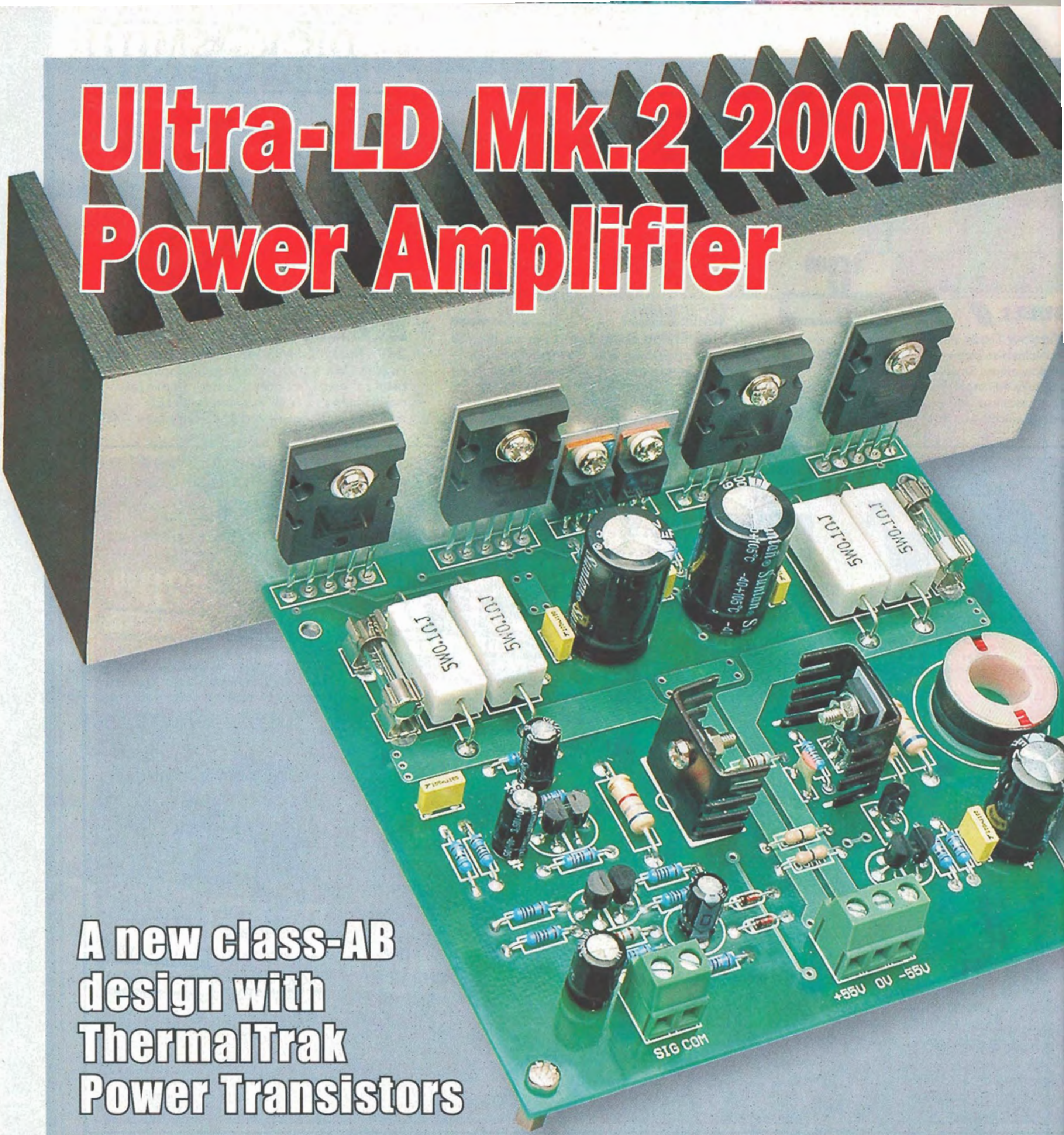
Ultra-LD Mk.2 200W Power Amplifier



A new class-AB design with ThermalTrak Power Transistors

This new amplifier module supersedes both the Plastic Power module described in the April 1996 issue and the Ultra-LD module presented in the March 2000 issue. It produces high power at very low distortion. In fact, as far as we are aware, it is the lowest distortion class-AB amplifier that has ever been published.

Pt.1: By LEO SIMPSON & JOHN CLARKE

Specifications & Performance

Output Power: 200 watts RMS into 4Ω; 135 watts RMS into 8Ω

Frequency Response at 1W: -3dB at 4Hz, -1dB at 50kHz (see Fig.4)

Input Sensitivity: 1.26V RMS for 135W into 8Ω

Input Impedance: ~12kΩ

Rated Harmonic Distortion: < .008% from 20Hz to 20kHz for 8Ω operation; typically < .001% (see Figs.5-8)

Signal-to-Noise Ratio: 122dB unweighted with respect to 135W into 8Ω (22Hz to 22kHz)

Damping Factor: <170 with respect to 8Ω at 100Hz; <50 at 10kHz

Stability: Unconditional

THE ULTRA-LD MK.2 AMPLIFIER Module uses the new On Semiconductor ThermalTrak power transistors in a circuit which is largely based on our high-performance Class-A amplifier which was featured in SILICON CHIP during 2007. The ThermalTrak transistors are a new version of the premium MJL3281A & MJL1302A and have an integral diode for bias compensation. As a result, the circuit has no need for a quiescent current adjustment or a "Vbe multiplier" transistor.

