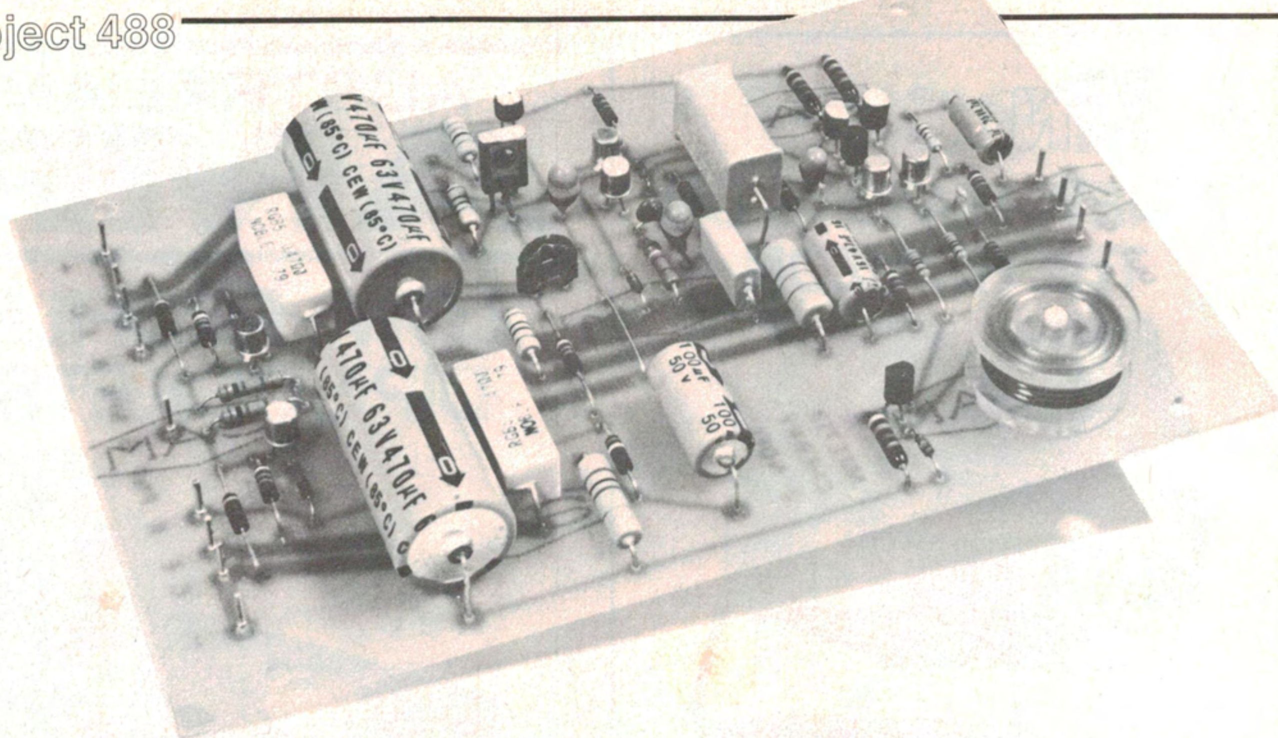

60 W amplifier module with two nested differentiating feedback loops

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This is the third, and concluding, part of Professor Cherry's series on Audio Amplifiers Using Nested Differentiating Feedback Loops. Here is a practical amplifier design, presented as a module, that can be incorporated into a new system or used to replace power amp modules in an existing system. As the feedback technique promises, distortion is very low.

THIS AMPLIFIER will perhaps be of most interest to home constructors who want to re-build an existing system and upgrade its performance without the expense of new major components. The power output transistors employed are the well-known types MJ802 and MJ4502 which have been around for several years and have proved their reliability. Indeed, the whole design is mature and home constructors should have no difficulty in making it work. Total harmonic distortion in this amplifier is only a few parts per million at low outputs at 1 kHz — stacks better than some well-known marks of class-A amplifiers!

The two previous parts of this series appeared in the October and November 1982 issues of ETI.

