6.101 Final Project Report

Class G Audio Amplifier

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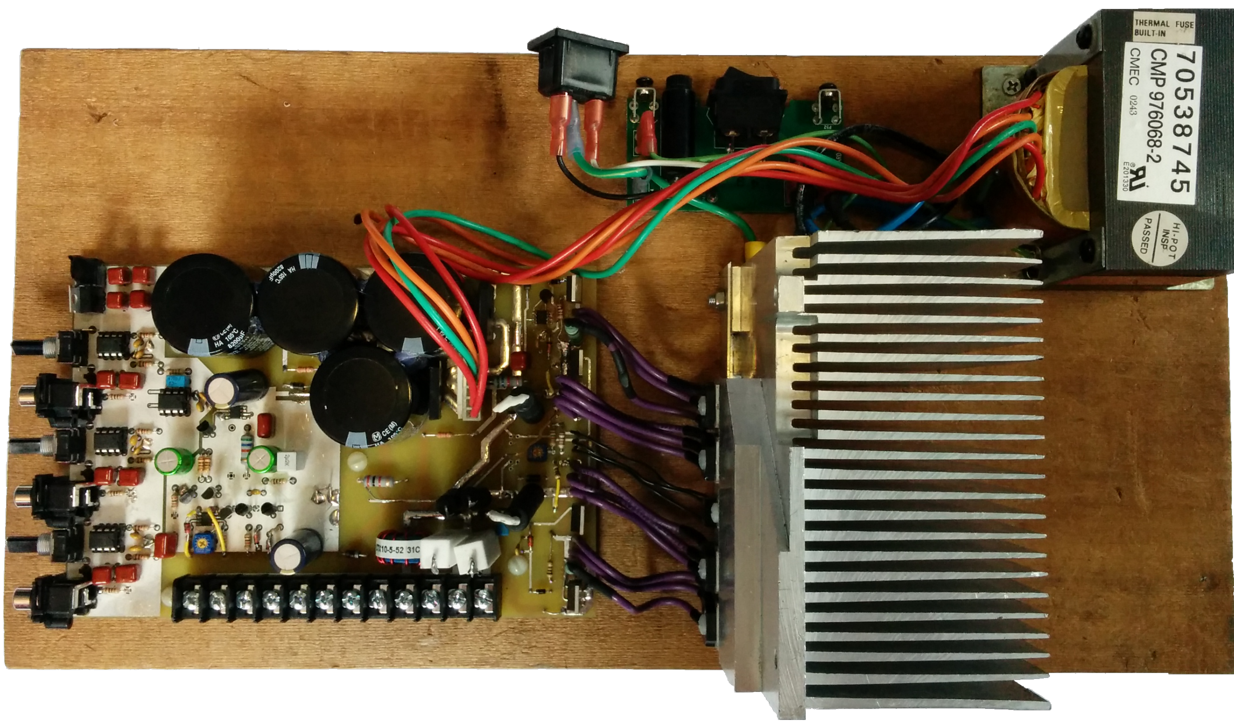

1 Introduction

For my final project, I designed and built a 150 Watt audio amplifier to replace the underpowered and unreliable 50 Watt amp that is currently driving the music system on my dormitory hall. The old amplifier tends to overload and go into thermal runaway. My design utilizes a class G (rail switching) output stage for increased efficiency and lessened cooling requirements, and has an aggressively temperature compensated biasing circuit to prevent runaway.

