ECE421 – Fall 2020

Final Project Report

Low Voltage Low Power Amplifier

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12-7-2020

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Objective

Long-Term Goal

My objective for this project is to lay out the groundwork for a long-term personal hobbyist project of creating my own low power audio-amplifier that will interface between a phone and a 32Ω-impedance pair headphones to boost the audio output of the phone to meet the maximum audio input limits of the headphones.

The goal moving past this initial project is to eventually create a potentiometer-controlled equalizer/audio amplifier that inputs a signal from a phone or iPod/mp3 player and inputs power from a 5V rechargeable battery and outputs an amplified/equalized audio signal to a pair of 32Ω headphones. Additionally, I want to put the design onto a PCB board and build a small enclosure for the PCB.

Short-Term Project Goal

For this project I want to lay out the groundwork for the amplifier design and have a working circuit that I can work towards optimizing and improving. Since 2.5mm audio jacks have 2 audio signals (tip-to-sleeve and ring-to-sleeve), I will only be building one amplifier for one of these signals for my Proof-of-Concept (later versions of the design will utilize 2 amplifiers with 1 amplifier per signal). Additionally, I will only have time to build a breadboard model of the design for testing instead of a prototype board circuit.

Research

To get a better idea of what type of amplification will be needed from this amplifier to get desired output, I had to look up the audio specs on the iPhone I will be using while prototyping as well as the headphones that will be used.

iPhone 11 Audio Output Limitations

It was difficult to track down any reliable sources online that pinpoint the absolute limit of the iPhone11. Luckily, a relatively new feature of the iPhone allows the user to see audio-output volume in real time and it looks like the audio limit is approximately ~100dB.

Parameter	Spec
Max SPL	~100dB

Table 1: Research – Observed iPhone 11 DAC Limits

MH40 Headphone Limitations

I was able to find more specs for the headphones I will be using to determine what type of limitations I will be dealing with (see **Table 2** for the specs).

Parameter	Spec
Max Voltage	$1.8V_{rms}$
Max Current	60mA
Max SPL	124dB
Impedance	32Ω
Efficiency	104dB/1mW

Table 2: Research – MH40 Headphone Limits (Source embedded in link)

Based on these two specs, I can now estimate the V_{rms} of the maximum output of the iPhone to be:

Parameter	Spec
Max P	~0.96mW
Max V_{rms}	~175mV_{rms}
Max V_{pk}	~245V_{pk}

Table 3: Research – Estimated iPhone 11 DAC Limits

Initial Drawing and Design

Design Specs

To get started, this design will utilize the "Low Power Audio Amplifier" from lecture 7 of this course (ECE521Lecture7.pdf) as well as the legacy op-amp circuit from Problem 1 of the graded exercise (ECE521exercise.pdf).

I don't want the quiescent current to heat up the BJTs during operation so I will try to set the $I_{quiescent}$ to about 5mA. Additionally, I will also reuse the R_E value of 22Ω. Now, since the I_C of all the transistors are only a few mA with their I_B's being in the tens of µA's, I will set the VBE to be about 0.6V.

Initial Drawing

Below in **Figure 1**, I have a drawing of the low-power audio amplifier with all of the voltages and currents filled in based on my estimates.

