If you can't afford a high-performance amplifier and loudspeakers, you can still have the best possible hifi sound, with this headphone amplifier and a set of high-quality headphones.

By NICHOLAS VINEN

Hifi Stereo Headphone Amplifier, Pt.1

YES, WE KNOW that the Ultra-LD amplifier modules described elsewhere in this issue are "over the top" for many people, especially those living in small home units and those who have to worry about sound levels annoying their neighbours.

But why not listen via a good pair of headphones? Spend a few minutes looking around the internet and you will find all manner of hifi headphone amplifiers that claim to have top-notch performance. In most cases, there is little or no performance data to prove it. Before spending upwards of $1000 on a headphone amplifier we'd want to know just how good it is!

Our new headphone amplifier has a performance virtually the same as our benchmark 20W Class A Stereo Amplifier (May-September 2007). Its distortion at 100mW is lower than that from even the best CD and BluRay players. So essentially what you hear

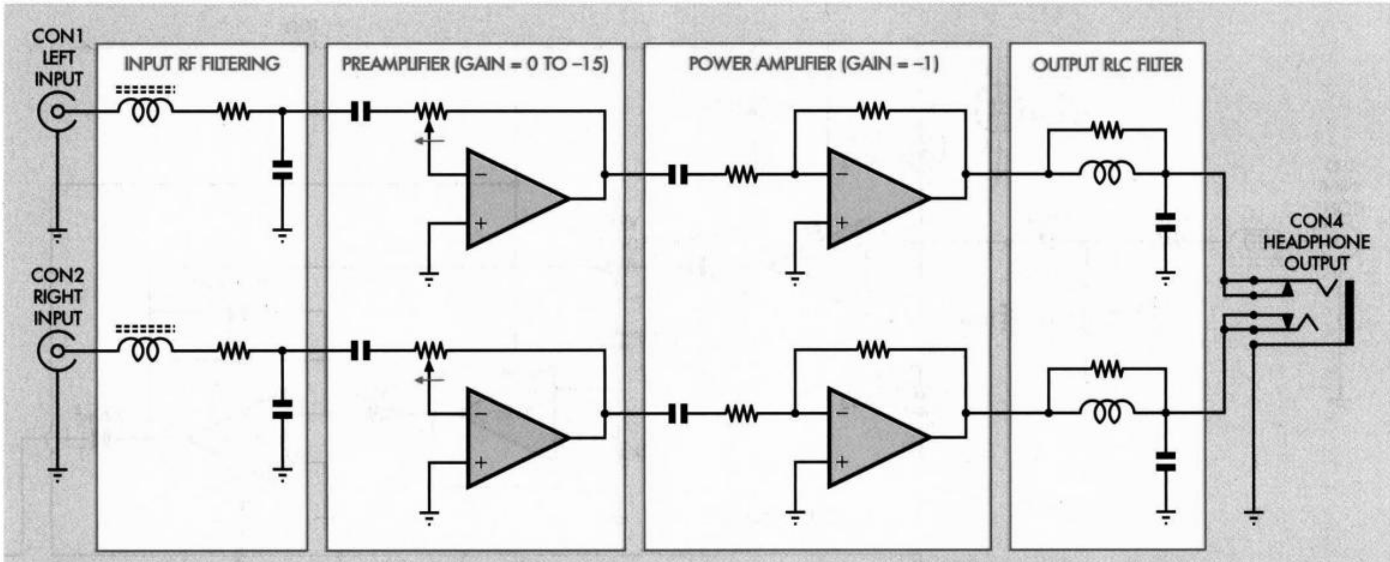


Fig.1: this block diagram shows the basic arrangement of the headphone amplifier. It incorporates RF filtering, a stereo preamplifier, stereo amplifier, output isolation filters and a regulated power supply.

is what is recorded on the CD – no more and no less.

This project does not supersede the Portable Headphone Amplifier for MP3 Players (April 2011) since that one is small, light and battery-powered. That design was intended for use "on the go" and to give much better sound than normally available from iPods and MP3 players.

This new headphone amplifier will also drive 8Ω loudspeakers and has a music power of 4.25W for both channels driven. This is more than adequate if you have reasonably efficient loudspeakers in your study, office or bedroom.

It is housed in a half-size 1U steel case just 210mm wide, 49mm high and 125mm deep and is powered by an AC plugpack (no 230VAC mains wiring). The interior of the case is filled by the PCB which accommodates all the components. There is no other wiring to do; just assemble the PCB, fit it into the case and you're finished.

Circuit features

Fig.1 shows the block diagram of the unit, while Fig.2 shows the complete circuit. It looks huge, doesn't it? That's partly because it shows both channels. It can be split into two sections, with the preamplifiers and power supply on the lefthand side and the power amplifiers on the righthand side.

The preamplifier for each channel is based on three op amps so three LM833 dual op amps are used. The preamp configuration is a classic Baxandall design. The preamplifier is inverting and has a gain range from zero to -15.

The reason for such a wide range in gain is that we have to provide for a large variety of headphone impedances and sensitivities. 8Ω headphones require a much lower voltage swing for the same power compared to 600Ω phones. Driving 8Ω headphones from a CD player (typically 2V RMS) may require a gain of 0.25 or less while using 600Ω phones with a line level signal (0.775V RMS or sometimes less) could require a gain of several times.

The Baxandall preamplifier circuit has the advantage that it varies its gain according to the setting of potentiometer VR1. As a result, the residual noise level is kept low at the low gain settings most commonly required. Like a traditional preamplifier, its gain can go all the way down to zero and up to some fixed number, in this case, 15.

Another advantage of this circuit is its log-like gain curve from a linear potentiometer, which generally have superior tracking compared to log pots. All but the most expensive "log" law potentiometers actually use a dual linear taper and so they don't really have an accurate log response either.

The two power amplifiers on the righthand side of the circuit are loosely based on the 20W Class-A Amplifier

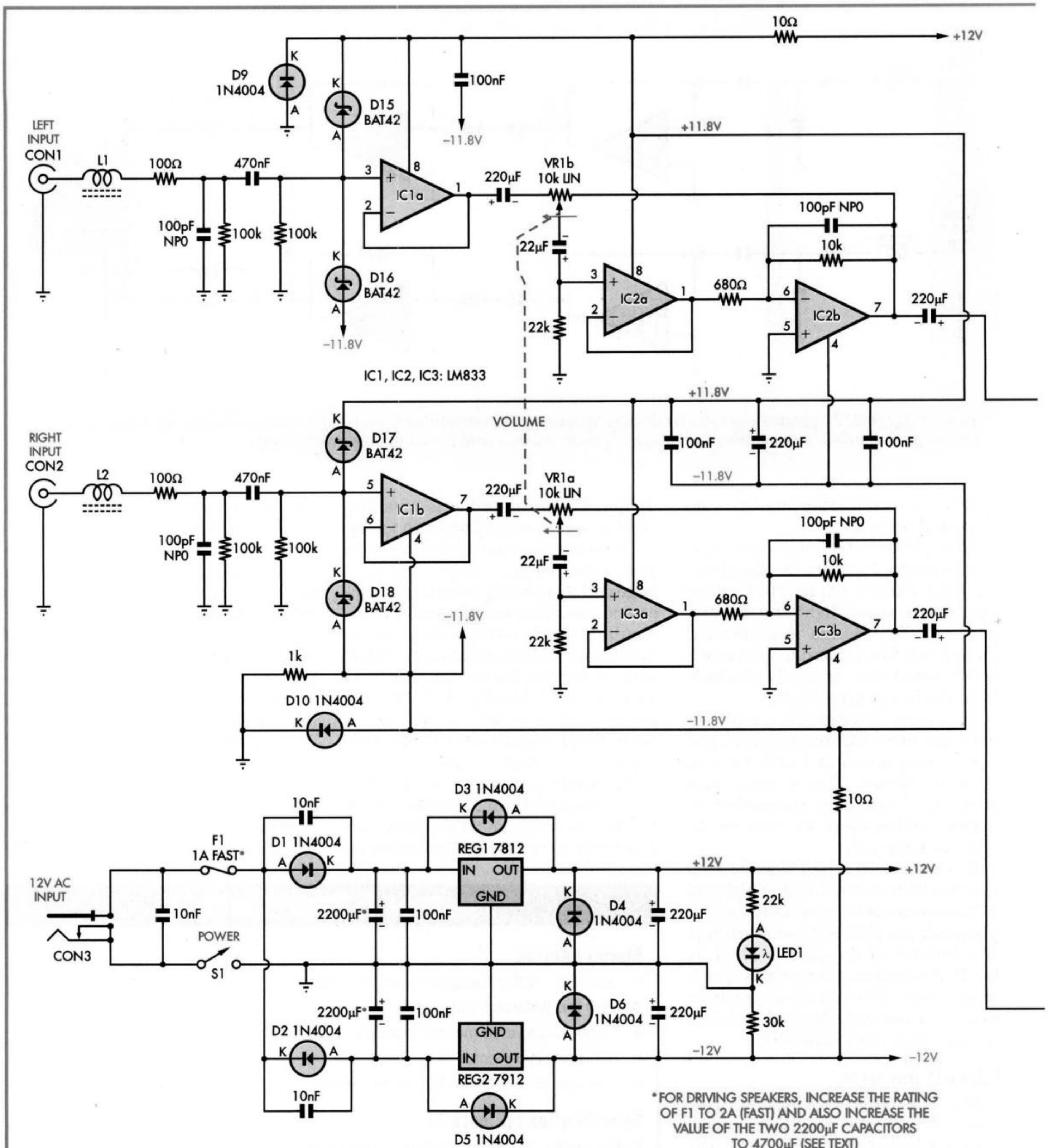
Features & Specifications

Main Features

- Suits 8Ω – 600Ω headphones and ear-buds
- Very low distortion and noise
- Plugpack-powered (no mains wiring)
- Short-circuit protected
- Can also drive efficient 8Ω loudspeakers

