ZD25 Mini Build Guide

(aka. The Holy Grail Follower)

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The ZD25-Mini Power Amplifier is a simplified version of the ZD25, which was inspired by the Pass Labs XA25 Power Amplifier. These amplifiers are characterized by the elimination of source degeneration of the output stage MOSFETs, taking advantage of the square law characteristics of the MOSFETs. As a result, the distortion is reduced and the Class-A output power is increased for a given idle current. See “The Square and Exponential Laws” by Nelson Pass https://positive-feedback.com/audio-discourse/the-square-and-exponential-laws.

The major changes from the ZD25 are:

- The discrete component front end is replaced by an OPA551 high voltage operational amplifier and an associated resistor network for mixed local and global feedback.
- The bias circuit has a novel modification to better control the bias current at all output power levels.

Figure 1: ZD25 Mini Full Custom Configuration

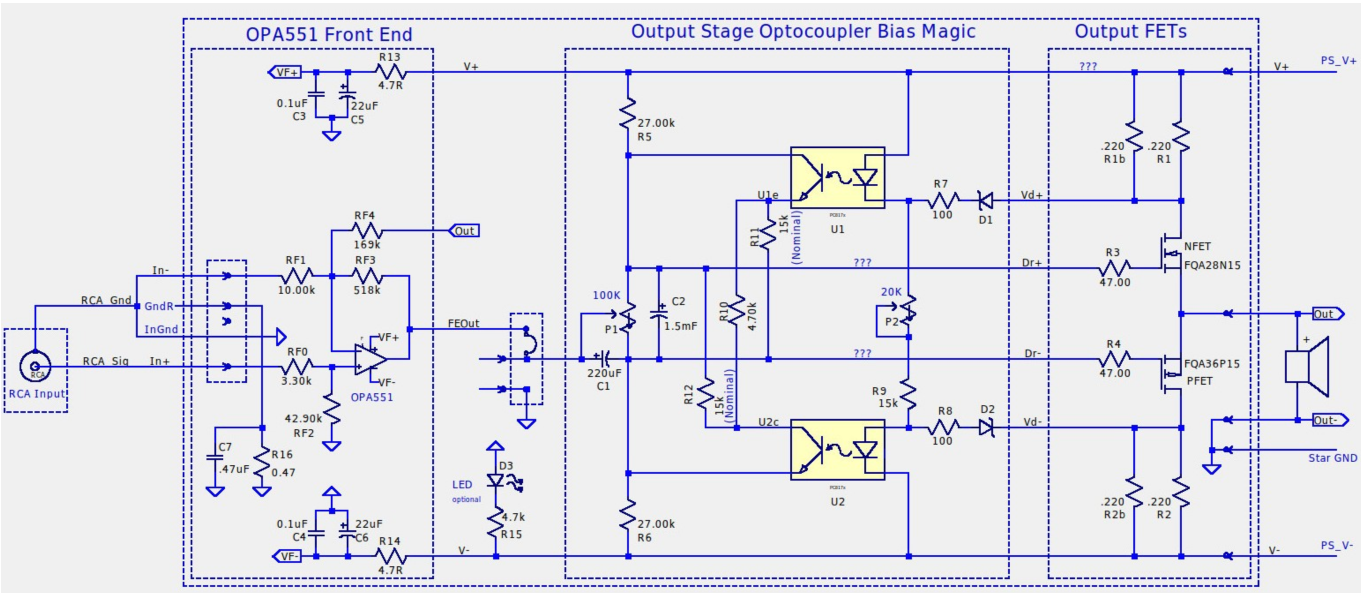

Figure 2: ZD25 Mini Baseline Schematic.

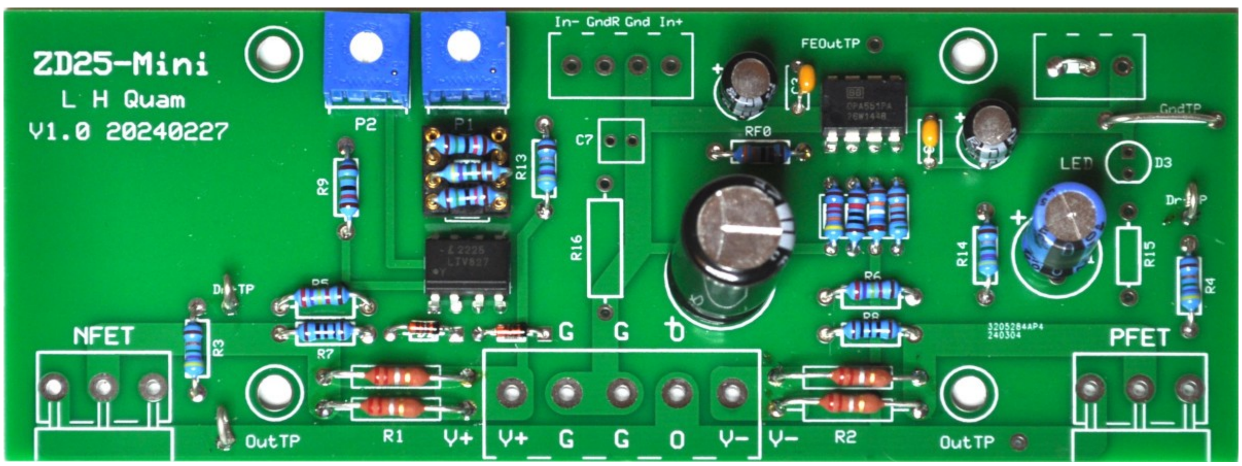

Figure 3: Baseline PCB

Baseline Specifications:

The baseline configuration is intended by be compatible with FirstWatt scale designs having +/-24V supplies and heatsinks suitable for 60W-70W per channel power dissipation.   With higher voltage/current power supplies and suitable heatsinks, much higher power levels are possible.

