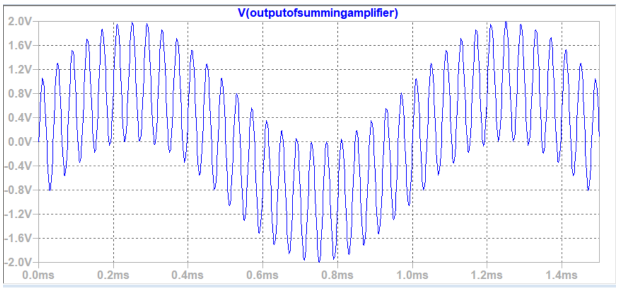

Fig. 8. Output waveform of summing amplifier

Fast Fourier Transform (FFT) characteristic of the output of summing amplifier is in Figure 9. As seen in FFT, the output of summing amplifier has two peaks at different frequencies, one of them is input signal and the other one is reference signal.

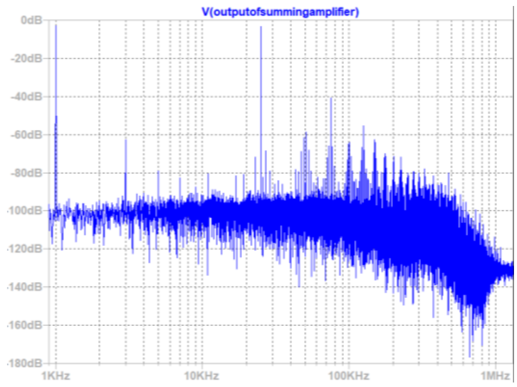

Fig. 9. FFT characteristics of the summing amplifier output

E. Transmitter

For transmitter, a common emitter with degeneration circuit is used. Since the infrared (IR) LED must be driven with current, using a BJT to adjust the current flows from LED is the most sensible solution. The circuit diagram of transmitter circuit is in Figure 10. As seen in Figure 10, the input is coming from the output of summing amplifier. IR LED's positive pin is connected to +12 V and other pin is connected to collector to bias IR LED. The current that flow through emitter is same as the current flows across the LED if ß >>1 assumed.

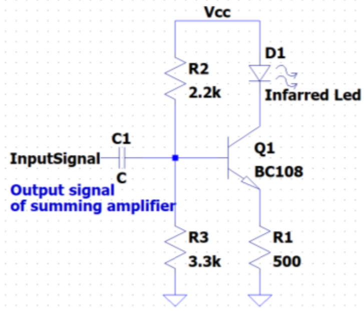

Fig. 10. Transmitter circuit diagram

The current waveform which flows from the emitter side is in Figure 11. The current is approximately 15 mA and the optimal current to drive an IR LED is also 20 mA [2].

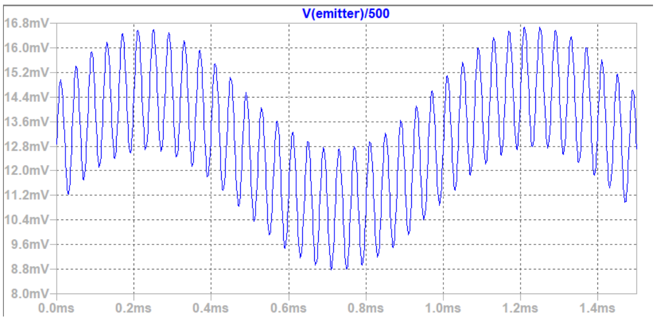

Fig. 11. Emitter current waveform

FFT characteristic of the emitter current is in Figure 12. As seen from FFT characteristic, the input and reference signals are still existing in the waveform. By using a common emitter with degeneration, no information is lost, and the IR LED is driven optimally.

