DESIGNING DISCRETE OPAMPS.

Notes and jottings on making opamps yourself with discrete transistors. A pointless pastime? Far from it.

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HOME BACK to Discrete Design

CONTENTS.

- Introduction
- History
- Circuit design
- List of diagrams

Diagrams are scaled down for convenience. Use "view image" or "save image" on browser to get full-size version.

INTRODUCTION.

This page deals with opamp design using discrete transistors, specifically BJT's. Once again this does not pretend to be an exhaustive guide, but concentrates on audio issues such as distortion. Many matters that can be found found in the standard textbooks are taken for granted. It does however gives information that I do not think appears anywhere else, mainly on the distortion behaviour of various configurations.
Some of this information is pretty much historical. That doesn't mean we should throw it away. You never know when you might need it...

Circuitry made with discrete transistors is not obsolete. It is appropriate when:

1. A load must be driven to higher voltages than the opamp can sustain between the supply rails. Opamps are mostly restricted to supply voltages of +/-18 or +/-20 Volts. Hybrid-construction amplifiers, typically packaged in TO3 cans, will operate from rails as high as +/-100 V, but they are very expensive, and not optimised for audio use in parameters like crossover distortion. Discrete opamps provide a viable alternative.
2. A load requires more drive current, because of its low impedance, than an opamp can provide without overheating or current-limiting; eg any audio power amplifier
3. The best possible noise performance is required. Discrete bipolar transistors can outperform opamps, particularly with low source resistances, say 500 Ohms or less. The commonest examples are moving-coil head amps and microphone preamplifiers.

4. **The best possible distortion performance is demanded. Most opamps have Class-B or AB output stages, and many of them (though certainly not all) show clear crossover artefacts on the distortion residual. A discrete opamp can dissipate more power than an IC, amd so can have a Class-A output stage, sidestepping the crossover problem completely.**

HISTORY.
The first IC opamps opened up a huge new area of electronic applications, but after the initial enthusiasm for anything new, the audio market greeted these devices with less than enthusiasm. There were good reasons for this. The first really practical opamp was the 741; the snag with using it for audio was the leisurely slewrate of 0.5V/usec, which made full output at 20 KHz impossible. For a period of at least five years, roughly from 1972 to 1977, the only way to obtain good performance in a preamp was to stick with discrete transistor Class-A circuitry, and this became recognised as a mark of high quality. The advent of the TL072 and the 5532 changed this situation completely, but there is still marketing cachet to be gained from a discrete design.

CIRCUIT DESIGN. The opamp in Fig 1 below is relatively conventional in design; its resemblance to a power amplifier circuit is obvious. It consists of 3 stages; the differential input stage, the voltage amplifier stage (VAS), and a unity-gain output stage.

