Ece Fundamentals II Final Project Report

Charles Ferraro
Electrical & Computer Engineering Undergrad
University of Virginia
Charlottesville, Virginia
cbf6yd@virginia.edu

Ethan Staten
Electrical & Computer Engineering Undergrad
University of Virginia
Charlottesville, Virginia
eas5ke@virginia.edu

Ronald Crump
Electrical & Computer Engineering Undergrad
University of Virginia
Charlottesville, Virginia
rc4dc@Virginia.edu

Christopher Hassert
Electrical & Computer Engineering Undergrad
University of Virginia
Charlottesville, Virginia
ch8jd@virginia.edu

***Abstract*—This paper is a report of our implementation of an audio frequency visualizer. The circuit includes the implementation of key concepts learned throughout the semester. This includes: Summing operational amplifiers, sallen key filters, high and low frequency peak detectors, and MOSFETs. This report flows in such a way where the analytical work is provided first, simulation and verification is provided second, and implementation provided last.**

Keywords—Operational Amplifiers (Op-Amp), Sallen Key Filters, Peak Detector, Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Light Emitting Diode (LED), Prototype Circuit Board (PCB).

I. Introduction

This design project was presented with a couple of design constraints that our design had to adhere to. These design constraints were broad and non-numerical as to encourage a more open end design process. These constraints are:

1. The input signal must be from an AUX cable/port.
2. Both circuit LEDs must respond to the input's high or low frequencies.
3. The circuit must contain a summing op-amp, high and low sallen key filters, peak detectors, and MOSFETs.

A rough layout of how the circuit schematic should flow was provided, and the created circuit schematic itself was in a program called Multisim (National Instruments Multisim Version 14.1). Thereafter, analytical work was done to find the values of the circuit components such that the design requirements are fulfilled. Following the analytical work we numerically simulated and verified each circuit design gradually throughout the entire project time. After the circuit components were successfully tested on a breadboard we thereafter carefully soldered the solved components onto a PCB board that we created prior to the beginning of the analytical calculations. It should be noted that our assembly process documented in this paper only shows the final values as the testing and experimental part of this project is too long to document. We changed values many times to create what we felt was the best we could do.

II. Song Choice

For our project we had to pick a song that we'll design our circuit around. This song that we decided the mii channel theme. This was picked due to it have a good assortment of distinct high and low frequencies. Many other mediums worked with our circuit including synthwave, but this provided the best visualization.

III. Individual Efforts

As required for the project report our individual efforts are listed in detail right after the name of each us. In order to increase efficiency we strictly divided up the work for each individual as listed.

- Charles Ferraro: Analytical calculations. PCB design. Experimentation & Testing.
- Ethan Staten: Circuit Assembly. Experimentation & Testing.
- Ronald Crump: Verified in multisim and assisted with PCB design. Experimentation & Testing.
- Christopher Hassert: Analytical Calculations. Numerical Verification.

IV. PCB Layout

Prior to the analytical, numerical, and experimental work of the project we created a PCB board layout in Multisim based on a generic circuit schematic of the project without any solved values. This generic schematic and the respected PCB we created are shown in Figure 1 and Figure 2.

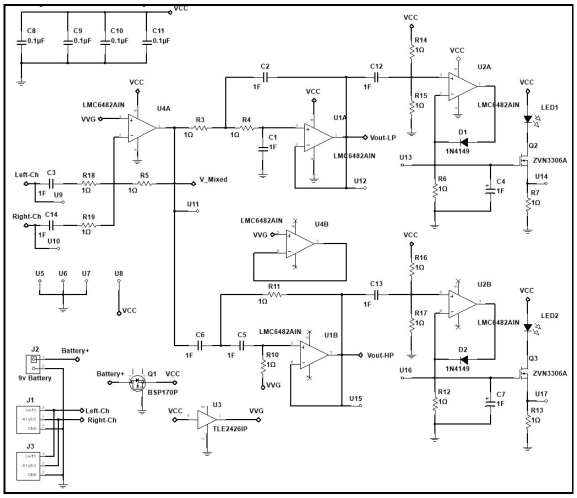

Figure 1: Generic Schematic Without Values

The PCB design was created carefully and with functionality in mind. Parts were placed together in such a way that they correspond to the schematics component placement of values. Power lines were centered around the three Op-Amps in the center of the board and the red and green LEDs were grouped together.

