Build the SC200... Part 1

This completely new amplifier circuit incorporates most of the features of modern amplifier modules, but uses easy-to-solder through-hole components. There are no tiny surface-mount components.

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Over the last 15 years or so, we have published a number of very popular audio amplifier modules. Some of these are best described as 'work-horse' designs, while others have been very low distortion, but being Class-A, they have the normal drawback of being quite inefficient.

So why are we producing this new *SC200 Module*? First, while earlier designs have been very successful, their distortion and noise performance could be improved. So in short,they are well overdue for a major upgrade.

Second, while some designs have been excellent, many used surface-mount components and would have been far easier to build – and presumably more popular – if through-hole components had been specified.

Main features

- *Easy to build*
- *Uses low-cost parts*
- *Low distortion and noise*
- *Compact PCB*
- *Able to produce specified power output on a continuous basis with passive cooling*
- *Onboard DC fuses*
- *Power indicator LEDs*
- *Fuse OK/blown indicator LEDs*
- *Clipping indicator LED*
- *Clean overload recovery with low ringing*
- *Clean square-wave response with low ringing*
- *Tolerant of hum and EMI fields*
- *Survives brief short circuits/overload without blowing fuses*
- *Quiescent current adjustment with temperature compensation*
- *Output offset voltage adjustment*
- *Output protection diodes (for driving 100V line transformers and electrostatic speakers)*

So in designing the *SC200 Module*, we have tried to make it much easier to build and at the same time, produce a module which is far ahead of ealier designs in all aspects of performance. All the semiconductors on the PCB are conventional through-hole components. Also, the small-signal transistors are readily available types and while the input pair of transistors won't give quite the same extremely low noise performance of some previous designs, they are cheap and readily available.

'Exotic' (ie, hard to source and/or expensive) devices have been avoided and this new design uses conventional 3-lead power transistors from Fairchild, types FJA4313 and FJA4213.

Main features

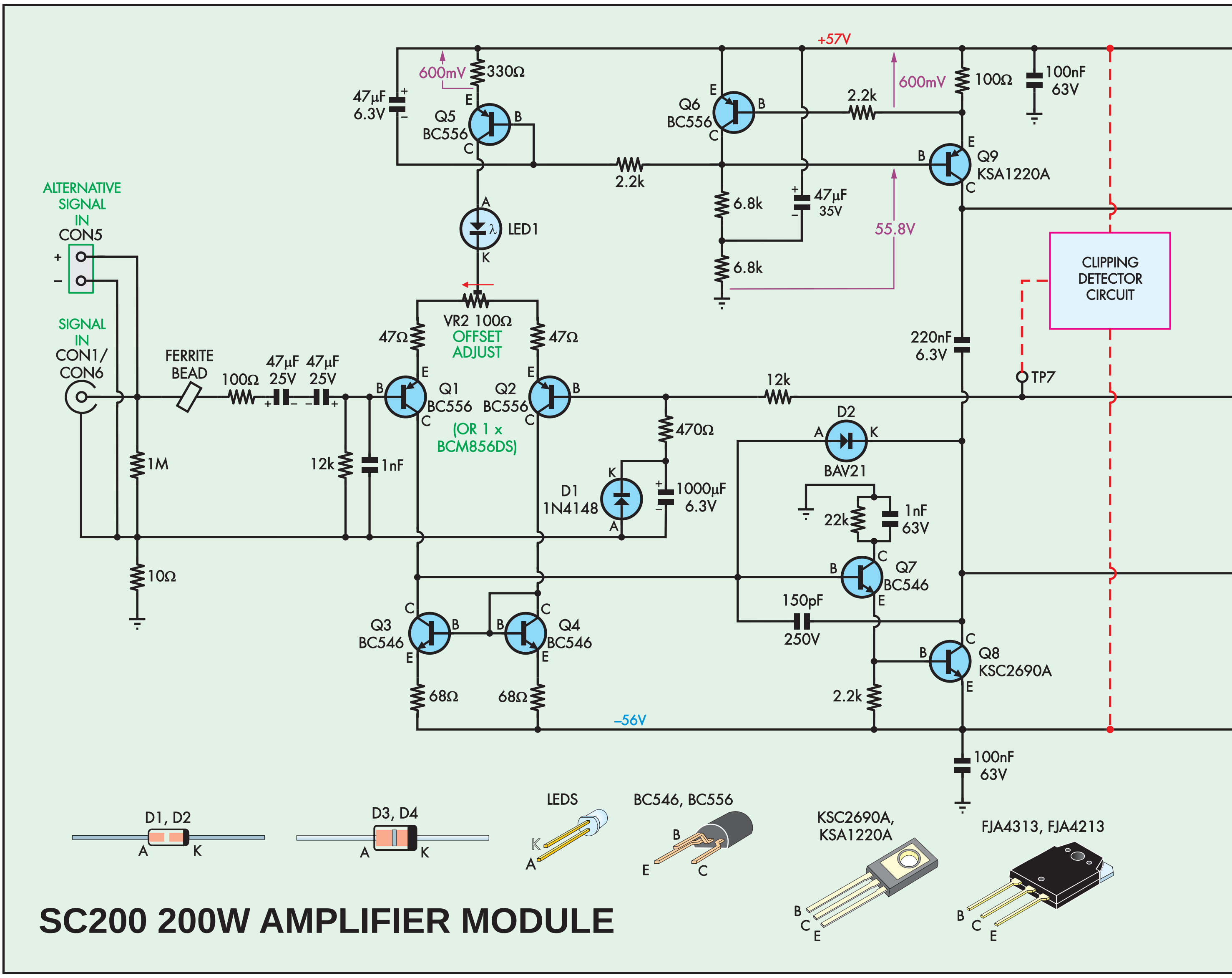
We've called this amplifier the 'SC200', indicative of its 200W power output into a 4Ω load. The design's main features are listed in a separate panel but some require additional comment.