2 System Outline

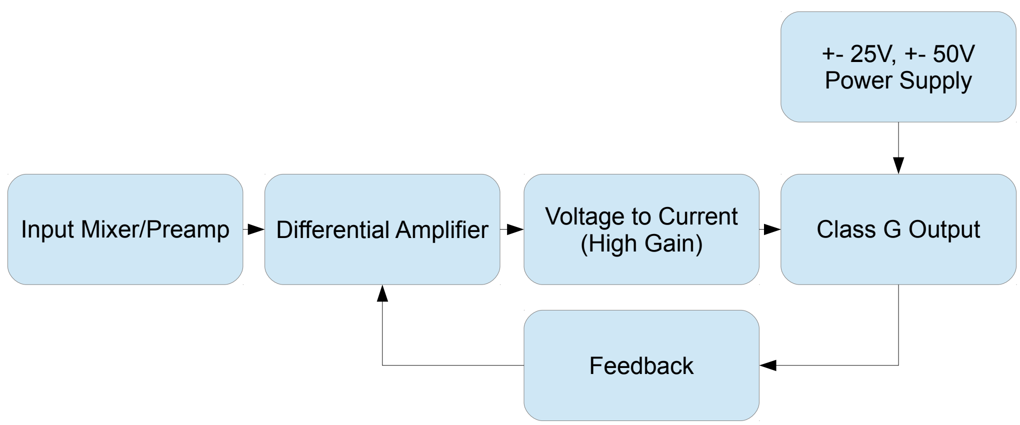

Figure 1: Amplifier Block Diagram

2.1 Input Mixer/Preamp

A simple op-amp circuit accepts 6 line level inputs, applies volume control to each stereo pair, sums the signals together, then amplifies the signals before feeding them into the main amplifier.

2.2 Differential Amplifier

The differential amplifier, implemented with a long tailed pair, subtracts an attenuated version of the output from the input signal and amplifies the difference.

2.3 High Gain Stage

The high gain stage is a transconductance amplifier that converts the output voltage from the differential amplifier to a current which drives the output stage. Most of the loop gain is concentrated in this stage. The amplifier is also compensated in this stage.

2.4 Class G Output

The class G output stage is the focus of my project. Essentially, it consists of a class AB amplifier (as constructed in lab 5) with a second set of output transistors wrapped around it. A basic illustration of this topology is shown in figure 2. The outer transistors are connected to a set of voltage rails that are roughly double the rails supplying the inner transistors, and only turn on when the output voltage is about to exceed the voltages available on the inner rails. This results in greatly improved efficiency for output signal amplitudes that do not cause the outer transistors to turn on (as shown in figure 3). This is of great benefit for signals with low average amplitude and high peak amplitude, as is often the case with music. The outer transistors may only turn on for a short instant to prevent clipping on the beat of a song while the rest of the song is efficiently amplified by the inner transistors.