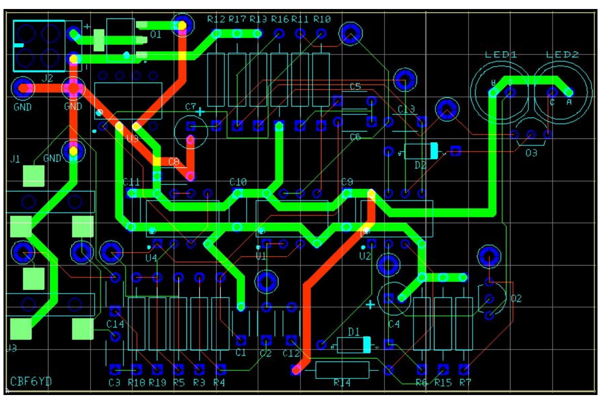

Figure 2: PCB Design

In the PCB design there were some connections that were in-efficiently routed throughout the board in the sense that they snake around components or other connections. If we had more time to design this PCB we would work on rerouting some inefficient connections and improve component placement. However, it should be noted that the connections had no perceivable impact on functionality of the circuit board and the success of the project.

V. Analytical Calculations: MOSFET

After the PCB design was fabricated and shipped we began on analytical calculations. Since the purpose of this project is to visualize the inputted audio we decided to begin the design process by beginning by performing the calculations for the MOSFET and the LED. Afterall, the whole purpose of the project is to turn on an LED based on the amplitude of the attenuated audio input. Therefore, if we can determine the voltage threshold for turning on the LED and its optimal brightness we can design the summing op-amp gain and the attenuation by the sallen key filters to meet the calculated thresholds.

However, before we began to calculate the threshold we decided to find Rs shown in Figure 3 such that when the MOSFET is in saturation the value of Rs would produce the most optimal brightness.

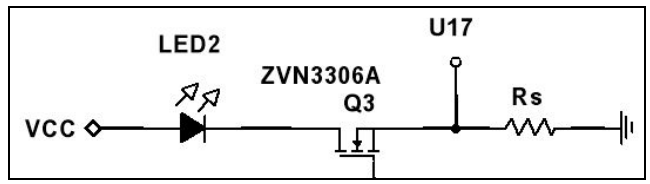

Figure 3: MOSFET with LED

Since brightness is subjective there were no analytical calculations for this part. Instead this small circuit was created on a breadboard. We put the voltage at the gate at 4.5 Volts since that was the voltage limit for the amplitude of the input signal. Any signal above 4.5 Volts would be clipped by the op-amp used in the project. The resistor value for Rs was changed out until the LED was sufficiently bright. After this process we determined that 47 Ohms was the best value for the resistor.

Continuing on we thereafter experimentally determined the V_{TN} (voltage threshold) for both MOSFETs so we could begin our analytical calculations. In order to determine V_{TN} we created the following circuit on a breadboard, shown in Figure 4.

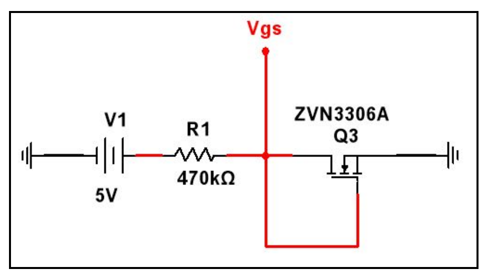

Figure 4: MOSFET Voltage Threshold Circuit

Using this circuit in Figure 4 we can ascertain the V_{TN} of the MOSFET through measuring Vgs. This can be done because of the following equation shown in Equation 1:

(1) $$\frac{K_N}{2}(V_{gs} - V_{TN})^2 = I_{ds}$$

Since our drain resistor is very high this means we can approximate the current (I_{ds}) to be zero. This turns the equation into:

$$\frac{K_N}{2}(V_{gs} - V_{TN})^2 = I_{ds}$$
$$\downarrow$$
$$\frac{K_N}{2}(V_{gs} - V_{TN})^2 \approx 0$$

This means that V_{gs} has to equal V_{TN}. Therefore upon measuring V_{gs} we can ascertain V_{TN}. We picked two MOSFETs randomly from our lab kit and measured the V_{TN} of both of them using this method. We determined both MOSFETs to have a V_{TN} of around 1.45 Volts.