Apart from exceptional performance, the *SC200* has quite a few features which were not thought of when we produced earlier amplifiers. These include on-board LEDs which indicate if the power rails are present and which change colour if the DC fuses blow.

And there is the clipping indicator circuit which drives an LED to show when the amplifier is being over-driven. This LED can be mounted on the amplifier front panel if desired and can be wired to multiple modules to indicate when any channel is clipping. Or you can simply have a clipping indicator for each channel in a stereo or surround sound amplifier.

Circuit description

The main amplifier circuit is shown in Fig.1. A 1MΩ resistor DC biases the input signal at RCA socket CON1 to 0V. The signal ground (ie, RCA socket shield) is connected



SC200 200W AMPLIFIER MODULE

to power ground via a 10Ω resistor, which improves stereo separation when modules share a power supply; it prevents a ground loop due to the grounds being joined directly both at the power supply module and at the signal source.

The signal passes through an RF-attenuating RC low-pass filter (100Ω/1nF plus ferrite bead) and is coupled to the base of PNP transistor Q1 via a pair of series-connected 47µF 25V electrolytic capacitors (which are together more compact and cost less than an equivalent non-polarised capacitor).

A 12kΩ resistor provides a path for Q1's base current to flow to ground. We have used readily available BC556 low-noise PNP input transistors for the input differential pair, Q1 and Q2. The input signal goes to the base of Q1, while negative feedback from the output goes to the base of Q2.

Both transistors have 47Ω emitter degeneration resistors for improved linearity, and they are fed with a common 2mA current via trimpot VR2 and power indicator LED1.

VR2 allows the current split to be shifted slightly between the two transistors to trim out base-emitter voltage mismatch and thus practically eliminate any output offset, and avoid excessive DC current when driving a line transformer or electrostatic speaker. LED1 has no effect on the operation of the circuit except to indicate when it is powered.

The currents from Q1 and Q2 go to a current mirror comprising two BC546 NPN transistors Q3 and Q4. The 68Ω emitter resistors help ensure that equal current flows through each transistor as the voltage across these resistors is much greater than the base-emitter voltage difference between the two.

Since the currents through Q3 and Q4 are held equal, any difference between the current from Q1 and Q2 must flow to the base of NPN transistor Q7. Thus, Q7's base current is proportional to the difference in input and feedback voltages. It forms the first half of a compound (Darlington-like) pair along with Q8, a 160V high-gain transistor. A 2.2kΩ resistor between its base and emitter speeds up switch-off.

Q7 and Q8 together form the Voltage Amplification Stage (VAS). Q8 has a constant-current source for its collector load, comprising Q6 and Q9. Together, these set the collector current for Q8 at around 6.5mA. As a result, the current flow to the base of Q7 is translated linearly to a voltage at Q8's collector, which controls the output stage.

