Discrete device Audio Amplifier

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1 Introduction to runaways

The 2022 summer was a hot one, and while suffering an intense heat wave one day I noticed my homebuilt audio amplifier started to hum. I also noticed it was much hotter than normal, and so it was its power supply. So, I took a multimeter and soon found its quiescent current was more than 700mA while a normal value was about only 40mA, so I suspected it was broken and turned it off. I built that amplifier many years ago using two TDA2002 integrated power amplifiers, and it worked well until this failure. But, after allowing it to cool for some minutes it was working normally again. But not so well, because I also noticed its quiescent current was slowly rising and I realized what the problem was: I was having a thermal runaway triggered by the high ambient temperature, the closed box of the homebuilt amplifier, and the crappy design of the TDA2002 internals. The thermal runaway happens this way:

1. The amplifier consumes an small quiescent current and, therefore, it dissipates some power.
2. The power dissipation increases the temperature of the chip.
3. The quiescent current increases with higher temperatures, and the same happens with power dissipation.
4. Go to point 2

If the amplifier is attached to a good heat sink there is a negative feedback because higher temperatures also means more heat is carried away from the chip and the temperature can stabilize at a low value. But in my case the heat sink provided to the amplifiers was not enough until I removed the box cover and allowed the air to flow around the chips.

But we can also ask the following question about point #3: Why is the quiescent current increasing with higher temperatures? This is the truly cause of the positive feedback in the thermal runaway, so, it would be very desirable to have here a negative coefficient.

Now, I understand why the obsolete TDA2002 chip was superseded with other models: It has a serious design flaw. These integrated solutions are an easy way to design a functional circuit in a hurry: You don't have to calculate anything, only to copy the reference design without asking yourself any question, and they work. But sometimes they also include some nasty surprises like the mentioned thermal runaway.

So now I keep the amplifier box open and I frequently touch the heat sinks to be sure they are cold, and of course, I never keep the amplifier powered if I'm not around. Or in other words: I no longer trust these chips. They have to be replaced the sooner the better, but, with what model? These ICs have quite short lifespans, I would like to have something long lived, like the NE555 but as an audio amplifier, yet I don't think such an IC exists. My solution here was to design a new audio amplifier myself using simple parts, like power transistors and well known operational amplifiers, but on simulations the performance of these circuits wasn't very good, to say the less, and I also realized I had no stock of my favorite TL08x opamps. Then, I tough about removing