This is also our first amplifier module to use a double-sided PC board. Ostensibly, there is no reason to use a double-sided board for a relatively simple circuit such as this, especially as our previous single-sided amplifier boards have had few links.

In fact, we have used the double-sided design to refine and simplify the external wiring to the PC board which has been arranged to largely cancel the magnetic fields produced by the asymmetric currents drawn by each half of the class-B output stage. We provide more detail on this aspect later in this article.

Power output of the new module is on a par with the above-mentioned Plastic Power module and significantly more than the original Ultra-LD module. As well, it uses a considerably simpler power supply than the Ultra-LD module.

Power output is 135 watts RMS into an 8-ohm load and 200 watts into a 4-ohm load for a typical harmonic distortion of less than .001%. The new module also has slightly higher gain than the Ultra-LD module but still manages to produce an improved signal-to-noise ratio of -122dB (unweighted) with respect to 135W into 8Ω. This is extremely quiet.

Design Features

- Very Low Distortion
- No adjustment for quiescent current required
- Double-sided PC board simplifies wiring
- PC board topology cancels class-B induced magnetic fields

A look at the accompanying performance panel and the performance graphs will show that this is a truly exceptional amplifier, bettered only by the Class-A amplifier described during 2007. In fact, some of the distortion figures we have obtained are so low, around .0007% for operation into 8-ohm loads, that we were amazed. We had expected this Class-AB amplifier to be better than anything we had published before – but not this good!

Circuit description

Fig.1 shows the full circuit of the new amplifier. As already mentioned, the front end of the circuit (ie, all except the output stages) is based on the Class-A amplifier published in May 2007 and subsequent issues. While the general configuration was designed to optimise performance of the Class-A design, it provides similar benefits to Class-AB operation, such as low residual noise and excellent power supply rejection ratio (PSRR).

We have already mentioned that there is no need for a "Vbe amplifier" stage and no quiescent current adjustment. Also the complementary-feedback pair (CFP) power output stage of the original Ultra-LD module has been discarded in favour of a more conventional complementary-symmetry Darlington emitter follower stage.

So let's go through the circuit in detail. The input signal is coupled via a 47μF non-polarised (NP) electrolytic capacitor and 100Ω resistor to the base of transistor Q1. This is one of the input differential pair (ie, Q1 & Q2) using Toshiba 2SA970 PNP low-noise transistors which are responsible for the very low residual noise of the amplifier. The 100Ω input resistor and 820pF capacitor constitute a low-pass filter with a -6dB/octave rolloff above 1.9MHz.

This is a much lower impedance network than our previous designs, in order to provide the lowest impedance for the signal source.

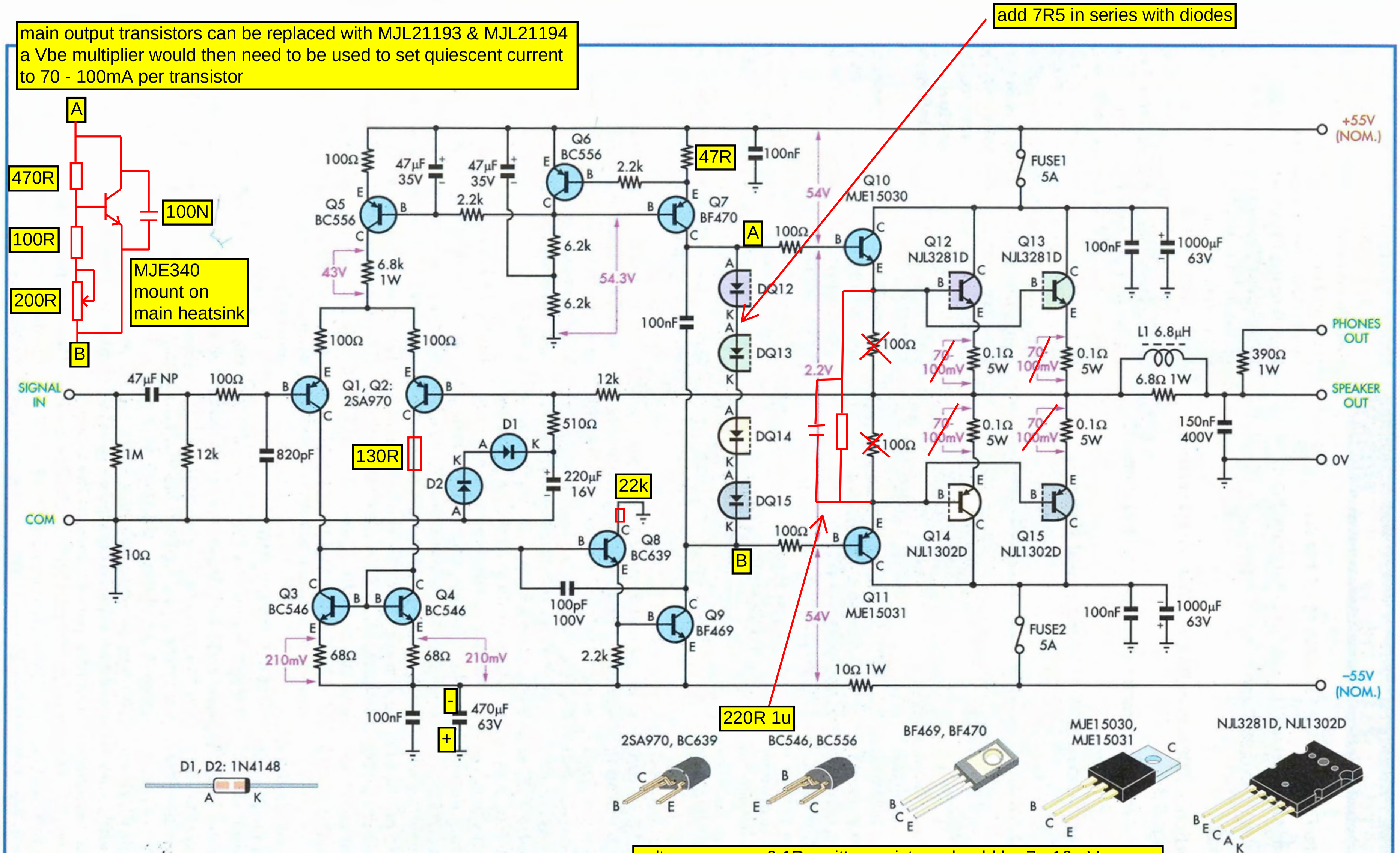
Both the bias resistor for Q1 and the series feedback resistor to the base of Q2 are set at 12kΩ (instead of 18kΩ in the original Ultra-LD and Plastic Power designs), again to minimise source impedance and thereby, Johnson noise.