PNP transistor Q5 provides a constant current of around 2mA to the input pair, and both it and Q9 are driven by Q6, which is set up to maintain a constant voltage across their emitter resistors. In other words, Q6 biases the bases of Q5 and Q9 to maintain an essentially static current through their collector-emitter junctions.

Output stage

The output stage consists of two pairs of Fairchild power transistors arranged as complementary emitter-followers. NPN transistors Q13 and Q14 are connected in parallel and source current for the speaker, while Q15 and Q16 are PNP types and sink current from the speaker.

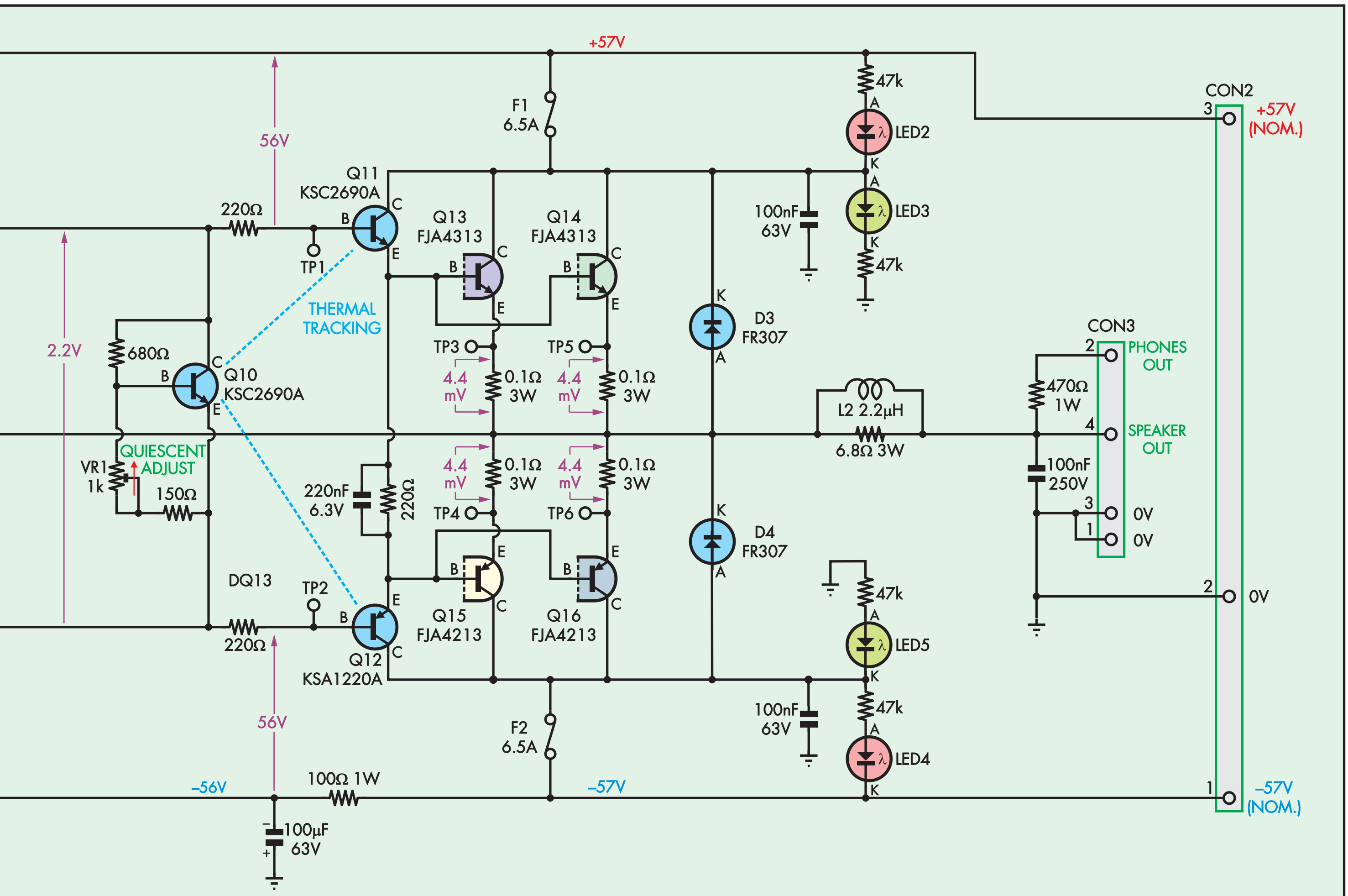


Fig.1: the complete circuit for the *SC200 Amplfier Module* minus the circuitry for the clipping detector, which is shown separately in Fig.2. Q1 and Q2 are the input transistors, while Q5 and Q6 are the constant-current source. The signal from the collector of Q1 is fed to the base of Q7, which together with Q8 forms the voltage amplification stage. Q9 is the constant current load for Q8, providing very linear operation. Q10 is the V_{BE} multiplier and provides a floating voltage source which biases the complementary Darlington output stage.

Surface-mount 3W 0.1Ω 1% emitter resistors ensure equal current sharing, linearise the output stage and produce a small amount of local feedback. They also serve as handy shunts for measuring the quiescent current.

Large power transistors require substantial base current due to limited gain; this is supplied by driver transistors Q11 and Q12. These effectively make the output stage a complementary Darlington.

The parallel 220Ω resistor and 220nF capacitor between the driver emitters speed up their switch-off when drive is being handed off from one to the other.