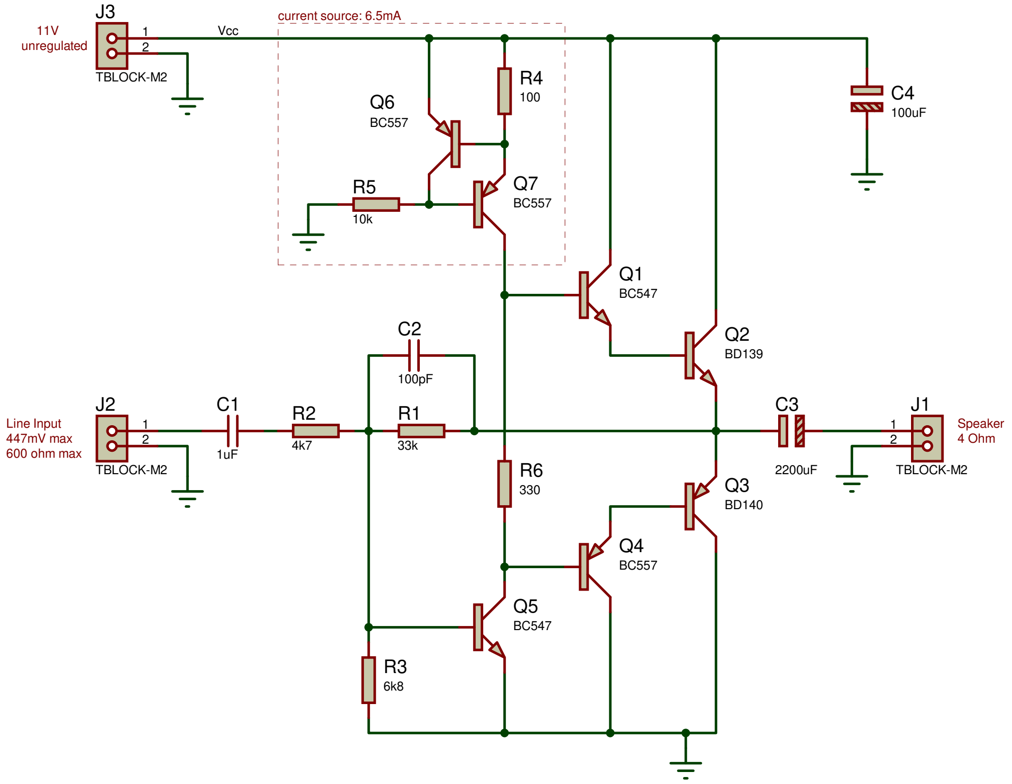

Figure 1: Schematic of the audio power amplifier (one channel)

the opamp and simulations turned very promising, so, at the end the design is made entirely with discrete transistors. They are cheap, easy to find or to replace with other models without problems, and they give the amplifier a vintage look only surpassed by tubes while also performing very well.

And, if properly built, the amplifier is going to have a negative temperature coefficient in its quiescent current, so no more thermal runaways are expected.

The TDA2002 was sold as a 10Watt Audio amplifier, but that was for a 16V supply and 2Ω load. In my previous amplifier the supply voltage was 12V and the speakers were 4Ω, thus reducing the real power to little more than 2W. Yet, the volume control was always close to minimum, so I think 1W of output is going to be enough and this requires only 2.8V of amplitude (5.6V peak to peak) over 4Ω. A line-out audio signal has a maximum amplitude of 0.447V, so the gain of the amplifier shouldn't be much higher than 2.8/0.447 or 6.25 (16dB) to avoid a severe clipping (this isn't a guitar amp).

2 The Circuit

The schematic of the amplifier is show in figure 1. It is a classic AB-class amplifier built around a complementary push-pull stage with transistors Q1 to Q4 acting as Darlinton emitter followers, and Q5 as the main amplifying stage. For the proper bias of the output transistors the resistance R6 is included along the Wilson current source build with Q6, Q7, R4, and R5.

The current source is what gives the amplifier its good performance: It increases the open-loop gain a lot, thus reducing the distortion in a feedback configuration. It also improves the PSRR (power supply rejection ratio), allowing the powering of the amplifier with a unregulated power supply with a considerable ripple without audible humming. And not just that, it also keeps the quiescent current of the amplifier stable, as we will see:

The current at the output of the source is:

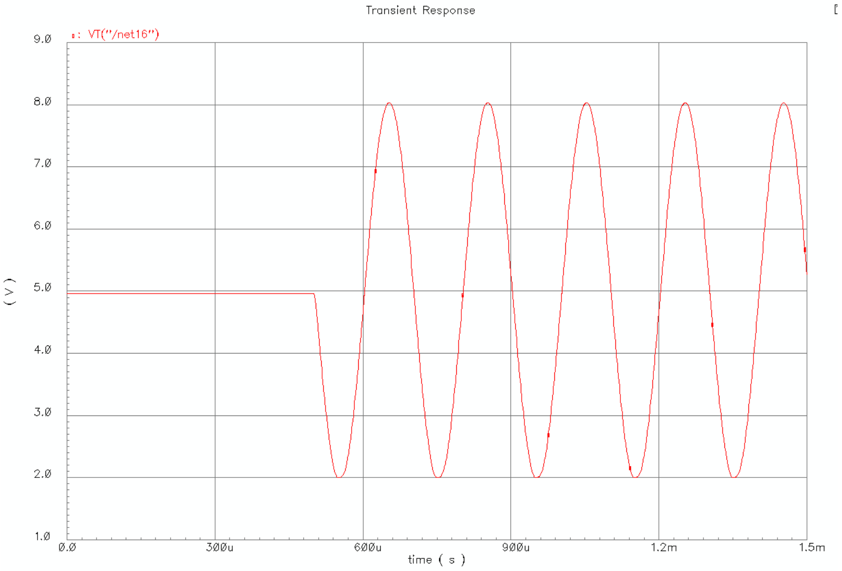

Figure 2: Transient simulation showing the output of the amplifier for a 5kHz, 0.447V, input sine wave starting at 0.5ms

$$I_{C7} = \frac{V_{EB6}}{R4}$$

V_{EB6} decreases with temperature (about -2mV/K), and the same happens with I_{C7} and the voltage across R6. But this last voltage has to be:

$$V_{R6} = I_{C7} * R_6 = V_{EB6}\frac{R_6}{R_4} = V_{BE1} + V_{BE2} + V_{EB3} + V_{EB4}$$

So, R6/R4 has to be 4 or a little less (it depends on the actual base-emitter voltages for the intended currents of the transistors). If the temperature increases all V_{BE} decreases, but the current across Q2 and Q3 remains the same, at least to a first approximation. But not all transistors are going to have the same working temperature. Q2 and Q3 dissipate much more power than Q1 and Q4 and they are going to become hotter. If Q6 is making a good thermal contact with Q2 or Q3, and it has a similar temperature while Q1 and Q4 are colder, the quiescent current through Q2 and Q3 is going to be reduced as their temperature increases. And also this current can be made lower than that of the TDA2002 to start with because we have an amplification stage with a lot of bandwidth and slew rate that can deal with crossover distortion quite well.

And talking about feedback, the voltage at the base of Q5 is going to be almost constant, and therefore we can consider that base as a "virtual ground" for AC signals, so, the amplifier resembles an opamp with an implicit positive input to ground and an inverter configuration where the ratio -R1/R2 defines the gain. On the other hand the DC voltage at the emitters of Q2 and Q3 is going to be:

$$V_O = V_{BE5} * \left(1 + \frac{R_1}{R_3}\right)$$

In this case R3 is used to adjust the output voltage to a convenient value (around 5V)

The capacitor C2 limits the bandwidth of the amplifier to about 40kHz, while C1 is an AC coupling for the input, and C3 for the output. This last capacitor has a big value because the speaker has a low impedance (4Ω) and we want a good frequency response for bass sounds.