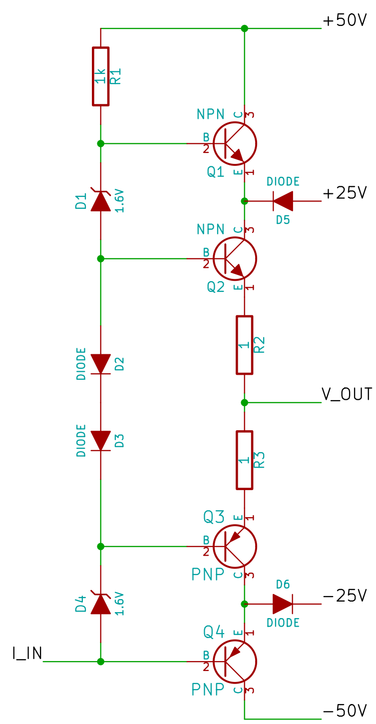

Figure 2: Schematic Class G Output Stage

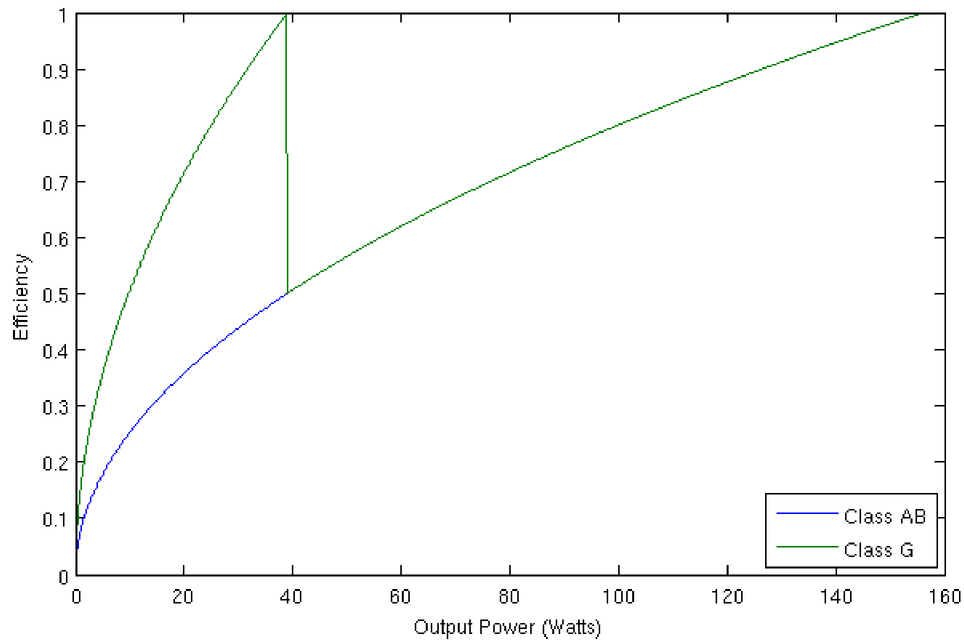

Figure 3: Efficiency Curves For Class AB and Class G amplifiers

2.5 Power Supply

In this iteration of the project, the the power supply is based on a simple 60Hz power transformer. I am considering constructing a smaller more efficient switching power supply at some point in the future.

3 Detailed Description of Design

3.1 Power Supply

The power transformer I used has one winding with five taps. Connected as shown in figure 4 with the center tap connected to ground, RMS voltages of about 30V and 15V are available on its outputs. Two full bridges rectify these voltages to make a 42V rail and a 20V rail. This rectification takes place at 120Hz, so large (8200uF) bus caps are present on each rail. A 1W $3.3k\Omega$ bleeder resistor across each bus capacitor ensures that dangerous voltages do not persist in the circuit for more than a few seconds after the amplifier is powered off. Two 12 voltage regulators provide a stable power supply for the op-amps in the input mixer. A handful of filter components reduce 120Hz hum in the supply rails for some of the low power filter stages.

3.2 Input Mixer/Preamp

The input mixer (figure 5) consists of three copies of the same block. In each block, stereo audio comes in on a pair of RCA jacks, is passed through DC blocking capacitors, and is