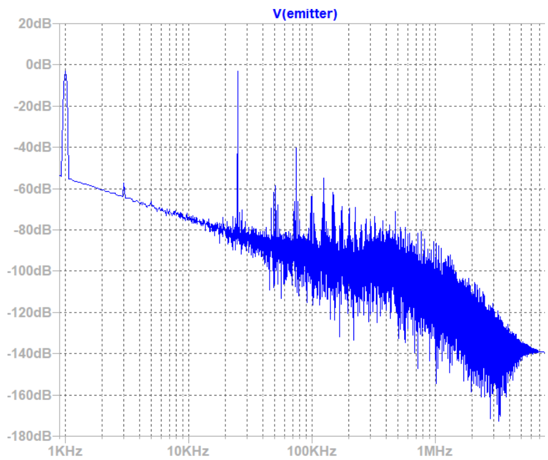

Fig. 12. FFT cahpar acteristics of emitter current waveform

At the end of this transmission, a modulated light signal that carries the frequency information of the input and reference signals is created. With this modulated light, transmission will be through the air. At the next part of the report, receiver side will be explained, at which the modulated signal will be converted into the electrical signal.

IV. Circuit Designs, Mathematical Analysis and Simulation Results of Subsystems at Receiver Side

In this section of the report, for each subblock at receiver side, circuit designs will be given, and they will be explained mathematically. Moreover, simulation results will be provided. Simulation results and theoretical designs are given at the same section to provide coherence and continuity in the report.

A. Receiver

In the receiver part, the modulated light sent from transmitter side should be detected, for that purpose a photodiode is used. Since the current supplied by photodiode is too small, an amplifier circuit is designed. A circuit diagram is in Figure 13.

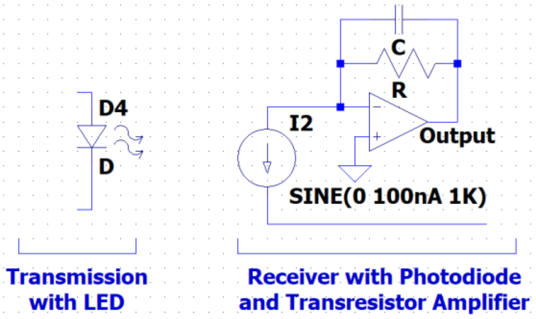

Fig. 13. Receiver circuit diagram

Since simulation is not applicable for modulated light signal, there is no simulation results for this part. From experimental results it is known that the output of this amplifier has the same waveform as the emitter current at transmitter part. The output of amplifier is sum of two signals, reference signal and input signal. The magnitude of it changes with the transmission quality. If the LED and photodiode align correctly, amplitude of the waveform increases. Moreover, the capacitor in the receiver circuit is used for stabilization of the circuit.

B. High Pass Filter

The received signal contains two signals inside. One is low frequency microphone signal while other is the high frequency reference signal. These two signals need to be separated; thus, high pass filter is used to obtain reference signal. To obtain a sharper filter, two passive RC filters are connected in series. The required resistance and capacitor values are calculated with (2). The designed circuit is in Figure 14.

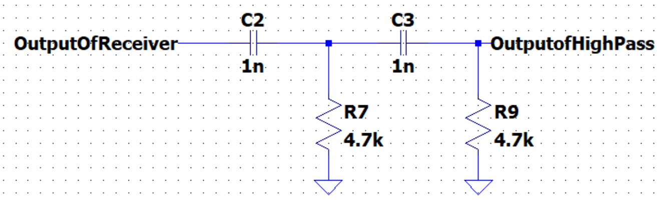

Fig. 14. Passive high pass filter circuit

For simulation, the reference signal is chosen as 25 kHz. The FFT characteristics of the output of the high pass filter can be seen in Figure 15. It is seen that only 25 kHz made a peak, which means it is separated from the low frequencies.

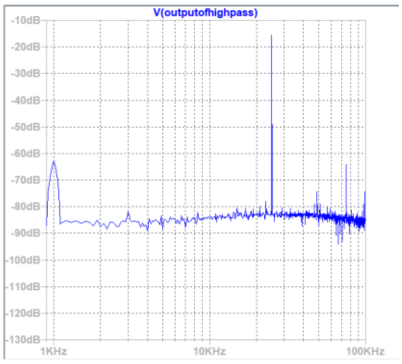

Fig. 15. FFT characteristics of the high pass filter

C. Low Pass Filter

The low pass filter is used to obtain the sound signal coming from the microphone. To obtain a sharper filter, two passive RC filters are connected in series. The required resistance and capacitor values are calculated with (2). The designed circuit is in Figure 16.