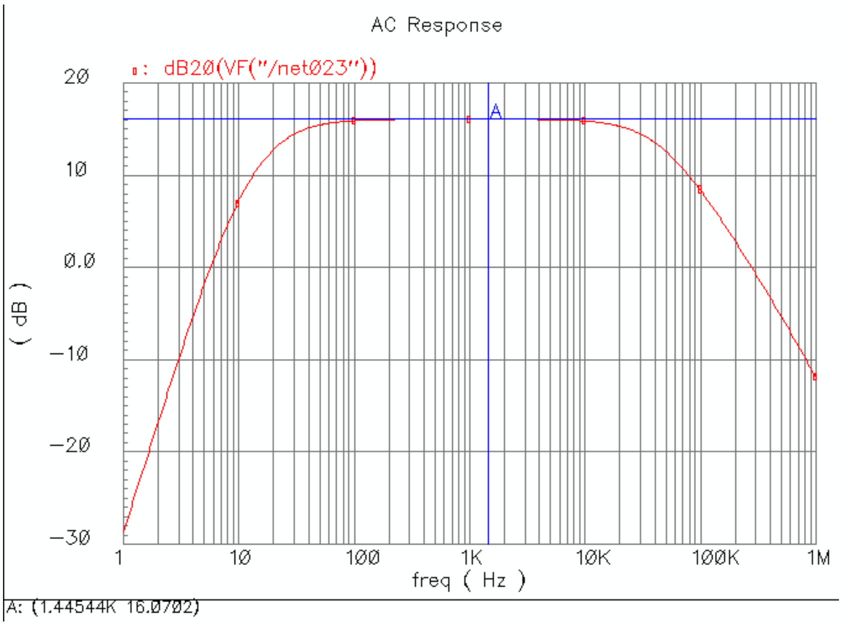

Figure 3: Frequency response of the amplifier

3 Simulation results

The circuit of figure 1 was simulated using Spice models for the transistors and the first result I want to show is the voltage as function of time at the output. In figure 2 the input remains at zero until time 0.5ms, and then a sine wave starts. In this figure the output at the emitters of Q2 and Q3 is shown, and the DC level at the start of the waveform is around 5V, allowing ±3V of output amplitude. The ending sinewave is inverted (the input starts rising), but almost perfect, without visible signs of distortion.

Then the small-signal frequency response is shown in figure 3, where a flat pass-band with the expected 16dB gain can be observed. The lower -3dB frequency is around 20Hz and the upper -3dB corner is at 40kHz. This last corner frequency is inversely proportional to C2.

Then came the time for the critical performance analysis: distortion simulation. Here the amplitude of an input sinewave was increased in steps and the resulting time-domain output transformed into a Fourier series with many harmonics. Apart from the fundamental tone, the dominant harmonics were the second and third. In the figure 4 the second harmonic increases sharply at the onset of clipping. Here this harmonic was -58dB below the fundamental, or 822 times smaller than the fundamental tone. This is very little distortion for a power amplifier.

Another parameter I wanted to get an estimate was the rejection of the supply ripple. An small-signal simulation, similar to the one of the frequency response but with the AC input placed in series with the supply source instead of the amplifier input, was carried out and its results shown in figure 5. Here we can see an attenuation of -47dB or in other words: the ripple voltage at the supply gets divided by 224 when it reachs the speaker. With this small amplitude there is no need to power the amplifier using a regulated supply because the hum will be inaudible.

There came also the time for another critical analysis, this time for the quiescent current through Q2 and Q3. Well, for R6/R4=330Ω/100Ω the resulting current was just 1.45mA, much less than the 20mA of the TDA2002, so, even with a positive temperature coefficient it would be difficult to enter a thermal runaway due to the little power involved. Anyway, I managed to carry out the simulation by changing only the temperature of the Q2, Q3, and Q6 transistors. In the figure 6 the increase in the temperature of Q6 was made lower than those of Q2 and Q3 (an 85% of temperature increase) because the thermal coupling between Q2 and Q6 is not going to be perfect. Even with this lower temperature the quiescent current keeps decreasing when the power