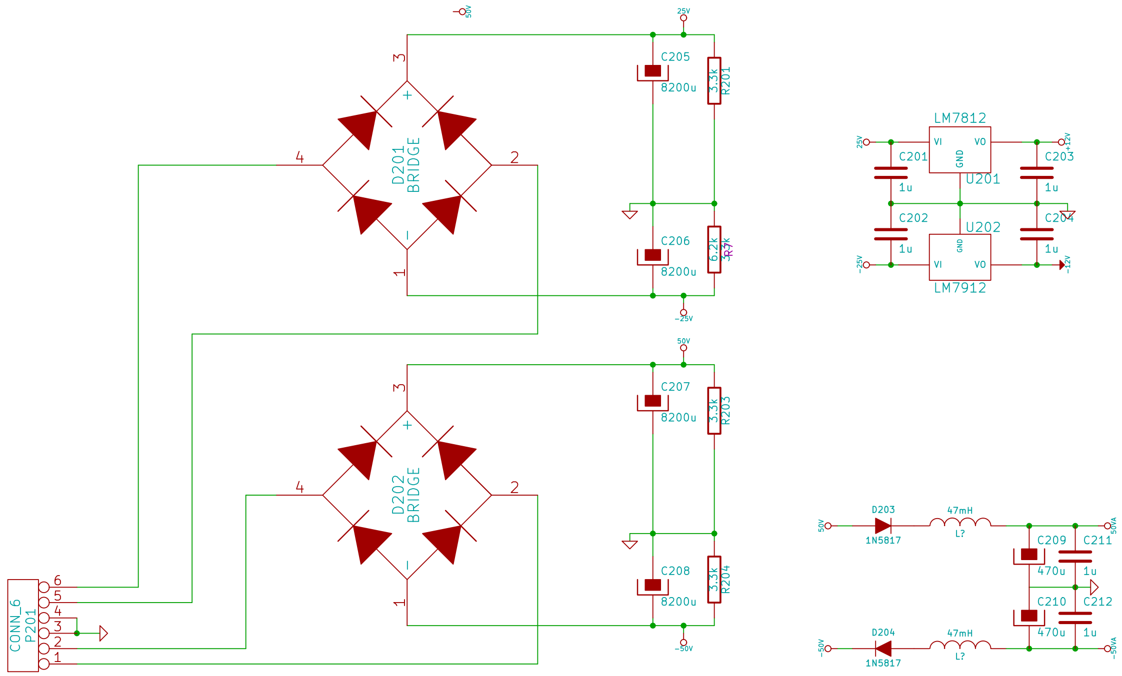

Figure 4: Power Supply

then attenuated by a dual log-taper potentiometer for volume control. The two channels are then buffered by an LF358 op-amp, and the resulting voltages are fed into a transimpedance amplifier that sums the signals from all of the input channels and multiplies the result by eight. This pre-amplification is necessary because of the limited gain-bandwidth product of the main amplifier.

3.3 Differential Stage

The differential stage (figure 6) is a long tailed pair with current mirror loads and current source biasing. The current mirror load provides high gain, but it also allows the bias current to be higher, which is helpful for achieving acceptable slew rate.

The emitters of the current mirror transistors are degenerated slightly. The 120Ω resistors drop about one V_{BE}, which is meant to linearise the load slightly, lessen the effect of any transistor mismatch, and allow the placement of the $5k\Omega$ output offset null potentiometer. The offset null capability of this amplifier is very important, because there is no DC blocking capacitor at the output.

The emitters of the main transistors in the differential pair are also degenerated. This reduces the gain of the differential stage to something on the order of 50dB, and again reduces the effect of transistor mismatch between Q401 and Q404. This is important, because the voltage these transistors must block precludes the use of any common matched transistor pair. I hand picked two well matched transistors for this pair.