Circuit description

Figure 15 is the complete circuit of one channel of the amplifier. The circuit is clearly based on Figure 10 (November '82 ETI), with major parameters

$$1/\beta = 32.9$$
$$\tau_X = 800\text{ ns}$$

The value of β is set by the overall feedback resistors R11 and R12 (470R and 15k — see Equation 1, Oct. '82). τ_X is set by:

a) R4 and R5 (330R) plus C6 and C8 (68p) in conjunction with the chosen value of β (see Equation 13, Nov. '82);

b) R15 and C7 (1k8 and 470p — see Equation 14, Nov. '82);

c) R33 and C14 (8R2 and 100n) plus the 8 ohm nominal load and L3 (6u8 H);

d) R12 and C4 (15k and 33p) via the other constants in Equation 15 (Nov. '82).

The first stage requires little comment. Q1 and Q2 operate at 1.5 mA each, Q3 is a current source, Q4 is a common-base stage to equalise the quiescent voltages on Q1 and Q2; Q5 and Q6 constitute a current mirror. R1 and C2 form a 200 kHz low-pass filter against RF interference.

The Rush current amplifier operates at 3 mA, set by R18, and it incorporates a catching diode (D1) to accelerate recovery from overdrive. Almost any small-signal diode would do — 1S44, 1N914, etc.

Q1 and Q2 should be high gain, low noise types: BC109 and BC549 are among the cheapest available. The others could be almost any small-signal types: BC107 and