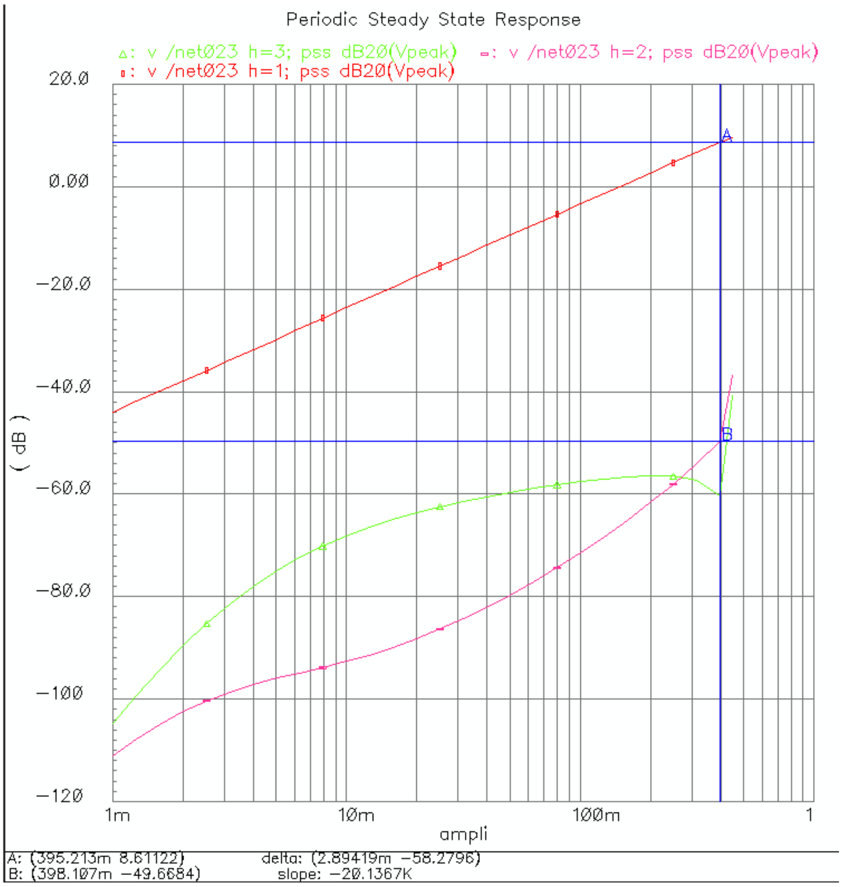

Figure 4: Distortion analysis showing the amplitudes of the first, second, and third harmonics.

