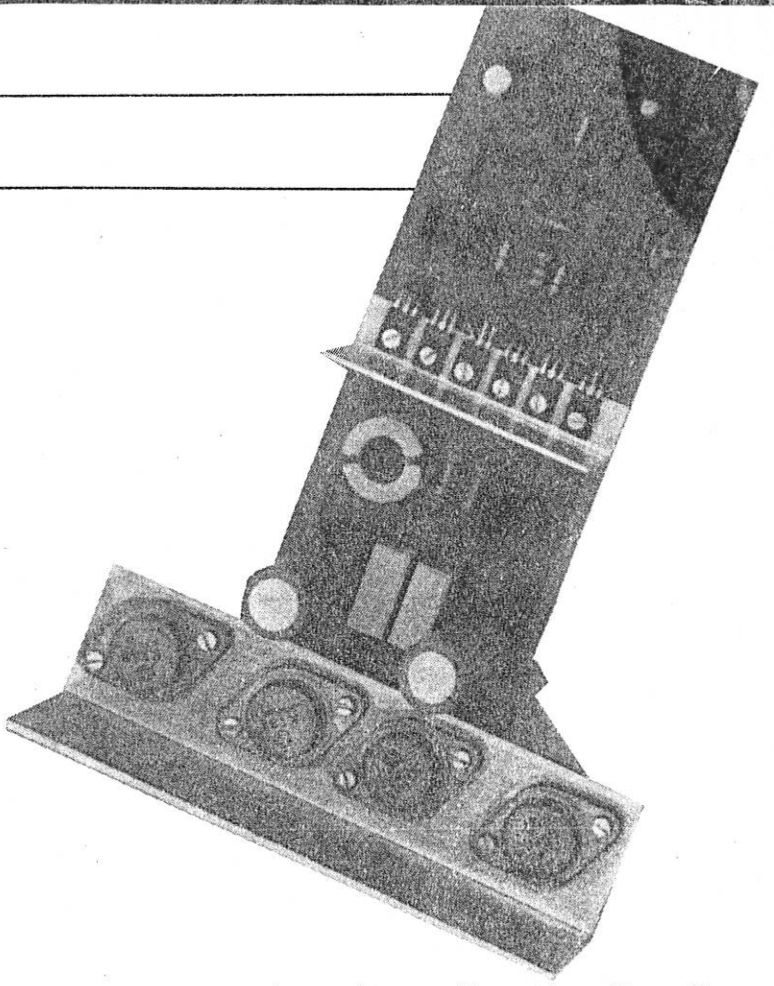
aem project 6500

A 'universal' MOSFET Amplifier module.

David Tilbrook

This power amplifier module is a high performance general purpose unit intended for use in a wide variety of applications. It can be configured with either two or four output devices to provide output powers of around 60 W and 100 W + into 8 ohms and will form the basis of several exciting projects to appear in this magazine in the near future.



AMONG commercial power amplifier designs there is a tendency to produce medium power, lower-priced units with an inferior level of overall performance. This project is an attempt to overcome this by providing a high performance, low-cost module for applications not requiring large power outputs.

The circuitry is based on my earlier Series 5000 power amplifier which featured MOSFET devices in the output stage. The basic module described here uses only a single pair of MOSFETs and the board is designed so that it fits vertically in a 3.5" (88 mm) high rack-standard (19") cabinet. Conveniently, this suits the module to a wide range of other standard, low-cost chassis. By the simple addition of another pair of output MOSFETs, off-board, power output can be effectively doubled without affecting the other performance parameters.

The module is capable of extremely good performance with second and third harmonic distortion figures below 0.001% at full power and intermodulation distortion below 0.003% at 10 kHz and at all operating powers below clipping. In addition, the module is unconditionally stable and free from slew-induced distortions (TIM). The MOSFET output devices have proven themselves very reliable over the years since my earlier design, much more so than bipolar transistors, and are, I think, ideally suited to this application.

MOSFET pros and cons

One of the main advantages of these devices can be understood by looking at the equivalent circuit of a typical power MOSFET. This is shown in Figure 1. The effective input impedance of the gate is determined by a 90 ohm resistance in series with a 30 pF capacitance to the drain, and a 500 pF capacitance to the source.

The combination of the input resistance and the gate-to-source capacitance forms a low-pass filter with a 3 dB cutoff point around 3.5 MHz. If driven correctly with a low impedance driver stage, the device is capable of extremely wideband performance and has slew rate characteristics that are vastly superior to bipolar transistors.

Another major advantage of MOSFETs can also be seen from the equivalent circuit. For audio frequencies, the input impedance is dominated almost entirely by the gate capacitances and so is effectively an open circuit. The device is voltage controlled (i.e. the source/drain resistance is roughly proportional to the gate/source voltage) so the driver stage need only supply enough current to overcome the input capacitance.

Unfortunately, the input capacitance is fairly high, so a relatively low impedance driver stage is needed to drive the MOSFET at high speed and this tends to offset the advantage of the high input impedance at low frequencies.

The relationship between the series gate resistance and the frequency response is shown in Figure 2. This is an important curve since it is usually wise to add a small amount of resistance in the gate circuit as their high speed, input capacitance and high impedance tend to make the devices unstable. The addition of external resistance, situated physically close to the gate, restricts the frequency response of the device slightly and greatly assists in assuring complete stability of the output stage.

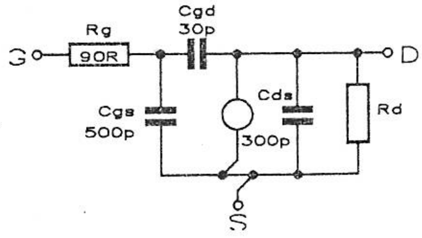


Figure 1. Equivalent circuit of a typical MOSFET.

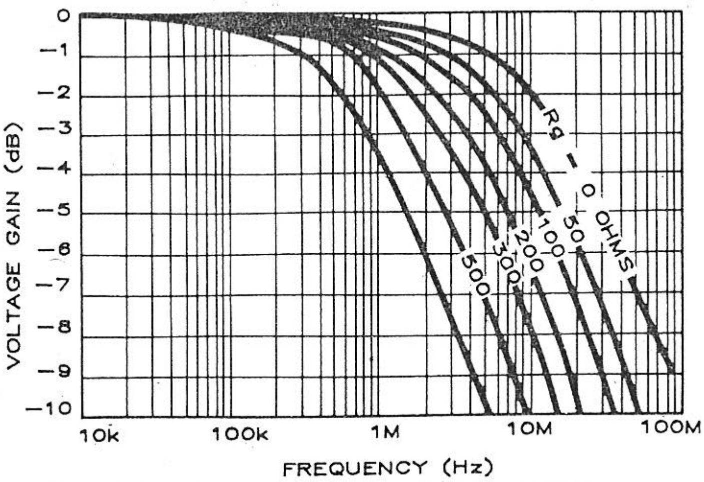


Figure 2. The frequency response of a typical power MOSFET and how series resistance in the gate affects it.

Probably the most important advantage of power MOSFETs over bipolar transistors is their inherent reliability. This stems from the fact that, for drain-source currents over about 100 mA, they have a **negative** temperature coefficient. Bipoplar transistors, on the other hand, have a **positive** temperature coefficient. This means that, if the base- emitter current of a bipolar transistor is kept constant, then the current flowing from the collector to the emitter, as a result of a constant applied voltage, will **increase** as the temperature of the device increases.

As a result, if some part of the chip area inside the transistor conducts more current than the rest of the chip, this region heats up more than the surrounding area. The positive temperature coefficient then encourages even more current to flow through this region. The result is an effect called **secondary breakdown** which leads to rapid destruction of the device.