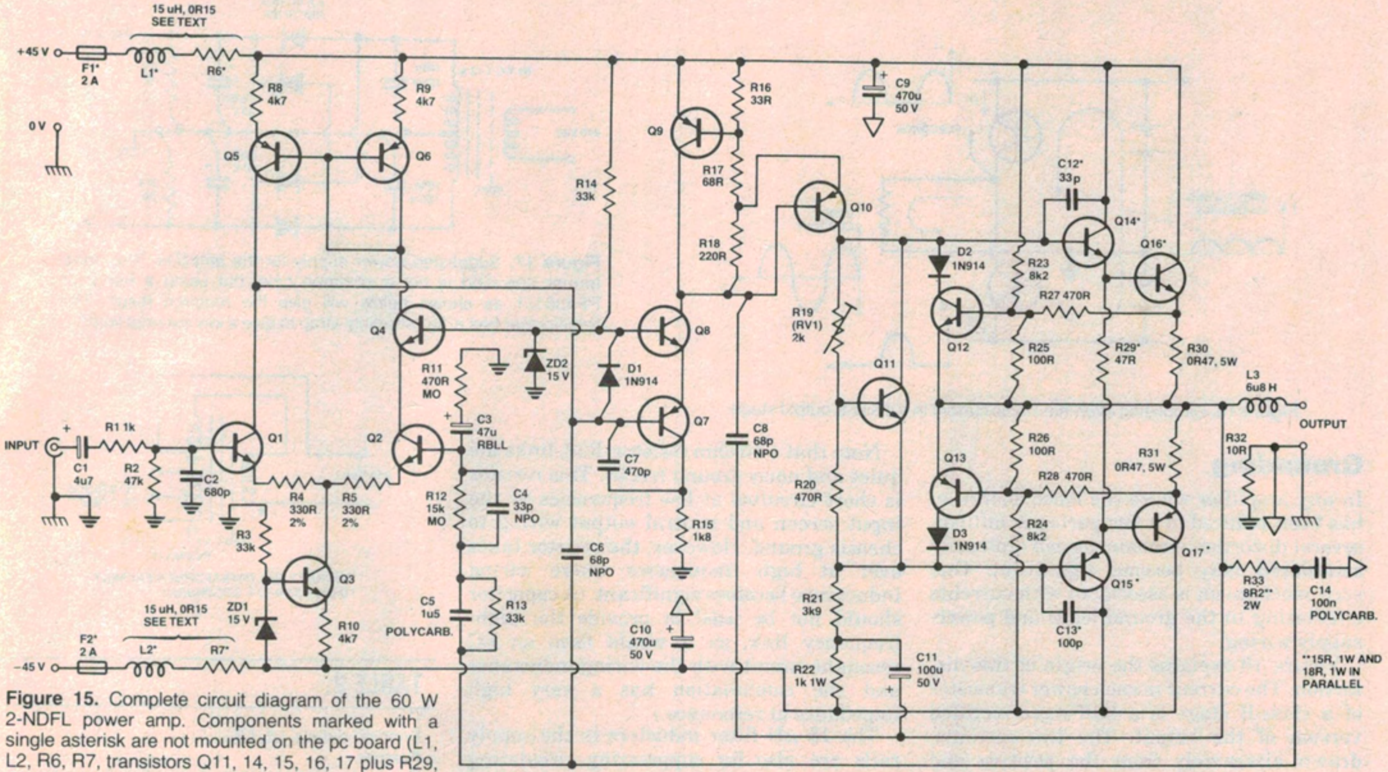


Figure 15. Complete circuit diagram of the 60 W 2-NDFL power amp. Components marked with a single asterisk are not mounted on the pc board (L1, L2, R6, R7, transistors Q11, 14, 15, 16, 17 plus R29, C12 and C13 — see Figure 20).

BC547 are readily available npn types, the BC177 and BC557 are suitable pnps.

The pre-driver, Q10, operates at 8 mA, and should be the prefered type BD140. Q9 protects the stage against damagingly large currents under fault conditions.

The driver and output transistors should be the types shown: BD139 and BD140 for the drivers, MJ802 and MJ4502 for the power transistors. Driver quiescent current is 25 mA, set by R29. The biasing transistor, Q11, could be any npn in a TO-126 pack that can be mounted on the heatsink; types BD135 and BD139 are readily available types that would suit. Quiescent current in the power transistors should be set to 40-60 mA by R19. *Be warned* that this quiescent current is almost zero until R19 is about three-quarters of its maximum resistance, after which the current increases very rapidly; be sure that R19 is set to *minimum resistance* when the amplifier is turned on for the first time.

A convenient way to check the quiescent current is by means of the voltage drop across R30 and R31; this should be 40-60 mV (total) for zero signal input to the amplifier.

Transistors Q12 and Q13 provide short-term protection for the power transistors. Short-circuit current is limited to about 4 A, and peak signal current is limited to 7 A. Long-term protection is provided by 2 A fuses in each supply rail; these should be 'ordinary' types, rather than delay or quick-blow. In the unlikely event of transistor failure, these fuses limit the loudspeaker current to 2 A, corresponding to 32 W into 8 ohms.

The common alternative of a single fuse in the loudspeaker lead is less satisfactory: it provides less protection for the amplifier; it provides less protection for the loudspeaker as the fuse must be rated to carry the full signal current, and it introduces distortion on large-amplitude, low-frequency signals.

Critical components

The majority of components in the amplifier are not at all critical. As already stated, almost any small-signal transistors and diodes can be used. Unless the contrary is indicated on the circuit, resistors can be standard ½ W types and capacitors can be the lowest available working voltage. A few components, however, do require special mention.

A feedback amplifier cannot be more linear than its feedback network, so the various components that constitute the feedback network should have small voltage coefficients. Specifically:

a) Overall feedback resistors R11 and R12 should be high-stability types, such as metal oxide or metal film;
b) C6 and C8 should be NPO ceramics, not hi-K types;
c) C5 and C14 should be polycarbonate, polystyrene or polypropylene types, but not polyester (for example mylar 'greencaps');
d) C3 should be an ordinary cheap aluminium electrolytic, definitely *not* one of the relatively expensive resin-dipped tantalum types (this is not a misprint!).

The 6u8 H inductor (L3) needs to be home-made. Winding data are given in the accompanying table, Table 1.

The bobbin should be mounted on the circuit board with a nylon screw; brass or steel must not be used, because of nonlinear eddy-current losses. ▶

HARMONIC ANALYSIS AT 1 kHz

harmonic	rated output 21.9 V 60 W	−20 dB 2.19 V 0.6 W
2nd	19 ppm	5 ppm
3rd	14	3.5
4th	2.5	2.5
5th	3.0	1.5
6th	‹1	‹1
7th	1.8	1.8
8th	‹1	‹1
9th	1.0	‹1
10th	1.8	‹1

Notice how the harmonics drop away at small signal amplitude. In this regard a class-B NDFL amplifier is more like a conventional class-A amplifier than a class-B amplifier.
1 ppm = 0.0001%

HARMONIC ANALYSIS AT 6 kHz

harmonic	rated output 21.9 V 60 W	−20 dB 2.19 V 0.6 W
2nd	115 ppm	40 ppm
3rd	100	25
4th	32	15
5th	40	9

Harmonics higher than the 3rd are ultrasonic and hence inaudible.

