Design of an Optical Wireless Communication System: Photophone*

*EE313 Term Project

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***Abstract* -Optical wireless communication (OCW) systems are systems that are capable of transmitting information with visible or non-visiblelight beams. Optical wireless communication devices are an easily applicable and cheap alternatives to RF systems in open sight areas or low distance communication needs. Although it has its own limitations, such as a strict need to have an open noiseless transmission medium, it enables users to create personal networks with low latencies and high data rates. There is also a growing interest towards optical wireless communication devices since they can also be utilized in solid state detectors and optical sources. In this paper, a basic demonstration of a basic optical wireless device, photophone, is applied and explained with simulations based on LTSpice software. The OCW system was put to several tests and it was observed that it is possible to transmit audio signals with precision with basic OCW systems which are driven by infrared LEDs. Results mostly coincided with simulation results and expectations. Application included some discrepancies, noise and clippings in the signal.**

***Index Terms* - Optical wireless communication, photophone, multiplexing, modulation, auto gain control, filtering, power amplification.**

I. Introduction

Optical wireless communication is a form of communication that uses visible, infrared, or ultraviolet light to transmit or receive data. In general, wireless communication uses radio-frequency (RF) band in the range of kHz-GHz. The most common examples of RF communication are AM, FM radio, cellular phone communication, and Wi-Fi. The usage of optical light instead of radio-frequency waves has several advantages and allows some application possibilities. Optical communication is fast and has a large bandwidth. Moreover, optical communication has the ability to operate under RF-sensitive areas. In this paper, the design of a special type of optical wireless communication named photophone, which includes speech transmission through the modulation of a light beam, will be investigated.

II. Related Work

The history of the photophone goes back to the 1880s. Alexander Graham Bell invented the first wireless speech communication system. He realized that light could be used for communication. What Alexander Graham Bell invented is the shape modulation of a mirror attached to a flexible material upon which the speaker's voice is directed. This invention drew the attention of the defense industry. USA and Germany started to develop wireless communication systems. Germany had a photophone that used infrared light for transmission in the 1930s. Until the 1950s, their attraction was kept high. In 1962, a TV signal was transmitted over 30 miles by using a GaAs diode in Lincoln Lab, MIT [1]. After the invention of the laser, optical wireless communication (OWC) was thought as the primary usage area for lasers and many experiments were done on different types of lasers. However, the results were disappointing. The laser could not cope with the atmospheric effects. Moreover, after the invention of fiber-optic technology, OWC was dominated by fiber-optic technology. Nowadays, the OWC is used in space technologies and RF-sensitive areas.

By looking at the history of OWC, it can be said that the dominant light sources for OWC are LEDs and lasers. The visible light technology of OWC is called visible light communication (VLC), and there are many led-based visible light communication applications [2]. LEDs are also used for infrared light communication systems [3]. Lasers are also common for OWC. For space applications, using lasers for communication has many advantages [4]. In this paper, the usage of IR LEDs for wireless communication will be investigated.

III. Design Methodology

The communication system consists of two basic parts: transmitter and receiver. The transmitter is responsible for getting input from the user and mixing it with a reference signal, then generating the optical transmission package to the light-emitting tool. The receiver obtains the package, indicates the transmission quality, and sounds the audio signal. The main design methodology is to divide the entire system into subsystems and bring them together. The subsystem graph can be seen in Figure 1.

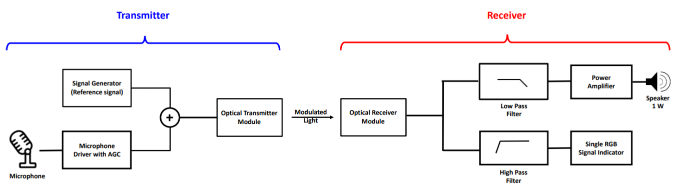

Fig. 1. Subsystem Diagram

Each subsystem will be explained detailed later. The advantage of dividing the system into subsystems is the ease of handling. By doing that, the opportunity of parallel working and easy debugging are obtained. After finishing the design of the subsystems, each subsystem is connected to the others one by one.

IV. Subsystems

In this section, each subsystem is explained detailed.