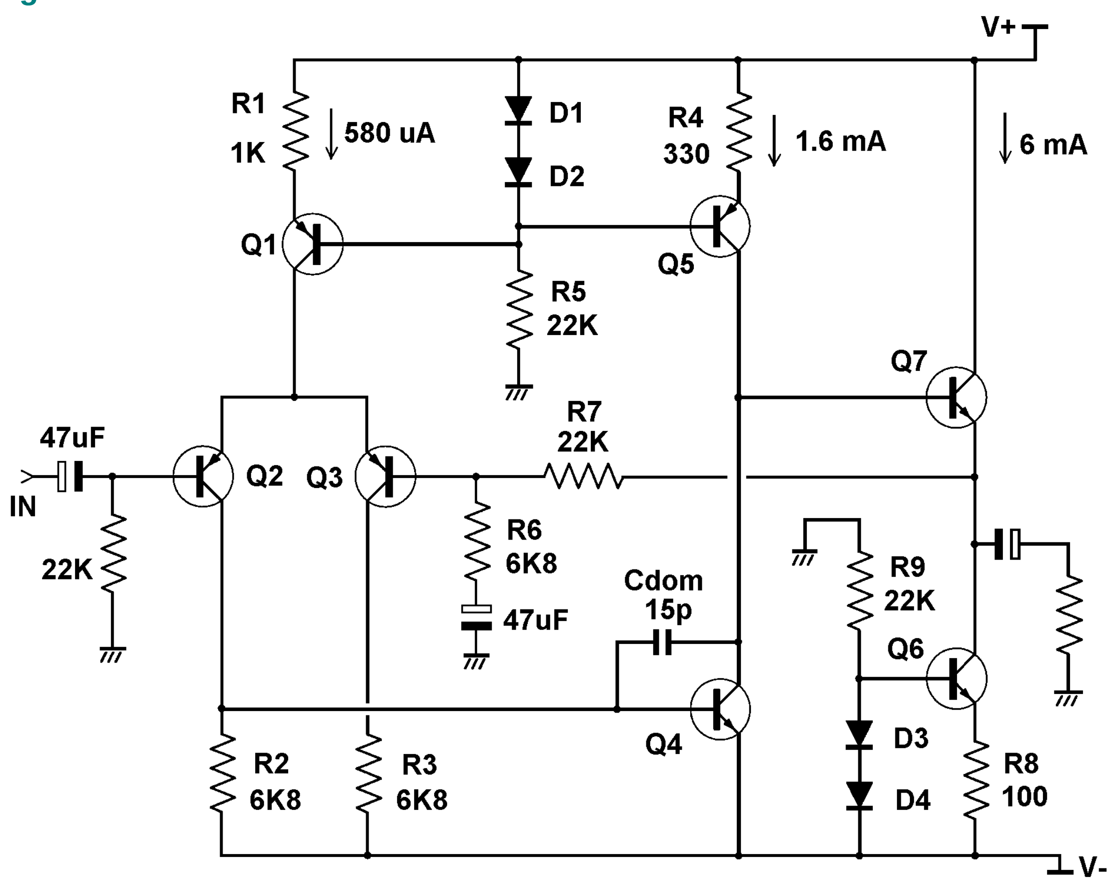


Fig 1 A typical discrete opamp circuit, with current-source output. dsctamp1.gif

The first stage subtracts the input and feedback voltages, generating the error signal that drives the negative-feedback (NFB) loop. The first stage is a transconductance amplifier, ie it turns a voltage input into a current output. The voltage/current characteristic of this stage is sigmoid, or s-shaped, and the most linear part is in the centre where the collector currents of the two transistors are equal. As a result the value of R2 in Fig 1 is crucial; if it is not twice R1, then the Ics are unbalanced and there is a wholly avoidable rise in 3rd-harmonic THD at high frequencies; this is demonstrated in Fig 2 below.
This issue is equally important for power amplifiers, and iis dealt with at greater length in the "Distortion In Powr Amplifiers" section of this site.

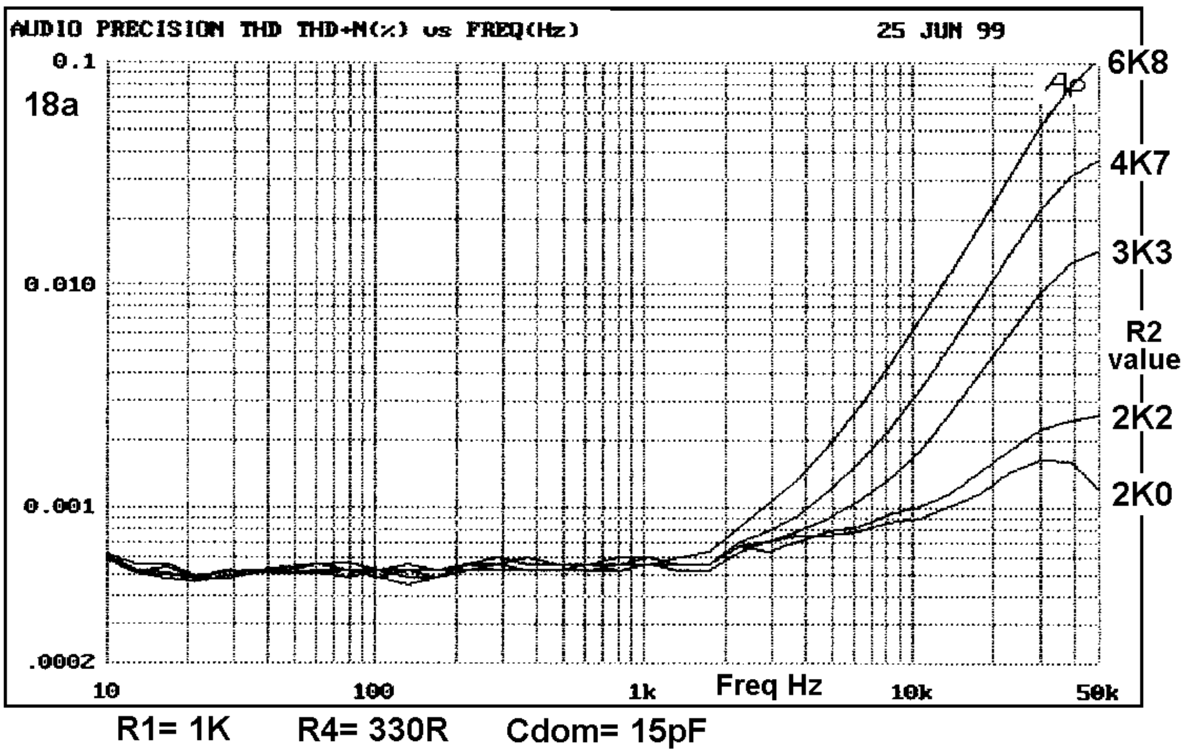


Fig 2: Reduction in high-freq THD as input stage approaches balance.