- RCA Input Impedance: 46k (Note 1)
- Voltage Gain: 22dB (13X)   (Note 2)
- Global Feedback Ratio: 12dB (4X)
- Distortion: THD @1W < 0.01%
- Output Power 8 Ohms: 25W @ <.05% THD
- Output Power 4 Ohms: 40W @ <.05% THD

- Damping Factor: > 100
- Power Supply: +/-24V 300W (Note 3)

Note 1: The ZD25-Mini can also support XLR or TRS balanced inputs with twice the voltage gain. However, the input impedance is assymetric: Z(In+)=46.4k Z(In-)=5.2k, which should not be a problem for most input sources.

Note 2: The Baseline ZD25-Mini voltage gain is 13x (22dB), but is easily modified by changing resistors RF1-RF4. See the Custom Build Guide.

Note 3: I have tested the amplifier with the SMPS voltages at +/-28.8V and everything seems to perform properly. See the "More Power" section. The opa551 front end does not drive its output to the rail voltages. The ZD25-Mini maximum output voltage swing will about 3V-3.5V below the rail voltage. Due to limitations of the opa551, the power supply voltages must not exceed +/-30V.

Requirements:

Power Supplies:

I have tested the amplifier with both switching mode power supplies (SMPS) and an ordinary linear power supply.   Both the front-end and output stages have very good power supply rejection ratios (PSSR), and do not need extreme filtering measures.

The SMPS used is the MeanWell LRS-150-24. For slightly higher cost I would recommend the LRS-200N2-24 which can supply significantly higher output current. I tested both the diyAudio Store DC Filter P089ZB Kit and ordinary CRC filters on the output of the MeanWell supplies and did not see significant noise reduction to justify their use.   The output voltages of both SMPS supplies are adjustable between 21.6 and 28.8V.

The linear supply I tested was originally used in an F7 build and produces only about +/-23V output due to the 18V secondary voltages of the Antek AS-3218 transformer. This limits the voltage swing of the amplifier output to about +/-19V and 22.5W into 8 Ohms.   I recently modified the linear supply to use an Antek As-4220 transformer with 20V secondaries.

Heatsinks:

The heatsinks shown in figure 1 are from HeatsinkUSA and are 10.08" wide x 7" long extrusions, mounted in a fin-to-fin configuration. The primary requirement of the heatsink is obviously to transfer the heat generated by the output FETs to the ambient air. Heatsinks are rated by C/W, the temperature rise above the ambient air temperature per Watt of power transferred to the heatsink.   These heatsinks are rated by the manufacturer at 0.8C/W/3", which for a 7" long heatsink gives 0.34C/W. With 24V rails and a bias current of 1.25A, the FETs dissipate 60W, giving 0.34C/W*60W=20.4C. This number pretty much agrees with what I measure in actual use.   Not all manufacturer heatsink ratings are very accurate. I tested a HeatsinkUSA 12" wide heatsink that was rated at 0.85C/W/3" and the actual temperature rise was more than twice as high, making it unusable.

More Power:

The power supply voltages can be increased to +/-30V and there is not really limit on the power supply wattage other than size and weight. The output FETs should be good up to around 80W-100W each. The main problem scaling to higher power will be the heatsinks. With the fin-to-fin configuration shown in figure 1 it is easy to add a pair of 120mm low noise fans to easily dissipate 2-3 times more wattage than with convection cooling.

I recently tested the ZD25 Mini with the LRS-150-24 SMPS voltages adjusted to +/-28.8V. Everything adjusted properly, the bias was stable and it easily produced 40W into 8 Ohms and 80W into 4 Ohms with THD below 0.03%. At those power levels I would suggest the LRS-200N2-24 supplies.

Another consideration regarding power supplies: your nominal speaker impedance. If you are driving a 4 Ohm speaker load you need more current, but less voltage for the same power output than to an 8 Ohm load. Thus for a nominal 4 Ohm speaker, a +/-23V (or less) supply might be fine with the bias current adjusted to what your heatsinks can handle.

Baseline Build Guide:

The baseline amplifier is to be built and used with only the minor variations and its BOM assumes that the power, input, and output wires and FETs are soldered to the PCB without connectors.

Bills of Materials:

The BOMs are listed at the end of this document and are also included in a zip file.

Mouser.com provides a convenient way to import BOMs. See https://www.mouser.com/help/tools/how-to-create-a-new-bom. I have provided two files containing the part numbers and quantities needed for **one channel**. Each file contains the required components at the top, and optional components at the bottom. When submitting the file to Mouser (I use their cut-and-paste method) remove to optional components that you do not want.

- BOM-OS-Mouser-format
- BOM-FE-Mouser-format

PCB Assembly:

The PCBs are assembled in the same manner as other amplifier boards and only require special attention to a couple of items:

- There was a minor PCB artwork error that requires a jumper wire to be on the backside. See figures 4 and 5 below. This jumper is easiest to add after the components are in place.
- A jumper is required to connect the front-end output to the output stage input. See figure 4. The Custom Build Guide discusses the use of an external front-end.