Power MOSFETs, on the other hand, with their negative temperature coefficient, tend to distribute current evenly over the chip surface and this has distinct advantages, leading to a more robust device and providing a more useful "safe operating area" (SOAR) characteristic.

Safe operating area

The SOAR defines the boundaries within which it is safe to operate a semiconductor device. Let's take a look at this important specification.

In the case of a transistor or MOSFET, one obvious boundary is the maximum possible voltage that can be applied. With bipolar transistors, this parameter is often specified as the collector-emitter voltage with the base left unconnected (i.e: open-circuit base), which is generally given as "V_{CEO}". In the case of MOSFET's, the analagous figure is the drain-source voltage "V_{DSO}" or "V_{DSX}".

The SOAR characteristics of a device are usually presented in the form of a graph with current on the vertical axis and voltage on the horizontal axis. The maximum allowable voltage can therefore be represented on the graph by a vertical line intersecting the horizontal axis at the rated voltage.

Another boundary limiting the area of safe operation is the maximum possible current that can flow through the device before damage occurs. This is a simple physical limitation often associated with the current handling capablility of the connecting wires inside the device. It is independant of voltage and is therefore represented on the SOAR graph by another straight line, this time horizontal, intersecting the vertical axis at the rated current.

A third limitation is set by the maximum power dissipation of which the device is capable. This is really a thermal limitation so the time for which the power is applied to the device is another determining variable in addition to the voltage and current. For any given time period the maximum temperature reached by the chip is proportional to the power being dissipated and this means to the product of voltage and current. So for any given time period this temperature limitation is equivalent to a power limitation. The voltage and current can take any value within the limits discussed above but are restricted to values such that the product of the voltage and the current is less than the absolute rating for that time period.

Unfortunately, the equation $P = VI$ for constant P does not represent a straight line, which makes plotting this boundary on the SOAR graph a little difficult. To overcome this problem SOAR curves are usually plotted on a log-log scale instead of the simpler linear scale graph. In this way we are effectively taking logs of both sides of the power equation, i.e:

$$\log P = \log(VI)$$

or

$$\log V + \log I = c$$

$$c = \log P = \text{a constant}$$

which is the equation of a straight line of slope -1.

To cater for the thermal limitation of the device a family of lines is usually shown on the SOAR graph rather than a single line. The usual approach is to include one line corresponding to the dc power dissipation and several others corresponding to power dissipation for shorter specified time periods.

In the case of bipolar transistors a fourth boundary to the area of safe operation is determined by the secondary breakdown discussed earlier. Power MOSFETs do not suffer from this limitation so the safe operating area for MOSFETs is bounded by only three straight lines while that for bipolar transistors is bounded by four straight lines (on the log-log scale.).

SOAR curves for the MOSFETs used in this project (Hitachi 2SK134 and 2SJ49) and for a typical bipolar transistor (2N3055) have been included here (see Figures 3 and 4).

At all times during the operation of a power amplifier the power dissipation in the output devices must be resticted so that the devices operate wholly within the safe operating area. The best way to ensure this is to graph the operating conditions for the devices used given the supply voltage and the worst expected operating conditions.

Figure 5 shows the output stage of a typical class AB output stage using MOSFETs. A split supply is used so that the output can be directly connected to the load without need of the coupling capacitor used in older designs. When the output is at 0 V both MOSFETs, Q1 and Q2, are held slightly on, so that a quiescent current flows directly from the positive to the negative supply, and the output sits at a voltage halfway between the two supply voltages i.e: 0 V.

In order to increase the output voltage in either the positive or negative direction, the appropriate MOSFET is turned on by a suitable gate voltage. When one of the MOSFETs, say Q1, is turned fully on, the output voltage approaches that of the positive supply. In this condition the voltage across Q2 approaches that of the total supply voltage, almost double the voltage present across each MOSFET when the out-

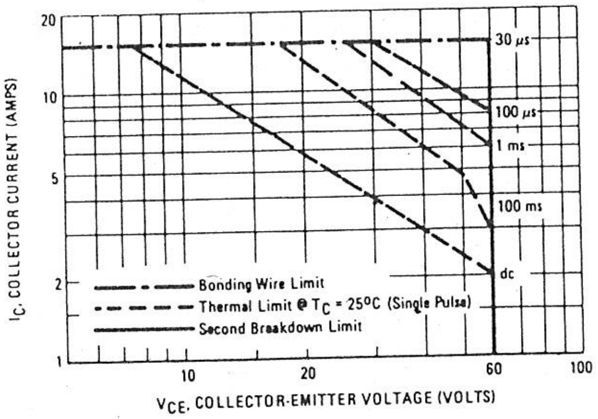


Figure 3. SOAR curves for the 2N3055.

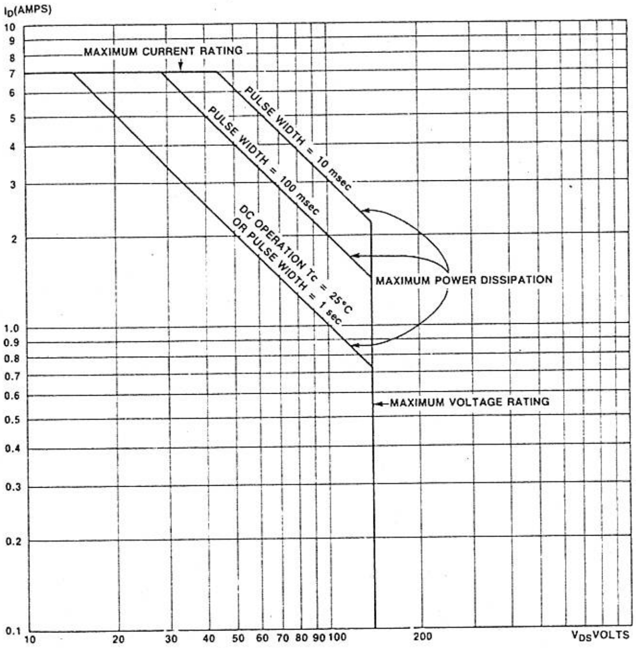


Figure 4. SOAR curves for the Hitachi MOSFETs.

put is at 0 V.

If a +/− 50 V supply is used for example, the voltage across Q2 will approach 100 V. Of course, some of the total supply voltage will be dropped across the two source resistors and the finite on-resistance of the MOSFETs themselves. In fact, the relatively high on-resistance of MOSFETs will cause a substantial voltage drop and this must be taken into account.

Another factor that must be taken into account when designing a power amplifier output stage is the likelihood that the power amplifier will at some stage be connected to a reactive load. Take for example the case of a load with a large capacitive component in series with 4 ohms of resistance. During the positive half cycle of an ac waveform with a peak voltage equal to the supply voltage, this capacitance will become charged to the positive supply voltage. If the capacitance is large enough this voltage could still be present during the subsequent negative half cycle. The full supply voltage, double the normal maximum supply voltage that can be applied to the load, is then present across the load so the active MOSFET must supply twice the normal maximum current.

Although this state of affairs exists only momentarily, while the capacitance is discharging, the output stage must be able

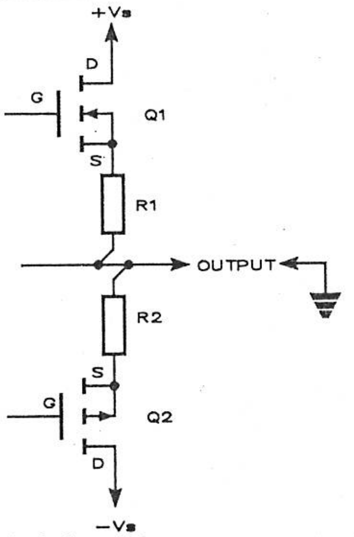


Figure 5. Typical class AB output stage using MOSFETs.