The gain of the amplifier is set by the ratio of the 12kΩ and 510Ω feedback resistors to a value of 24.5, while the low-frequency rolloff (-3dB) of the gain is set by the 220μF capacitor to 1.4Hz.

Feedback capacitors

Some readers may wonder why we used such large electrolytic capacitors in the input and feedback networks. The answer is that we are acting to eliminate any effects of capacitor distortion in the audio pass-band and as noted above, to minimise the source impedance "seen" by the input transistors.

To explain this point, consider that the typical source impedance of a DVD or CD player is only a few hundred ohms. If we use a much smaller input capacitor, say 2.2μF, its impedance will be 1447Ω at 50Hz. This will only have a small effect on the frequency response but represents a very large increase in the source impedance "seen" by the input stage. By contrast, the 47μF input capacitor will have an impedance of only 67Ω.



SC ©2008 **ULTRA-LD MK.2 200W AMPLIFIER MODULE**

Fig.1: the circuit employs the new ThermalTrak power transistors from On Semiconductor. These have an integral diode which is used to control the quiescent in the Class-B output stage. The four diodes are shown separately on this circuit (ie, DQ12, DQ13, DQ14 & DQ15) for clarity but are actually integral with the output transistors which have five connecting leads instead of three. Note that the various voltages marked on the circuit will vary according to the supply rails.

Parts List

1 double-sided PC board coded 01108081, 135 x 115mm
1 heatsink 200L x 75mmH x 46Dmm
4 M205 PC mount fuse clips (F1,F2)
2 5A M205 fast blow fuses
1 6.8µH air-cored inductor (L1) (or 1 20mm OD x 10mm ID x 8mm bobbin and 1.5m length of 1mm enamelled copper wire)
2 3-way PC-mount screw terminals, 5.08mm spacing (Altronics P 2033A) (CON2, CON3)
1 2-way PC mount screw terminals with 5.08mm spacing (Altronics P 2032A(CON1-CON3)
2 TO-220 mini heatsinks 19 x 19 x 9.5mm
2 TO-220 Silicone insulating washers
4 TO-264 ThermalTrak silicone insulating washers
2 Transistor insulating bushes
4 M3 tapped x 9mm standoffs
6 M3 x 20mm screws
2 M3 x 10mm screws
8 M3 x 6mm screws
8-M3 nuts

Semiconductors
2 2SA970 PNP transistors (Q1, Q2)
2 BC546 NPN transistors (Q3,Q4)
2 BC556 PNP transistors (Q5,Q6)
1 BC639 NPN transistor (Q8)
1 BF470 PNP transistor (Q7)
1 BF469 NPN transistor (Q9)
1 MJE15030 NPN transistor (Q10)
1 MJE15031 PNP transistor (Q11)
2 NJL3281D NPN ThermalTrak transistors (Q12,Q13)
2 NJL13020D PNP ThermalTrak transistors (Q14,Q15)
2 1N4148 switching diodes (D1,D2)

Capacitors
2 1000µF 63V PC electrolytic
1 470µF 63V PC electrolytic
1 220µF 16V PC electrolytic
2 47µF 35V PC electrolytic
1 47µF NP electrolytic
1 150nF 400V MKT polyester
4 100nF 63VW MKT polyester
1 820pF ceramic
1 100pF 100V ceramic (eg, Altronics R 2882)

Resistors (0.25W, 1%)

1 1MΩ	8 100Ω
2 12kΩ	3 68Ω
1 6.8kΩ 1W	1 6.8Ω 1W
2 6.2kΩ	1 10Ω 1W
3 2.2kΩ	4 0.1Ω 5W
1 510Ω	2 0Ω
1 390Ω 1W	
2 470Ω 5W (for testing)	

Transistor Quality

To ensure published performance, the 2SA970 low-noise transistors (Q1 & Q2) must be from Toshiba. Be wary of counterfeit parts, as reported by us in the past.