Specifications (Figs.3-7)

Rated power: 100mW (8-100Ω), 25mW (600Ω)
THD: 0.0006% @ 1kHz; 20Hz-22kHz bandwidth
Signal-to-noise ratio: -113dB unweighted; 20Hz-22kHz
Frequency response: ±0.15dB, 20Hz-20kHz
Channel separation: -73dB @ 1kHz
Maximum power: 4.25W (8Ω), 3W (16Ω), 1.5W (32Ω), 800mW (60Ω), 80mW (600Ω)
Class-A power: 18mW (8Ω), 36mW (16Ω), 72mW (32Ω), 80mW (600Ω)
Music power: 4.25W into 8Ω, both channels driven (see text)



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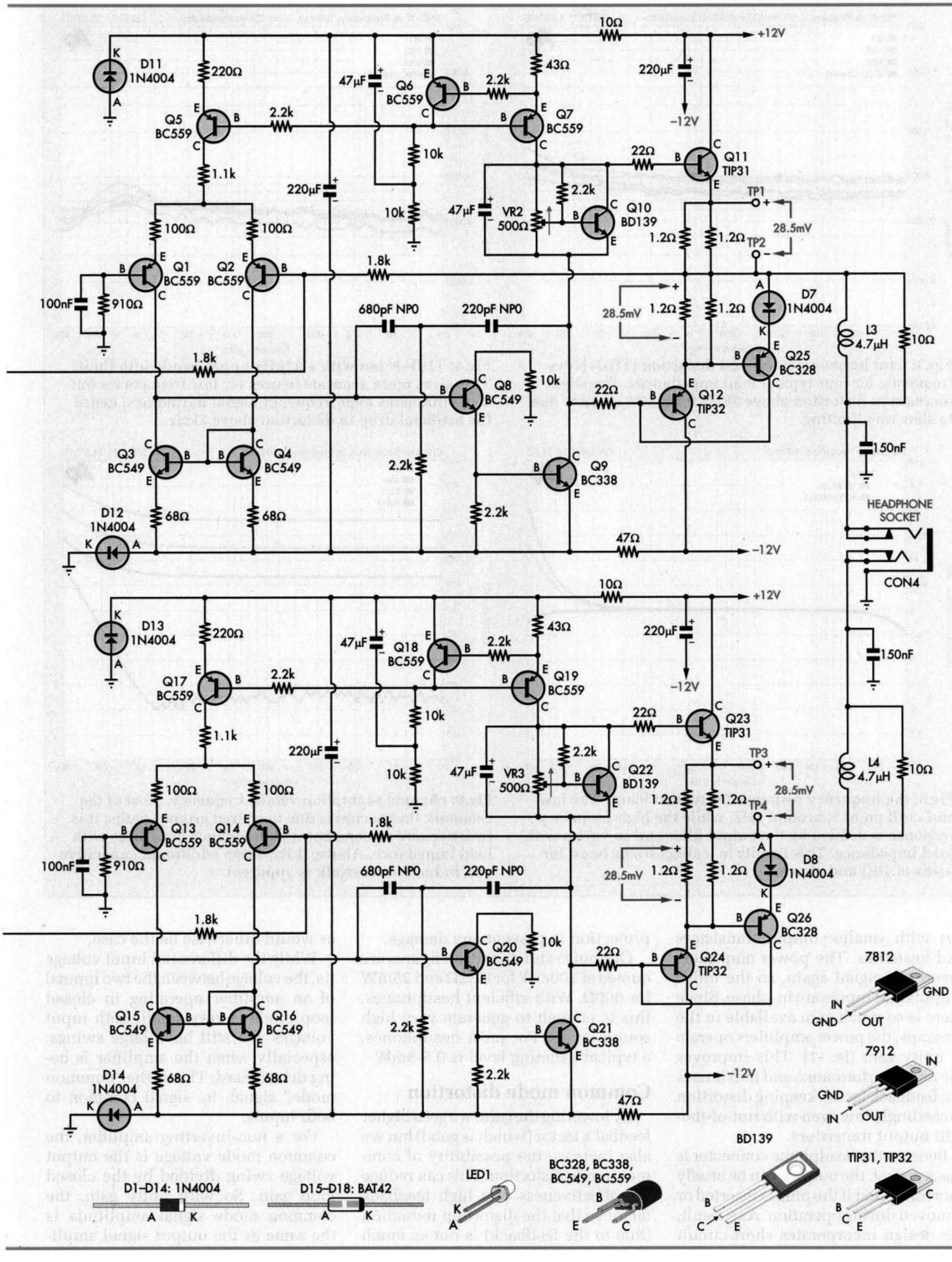
HI-FI STEREO HEADPHONE AMPLIFIER

Fig.2: the complete circuit of the Hifi Stereo Headphone Amplifier. The stereo preamplifier section is at upper left and is based on three low-noise dual op amps (IC1-IC3). This stage provides a variable gain of 0-15 depending on the setting of VR1 which functions as the volume control. The two identical power amplifiers are shown at right and these drive the headphones via RLC filters (for stability) and a 6.35mm jack socket. The linear regulated power supply is at lower left and this derives regulated ±12V rails from a 12V AC plugpack.


D11
1N4004
220Ω
Q5
BC559
2.2k
1.1k
47µF
Q6
BC559
2.2k
43Ω
Q7
BC559
10k
220µF
10k
47µF
VR2
500Ω
2.2k
Q10
BD139
22Ω
Q11
TIP31
10Ω
+12V
220µF
-12V
TP1
TP2
28.5mV
1.2Ω
1.2Ω
100Ω
100Ω
Q1
BC559
Q2
BC559
1.8k
100nF
910Ω
680pF NP0
220pF NP0
1.2Ω
1.2Ω
28.5mV
D7
1N4004
L3
4.7µH
10Ω
Q25
BC328
1.8k
Q8
BC549
10k
22Ω
Q12
TIP32
150nF
Q3
BC549
Q4
BC549
2.2k
Q9
BC338
2.2k
68Ω
68Ω
D12
1N4004
47Ω
-12V
HEADPHONE
SOCKET
CON4
D13
1N4004
220Ω
10Ω
+12V
43Ω
47µF
Q18
BC559
2.2k
220µF
150nF
Q17
BC559
2.2k
Q19
BC559
-12V
1.1k
10k
22Ω
Q23
TIP31
220µF
2.2k
10k
47µF
VR3
500Ω
Q22
BD139
L4
4.7µH
10Ω
TP3
28.5mV
TP4
100Ω
100Ω
Q13
BC559
Q14
BC559
1.8k
100nF
910Ω
680pF NP0
220pF NP0
1.2Ω
1.2Ω
1.2Ω
1.2Ω
28.5mV
D8
1N4004
-12V
1.8k
Q26
BC328
Q20
BC549
10k
22Ω
Q24
TIP32
7812
GND
IN
OUT
GND
Q15
BC549
Q16
BC549
2.2k
Q21
BC338
7912
IN
GND
IN
OUT
2.2k
D14
1N4004
68Ω
68Ω
47Ω
BD139
D1–D14: 1N4004
D15–D18: BAT42
LED1
BC328, BC338,
BC549, BC559
TIP31, TIP32
A
K
B
E
C

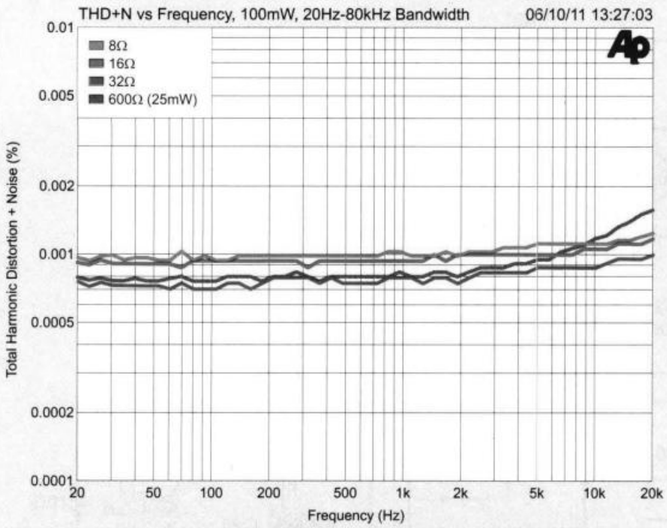


Fig.3: total harmonic noise and distortion (THD+N) vs frequency for four typical load impedances. The slight increase in distortion above 3kHz for a 600Ω load is due to slew rate limiting.