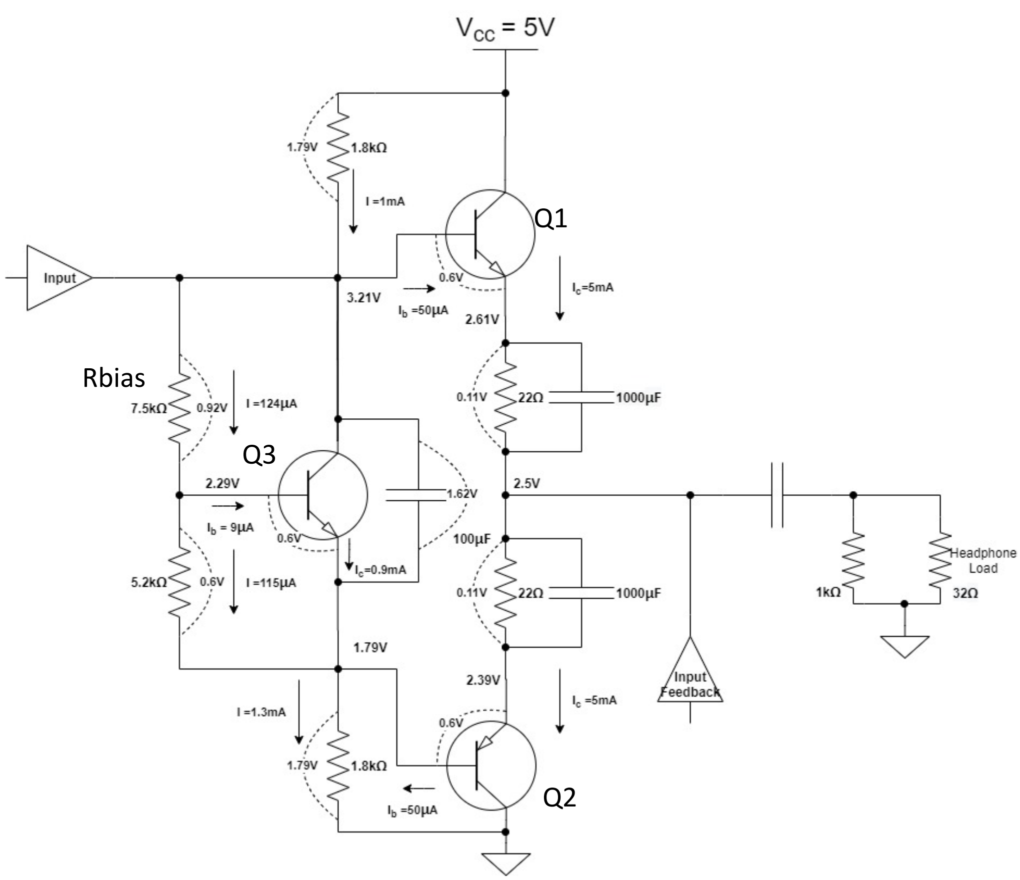

Figure 1: Initial Design – Drawing with Nodal Voltages and Current Estimates

Initial Design LTspice Simulation

Simulation from Initial Design

To get a more ‘accurate’ simulation with the 2N3904/2N3906 BJTs, I went into the following model library:

C:\Program Files\LTC\LTspiceXVII\lib\cmp\standard.bjt

Copied the 2N3904 and 2N3906 models into the circuit drawing as Spice Directives and modified the forward beta values ‘BF’ to 100 to match the suggested beta from lecture.

