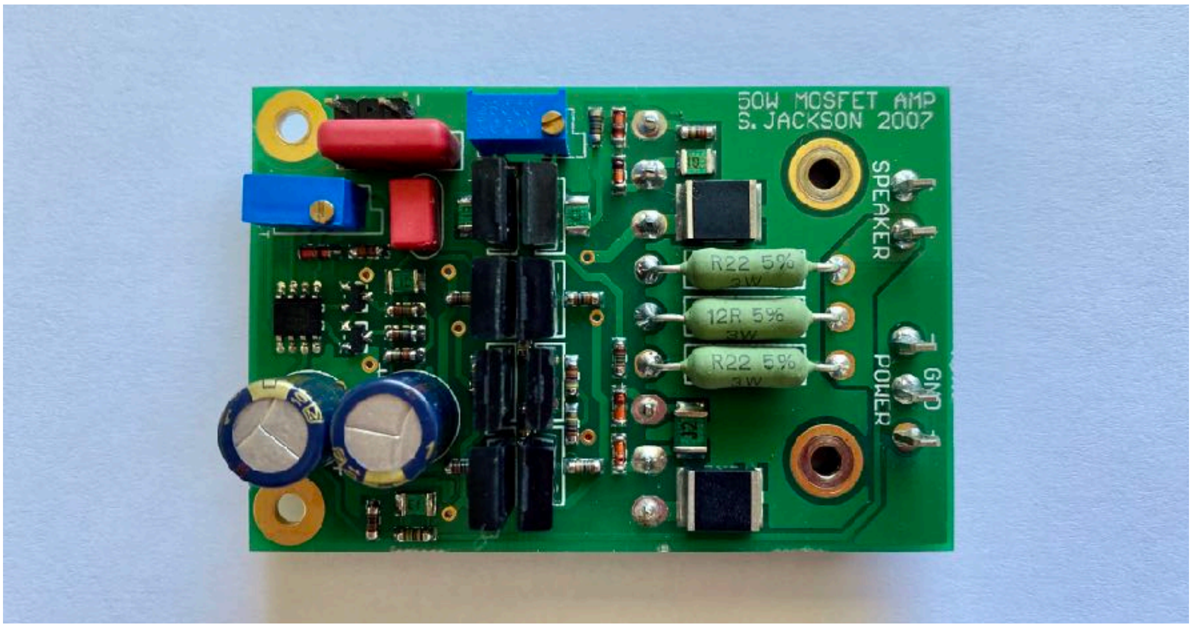
AEM6000 Based 50W Amplifier

Construction Notes

This amplifier is based on the AEM6000 design, originally by David Tilbrook, published in 1987. It is an evolution of his original design, making use of more modern transistors, and laid out using a double sided through-hole plated printed circuit board (PCB) with some changes to the VAS topology.



A complete power amplifier PCB top view, assembled with MELF resistors and mica capacitors. Note the power transistors are mounted on the underside of the PCB.

At 50W RMS output, it's adequate for driving most speakers up to around 6" diameter, and mid-ranges and tweeters in bigger speaker systems. The amplifier's reasonably good distortion and very low noise specs make for good transparency, and being based on lateral MOSFETs it's very difficult to damage.

This design is free for use for non-commercial purposes.

Specifications

Power handling:	50W RMS into 8Ω load.
Frequency response:	+/- 0.1dB from 20Hz to 20KHz.
Gain	16 (stable with gain as low as 6).
Distortion + Noise:	<0.0005% (1KHz, 0.1W to 50W into 8Ω).
	<0.003% (10KHz, 0.1W to 50W into 8Ω).
Noise (input referred):	8nV/√Hz (measured at 10KHz, input shorted).
Slew rate:	10V/μs
Input impedance:	100KΩ (set by resistor).
Size:	75mm x 50mm PCB.
Power supply requirement:	2 x 40-60V DC. Lower voltages possible.
Idle power:	5.6W with +/-40V supply.

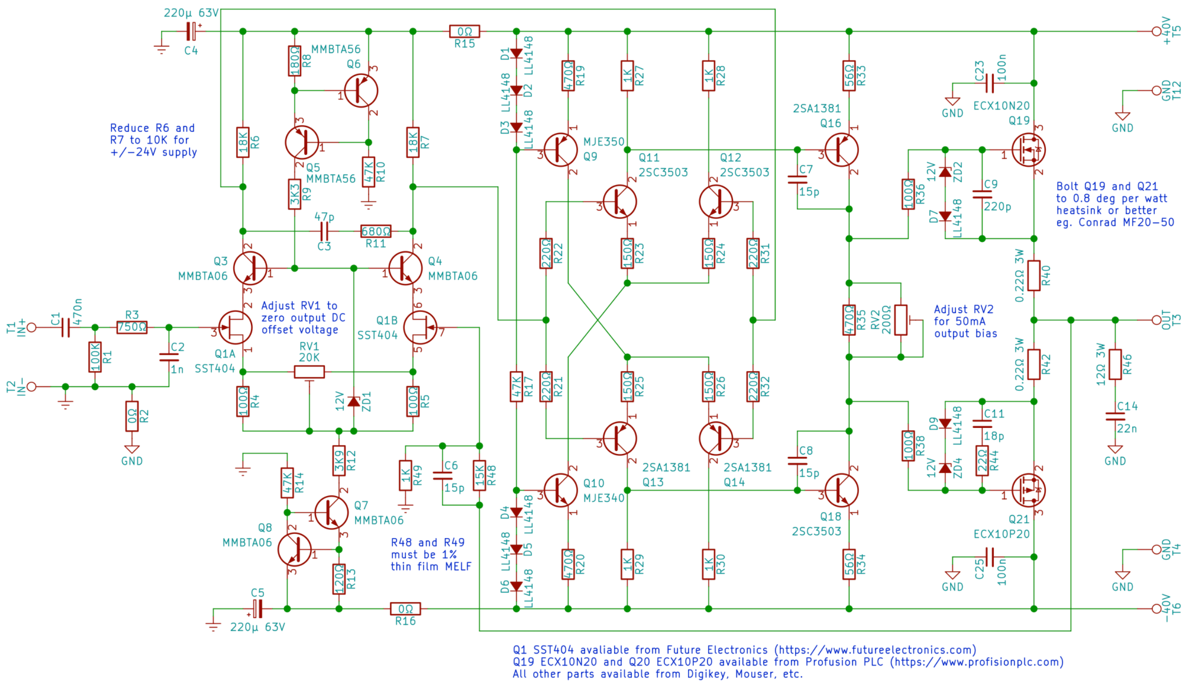
Description

The AEM6000 is an extremely well regarded amplifier making use of Hitachi lateral MOSFETs. It was designed by David Tilbrook as a successor to the ETI477, and published in Australian Electronics Monthly in the nineteen eighties.

With changes in availability of components, the AEM6000 is now extremely difficult to build. The amplifier was designed prior to the widespread use of modelling tools, so is not optimised. Additionally it makes use of a large single-sided PCB, with through-hole components throughout, like most kitset amplifiers of the period.

