General purpose 150 W MOSFET power amp module

Here's a high power, general purpose power amplifier module for guitar and PA applications employing rugged, reliable MOSFETs in the output.

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Geoff Nicholls

SINCE publishing the ETI-477 MOSFET amp in the January, February and March 1981 issues, we have received a continued demand for a general-purpose MOSFET power amp module suitable for guitar or PA applications. The ETI-477 can of course be used but is unnecessarily complex for this purpose. To fill this demand we have developed the ETI-499 module. It produces similar power levels to the ETI-477 (i.e: around 100 W RMS into an 8 ohm load or around 150 W into a 4 ohm load when used with the Ferguson PF4361/1 transformer), but has been designed with constructional simplicity as the foremost consideration. The power supply circuitry is included on the pc board so that the only connections to the board are from the power transformer, input sockets and output terminals. This greatly simplifies construction and installation and ensures that all power supply wiring is done with the necessary high current handling capability. In all transistor amplifiers, but especially with MOSFETs, the resistance between the main filter capacitors and the output devices must be kept as low as possible if low distortion and stability are to be ensured.

SPECIFICATIONS — ETI-499

Power output
150 W RMS into 4 ohms
100 W RMS into 8 ohms
(at onset of clipping)

Frequency response
20 Hz to 20 kHz, +0 −0.5 dB
10 Hz to 60 kHz, +0 −3 dB
(measured at 1 W and 100 W levels)

Input sensitivity
1 V RMS for full output

Hum
−98 dB below full output

Noise
−114 dB below full output

Total Harmonic Distortion
0.006% at 1 kHz
0.03% at 10 kHz
(measured at 12 W level)

Stability
Unconditional — tested to full output driving 3.5 uF short circuit at 10 kHz.

The circuit used in the ETI-499 is a development from one published in the Hitachi application notes for these MOSFETs. The original circuit used very high-gain bipolar driver transistors developed especially by Hitachi for use as MOSFET drivers. Unfortunately these devices are at present unavailable in Australia. Since these are an extremely fast device, replacement by more common bipolars limits the open loop bandwidth and causes the amplifier to be unstable. The main departures from the Hitachi circuit are therefore to ensure a stable design with common transistors.

We used the BF469 and BF470 as drivers. These are a complementary video output pair supplying good slew rate and V_{ceo} figures at a reasonable price. The resulting power amp module is fast and stable, with distortion figures completely adequate even for many high fidelity applications. The module is easy to construct and capable of withstanding continued clipping or full-power operation for extended periods when provided with a suitable heatsink.

Why MOSFETs?

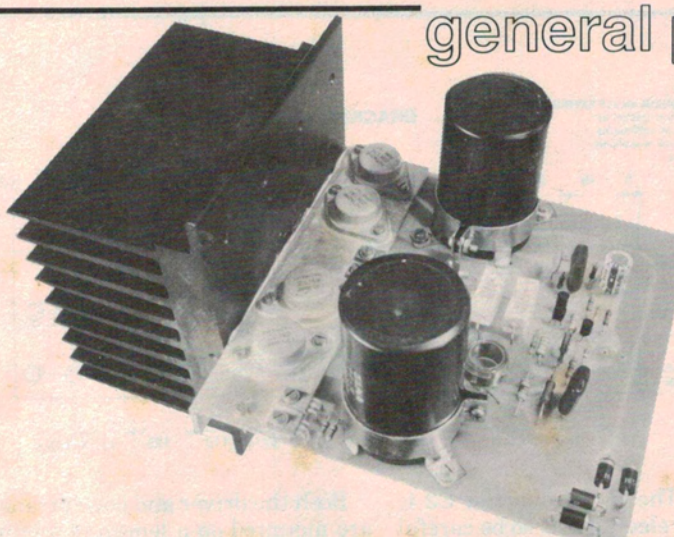
The power MOSFET is a relatively recent development and offers several distinct advantages over the more common bipolar transistor. To understand these differences it is helpful to look at some of the characteristics of bipolar output transistors.

Most power amplifiers employ bipolar transistors in a common-collector or emitter-follower configuration. The relationship between the output signal voltage and the input signal voltage is a function of the load impedance and the forward transfer admittance of the particular device. Forward transfer admittance is commonly given the symbol y_{fs} and its non-linear characteristic gives rise to distortion in the output stage. With bipolar transistors, the greatest non-linearity occurs for low input voltages, typically between 0 V and 0.6 V. Once outside this voltage range the forward transfer admittance is high and quite linear. So most of the distortion generated in a bipolar output stage occurs at low signal voltages and is called *crossover distortion* (for a more detailed explanation of crossover distortion refer to the article on the ETI-477 power amp module published in January 1981).