Microphone with Automatic Gain Control

To get the voice of the user, a microphone circuit is needed. For this purpose, an electret microphone with a pre-amplifier circuit is used. The microphone driver circuit can be seen in Figure 2. This circuit is a basic common emitter BJT amplifier topology with a feedback resistor in order to stabilize biasing further. As we have used a resistive electret microphone, we can regard it as a resistor in amplifier desing and try to amplify the voltage changes over that resistor.

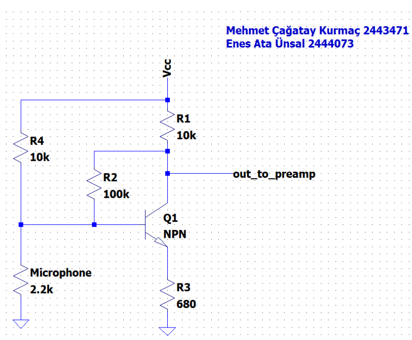

Fig. 2. Microphone Driver Circuit

The output of the driver circuit goes to the automatic gain controller. The automatic gain controller is a type of circuit that makes the output independent of the amplitude of the input signal. The controller makes the output signal amplitude stabilized. This allows to have a solid signal at the output stage, and the microphone works independently from the amplitude of the input range. The circuit diagram of automatic gain controller is given in Figure 3. This circuit has 3 parts in order to achieve automatic gain control. Main amplifier stage is Q2. This part operates as a common emitter amplifier. Its output is sampled by an emitter follower in Q3. Then, a peak rectifier is formed at the emitter of Q3. This rectified peak generates a voltage drop at C4. Whenever the input signal is increased, we have a greater output voltage at Q2. Then, this increase leads to in increase in voltage over C4. And this voltage is fed back to the base of Q1. As we have a forward biased BE junction, and a reverse biased CE junction with the increase in V_{base}, Q1 operates in saturation mode. Thus, it acts as a voltage controlled resistor in parallel with Q2's base biasing resistors and r_π. As r_π and resistance of Q1 is dominant resistances, those determine the ratio of input resistor being fed to Q2. As C4 increases, R_{Q1} increases and input voltage share of Q2 decreases. Thus, we have obtained automatic gain control.

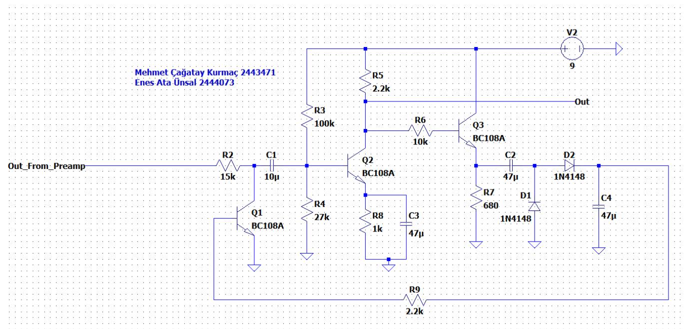

Fig. 3. Automatic Gain Controller

With the help of these two circuits, the first subsystem is completed.

Reference Signal

For this project, it was allowed to use the external signal generator to obtain a reference signal. The purpose of using a reference signal is called multiplexing. Multiplexing is a method to have a signal that indicates more than one piece of information by using time and frequency domains. The microphone signal is mixed with a high-frequency reference signal in this project. This reference signal will be filtered at the receiver stage. The filtered signal will be used to determine the quality of the received signal. The reason why only the user's input cannot be used as the reference signal is that the user's voice cannot be precisely determined. The user may rotate the microphone, get close, or get away from the microphone. This is why we cannot rely on the user. After the theoretical background of multiplexing was investigated deeply, the frequency and amplitude values were determined. The amplitude of the reference signal was limited since it might cause saturation on the LED driver circuit. Theoretical calculation of the amplitude was done, and the reference signal was determined as 1 V_{pp} and 25 kHz as we wanted to avoid saturation and be able to easily filter out the reference signal from our output.

Summing Amplifier

To mix the microphone signal and the reference signal, a basic op-amp summing amplifier is used. The circuit diagram of the summing amplifier can be seen in Figure 4. In this summing amplifier, we have also summed a DC signal in order to effortlessly bias the LED driver's BJT.