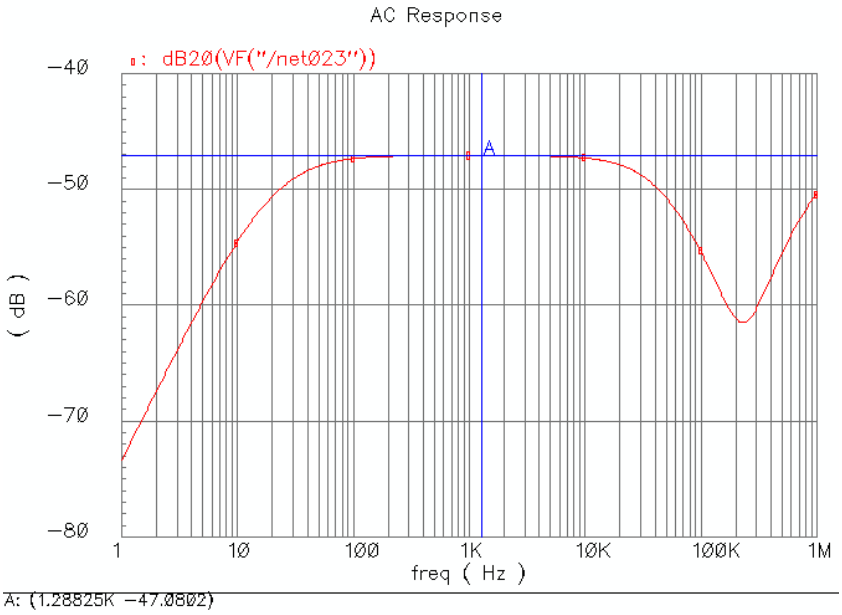

Figure 5: Power supply rejection of the amplifier

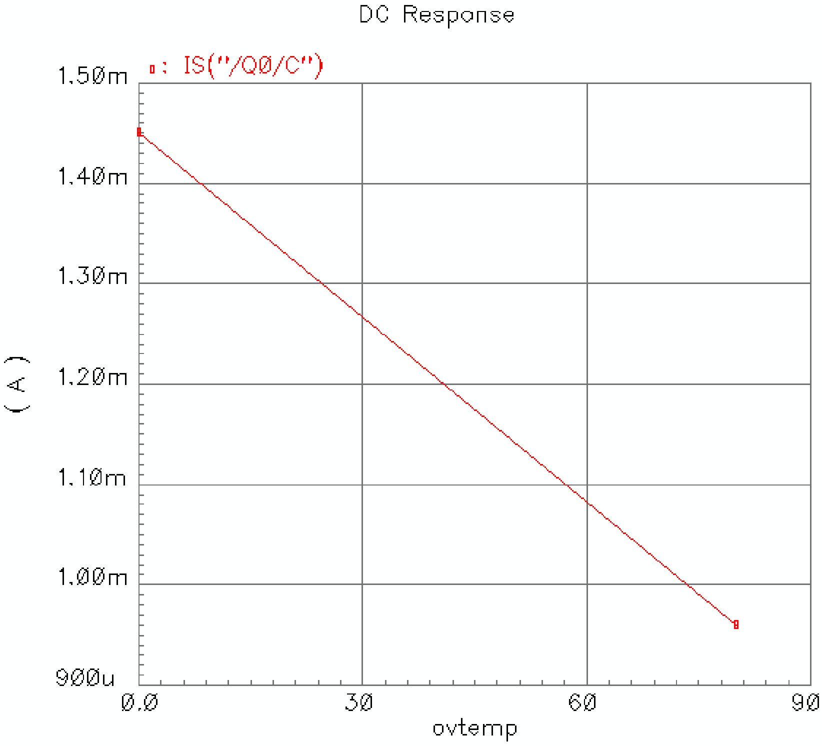

Figure 6: Quiescent current as a function of the power transistors temperature to ambient difference ($T_{Q6} = T_{AMB} + 0.85 * (T_{Q2} - T_{AMB})$)

transistors get hot, but not too much, and for lower temperature ratios in Q6 the quiescent current can have a positive temperature coefficient. So, a good thermal contact between Q2 and Q6 is strongly recommended.

And, talking about power dissipation, Q2 and Q3 can dissipate close to 1Watt for a maximum amplitude sinewave into a 4Ω load, so, a good heat sink is also needed for those transistors. But the good thing about this design is that for small amplitudes the power dissipation is also quite low thanks to the small quiescent current.

4 Experimental results

The amplifier was mounted into a breadboard and tested. It produced a sound identical to that of the TDA2002 (Linear amplifiers are quite boring: they all sound the same) For the usual volume levels the output transistors were still cold and no heat sinks were needed. Also, the thermal contact between Q2 and Q6 wasn't included (these two transistors ought to be glued together) The amplifier was kept operating for a long time without any problem.

In order to test the amplifier at its maximum power without disturbing the neighbors the speaker was replaced with a dummy load and the sound source with a signal generator. An scope screenshot is shown in figure 8. In this case the output transistors became quite hot as it did the dummy load resistor, but no signs of thermal runaway were observed, even with Q6 at room temperature.