This marks my fourth iteration of this amplifier. My first was reasonably faithful to the original, differing mainly by substituting 2SK1058 and 2SJ162 flatpack lateral power MOSFETs for the TO-3 devices in the original, plus substituting an SST-404 dual JFET for the original input JFET. Iteration two was simply a 50W version of iteration one. This and the iteration three design (100W) alters the topology slightly, dispensing with the differential-symmetrical VAS stage in favour of a simpler non-differential stage. VAS and second stage transistors are higher-performance 2SC3503 and 2SA1381, and the compensation networks and biasing is optimised for increased amplifier speed whilst reducing quiescent consumption

Referring to the amplifier schematic, Q1 forms a differential pair, with the amplifier input connected to one side and the feedback point (divided by 16 via R48 and R49) on the other. Q7 and Q8 form a 5mA current sink to bias the input stage. 800µA flows through each JFET, and the balance is used to bias a cascode, comprising Q3 and Q4. The cascode stage ensures the input JFETs only have 12V across them regardless of supply voltage, and also speeds the input stage up, by virtue of reducing miller capacitance effect. The current source comprising Q5 and Q6 source current into the cascode bases.



The amplifier schematic. A full-page version of this diagram is included at the end of this document.

Using a pair of current sources to run the cascode allows for improved CMRR (and thus better PSRR) than if the cascode were simply biased at a set voltage.

R6 and R7 are loads for the first stage. The resistance here is optimally such that the first stage gain is maximised for a given supply voltage. 18KΩ works well for a +/-40V supply. If the supply is reduced much below this, the load resistors must be adjusted accordingly. I have built a pair for some 4” speakers with +/-24V supplies that runs happily with 10KΩ load resistors.

The second stage is a symmetrical pair of differential amplifiers to provide further gain, comprising Q11-Q14. Q11 and Q12 are biased by Q10, which forms a constant current sink. Q13 and Q14 are biased by Q9. Each side of the differential amps runs 1.2mA, meaning that these transistors do not need heat sinks.

2SC3503 and 2SA1831 provide a modest speed increase over the original MJE340 and MJE350, due to reduced C_{ob} of 2.6pF.

The output transistors are driven by Q16 and Q18. These transistors are also swapped from MJE340 and MJE350 to 2SC3503 and 2SA1831, again providing a modest speed increase.

The current through this stage is referred back to the tail currents for the preceding stage, via R27 and R29. 1K, along with 56Ω on the transistor emitters, drives the stage at 10mA, which is ample to quickly charge and discharge the MOSFET gates and ensure good slew rate, but still low enough to allow operation of the transistors without heat sinks.

R35 in parallel with RV2 sets the final output stage bias current. I have found 50mA to be ample to reduce THD (both at 1KHz and 10KHz) to difficult to measure values. There is established lore in the audio DIY community that lateral MOSFETs must be biased at 100mA per stage or more. This comes about mainly through their use in unsophisticated amplifiers with inadequate open loop gain and slew-rate to correct crossover distortion. A straightforward cheat to obtain better distortion numbers in this case is to wind the wick up and turn a fan on. If 100mA is truly desired then it will be necessary to replace RV2 with a 500Ω trimpot.

On the topic of output stage quiescent current, 2SK1058 and 2SJ162 are positive temperature coefficient to around 50mA. After this they are negative. This means that if the bias current is set much below 50mA, it will not be very stable. Exicon devices (ECX10N20 and ECX10P20) are much better in this regard. The bias current can be set to just a few mA, such that the amplifier is mostly class B, and the bias stays quite stable. I have a pair (my +/-24V ones) that run at around 20mA, resulting in an overall amplifier idle power of just over 2W, unheard of for lateral MOSFETs.

Bias currents are as follows:

Stage 1:	0.8mA per JFET (1.6mA total)
Stage 2:	1.2mA per side (2.4mA total)
Stage 3:	10mA
Output MOSFETs:	50mA

Compensation is straightforward, with poles provided by C3 in series with R11, C7 and C8 providing conventional miller compensation, R46 and C14 providing an output Zobel network, and C6 compensating the feedback path.

The amplifier is laid out on a 75mm x 50mm PCB, using a minimum trace width and spacing of 15 thou. It omits the bulk filter capacitors, but can be mounted directly to the amplifier heatsink.

The end result is a robust, dependable, fast, quiet and reasonably cool amplifier, that has been (disparagingly) referred to as clinical. To my mind this is exactly what an amplifier should be. I've had half a dozen in near constant use for years, driving for example my Ariel transmission line speakers, my original noisePlank, noiseUnit (in prototyping), a pair of Infinity RS-5b speakers, and some DIYAudio "reference" speakers. It's my go-to amplifier.

PCB Manufacture

The following files are included to enable manufacture of the amplifier PCB:

AEM6000_Based_50W_Amp.GTO	Top layer component overlay
AEM6000_Based_50W_Amp.GTS	Top layer solder mask
AEM6000_Based_50W_Amp.GTL	Top copper layer
AEM6000_Based_50W_Amp.GBL	Bottom copper layer
AEM6000_Based_50W_Amp.GBS	Bottom layer solder mask
AEM6000_Based_50W_Amp.GBO	Bottom layer component overlay
AEM6000_Based_50W_Amp.GKO	Board outline
AEM6000_Based_50W_Amp.TXT	Drill file

The .G** files are in RS-274x Gerber files with embedded apertures. The .TXT file is the drill file in Excellon format.

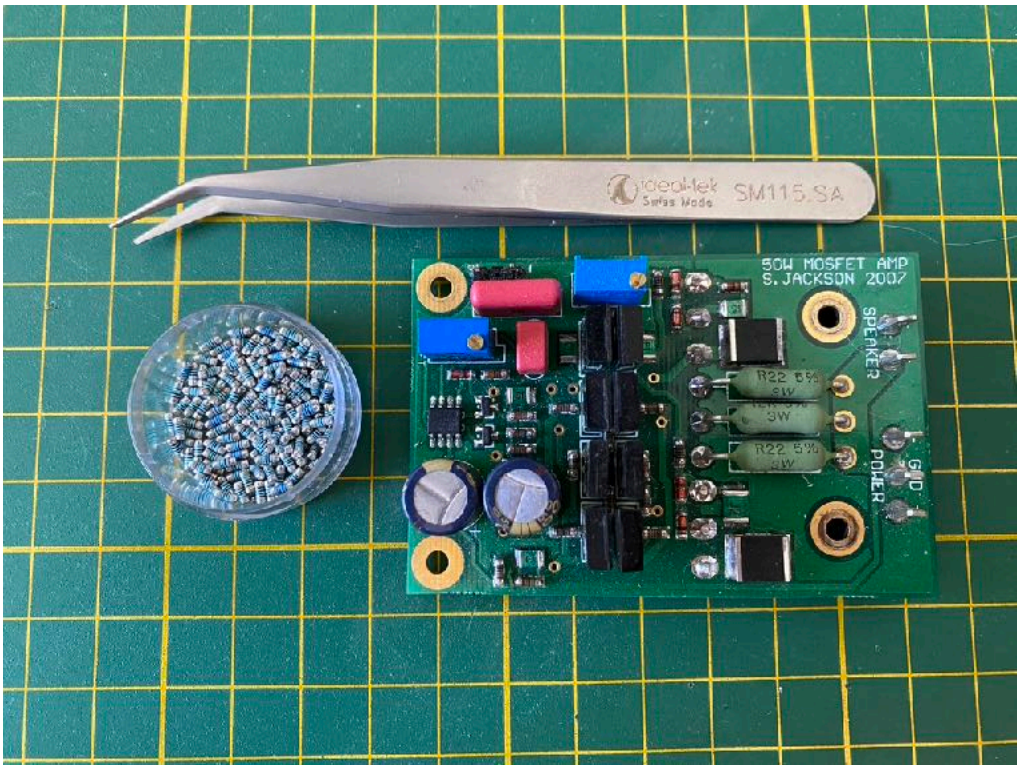
The PCB should be manufactured to the following specifications:

PCB material:	FR4
PCB size:	2950 x 1950 mils (74.9mm x 49.5mm)
PCB thickness:	62 mils (1.6mm)
Construction:	2 Layer with plate-thru holes
Copper weight:	1oz min (2oz preferred)
Soldermask:	Green, both sides
Overlay:	White, both sides.
Finish:	Electroless Nickel Immersion Gold (ENIG)
Min hole:	30 mils (0.76mm)
Max hole:	125 mils (3.2mm)

Assembly

Despite gnashing of teeth regarding surface mount components, this amplifier is not particularly difficult to build. The smallest components are 1206 or MELF resistors and SOT-23 transistors. Reflow ovens and hot air tools are not required. It is amenable to hand-assembly using a soldering iron..