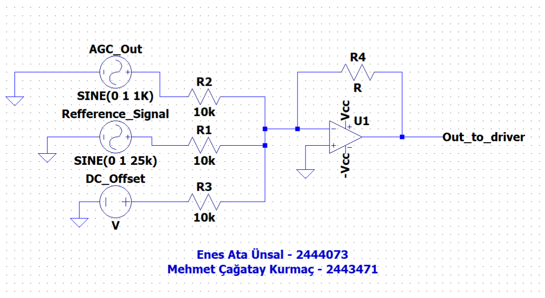

Fig. 4. Summing Amplifier

LED Driver Circuit

As mentioned before, infrared light was used as a transmitter for obtaining a higher transmission quality. Visible light was not chosen because it can be easily disturbed by other light sources in the laboratory. In IR LEDs, we don't have that problem. It was realized that infrared LEDs are commonly used in communication after literature search. Therefore, infrared LED was chosen for the project. After the decision of the visual transmitter, a circuit to drive that transmitter was needed. The circuit in Figure 5 is designed as an LED driver. This driver is a common emitter BJT amplifier. The reason behind the choice of the amplifier is that LED's illumination is linearly related with the current passing through the LED. Not the voltage drop over the resistor. Thus, we needed a transconductance amplifier to convert obtained output voltage to current.

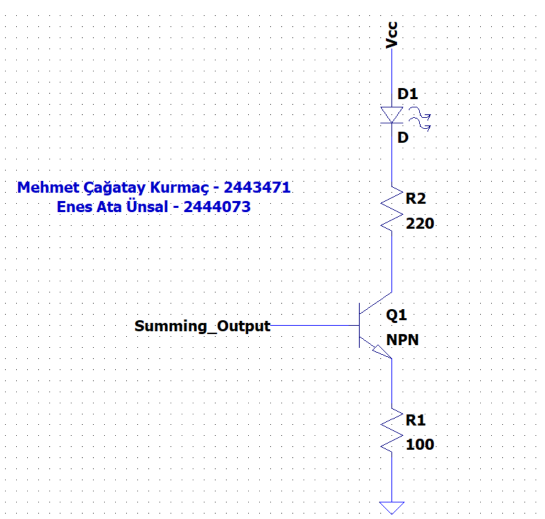

Fig. 5. IR LED Driver Circuit

The IR LED is driven with a DC current offset because it cannot transmit the negative part of the signal otherwise. Biasing current is adjusted as the oscillations over the LED's light are distinct enough beside the DC collector current. By constructing the LED driver circuit, the transmitter part is completed.

Receiver

To perceive the transmission light, a receiver circuit has to be made. As a receiver unit, two options were considered: photodiode and phototransistor. Firstly, photodiode is used for current source. By a transimpedance amplifier, this current would be amplified to a moderate level of voltage. However, the transimpedance amplifier could not work properly. The change in input signal could not be observed well at the output of transimpedance amplifier. Therefore, the phototransistor was considered as a safe choice and the receiver circuit was designed with phototransistor.

The two specifications of phototransistor were considered: to be able to operate in infrared light and to be able to work until 25 kHz. The model of phototransistor was chosen according to these specifications. A common emitter amplifer was designed as the receiver circuit. The receiver circuit can be seen in Figure 6.

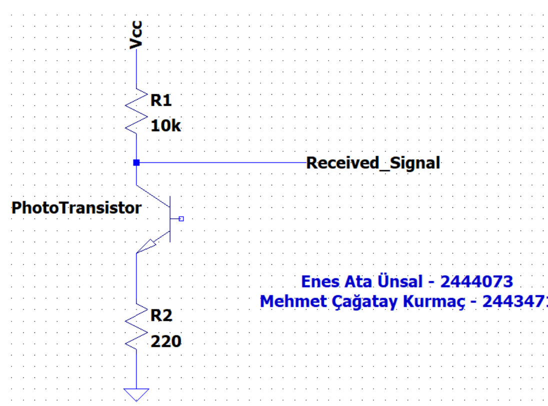

Fig. 6. Receiver Circuit

At the output of the receiver circuit, it was observed that the signal has a considerably low amplitude. Therefore, another common emitter amplifier is used to amplify the output signal of the receiver circuit, as the indicator circuit requires higher voltages to operate properly.