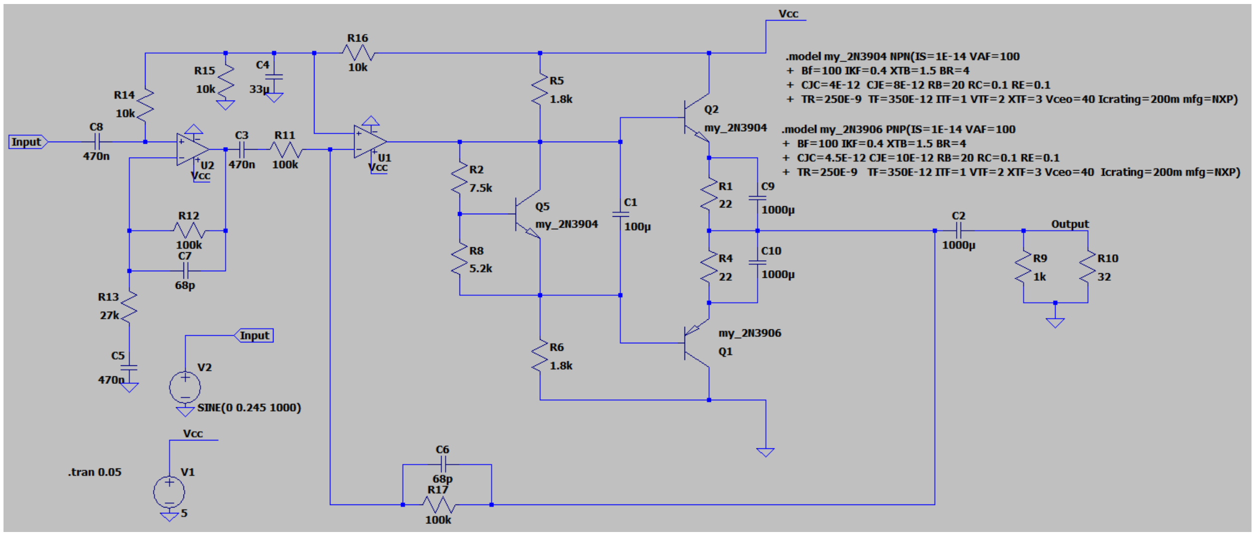

Figure 2: Initial Design LTspice Simulation - Circuit Diagram

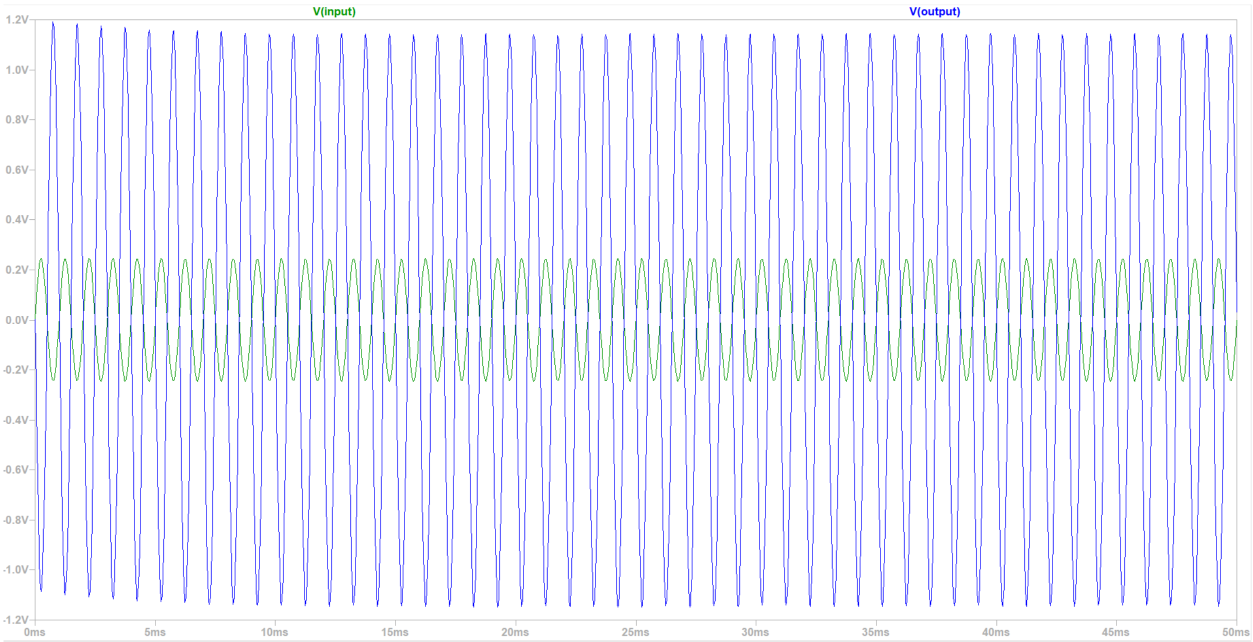

Figure 3: Initial Design LTspice Simulation – Simulation Results

Modified Design for Similar Resistor and Capacitor Values

Now, to do the build, I am limited to the resistor and capacitor values that I have in my personal component stock. I also adjusted some of the op-amp gain resistor values to keep the amplifier voltage from being too large and damaging my headphones since the iPhone max voltage is near the peak dB rating of the headphones (note slight voltage difference in **Figure 5**).