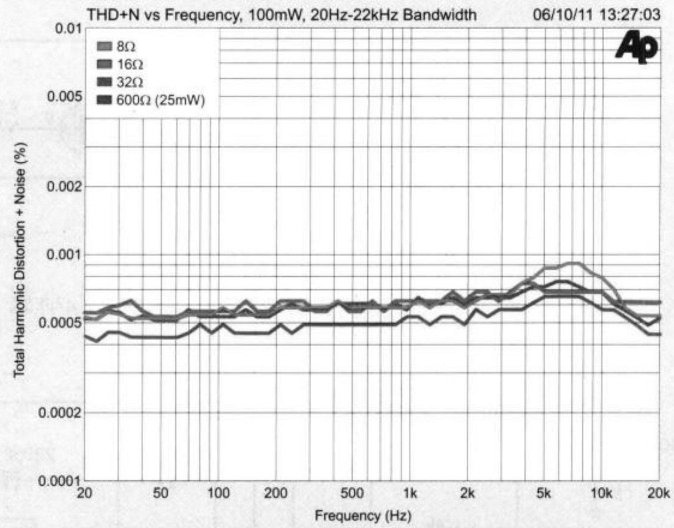


Fig.4: THD+N but with a 22kHz upper bandwidth limit. This gives more accurate figures for low frequencies but also eliminates high-frequency signal harmonics, hence the artificial drop in distortion above 7kHz.

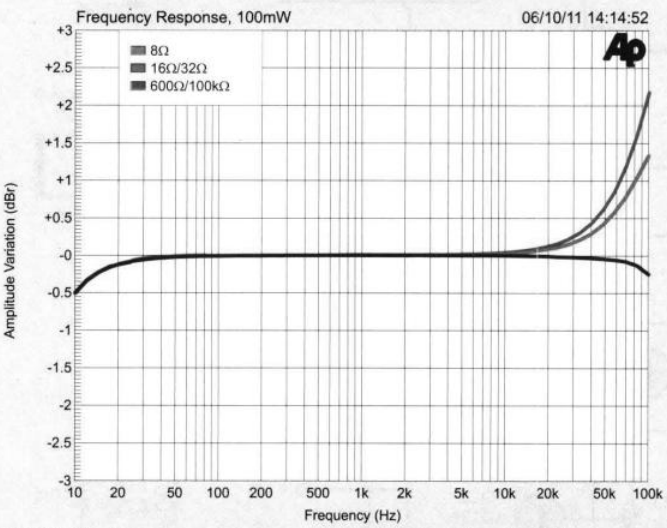


Fig.5: the frequency response for typical loads. The low-end -3dB point is around 3Hz, while the high-frequency response is defined by the output filter and so varies with load impedance. This results in a slight treble boost for loads of 16Ω and above.

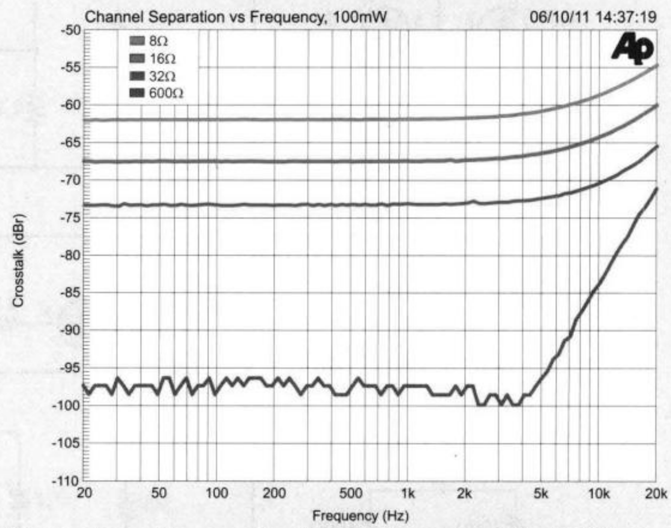


Fig.6: channel separation versus frequency. Most of the crosstalk that occurs is due to shared ground paths; it is resistive and so constant with frequency but varies with load impedance. Above 5kHz, some additional capacitive and inductive crosstalk is apparent.

but with smaller output transistors and heatsinks. The power amplifiers invert the signal again, so the unit's outputs and inputs are in-phase. Since there is so much gain available in the preamps, the power amplifiers operate at unity gain (ie, -1). This improves the noise performance and maximises the feedback factor, keeping distortion exceedingly low even with run-of-the-mill output transistors.

Because the headphone connector is a jack socket, the outputs can be briefly short circuited if the plug is inserted or removed during operation. As a result, the design incorporates short-circuit protection to prevent any damage.

Our noise and distortion figures are quoted at 100mW for 8-32Ω and 25mW for 600Ω. With efficient headphones, this is enough to generate very high sound levels. For most headphones, a typical listening level is 0.5-5mW.

Common mode distortion

By lowering the gain, we get a higher feedback factor (which is good) but we also increase the possibility of common-mode distortion. This can reduce the effectiveness of a high feedback factor so that the distortion reduction (due to the feedback) is not as much as would otherwise be the case.

While the differential input voltage (ie, the voltage between the two inputs) of an amplifier operating in closed loop mode is very small, both input voltages can still have large swings, especially when the amplifier is being driven hard. This is the "common mode" signal, ie, signal common to both inputs.

For a non-inverting amplifier, the common mode voltage is the output voltage swing divided by the closed loop gain. So with unity gain, the common mode signal amplitude is the same as the output signal amplitude, which for our amplifier can be nearly 20V peak-to-peak. Typically, if the common mode signal exceeds 1-2V RMS, common mode distortion can become the dominant distortion mechanism, marring its performance.

This is due to "Early effect" in the input transistors (named after James M. Early of Fairchild Semiconductor). This is caused by the effective width of the transistor base junction varying with its collector-base voltage (see **http://en.wikipedia.org/wiki/Early_effect**).

If the common mode voltage is large enough, the result is modulation of the input transistors' beta and this reduces the overall linearity of the amplifier. These non-linearities cannot be corrected by negative feedback since they occur in the input stage.

The solution is to use an inverting amplifier, as we have in this case. Its non-inverting input is connected to ground and so the inverting input is held at "virtual ground" too, regardless of the output voltage. This configuration has so little common mode voltage that it can't suffer from common mode distortion. To make a power amplifier inverting, we rearrange the feedback network in the same manner as we would with an op amp. In fact, common mode distortion in op amps can be reduced using the same method.

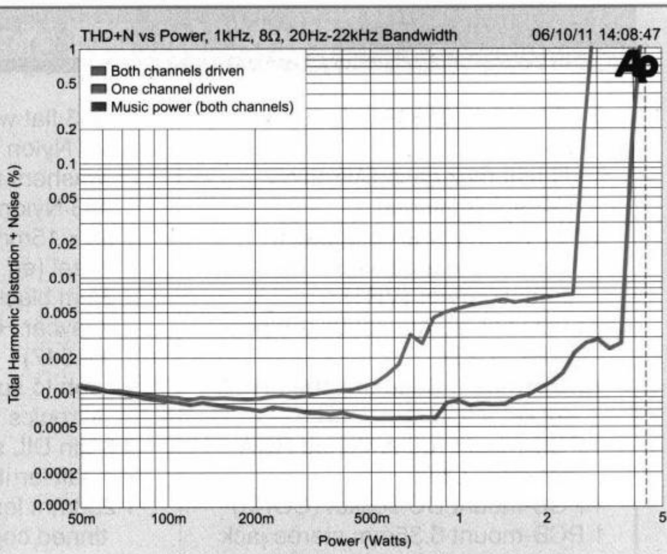
The main disadvantage of the inverting configuration is that the input impedance is low, as determined by the resistor from the signal source to the inverting input. For good noise performance, its value must be low (minimising its Johnson-Nyquist thermal noise). In this case, the preamplifiers provide the amplifiers with a low source impedance, so it isn't a problem.

No driver transistors

If you compare the amplifier circuits to our previously published amplifier designs such as the Ultra-LD Mk.3 or 20W Class-A Amplifier, you will find many similarities.

As with the Ultra-LD Mk.3 amplifier, this design uses 2-pole frequency compensation. As a result, the headphone amplifier has particularly low distortion at high frequencies. For a detailed explanation of the advantages of 2-pole compensation, refer to the article published in the July 2011 issue on "Amplifier Compensation and Stability".

Fig.7: total harmonic distortion and noise versus power with the larger filter capacitors and a 2A plugpack. Music power is 4.25W (both channels driven) but continuous output power is limited by the power supply.