Assembly is aided significantly by the use of tweezers that are optimised for handling MELF resistors and diodes, such as the Ideal-tek SM115.SA, which has a small notch in the tip that locates the parts.



Notched tweezers for working with cylindrical MELF parts.

I am short sighted, so tend to work close-up and see fine detail. If you are not, I suggest working under a magnifying lamp or similar.

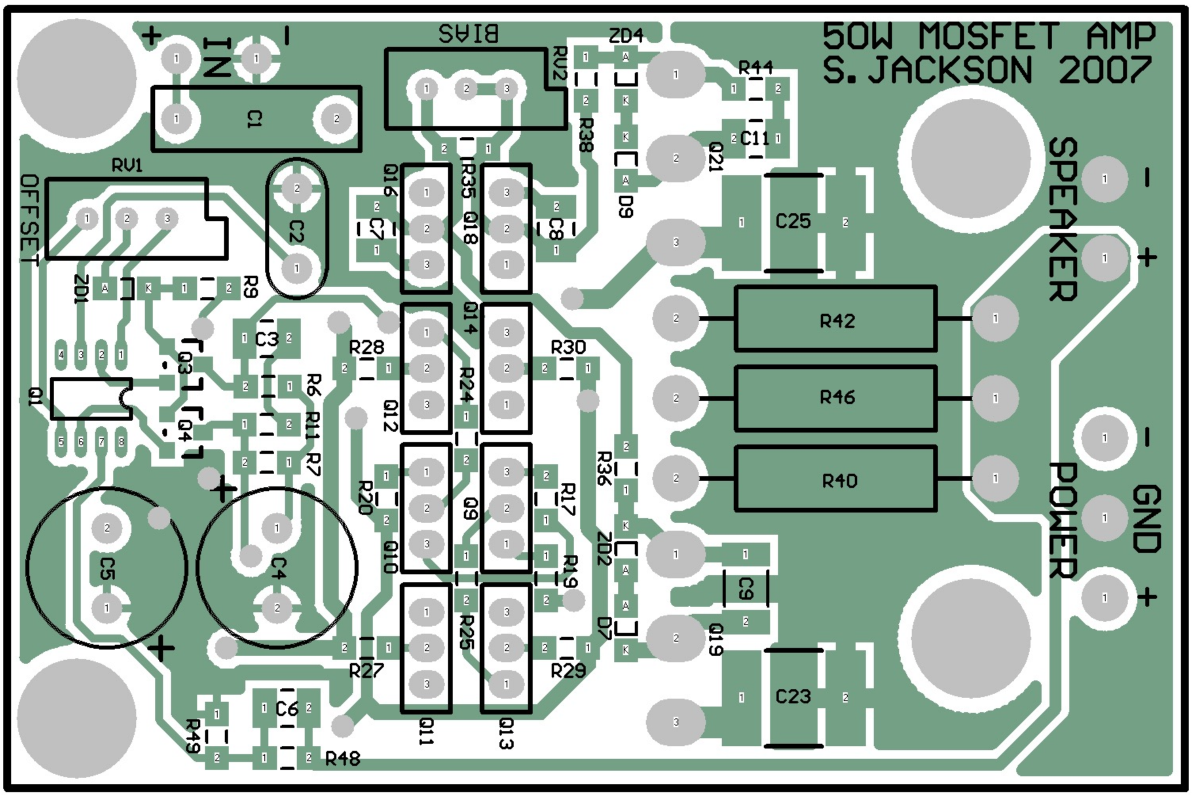
Use a good quality soldering iron with a fine, temperature controlled tip. Keep the temperature down and work slowly and methodically. I use a Metcal MX-500P, with an STTC-038 (1.5mm 350°) tip for surface mount parts, and an STTC-036 (2.5mm 350°) tip for through-hole components.

Use SN62 tin/lead/silver solder (I find 0.7mm & 0.5mm handy), and add some Rosin Mildly Activated (RMA) flux to the board to aid wetting.

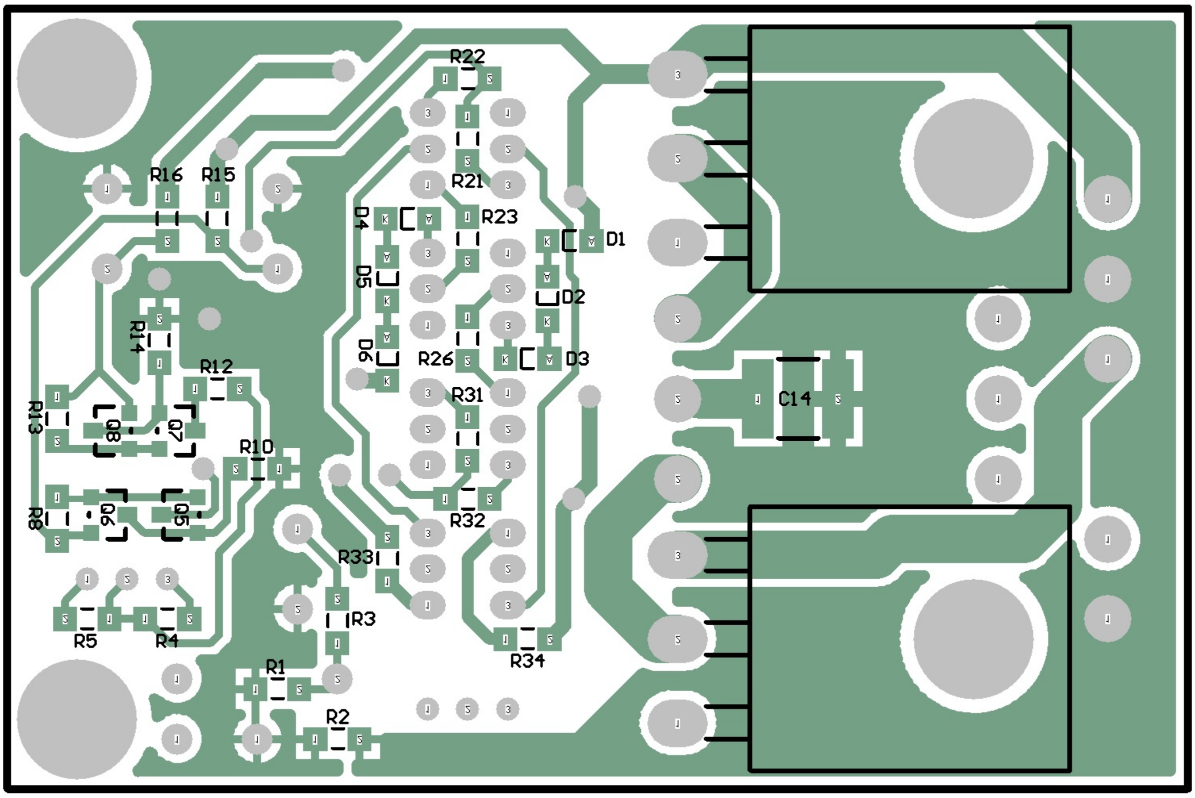
Assembly begins with resistors and surface mounted capacitors. I find the most straightforward method to mount parts is to put a dab of RMA flux on the pads, then tin one pad with solder. Pick up the part to be mounted with the tweezers and solder one end to the tinned pad. Finally solder the other end as a separate operation.