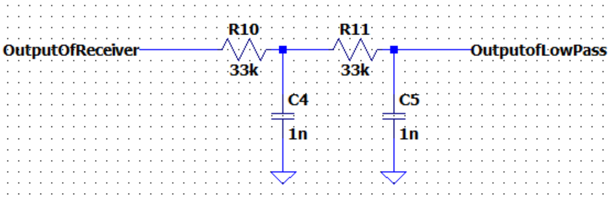

Fig. 16. Passive low pass filter circuit

For simulation, the reference signal is chosen as 25 kHz. The FFT characteristics of the output of the high pass filter can be seen in Figure 17. It is seen that 1 kHz signal is at least 30 dB larger than the other signals, which means it is filtered successfully.

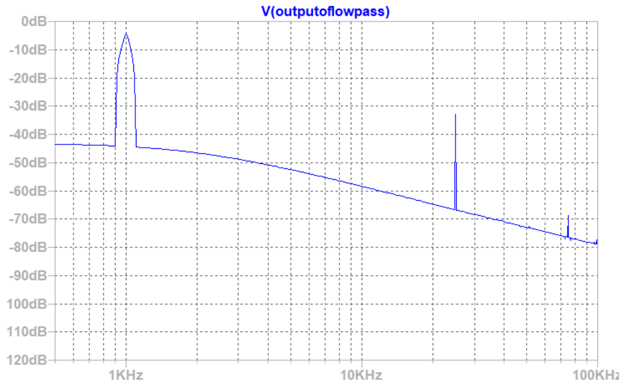

Fig. 17. FFT characteristics of the low pass filter

D. Amplifier Circuit

After the signals are transmitted and pass through the low pass and high pass filter, they lose more of their amplitude. To obtain the desired amplitude, an amplifier circuit is used. The amplifier circuit is in Figure 18. It is important that there always must be a continuous DC connection between ground and each of the input terminals of the op amp. As a result, without the resistance R3 to the ground, the AC-coupled noninverting amplifier will not function. To reduce the output voltage resulting from input bias currents, R3 is selected similarly to R2. If the amplifier circuit is not designed like in Figure 18, the output voltage will just be a noise.

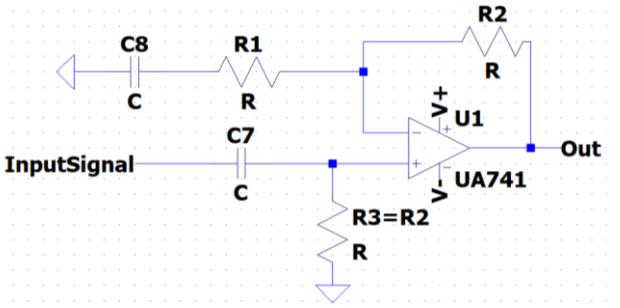

Fig. 18. Amplifier circuit diagram

E. *Peak Detector and RGB LED Indicator*

Output of the high pass filter, which is reference signal, is used for operating a Signal Level Indicator. The signal level indicator circuit consist comparators. But the reference signal is in AC waveform, this signal should be converted to DC to be used in comparator circuit. To convert this signal from AC to DC, a peak detector circuit is constructed [5]. The peak detector circuits are used to determine the peak value of an AC signal. If the signal is 2cos(wt), the output of peak detector will be 2V (DC). The circuit diagram for peak detector is in Figure 19.

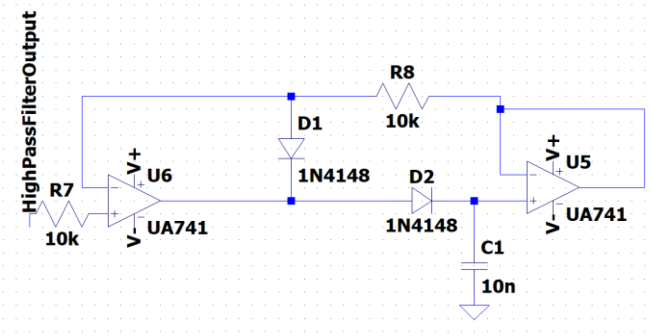

Fig. 19. Peak detector circuit diagram

Also, the output of peak detector for various sinusoid inputs is also in Figure 20.