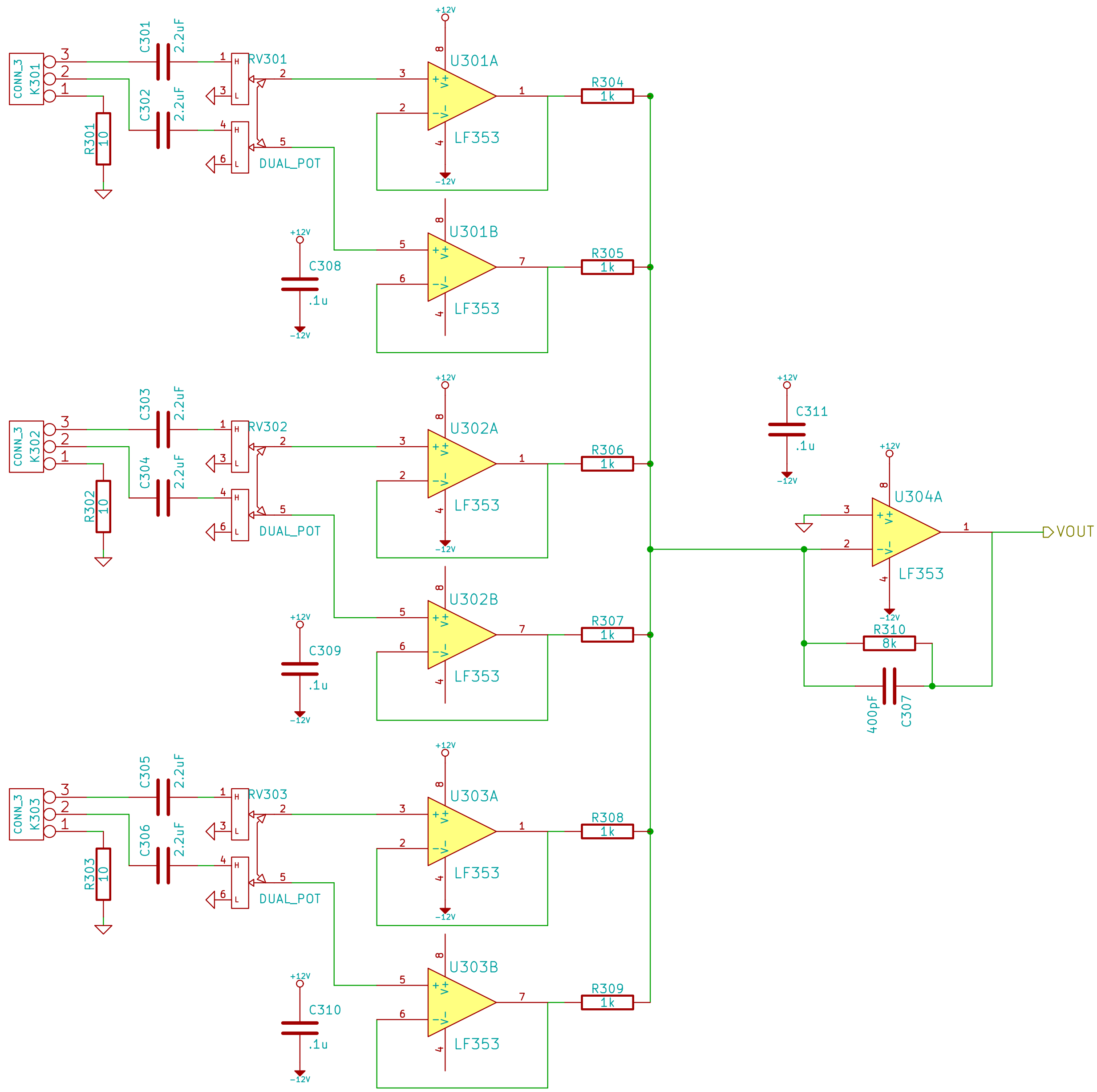

Figure 5: Input Mixer and Preamp

C401 and C402 are both 100uF non-polarized electrolytic capacitors. Their presence sets the input impedance into both the inverting and non-inverting inputs to $2k\Omega$, which helps keep output offset to a minimum. C401 blocks any DC component from the preamp, and C402 causes the feedback ratio to approach unity at DC.

The feedback ratio from the output is $\frac{1}{21}$, which sets the overall gain of the amplifier to 21, or 26.4dB.

The current source and current mirror loads are both implemented with matched pair ICs (SSM2220 PNP, SSM2212 NPN). These ICs have extremely good current gain, V_{BE}, and thermal matching. Their collector emitter breakdown voltage is only 40 volts though, so I added a high voltage transistor to the current source to make a Wilson current source. The current source should provide approximately $7.5mA$.