Next mount the SOT-23 transistors, and then the input JFET. Take static precautions when handling the JFET, as its gates are static sensitive.

The PCB has no designators, as the parts are packed in fairly closely, making designators difficult to place. Instead, please refer to the stuffing diagrams below in conjunction with the parts list for component placement:

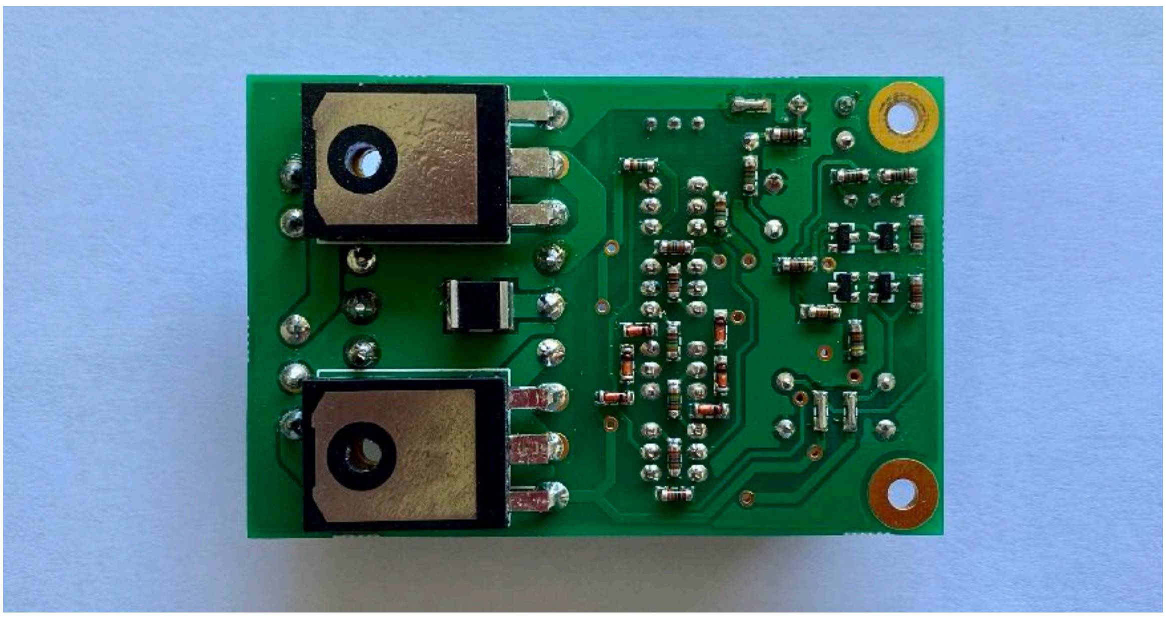


Top layer stuffing diagram



Bottom layer stuffing diagram

Finally mount the through-hole parts. Take care bending the leads of the output transistors to ensure that the hole in the transistor case lines up with the hole in the PCB. It's a good idea to put an M3 screw through the PCB and transistor prior to soldering.



The underside of a completed amplifier. Note the substitution of wire links for the 0Ω resistors. Further note how the output transistors are mounted to the underside with their heatsink tabs down.

Note that all TO-126 devices are mounted such that their metal backs face one another. The metal backs on the output transistors must be down, away from the PCB on the underside, so that they are in contact with the heatsink (via some insulating thermal pads) when the amplifier is mounted.

Put a popsicle stick under the three 3W power resistors when mounting them to ensure they are raised slightly from the PCB. They do not get particularly hot in use, but if the amplifier is oscillating the middle one (12Ω) will dissipate several watts, and get too hot to touch.

Power Supply and Heatsink

Choice of power supply is dictated by load resistance and output power requirement. 40V rails are adequate to supply 50W into 8Ω. In this case the output is 20V RMS (28V peak). For a 4Ω load, drop the voltage to about 36V.

A 2 X 30VAC, 100 VA power transformer is more than adequate for a typical 6-8Ω speaker, with a 5A bridge rectifier and 6800µF 63V filter capacitors.

A 0.8˚C/W heatsink is adequate for normal use. I designed it with the Conrad MF20-50 in mind. For testing purposes a fan is useful, or else use a bigger heatsink.

Initial Setup

As with all amplifiers, some care must be taken in initial power-up. Mistakes can result in expensive blown transistors.

Double check everything, to ensure the amplifier is built correctly. The reference photos should be useful as comparisons. Scrub the board thoroughly to remove all traces of flux using isopropyl alcohol and a stiff brush, and mop up flux residue with cotton buds or lint-free wipes. Check every solder connection under a magnifying glass. Check the orientation of the diodes and capacitors.

Mount the amplifier to a heatsink, with thermal pads under the output devices. Double check using a multimeter that nothing is grossly shorted out before applying power.

I like to initially power these small amplifiers up using a lab supply. My supplies (venerable Thurlby PL320s) have been tweaked to do 40V, 2A, which is just the ticket for this job. If a lab supply is not available, use either a light bulb or large power resistor in series with both sides of the supply in order to limit current.

Start with no load connected, and the input shorted.

Overall quiescent current should be around 70mA at +/-40V. Prior to setting the output stage bias it won’t be anywhere near this, but values more than ~200mA are indicative of oscillation.

Put a multimeter across the amplifier output and check for DC volts. Adjust RV1 to zero the output voltage. The output DC should be stable well under 10mV.

Next put a multimeter across R40 and adjust RV2 to obtain 11mV. This sets the bias current to 50mA.

At this stage the power supply should show 70mA, plus or minus say 5mA. If it doesn’t, something is amiss.

Go make a cup of tea, to allow the amplifier to fully come up to temperature, and double-check the settings. It’s normal for the offset to drift by a few mV, as the temperature coefficient of the input JFET match is only specced to 25μV/°C. It’s also normal for the quiescent current to drop a little, due to the negative temperature coefficient of the MOSFET transconductance. This is a good thing. It’s one of the features that makes lateral MOSFETs so hard to kill.

The amplifier should now be ready to use. Transfer to a real power supply (something like a 2 x 30V, 100VA toroidal, with a pair of 6800μF 63V filter caps after the rectifier should be plenty). Again check for rookie mistakes, then cross your fingers and turn it on.

Testing

I like to run the following tests to confirm operation of the amp.

A quiescent current check, in conjunction with biasing. This should show around 70mA on each supply with 40V supplies and 50mA bias.

A check and adjustment of the output DC voltage, which should be better than 10mV. I like to return to this a couple of times during testing, to satisfy myself that it’s stable as the amplifier heats up.