Quiescent current stabilisation

The four base-emitter junctions in the output stage, plus the voltage across the emitter resistors adds up to around 2.2V (as shown just to the left of Q10 in the circuit diagram) and thus a similar DC bias must be maintained between the bases of Q11 and Q12 to keep the output transistors in partial conduction most of the time; otherwise, there will be substantial crossover distortion each time the signal passes through 0V.

The reason is that when the signal polarity changes (ie, from positive to negative or vice versa), the output current drive is handed off from one set of output transistors to the other; ie, from Q13 and Q14 to Q15 and Q16, or the other way around.

This transition has to be smooth or else there will be a step in the output voltage and the way to smooth it is to ensure that there is overlap between the conduction of both pairs. In other words, with the output at zero volts, all four transistors are passing some current. This is known as the quiescent current.

This partial conduction requirement is a defining characteristic of Class-AB (otherwise, it would be Class-B).

To maintain a more-or-less constant quiescent current we need a 'floating' voltage source of 2.2V between the bases of Q11 and Q12, and this is provided by the V_{BE} multiplier Q10 and its associated components.

However, since the base-emitter voltages of the six transistors in the output stage all vary with temperature, a fixed floating voltage source is not suitable.

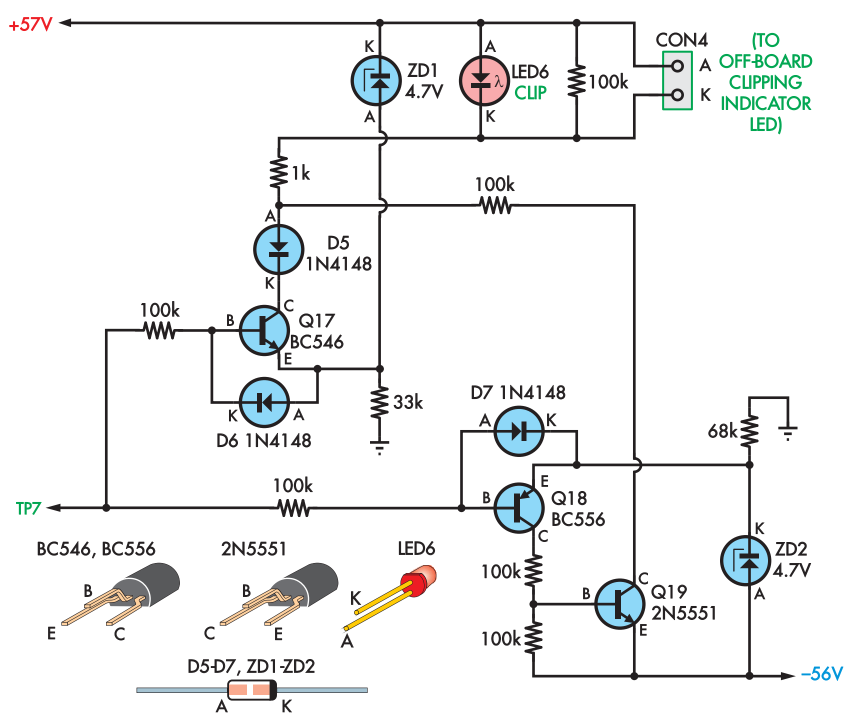
The base-emitter voltages drop with increasing temperature at around 2mV/°C, so a fixed voltage source of 2.2V would lead to increased current as the output transistors heated up and ultimately, to thermal runaway and destruction.