Thereafter we began our analytical calculations for what amplitude of the non-attenuated frequencies should be such that the LED consistently lights up. To do this we used the conditions for the MOSFET regions. These equations are shown in Equation 2, Equation 3, and Equation 4.

For MOSFET Cutoff:

(2) $$V_{GS} < V_{TN}$$

For MOSFET Triode Region:

(3) $$V_{GS} \geq V_{TN},\ V_{DS} \leq V_{GS} - V_{TN}$$

For MOSFET Saturation Region:

(4) $$V_{GS} \geq V_{TN},\ V_{DS} \geq V_{GS} - V_{TN}$$

We discovered that the MOSFET was never going to be in the saturation region given the following calculations:

$$V_{DS} \geq V_{GS} - V_{TN}$$
$$\downarrow$$
$$V_D - V_S \geq V_G - V_S - V_{TN}$$
$$\downarrow$$
$$V_D \geq V_G - V_{TN}$$
$$\downarrow$$
$$V_{CC} - V_{diode} \geq V_G - V_{TN}$$
$$\downarrow$$
$$V_{CC} - V_{diode} \geq V_G - V_{TN}$$
$$\downarrow$$
$$V_{CC} - V_{diode} + V_{TN} \geq V_G$$

Given that V_{CC} is 9 Volts and V_{TN} is approximately 1.45 Volts it is evident that since V_G has a limit of 4.5 Volts that the MOSFET can never be in saturation region. Therefore, it became evident that the two regions we'll be transitioning from to make the flicker of the LED happen is cutoff and triode. This means that in order to achieve the flickering the input signal must go above or below V_{TN} depending on the frequency. We decided that a input signal maximum of 2.5 Volts and input signal minimum of 0 Volt was the best choice. This translated to a desired unfiltered 2 Volt peak to peak input signal with a 1 Volt DC offset.

Our thought process was that the higher the amplitude of the unfiltered signal meant that the attenuation by the sallen key filters could potentially be inefficient for signals around the cutoff frequency. By having the amplitude close to V_{TN} there was a reduced risk of attenuated frequencies from being unable to fall below V_{TN}.

After testing the MOSFET on a breadboard and changing V_G from 0 Volts to 1 Volt to 2 Volts we observed that it properly turned the LED off and on as we expected. This validated our thoughts and made us continue the design process in which we wanted the input audio signal amplitude to be around 1 to 2 Volts in amplitude.

VI. Analytical Calculations: Peak Detector

With this in mind we thereafter began designing the peak detector. In order to ascertain the values for the peak detector we attempted to calculate a RC time constant with the equation shown in Equation 5.

(5) $$f_{min} = \frac{1}{\tau} = RC$$

This equation was used in a previous lab and shown useful to that particular lab. It was an equation that suggested that the minimum frequency you want your peak detector to work at is what will determine the RC time constant of the peak detector circuit; which is shown in Figure 5.

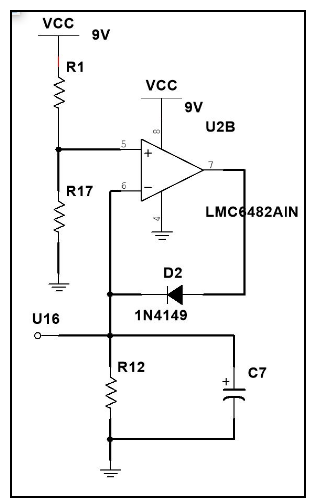

Figure 5: Peak Detector

We realized that this equation wasn't sufficient, and we couldn't find a satisfactory equation that would give us our desired values. Therefore we ran a transient simulation of the peak detector with a sample piece of music using the LVM source voltage in Multisim. We then adjusted the values until the peak detector results were desirable.