TABLE 1.

Winding details, L3.

Former
Turned from 25 mm diameter polystyrene rod to give 12 mm internal bobbin diameter with 7.5 mm winding space between cheeks.

Wire & winding
Take a 1190 mm length of 1.25 mm diameter enamelled copper wire and wind it onto the former. Leave 20 mm or so lead length at start and finish.

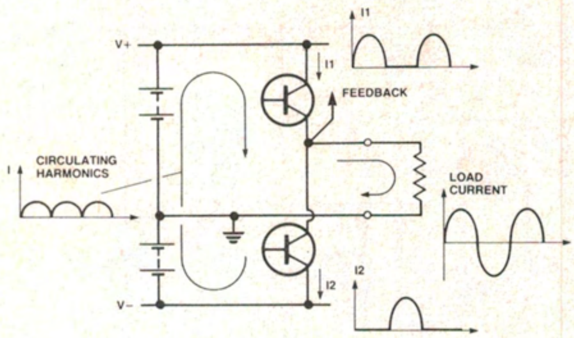


Figure 16. Circulating even-harmonic current in a class-B output stage.

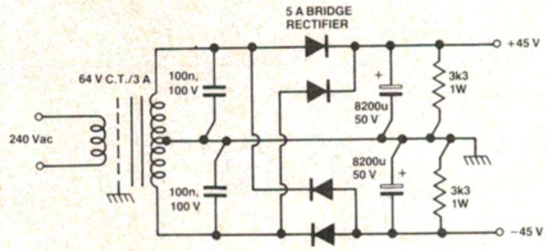
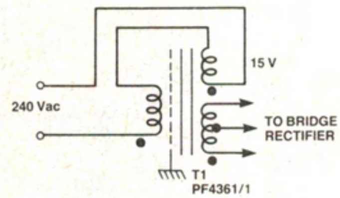


Figure 17. Suggested power supply for the amplifier. The transformer specified is not a common type, but using a Ferguson PF4361/1 as shown below will give the required result. This transformer has a 'flux shorting' strap to give a low external field.



'BUCKING' THE TRANSFORMER PRIMARY TO GIVE 33-0-33 V SECONDARY

Grounding

In any amplifier where the basic distortion has been reduced to a few parts per million, several distortion mechanisms not ordinarily considered may become significant. One such mechanism is associated with currents circulating in the ground leads and power-supply wiring.

Figure 16 explains the origin of this distortion. The current in each power transistor of a class-B stage is a half-wave rectified version of the output. The two currents, drawn alternately from the positive and negative supplies, are equivalent to a circulating full-wave rectified current and this is basically an even-harmonic distortion of the signal output. If there is any mutual inductance between the power-supply wiring (including the grounds) and the signal wiring (also including the grounds), then an even-harmonic distortion is induced in the amplifier and feedback is powerless to correct it.

The circuit board has been laid out so as to minimise this effect. The areas enclosed by some tracks are critical, and home constructors making their own pc boards are cautioned to follow the layout exactly; you can obtain artwork from ETI (see page 64) or, better still, purchase a ready made board.

Note that the circuit uses three distinct ground symbols:

a) ⏚ is the *quiet ground* track on the circuit board (one per channel).

b) ▽ is the *noisy ground* track on the circuit board (one per channel).

c) ⏚ is the metal chassis ground (there are six connections to the chassis in total).

Each channel is connected to chassis ground at two points. The input socket is connected to the chassis (rather than insulated from it), the input lead from socket to circuit board is screened, and the quiet ground track is connected to chassis ground at the input socket via the screen. Similarly, the neutral output terminal is screwed into the chassis, the leads from the circuit board to the output terminals are a twisted pair and the noisy ground track is connected to chassis ground at the output terminals via the neutral output lead. The remaining two connections to chassis are in the power supply (Figure 17).

Note that a 10 ohm resistor, R32, links the quiet and noisy ground tracks. This resistor is short circuited at low frequencies by the input screen and neutral output wiring to chassis ground. However, the resistor takes over at high frequencies where wiring inductance becomes significant. (A capacitor should not be used to provide the high-frequency link, as it would form an LC resonant circuit with the wiring inductance and the combination has a very high impedance at resonance.)