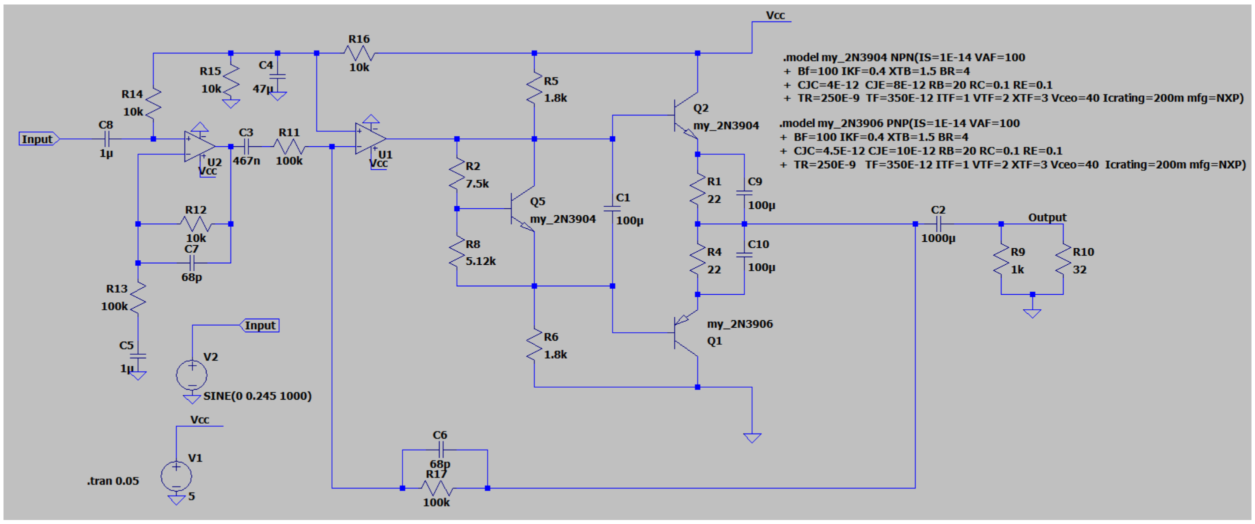

Figure 4: Modified LTspice Simulation – Circuit Diagram

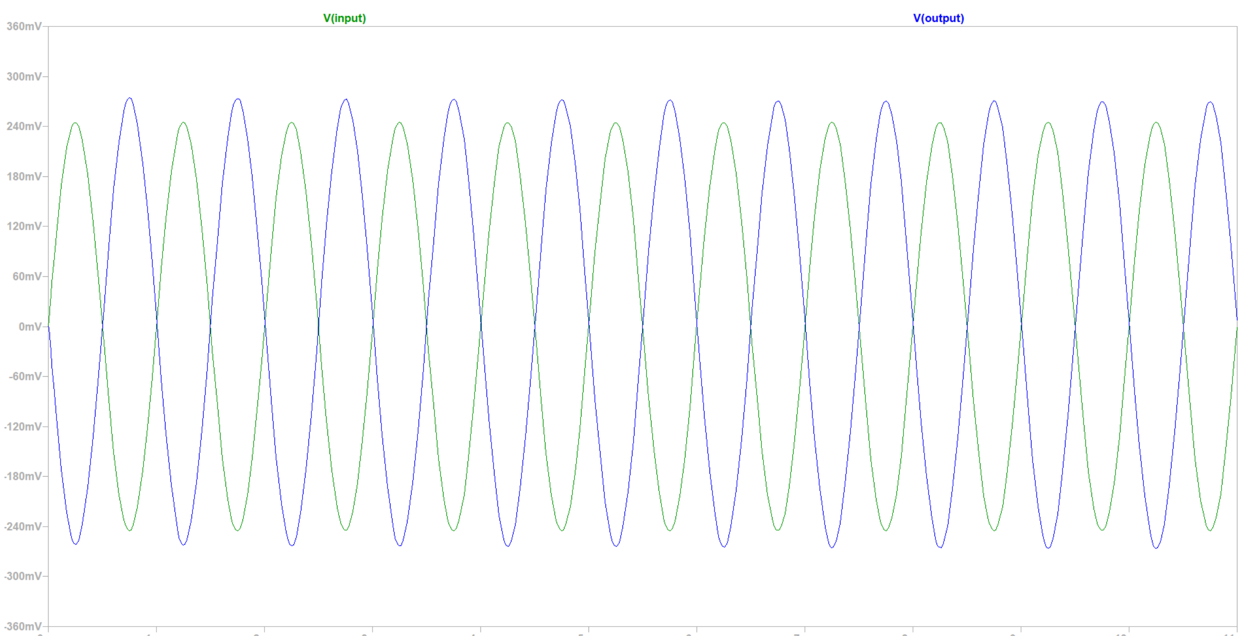

Figure 5: Modified LTspice Simulation – Simulation Results

Breadboard Prototype Testing

Breadboard Amplifier Prototype Build

To keep the circuit simple, I laid the circuit out such that the left-most power rail is input voltage (from phone audio jack), the terminal strips between the left-most and center power rails contain the op-amp input stage, the middle power rail is V_{CC} power to the circuit (5V supply), the terminal strips between the middle and right-most power rail is the transistor output stage, and the rightmost rail contains the output voltage (to load).