We recommend that all other transistors be from reputable manufacturers, such as Philips (NXP Semiconductors), On Semiconductor and ST Microelectronics. This applies particularly to the MJE15030 & MJE15031 output driver transistors.

Readers might also wonder why we have not used a non-polarised (NP) electrolytic for the 220µF capacitor in the feedback network since this is normally preferable where the capacitor's operating voltage is extremely low. The answer is that an NP electrolytic could have been used except for its greater bulk and we wanted to minimise any extraneous signal pickup which could happen with a physically larger capacitor.

Extraneous signal pickup is one of the unwanted side-effects of a much wider frequency response – the amplifier is more prone to EMI and in the extreme case, to supersonic oscillation, if the wiring details are not duplicated exactly.

Diodes D1 & D2 are included across the 220µF feedback capacitor as insurance against possible damage if the amplifier suffers a fault which pegs the output to the -55V rail. In this circumstance, the loudspeakers would be protected against damage by a loudspeaker protection module (such as that published in the July 2007 issue of SILICON CHIP) but the 220µF capacitor would be left to suffer reverse current.

Note that we have used two diodes here instead of one, to ensure that there is no distortion due to the non-linear effects of a single diode junction at the maximum feedback signal level of about 1V peak.

Voltage amplifier stage

Most of the voltage gain of the amplifier is provided by Q9 which is fed via emitter follower Q8 from the collector of Q1. The emitter follower transistor is a BC639 which has higher ratings than the BC546 used for this function in the Class-A amplifier. It is used to buffer the collector of Q1, to minimise non-linearity.

Q9 is operated without an emitter resistor to maximise gain and its output voltage swing. We need to maximise voltage swing from the voltage amplifier stage in order to obtain the maximum power output from the output stages.

The collector loads for Q1 & Q2 are provided by current mirror transistors Q3 & Q4. Similarly, the collector load for Q9 is provided by a constant current load comprising transistors Q6 & Q7. Interestingly, the base bias voltage for constant current source Q5 is also set by Q6. Q5 is the constant current "tail" for the input differential pair and it sets the collector current through these transistors.

The reason for the rather complicated bias network for Q5, Q6 and Q7 is to produce a major improvement in the power supply rejection ratio (PSRR) of the amplifier. Similarly, the PSRR is improved by the bypass filter network consisting of the 10Ω 1W resistor and 470µF 63V capacitor in the negative supply rail.

Why is PSRR so important? Because this amplifier runs in class-B, it pulls large asymmetric currents which can be 9A peak or more, from the positive and negative supply rails.

Let's explain this. When the positive half of the output stage (Q12 & Q13) conducts, the DC current drawn is effectively the positive half-wave of the signal waveform, ie, rectification takes place. Similarly, when the negative half of the output stage (Q14 & Q15)

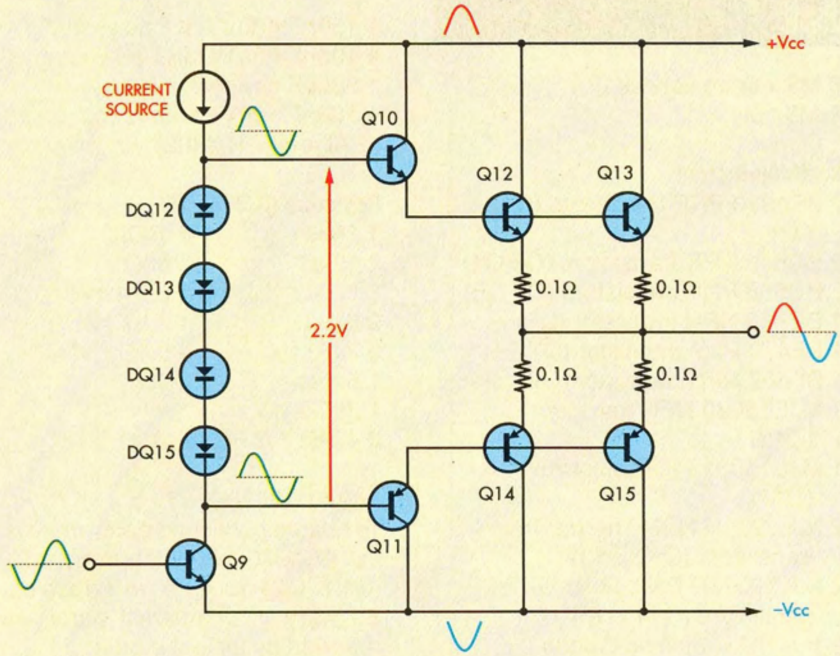


Fig.2: this schematic demonstrates how the four integrated diodes of the output transistors set the quiescent operating conditions of the Darlington emitter follower output stage. Note that the voltage drop across each diode is quite low at round 0.55V.

conducts, the DC current is the negative half wave of the signal.

So we have half-wave rectification ripple of the signal superimposed on the supply rails, as well as the 100Hz ripple from the power supply itself. And while the PSRR of an amplifier can be very high at low frequencies, it is always poorer at the high frequencies. So what happens is that these nasty ripple voltages inevitably get into the earlier stages of the amplifier and cause distortion. Which is why we need to keep these ripple voltages to a minimum.

That is why we employed separate regulated high-voltage supply rails for the original Ultra-LD amplifier. However, the extra filtering we employed in the Class-A amplifier (using techniques suggested by Douglas Self) now performs much the same function in this new Class-AB amplifier module so that we can dispense with the regulated supplies.