Highpass Amplifier

To filter the received reference signal, a highpass filter was needed. For this purpose, the Sallen-Key highpass filter [5] is used. The cut-off frequency is tuned to 20 kHz.

The Sallen-Key filter with arranged values can be seen in Figure 7.

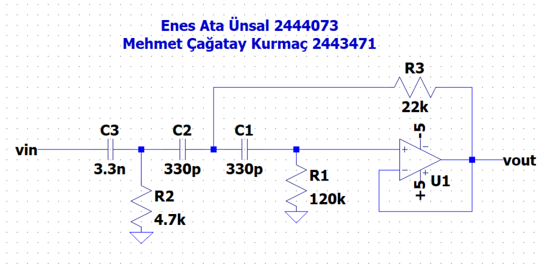

Fig. 7. Sallen-Key Filter

Signal Indicator

The filtered high-frequency signal continues to an indicator circuit. This circuit evaluates the input signal and gives a visual output of quality with an RGB led.

Before continuing the indicator, a peak detector obtains the peak of the input signal and gives it to the indicator circuit. The peak detector circuit can be seen in Figure 8.

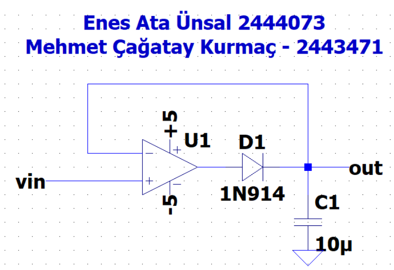

Fig. 8. Peak Detector Circuit

The working mechanism of the signal indicator relies on the fact that the different legs of RGB LED can be treated as individual LEDs. The boundaries of different levels of input signal is given in Table I.

TABLE I
SIGNAL QUALITY TABLE

Signal Range	Quality	Color
$V_{in} > 4.5$V	Excellent	Green
4.5V $> V_{in} > 3.5$V	Good	Green + Blue
3.5V $> V_{in} > 2.5$V	Moderate	Blue
2.5V $> V_{in} > 1.5$V	Weak	Blue + Red
1.5V $> V_{in} > 0.5$V	Poor	Red
0.5V $> V_{in}$	No Signal	Relay Output

A relay is used to cut the electrical connection of the speaker. When the received signal is low, the relay will cut the power delivered to the speaker in order to prevent disturbing sound.

By looking at the level table, the working intervals can be determined. The working interval for each color of RGB LED is given in Table II.

TABLE II
RGB COLOR WORKING INTERVAL TABLE

Color	On State Interval
Green	$V_{in} > 3.5$V
Blue	4.5V $> V_{in} > 1.5$V
Red	2.5V $> V_{in} > 0.5$V

After determining the working intervals, a comparator circuit can be designed. The circuit model of the LED is designed as three distinct LEDs which have the same ground. The signal indicator circuit can be seen in Figure 9.

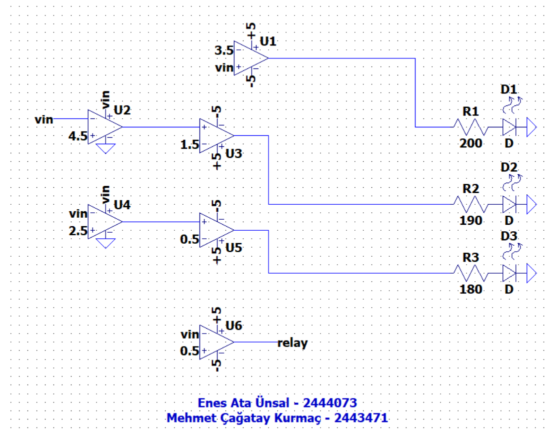

Fig. 9. Signal Indicator Circuit

In the signal indicator circuit, the first stage opamp of two-stage opamps is fed with the input signal. This allows using the signal at the input of the second opamp. Since the opamp has a large input resistance, this operation will not cause a problem.

Lowpass Filter

To avoid the speaker from high-frequency signals and to get a clean sound, a lowpass amplifier is designed before the speaker circuit. The cutoff frequency is determined as 3.5 kHz.

The lowpass filter can be seen in Figure 10.