Figure 6. Table giving the voltage-current predictions for the output stage of the module, assuming a supply voltage of 35 V and a load impedance of four ohms.

V source	V load	I load	V MOSFET	2 x V MOSFET
0	0	0	35	70
5	3.85	0.96	29.79	59.6
10	7.69	1.92	24.60	49.2
15	11.54	2.89	19.36	38.8
20	15.38	3.85	14.15	28.3
25	19.23	4.81	8.94	17.9
30	23.08	5.77	3.73	7.46
35	26.92	6.73	0	0

to cope with it. One of the advantages of MOSFETs over bipolar transistors is that they are capable of much larger current pulses as can be seen by looking at the SOAR curves in Figures 3 and 4.

In order to obtain a curve that can be plotted against the SOAR characteristic for a proposed output device a table can be constructed, similar to that shown in Figure 6, from which a set of voltage and current predictions are obtained that represent the operating conditions of the output device.

The table shown in Figure 6 assumes a supply voltage of +/− 35 V and a load impedance of 4 ohms. Column 1 in the table lists various values of an effective source voltage neglecting the effect of the resistance of the MOSFET. Column 2 shows the corresponding voltage that will be supplied to the load after the effects of the MOSFET on-resistance and the source resistors are taken into account. Column 3 shows the corresponding load current while column 4 shows the voltage dropped by the MOSFET. In column 5 the MOSFET voltages are doubled and these voltages, together with their corresponding currents from column 3, are plotted on the SOAR curve of the proposed output device; see Figure 7.

Although the resulting curve crosses the dc power dissipation limit it is well within the 100 mS limit and is also well within both the maximum current and maximum voltage ratings of the device. A single pair of these MOSFETs is therefore suitable for use with this supply voltage and the power amplifier should be capable of delivering in excess of 60 watts into an 8 ohm load and in excess 100 watts into a 4 ohm load.

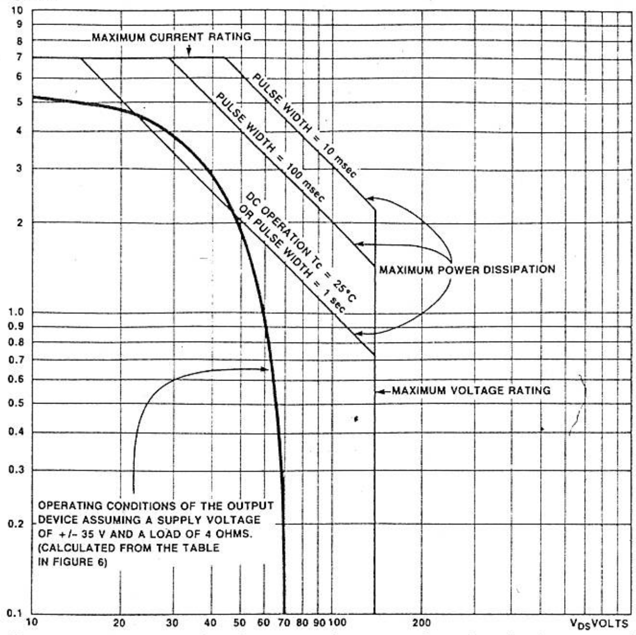


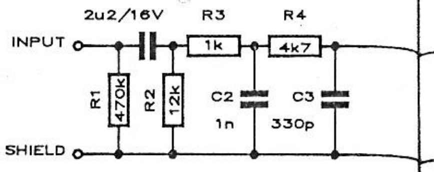
Figure 7. Curves of safe operating area for the devices used with a curve of operating conditions superimposed (4 ohm load, 35 V supply rails).

LEVEL

We expect that constructors of an

INTERMEDIATE

level, between beginners and experienced persons, should be able to successfully complete this project.



N.B The shield must be connected at 0V BEFORE applying power. (see text)

Construction

The module can be constructed in one of two versions. The standard version utilises two MOSFETs in the output stage and will deliver around 60 W into an 8 ohm load. Both of these devices mount *through* a heatsink bracket to the pc board.

If the module is required to deliver more power than this a second pair of MOSFETs can be added which should also be mounted on the heatsink bracket. These devices are wired-in manually using short, heavy-gauge wires which are soldered to the copper side of the pc board. It is important that these wires be kept as short as possible to prevent any possibility of RF instability. Remember that power MOSFETs are inherently large bandwidth devices and this characteristic, coupled with their extremely high input impedance, invariably leads to RF instability problems if the correct measures are not taken to prevent it.

The wiring system shown in the accompanying construction diagrams completely eliminates this problem and should be adhered to closely. We built prototypes in both single and dual MOSFET-pair configurations and subjected these to rigorous stability testing, such as operating the modules into very difficult loads and with 'difficult' input signals. All of the units performed flawlessly. A complete specification showing the performance of the prototype units has been in-

AEM 6500 CIRCUIT OPERATION

This power module shares its principles of operation with my earlier Series 5000 design and has an identical differential pair input and voltage amplifier stage. The voltage amplifier is a full differential design providing lower distortion and greater open-loop gain than would be obtained from a more conventional design. The larger open-loop gain provided compensates for the slightly higher distortion caused by the MOSFET output stage compared to bipolar, by enabling a larger amount of overall negative feedback.

The design is free of slew-induced distortions by ensuring that the speed of the amplifier is determined entirely by an input filter. This is a two-pole filter with a cut-off frequency of nominally 150 kHz. The square wave performance of the amplifier exhibits a near perfect bandwidth-limited response which is free of any overshoot or ringing and observations made of the negative feedback loop verify that the feedback loop is sufficiently fast to provide freedom from feedback loop saturation.

The input filter is formed from resistors R3-R4 and capacitors C2-C3. C1 is an input decoupling capacitor while R2 provides a 0 V connection to the base of Q1. Resistor R1 simply provides an earth reference for the positive side of C1.