The main difference is that the two output transistors are driven directly from the voltage amplification stage, with no driver transistors in between. In this case, the output current is quite small due to the relatively low power, so we can get away without the driver stage as long as the output transistors have a good beta figure.

In this case, we are using readily available TIP31 (NPN) and TIP32 (PNP) transistors, rated at 3A and 40W each; more than enough for our needs. They have an excellent beta for a power transistor, at around 200 for 100mA and 25°C.

How it works

Let's start with the preamp stages and since both channels are identical, we will just describe the left channel. Any RF signals picked up by the input leads are attenuated by a low-pass filter consisting of a ferrite bead, a 100Ω resistor and a 100pF capacitor. The ferrite bead acts like an inductor to block RF. The signal is then coupled via a 470nF capacitor to pin 3 of op amp IC1a which is configured as a voltage follower. This provides a low source impedance to the preamp gain stages comprising IC2a & IC2b.

IC1a's output is fed to the following stage via a 220μF electrolytic capacitor. This large value ensures good bass response and avoids any distortion that may arise from the typical non-linearity of an electrolytic capacitor.

The signal passes to the non-inverting input of IC2a (pin 3) via volume control potentiometer VR1 and a 22μF electrolytic capacitor. This capacitor ensures there is no DC flowing through VR1, which would otherwise cause a crackling noise when it is rotated.

IC2a buffers the voltage at the wiper of VR1 to provide a low impedance for inverting amplifier IC2b. IC2b has a fixed gain of 14.7, set by the 10kΩ and 680Ω resistors. The 100pF feedback capacitor is there to improve circuit stability and reduce high-frequency noise.

Volume potentiometer VR1 is part of the feedback network from the output from IC2b to the input at the 220μF capacitor (from pin 1 of IC1a). Hence IC2a & IC2b form a feedback pair with the overall gain adjustable by VR1.

When VR1 is rotated fully anti-clockwise, IC2b's output is connected directly to VR1b's wiper. Thus IC2b is able to fully cancel the input signal (as there is zero impedance from its output to the wiper) and the result is silence (no output signal) from the preamplifier.

Conversely, when VR1 is fully clockwise, VR1b's wiper is connected directly to the input signal, which is then amplified by the maximum amount (14.7 times) by IC2b. At intermediate settings, the signal at the wiper is partially cancelled by the mixing of the non-inverted (input) and inverted (output) signals and the resulting gain is intermediate.

The way in which this cancellation progresses as VR1 is varied provides a quasi-log law gain curve.

IC1 needs input protection

Because the headphone amplifier may be turned off when input signals

Parts List: Hifi Stereo Headphone Amplifier

1 PCB, code 01309111, 198 x 98mm
1 1U half rack case (Altronics H4995) (optional)
1 12V AC 1A or 2A plugpack
1 10kΩ dual gang linear 16mm potentiometer (VR1)
2 500Ω sealed horizontal trimpots (VR2, VR3)
1 PCB-mount white switched RCA socket (CON1)
1 PCB-mount red switched RCA socket (CON2)
1 PCB-mount DC socket (CON3)
1 PCB-mount 6.35mm stereo jack socket (3PST) with extended pins (Jaycar PS-0190 or equivalent) (CON4)
1 PCB-mount right-angle SPDT mini toggle switch (S1) (Altronics S1320)
2 M205 PCB-mount fuse clips (F1)
1 M205 1A fast-blow fuse (F1)*
6 PCB-mount 6021-type flag heatsinks (Element14 Order Code 1624531; Jaycar HH8504, Altronics H0637)
8 TO-220 insulating washers
6 TO-220 insulating bushes
2 plastic former bobbins (Jaycar LF1062, Altronics L5305)
1 2m length 0.8mm diameter enamelled copper wire
1 25mm length 25mm diameter heatshrink tubing
6 PCB pins
4 M3 x 15mm machine screws
6 M3 x 10mm machine screws
10 M3 nuts
18 M3 flat washers
4 M3 Nylon nuts with integral washers (Jaycar HP0150) or M3 Nylon nuts and washers
1 35 x 15mm section of tin plated steel (eg, cut from a tin can lid)
1 3mm black plastic LED clip (Jaycar HP1100, Altronics H1547)
1 knob to suit VR1 (suggested: Altronics H6213)
3 8-pin DIL sockets (optional)
2 small ferrite beads
1 250mm length 0.7mm diameter tinned copper wire

Semiconductors
3 LM833 dual low noise op amps (IC1-IC3)
1 7812 positive 12V linear regulator (REG1)
1 7912 negative 12V linear regulator (REG2)
2 TIP31 3A NPN transistors (Q11, Q23)
2 TIP32 3A PNP transistors (Q12, Q24)
2 BD139 1.5A NPN transistors (Q10, Q22)
2 BC328 PNP transistors (Q25, Q26)
2 BC338 NPN transistors (Q9, Q21)
6 BC549 NPN transistors (Q3-Q4, Q8, Q15-Q16, Q20)
10 BC559 PNP transistors (Q1-Q2, Q5-Q7, Q13-Q14, Q17-Q19)
1 3mm blue LED (LED1)
14 1N4004 1A diodes (D1-14)
4 BAT42 Schottky diodes (D15-D18) (or use BAT85, Altronics Cat. Z0044)

Capacitors
2 2200µF 25V electrolytic*
11 220µF 25V electrolytic**
4 47µF 16V electrolytic**
2 22µF 16V electrolytic**
2 470nF MKT
2 150nF MKT
7 100nF MKT
3 10nF MKT
2 680pF C0G/NP0 ceramic
2 220pF C0G/NP0 ceramic
4 100pF C0G/NP0 ceramic

Resistors (0.25W, 1%)

4 100kΩ	2 680Ω
1 30kΩ	2 220Ω
3 22kΩ	6 100Ω
8 10kΩ	4 68Ω
10 2.2kΩ	2 47Ω
4 1.8kΩ	2 43Ω
2 1.1kΩ	4 22Ω
1 1kΩ	6 10Ω
2 910Ω	8 1.2Ω (1% or 5%)

Notes
* For driving speakers, upgrade the plugpack to 12V AC 2A, the fuse to 2A and the power supply capacitors to 4700µF 25V (diameter ≤16mm, height ≤30mm, eg, Futurlec C4700U25E105C).
** Low ESR 105° types can be used if their diameter is no more than 6.3mm for 22µF/47µF and 8mm for 220µF.

are present, IC1's input transistors can be subjected to relatively high voltages; up to 2.5V RMS or maybe 7V peak-to-peak. This will not damage IC1 immediately but over many years, it could degrade the performance. This is because normally very little current flows through the op amp inputs and so the metal traces within the IC are thin. If enough current passes through the inputs (5mA or more), "metal migration" can cause degradation and ultimately failure.

For that reason we have included small-signal Schottky diodes D15 & D16 to protect pin 3 of IC1a (and D17 & D18 for pin 5 of IC1b) when the unit is switched off but a large signal is applied. They clamp the voltage at that input to within ±0.3V of the supply rails under normal conditions, preventing current flow through the op amp input transistors should their junctions be reverse-biased.