The scope grab on page 30 in this article gives a graphic demonstration of the signal rectification phenomenon we have just described. The centre (yellow) trace shows a 1kHz sinewave output signal from the amplifier at 100W into an 8-ohm load. The top (red) trace shows the ripple on the positive supply.

Note the large 100Hz sawtooth component which is ripple from the power supply. Superimposed on this is the half-wave rectified signal frequency at 1kHz. The bottom (blue) trace shows the same process on the negative supply rail.

The 100pF capacitor between the collector of Q9 and the base of Q6 sets the open-loop bandwidth of the amplifier. Since it is subject to the full output voltage swing of the voltage amplifier stage, it must have a rating of 100V or more.

Output stage

The output signal from the voltage amplifier stage Q9 is coupled to driver transistors Q10 and Q11 via 100Ω resistors. These protect Q7 and Q9 in the event of a short circuit to the amplifier output which could possibly blow these transistors before the fuses blow. The 100Ω resistors also have a secondary function in acting as "stopper" resistors to help prevent parasitic oscillation in the output stage.

As already mentioned, the output stage uses complementary Darlington transistor pairs rather than the complementary feedback pairs (CFP) used in the previous Ultra-LD module and the Class-A modules. There are two reasons for this approach. First, we are using the highly linear ThermalTrak output transistors with their integral bias compensation diodes. To take advantage of these diodes we need to employ Darlington emitter followers, as will be explained in a moment.

Second, a CFP output stage does not give good current sharing between the paralleled output transistors and we wanted this in order to make this new Ultra-LD Mk.2 suitable for delivering full power into 4-ohm loads.

Bias compensation

With four Thermaltrak power transistors used in the output stage, we have four integrated diodes available for bias compensation. As shown on the circuit, the four diodes are connected in series between the collector of Q7 and the collector of Q9. Some readers may be aware that this arrangement, together with an adjustable series resistor, was a common method for setting the output quiescent current, before the "Vbe multiplier" became the standard method over 30 years ago.

Now for a given bias setting in any Class-B amplifier, the base-emitter voltage in the output transistors will drop with a rising temperature. So as the output transistors heat up, they draw more current which makes them hotter and soon you have "thermal runaway" and eventual transistor destruction.

Since the bias setting for the output stage transistors is set by the voltage drop across the four integrated diodes, there is little chance of thermal runaway. Not only are the diodes matched to the base-emitter junctions of the transistors, they are also on the same die (chip) so the tracking between the two is very close.

This is a great advantage over a Vbe multiplier transistor mounted on the heatsink because the latter arrangement inevitably has a considerable thermal lag which can be as much as

WARNING!

High DC voltages (ie, ±55V) are present on this amplifier module when power is applied. **In particular, note that there is 110V DC between the two supply rails.** Do not touch the supply wiring (including the fuseholders) when the amplifier is operating, otherwise you could get a lethal shock.