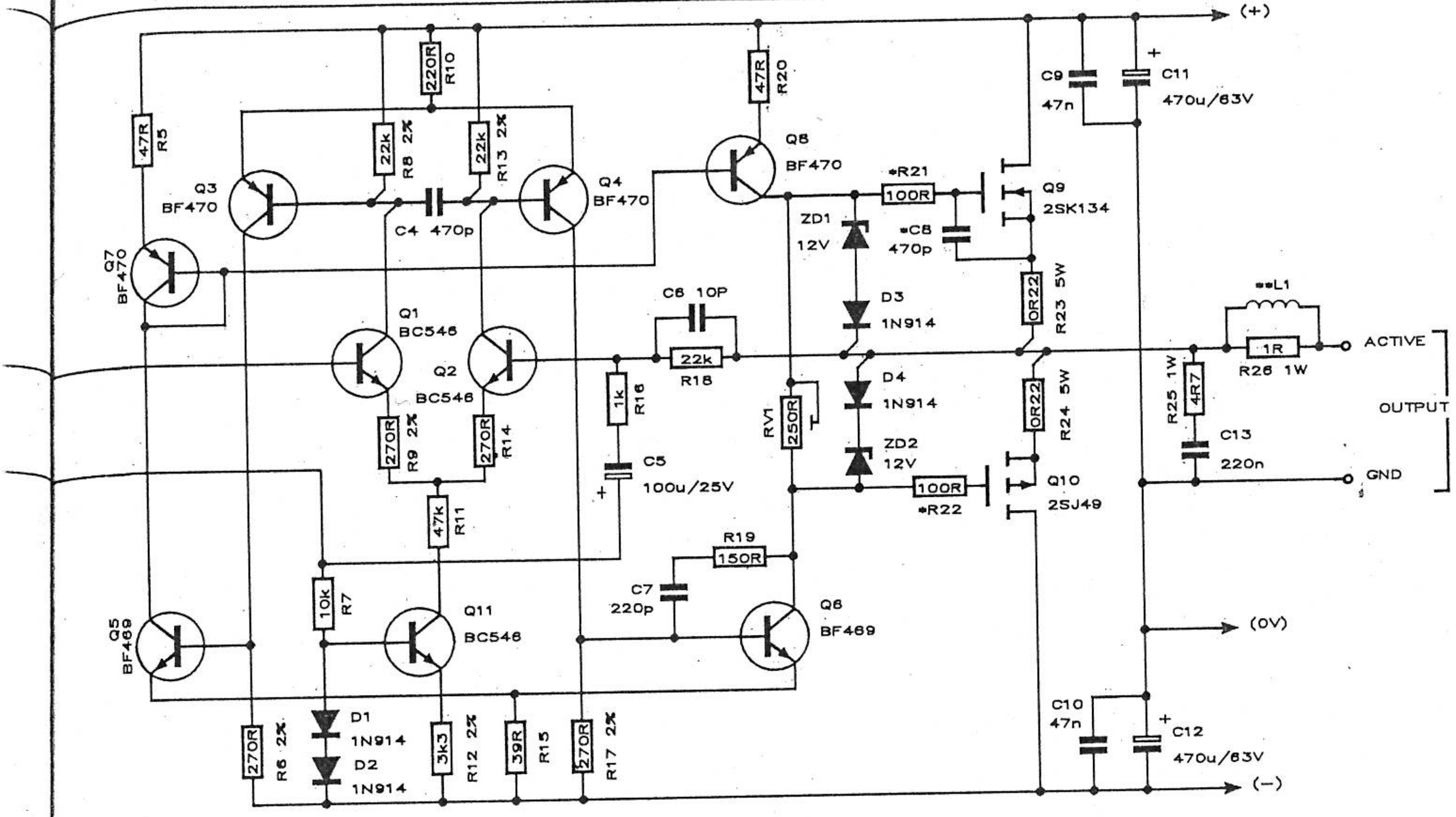
Input signals are coupled via this filter to the differential pair formed by transistors Q1 and Q2, their associated emitter resistors R9 and R14, and a constant current source formed by Q11 and its voltage reference D1, D2 and R7. This is a conventional constant current source (actually a constant current sink) set to a current of approximately 200 uA. This ensures that the input differential pair operates in a low noise region of the device characteristics.

Most of the voltage gain in the design is provided by the differential voltage amplifier discussed above which consists of Q3 to Q8. This is a two-stage amplifier with a current mirror load on the second stage formed by Q7 and Q8.

The output stage provides all of the current gain and is formed with the two power MOSFETS Q9 and Q10. The diode/zener diode string ZD1, ZD2, D3 and D4 ensure that the gate voltage applied to the MOSFETS never exceeds 12.6 V which might otherwise cause damage to them. The gate resistors R21 and R22, and capacitor C8, help to ensure stability of the output stage, as do the source resistors R23 and R24. The passive output filter formed by L1, R26, R25 and C13 ensures stability when the amplifier is connected to a variety of inductive loads. R25 and C13 provide a load to the power amplifier at high frequencies so it is imperative that C13 be a non-inductive type of capacitor. Similarly, try to avoid using inductive resistors, particularly in the case of R25.

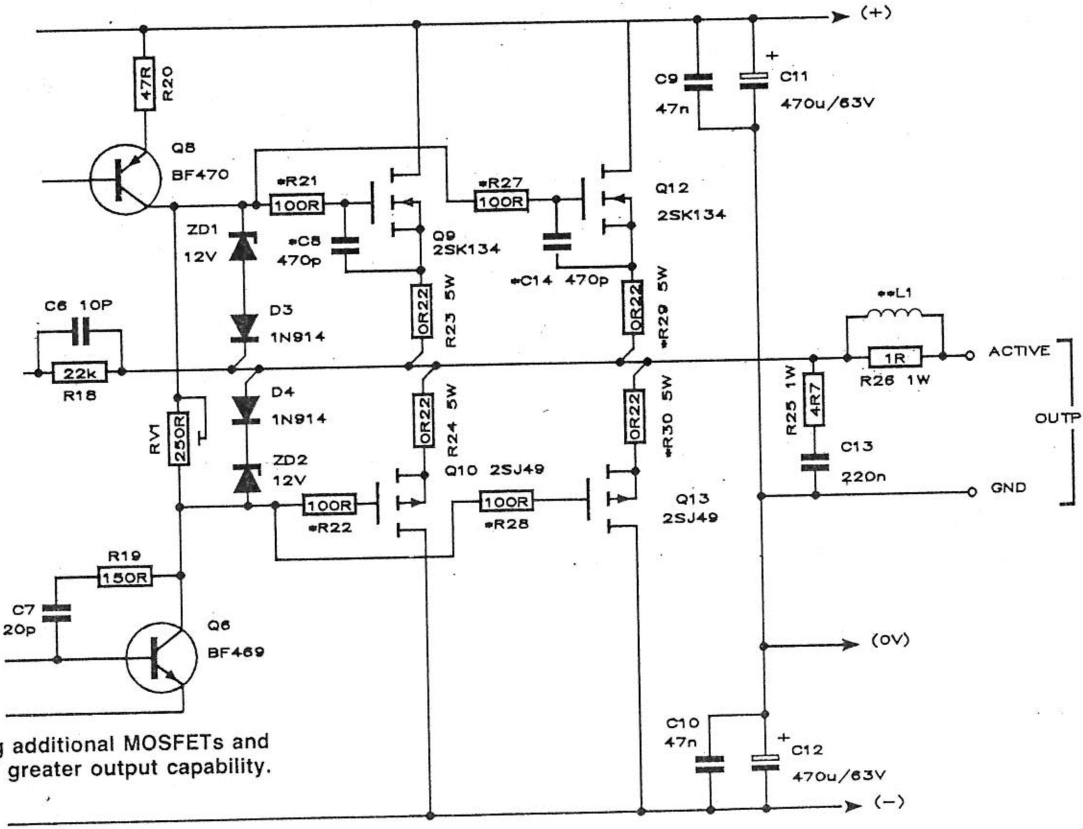
The filter capacitors C9, C10, C11 and C12 act as a final stage of supply filtering and help to ensure stability at high frequencies, by providing a short to 0 V close to the output stage, for any RF that might otherwise be present on the supply lines.

The present potentiometer, RV1, permits adjustment of the voltage difference between resistors R21 and R22, and therefore between the gates of the MOSFETS. No thermal sensing transistor is used to correct for temperature variations in the quiescent current, standard practice with bipolar output stages, because of the thermal characteristics of the power MOSFETS.