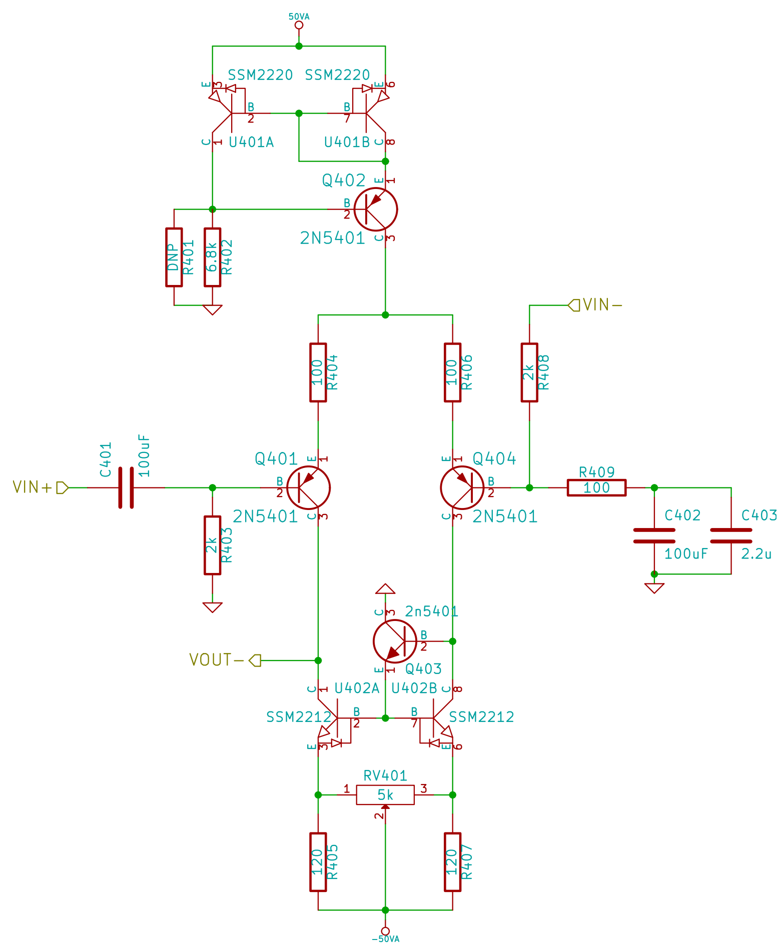

Figure 6: Differential Stage

3.4 High Gain Stage

The high gain stage (figure 7) is a transconductance amplifier that converts the output voltage from the differential amplifier to a current which drives the output stage. The voltage gain of this stage is hard to calculate because it depends entirely on the impedance of the output stage, but in simulation it appeared to be about $50dB$. The compensation capacitor is miller multiplied by this gain, and serves to reduce the loop gain at high frequencies. This stabilizes the amplifier with dominant pole compensation. The chosen value of 1nF was arrived at through an initial guess derived from simulation results and experimentation with the finished amplifier. It provides a bandwidth of about 22kHz, just outside of the audible range.

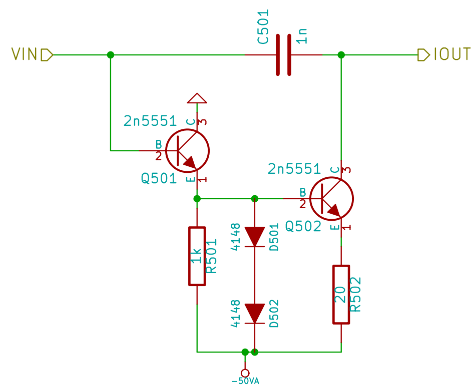

Figure 7: Compensated High Gain Stage

3.5 Output Stage

As discussed earlier, the class G output stage is the focus of my project. A full schematic of my output stage is shown in figure 8.

3.5.1 Output Switches

I'm using Darlington pairs to decrease the bias current needed in the high gain stage. The outer transistor in each pair is a NJW3281G (NPN) or NJW1302G (PNP). These are extremely high power ($VCEO = 250V, P_{DMAX} = 200W$) transistors designed specifically for high power audio amplifiers. They come in a TO-3P package and are extreme overkill for this amplifier, but they're only a few dollars apiece so who cares. The inner transistors are complementary power transistors in TO-220 packages. Only the outer transistors are coupled to the heat sink.

3.5.2 Biasing

As we learned in lab 5, a voltage of $2 \cdot V_{BE}$ ($4 \cdot V_{BE}$ for darlington pair outputs) placed between the bases of the output transistors reduces crossover distortion by biasing both transistors slightly on at all times. Unfortunately, transistor current rises with temperature and is exponentially related to applied voltage, which makes the bias current in the output stage hard to control. The addition of 1Ω degeneration resistors between the emitters of the output transistors linearizes the voltage to current relation to an acceptable degree, but thermal stability is still a problem. If too much bias current is passing through the output transistors, they will heat up, which will cause them to pass even more current for a given bias voltage. The solution is to reduce the applied bias voltage when temperature begins to rise. The is accomplished with the "rubber diode" formed by Q601, R603, R604, and RV601. Q601 is a Darlington pair attached to the same heat sink as the output transistors, and its V_{BE} therefore tracks those of the output transistors fairly well with changing temperature. The two V_{BE}s of Q601 are applied across RV601 and R604, which programs the current through R603 and thus the voltage generated by the bias circuit. RV601 is used to adjust this bias voltage for a desired output bias current. I chose to set the output bias current to about 50mA.