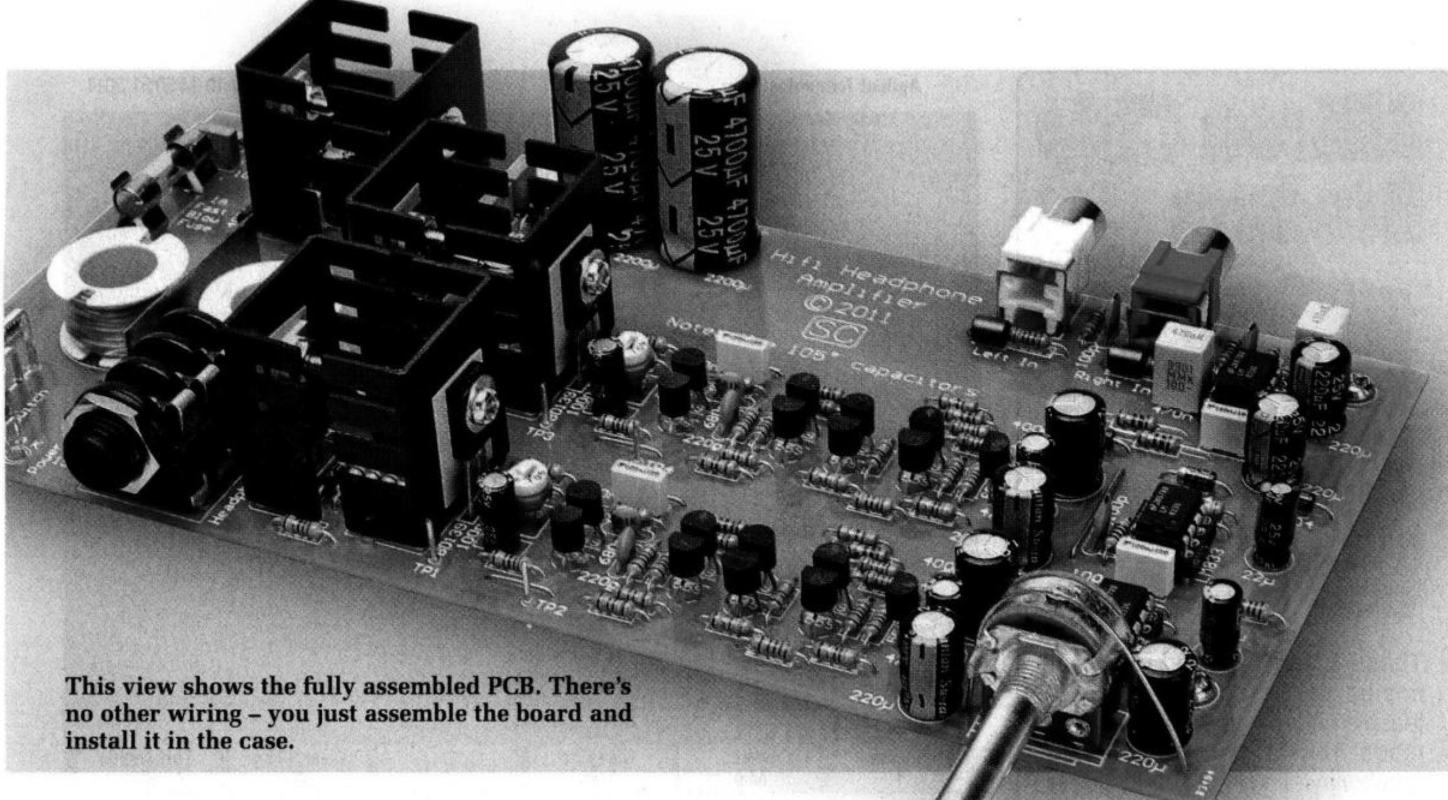
So if the unit is off and the supply rails are zero, the input voltages will be similarly limited to ±0.3V.

The BAT42 diodes have been carefully selected to clamp the op amp input voltages appropriately without having so much leakage current that they will introduce distortion into the signal (Schottky diodes normally have a much higher reverse leakage current than standard silicon diodes). For more information on protecting op amp inputs, see Analog Devices tutorial MT-036, "Op Amp Output Phase-Reversal and Input Over-Voltage Protection".

We also tested BAT85 diodes (Altronics Z0044). These have slightly higher capacitance when reverse-biased (10pF compared to 7pF) and a significantly higher reverse leakage current (400nA at -15V/25°C compared to 75nA). However, testing shows no measurable increase in distortion with these in place of the BAT42s so they are an acceptable substitute.

Amplifier circuit

Low-noise PNP transistors Q1 & Q2 are the differential input pair, with the



This view shows the fully assembled PCB. There's no other wiring – you just assemble the board and install it in the case.

base of Q1 being the non-inverting input to the amplifier and the base of Q2 being the inverting input. Q1's base is tied to ground by a 910Ω resistor (to match the 900Ω source impedance at the base of Q2) and is bypassed by a 100nF capacitor to reduce high-frequency noise.

The signal from the preamplifier is fed to the base of Q2 via a 1.8kΩ feedback resistor, so that the amplifier works in the inverting mode. 1.8kΩ is the lowest value resistance that IC2b can drive in parallel with its own feedback network.

PNP transistor Q5 operates as a 3mA constant current source (0.65V ÷ 220Ω) to feed the Q1/Q2 input pair. Negative feedback for current regulation is provided by another PNP transistor, ie, Q6. It has a bootstrapped collector current sink (two 10kΩ resistors and a 47µF capacitor), so that it operates consistently.

NPN transistors Q3 and Q4 form a current mirror for the input pair, with 68Ω emitter resistors to improve its accuracy. Any difference in the current through Q1 and Q2 must then flow to the base of NPN transistor Q8. So Q1-Q5 form the transconductance stage of the amplifier.

Together, Q8 and Q9 form a Darlington-like transistor, configured as a common-emitter amplifier. PNP transistor Q7 acts as a constant current source for its collector load, sourcing about 15mA (0.65V ÷ 43Ω). Q6 provides current regulation feedback for Q7 as well as Q5.

The 680pF and 220pF capacitors between Q9's collector and Q8's base, together with the 2.2kΩ resistor from their junction to the negative rail, form the 2-pole frequency compensation scheme mentioned earlier. Together, transistors Q7-Q9 are the voltage amplification stage.

V_{BE} multiplier

Between Q7 and Q9 is Q10 which functions as a V_{BE} multiplier to set the quiescent current for the output transistors Q11 & Q12. Q10 is mounted on the back of Q11's heatsink so that its junction temperature tracks the output stage. Thus, its V_{BE} tracks that of the output transistors (Q11 and Q12), so the bias voltage varies to compensate for changing output transistor temperature, keeping the standing current through them more or less constant.

VR2 is used to adjust this current, while the 2.2kΩ resistor prevents the bias from becoming excessive if VR2's wiper goes open circuit, as it may do while it is being trimmed. A 47µF capacitor filters the bias voltage, improving distortion performance when the output voltage swing is large.

The resulting bias voltage is applied between the bases of output transistors Q11 (NPN) and Q12 (PNP) via 22Ω stopper resistors, which prevent parasitic oscillation. Each output transistor has a 0.6Ω emitter resistor (two 1.2Ω resistors in parallel) which helps to linearise the output stage and stabilise the quiescent current.

Current limiting

While it's always a good idea to plug and unplug the headphones while the power switch is off, we can't rely on that and we don't want the output transistors to blow when it happens. Therefore, both Q11 and Q12 are protected against over-current conditions.

Q11 is current-limited because the 15mA current source (Q7) sets a maximum limit for its base current. According to the TIP31 data sheet, at 25-125°C, the maximum collector current will be about 1.25A; well within its safe operating area (SOA) so as long as the short-circuit is brief.

Q12 is more of a concern because Q9 can sink significantly more than 15mA. The 10kΩ resistor at Q8's collector ultimately limits how much current Q9 can sink as follows. Q8's maximum collector current is around (12V - 0.7V) ÷ (10kΩ + 2.2kΩ) = 1mA. Q9's maximum current gain figure is around 165 (according to the BC338 data sheet), so the maximum Q9 can sink is about 165mA. Hence Q9 is a BC338 (a BC549 has a continuous collector current limit of 100mA).

However, if this much current were sunk from Q12's base then it would fully saturate (turn on hard), exceeding its SOA and possibly causing it to fail.

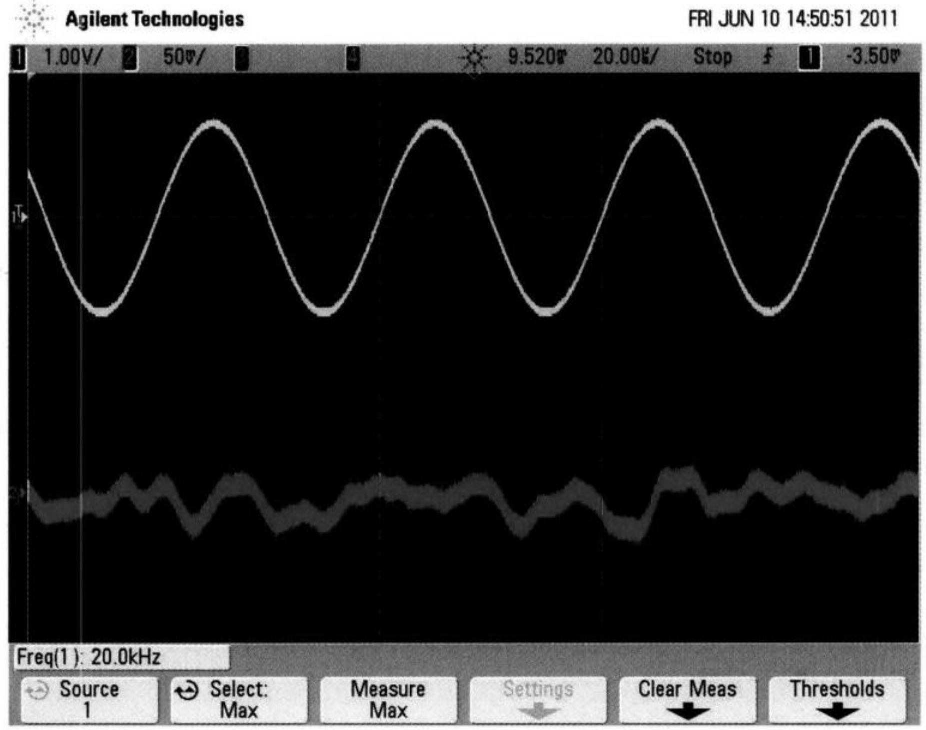


Fig.8: the green trace in this scope grab shows the distortion residual for 100mW into 32Ω at 20kHz. Most of this is actually noise with very little harmonic content. Into lower load impedances (eg, 8Ω) the distortion becomes more apparent and is primarily third harmonic, with some higher harmonics.