V_{BE} multiplier

So our floating voltage source must not only be adjustable, to compensate for manufacturing variations in the output transistors and emitter resistors, it must also automatically reduce the bias as the amplifier heats up, so that the quiescent current remains reasonably constant.

But first, let's explain the basic concept of a 'V_{BE} multiplier' before we consider how it tracks and adjusts for changes in operating temperature.

The V_{BE} multiplier is sometimes referred to as an 'amplified diode' and this gives some insight into its operation. Consider that the base-emitter voltage of a conducting transistor is around 0.6V. The bias network to our V_{BE} multiplier comprises the 680Ω



CLIPPING DETECTOR FOR SC200 AMPLIFIER

Fig.2: the clipping detector monitors the output waveform and lights LED6 whenever the output voltage comes within about 4V of either supply rail. This indicates the onset of clipping. NPN transistor Q17 detects positive signal excursions, while PNP transistor Q18 detects when the output signal approaches the negative rail.

resistor between collector and base and the 1kΩ trimpot and 150Ω resistor between base and emitter. This forms a divider between its collector and emitter, with a tap at the base.

We already know that the voltage between base and emitter is 0.6V and since the beta (DC current gain) of the transistor is quite high (>100), it will draw negligible base current, so the current through the two resistors and trimpot VR1 will essentially be identical. Furthermore, since we will have 0.6V between base and emitter, it follows that we need 1.6V between collector and base, if we are to obtain 2.2V between collector and emitter.

So, to adjust the resistance of VR1 to obtain 1.6V between collector and emitter, we need a resistance ratio between collector/base and base/emitter of 1.6V÷0.6V or 2.6666:1. This means the total resistance of VR1 and its series 150Ω resistor will be 680Ω × 0.6 ÷ 1.6 = 255Ω. And that means that trimpot VR1 must be set to a value of 255Ω – 150Ω = 105Ω.

We can therefore calculate the total resistance of the divider between collector and emitter at around 255Ω + 680Ω = 935Ω and therefore 2.2V / 935Ω = 2.35mA will flow through it.

The remainder of the 6.5mA (ie, 4.15mA) must flow through the collector/emitter junction of Q10.

But what if the external operating conditions around the V_{BE} multiplier act to increase the voltage between its collector and emitter above 2.2V? If that did happen, the resistive divider would cause its base-emitter voltage to increase but that would force the transistor to turn on harder and that would have the effect of reducing the collector-emitter voltage.

So the V_{BE} multiplier transistor is instead forced to operate with a constant collector-emitter voltage! In other words, it operates as a shunt voltage regulator, maintaining a constant voltage across the collector/emitter junction even if the current passing through it varies (but as long as it's higher than the 2.35mA required for the divider to operate properly).

Thermal tracking

So how does V_{BE} multiplier transistor Q10 adjust for temperature changes in the output transistors? We make it do that by mounting Q10 on the heatsink immediately between driver transistors Q11 and Q12. Furthermore, Q10 is the same transistor type as Q12, so the thermal tracking of the driver transistors and by extension, that of the four output power transistors, is quite good; not perfect, but quite good.

So if the temperature of the heatsink rises by 50°C, that would mean that the required base-emitter voltages of all seven transistors (for a given collector current) on the heatsink will reduce by 50 × 2mV = 100mV.

If the base-emitter voltage of Q10 has reduced by 100mV, given that it operates with a gain of (1.6 + 0.6)÷0.6 = ~3.7 times, the voltage of our floating source will be reduced to 2.2V – 100mV × 3.7 = 1.83V and this voltage will be applied across the four base-emitter junctions of the complementary Darlington output stage transistors. That means that even though the transistor junction temperatures may have increased by 50°C, their quiescent current should remain much as it was at much lower temperatures.