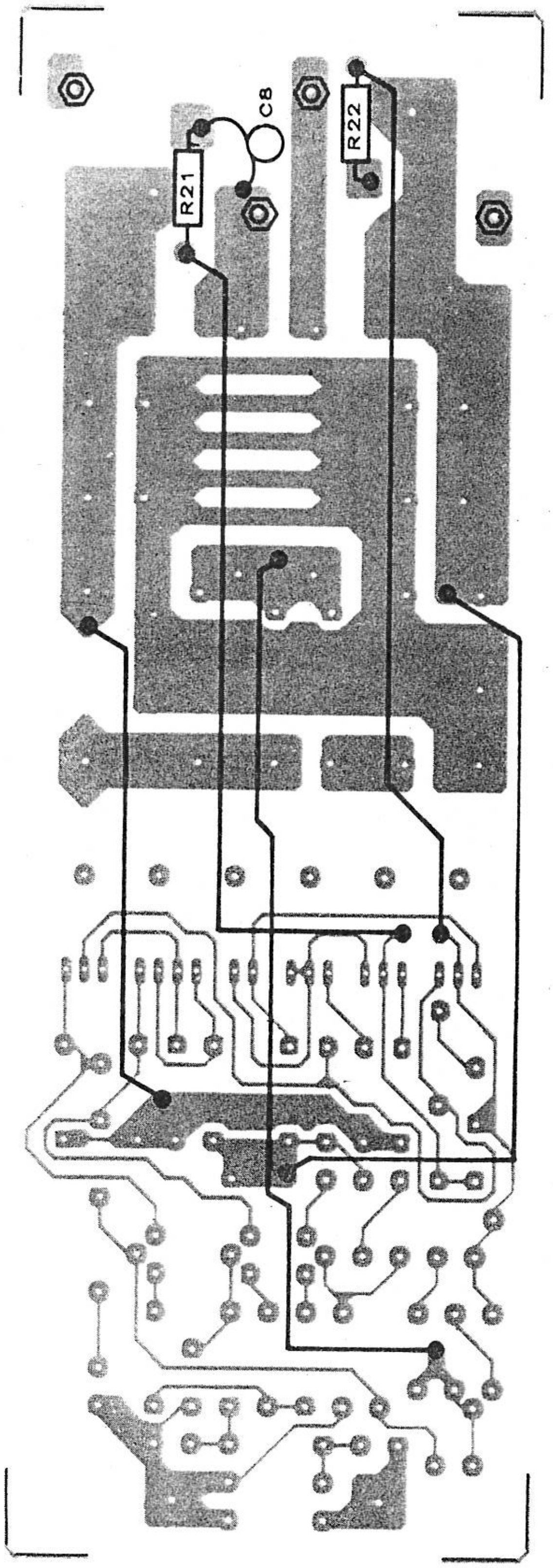
* Mounted on rear of pc board

** L1 consists of 0.8mm enamel wire (two layers of 10 over a 14mm plastic former — see text)

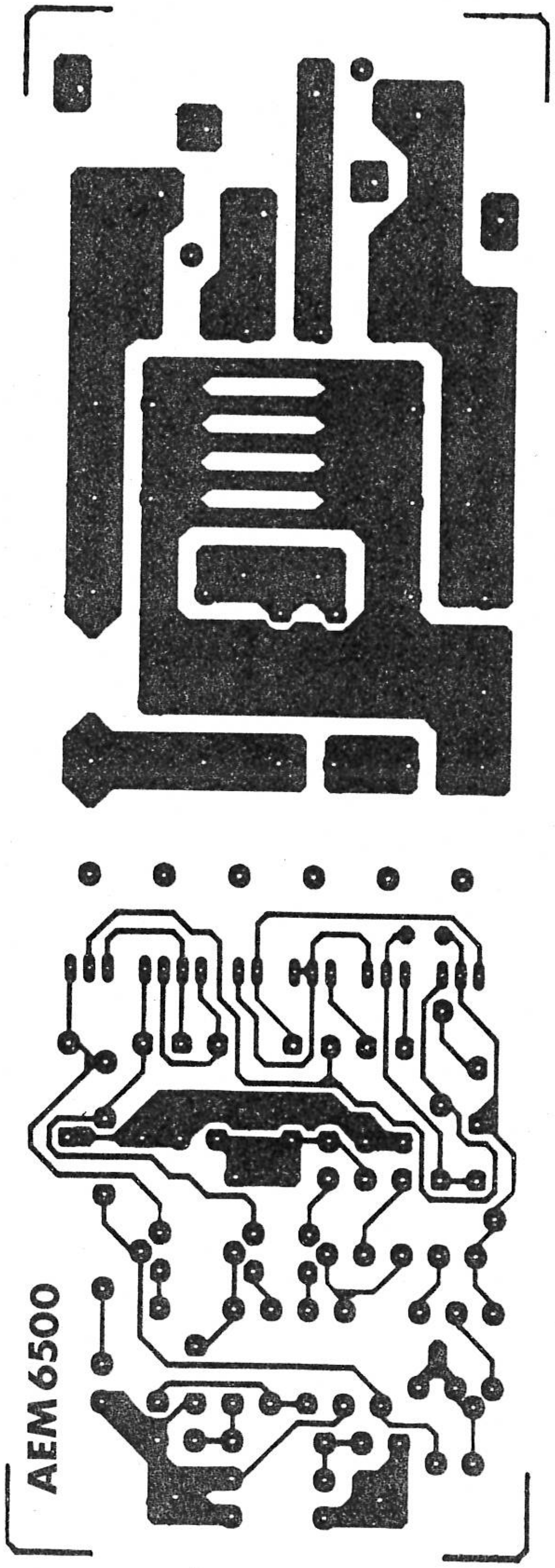


Circuitry showing additional MOSFETs and componentry for greater output capability.

COMPONENT OVERLAY SHOWN FROM THE COPPER SIDE FOR A SINGLE OUTPUT PAIR



The links required on the copper side of the board.



Printed circuit artwork, full size.

cluded elsewhere in this article.

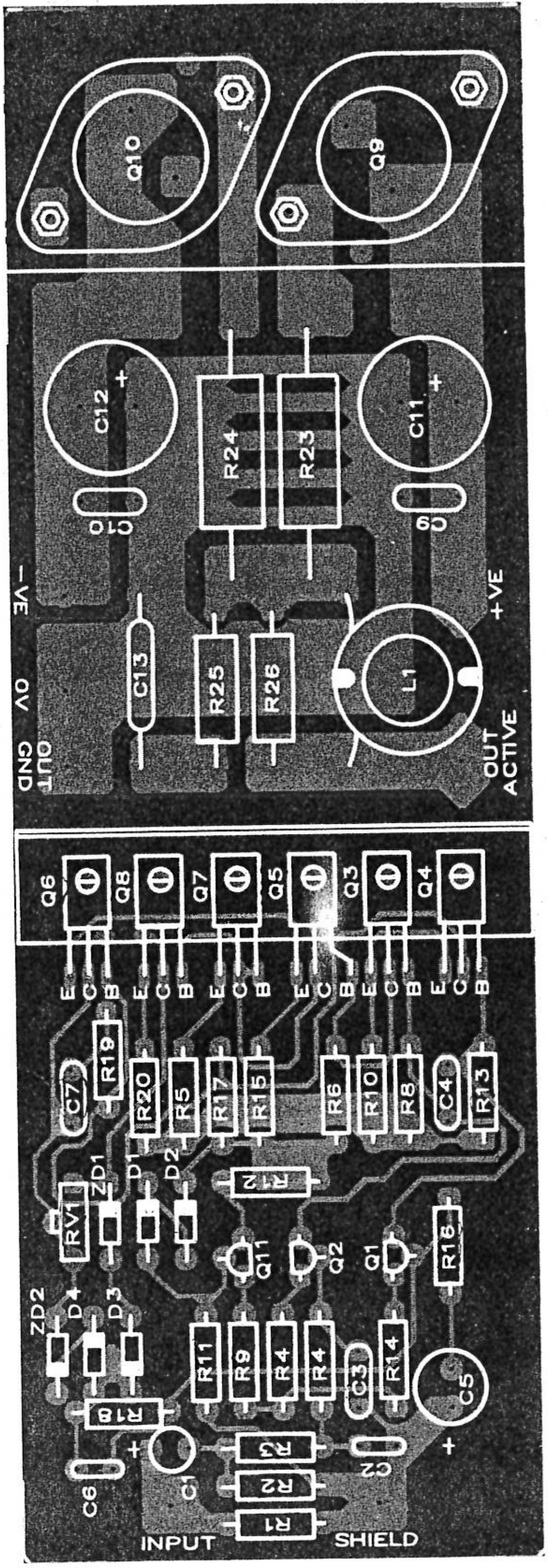
A few components apart from the links, are fitted to the rear of the pc board. This enabled resistors R21 and R22, which are associated with the gates of the MOSFETs, to be located as close as possible to the MOSFETs themselves. Similarly, C8, a 470 pF capacitor, is mounted on the rear of the pc board as close to the gate of the 2SK134 MOSFET as possible.