- Sense Resistors R1, R1b, R2, R2b: The resistors should be mounted slightly elevated above the PCB to make it easy to attach multimeter leads to each end of one of the resistors for the purpose of bias current adjustment.
- FETs: As with other power amplifier PCBs, the output FETs are the last components to be attached. The FETs should be mounted to the heatsinks at the proper UMS (Universal Mounting Specification) locations and the leads bent upwards so that the PCB can be lowered into place over the leads and aligned with its mounting holes.
- Test Points (optional): Thru holes are provided small wire loops for attaching test probes. These thru holes are marked with <xxx>TP silkscreen labels. For a pair of thru holes are provided for a longer, straight ground reference wire. See figures 3 and 4.

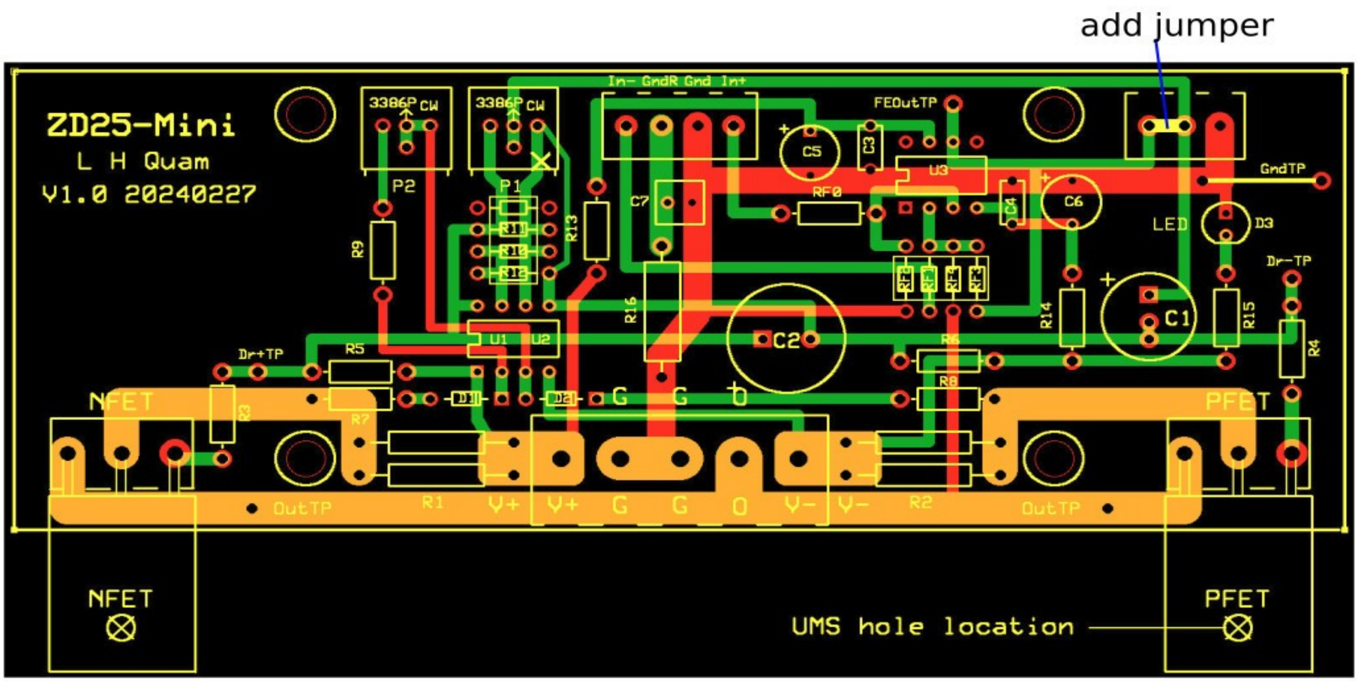

Figure 4: Printed circuit board layout. Red traces on top layer.

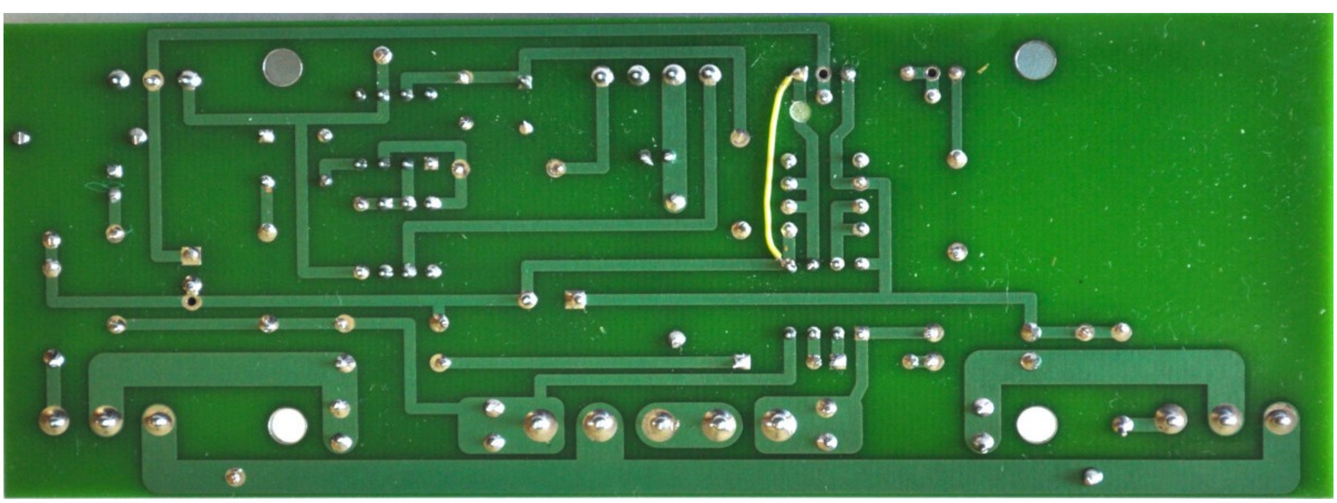
Figure 5: Bias circuit bug fix.