Thereafter we calculated the RC time constant of those desired values. Since we have only a limited amount of components in our physical lab kits we had to determine which combination of capacitors and resistors could produce a similar time constant. In order to do this we used a MATLAB script that we created to iteratively determine that combination. A screencap of a portion of this script is shown in Figure 6.

```
R1 = 0;
C1 = 0;
tau = 1/(5000*2.2e-5);
error = 1;

for indexR1 = 1:length(resistor_values_in_lab_kit)

    for indexC1 = 1:length(capacitor_values_in_lab_kit_electro)

            R1 = resistor_values_in_lab_kit(indexR1);
            C1 = capacitor_values_in_lab_kit_electro(indexC1);

            if ((tau + error) >= 1/(R1*C1) && ((tau - error) <= 1/(R1*C1)))

              disp("-----------------");
              disp("Tau: " + (1/(R1*C1)));
              disp("R1: " + R1);
              disp("C1: " + C1);

            end

    end

end
```

Figure 6: MATLAB Peak Detector Script

From this we ascertain that R_{12} must equal 470kΩ and C_7 must equal 1µF.

Later in the design process we determined the values for the voltage divider of the peak detector. These values were initially designed such that the DC offset of the input signal would be 1 Volt. However, upon a lot of testing we designed the voltage divider such that the DC offset is approximately 1.3 Volts.

VII. Assembly Process: MOSFET and Peak Detector

We implemented the peak detectors and the MOSFET/LED after the Sallen key filters. Our values for the peak detector and MOSFET were determined experimentally to see what would be best. We built our first design on a breadboard, and after testing it and receiving the correct output, we soldered the components on our PCB.

VIII. Analytical Calculations: Sallen Key Filters

We decided on a cutoff frequency of 230 Hz for the low pass sallen key filter and a cutoff frequency of 700 Hz for the high pass sallen key filter. Our logic was that since we wanted our songs to be electronic we wanted the heavy base be shown along with the high frequency electronic notes. Using a MATLAB script, we determined which resistor and capacitor values for each Sallen key filter within a certain error range of our desired Q and cutoff frequency values. This MATLAB script is shown in Figure 7. The equations we used within the MATLAB script along with the error tolerances are shown in Equation 6, Equation 7, and Equation 8.

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \tag{6}$$

$$Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 C_2 + R_2 C_2} \tag{7}$$

$$Q \pm 0.008, \omega_o \pm 150 \tag{8}$$

It should be noted that the error for ω_o isn't as huge as it seems. ω_o was multiplied by 2 and π so ±150 was considered reasonable.

```
for indexC1 = 1:length(capacitor_values_in_lab_kit)

    for indexC2 = 1:length(capacitor_values_in_lab_kit)

        R1 = resistor_values_in_lab_kit(indexR1);
        R2 = resistor_values_in_lab_kit(indexR2);
        C1 = capacitor_values_in_lab_kit(indexC1);
        C2 = capacitor_values_in_lab_kit(indexC2);

        if (((Q + 0.01) >= (sqrt(R1*R2*C1*C2) / (R1*(C1+C2)))) && ...
            ((Q - 0.01) <= (sqrt(R1*R2*C1*C2) / (R1*(C1+C2)))) && ...
            (wo + 40 >= (1/sqrt(R1*R2*C1*C2))) && ...
            (wo - 40 <= (1/sqrt(R1*R2*C1*C2))))
           disp("Q: " + (sqrt(R1*R2*C1*C2))/(R1*(C1+C2)));
           disp("wo: " + 1/sqrt(R1*R2*C1*C2));
           disp("R1: " + R1);
           disp("R2: " + R2);
           disp("C1: " + C1);
           disp("C2: " + C2);
           disp("--------------------------");
```

Figure 7: MATLAB Sallen Key Filter Script

Ultimately the best values that the script produced that best met our Q and ω_o values are shown below for the respective filter. Though these values shown are the final values we used we went through a few other values that were unsatisfactory. This is explained in the assembly process section.