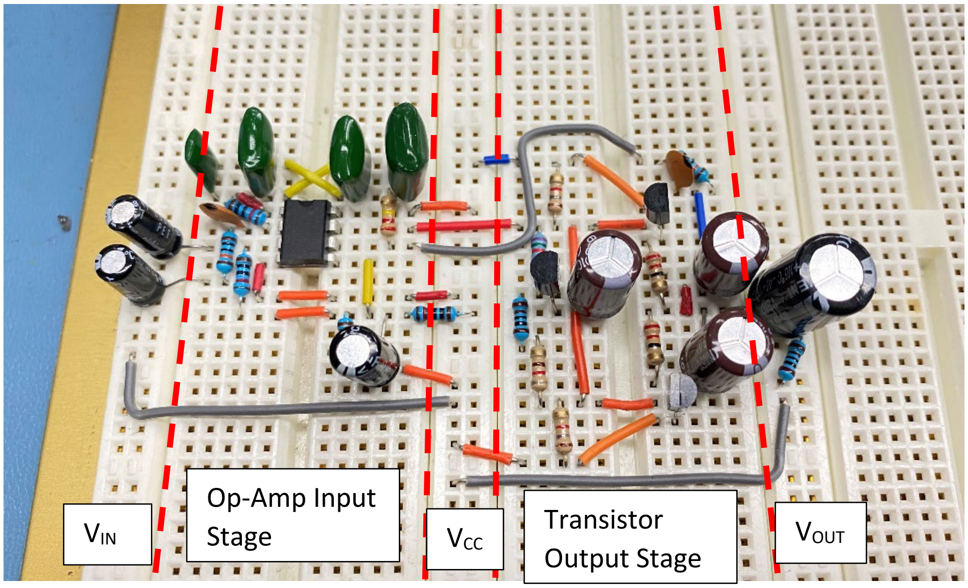

Figure 6: Breadboarded Amplifier Prototype

iPhone Audio Output

To get a good comparison, the voltage signal from phone to headphones will be measured on an oscilloscope (Fortunately, I was able to stay late at work to use their scope and thermal imager.). To accomplish this, I used two 2.5mm jack audio cables, two female 2.5mm jack to screw terminal block adapters, my iPhone with a 1000Hz sine wave YouTube video (link), and my 32Ω headphones. In **Figure 7** below, we can see the V_{RMS} measures to be 185mV_{RMS} which gives us maximum output power from the phone's DAC to be 1.1mW.

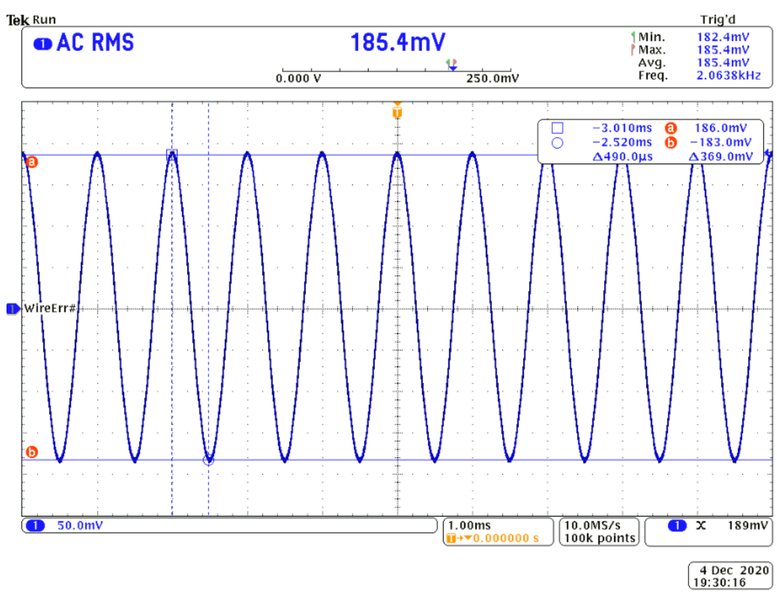

Figure 7: iPhone Maximum Audio Output to Headphone Load with 1kHz Test Output

Amplifier Prototype Audio Output

When plugging the phone output signals into the input of the amplifier circuit, a 5V linear lab power supply into the V_{CC}, and the headphones with scope probe on the output of the circuit. At 100% volume on the phone, the output voltage was distorted (shown in **Figure 8**).