Chassis Wiring:

The figures below provide some suggested chassis wiring schemes. Note that the In- pin is connected to ground for non-inverting RCA inputs.

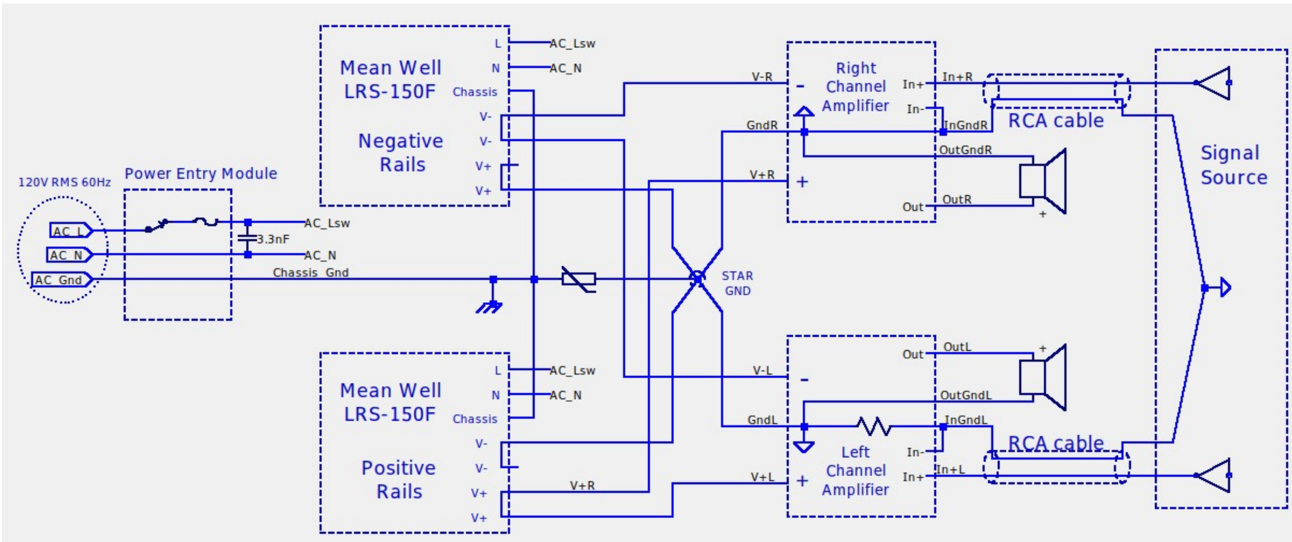

Figure 6: SMPS Chasssis Wiring

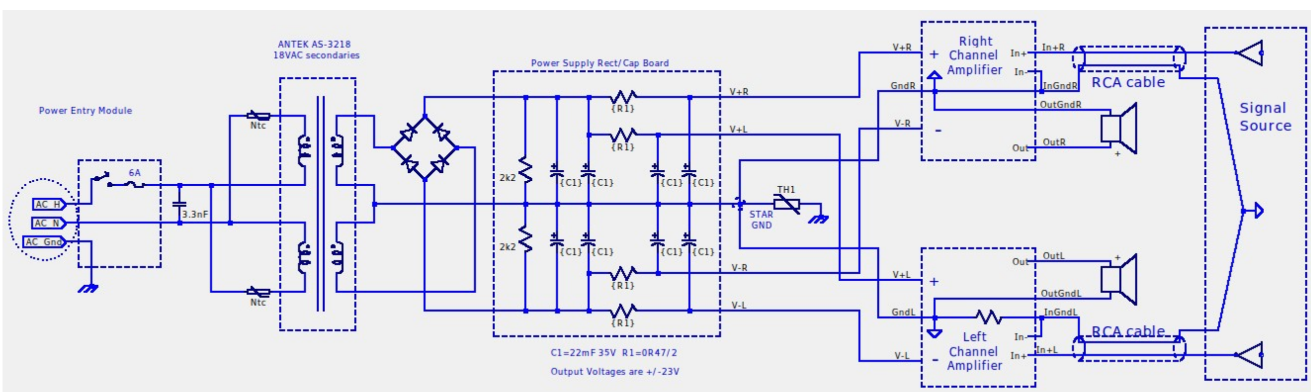

Figure 7: Linear Power Supply Chassis Wiring

An optional star ground PCB has been provided to help in reducing potential ground loop problems. It has two mounting holes, one of which is for attachment to chassis ground using a conductive spacer.

Pot Adjustments:

Before first applying power to the PCBs, adjust P1 to the center of its range and P2 to maximum counter clockwise position on both PCBs. It helps to have two multimeters, one each pot.