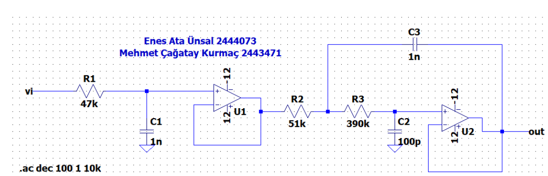

Fig. 10. Lowpass Filter

Speaker Driver and Output

In order to drive the speaker at the output, obtained output signal from lowpass filter is fed through a class B power amplifier, presented in Figure 11. This circuit is also called a "push-pull" circuit, since during its operation, neither of the transistors remain in ON mode. During opposite signed half-cycles, they operate consecutively. One major downside of this amplifier is as the form of a voice signal is not a pure sinusoid, we cannot have a smooth transition between push and pull stages. Thus, we hear distortions. Main advantage of this circuit is that as both of the transistors operate in common collector mode, we have a very low output voltage. Which allows our amplifier to pass the signal to the low-impedance speaker.

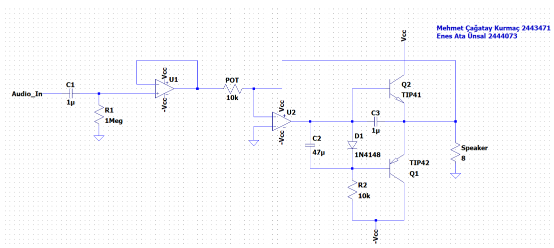

Fig. 11. Class B Amplifier Circuit

V. Simulation Results

To simulate the circuits, LTSpice software was used. However, it was hard to simulate some of the circuits in the system such as receiver module. Thus, some of the experimental results were used to obtain accurate predictions about rest of the modules.

First simulated module is the microphone preamplifier module. In simulation, Output of the preamplifier if a $10mV_{pp}$ signal was received from the microphone is obtained. Results are shown in Figure 12.

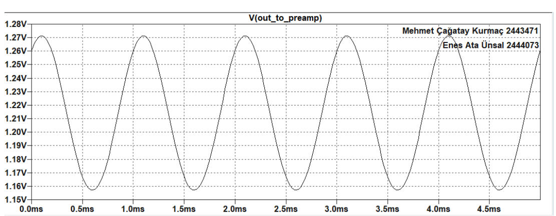

Fig. 12. Output Of The Preamplifier Circuit in Simulation

Secondly, AGC module was simulated for different input values. Results are shown in Figure 13. As expected, For input values from 50 mV to 250 mV with 50mV increments, circuit nearly has the same gain.

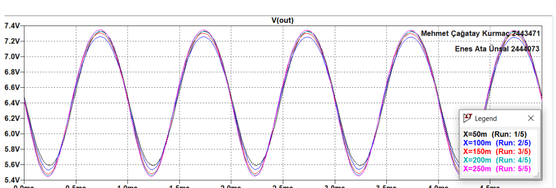

Fig. 13. Output Of The Auto Gain Controller Circuit in Simulation

Next, IR LED driver circuit is simulated with the approximated output of the summing amplifier circuit. The output of the summing amplifier is not included in simulation as it is not a significant step. The results are shown in Figure 14. As it can seen in the current vs. time plot, LED has a DC offset gain and has an AC part. Which allows us to transmit the signal completely without cutoffs in negative cycles.

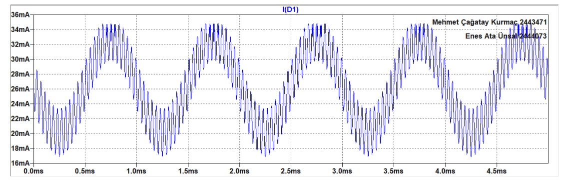

Fig. 14. Output Of The Auto Gain Controller Circuit in Simulation

As it wasn't possible to find a proper way to simulate a phototransistor in the receiver unit, its simulation results couldn't be obtained. The rest of the modules are simulated considering the experimental results, which are provided in the next section.

After receiving the signal, there are two branches. One of them leads to the signal indicator, and the other branch leads to speaker driver. Before the speaker driver, there is a lowpass filter stage to filter out the high-frequency reference signal in order to get rid of potential noises.

The simulation result of the highpass filter is given in Figure 15.