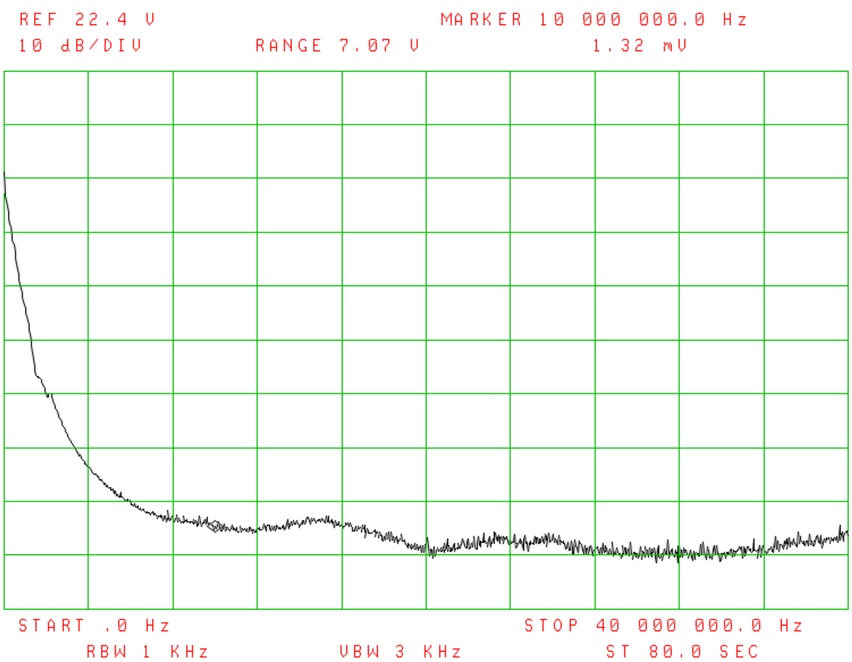
Here are some selected DC voltages throughout circuit (indicative values taken from operating amp)

Node	**Voltage**
Q1 sources wrt GND	0.53V
Q1 drains wrt GND	12.0V
Q3 & Q4 collectors wrt GND	27.0V
Q9 collector wrt GND	28.0V
Q10 collector wrt GND	26.0V
Across R35	1.26V
Across R40, R42	11.0mV

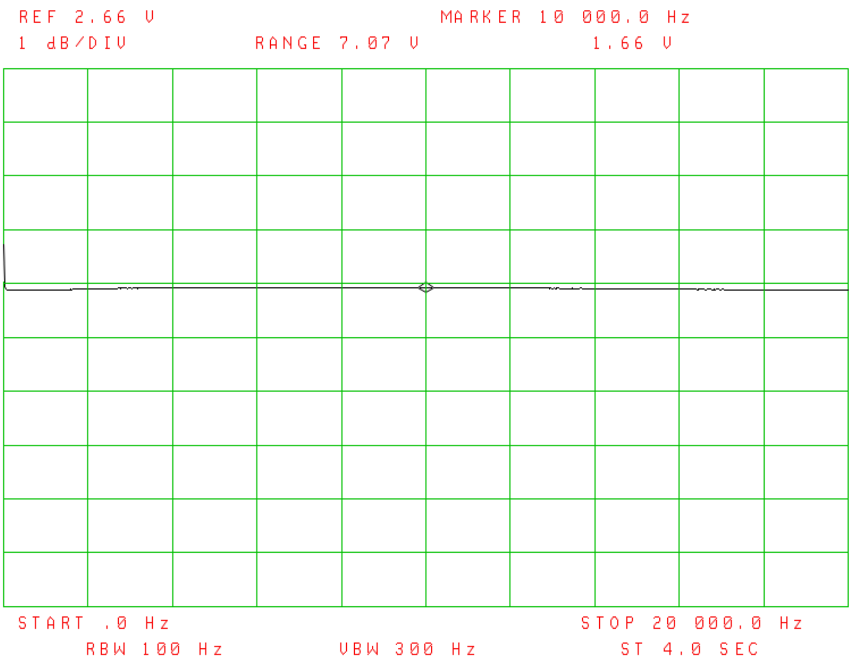
They're really more of use to diagnose what's going wrong with a misbehaving amplifier. I don't generally check any of these unless something is wrong.

This is where the "does it work" tests can probably end. Put an input on it and connect the output to a speaker, and enjoy. Really if there are any gross errors it'll be seen in excessive quiescent current or inability to bias and zero.

I like to perform an oscillation check, where I connect the amplifier output to an 8Ω load, and also to my HP3585B spectrum analyser, and connect the amplifier input to the spectrum analyser tracking generator, and do a quick sweep from DC to 40MHz. With the input HF filter at around 100KHz, there should be a quick drop-off from there to the spectrum analyser noise floor, all the way to 40MHz.



Oscillation check, showing a clean drop-off from the input HF filter, and nothing of interest out of band.

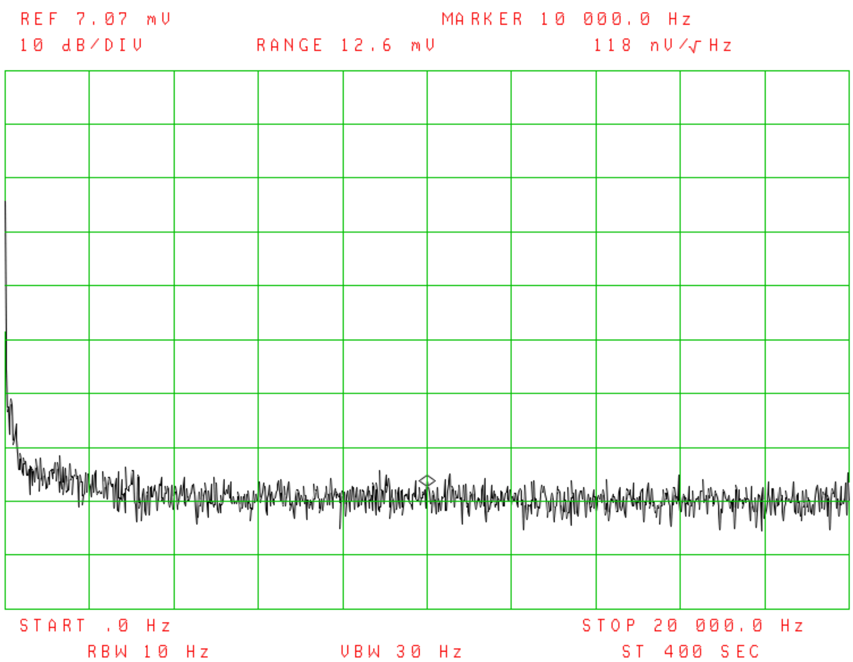


Bandpass from DC to 20KHz, 1dB per division.

Next I perform a bandpass sweep test, from DC to 20KHz with the tracking generator. I find changing to 1dB/div is necessary to see any features in the passband. It should be flat.

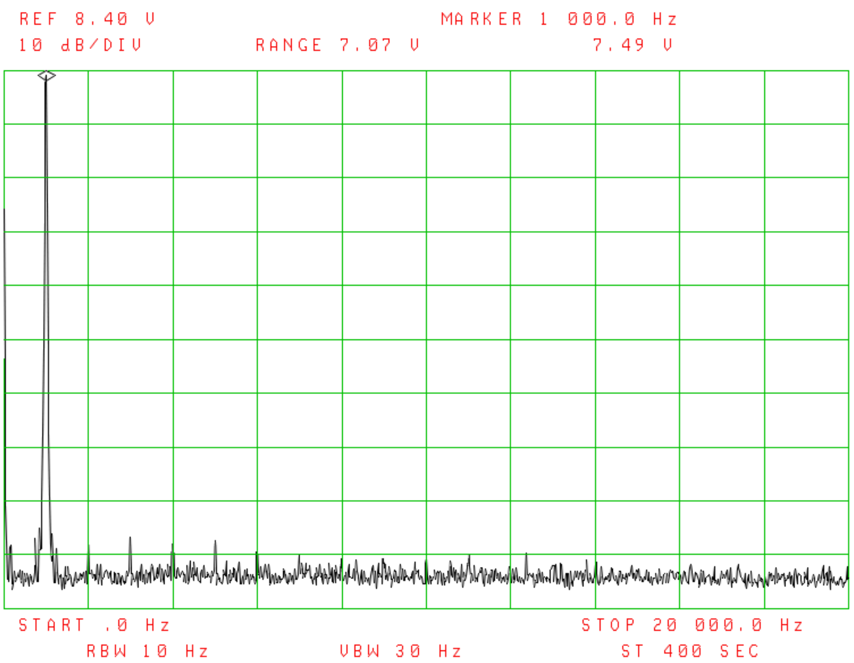
A noise level test is next. This one shows if there's anything weird going on with the input JFET (you did take proper static precautions when handling it, didn't you?). To perform this one, I short the amplifier input with a jumper wire, and perform a slow 10Hz resolution bandwidth sweep from DC to 20KHz with HP3585B marker set to noise level at 10KHz. The 3585B does the math to work out the noise in a 1Hz bandwidth automatically.