The connections between the bulk of the electronics and the output stage are made by links on the rear side of the pc board. These run a fairly long distance and should be made using insulated wire. Normal grade ("10 x 0.2 mm") insulated hookup wire will suffice. These links and components should be left to the last stage of construction to ensure they do not hinder the soldering of the majority of components.

Start the construction, as usual, by mounting resistors and non-polar capacitors. The diodes, zener diodes and transistors, followed by the smaller polarised capacitors, can then be soldered in place.

The bipolar transistors, Q3-Q8, are all mounted on a common heatsink fabricated from a piece of aluminium extrusion. A 71 mm length of 25 mm x 15 mm aluminium (1.6 mm thick) should be used and all of these transistors should be insulated from this heatsink. The best way to mount these devices is to start by bending the leads of each device and, after using a light smear of thermal paste between the faces of the transistors and their insulating washers and between the insulating washers and the heatsink, the transistors can be bolted to the heatsink and pc board. Once all of the transistors have been bolted in place the leads can be soldered.

The remainder of the passive components can now be soldered in place. The inductor L1 is made by winding 20 turns of 0.8 mm (20 swg) enamel-covered copper wire over a cir-



Component overlay for the board.

Expected cost;
$48-$55 (60 W version)
$60-$68 (100+ W version)

aem6500 PARTS LIST

Semiconductors

Q1,2	BC546
Q3,4	BF470
Q5,6	BF469
Q7,8	BF470
Q9	2SK134
Q10	2SJ49
Q11	BC546
D1,2,3,4	1N914
ZD1,2	12 V/400 mW zener

Resistors

all 1/4 W, 5% unless noted otherwise.

R1	470k
R2	12k
R3	1k
R4	4k7
R5	47R
R6	270R, 1%
R7	10k
R8	22k, 1%
R9	270R, 1%
R10	220R
R11	47k
R12	3k3, 1%
R13	22k, 1%
R14	270R
R15	39R
R16	1k
R17	270R
R18	22k
R19	150R
R20	47R
R21,22	100R
R23,24	OR22, 5 W *
R25	4R7, 1 W
R26	1R, 1 W
Rv1	250R vert. mount trimport

* Low-inductance type preferred, carbon or wirewound (see text).

Capacitors

C1	2u2/16 V RB electro.
C2	in greencap
C3	330p NPO ceramic
C4	480p NPO ceramic
C5	100u/25 V RB electro.
C6	10p NPO ceramic
C7	220p NPO ceramic
C8	470p NPO ceramic
C9,10	47n/63 V *
C11,12	470u/63 V RB electro.
C13	220n/63 V *

* Must be low-inductance metallised polyester type, e.g: Elna greencap, Wima MKT, etc.

Miscellaneous

1 x aem6500 pc board; 10 sets bolts/nuts/washers; 10 x insulated transistor mounting bushes; 6 x TO126 insulating washers; 2 x TO3 insulating washers; 1 x aluminium' L-bracket 15x25x1.6 mm, 71 mm long; 1 x aluminium L-bracket 40x40x3.2 mm, 71 mm long; about 1 m hookup wire, about 200 mm of 3 mm spaghetti, etc.