Q25 and D7 prevents this. Should the current flow through Q12's collector-emitter junction exceed 2A (within its SOA), the drop across the 0.6Ω emitter resistor exceeds 2A x 0.6Ω = 1.2V.

At this point, Q25's base-emitter voltage increases beyond 1.2V - 0.6V = 0.6V and so Q25 starts to turn on, shunting current around Q12's base-emitter junction and preventing Q12 from turning on harder. Any current sunk by Q9 beyond that necessary for Q12 to pass 2A goes through D7 and Q25 rather than Q12's base-emitter junction.

Output RLC filter

The output filter isolates the amplifier from its load, improving stability. Because this amplifier circuit is already fairly stable (thanks to its simple output stage), we can get away with slightly less inductance than usual (4.7μH rather than 6.8μH or 10μH). We can thus use a thinner gauge wire which is slightly easier to wind, for roughly the same DC resistance.

Ideally, the output filter should be optimised for the expected load impedance but because headphones have such a wide range of impedances, all we can do is compromise and specify an intermediate value. As a result, for higher impedances, the amplifier has a slightly elevated response at above 20kHz (see Fig.5).

For 8Ω operation, there is a very slight roll-off at the high-frequency end of -0.02dB at 20kHz. At around 10-12Ω, the high frequency response will be virtually flat and then for higher load impedances, up to infinity, the gain is as much as +0.13dB at 20kHz. The increase is slightly lower (+0.09dB) for the most common impedances of 16Ω and 32Ω. This deviation is so small as to be imperceptible.

In fact, all our amplifier designs using this type of output RLC filter (devised by Neville Thiele) have such a response with higher than usual output impedances or no load.

Power supply

The 12V AC plugpack plugs into an on-board DC connector (CON3). A 1A fuse protects the plugpack in case of a board fault or overload.

The power switch (S1) is in the ground leg so that the tracks to and from it (near the edge of the PCB) have minimal AC voltage. This eliminates electrostatic radiation, preventing any coupling to nearby signal tracks.

The incoming AC is half-wave rectified by diodes D1 & D2, with three

A half-size 1-unit steel case is used to house the assembled Headphone Amplifier PCB. Pt.2 next month has all the construction and setting-up details.

10nF metal film capacitors for RF and switching suppression. The resulting ±16V rails (nominal; under light load, closer to ±20V) are regulated to ±12V using 3-terminal regulators REG1 & REG2.

So why are we regulating the supply for the whole device rather than just the op amps? Essentially it is because the amplifiers draw so little power when driving headphones that they might as well run off the regulated rails. In addition, the unregulated supply ripple is 50Hz because of the half-wave rectifiers (rather an 100Hz). The regulated supply rails give a lower hum and noise figure.

Switch-on/off behaviour

The circuit has been carefully designed to avoid loud thumps from the headphones when the unit is switched on or off. With a power amplifier, this is usually taken care of with an output muting relay that is also used for speaker protection. Since this amplifier has a low power output and a limited output current, a protection relay isn't necessary.

That is not say that you won't hear any thumps at all. That will depend, in part, on the efficiency of your headphones. However, any thumps you do hear will be very slight.

This has partly been achieved by removing the capacitor which would typically be between Q5's base and the positive rail (as present in the 20W Class-A Amplifier and the Ultra-LD Mk.3). This is not necessary with a regulated supply and if present, it delays the operation of the constant current source controlled by Q5 by several hundred milliseconds at switch-on. This would have caused a loud thump from the headphones had it been retained.

Diodes D11 & D12 (D13 & D14 in the right channel) are also important for proper switch-on behaviour. While the ±12V regulated rails are already protected to prevent the positive rail from going negative and vice versa, the RC filtered supply rails for the early amplifier stages can still suffer from this problem unless extra steps are taken. That's because the filter resistors isolate the capacitors from the clamp diodes D4 & D6.

Without D11 and D12, the positive filtered rail could be briefly pulled negative and this would cause an amplifier output excursion.

The different positive and negative rail filter resistors (10Ω and 47Ω respectively) allow the positive rail to come up more quickly which also helps achieve a clean switch-on. Together, these details allow the amplifiers to operate normally just milliseconds after both filter capacitors are partially charged.

Similarly, diodes D9 & D10 clamp the RC-filtered supply for the op amps in the preamplifier. Without these, the op amp input transistors may become briefly reverse-biased at switch on, causing supply current to flow into the AC-coupling capacitors and again causing a thump to be generated.

Finally, the 1kΩ resistor in parallel with D10 discharges the op amp negative supply rail faster than the positive rail when power is removed. The op amps are prone to oscillation when their supply capacitor is mostly discharged and this can cause a "chirp" at switch-off. With the 1kΩ discharge resistor, this chirp is made very short and often eliminated entirely.

Increasing the output power

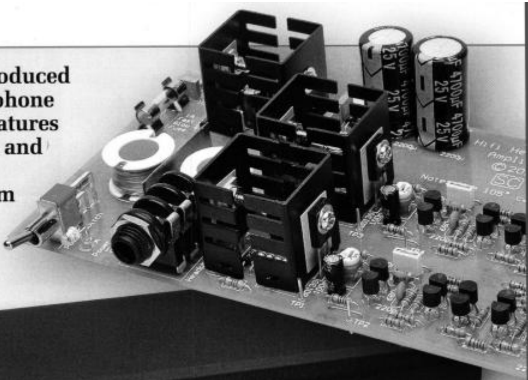
While the circuit as presented is capable of driving loudspeakers, a few small changes can usefully increase the power output. If the 2200μF filter capacitors are changed to 4700μF, it increases the current they can supply before regulator drop-out begins.

Also, a 12V AC 2A plugpack can be used in combination with a higher rated 2A fuse. This increases the available output power a little more. The THD+N vs power graph (Fig.4) shows the performance when both modifications are incorporated.

Next month

Next month, we shall present the construction details and describe the setting-up procedure. **SC**

Last month we introduced our new Hifi Headphone Amplifier which features very low distortion and noise. It can even drive efficient 8-ohm speakers. This month, we show you how to build and test it.



By NICHOLAS VINEN

Hifi Stereo Headphone Amplifier, Pt.2

THE ASSEMBLY of the Hifi Stereo Headphone Amplifier is straightforward, with all the parts mounted on a single PCB coded 01309111 and measuring 198 x 98mm. Apart from the PCB, there is no other wiring.

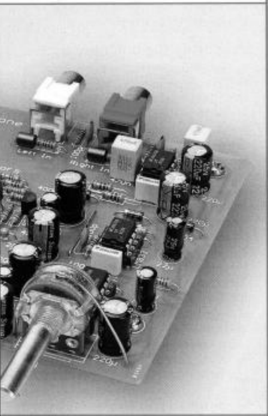
Fig.9 shows the parts layout on the board. Before starting assembly, it's a good idea to test-fit the larger components (eg, the jack socket, heatsinks, RCA sockets and so on) to check that their mounting holes are large enough.

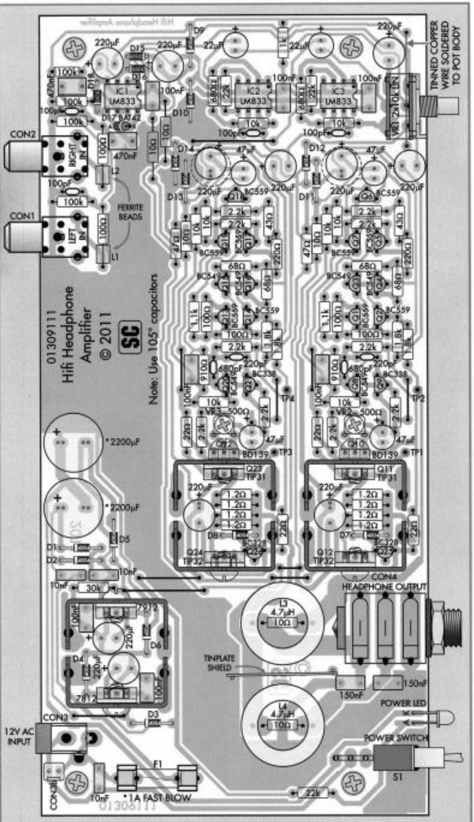
That done, begin by installing the 10 wire links using 0.7mm-diameter tinned copper wire or component pigtail off-cuts (don't forget the one near CON3). Once those are in, install the resistors, noting that two (both 100Ω just below the RCA sockets) have ferrite beads on their leads. Check each resistor with a DMM set to Ohms mode before soldering it into place.

Follow with the 14 1N4004 diodes, taking care to ensure they are all correctly orientated. In each case, the stripe faces to the left or the bottom of the board. The four BAT42/BAT85 small-signal Schottky diodes (D15-D18) near IC1 (upper-left) can then go in. Their orientations vary so take care.