This rise in first-stage distortion with frequency is because:

- **At high freqs more current flows through Cdom. At the input side of the capacitor this can only be provided by the input stage, which has to work harder: in other words, the error voltage is greater so the output current has a larger swing over more of the transfer characteristic.**
- **There is less global NFB at high frequenciess.**

The first-stage output current flows into the second voltage-amplifier stage. This is a transadmittance amplifier, ie current in becomes voltage out. The input is at low impedance (a sort of virtual-earth) because of the local NFB through dominant-pole capacitor Cdom, and so well-adapted to accepting the output current from the first stage.

The third stage is a unity-gain buffer, isolating the VAS collector from external loads.

The higher the quiescent current in this stage (shown here as 6mA) the lower the load impedance that can be driven symmetrically.

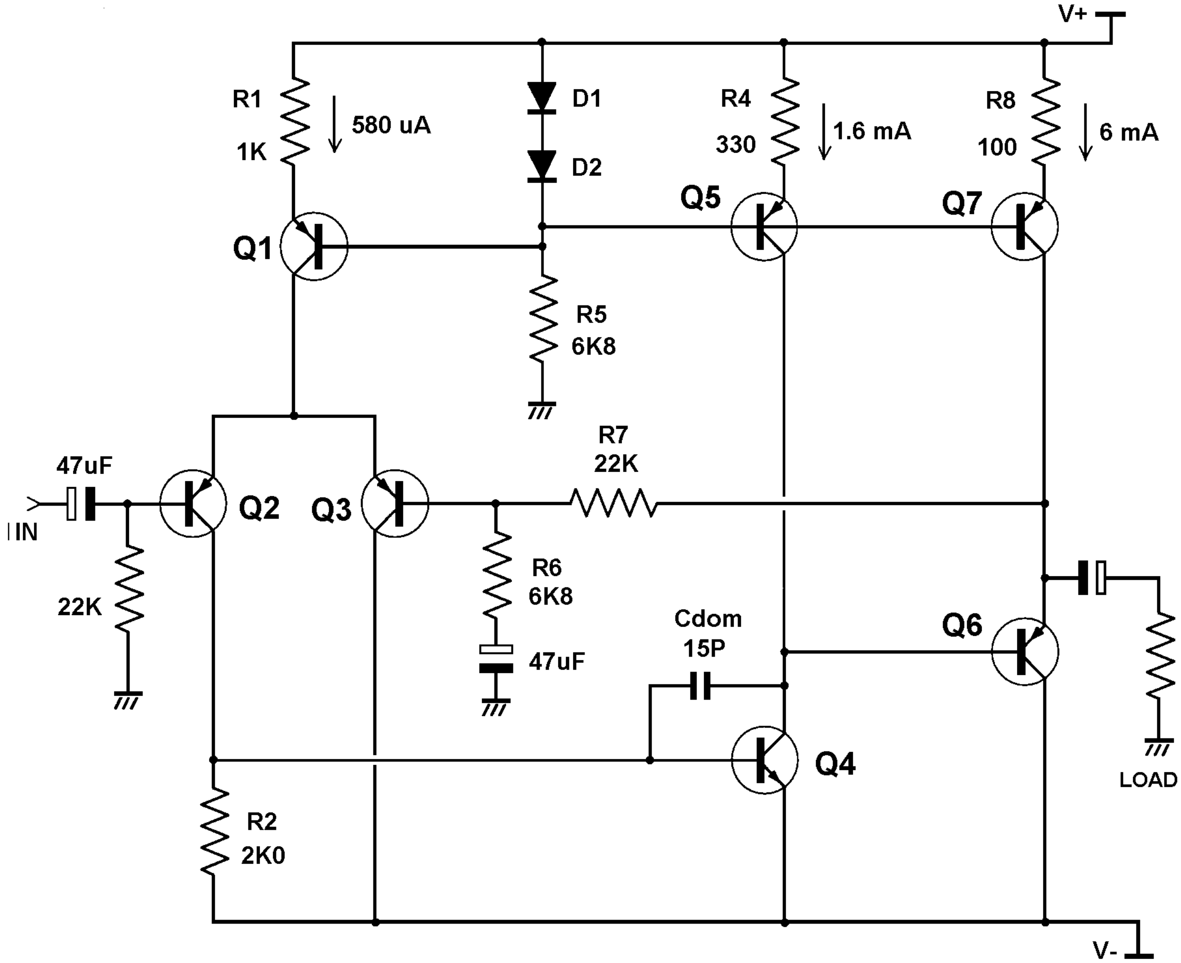
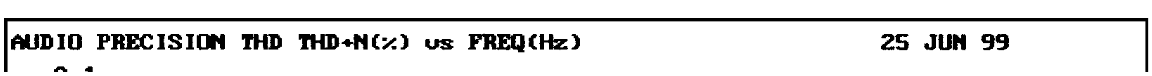