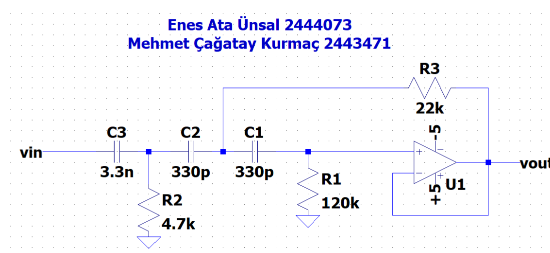

Fig. 15. Simulation Result of Highpass Filter

The signal indicator was designed in simulation. Tests were done with different input levels. Five colors were obtained. The five simulation scenarios are given in Figure 16, 17, 18, 19, 20 for Vin = 5,4,3,2,1 V respectively.

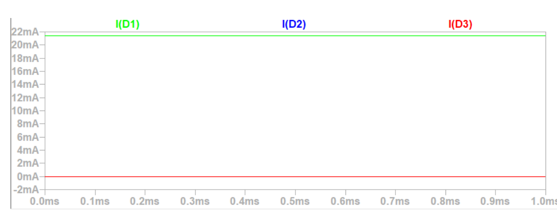

Fig. 16. Output of the RGB LED for 5V input

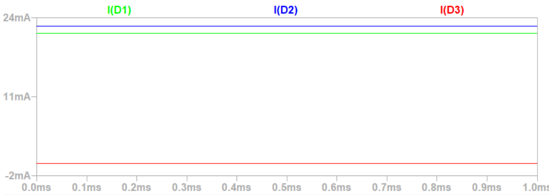

Fig. 17. Output of the RGB LED for 4V input

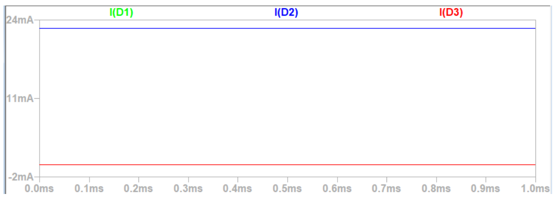

Fig. 18. Output of the RGB LED for 3V input

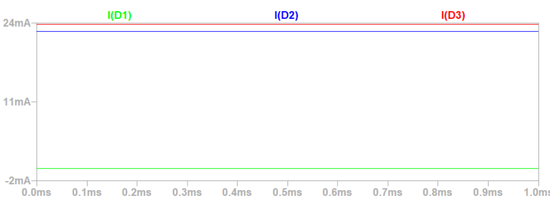

Fig. 19. Output of the RGB LED for 2V input

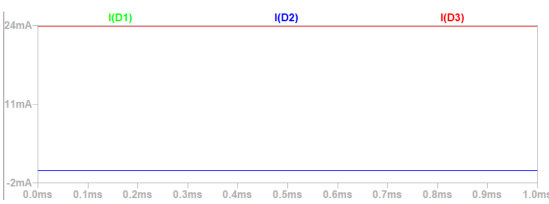

Fig. 20. Output of the RGB LED for 1V input

The other receiver branch includes the lowpass filter and the speaker unit. The simulation result of the lowpass filter is given in Figure 21.

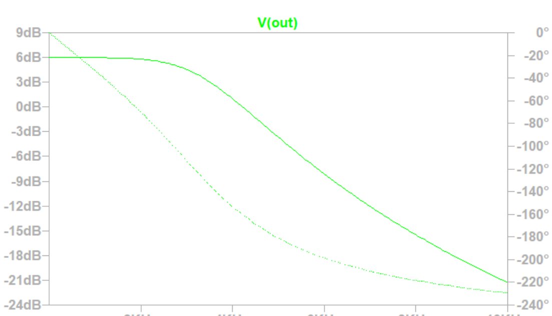

Fig. 21. Simulation Result of Lowpass Filter

The speaker driver is connected to the output of the lowpass filter stage. At this point, circuit is able to nearly give a pure sinusoid signal. This output is fed to the driver, which is a class B power amplifier. Output current to the speaker is given in Figure 22. The output is given in the form of speaker current to determine the power output. Minimum AC current required for the 1W output from a 8Ω speaker is 0.5 A. As we can see from the plot, the circuit can theoretically supply this current.