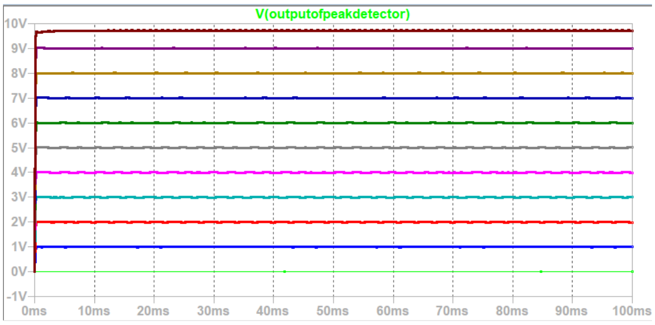

Fig. 20. Output of peak detector for different AC inputs

In RGB indicator circuit five comparators are used. The circuit diagram is in Figure 21.

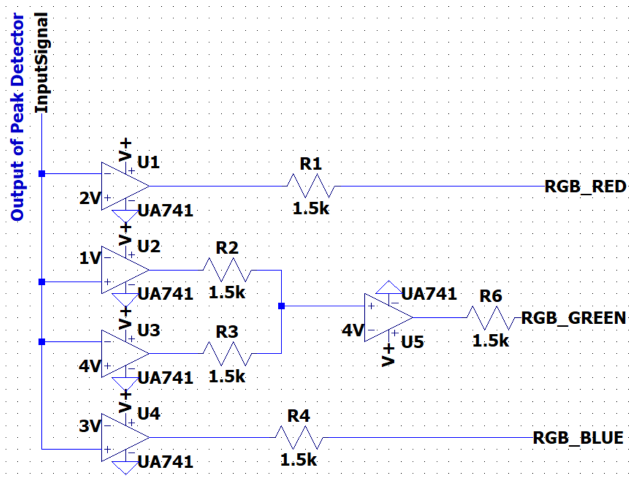

Fig. 21. RGB circuit diagram

If the signal is less than 2 Volts red will be open, if the signals is between 1 – 4 Volts green will be open and if the signal is bigger than 3 Volts the blue will be open. Color, voltage and signal quality relations are in Table 1.

TABLE I. RGB INDICATOR COLOR TABLE

Voltage (V)	Colors				Signal
	Red	*Green*	*Blue*	*Resulted Color*	
< 1	ON	OFF	OFF	Red	no signal
1 - 2	ON	ON	OFF	Yellow	weak signal
2 - 3	OFF	ON	OFF	Green	moderate signal
3 - 4	OFF	ON	ON	Cyan	good signal
> 4	OFF	OFF	ON	Blue	excellent signal

Simulation result for RGB indicator is in Figure 22. As seen in the figure, the theoretical approach is consistent with the simulation results.

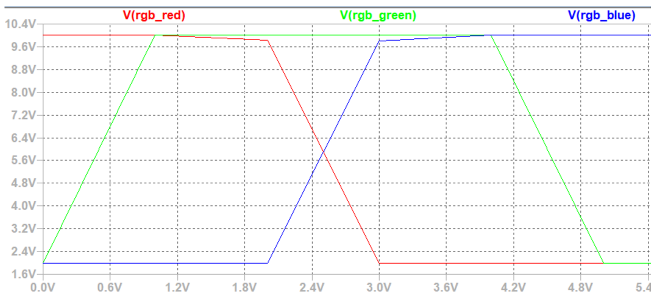

Fig. 22. Simulation results for RGB indicator circuit

F. *Power Amplifier and Speaker*

After filtering the microphone signal at the receiver side, it needs to be fed into the speaker circuit to be heard. To operate the speaker, at least 1 Watt output power is needed. To achieve the required 1 watt output power a Class AB power amplifier is used.

The Class AB amplifier is a combination of Class A and Class B amplifiers. Also, the Class AB amplifier is more efficient than Class A amplifier, moreover it has lower distortion than Class B amplifier. In other words, Class AB amplifiers takes advantages of both types [4]. Power amplifier circuit design is in Figure 23.