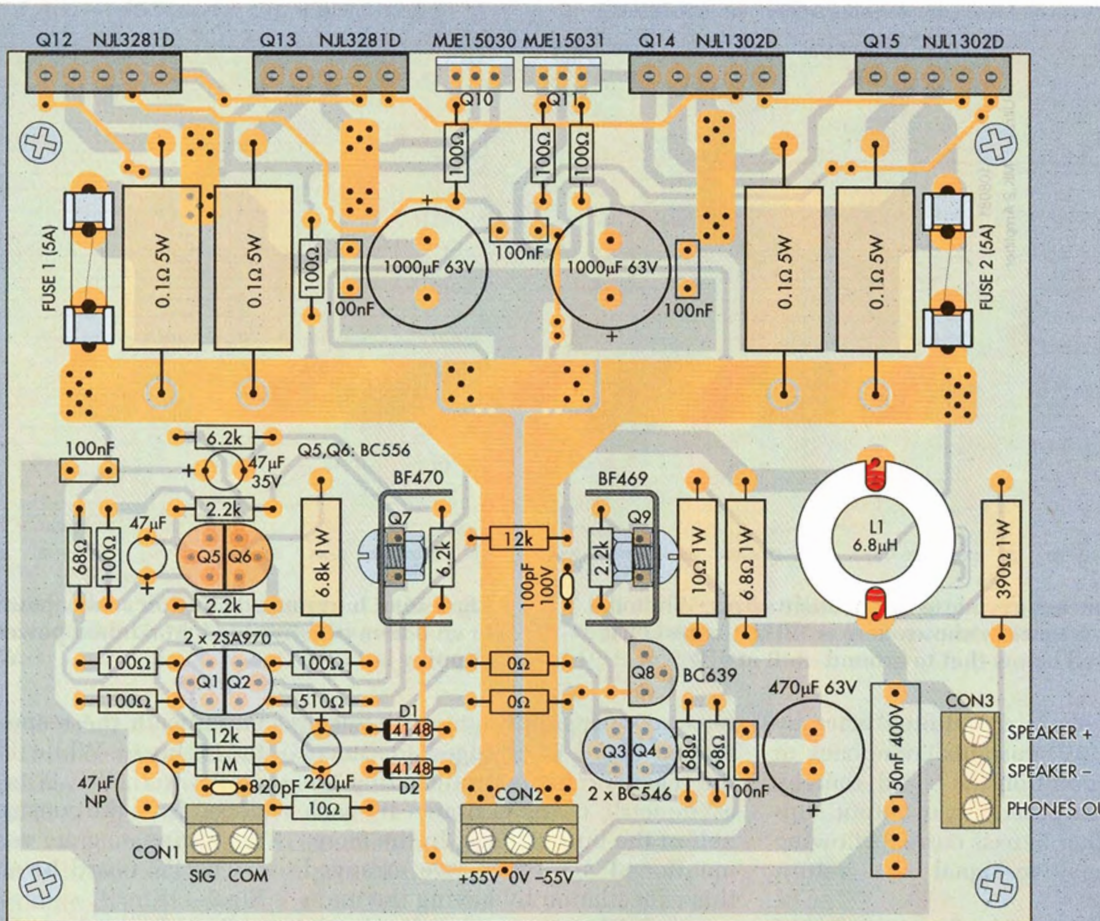


Fig.3: the PC board parts layout of the new amplifier module. The double-sided design allows much better cancellation of magnetic fields due to the asymmetric currents in the output stage.

30 minutes (depending on the size of the heatsink).

With the Thermaltrak transistors, we don't have to worry about thermal lag or runaway. The quiescent current settles quickly at switch-on. Thereafter, it can drift about, depending on the supply voltage and signal conditions but it will always come back to the initial "no-signal" value. On Semiconductor also claim that the harmonic distortion of the amplifier is lower than it would be with a Vbe multiplier stage.

Fig.2 shows the method of setting the output quiescent current. As depicted here, the four integrated diodes compensate for the four base-emitter junctions which control the quiescent current in the output stage. These are the two base-emitter junctions in the driver stages (Q10 & Q11) and the two paralleled base-emitter junctions of the four output transistors (Q12, Q13 & Q14, Q15).

The quiescent current is set by the difference in voltage drops between the aforementioned base-emitter junctions and the four diodes and this voltage difference appears across the 0.1Ω emitter resistors of the output. Typically, the voltage across the emitter resistors will be around 70-100 millivolts, giving a quiescent current of around 70-100mA for each transistor; somewhat higher than we would have set with a Vbe multiplier.

Output RLC filter

The remaining circuit feature to be discussed is the output RLC filter, comprising a 6.8μH air-cored choke, a 6.8Ω resistor and a 150nF capacitor. This output filter was originally produced by Neville Thiele and is still the most effective output filter for isolating the amplifier from any large capacitive reactances in the load, thereby ensuring unconditional stability. It also helps attenuate any RF signals picked up by the loudspeaker leads and stops them being fed back to the early stages of the amplifier where they could cause RF breakthrough.

Note that if the amplifier is intended for an application that requires continuous high-power output at frequencies of 10kHz or more, then the 6.8Ω resistor will need to be a 5W or 10W wirewound resistor.

Fuse protection

The output stages are fed via 5A fuses from the ±55V rails. These provide the only protection to the amplifier against short-circuits or other failures which could cause high current drain. **Note that we recommend the use of a loudspeaker protector such as the one described in the July 2007 issue.**

Double-sided PC board

As already noted, a double-sided PC board is used to simplify the power supply wiring. The general layout of the PC board is very similar to that used in the SC480 amplifier featured in the January & February 2003 issues which was itself a refinement of the layout used in the original Ultra-LD module. As such, the PC board has two important features.

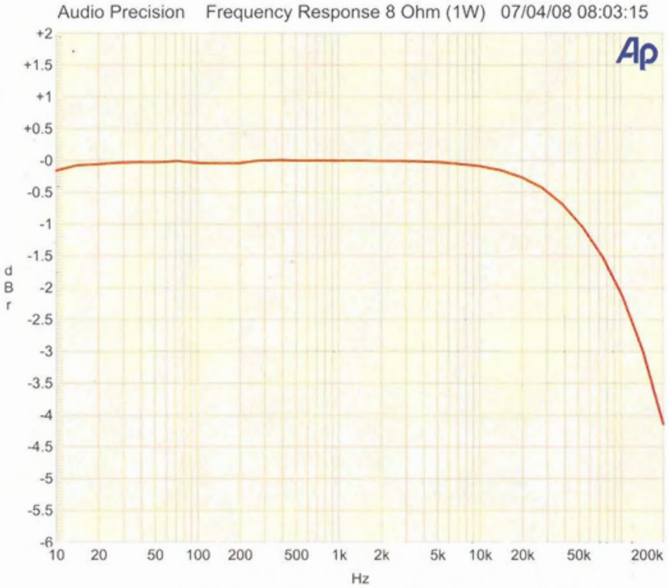


Fig.4: frequency response at 1W into 8 ohms. While the minimum frequency shown here is 10Hz, the response extends well below that to around -3dB at 4Hz.