The most common method used to overcome this problem is to make use of bias current. A fixed voltage of around 0.6 V is applied to the bases of the output transistors so that the applied signal voltage does not have to operate the transistor over the most non-linear region. However, a problem arises with this technique because this voltage must be controlled extremely accurately. Even 0.5 V in excess of the correct voltage will saturate the output devices, probably destroying them. Furthermore, as the output devices heat up due to normal operation, the bias voltage must be decreased to maintain the same operating conditions. This is very difficult to do accurately enough, so the power amp is often running either with insufficient bias current or is dangerously close to destruction.

The problem occurs because the bipolar transistor has a positive temperature coefficient. This means that as the

general purpose mosfet amp



temperature of the device is increased the collector-emitter current will increase if the base-emitter voltage is held constant. The increased current causes further heating and a further increase in current. This condition is called *thermal runaway* and results in the destruction of the output device.

Another problem with conventional bipolar output transistors is speed. The techniques used in the construction of these devices to ensure broad SOAR characteristics (SOAR stands for Safe Operating ARea) usually conflict with those to ensure high speed. Since the output transistors must handle the largest currents they are usually the slowest devices in the amplifier and determine the maximum signal slope that can be handled by the amplifier before distortion results. Distortion generated by this mechanism is called *slew-induced distortion* and *transient intermodulation distortion*. Once unnecessarily high signal slopes have been removed by a suitable filter at the input of the power amp the only solution is to increase the slew rate of the output devices.

One of the major advantages of power MOSFETs is their extremely high speed. When driven correctly the MOSFETs used in this project can switch a current of around 2 A in 30 nanoseconds! This is roughly *100 times* the speed of commonly available bipolars. Another advantage of MOSFETs is their very high input impedance. Unlike the bipolar transistor, they are a voltage-controlled device and require only enough drive current to overcome their input capacitance. Probably their most important advantage over bipolar transistors, however, is that *they have a negative temperature coefficient.* Heating causes an increase in the resistance of the device, so MOSFETs are inherently self-protecting. If one part of the device attempts to conduct more current it heats up more than the surrounding region, increasing its resistance, which distributes current over the rest of the device. Similarly if several devices are used in parallel, the negative temperature coefficient will ensure that all devices share current equally. In guitar and PA applications the negative temperature coefficient of MOSFETs provides the amplifier with unprecedented reliability, and the high speed helps to eliminate the problem of slew-induced distortion.

On the other hand a disadvantage with MOSFETs arises from their relatively low forward transconductance when compared to a good bipolar transistor. Although the transconductance of bipolars is highly non-linear when the base emitter voltage is below 0.6 V, it increases dramatically once outside this region. The MOSFET, although not as non-linear for small voltages, never achieves the forward transconductance of the bipolar transistor. The distortion generated by the power MOSFETs is therefore higher than that of bipolar transistors and must be reduced to acceptable limits through the use of negative feedback. This is not a real problem, however, since the high input impedance eliminates at least one stage of a conventional bipolar amplifier design. This allows a simpler circuit with fewer active devices and consequently improved stability margins, allowing greater levels of overall negative feedback before oscillation results.

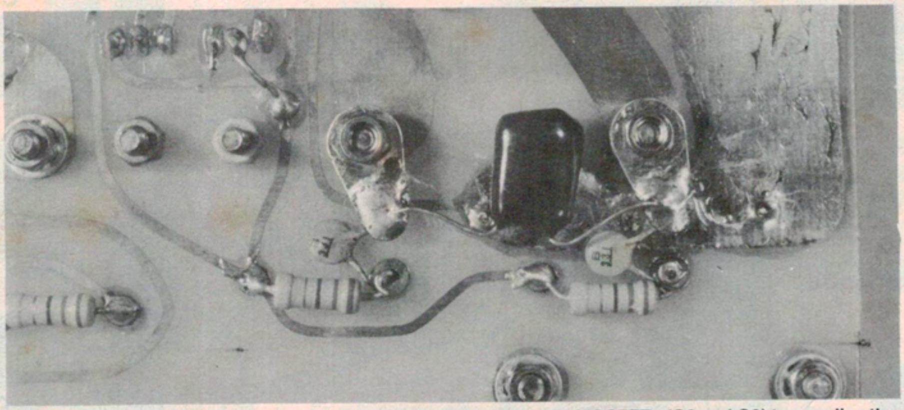
Construction

Construction of the ETI-499 is relatively simple, since all the components mount on the pc board, including the output transistors and power supply components. The design of a good pc board pattern is often as difficult as the design of the original circuit! This is especially true for power amplifiers or any circuit in which both large and small currents are involved. The problem of large currents occurs because of voltage drops across earth return paths, destroying the integrity of earth reference points for small signal currents. To overcome this problem, the pc board must be designed to ensure the ▶

HEATSINKING

The heatsink will need to dissipate around 100 W when the module is run at full output for lengthy periods. A heatsink with a thermal capacity of around 0.65°C/watt is recommended if free-air cooling is contemplated. A 152 mm length of Philips 65D6CB will do nicely (cost — around $30). Alternatively, the module may be mounted on one of the ETI-designed Series 5000 heatsink panels. In fact, two modules may be mounted on a Series 5000 heatsink panel. The panels are available at some suppliers or direct from us (see page 49).