The 15 μH filter inductors in the supply rails are also for suppressing circulating currents (R6 and R7 represent the winding resistances of L1 and L2).

This amplifier employs only two nested differentiating feedback loops and its distortion is not down to the ultimate limit. The benefit of including the filter inductors is therefore marginal. The author is not blessed with 'golden ears' and cannot hear the effect of removing the filters, although the difference is clearly measurable. The filters should certainly be included in amplifiers that use three or more NDFLs. As the inductors must be home made, and therefore cost nothing but time, and as they do make a measurable (if small) improvement, most home constructors will probably wish to include them. Winding data are given in Table 2.

TABLE 2.

Winding details, L1, L2.

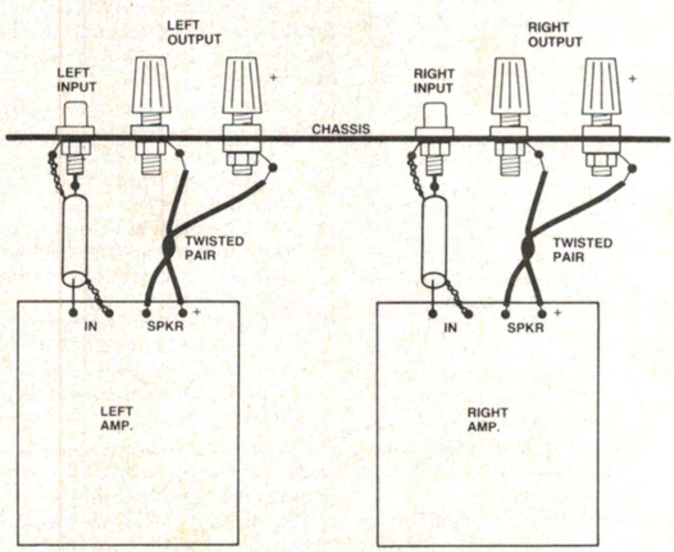
Former

Turned from 20 mm diameter polystyrene rod to give 12 mm internal bobbin diameter with 7.5 mm winding space between cheeks. Two are needed.

Wire & winding

Take two 1680 mm lengths of 0.75 mm diameter enamelled copper wire and wind onto each former leaving 20 mm or so lead length at start and finish.

The precise values of inductance and resistance are not important — ±50% is good enough — but do not use the 1.25 mm wire from L3 as something like 0.1 ohm series resistance is essential. For a similar reason, do not parallel the 470 μF bypass capacitors C9 and C10 with high-frequency types. Brass or steel mounting screws are perfectly satisfactory for the filter inductors, as linearity is not important. ▶



The right connections. Showing the general technique of connecting inputs, outputs and grounds to a stereo pair of ETI-488 modules.

Low-frequency compensation

A feature of Figure 15 not discussed so far is a low-frequency compensating circuit, R13 and C5.

Amplifiers of the basic circuit topology of Figure 2 (Oct. '82) have a group delay which is different for different signal frequencies. Some frequencies take longer or shorter times than others to pass through the amplifier. High-frequency group delay in NDFL amplifiers can be corrected as described in the last part (Nov. '82), by a small capacitor in the feedback network (see Equation 15). Errors in low-frequency group delay, in both Figures 2 and 10 (Oct. and Nov. '82), are associated with the input coupling capacitor and the capacitor in series with R_{F1}. Low-frequency square-wave inputs are reproduced with a 'tilt' as in Figure 18(a).

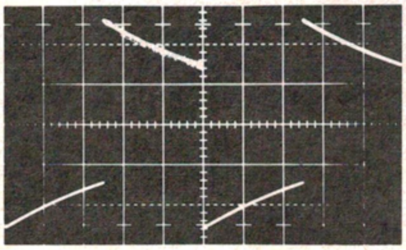


Figure 18a. Square wave response of the amplifier without group-delay compensation.

One approach to this problem is to use a truly direct-coupled amplifier, with no capacitors in series with the signal path; commercial audio power amplifiers of this type appeared in the 1970s. Unfortunately, such amplifiers are prone to drift. A significant dc voltage may appear at the output even when there is no input. Although it is possible to reduce drift in a power amplifier to an acceptable level, it is not possible with today's technology to build a system that is truly direct-coupled from pick-up input, through the RIAA network and the power amplifier.