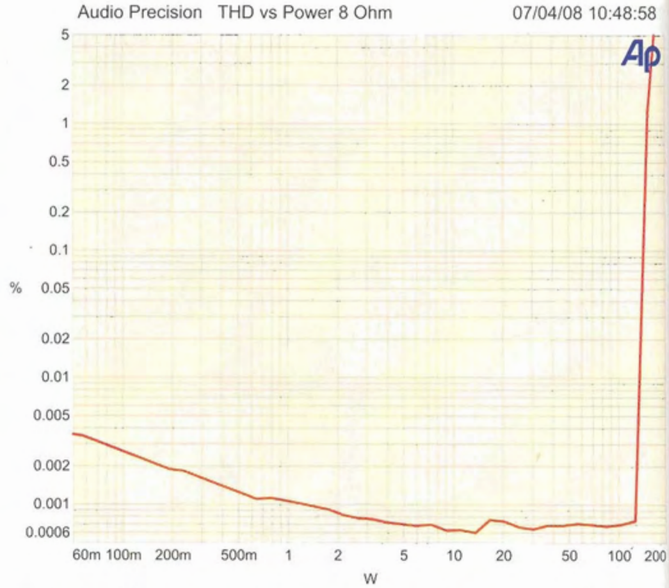


Fig.5: total harmonic distortion versus power at 1kHz into to an 8-ohm resistive load. Maximum power at the point of clipping is 135W.

First, it has "star earthing" whereby all earth (0V) currents come back to a central point on the board, thereby avoiding the possibility of output, supply and filter bypass currents flowing in the sensitive signal earth return conductors.

More importantly, the placement of heavy copper supply and earth tracks on the board is arranged to cancel the magnetic fields produced by the asymmetric currents drawn by each half of the output stage. In the aforementioned amplifiers, we arranged this cancellation by having the main supply leads to the module lie closely underneath the respective tracks on the PC board. While this arrangement works well, if it is to be effective it depends on the constructor following the wiring diagram very closely.

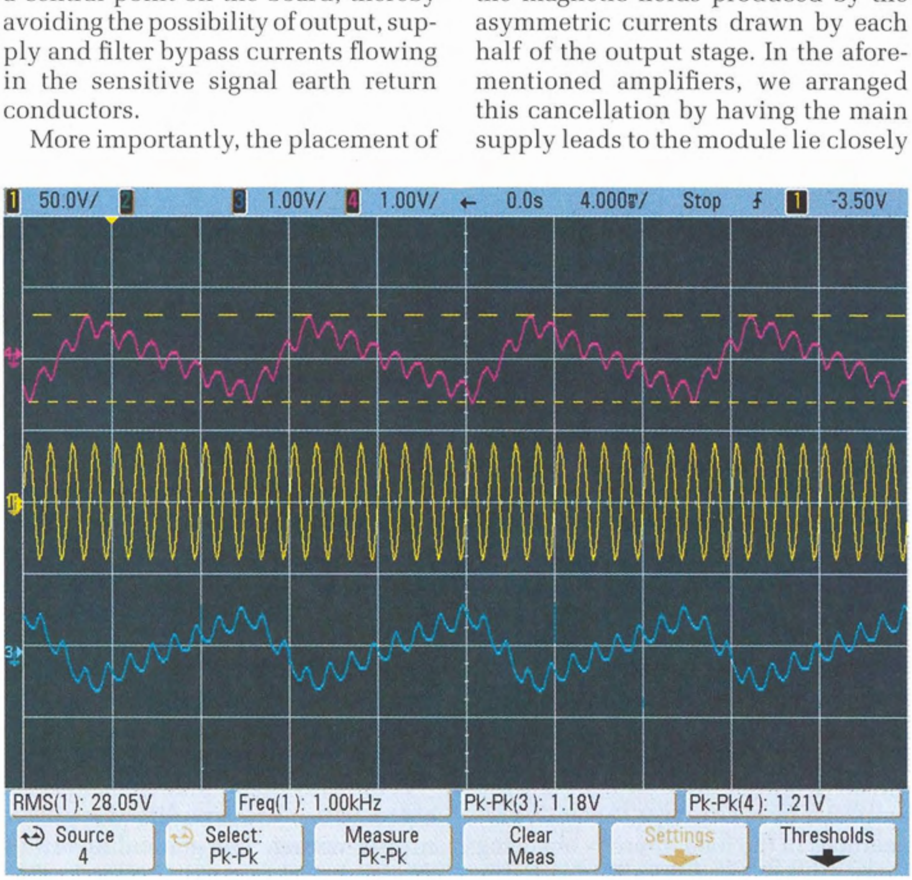
The PC board layout is shown in Fig.3.

To visualise how the field cancellation occurs, consider how the positive rail fuse (Fuse1) is placed close and parallel to the emitter resistors for Q12 & Q13. So the magnetic field produced by the half-wave currents in Fuse1 are more or less cancelled by the same current flowing back through the emitter resistors. The same mechanism applies with Fuse2 in the negative rail and the emitter resistors for Q14 & Q15.

Now consider the two heavy tracks which carry the positive and negative supply rails from the connector CON2 up the centre of the PC board and then diverge at rightangles to the two fuses, Fuse1 & Fuse2. Directly under the diverging supply tracks are the tracks which connect the pairs of emitter resistors together to connect them to the output via the RLC filter. Almost complete magnetic field cancellation takes place because of this track arrangement.

Finally, the main earth (0V) return track to CON2, underneath the board, cancels the magnetic field produced by the main supply tracks running on the top centre of the board.

By the way, merely twisting the positive and negative supply wires of a



This scope grab gives a graphic demonstration of the signal rectification phenomenon in the Class-B output stage. The centre (yellow) trace shows a 1kHz sinewave output signal from the amplifier at 100W into an 8-ohm load. The top (red) trace shows the ripple on the positive supply. Note the large 100Hz sawtooth component which is ripple from the power supply. Superimposed on this is the half-wave rectified signal frequency at 1kHz. The bottom (blue) trace shows the same process on the negative supply rail.