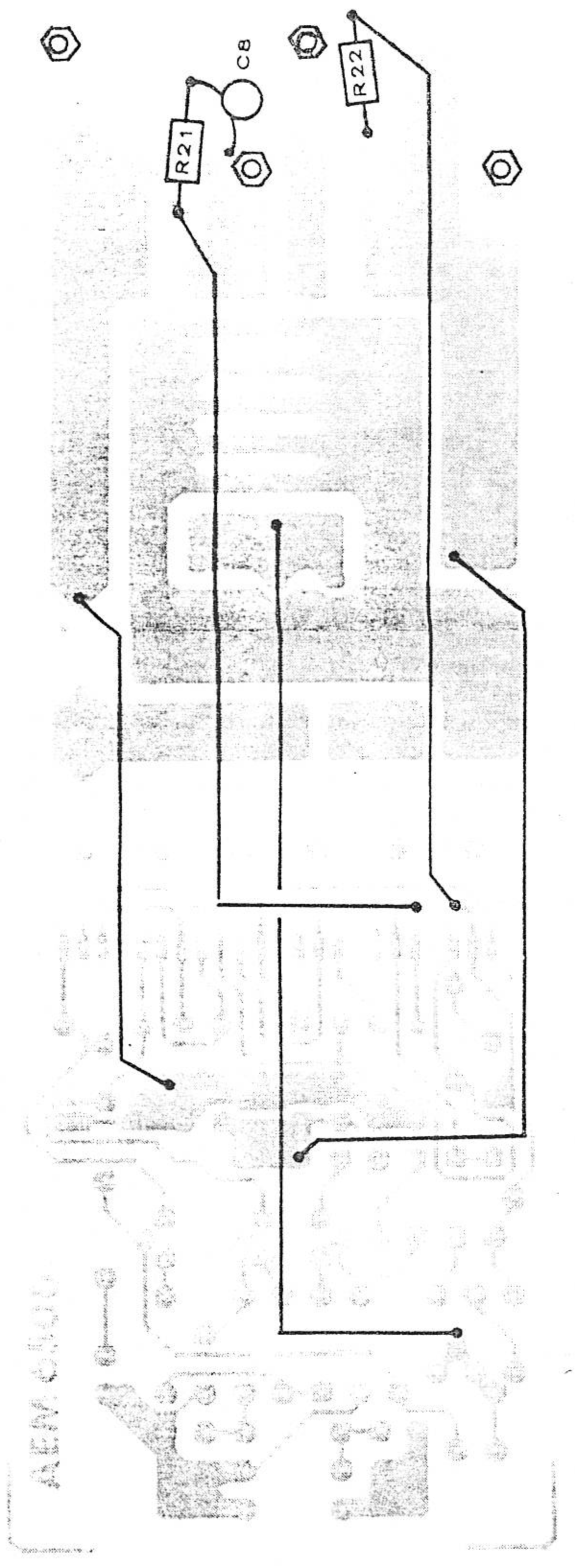
Extra parts for higher power version

Q12	2SK134
Q13	2SJ49
R27,28	100R
R29,30	OR22, 5 W
C14	470p

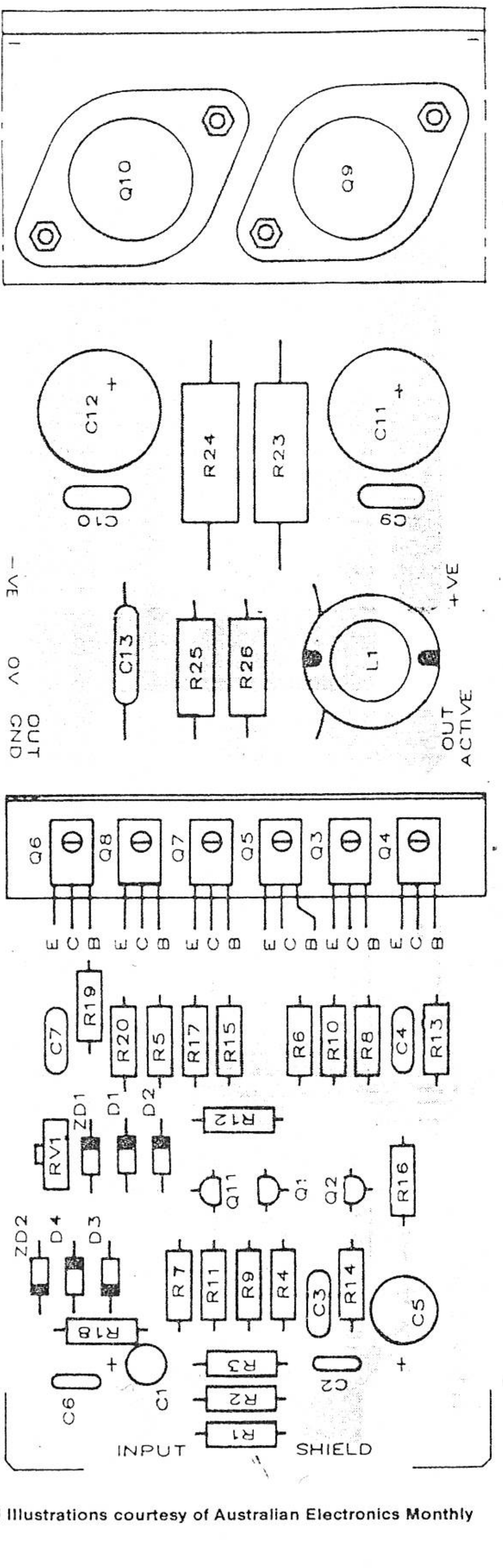
150 mm length of 40x40x3.2 mm aluminium L-bracket; two sets of TO3 insulators and mounting bushes; four sets of 6 BA bolts/nuts/washers and two solder lugs.

COMPONENT LOCATION

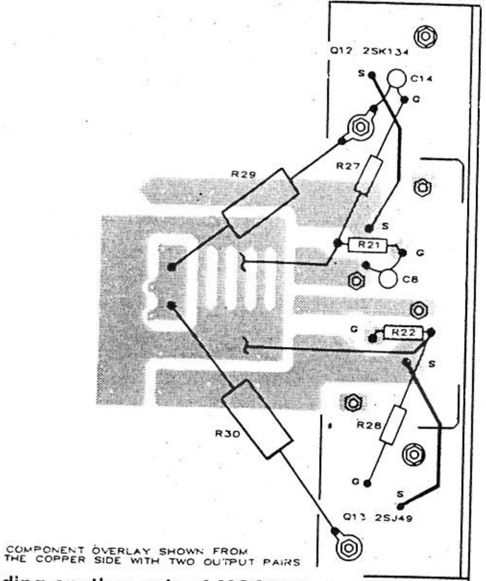
COMPONENT OVERLAY SHOWN FROM THE COPPER SIDE FOR A SINGLE OUTPUT PAIR



The links required on the copper side of the board.



Text and Illustrations courtesy of Australian Electronics Monthly

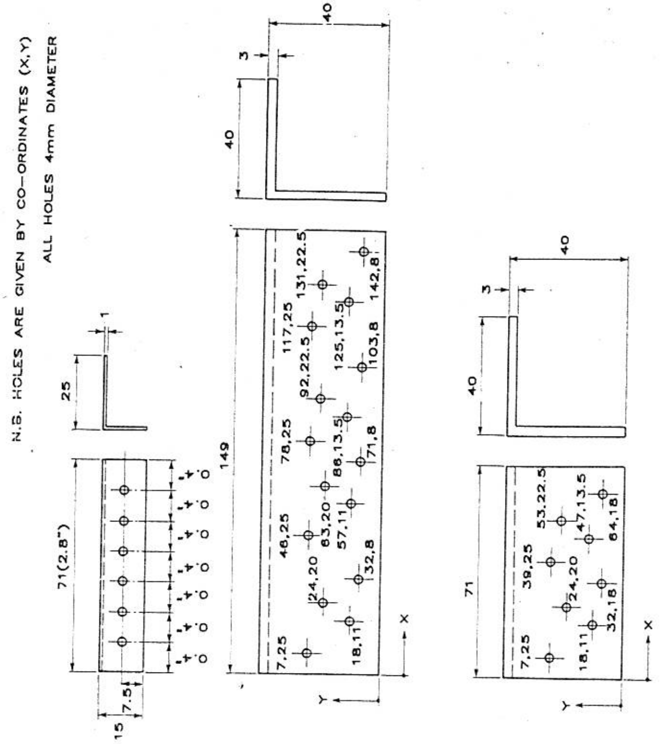


Adding another pair of MOSFETs for additional power capability. This shows details of the longer bracket required and how the additional components are wired in.

cular former of approximately 14 mm diameter. A plastic bobbin from a suitable-sized pot core can be used. In the prototype, the bobbin from a P26/16 pot core was used on which two layers of ten turns were wound.

The main output pair is mounted on a 71 mm length of 40 x 40 mm (5 mm thick) aluminium extrusion used to conduct the heat generated by the output devices to the main heatsink. The source connection to each MOSFET is made via the case of the devices so these must be insulated from the extrusion. Use metal screws to mount these devices but insulate these screws from the extrusion using short lengths of plastic spaghetti. These screws make the source connections from the case of each device through to the copper side of the pc board.

Details of the aluminium brackets for mounting the driver stage and output devices. The larger bracket in the middle is only required if you are using four output MOSFETs.



As usual, apply a thin smear of thermal paste between all surfaces that must conduct heat. i.e: between the MOSFETs and their insulators, between the insulators and the extrusion and between the extrusion and the main heatsink.

Once the MOSFETs have been bolted in place solder their pins. Finally, using a multimeter check that the MOSFETs and all of the bipolar transistors are insulated from their respective heatsinks. In the case of the two MOSFETs, check for conductivity between the cases of each device and the heatsink extrusion, while for the bipolar transistors check for conductivity between the centre leads of each device and their heatsink. If all is well and non-conductivity is detected, even on the largest resistance range, solder the final components and links to the rear of the pc board as discussed earlier.

The wiper of the preset potentiometer, RV1, should be adjusted so that it is wound fully counter-clockwise. i.e: adjust it so that the wiper is at the end of the preset *closest* to the MOSFETs. In this way the quiescent current of the output stage is set a minimum.

Setting up procedure

The setting up procedure is straightforward, with only the preset RV1 to be adjusted. Made a final check that all components are in their correct positions, ensuring that the orientation of all polarised components are correct.

The pc board does not provide a 0 V connection to the earth. This connection is best made *at the input terminals.* A circuit showing the best connection of a pair of power amplifier modules to the power supply and to the input and output terminals has been included here. This scheme will ensure fredom from hum loops and compatibility with the largest number of preamplifiers.