In the last few years a generation of amplifiers has appeared which include some form of servo amplifier to correct the drift. All circuits known to the author re-introduce the problem of group delay, albeit in a lesser form.

The approach adopted in this design is to retain the coupling capacitors and thereby eliminate drift, but include a group-delay correcting circuit. Figure 19 shows the outline. Group delay is optimally compensated if:

$$R_{F3} = 2\,R_{F2}\,, \qquad (16)$$

$$R_{F2}\,C_{F2} = R_{F1}\,C_{F1} \qquad (17)$$

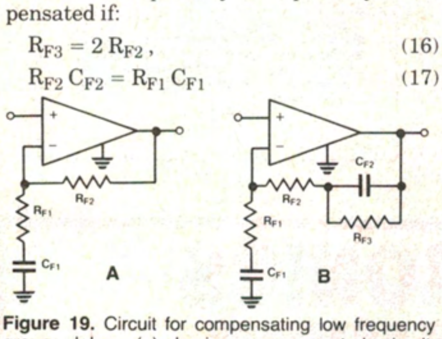


Figure 19. Circuit for compensating low frequency group delay: (a) basic uncompensated circuit; (b) compensated circuit.

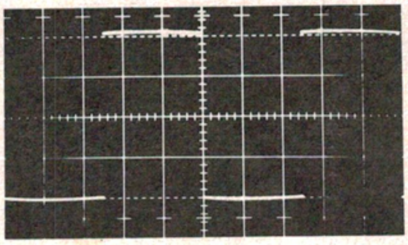
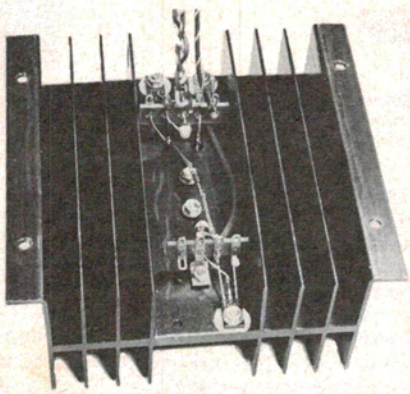


Figure 18b. Square wave response of the amplifier with group-delay compensation — note the improvement over Figure 18b.

Figure 18(b) shows the improvement in square-wave response.

Low-frequency group-delay compensation could well be included in audio power amplifiers and preamplifiers other than NDFL types.



Heatsink. Showing components mounted on the heatsink.

Construction

Assembly of the printed circuit board is quite straightforward. It is probably best to commence by soldering all the resistors in place. Note that R33 could be either a 2 W type (not common) or two 1 W resistors (15R and 18R) in parallel. Note that Noble brand resistors have been used for the emitter ballast resistors of Q16 and Q17 (R30 and R31). These have very low inductance and other types may be used and work successfully, but if you have trouble with high frequency instability, these resistors are likely to be the culprit. Mount R30 and R31 a few millimetres above the board. There are several other things to note about the resistors. R4 and R5 should be 1% or 2% tolerance and R11 and R12 should be either metal oxide or metal film types, as mentioned earlier.

Assemble the diodes next, making sure you get them all the right way round. Install the links next. Follow with the capacitors. Note that C5 and C14 must be polycarbonate types and C4, 6 and 8 must be NPO ceramics. None of the other ceramic capacitors should be hi-K types, as mentioned earlier. When mounting C9 and C11, see that there is three or four millimetres between the capacitor body and the adjacent 5 W resistors (R30 and R31) to allow for convection around the latter.

The transistors may be mounted now. See that each is oriented correctly. Wind L3 next and mount it on the board. Details are given in Table 1. It is not necessary to strictly follow the former dimensions given, but the inductance needs to be close to 6u8 H and wound from 1.25 mm wire at least, for low resistance.

To terminate connections leading to and from the board, pc stakes were used, as can be seen in the photograph.