Potentiometers P1 and P2 are adjusted as follows:

- P2 is adjusted first. Connect a multimeter across either sense resistor R1 or R2. The meter should be on a voltage range to accurately measure 0.137Vdc.   Apply power. Wait for about 10 seconds (the bias circuit has a long time constant) before the meter starts to indicate voltage across the sense resistor. Slowly adjust P2 clockwise to obtain 0.137Vdc.

- P1 adjusts the output offset voltage. Connect a multimeter to the output terminals (or to the ground and output test points on the PCB). Adjust P1 for a voltage as close to zero as possible.

- These adjustments will require some iteration as the heatsinks warm up.

If everything has adjusted properly, the amplifier should be ready to hook up and enjoy.

Custom Build Guide:

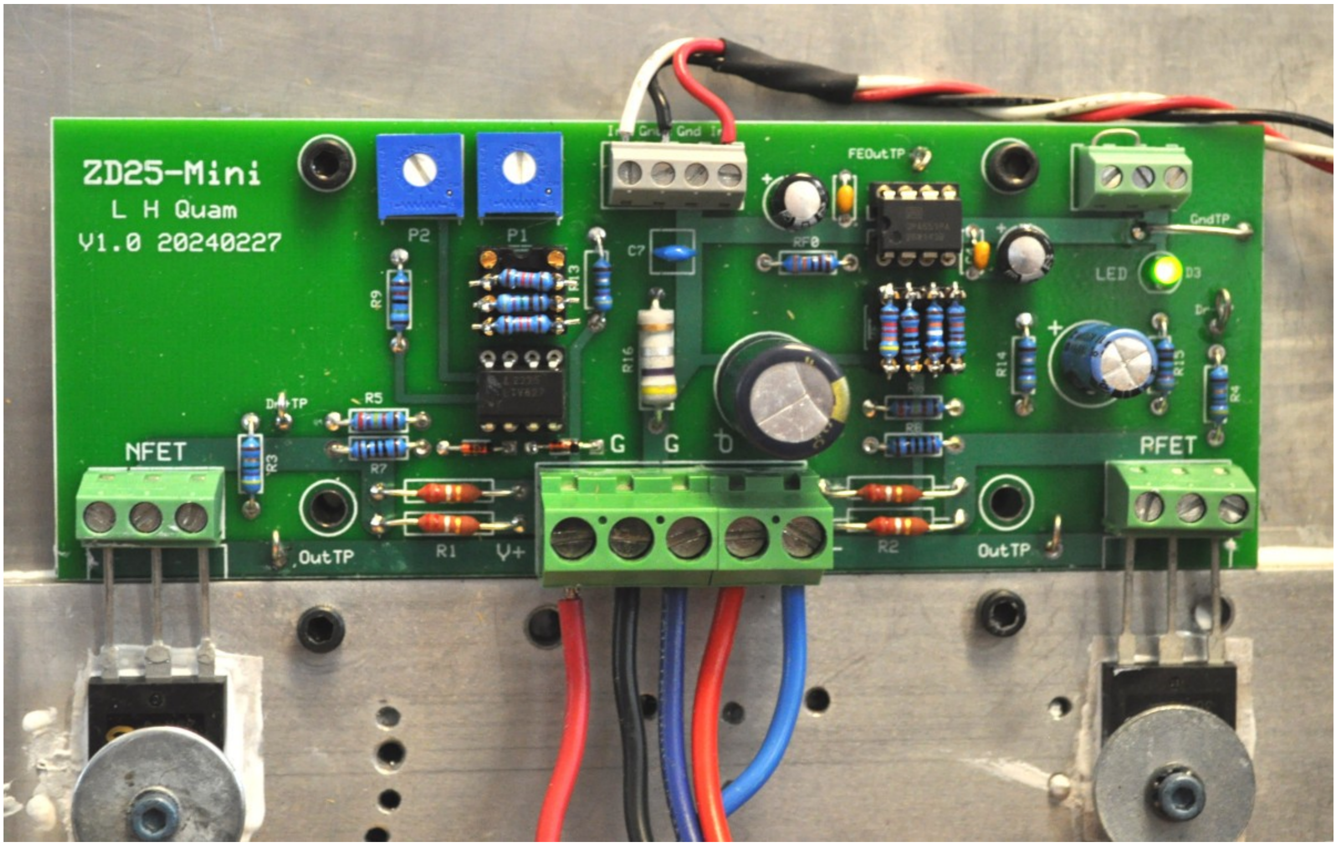

Figure 8: Custom PCB with all Connectors

PCB Connectors:

There are optional connectors for:

- V+, V-, Gnd, OutGnd, Out.
- In-, GndR, Gnd, In+
- PFET, NFET
- FEOut, OSIn, Gnd

Figure 8 shows the PCB with all of the connectors installed and the output FETs mounted on a ¼" thick aluminum riser, making it possible to change FETs without unsoldering and resoldering.

XLR and TRS Balanced Inputs:

The front-end stage has both In+ and In- connections. In the baseline RCA configuration, In- is jumpered to ground.