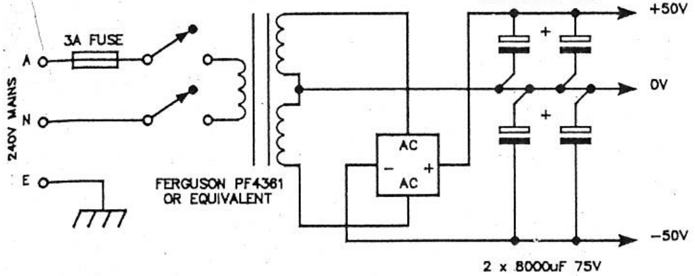
For the purposes of the setting up procedure, solder a separate wire from the input earth to the 0 V of the power supply. Connect the main 0 V point on the power amplifier module to the power supply. Also for the purposes of setting up, connect the positive and negative lines from the power supply to the power amplifier via 10 ohm 0.5 W resistors so that the resistors are connected in series with each supply line. Connect a multimeter, set to read voltage, across the output terminals.

When all of these connections have been made the module can be powered up. The voltage read on the multimeter should be close to 0 V. If this is not the case, or either of the resistors fitted to the supply lines exhibit signs of excessive power dissipation (i.e. they get hot, char or burst into flames), turn the module off *immediately* to prevent any further damage to components.

If the output voltage is close to 0 V check the actual voltage by increasing the multimeter sensitivity as required. This voltage should be within 20 or 30 mV of zero. If this is correct, set the multimeter to measure 1 V and connect it across the 10 ohm resistor placed in the positive supply line. Adjust the quiescent control preset so that the voltage measured across the resistor is 1 V. This will ensure that the quiescent current is set to 100 mA. At this current the output devices begin to operate with a negative temperature coefficient which ensures a stable operating point.

Output power/power supply requirements

As can be seen from the table in Figure 6 a supply voltage of 35 V will cause a minimum peak voltage of just of 6.7 A



Circuit of a suggested power supply. Note that the bridge rectifier should be able to handle the in-rush current of the supply capacitors. A PB25 would do for a single module, a PB40 for two.

when the amplifier is connected to a 4 ohm loud. Since the maximum current rating of the MOSFETs is 7 A this voltage should not be exceeded if operation with 4 ohm loadspeakers is anticipated. If the modules are to be used in a power amplifier intended for general hi-fi applications a supply voltage of around 35 V at full load should probably be considered the maximum recommended voltage, leading to a maximum output power of around 60 W to 70 W.

In certain applications however, such as when the module is permanently connected to a driver with known impedance characteristics, this voltage rating, and hence the output power, can be increased. If a driver were used, for example, with a minimum impedance of 8 ohms the supply could be increased to around 50 V, with a consequent increase in output power to around 100 W.

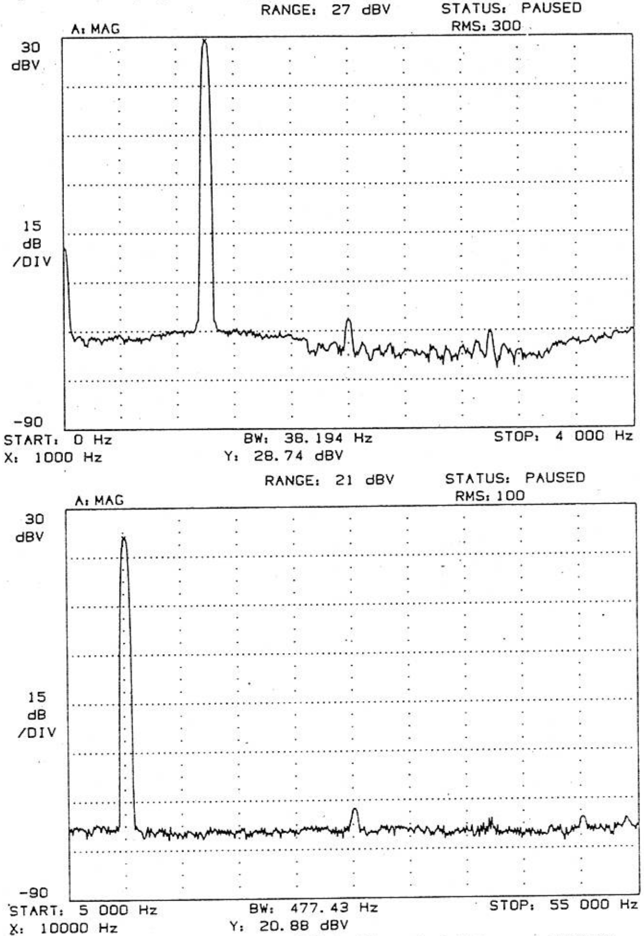
In general hi-fi applications the output power can be increased to over 100 W by the addition of a second pair of MOSFETs. Under these conditions the module will produce in excess of 170 W into a 4 ohm load.

Most loudspeakers have impedance characteristics that vary as a function of frequency. A loudspeaker with a nominal impedance rating of 8 ohms, for example, usually has a dc resistance of between six and seven ohms and the impedance will actually decrease to this value over a certain frequency range.

If a general purpose hi-fi amplifier is required with an output power of aound 100 W, then two pairs of output devices should be used. Construction details showing the longer heatsink bracket and mounting of the additional components have been included too.

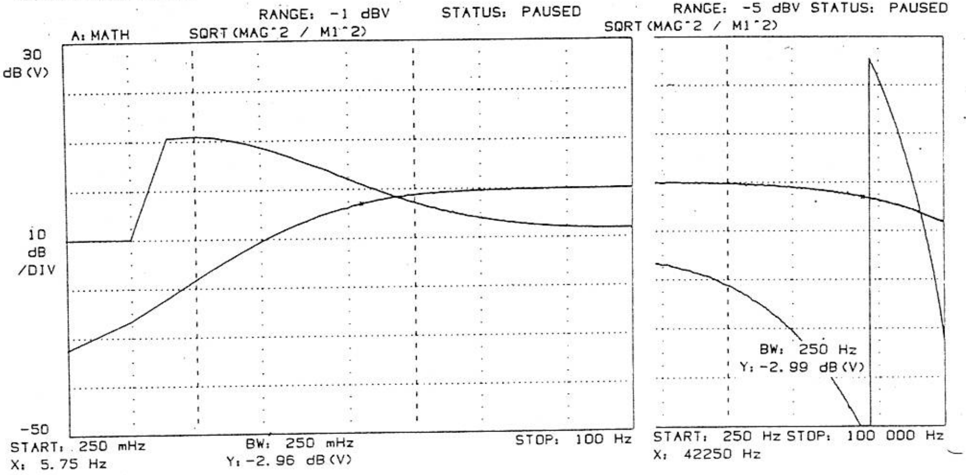
Performance

The measured performance of the prototype module, shown in the spectral analysis charts and the table, shows just how good a performance it achieves. Just as important, however, the subjective performance has proved to be *impeccable.* A vital factor affecting the performance of any amplifier is the accompanying power supply which should be a low impedance, maximum capacity design to ensure good regulation. This is particularly important for a supply that will be shared by two modules, although this design, using differential pairs throughout its voltage amplifier stage, has a particularly good supply rejection characteristic.



ABOVE, Upper curve: — Distortion at 1 kHz and 100 W output; Lower curve: — Distortion at 10 kHz and 80 W output, showing freedom from slew-induced distortions.

BELOW: Frequency and phase response of the amplifier. The right hand portion shows the upper frequency section. Bandwidth is 5.75 Hz to 42.25 kHz at -3 dB. Phase response is quite smooth and varies less than 90 degrees within the bandwidth limits.



SPECIFICATIONS

Power output
Depends on power supply and configuration; max. — 100 W RMS into 8 ohm load.

Frequency response
Flat within +/- 0.4 dB from 8 Hz to 20 kHz.

Input sensitivity
1.2V rms for 100 W out

Noise
-100 dB below full output.

Harmonic distortion
See spectrum analyser graphs.

Intermodulation distortion
(0.003% at 100 W) (50 Hz & 7 kHz mixed 4:1).

Stability
Unconditionally stable