Fig 3 An improved discrete opamp, with the input stage balanced and the output stage inverted to share the biasing diodes, and so reduce component count. dsctamp2.gif

The operating conditions of the opamp are set by the three currents shown on the circuit diagrams:
The tail current of the first stage is probably the most critical, as this sets:

- **The transconductance of the input pair. This in turn affects the open-loop gain of the amplifier and therefore stability when the loop is closed.**
- **The maximum output slew rate.**
- **The noise performance. This is normally determined by a combination of the source resistance (of the external source which is driving the amplifier) and the collector current. The lower the source resistance, the higher the Ic required for minimal noise.**
- **The input bias currents, and hence DC accuracy in some cirumstances. Transistor beta also has a major influence on this.**



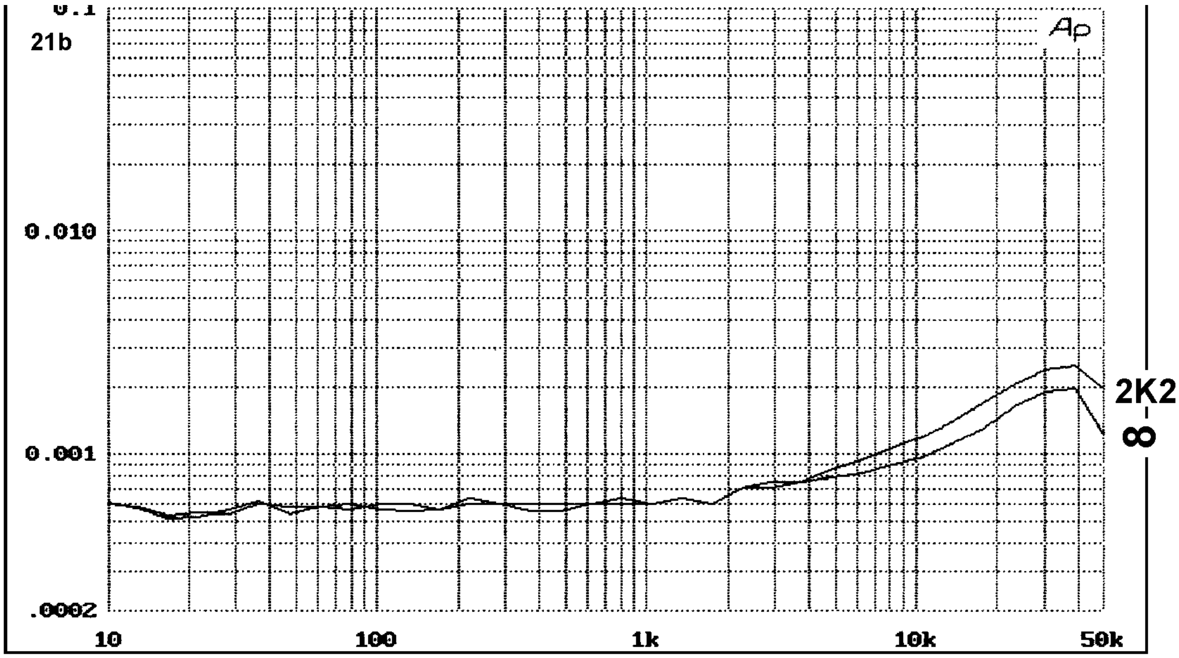


Fig 4 THD of the improved opamp circuit. Showing that the effect of a 2K2 load on linearity is negligible. 8 Vrms out. 21B

DIAGRAMS.

- **Fig 1 A typical discrete opamp circuit, with current-source output. dsctamp1.gif**
- **Fig 2 The discrete opamp of Fig 1. High-frequency THD is markedly reduced as the input pair is brought closer to balance by reducing the collector resistor to 2K0. 18A**
- **Fig 3 An improved discrete opamp, with the input stage balanced and the output stage inverted to share the biasing diodes. dsctamp2.gif**
- **Fig 4 The improved opamp circuit. Effect of 2K2 load on linearity is negligible. 21B**