If you are using sockets for IC1-IC3, install them now with the notches to the right as shown. Alternatively, you can solder the ICs direct to the board with the same orientation.

The MKT and ceramic capacitors are next on the list, followed by the 20 small-signal transistors. There are four different types so be sure to install the correct type at each location. Use a small pair of needle-nose pliers to crank the transistors leads so that they mate with the board holes and take care to ensure that each transistor is correctly orientated.





*WHEN DRIVING LOUDSPEAKERS, INCREASE RATING OF F1 TO 2A & REPLACE THESE CAPACITORS WITH 4700µF 25V

Fig.9: follow this PCB overlay to assemble the headphone amplifier. Note that the specified case has no ventilation, so we recommend the use of 105° electrolytic capacitors for long-term reliability.

The two 500Ω trimpots and the fuseholder clips can now go in. Check that the small fuse clip retention tabs are towards the outside before soldering the fuse clips, otherwise you won't be able to fit the fuse later on.

That done, fit PCB pins at test points TP1-TP4 plus another two to support the tinplate shield between inductors L3 & L4. Once they're in, fit the electrolytic capacitors but leave the two 2200µF filter capacitors out for the time being.

Installing the LED

Before installing the 3mm blue LED, you need to bend its leads down by 90° exactly 4mm from the rear of the lens. Be sure to bend the leads in the right direction though, so that the longer anode lead goes through the hole marked "A" on the layout diagram.

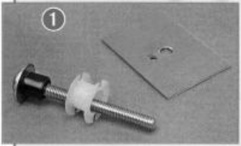
Once the leads have been bent down, solder the LED in place with the horizontal section of its leads 6.5mm above the PCB surface (a cardboard spacer can be used to set the height). This ensures that it will later line up with its front panel hole and will be in line with the centre shaft of the adjacent switch (S1).

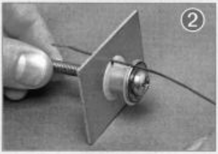
Winding the inductors

The two air-core inductors (L3 & L4) are wound on small plastic bobbins. It is much easier to wind them if you make a winding jig, as shown in the adjacent panel.

To wind the first coil, first secure the bobbin to the jig with one of its slots aligned with the hole in the end cheek. That done, feed about 20mm of a 1m-length of 0.8mm-diameter enamelled copper wire through the

A Winding Jig For The Inductors

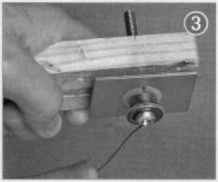




The winding jig consists of an M5 x 70mm bolt, two M5 nuts, an M5 flat washer, a piece of scrap PC board material (40 x 50mm approx.) and a scrap piece of timber (140 x 45 x 20mm approx.) for the handle.

The flat washer goes against the head of the bolt, after which a collar is fitted over the bolt to take the bobbin. This collar should have a width that's slightly less than the width of the bobbin and can be wound on using insulation tape. Wind on sufficient tape so that the bobbin fits snugly over this collar.

Next, drill a 5mm hole through the centre of the scrap PC board material, followed by a 1.5mm exit hole about 8mm away that will align with one of the slots in the bobbin. The bobbin is then slipped over the collar, after



which the PC board "end cheek" is slipped over the bolt. Align the bobbin so that one of its slots lines up with the exit hole in the end cheek, then install the first nut. The handle is then fitted by drilling a 5mm hole through one end, then slipping it over the bolt and installing the second nut.

hole, then carefully wind on 20.5 turns before bending the end down so that it passes through the opposite slot in the bobbin. Trim the "finish" end of the wire to 20mm (to match the start end), then secure the winding with a layer of insulation tape and remove the bobbin from the winding jig.

A 10mm-length of 25mm-diameter heatshrink tubing is used to finally secure the winding. Slip it over the outside and gently heat it to shrink it down (ie, be careful to not melt the bobbin).

The second coil is wound in exactly the same manner. Once it's finished, scrape the enamel off the leads on both inductors and tin them before fitting them to the PCB.

Completing the PCB assembly

The PCB can now be completed by fitting the remaining large items, starting with the SPDT power switch. Make sure it sits flat against the PCB and is at right-angles to it before soldering its pins. The power socket can then go in, followed by the RCA sockets (CON1 & CON2).

Use a red RCA socket for CON1 (right) and a white RCA socket for CON2 (left). Be sure to push the sockets all the way down onto the board, so that their plastic locating tabs go into the corresponding holes, before soldering their pins.

The tinplate shield between the two inductors can now be installed. This shield measures 35 x 15mm and can be cut from the lid of a large Milo tin using tin snips. File the edges smooth after cutting, then temporarily position it between the two PC pins and mark their locations.

That done, hold the shield in an alligator clip stand and melt some solder onto either side at the marked locations. It may take 10 seconds or more to heat it enough for the solder to adhere.

Finally, melt some solder onto the tops of the two PC pins before fitting the shield in position and remelting the solder to secure it.

Preparing the potentiometer

The 16mm dual-gang potentiometer (VR1) may need to be modified before installing it on the board. Take a look at the pot – the flat section of the shaft must extend all the way back to the threaded mounting bush. If not, this flat section must be extended.

To do this, lightly clamp the tip of the shaft in a vice with the flat section facing upwards and use a file to extend this section back to the threaded bush. Once that's done, cut the shaft to a length of 7mm and file off any burrs.

It's also necessary to remove a small area of the metal passivation layer on the top of the pot body (use a file), after which the pot can be soldered to the PCB.

The metal body of the pot must be earthed. This is done by first soldering an 80mm-length of tinned copper wire to an adjacent pad immediately below the pot (ie, between it and the adjacent 220μF capacitor). This wire is then looped across the top of the pot, pulled down and soldered to the top-right pad on the PCB and to the pot's body (ie, where you exposed the bare metal earlier).

Mounting the heatsinks

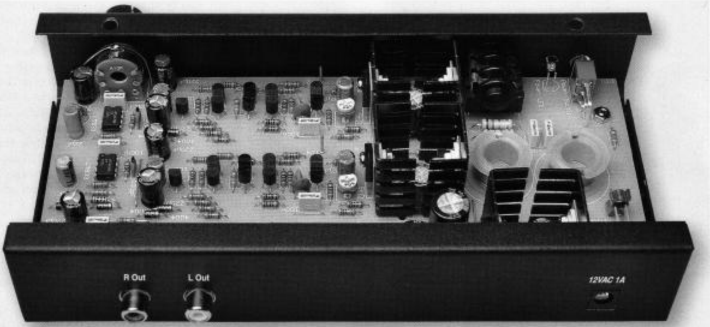
The two regulators and six power transistors are mounted on six large flag heatsinks. These have two posts which pass down through the PCB for support.

Start by loosely fitting the 7812 and 7912 regulators to their heatsinks as shown in Fig.10(A). Note that, in each case, the regulator's metal tab must be isolated from its heatsink using an insulating bush and silicone washer.

That done, fit the 7812 regulator assembly through the lower set of holes just above CON3 and D3 (see Fig.9). If the heatsink has "solderable" pins, flip the board over and solder one, then double-check that it is sitting perfectly flush with the board before soldering the other. Since you have to heat up quite a bit of metal, it could take 15 seconds or more before the solder adheres to the post.

Alternatively, if the heatsink doesn't have "solderable" pins, use pliers to bend the tabs outwards far enough so that it is secured to the board.

Having secured the heatsink, check that the insulating washer is properly



The PCB assembly is a neat fit inside the recommended Altronics case. Note how the body of the volume control pot (top, left) is earthed using a length of tinned copper wire. This wire is looped across the top of the pot's body and is terminated in solder pads on either side (see Fig.9).

aligned with the regulator and tighten the mounting screw. The regulator's leads can then be soldered. Repeat this procedure for the 7912 regulator.

The two TIP32 power transistors (Q12 & Q24) are mounted in identical fashion to the regulators. By contrast, the heatsinks for the two TIP31 power transistors (Q11 & Q23) have the BD139 V_{BE} multiplier transistors mounted on the other side. Fig.10(B) shows the mounting arrangement. Be sure to insulate all the transistors from the heatsinks using silicone washers and insulating bushes as necessary.

You can now fit the 6.35mm jack socket. The type we used does not sit right down on the board due to the shape of its pins but rather sits above the board by about 4mm. If your jack socket does not have "necked" pins, you will either need to extend them or its front panel hole will have to be lowered by 4mm when you drill it later.

Finally, fit the two 2200µF capacitors. As mentioned in Pt.1, if you use 4700µF 25V capacitors (ie, for more output power), they must be no taller than 30mm and no more than 16mm in diameter, otherwise the assembly will not fit into the specified case.

Test & adjustment

The assembled board can now be tested. First, turn both trimpots and the volume control potentiometer fully anti-clockwise, then clip a multimeter set it to its highest AC amps mode across the fuseholder (without the fuse in place). The easiest method is to use alligator clip leads.