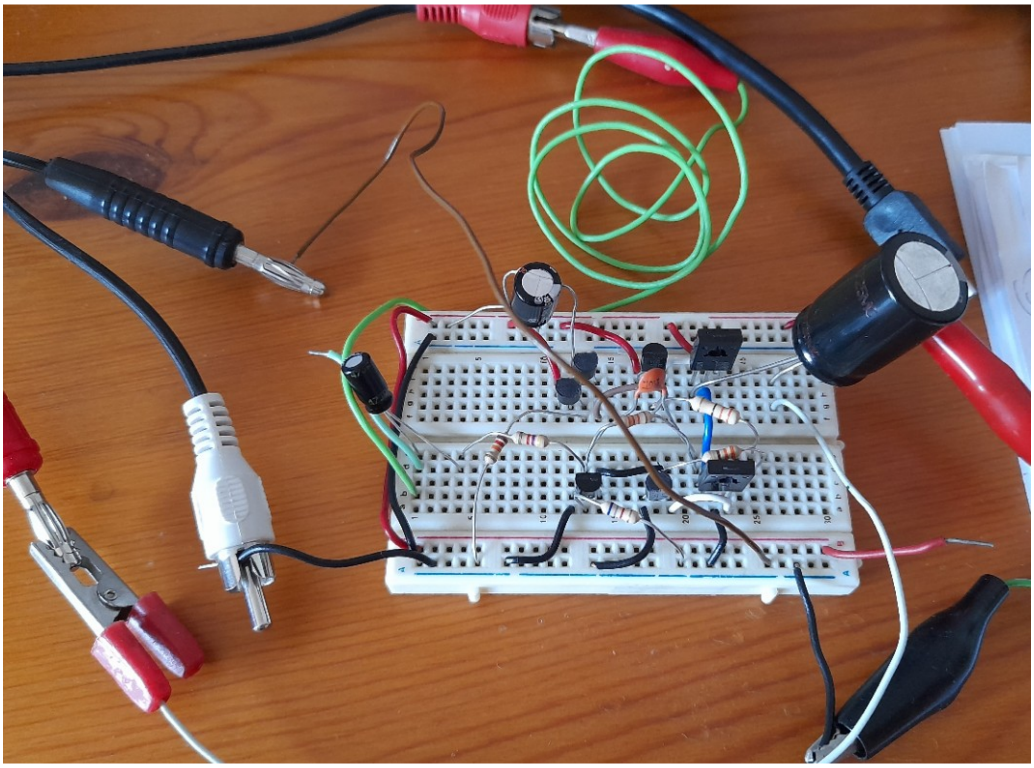

Figure 7: The amplifier mounted into a breadboard and working.

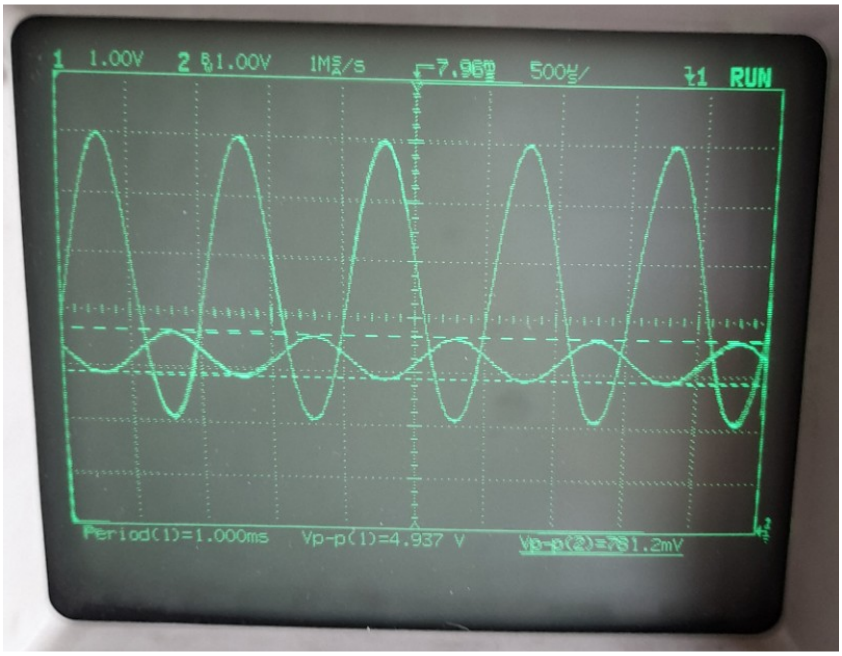

Figure 8: Output signal with a sine wave and a dummy load.

5 Stereo AMP on a PCB

An stereo version of the amplifier is presented in figure 9. Here, a single sided PCB was also designed to host all the components. This is basically a duplicate of the previous amplifier, I only want to remark the placement of the power transistors that would allow the sharing of heat sinks for the two PNP and two NPN transistors, and also the placement of the temperature sensitive transistors Q10 and Q13 very close to Q2 and Q7.