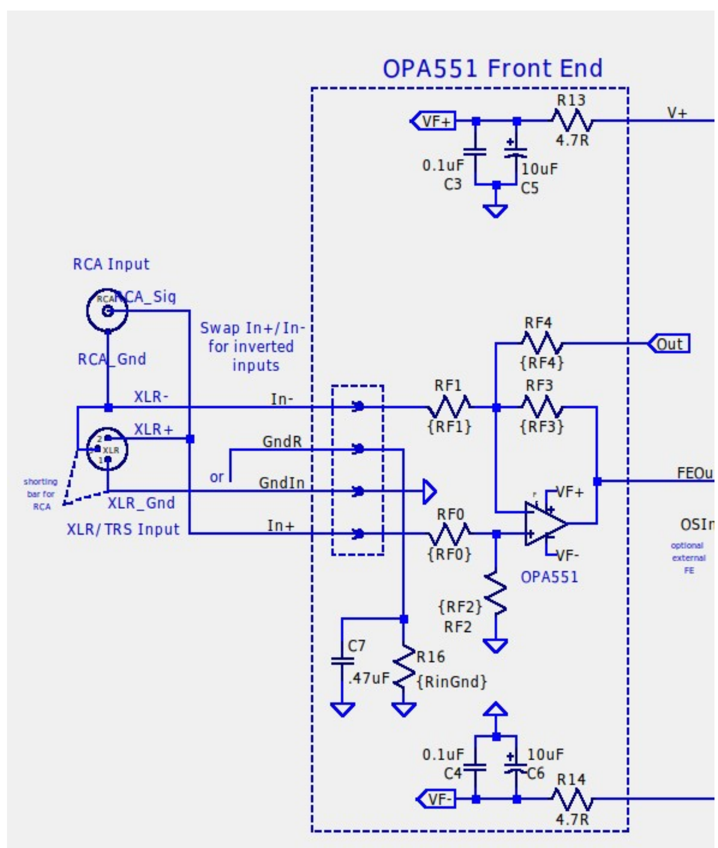

Figure 9: XLR and RCA Inputs

For balanced inputs both In+ is wired to XLR pin 2, In- to XLR pin 3, and Gnd to XLR pin 1, as shown in figure 9.

As shown, it is possible to wire the chassis with both RCA and XLR connectors, requiring a shorting bar between XLR pins 1 and 3 when using the RCA connector. (Several Nelson Pass amplifiers used this "trick").

TRS connectors are attached similarly, and Neutrik makes a combo XLR/TRS connector, shown in figure 1 below the RCA connector.

A caveat about balanced inputs: Due to the nature of the front end circuit, the In+ and In- have different input impedances. See the subsection below regarding the input impedances.

The Front End:

Input Impedances:

With the values shown in the schematic (figure 2), the input impedances are:

- Z(In+)=46.2K always
- Z(In-)=5.18k balanced
- Z(In-)=10k unbalanced inverted

In general:

- Z(In+) = RF0+RF2 always
- Z(In-) = RF1*(RF2+RF0))/(2*RF2+RF0) balanced
- Z(In-) = RF1 unbalanced inverted

Gain and Feedback:

The front end gain and feedback levels are determined by the resistor values of RF0-RF4. Conversely, it is possible compute the values of the feedback resistors RF2, RF3, and RF4 given the gain Acl and feedback (β) levels and the RF0 and RF1 resistor values.

- RF2=Acl*RF0
- RF3=(Acl*RF1)/β
- RF4=(Acl*RF1)/(1-β)
  where Acl is the desired closed loop gain and β = 10^(-FBdB/20) is the desired level of feedback from the output stage.

The baseline values of RF2-RF4 shown in in the schematic (figure 2) were derived from these equations and rounded to nearby 1% resistor values with RF0=3.3K, RF1=10K, Acl=13, and β=.25 (FBdB=12).

If you want to operate the output stage with no global feedback:

- β=1
- RF3=Acl*RF1
- RF4 omitted

External Front End:

You can totally omit (or not) the components in the Front End BOM and connect an external front end to the (unfortunately unlabelled) connector or thru holes in the upper right of figures 3, 4 and 8. Make sure the jumper is removed if the front end components are also installed.

Other FETs:

The FQA28N15 and FQA36P15 FETs where chosen because they are well matched in transconductance and some other properties when operated undegenerated, class-A, push-pull. The primary parameter I used in matching NFET/PFET pairs was "transconductance" [1] at the desired operating point of 24V, 1.25A into an 8 Ohm load. When at N/P pair is well matched, the push pull output stage remains in the class-A mode of operation at higher power output levels.

The figure 10 shows a comparison of 4 different pairings of FETs driving a 4 Ohm load at 4 Watts and 40 Watts. The plots show the currents through the FETs. The top plots show a "mythical" pair of perfectly matched square-law FETs. As can be seen, the FQA28N15/FQA36P15 most closely matches the square law behavior, remaining longer in class-A. The IRFP pair is worst.