I generally get something like 120nV/√Hz at the output, which gives me 8nV/√Hz input referred. To put things in context, this is about the same as an OPA2134 low-noise FET-input opamp. Who needs preamps!



Amplifier output noise level with input shorted. 118nV/√Hz at the output is 7.4nV/√Hz input referred (x16 gain)

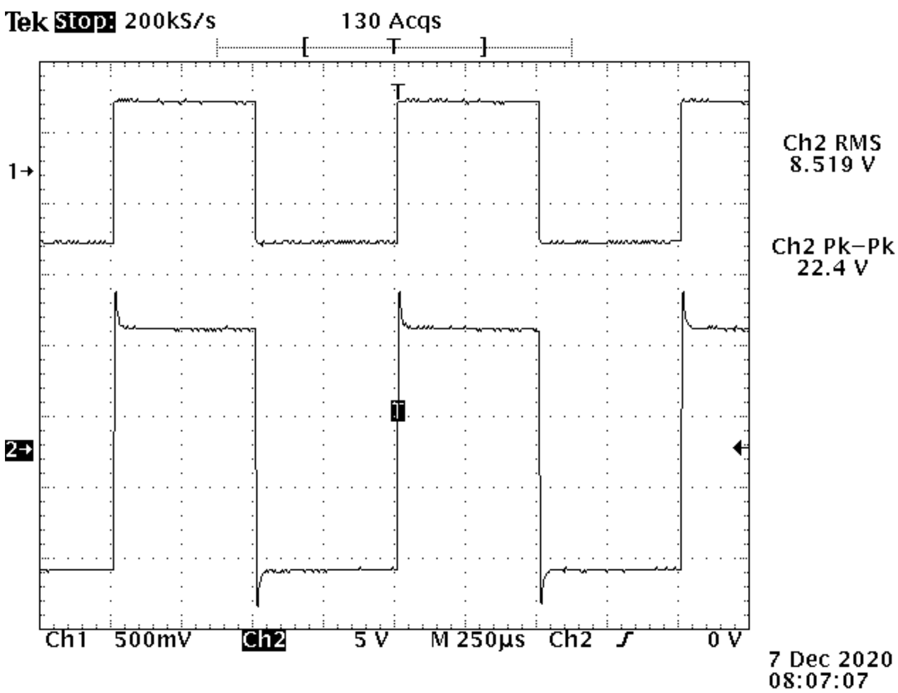
Finally I connect a synthesiser to the input and 8Ω load to the



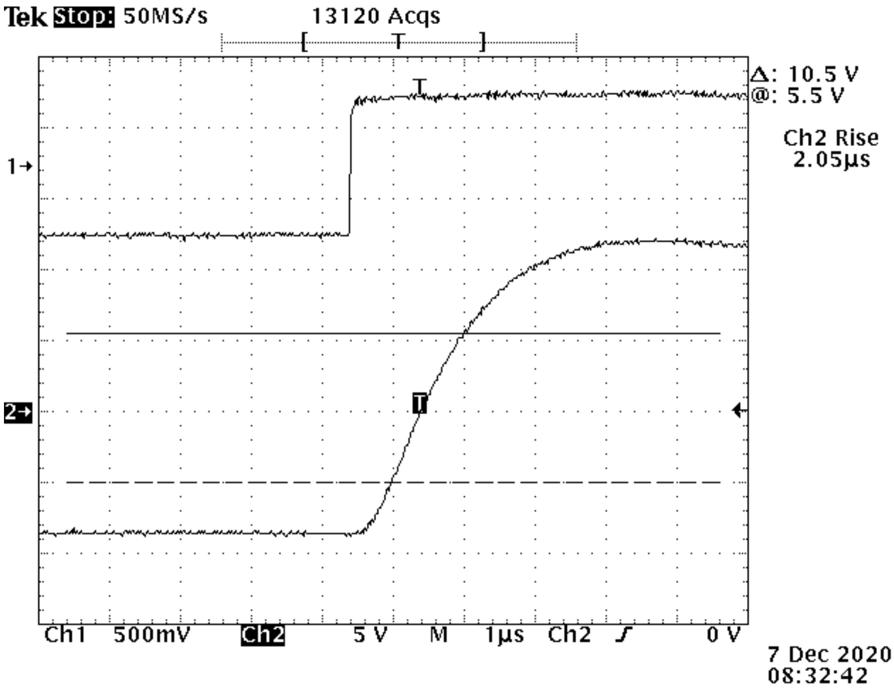
1KHz quick and dirty THD measurement using HP3325B as source.

output, and check for a correct output. A 20dB pad or CRO probe may be necessary to protect the spectrum analyser input at this stage. Below shows 1KHz in from my HP3325B synthesiser at 0.47V RMS in, providing 7.5V RMS out. Note that most synthesisers specify output into 50Ω. The input impedance of the amplifier is 100KΩ, so the levels will be out by around a factor of 2. If in doubt, measure.

The THD measurement shown is limited by the HP3325B output harmonics. It's possible to do a much better measurement to uncover the amplifier THD, but this requires many hours of patience with a low-distortion oscillator and a notch filter on the spectrum analyser. I did that with the 100W version of this amplifier, and have extrapolated the figures for the specification for



Square wave response showing moderate overshoot

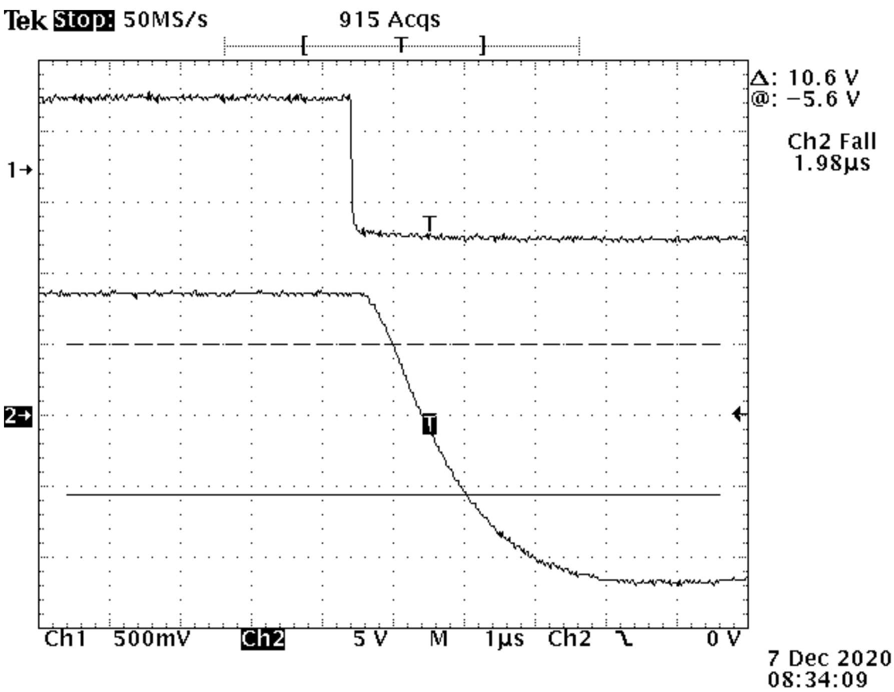


Rising edge, showing slew rate of around 10V/µs

this one.