Sallen Key High Pass:

$$R_{10} = 820k\Omega,\ R_{11} = 390k\Omega,\ C_5 = 2.2e^{-10}F,\ C_6 = 1e^{-9}F$$

Sallen Key Low Pass:

$$R_3 = 180k\Omega,\ R_4 = 390k\Omega,\ C_1 = 1e^{-9}F,\ C_2 = 4.7e^{-9}F$$

IX. Assembly Process: Sallen Key Filters

When assembling the circuit out group determined that the Sallen key filters would be the first thing constructed and tested. The first prototype was implemented on a breadboard to confirm the analytically determined values. After encountering numerous problems with LabView, the values used for the capacitors in both Sallen key filter circuits were then substituted such that all the capacitors were ceramic; thus, also altering the other component values. However, after redesigning the circuit with ceramic capacitors LabView supplied the following bode plots for each of our filters.

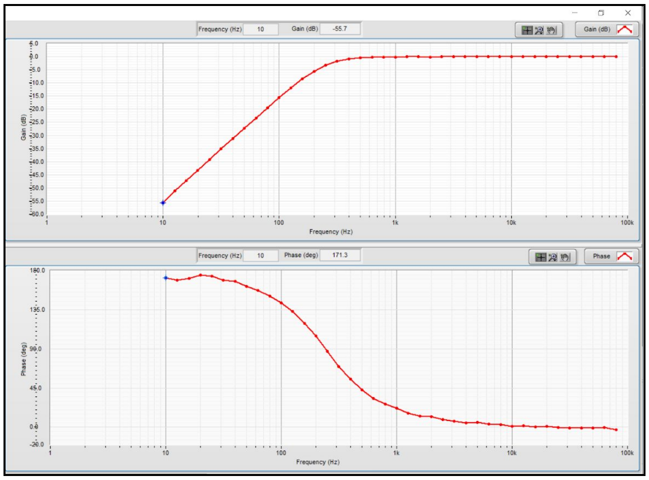

Figure 8: Measured Frequency Response High Pass Sallen Key Filter

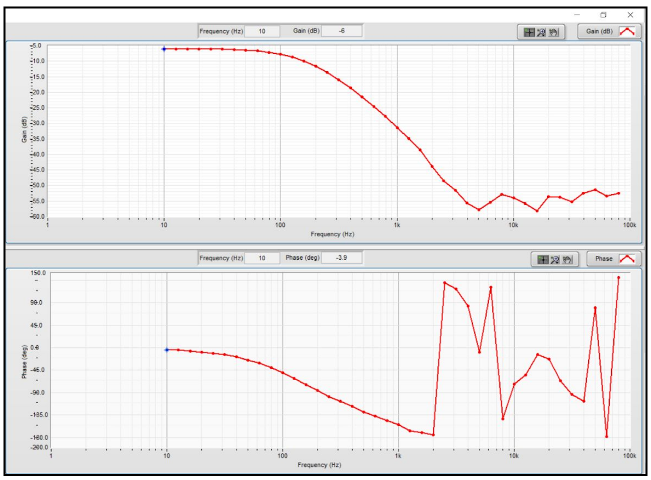

Figure 9: Measured Frequency Response Low Pass Sallen Key Filter

To confirm these values are correct and this system was built correctly the gain of both circuits were estimated and approximated to be relatively the same as the analytically derived values. Once all component values were established, the pieces were soldered into the board as the next section of the circuit was verified.

X. Analytical Calculations: Summing Op-Amp

Our group determined that the summing op-amp portion of the audio-visualizer circuit would be constructed last. After testing the the circuit with a sinusoidal signal of ~1-2 we began to test it with music. We surprisingly found that the input audio was in this range as well. Therefore, we decided that no gain was needed for the summing op-amp. However, we noticed that the audio file for both the left and the right channels was the same signal. Therefore, if the gain of the summing op-amp was one then it would still add the signal onto itself making it twice as bigger. We decided then the gain of the op-amp would be in actuality ½ such that the input signal is not twice as big.

The analytical equations we used are shown in Equation 9 onwards.