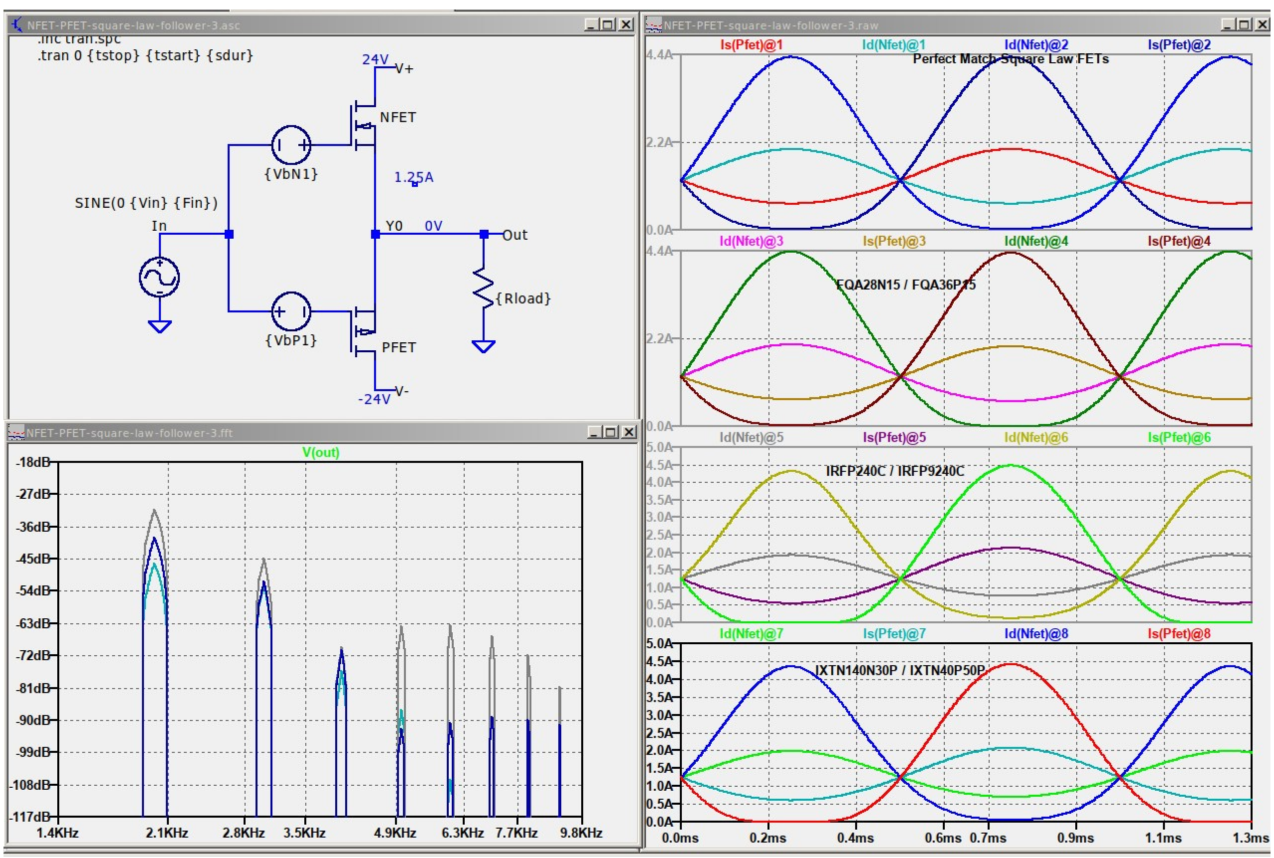

Figure 10: Four different pairing of FET types driving a 4 Ohm load at 4 W and 40W

1 Transconductance is usually defined as dI(drain)/dVgs at a constant value of Vds, i.e. a zero impedance load. My measurement of "transconductance" has an 8 Ohm load.

It is very easy to measure the relative transconductances of the pair of FETs installed in the ZD25-Mini. Apply a sine wave input to produce around 4Vrms at the amplifier output. Attach one or two multimeters on a low AC voltage range across bias sense resistors R1 and R2. Look at the ratio of the voltages across R1 and R2. You would like it to be in the range .9 to 1.1.

Of course, transconductance isn't the only parameter that determines a good sounding output stage. I happened to get lucky having FQA28N15 and FQA36P15 FETs to try.

The recommended way to experiment with other FETs is to add 3-pin connectors (Mouser 651-1729131 or equivalent) to the PCBs and mount the FETs to a ¼" thick aluminum riser attached to the heatsink with conductive paste and screws as shown in figures 1 and 8.

Bias Constancy:

Back in 2018 when I was working the design of my original ZD25 I noticed that by connecting phototransistor outputs of the dual optocoupler circuit in series the bias current increased with output power, whereas when in connected in parallel the bias current decreased with output power. This is discussed at length starting around post #1251 here: https://www.diyaudio.com/community/threads/f4-beast-builders.300233/post-5361628. I actually tested both topologies in the ZD25 and settled on the series configuration.

The way in which the bias current changes is most noticeable during spectral measurements at higher power levels. After 1-2 seconds the harmonics decrease for the series configuration, or increase for the parallel configuration. **I do not really know how much this really affects normal listening even at high power levels.** How long do high amplitude passages near clipping persist? OTOH, if your are an amplifier manufacturer, such as Pass Labs, sending your amplifiers to Stereophile for evaluation, you would not want the parallel optocoupler configuration because their bench testing would likely measure the THD higher than it really should. Enough for the history.

Early in the ZD25-Mini design I discovered that by adding 3 resistors to the dual optocoupler bias circuit I could achieve an arbitrary mix of the series and parallel behaviors, as shown in the schematic of figure 2. The primary variable in the mix is the resistor values for R11 and R12 (the same value is used for both). Decreasing R11 and R12 creates more of the parallel behavior, and increasing creates more of the series behavior. The "correct" value depends on a variety of factors, such as rail voltage, the particular FETs, and output load impedance. For the typical FQA FET pairing the value of 16K Ohms appears to be "good enough", but some diyers might want to fine tune the value. Here is the procedure:

Fine Tuning the Bias Circuit:

The easiest way to observe the bias constancy is to measure the DC voltage between the Dr+TP and Dr-TP testpoints. I refer to this voltage as V(G1,G2). Measure that voltage at idle and with a high amplitude sine wave, such as 11Vrms output. You will observe an increase or decrease that stabilizes after about 8-10 seconds. For a significant decrease in V(G1,G2), increase R11 and R12, and visa-versa. What is a significant increase or decrease? Good question.