In practice, the process is not quite that good, so we also have local

Specifications

Output power (230VAC mains)	*200W RMS into 4Ω, 135W RMS into 8Ω*
Frequency response (10Hz-20kHz)	*+0,–0.05dB (8Ω); +0,–0.12dB (4Ω)*
Input sensitivity	*1.26V RMS for 135W into 8Ω; 1.08V RMS for 200W into 4Ω*
Input impedance	*11.85kΩ shunted with 1nF*
Rated Harmonic Distortion (4Ω, 8Ω)	*<0.01%, 20Hz-20kHz, 20Hz-30kHz bandwidth*
Signal-to-noise ratio	*–116dB unweighted with respect to 135W into 8Ω(20Hz-20kHz)*
Damping factor	*~250*
Stability	*unconditionally stable with any nominal speaker load ≥4Ω*
Music power	*170W (8Ω), 270W (4Ω)*
Dynamic headroom	*1dB (8Ω), 1.3dB (4Ω)*
Power supply	*±57V DC from a 45-0-45 transformer*
Quiescent current	*88mA nominal*
Quiescent power	*10W nominal*
Output offset	*typically <10mV untrimmed; <1mV trimmed*

Parts list – SC200 Amplifier Module

1 double-sided PCB available from the *EPE PCB Service*, coded 01108161, 117 × 84mm
1 diecast heatsink, 200 × 75 × 28mm
4 M205 fuse clips (F1,F2)
2 6.5A fast-blow M205 fuses (F1,F2)
1 small ferrite bead (FB1)
1 2.2µH air-cored inductor (L2) (***or*** 1 20mm OD × 10mm ID × 8mm bobbin and 1m of 1.25mm diameter enamelled copper wire, plus 10mm length of 20mm diameter heatshrink tubing)
1 1kΩ 25-turn vertical trimpot (VR1)
1 100Ω mini horizontal trimpot (VR2)
1 switched horizontal RCA socket (CON1) OR
1 2-pin polarised header (CON5) OR
1 vertical RCA socket (CON6)
1 4-way pluggable terminal block with socket, Dinkle 4EHDV or equivalent (CON2)
1 4-way pluggable terminal block with socket, Dinkle 3EHDV or equivalent (CON3)
4 TO-3P insulating washers
3 TO-126 or TO22- insulating washers
7 15mm M3 machine screws with nuts
6 6mm M3 machine screws with nuts
4 9mm M3 tapped nylon spacers
8 PCB pins (optional; TP1-TP7)

Semiconductors
2 FJA4313 250V 17A NPN transistors, TO-3P (Q13,Q14)
2 FJA4213 250V 17A PNP transistors, TO-3P (Q15,Q16)
3 KSC2690A medium-power NPN transistor (Q8,Q10,Q11)
2 KSA1220A medium-power PNP transistors (Q9,Q12)
3 BC546 NPN transistors (Q3,Q4,Q7)*
4 BC556 PNP transistors (Q1,Q2,Q5,Q6)*
1 blue 3mm or SMD 3216/1206 LED (LED1)
2 red 3mm or SMD 3216/1206 LEDs (LED2,LED4)
2 green 3mm or SMD 3216/1206 LEDs (LED3,LED5)
1 1N4148 small-signal diode (D1)*
1 BAV21 high-speed signal diode (D2)*
2 FR307 3A fast-recovery diodes (D3,D4)

Capacitors
1 1000µF 6.3V electrolytic
1 100µF 63V electrolytic
1 47µF 35V electrolytic
3 47µF 25V electrolytic
2 220nF 50V multi-layer ceramic or MKT
1 100nF 250VAC MKP
4 100nF 63V/100V MKT
2 1nF 63V/100V MKT
1 150pF 250V C0G/NP0 ceramic or MKT/MKP

Resistors (all 0.25W, 1% unless otherwise specified)
1 1MΩ 4 47kΩ 1 22kΩ
2 12kΩ 2 6.8kΩ 3 2.2kΩ
1 680Ω
1 470Ω 1W 5% through-hole or SMD 6332/2512
1 470Ω 1 330Ω 3 220Ω
1 120Ω
1 100Ω 1W 5% through-hole or SMD 6332/2512
2 100Ω 2 68Ω 2 47Ω
1 10Ω
1 6.8Ω 1% 3W SMD 6332/2512
4 0.1Ω 1% 3W SMD 6332/2512

Additional parts for clipping detector circuit

1 2-pin header and matching plug (optional; CON4)

Semiconductors
1 BC546 NPN transistor (Q17)*
1 BC556 PNP transistor (Q18)*
1 2N5551 high-voltage NPN transistor (Q19)
1 yellow, amber or red LED (LED6)
2 4.7V 0.4W/1W zener diodes (ZD1,ZD2)*
3 1N4148 small-signal diode (D5-D7)*

Resistors (all 0.25%, 1%)
6 100kΩ 1 68kΩ 1 33kΩ 1 1kΩ

**** SMD versions can be substituted; see text next month***

feedback provided by the 0.1Ω 3W emitter resistors for the output transistors. If the voltage across these emitter resistors increases, due to increasing quiescent current, that will tend to reduce the base-emitter voltage (by subtraction) and therefore the current will reduce (or at least, not increase by as much as it would without them).