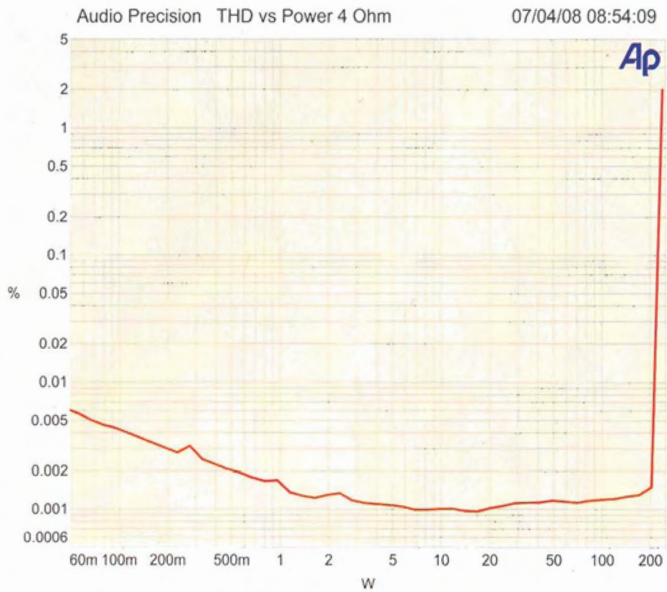


Fig.6: total harmonic distortion versus power at 1kHz into a 4-ohm resistive load. Maximum power at the point of clipping is 200W.

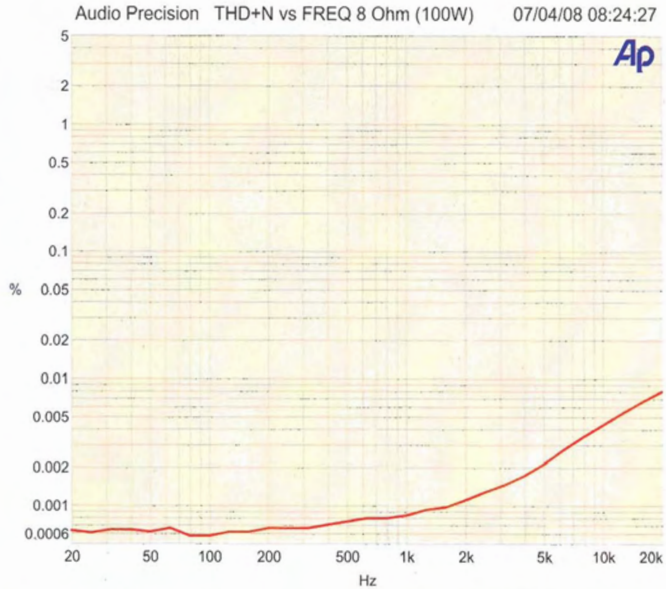


Fig.7: total harmonic distortion versus frequency into an 8-ohm resistive load. This is measured with a bandwidth of 10Hz to 80kHz.

class-B amplifier together gives no magnetic field cancellation at all in the absence of the return earth. Why? Simply because the positive half-wave currents do not occur at the same time as the negative half-wave currents.

To sum up, the Class-B magnetic field cancellation technique employed is important because it greatly reduces the overall harmonic distortion of the amplifier. In the SC480 module, it produced good results from ordinary power transistors. In this design, with a double-sided PC board complementing the new very linear ThermalTrak power transistors and special filtering of the supply rails, the results are very much better.

Finally, we need to clear up a few points. At various times we have referred to this amplifier as operating in class-B and in class-AB. Strictly speaking, the amplifier operates in class-AB, ie, a mixture of class-A which means that a constant current flows in the output stage and class-B which refers to the separate operation of the positive and negative sections of the output stage.

Coming next month

Next month, we will describe the assembly of the module and a suitable power supply. **SC**

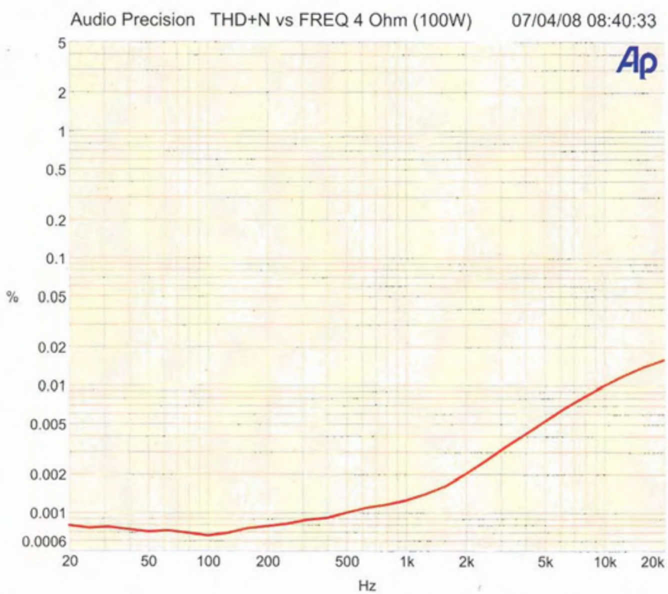


Fig.8: total harmonic distortion versus frequency at 100W into to a 4-ohm resistive load, measured with a bandwidth of 10Hz to 80kHz.