The bias current is related to V(G1,G2). If the FETs have nearly equal transconductances gm, ΔIq=ΔV(G1,G2)/2 * gm. Thus with gm=4S and ΔV(G1,G2)=0.1V, ΔIq=.2A. .2A/1.25A=16%. A decrease in Iq of more than 15% is probably worrisome, as is an increase of more than 30% or so.

If you are not worried about the bias current temporarily becoming very large, totally remove R11 and R12.

DIP Socket and Carrier for Bias Circuit Resistors:

If you choose to make modifications to resistors R11 and R12 I recommend that you add a 8-PIN DIP socket (Mouser 575-11043308). The leads of resistors R10-R12 can be inserted into the DIP socket and easily changed. When the preferred values are determined, mount the resistors to an 8-pin DIP carrier (Mouser 437-1601030800001101) and plug it into the socket.

Ground Loop Breaker:

The optional components R16 and C7 can be used on one of the PCBs to reduce ground noise induced into the wiring from the power supplies. When used, the RCA (or XLR) connector ground of the one PCB is connected to GndR on the terminal block or through hole. The noise levels I have measured are so low (<100uV) that this is probably overkill, but there might be situations where loop breaker is really needed.

Output Stage BOM:

```
R1,R2 4 x 0.22R 1W resistors  - Mouser 279-RR01JR22TB
R3,R4 2 x 47R 1/4W resistors  -   603-MFR-25FBF52-47R5
R5,R6 2 x 27K 1/4 watt resistors  603-MFR-25FBF52-27K4
R7,R8 2 x 100R 1/4 watt resistors   603-MFR-25FBF52-100R
R9    1 x 15K 1/4 watt         603-MFR-25FBF52-15K
R10   1 x 4.7K 1/4 watt        603-MFR-25FBF52-4K75 (or 603-MFR25SFTE26-4K7)
R11,R12 2x nominal 15K 1/4 watt  FET dependant -- recommend buying all of the
following
  603-MFR-25FBF52-15K (or 603-MFR25SFTF26-15K)   nominal value
  603-MFR-25FBF52-12K (or 603-MFR25SFTF26-12K)
  603-MFR-25FBF52-18K (or 603-MFR25SFTF26-18K)
P1 1 x 100K trimmer pot  Mouser 652-3386P-1-104
P2 1 x 20K trimmer pot   Mouser 652-3386P-1-203
C1 1 x 220uF 25V electrolytic Mouser 647-UKA1E221MPD  audio grade   LS=3.5mm D=8mm
C2 1 x 1.5mF 25V electrolytic  Mouser 667-EEU-FP1E152B LS=5mm D=12.5mm   L=20mm
D1,D2 2 x  9.1V zener Mouser 78-BZX55B9V1
U1,U2 1x PC817 optocoupler (Igain=1.5m) Mouser 859-LTV-827 or Digikey 160-2039-5-ND
4 x #6 (M3) L=6.3mm nylon spacers Mouser 144-SS6-2

Optional LED
  D3 1 X green LED T-1     Mouser 78-TLHG4401 or similar
  R15 1 x 4.7K 1/4 watt          603-MFR-25FBF52-4K75
Optional (recommended) 8-pin DIP socket  Mouser 575-11043308 for R10,R11,R12
```

Optional 8-pin DIP component carrier w/forked contacts Mouser 437-1601030800001101 - See Build Guide
Optional connector blocks for power and output.
  2-terminal connector block .25in pitch Mouser 571-796740-2
  3-terminal connector block .25in pitch Mouser 571-796740-3
  (these 2 block join together for 5 terminals)
Optional 3-terminal connector block for external front end.
    .15in pitch Mouser 651-5442769 or 651-1985836
Optional connector blocks for experimentation with different FETs without soldering/desoldering the FETs.
     Needs heatsink riser. See Custom Build Guide.
  2 x 3-terminal connector block .2in pitch Mouser 651-1729131

Front End BOM:

(RF0-RF4 values assume closed-loop gain of 13X and 12dB global feedback)
RF0 1 x 3.3k 1/4 watt 603-MFR-25FBF52-3K3
RF1 1 x 10k 1/4 watt 603-MFR-25FBF52-10K
RF2 1 x 43.2k 1/4 watt 603-MFR-25FBF52-43K2
RF3 1 x 511k 1/4 watt 603-MFR-25FBF52-511K
RF4 1 x 169k 1/4 watt 603-MFR-25FBF52-169K
R13,R14 2 X 4.7R 1/4W 603-MFR-25FBF52-4R7
C3,C4 0.1uF ceramic cap   Kemet 80-C317C104M5U5TA
C5,C6 22uF 35V electrolytic caps 667-ECE-A1VKS220B
U3 opa551PA high voltage opamp Mouser 595-OPA551PA Digikey OPA551PA-ND
Optional 8-pin DIP socket Mouser 575-11043308 for RF1-RF4
    and 8-pin DIP component carrier w/forked contacts Mouser 437-1601030800001101
Optional 4-terminal connector block for inputs.
    .15in pitch Mouser 651-5430179 or 651-1932410
Optional ground-loop breaker - one PCB only
  C7 1 x 0.47uF 25V ceramic cap 810-FG14X7R1E474KNT6
  R16 1 x 0R47 1W 603-RSF100JB-73-0R47