Next, connect the 12VAC plugpack and apply power. You should get a reading of 120mA ±20mA (no op amps installed) or 160mA ±20mA (op amps installed). If the current does not fall inside this range after about a second, switch off the plugpack at the wall and check the board for faults such as solder bridges between pads and tracks.

Assuming it's OK, switch off, install the op amps if they aren't already on the board and check the current consumption again (ie, it should be 160mA ±20mA).

Now turn the power off, install the fuse and connect a multimeter set to volts/millivolts mode between TP1 & TP2. That done, switch on and check the reading – it should be very close to 0mV.

Now slowly adjust VR2 clockwise. At first nothing will happen but eventually the reading should start to rise. Adjust it for a reading of 28.5mV. This sets the quiescent current in the left channel to 47.5mA. Note that this reading may slowly rise as the transistors warm up so leave it on for a few minutes and then re-adjust it.

Once that's done, switch off and connect the multimeter between TP3 & TP4. VR3 can now be adjusted for a reading of 28.5mV, to set the quiescent current in the right channel.

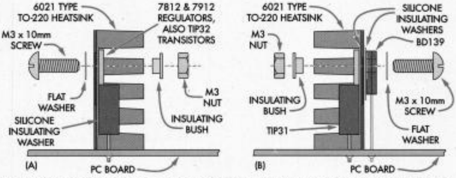


Fig.10: follow this diagram to install the regulators and output transistors on their heatsinks. Make sure that the metal tabs of all devices are isolated from the heatsinks using insulating washers and bushes as required. Note that the heatsinks should be either soldered or clamped to the PCB before soldering the device leads, to avoid stress fractures.

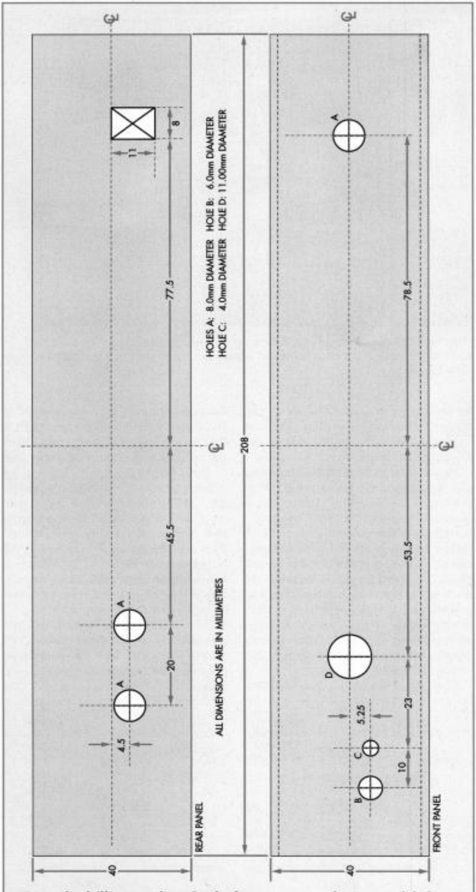


Fig.11: the drilling templates for the front & rear panels. Start each hole with a small pilot drill and then enlarge it using larger drills and a tapered reamer as necessary. The rectangular cut-out is made by drilling and reaming a 6mm hole in the centre and then shaping it using a flat needle file. Be sure to correctly position the templates before drilling the holes.

The final test is to connect a signal source and headphones and slowly turn the volume up. If you hear clear, undistorted sound from both channels then the board is working properly.

Provided the quiescent current is set correctly for both channels, the idle current will be about 340mA (AC RMS), giving a power consumption of about 4W. With headphones, this does not usually increase but it may be higher when driving loudspeakers, depending on the volume level and speaker efficiency.

Drilling the case

A half-size 1-unit steel case (Altronics H4995) is used to house the PCB assembly. Other cases are also suitable provided the PCB fits, although you will probably have to chassis-mount the RCA input sockets and power connector. If chassis-mounting the RCA connectors, it will be necessary to use shielded cable to connect them to the PCB.

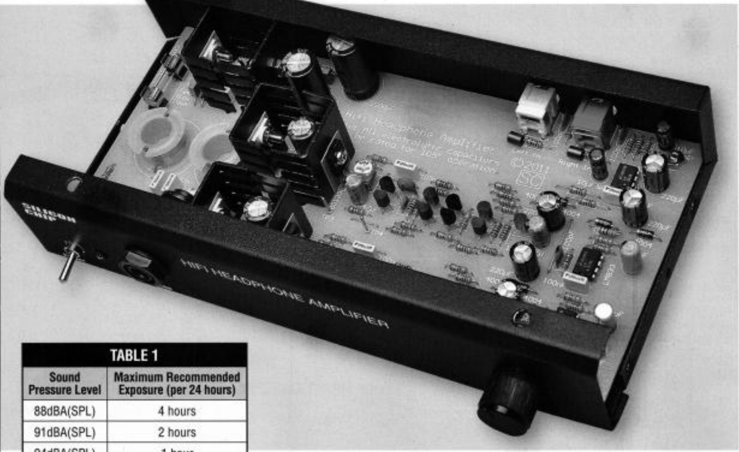
The drilling templates for the Altronics case are shown in Fig.11. Disassemble the case entirely first, by removing all the screws. It separates into three pieces: the aluminium base (and rear panel), the front panel and the steel lid. Remove the feet as well and place them and the screws into the provided snap-lock plastic bag for safe-keeping.

Next, download and print out the drilling templates and attach them to the front and rear panels. Use a punch to mark the centre of each hole. Alternatively, you can start the holes with a small bit (say 1mm) and a hand-drill. Either way, drill pilot holes (eg, 1.5mm) in each location before enlarging them to size using larger drills and a tapered reamer.

The hole which must be the most accurately placed is that for the power switch. The LED leads can be bent to compensate for any inaccuracy in its mounting hole position and those for the output socket and volume control can just be made slightly oversize. Note that the hole for the power LED is drilled to 4mm to suit a plastic LED clip.

The rectangular cut-out for the power socket is made by first drilling and reaming a 6mm hole in the centre before carefully enlarging it to a rectangular shape with a flat needle file.

Once the drilling has been completed, download the front and rear-



Another view inside the completed unit. Make sure that the screws used to secure the lid clear the underside of the PCB – see text. Note that the PCB shown here is a prototype and differs slightly from the final version shown in Fig.9.

TABLE 1

Sound Pressure Level	Maximum Recommended Exposure (per 24 hours)
88dBA(SPL)	4 hours
91dBA(SPL)	2 hours
94dBA(SPL)	1 hour
97dBA(SPL)	30 minutes
100dBA(SPL)	15 minutes
103dBA(SPL)	7 minutes
106dBA(SPL)	3 minutes
109dBA(SPL)	1 minute
112dBA(SPL)	30 seconds
115dBA(SPL)	15 seconds

panel labels (in PDF format) from the SILICON CHIP website and print them out. These labels can then be trimmed and laminated before affixing them to the panels using double-sided adhesive tape. The holes are cut out using a sharp hobby knife.

Mounting the board

The PCB assembly is mounted on the same machine screws that secure the rubber feet to the case. Remove the supplied short machine screws from the feet and insert M3 x 15mm screws instead, then re-attach them to the base. Once they're all in place, slip three M3 flat washers over each screw thread, then fit a Nylon nut/washer combination over the top, with the larger "washer" section at the top (note: if you can't get these, use separate Nylon nuts and washers instead, with the washers on top).

Next, undo the two rear two screws until only a tiny bit of thread is sticking out above the Nylon washers (say 1mm), then introduce the board by pushing the RCA sockets and DC input connector through their respective holes. It's then just a matter of dropping the front of the board down onto the screw threads, after which you can re-tighten the rear mounting screws.

The lid is held in place by two screws on each side and these should just clear the underside of the PCB. Temporarily fit these screws (ie, without the lid) to check this. If any of screws do foul the PCB you will need to remove it and add more M3 flat washers under the Nylon nuts.

Once it's correct, fit M3 nuts to all four screws to secure the PCB in place, then remove the nuts and washers from the jack socket and volume control pot. The front panel can then be attached by slipping it into place and installing the two screws at the bottom. Once it's secured, push the plastic LED clip into place and push the LED into the clip from the back.

The assembly can now be completed by reinstalling the washers and nuts for the jack socket and volume control, attaching the knob and fitting the lid.

Using it

Finally, here are a couple of tips for using the headphone amplifier.

First, always turn the volume knob right down before donning the headphones and then turn it up to a comfortable level. If you don't do that, you risk hearing damage. This particularly applies if somebody has left the volume control turned fully up or if the signal source is much louder than it was the last time you used the headphone amplifier.

Similarly, do not listen at high volume levels for long periods. This is especially critical with a headphone amplifier as it's easy to expose yourself to damaging sound pressure levels without too much apparent discomfort (and without anyone else noticing).

Table 1 shows the recommended maximum exposure periods for various sound pressure levels (SPLs) ranging from 88-115dBA. In short, don't make a habit of listening to loud music via headphones. **SC**