(9)
$$v_o = -\left(\left(\frac{R_f}{R_1}\right)V_1 + \left(\frac{R_f}{R_2}\right)V_2\right)$$
$$\downarrow$$
$$v_o = -\left(\left(\frac{560k\Omega}{1M\Omega}\right)V_1 + \left(\frac{560k\Omega}{1M\Omega}\right)V_2\right), V_1 = V_2$$
$$\downarrow$$
$$\frac{v_o}{V_1} = -1.12$$

XI. Assembly Process: Summing Op-Amp

The prototype was first constructed on a breadboard. Multiple values were tested in the breadboard to determine the voltage and frequency responses of the summing op-amp. After evaluation of a few sets of resistor values, we decided to utilize 1MΩ resistors for R18 and R19 in the circuit schematic. We also decided to use a 560kΩ resistor for the R10 component. After experimentally verifying the accuracy of the chosen components, we tested the frequency response of the summing op-amp in two stages. We first tested the summing op-amp by itself to see if the expected output occurred. Once we confirmed that the output was correct, we connected the summing op-amp to the rest of the circuit and inputted several songs through the whole prototype. At this point, the individual components testing and construction phases are finished.

XII. Completed Circuit Figures & Measurements

The completed and final circuit with all the values are shown in Figure 10.

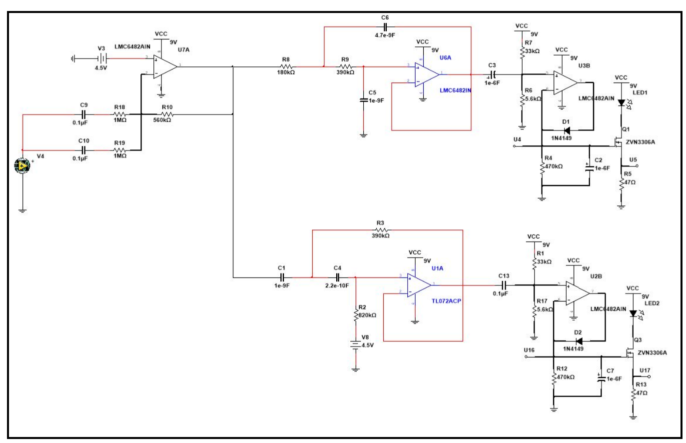

Figure 10: Completed Circuit with Values

From this circuit we thereafter measured the response for a couple key frequencies. One frequency measured is shown in Figure 11.

Figure 11: Vg High Pass MOSFET Voltage with 2.5 Volt Sinusoid Signal at 1500 Hz

This is the response from the circuit at 1500 Hz, particularly this is measurement from the high pass voltage gate going into the MOSFET. Here we can see that the signal is properly non-attenuated and high above V_{TN} at around 2.45 Volts.

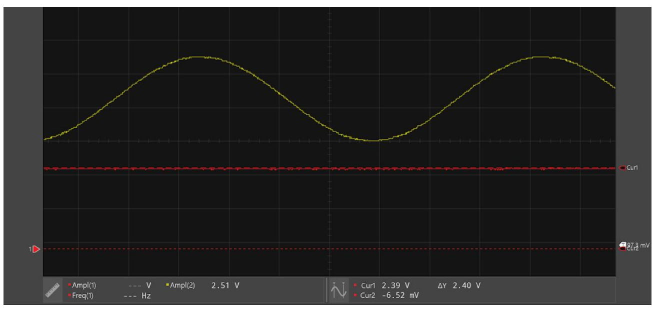

Figure 12: Vg High Pass MOSFET Voltage with 2.5 Volt Sinusoid Signal at 700 Hz

The signal was changed in frequency. Here in Figure 12 we can see that the frequency 700 Hz is properly non-attenuated by the high pass filter. It slightly shows a V_g voltage a little less than 1500 Hz, but still well above V_{TN}.