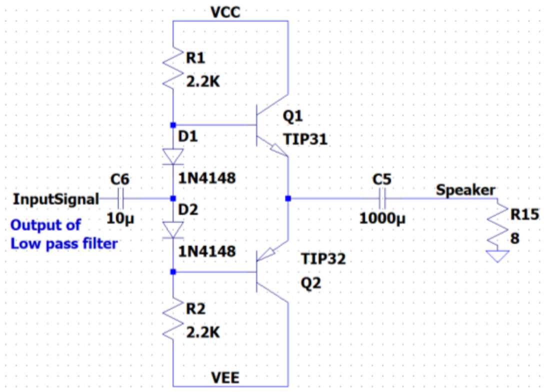

Fig. 23. Class AB power amplifier circuit diagram

The circuit consist of two diode one NPN and one PNP power transistors and resistors to bias them. Since the current flowing from the resistor would be high, power transistors are preferred. For that purpose, TIP31 and TIP32 power transistors used. To avoid DC input and output, capacitors are used. Diodes are used to adjust voltage drop across BJT's. Also, the circuit is symmetrical. When the input voltage is positive (0 to 180 degree) the NPN transistor works. When the input voltage is negative (180 to 360 degree) the PNP transistor works and at the output the signals are summed.

The output waveform of the speaker circuit is in Figure 24. In order to get 1watt power, 8 Vpp voltage is needed at output of power amplifier. For that purpose, input voltage is adjusted by using noninverting amplifiers (op-amp). As seen in Figure 24, the output voltage swing is around 9 Vpp. Output power can be calculated from the (4) (8 ohm resistance speaker is used in the circuit).

$$P = V_{RMS}^2 / R \qquad (2)$$

[[4.5 / sqrt(2)]^2] / 8 = 1.25 Watts

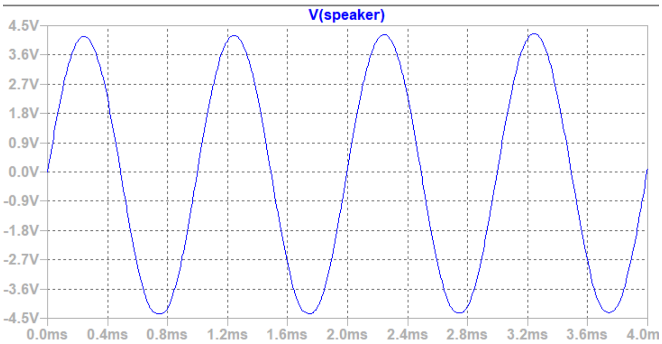

Fig. 24. Output waveform of the power amplifier circuit

G. *Extra*

In addition to the circuits explained earlier, there are two extra feature that this photophone should have. The first one is building an LED circuit, in which LED will be on if the audio signal gets clipped during the any stage of the receiver. This clipping happens when the signal at receiver side reaches the same amplitude as supply voltages. Circuit designed for this purpose is in Figure 25. At the lab, its measured that if the reference signals exceed 10Vpp, clipping occurs. Moreover, the output of peak detector is 5V while input signal is 10Vpp. After finding cutoff value, a clipping detector is made with a basic comparator.

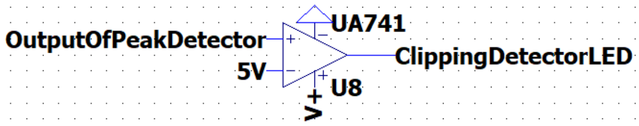

Fig. 25. Clipping detector circuit diagram

The second feature is turning the speaker off. When there is no signal, i.e., the RGB LED is red, the speaker must be turned off to not hear any noises. The circuit designed for that purpose is in Figure 26. The output of the relay goes to +VCC terminal of power amplifier, and the inverted version of output of the relay goes to -VCC terminal of power amplifier. In the power amplifier there are two op-amps (preamplifier) and 2 BJT's (power amplifier) without +VCC and -VCC they will not work; thus the speaker cannot operate.

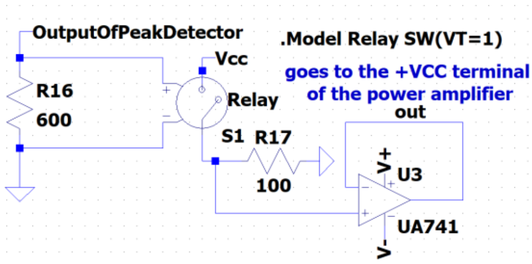

Fig. 26. Relay circuit diagram

V. Experimental Results and Their Comparison with Theoretical Work

Results of the real life experiments and the comparison with simulation results will be provided in this part.