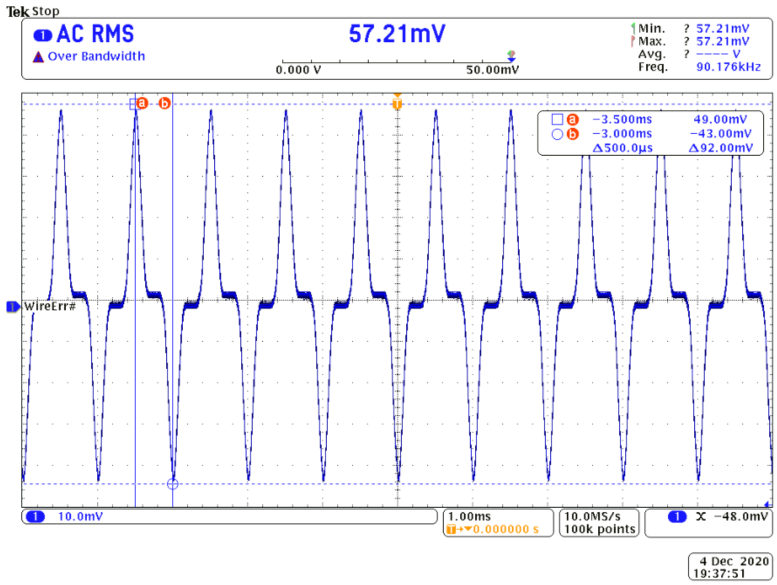

Figure 8: Maximum Audio Output with Amplifier (with Distortion)

When the volume was reduced by two 'levels' (roughly approximately 88% maximum volume), the distortion went away, but the output amplitude stayed approximately the same (**Figure 9**). With the V_{RMS} of $43mV_{RMS}$ which only sourced 0.06mW which is only about 6dB of sound which was very faint in volume.

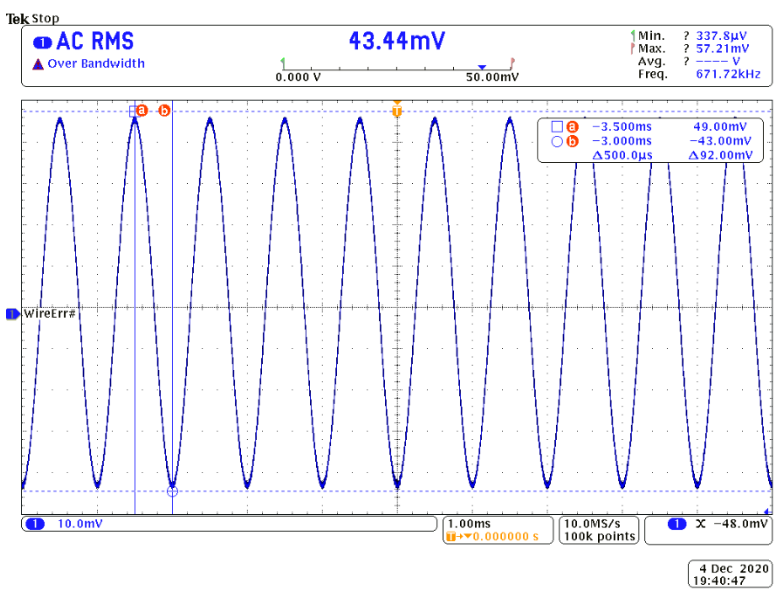

Figure 9: Reduced Volume Audio Output with Amplifier (without Distortion)

Thermal Observations

I did notice that when I turned the circuit on with the 5V lab power supply, the supply read-out an output current of 35mADC which is higher than the few mA I was expecting. With this quiescent current this high, I though it would be a good idea to observe the circuit through a thermal imager. As I suspected, the transistors were heating up. After a minute or two of warming up, the transistors seemed to stabilize at the temperatures in **Figure 10** below (102°F, yikes!). With these higher temperatures, I suspect this to partially be the source of the performance issues observed in the circuit.