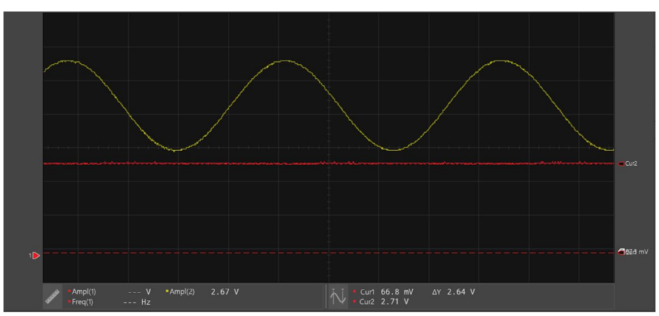

Figure 13: Vg High Pass MOSFET Voltage with 2.5 Volt Sinusoid Signal at 300 Hz

Next we decided to measure the gate voltage over at the low pass filter MOSFET. Here we can see a similar success with a non-attenuated peak voltage at around 2.45 Volts.

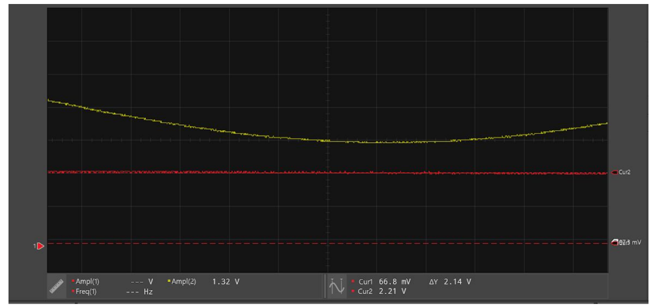

Figure 14: Vg High Pass MOSFET Voltage with 2.5 Volt Sinusoid Signal at 40 Hz

Here we measured the voltage at V_g at the gate, but with a significantly lower frequency signal. This signal, 40 Hz, was the lowest frequency we can pass that wasn't being drastically attenuated. This attenuation was because of the blocking capacitors, which is why for many values we have large resistor impedances. Here we can see that the voltage at the gate is at a low of ~2.0 Volts. Still enough to turn on the LED.

Shown below in Figure 15 is a final transient of our simulated circuit with an LVM file of ~6 seconds with our chosen song, note that this selection is not from the beginning.

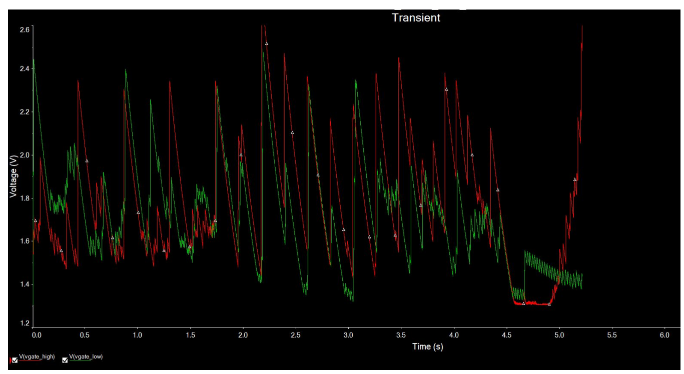

Figure 15: Transient Response of Simulated Circuit

It was this transient response from this circuit that prompted us to choose this song. The very distinct and high amplitude responses made it ideal to be used to showcase the circuit.

XIII. Recommended Project Improvements

A more in-depth discussion about the individual components of the Audio-Visualizer circuit would be of great value to future Fun 2 classes. Talking to some of our peers, we came to the consensus that we were spending a few hours just to understand how each circuit portion acted individually and interacted with each other. If there was a lecture that discussed each component individually and how it interacted with the system as a whole, we feel that we would have saved some time and headache in circuit construction and debugging.

Furthermore, to improve this experiment for another class, minimal parameters should be implemented on capacitor and resistor values. Our group chose values of capacitance, which were electrolytic capacitors in our lab binder these electrolytic capacitors then however, became troublesome when experimentally testing the high and low pass filters in Labview. The program kept freezing until ceramic capacitors were used, resulting in large sums of time wasted debugging the program. Another solution to this issue would be to use another program that uses the virtual bench to confirm the filters.

An easier way to choose appropriate songs and split them into left and right channels. We spent a significant amount of time initially trying to choose a good song for this project. Perhaps a list of example songs, what criteria are important, and a simple way to split the song into the two separate channels would help future students in saving time in the beginning that could be spent on analyzing the circuit.