Assembly of the components mounted to the heatsink comes next. The heatsinks in the original were 5" (127 mm) lengths of blackened Philips #56230, each having a thermal resistance to ambient of about 1°C/W at 50°C. Other types could of course be substituted. The specified thermal resistance permits continuous operation at full power. Smaller heatsinks (up to 2°C/W) could be substituted if the amplifier is to be used only for domestic sound reproduction. A 225 mm length of single-sided radial-fin type heatsink (e.g: D.S.E. No. H-3426 or Electronic Agencies H-2429 would suit). Other suitable similar types are Rod Irving's HS3, which is only 150mm long or a 150 mm length of

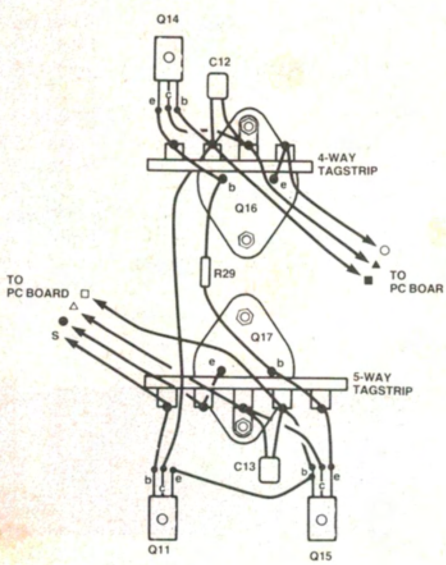
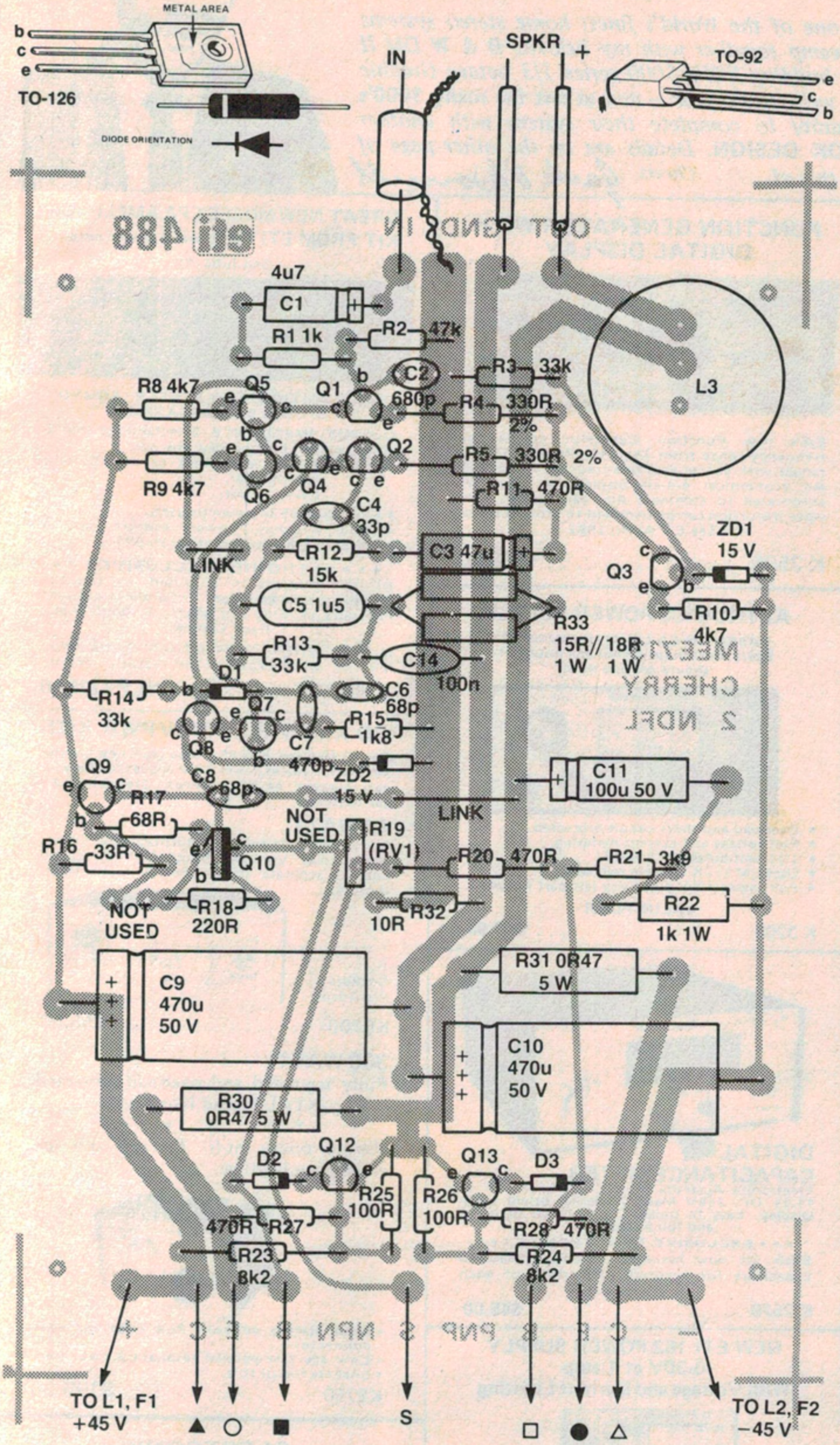