At first the transmitter side is built, and the test results are obtained. The AGC circuit is tested by taking input from the signal generator at 1 kHz. These results are in Table 2. It is seen that the output waveform amplitude of AGC changes slightly with changing input. To prevent the saturation of the signal at AGC's output, some resistance and capacitance values are changed during experimental work. We observe slight differences with simulation and experimental results, which is caused by nonideality of the circuit components.

TABLE II. AGC Output Amplitude Table

Given Input	Output of AGC During Experimental Work (Vpp)	Output of AGC in Simulations (Vpp)
10 mVpp	2.24	3.4
20 mVpp	2.38	3.43
30 mVpp	2.49	3.5
40 mVpp	2.95	3.54
50 mVpp	3.17	3.6

Microphone driver circuit worked properly, but due to the outside noises, during FFT analysis peaks observed at different Hertz values. The input given to the microphone was 1 kHz and it has the largest amplitude among the other frequencies. This input was given to AGC and the output of the AGC connected to the low pass filter. At the amplitude of this input signal, decrease is observed. Moreover, connecting a 100kohm resistance at the input of the AGC feedback was found after experimental work. Otherwise, the capacitor could not discharge. But this was not a problem during simulation work.

Later the summing amplifier circuit is tested. At the output of the summing amplifier, decreases at the amplitudes of the signals are observed. During simulation work, these decreases were not observed since the components are seen as ideal and perfect. Output waveform of the summing amplifier can be seen in Figure 27.

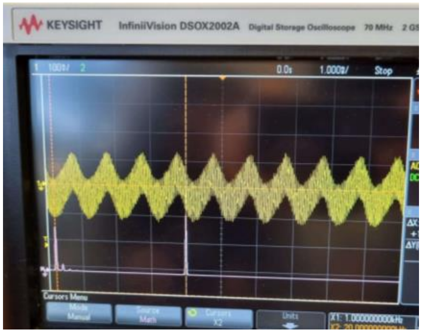

Fig. 27. Output waveform at summing amplifier

Then this summed signal is transmitted with IR LED. The main problem here was the alignment of the receiver and transmitter. Slightest misalignment resulted in “no signal” condition. At the theoretical work, one can act like the signal is transmitted perfectly. But at experimental work, received signal has smaller amplitude compared to transmitted one. This problem is solved with amplifier connected to the receiver. At some points, the gain of this amplifier was changed and the perfect value was found. Moreover, during simulations, constructing a basic amplifier with op-amp was enough. However, to provide the DC path to the op-amp, the amplifier circuit is changed, and constructed as the one in Figure 18. The output waveform at the receiver side can be seen in Figure 28.

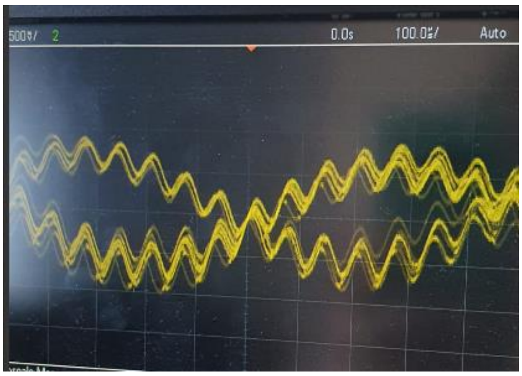

Fig. 28. Output waveform at receiver side

The received signal is connected to high pass and low pass filters with buffers. The 1 kHz waveform at the output of the low pass filter is in Figure 29. This waveform is not perfect sinusoid like it was in the simulation work. However, this was expected, due to non-perfect transmission and noises coming from the environment.