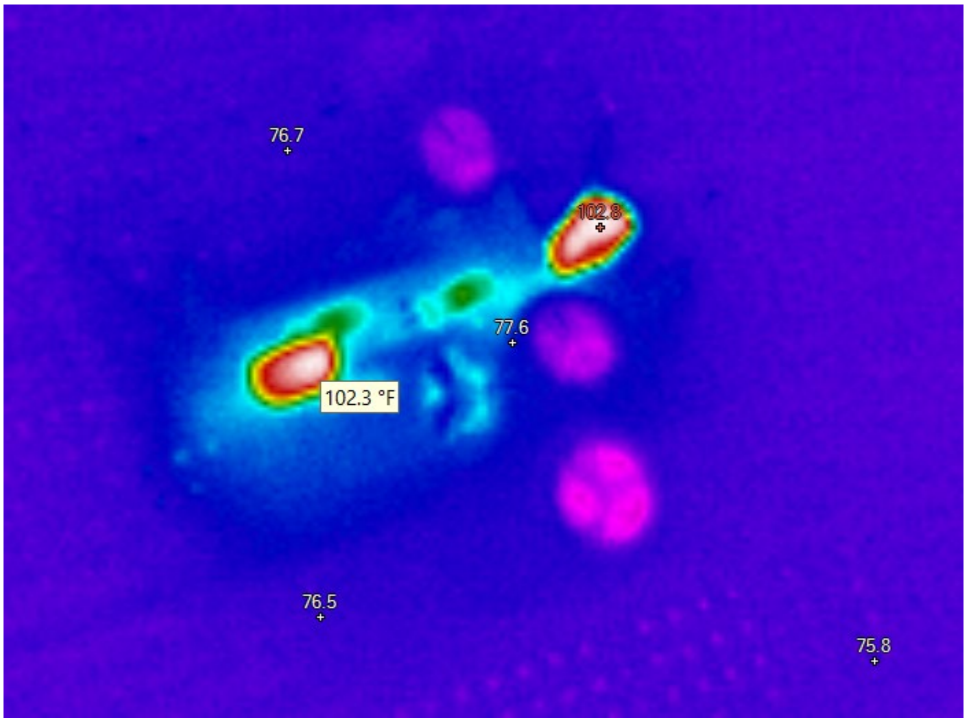

Figure 10 Thermal Image of Audio Amplifier Under Load

Amplifier Prototype DC Measurements

Now, I wanted to check the circuit voltages out to figure out what I can change to improve the design.

Node	Node Voltage
N1	4.304V
N2	0.985V
N3	3.312V
N4	1.716V
N5	2.509V
N6	1.578V

Table 4: Amplifier Prototype DC Measurements

These measurements give us $V_{BE,Q1}$ = 0.992V, $V_{BE,Q2}$ = 0.731V, $V_{BE,Q3}$ = 0.593V, Iquiescent = 36mA. The 4-resistor bias amplifier driving the output BJTs, the top 1.8kΩ resistor has approximately 0.39mA current through it and the bottom 1.8kΩ resistor has about 0.55mA current through it. To fix some of these issues, I can increase the R_E resistance value on Q1 and Q2 to reduce quiescent current. I can also adjust the VBE of Q1 and Q2 in my estimates as well to help adjust the R_{bias} resistor value. Additionally, I can find a better spice model to simulate the op-amp input stage of the circuit. Currently, I am using a 'universal' op-amp to simulate this circuit in LTspice.