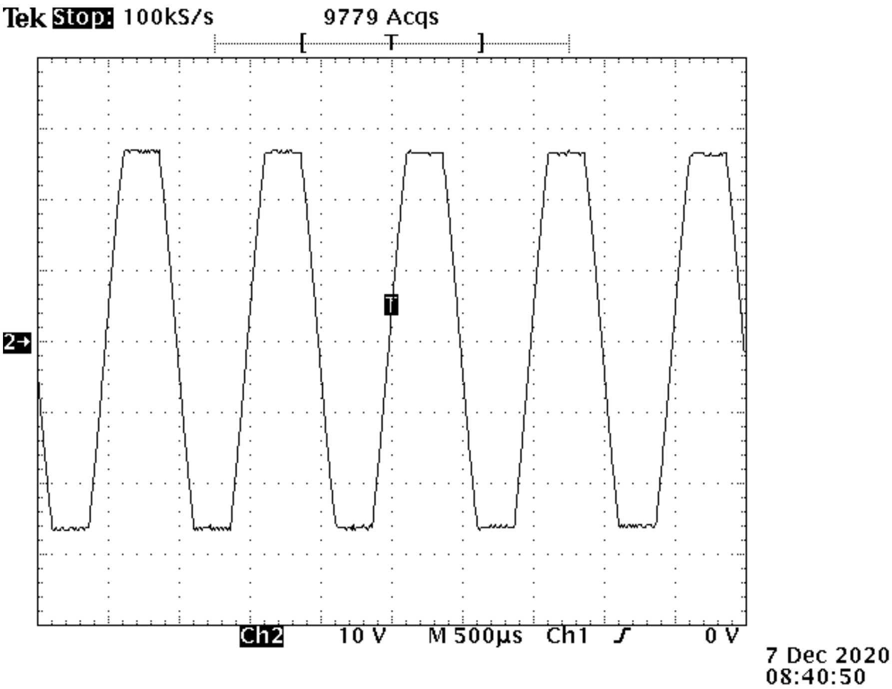
Slew response is another good thing to measure. A misbehaving or poorly compensated amplifier won't faithfully reproduce square waves. I like to compensate amplifiers such that there's a little bit of overshoot, but no ringing. I find that provides better slew rate and thus improved transient response.

Zooming in to the edges makes it possible to directly measure slew rate. The convention is to measure in volts per µs, so select 1µs per division, and position the waveform so that the steepest part of the edge is between two divisions. Now put horizontal cursors at the intersection of the waveform and 1µs division spots, and simply read off the slew rate.



Falling edge, showing slew rate of around 10V/µs

The slew rate should be reasonably well balanced. The N-channel and P-channel MOSFETs have wildly different capacitances. Normally this would make for very different slew rates. The function of the capacitors added between gate and source is to roughly even the slew rate out.



Clipping response, showing no significant rail sticking or ringing.

Finally push the amplifier into clipping, to ensure all is well. Clipping response is one of the best ways to tell if there is something amiss with the compensation. The amplifier should clip cleanly, without ringing, sticking to the rails, or bursting into oscillation.

At this point the amplifier should be stinking hot. Let it cool down for a while, connect it to a speaker, and play some music.

Parts List

Resistors:

Designator	Description	Package	Supplier	Part Number
R1	100K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1003FB3
R2	0R link	MELF 0204	Mouser	OMM02040000000B0
R3	750Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C7500FB3
R4	100Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1000FB3
R5	100Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1000FB3
R6	18K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1802FB3
R7	18K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1802FB3
R8	180Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1800FB3
R9	3K3 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C3301FB3
R10	47K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4702FB3
R11	680Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C6800FB3
R12	3K9 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C3901FB3
R13	120Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1200FB3
R14	47K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4702FB3
R15	0R link	MELF 0204	Mouser	OMM02040000000B0
R16	0R link	MELF 0204	Mouser	OMM02040000000B0
R17	47K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4702FB3
R19	470Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4700FB3
R20	470Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4700FB3
R21	220Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C2200FB3
R22	220Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C2200FB3
R23	150Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1500FB3
R24	150Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1500FB3
R25	150Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1500FB3
R26	150Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1500FB3
R27	1K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1001FB3
R28	1K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1001FB3

Designator	Description	Package	Supplier	Part Number
R29	1K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1001FB3
R30	1K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1001FB3
R31	220Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C2200FB3
R32	220Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C2200FB3
R33	56Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C5609FB3
R34	56Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C5609FB3
R35	470Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C4700FB3
R36	100Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1000FB3
R38	100Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1000FB3
R40	220mΩ 3W 5% wirewound	13mm x 5mm dia axial	Mouser	AC030002207JAC00
R42	220mΩ 3W 5% wirewound	13mm x 5mm dia axial	Mouser	AC030002207JAC00
R44	22Ω 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C2209FB3
R46	12Ω 3W 5% wirewound	13mm x 5mm dia axial	Mouser	AC03000001209JAC00
R48	15K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1502FB3
R49	1K 0.4W 1% 50ppm	MELF 0204	Mouser	MMA02040C1001FB3
RV1	20K 25 turn trimpot, top adjust	3296W	Mouser	3296W-1-203LF
RV2	200Ω 25 turn trimpot, top adjust	3296W	Mouser	3296W-1-201LF

Substitution Notes:

1206 thick-film resistors are fine as substitutions for MELFs, except in the case of R48 and R49. These parts form the feedback divider, and any voltage coefficient or thermal coefficient here will directly affect the THD.

If MELFs are unavailable, substitute thin-film 1206 chip resistors here instead.

Capacitors:

Designator	Description	Package	Supplier	Part Number
C1	470n 63V 5% MKS film	13mm x 4mm MKS	Mouser	MKS4C034703C00JB00
C2	1n 100V 5% FKS film	7mm x 3mm FKS	Mouser	FKS2D011001A00JA
C3	47p 500V 5% mica	3.2mm x 2.5mm chip	Mouser	MC12FD470J-TF
C4	220µ 63V 105˚ electrolytic	10mm dia radial	Mouser	EEU-FC1J221XB
C5	220µ 63V 105˚ electrolytic	10mm dia radial	Mouser	EEU-FC1J221XB
C6	15p 500V 5% mica	3.2mm x 2.5mm chip	Mouser	MC12ED150J-TF
C7	15p 500V 5% mica	3.2mm x 2.5mm chip	Mouser	MC12ED150J-TF
C8	15p 500V 5% mica	3.2mm x 2.5mm chip	Mouser	MC12ED150J-TF
C9	220p 500V 5% mica	4.5mm x 3.2mm chip	Mouser	MC18FD221J-TF
C11	18p 500V 5% mica	3.2mm x 2.5mm chip	Mouser	MC12ED180J-F
C14	22n 100V PET	5.7mm x 5.0mm chip	Mouser	SMDTD02220QAKP00
C23	100n 100V PPS	7.2mm x 6.0mm chip	Mouser	SMDIC03100TA00KQ00
C25	100n 100V PPS	7.2mm x 6.0mm chip	Mouser	SMDIC03100TA00KQ00

Substitution Notes:

C0G or NP0 ceramic capacitors make fine substitutes for the mica caps. I see no decrease in performance through the use of ceramic. Do not, however, substitute other dielectrics (X7R etc.), as there will be an increase in distortion.