By the way, the 220Ω resistors between either end of the V_{BE} multiplier Q10 and Q11/Q12 act as RF stoppers and also limit current flow under fault conditions (eg, a short circuit).

Feedback and compensation

Negative feedback goes from the junction of the output emitter resistors to the base of Q2 via a 12kΩ/470Ω resistive divider, setting the closed-loop gain to 25.5 times (+28.5dB). The bottom end of the feedback network is connected to ground via a 1000µF electrolytic capacitor.

This has a negligible effect on the low-frequency response, but sets the DC gain to unity, so that the input offset is not magnified at the output by the gain factor of 25.5.

The 150pF compensation capacitor is connected between the collector of Q8 and the base of Q7, ie, it is effectively a Miller capacitor for the VAS 'Darlington' (in a real Darlington, the collectors would be common). This is a single-pole compensation arrangement which rolls off the open-loop gain at a high frequency to give unconditional stability with highly reactive loads across the amplifier's output.

The 22kΩ resistor in series with the collector of Q7 limits its current under fault conditions. Should the amplifier outputs be shorted, it will try to pull the output either up or down as hard as possible, depending on the offset voltage polarity.

If it tries to pull it up, the output current is inherently limited by the approximate 6.5mA current source driving Q11 from Q9. However, if it tries to pull down, Q8 is capable of sinking much more than 6.5mA.

The 22kΩ resistor limits Q8's base current to around 2mA and since Q8 has a beta of around 120, Q8's collector will not sink much more than 240mA. This is still enough to burn out Q12's 220Ω base resistor, but that may be the only damage from an extended short circuit; very brief short circuits should not cause any lasting damage.

Note that the 22kΩ resistor will cause Q7's collector voltage to drop as it is called on to supply more current, and the Early effect means its gain will drop when this happens. This can cause local negative feedback and oscillation. A low-value

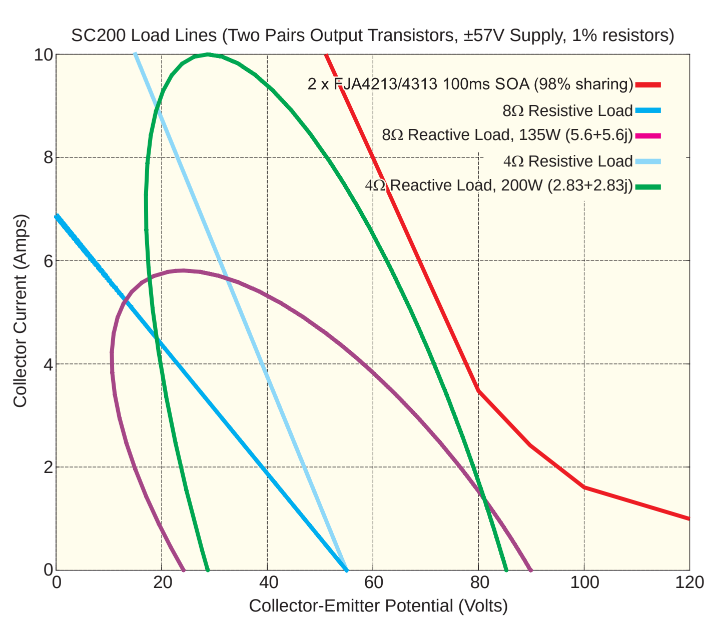


Fig.3: this diagram shows resistive (straight) and reactive (curved) load lines for operation into loudspeaker loads. Note that all the load lines are comfortably inside the safe operating area (SOA – red line) of the paralleled output transistors.

capacitor in parallel with the 22kΩ resistor prevents this while still allowing the current to Q8's base to quickly drop to 2mA during a short circuit.