3.5.3 Zener diodes

Two zener diodes (D601 and D6602) control the voltages at which the outer transistors begin to turn on and draw power from the high voltage rails. To avoid saturating the inner transistors, this should happen a little bit before the output voltage actually clips. Counting V_{BE}s from the collector of Q606, it looks like we need at least 2V of headroom plus a little to keep Q606 from saturating. The 2N4729 is a 3.6V Zener diode, which should be plenty. A slightly smaller Zener or even a chain of four normal diodes could probably be used.

3.5.4 Output Protection

Q603 and Q604 are present to protect the amplifier from output short circuit. If enough current flows through R610 or R611 to produce $0.6V$ across the base-emitter junction of one of these transistors, then that transistor will turn on and clamp the voltage generated by the high gain stage to prevent the output current from rising further. The values shown for R610 and R611 would limit output power to much less than $150watts$. 0.1Ω Would be more appropriate.

3.5.5 Output Network

This amplifier is intended to drive a distributed system of transformer coupled speakers over fairly long runs of speaker wire. At high frequencies, those wires could begin to look like transmission lines of arbitrary length and impedance, which could cause the amplifier to become unstable. At high frequencies (hundreds of kHz), the output inductor becomes an open and "disconnects" any output load from the amplifier, while the $100nF$ capacitor damps the output by shorting it to ground through a 10Ω resistor.

4 Build Process and Reflection

4.1 Circuit Design

I completed the design for my amplifier mostly over Spring break. Starting with what we learned in 6.101, I spent a lot of time researching various amplifier designs, and tried to make educated decisions about all of my topologies and part values. In particular, the articles at