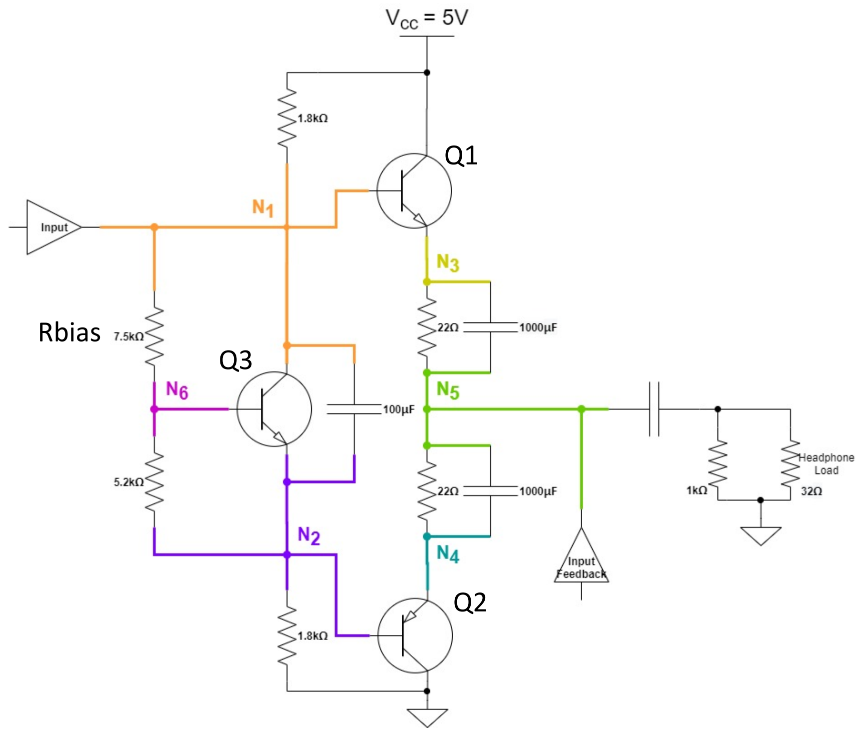

Figure 11: Amplifier Prototype DC Measurement Diagram

Circuit Value Adjustments

To get the quiescent current down, I replaced R_{bias} with a potentiometer and adjusted the resistance to 1.4kΩ. The current draw on from the lab power supply went down to around 2-4mA which brings the quiescent current down to only a couple mA. With this change, the transistors did not go into thermal runaway like before. I was able to find some more 1000µF to replace the 100µF

With this change, the gain of the circuit matched closer to the simulation in **Figure 5**. I wanted to get a bit more gain out of the circuit to see when I'd start to see voltage clipping on the peaks. I adjusted R11 from **Figure 4** to 22kΩ (after changing the value a few times). The output of the circuit after these changes is shown in **Figure 12** below.

When plugging changing the audio signal from a pure sine wave to actual music, the volume had to be reduced slightly to get rid of the more obvious audible distortions but overall the volume was quite a bit louder than what the iPhone output limits the output and the sound quality wasn't bad.

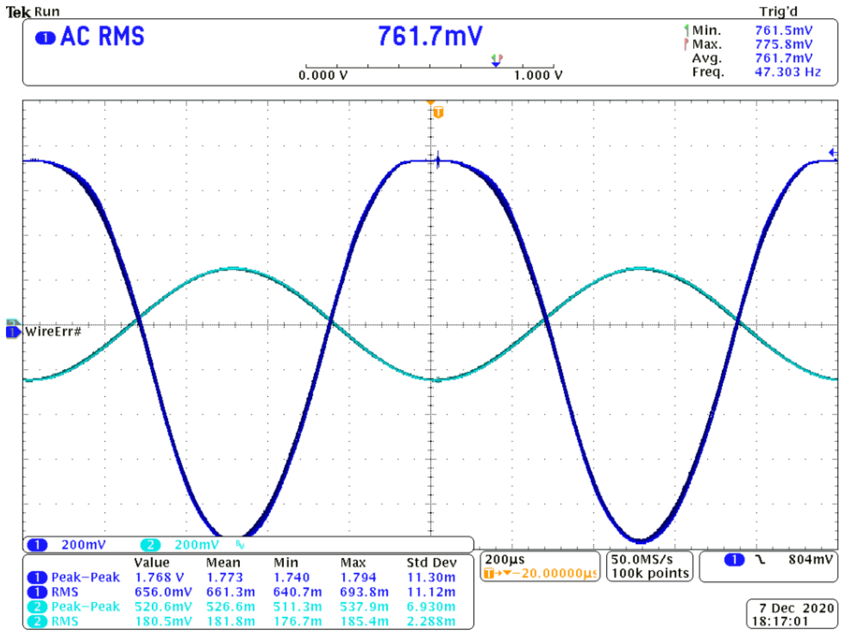

Figure 12: Adjusted Amplifier Circuit

Lessons Learned

From this short design process, I learned:

1. What headphone sensitivity is in terms of SPL/mW.
    a. And a general idea of how much power is needed for certain levels of loudness from SPL.
2. That I should use V_{BE} of 0.6V for only the driver transistors and not output stage (load) transistors (which I should use 0.7V).
3. Testing breadboarded designs with strategically placed potentiometers can save a lot of time debugging a circuit and give me more intuitive understanding how each component effects the circuit.

Moving Forward

Since I still want to build myself a more finished design, I will be working on this project past this course. I have created a github project to reflect my status as I continue to develop this long-term project over time. Next I plan on fine-tuning the gain of the design so I don't hear anymore distortion at any volume level from the iPhone and then I would like to start adding some active filters to make the design into an equalizer amplifier since iPhone doesn't have equalizer controls outside of their Apple Music app.