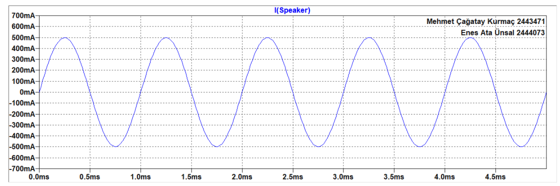

Fig. 22. Output of The Power Amplifier

VI. Experimental Results

In the experimental results, we only recorded the milestones we have achieved throughout the experiment. These milestones were an operating AGC, operating transmitter and filters, an operating signal indicator and being able to receive sound from the speaker. General methodology was applied in order to consecutively achieve these milestones. The output of the AGC obtained in the laboratory is presented in Figure 23. The main discrepancy between simulation and actual results are the output DC offsets. This might be caused by many reasons including the discrepancies between actual values of the components or transistor characteristics. Overall, the circuit satisfied the operating requirements.

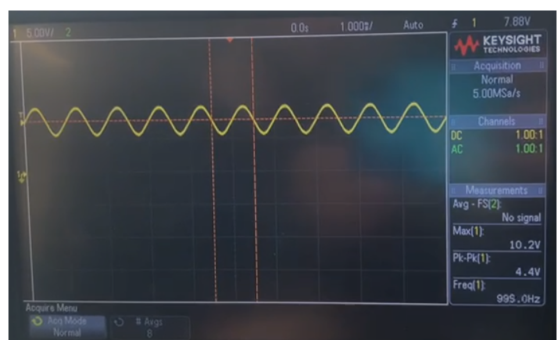

Fig. 23. Output of The Auto Gain Control Circuit In Laboratory

Lowpass amplifier's output is given in Figure 24. Importance of this output is that this circuit directly gives input to the speaker driver. This resulting signal indicates that the circuit have successfully transmitted a 1 kHz sinus signal to the receiver with a reference signal and then successfully filtered out the reference signal from the input. And the signal is ready to be passed from speaker.

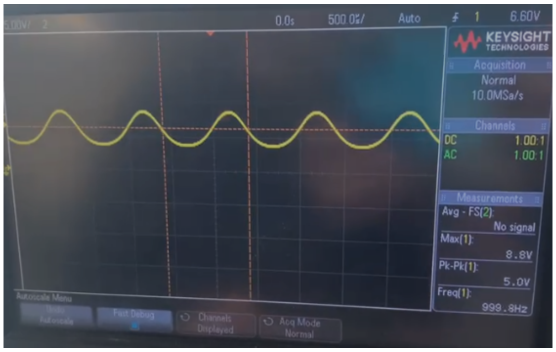

Fig. 24. Output of Lowpass Filter Circuit In Laboratory

Highpass amplifier's output is given in Figure 25. This output indicates that we can isolate the reference signal and process it to indicate the received signal's quality. Indicator circuit's operation can be observed by clicking here.

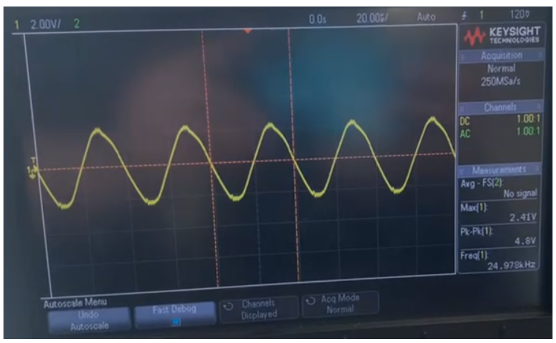

Fig. 25. Output of Highpass Filter Circuit In Laboratory

As the last stage, the complete system were put to test if it could transmit, receive and play audio signals. Although some unexpected distortions and clippings occurred, system still operated and was able to transmit the audio. Operation of the system can be observed by clicking here.

VII. Conclusion

In conclusion, A simple optical wireless communication system is constructed and applied in this paper. The system was intended to operate as photophone and required to include automatic gain control from the input. It was also required that receiver unit was able to track the signal's strength with the help of a reference signal included in the transmitted signal. The design started from simulations and then proceeded to modular implementation and ended with integrated system tests. Although there were discrepancies between design phase and the outcome of the designed system, the results were indicated that it was possible to create a reliable transmission system with infrared light beams. The paper provides a simple and didactic procedure for further understanding on optical wireless communication systems.

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