Capacitors across the supplies are much less critical.

Diodes:

Designator	Description	Package	Supplier	Part Number
D1	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D2	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D3	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D4	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D5	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D6	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D7	LL4148 small signal diode	MELF Diode	Mouser	LL4148
D9	LL4148 small signal diode	MELF Diode	Mouser	LL4148
ZD1	12V 0.5W Zener	MELF Diode	Mouser	BZV55B12 L1
ZD2	12V 0.5W Zener	MELF Diode	Mouser	BZV55B12 L1
ZD4	12V 0.5W Zener	MELF Diode	Mouser	BZV55B12 L1

Substitution Notes:

None.

Transistors:

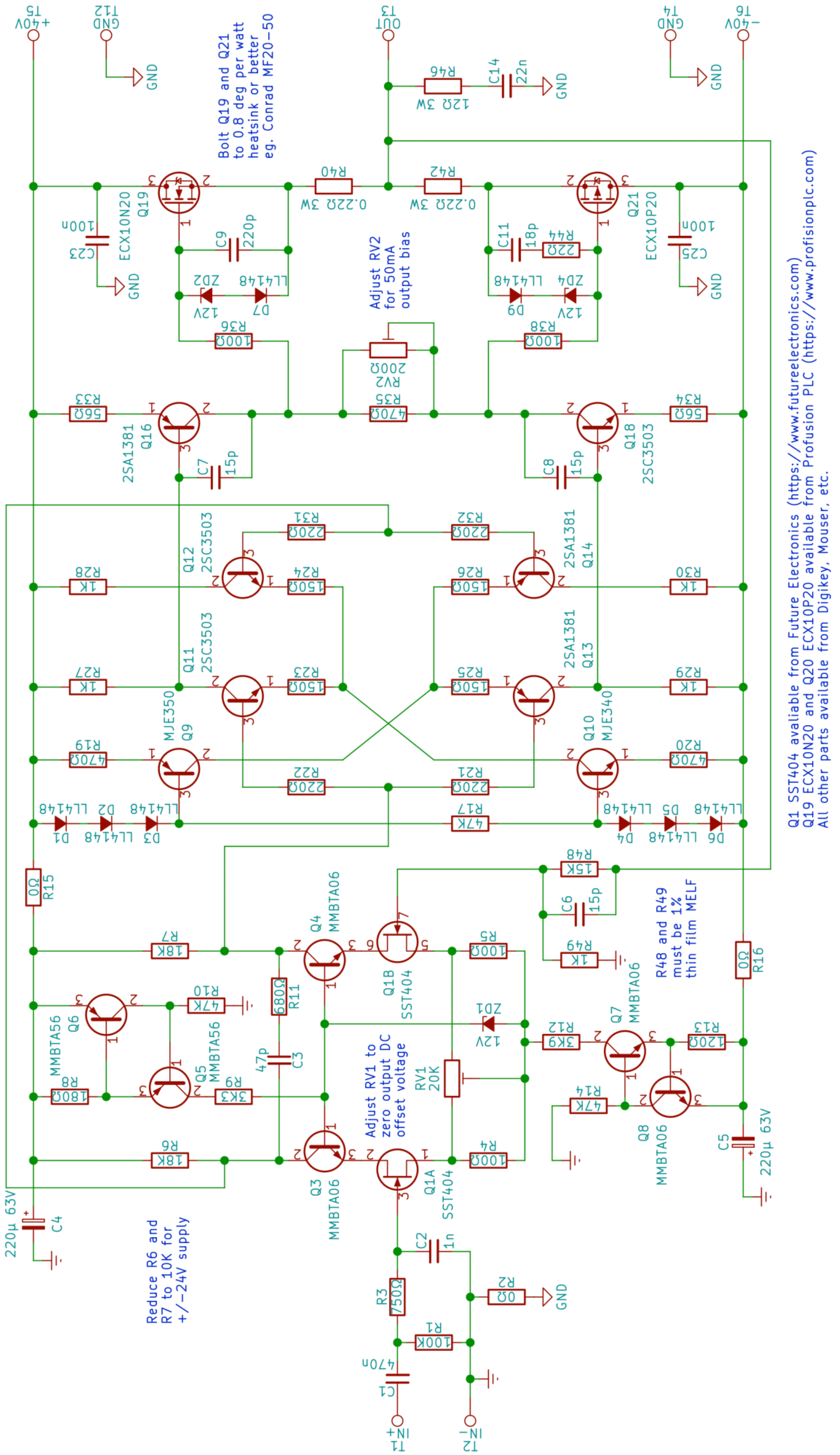
Designator	Description	Package	Supplier	Part Number
Q1	SST404 dual matched N-JFET	SO-8	Future Electronics	SST404-LF
Q3	MMBTA06 NPN transistor, 500mA 80V	SOT-23	Mouser	MMBTA06LT3G
Q4	MMBTA06 NPN transistor, 500mA 80V	SOT-23	Mouser	MMBTA06LT3G
Q5	MMBTA56 PNP transistor, 500mA 80V	SOT-23	Mouser	MMBTA56LT3G
Q6	MMBTA56 PNP transistor, 500mA 80V	SOT-23	Mouser	MMBTA56LT3G
Q7	MMBTA06 NPN transistor, 500mA 80V	SOT-23	Mouser	MMBTA06LT3G
Q8	MMBTA06 NPN transistor, 500mA 80V	SOT-23	Mouser	MMBTA06LT3G
Q9	MJE350 PNP transistor, 500mA 300V	TO-126	Mouser	MJE350G
Q10	MJE340 NPN transistor, 500mA 300V	TO-126	Mouser	MJE340G
Q11	2SC3503 NPN transistor, 100mA 300V	TO-126	Mouser	KSC3503DS
Q12	2SC3503 NPN transistor, 100mA 300V	TO-126	Mouser	KSC3503DS
Q13	2SA1381 PNP transistor, 100mA 300V	TO-126	Mouser	KSA1381ESTU
Q14	2SA1381 PNP transistor, 100mA 300V	TO-126	Mouser	KSA1381ESTU
Q16	2SA1381 PNP transistor, 100mA 300V	TO-126	Mouser	KSA1381ESTU
Q18	2SC3503 NPN transistor, 100mA 300V	TO-126	Mouser	KSC3503DS
Q19	ECX10N20 N-Channel Lateral MOSFET, 8A 200V	TO-247	Profusion PLC	EXC10N20
Q21	ECX10P20 P-Channel Lateral MOSFET, 8A 200V	TO-247	Profusion PLC	EXC10P20

Substitution Notes:

Q19 and Q21 may be substituted with 2SK1058 and 2SJ162. Please be aware that the vast majority of transistors purporting to be 2SK1058 or 2SJ162 parts are fakes, as these have been out of production for a long time.

MJE340 and MJE350 are good substitutes for 2SC3503 and 2SA1381, however there will be a small increase in distortion.

Schematic


Bolt Q19 and Q21
to 0.8 deg per watt
heatsink or better
eg. Conrad MF20-50
Adjust RV2
for 50mA
output bias
Adjust RV1 to
zero output DC
offset voltage
Reduce R6 and
R7 to 10K for
+/-24V supply
R48 and R49
must be 1%
thin film MELF
Q1 SST404 avaliable from Future Electronics (https://www.futureelectronics.com)
Q19 ECX10N20 and Q20 ECX10P20 available from Profusion PLC (https://www.profusionplc.com)
All other parts available from Digikey, Mouser, etc.