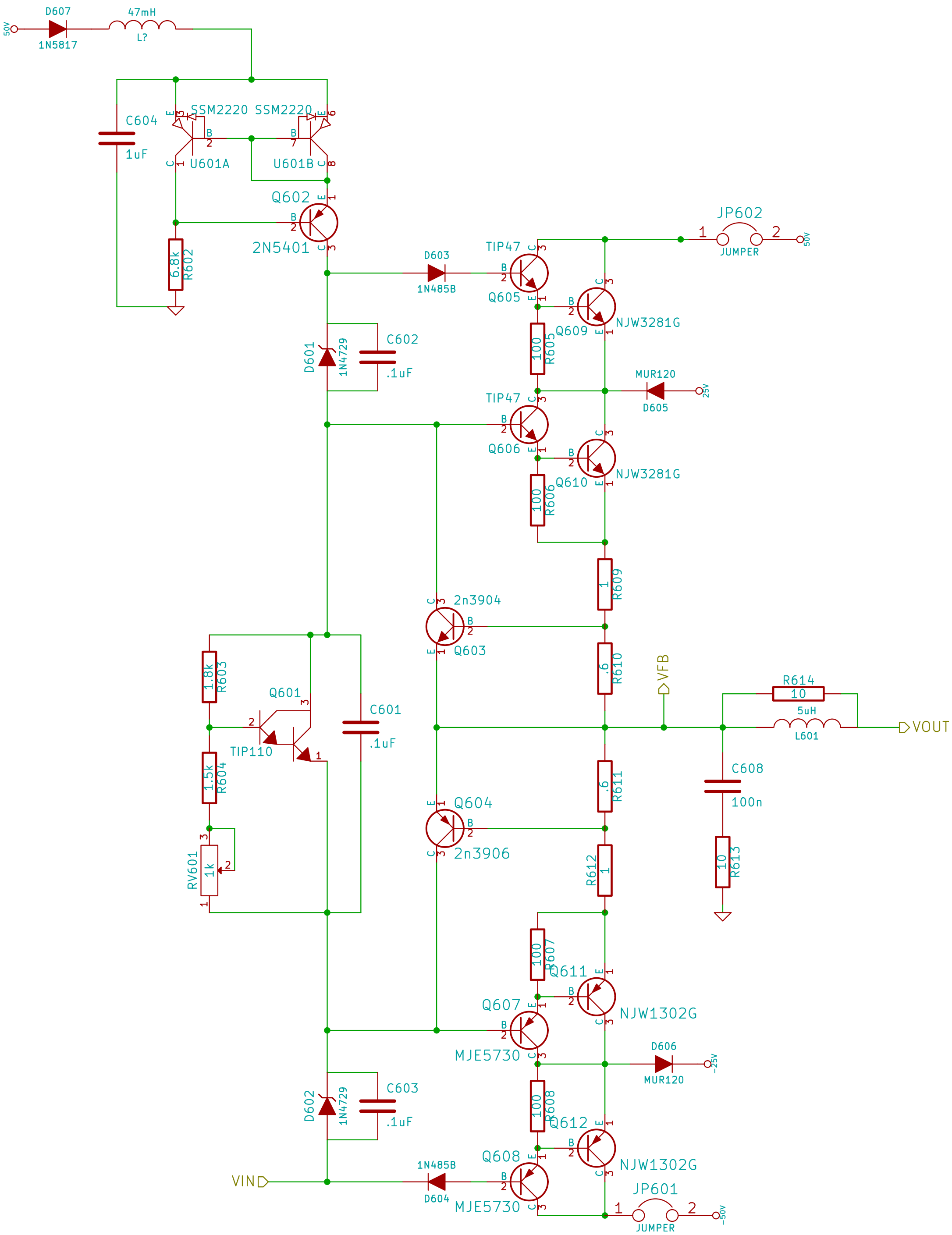

Figure 8: Class G Output Stage

sound.westhost.com were very helpful. By the end of Spring Break, my amplifier worked pretty well in LTSpice.

4.2 PCB Design

This is a fairly large and complex circuit, and my goal was to create something permanent and useful, so I decided to order printed circuit boards for this project as the course suggested. I used KiCad to generate all of my schematics and design my PCB. KiCad is a suite of free and open source EDA tools. I prefer it to Eagle because free software makes me feel warm and fuzzy on the inside, I am free to use the circuits I design for commercial purposes, and there are no arbitrary limits on board size.

It took me longer than I expected to finalize my design, so I didn't start working on the PCB until much too late. I made several errors, but luckily I was able to correct them with a sharp knife and some extra wires. Whoops.

4.3 Results And Observations

My amplifier works well. It has a lower $3dB$ point of $8Hz$ and an upper $3dB$ point of $22kHz$. I wasn't able to measure the THD of my amplifier, but there isn't any obvious noise in the output and it seems very stable even into loads less than 6Ω. Notably, I had very bad ringing issues before I populated C601, C602, and C603.

The heat sink I used is much larger than is needed, so even at full power it barely gets warm to the touch.

I originally planned on using LM358 op amps in the input mixer, but I quickly found that the LM358 has very bad crossover distortion unless you bias the output into conduction with a resistor to the negative supply rail. This seems like a very silly problem for an op-amp to have, but luckily the LF353 has the same pinout and does not have noticeable crossover distortion.

I ended up removing the output protection transistors, because they seemed to turn on slightly and distort the output far before I expected them to, and this was preventing me from powering 8Ω loads. A more complex circuit may be needed to add some hysteresis to the output protection feature.

4.4 Possible Revisions

The matched pair ICs that I used (SSM2212 NPN, SSM2220 PNP) cost more than $8 apiece and only come in SOIC packages. For this reason, it might make mores sense to use single transistor current sources instead of the Wilson current mirrors used in my design. A DIP version of the PNP matched pair is available, and it therefore might even make sense to invert the entire front end of the amplifier so that a PNP current mirror could be used as the load in the differential stage.

Several of the design decisions I made here (output transistors, heat sink size, suggestion of a 400W power supply) are obviously overkill for the power level this amplifier can handle. This is because I have vague plans to modify the design for higher voltage and higher power operation at some point in the future. After completing this entire project, I see that with a few small modifications, the voltage rails and output power of this amplifier could easily be increased substantially. There are number of transistors (Q401, Q402, Q404, Q502, Q602) which must block the full voltage of the high voltage rails and pass a bias current on the order of 10mA, which pushes the power handling capabilities of the TO-92 package. Selecting metal can or TO-220 transistors would allow these critical components to dissipate much more power, and the voltage rails could probably be doubled.