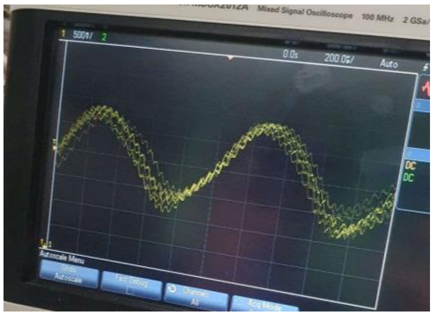

Fig. 29. Output waveform of low pass filter (1 kHz sine wave)

The 25 kHz (reference signal) waveform at the output of the high pass filter is in Figure 29.

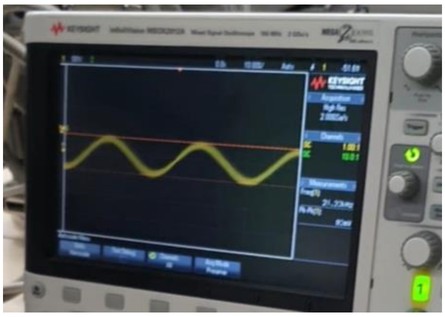

Fig. 30. Output waveform of high pass filter (25 kHz sine wave)

Then the output of this high pass filter is connected to the RGB LED indicator. Due to shorts and touching problems between resistor, this circuit was hard to control. After reconstructing it for several times, five colors are obtained. These colors can be seen in Figure 31. The results were similar to the theoretical work.

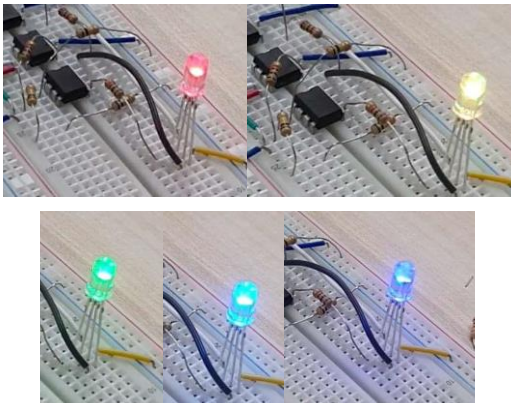

Fig. 31. Indicator colors of RGB LED (red, yellow, green, cyan, blue)

At last step, the power amplifier circuit is built. Output of 1.25 Watt is obtained at the speaker, but the main problem was distorted signal. This distortion was caused due to the transmission through air. When the input of the power amplifier was provided from the signal generator, this circuit worked perfectly. For overall circuit, power amplifier had a slight distortion. Moreover, the power transistors were heating too much, which resulted in increase in current consumption. Thus, heatsinks were connected to the BJTs. Also, while power amplifier works, a fan was cooling the circuit. As a result, the optimum working conditions are provided for the circuit. This circuit has no heating problem during simulation work, as expected. Having these precautions was a surprising. After the first test, the fan and heatsinks are bought and connected to the circuit.

For overall circuit, it is observed that the experimental results are sometimes similar to simulation results. The discrepancies are mostly caused due to noises, nonideality of the circuit elements and the imperfect transmission of the signal. Moreover, the heating problem was not expected but for each problem, a solution is provided and a photophone is obtained successfully.

VI. COMPONENTS LIST AND BUDGET

List of the components used, and the cost of each component and the overall project is in Table 3.

TABLE III. COMPONENT LIST AND COST TABLE

Components	Number of Used Components	Cost (TL)
UA741 Op-Amp	24	84
TIP31-C Power Transistor	1	4
TIP32-C Power Transistor	1	4
BC108 BJT Transistor	4	60
Capacitors and Resistors	various	20
3 Watt 8 Ohm Speaker	1	30
Electret Microphone	1	3
1N4148 Diode	4	1
Breadboard	6	120
Infrared Photodiode	1	4
Infrared LED	1	4
RGB LED	1	4
Heatsinks	2	8
Small Fan	1	17
Total Cost = 363 TL		

VII. CONCLUSION

In conclusion, theoretical design, simulation results and experimental results are provided. This project has several parts which are connected to each other. During simulation work, each part worked perfectly, but for experimental work and demo procedure, the results differ from the simulations. These discrepancies are caused due to noises, nonideality of the components and the problems which cannot be observed until the experimental tests (like heating of the power amplifier). Overall, the implementation of this circuit was successful, since the sounds coming from the microphone was heard from the output of the speaker. And this is the most crucial part of the photophone design.

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