Figure 20. Wiring diagram for the components mounted on the heatsink.

PATENT PROTECTION

The principle of nested differentiating feedback loops, on which this amplifier depends, is patented in Australia and principal overseas countries.

Commercial enquiries should, in the first instance, be directed to the Legal Office, Monash University, Clayton Vic. 3168. Australian manufacturers can expect very favourable licencing terms.



PARTS LIST — ETI-488

Resistors	all 5%, ½W unless noted
R1	1k
R2	47k
R3, 13, 14	33k
R4, R5	330R, 2%
R6, R7	see text
R8, 9, 10	4k7
R11	470R, MO or MF*
R12	15k, MO or MF*
R15	1k8
R16	33R
R17	68R
R18	220R
R19 (RV1)	2k min. vert. mount trimpot.
R20, 27, 28	470R
R21	3k9
R22	1k, 1 W
R23, R24	8k2
R25, R26	100R
R29	47R
R30, R31	0R47, 5 W
R32	10R
R33	8R2, 2 W or 15R and 18R, each 1 W
Capacitors	
C1	4u7, axial electro.
C2	680p ceramic
C3	47u axial electro.
C4	33p 100 V NPO ceramic
C5	1u5 polycarbonate
C6, C8	68p 100 V NPO ceramic
C7	470p ceramic
C9, C10	470u/50 V axial electro.
C11	100u/50 V axial electro.
C12, C13	33p 100 V ceramic
C14	100n/100 V polycarbonate
Inductors	
L1, L2	15 uH (see text and Table 1)
L3	6u8 H (see Table 2)
Semiconductors	
D1, 2, 3	1S44, 1N914, 1N4148 etc
Q1, Q2	BC109, BC549 etc
Q3, 4, 8, 12	BC107, BC547 etc
Q5, 6, 7, 9, 13	BC177, BC557 etc
Q11, Q14	BD139
Q10, Q15	BD140
Q16	MJ802
Q17	MJ4502
ZD1, ZD2	15 V zener
Miscellaneous	
F1, F2	2 A standard fuse

ETI-488 pc board; one 4-way and one 5-way tagstrip; heatsink to suit (see text); pc stakes; bobbins for inductors, wire, etc.

*** metal oxide or metal film.**

Price estimate **$30 — $35**
(less heatsink)

Autotron 'XA' type heatsink. Use one heatsink per channel.

Three small components are mounted on the heatsink adjacent to the transistors to keep certain leads short: R29, C12 and C13. Construction is very much simplified if a 4-way tagstrip is installed under one of the collector mounting bolts of Q16 and a 5-way strip under one of Q17's mounting bolts. Figure 20 shows details.

The collector and emitter leads from each power transistor to the circuit board should be twisted. The base leads to Q14 and Q15 could be twisted in with the corresponding collector and emitter leads (although this is not necessary) and the base lead of Q11 can be kept separate. Note that all transistors must be insulated from the heatsink.

The pc board is a Monash University 'universal' type for NDFL power amplifiers and there is provision on it for two components not used in the present amplifier (both near Q10). Note also that the BD140 specified for Q10 needs its leads dressed to fit the board — the collector and emitter leads should be bent about 0.1" sideways (see the overlay). ●