A short video with the amplifier working is linked here:
`http://www.ele.uva.es/~jesus/amplivideo.mp4`

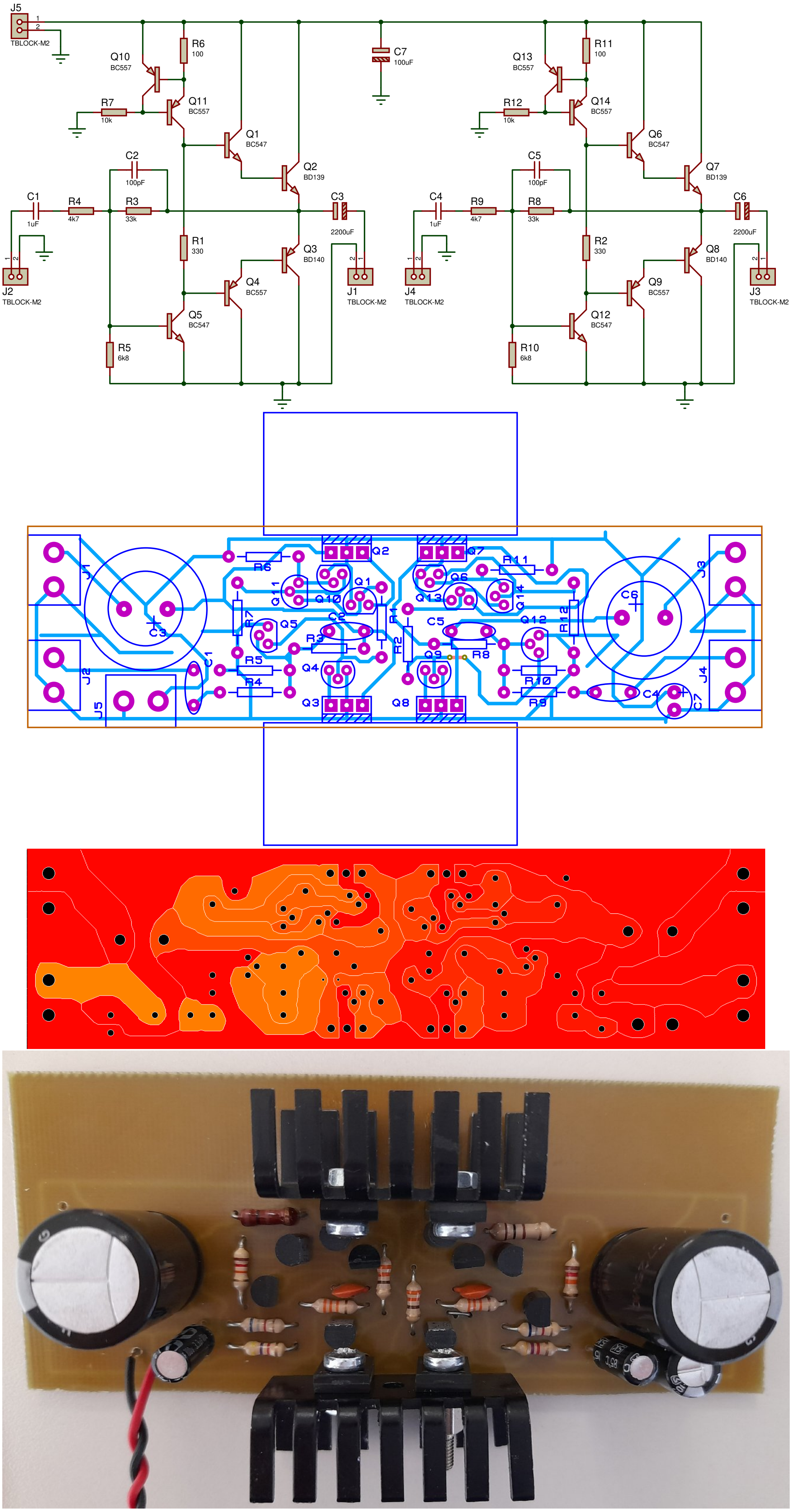

Figure 9: Schematic of the stereo amplifier, layouts, and board.