Output filter

The 0.1Ω 3W emitter resistors of output transistors Q13-Q16 are connected to the output at CON3 via an RLC filter comprising a 2.2µH series inductor in parallel with a 6.8Ω 3W surface-mount resistor, with a 100nF capacitor across the output terminals. The inductor isolates any added capacitance at the output (eg, from the cables or the speaker's crossover network) from the amplifier at high frequencies, which could otherwise cause oscillation. The resistor reduces the inductor's Q to damp ringing, and also forms a Zobel network in combination with the 100nF capacitor, which also aids stability.

Driving a line transformer

While a very low output offset voltage gives slight benefits when driving normal speakers, it's absolutely critical when driving a 100V line transformer (for professional PA applications) or electrostatic speaker (which will typically have an internal transformer).

That's because the DC resistance of the primary winding will be much lower than that of a loudspeaker's voice coil, so a lot of DC current can flow with an output offset voltage of just a few millivolts.

The other requirement for driving a transformer is to have protection diodes on the amplifier output to clamp inductive voltage spikes which occur when the amplifier is driven into clipping (overload).

These would otherwise reverse-bias the output transistor collector-emitter junctions, possibly causing damage. D3 and D4 are 3A relatively fast recovery diodes with low junction capacitance for their size and we have checked that they do not have any impact on performance.

So there should be no changes necessary to use this module in a PA amplifier or to drive electrostatic speakers, as long as the output offset voltage is trimmed out during set-up.

> **WARNING!**
>
> High DC voltages (ie, ±57V) are present on this amplifier module. In particular, note that there is 114V DC between the two supply rails. Do not touch any wiring (including the fuseholders) when the amplifier is operating, otherwise you could get a lethal shock.

Indicator LEDs

We have already mentioned a blue LED1 connected in series with the input pair current source and which is lit whenever the board has power applied. Since there is an ~50V drop required from Q5's collector to VR2's wiper, the power to operate this LED is effectively free.

We've also included red/green LEDs LED2-LED5 to indicate the status of the output stage power rails. It isn't always obvious that a fuse has blown without careful inspection.

In the case of LED2, assuming F1 has not blown, the voltage at either end of the fuse-holder is the same so no current will flow through the red junction. However, LED3 is connected between the collectors of Q11, Q13 and Q14 and ground via a 47kΩ current-limiting resistor, so it will light up.

If fuse F1 blows, the collector voltages will drop to near 0V, so green LED3 will turn off but the full rail voltage will be across the fuse-holder and so the red LED2 will switch on. Similarly, LED5/LED4 indicates green/red when F2 is OK/blown.

These LEDs will also indicate if one of the two supply rails is missing (eg, due to a wiring fault); in this case, LED1 will probably still light up so it might not otherwise be obvious.

Clipping indicators

Now we can talk about the on-board clipping detector/indicator circuit. This involves just a few components and will indicates whenever the amplifier is driven into clipping, which may not be obviously audible.

It can drive an external LED mounted on the front panel of the amplifier. These components may be omitted if they are not required.

The clipping detector circuit is shown in Fig.2. Zener diode ZD1 derives a reference voltage 4.7V below the nominally 57V positive rail, ie, at about +52V. This is connected to the emitter of NPN transistor Q17. Its base is connected to the amplifier's output via a 100kΩ current-limiting resistor, with diode D6 preventing its base-emitter junction from being reverse-biased.

At the onset of clipping, the speaker voltage will rise above the +52V reference plus Q17's base-emitter voltage, ie, to about +53V. Q17 will switch on and sink current via LED4, a 1kΩ current-limiting resistor and isolating diode D5, lighting up clipping indicator LED6. As the reference voltage is relative to the positive rail, any variations in supply voltage will be accounted for.

ZD2, PNP transistor Q18 and diode D7 work in an identical manner for negative excursions.

However, Q18 drives LED6 via high-voltage NPN transistor Q19, which acts as a level shifter. The 100kΩ resistor in series with its collector limits the LED current to a similar level (1mA) despite the much higher rail voltage differential.

This is not the simplest clipping detector circuit, but it presents an almost completely linear load to the amplifier output, to minimise the possibility of any distortion due to its input load current.

It's connected to the driven end of L2 to give the amplifier the best chance to cancel out any non-linearities in the load it introduces.

Next month

Have we whetted your collective appetites? Next month, we will present the full details of performance and construction details.