If fan-forced cooling is contemplated, then a heatsink rated at 1.2 to 1.5°C/watt should be used. A 225 mm length of commonly available extruded 'fan' type heatsink will do the job. This type of heatsink is flat on one side, the other side having two sets of fins fanning out from a central channel. A suitable length will set you back about $10. A fan will set you back around $20 to $30, unless you have one lying around.



Compensation capacitors are required for the two 2SK134 output MOSFETs (Q8 and Q9) to equalise the input capacitances between the n-channel and p-channel output devices. They are mounted under the board as shown here. Solder lugs are placed on top of the mounting nuts and held with another nut each. C6 and C7 mount from these to the pads shown, while C7 mounts between them. Note the resistors mounted under the board also.

validity of the earthing arrangement. If at all possible, the pc board published should be used, as departures from this design could seriously affect amplifier performance.

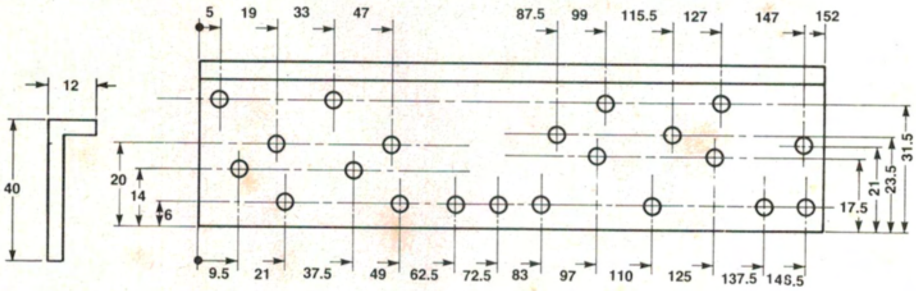
Commence construction by soldering all the resistors onto the circuit board with the exception of the four 0R22 output resistors. These effectively connect all the sources of the MOSFETs together and make it difficult to locate faults in the mounting of the MOSFETs. Solder the 1 W resistors slightly above the circuit board since these can become hot under certain conditions. The components marked with an asterisk on the circuit diagram are mounted on the rear of the pc board. They should be mounted close to the MOSFETs. Do not solder the resistors to the rear of the circuit board at this stage. These are best left until after the MOSFETs have been mounted.

Solder the capacitors onto the circuit board with the exception of those on the rear of the board and the two large electrolytics. The 100u capacitor C3 is the only other electrolytic, so be careful with the orientation of this component. The capacitor is marked to indicate which of its leads are to be connected to a positive or negative voltage. Check the correct orientation on the overlay diagram. This also applies to the diodes and zener diodes used in the circuit, which can be mounted next.

Both the driver and power transistors are mounted on a length of aluminium angle extrusion, which is bolted to the pc board by bolts through the transistor mounting holes. This is shown in the accompanying diagrams. The extrusion is used to conduct the heat generated by the output and driver transistors to the heatsink, which will also be bolted to the extrusion. If you purchase the mod-

ALL 4 mm DIA.
MATERIAL 40 x 12 x 3 ALUMINIUM ANGLE EXTRUSION
Drilling details for the heatsink bracket assembly. All dimensions are in millimetres. Suitable aluminium angle stock is available from Alcan Handyman stores.

BRACKET DRILLING DETAILS



PARTS LIST — ETI-499

Resistors .... all ½ W,5% unless stated
R1,R2 .... 100k
R3,R11 .... 1k
R4,R5,R18-R21 .... 220R
R6,R7 .... 3k9
R8 .... 22k
R9 .... 680R
R10 .... 10k
R12,R15,R16,R17 .... 100R
R13 .... 33k
R14 .... 10k 1 W
R22-R25 .... 0R22 W
R26 .... 4R7 1 W
R27 .... 1R 1 W
RV1 .... 100R preset
RV2 .... 250R preset

Capacitors
C1,C9 .... 220n greencap
C2 .... 2n2 greencap
C3 .... 100u/25 V electrolytic
C4 .... 33p ceramic
C5 .... 6n8 greencap
C6,C8 .... 330p ceramic
C7 .... 47n greencap
C10,C11 .... 100n greencap
C12,C13 .... 8000u/75 V electrolytic

Semiconductors
Q1,Q2,Q3 .... BC546
Q4,Q5 .... BF470
Q6,Q7 .... BF469
Q8,Q9 .... 2SK134 Hitachi MOSFET
Q10,Q11 .... 2SJ49 Hitachi MOSFET
D1-D4 .... 1N914
D5-D8 .... 1N5404
ZD1,ZD2 .... 12 V 400 mW zener

Miscellaneous
ETI-499 pc board; plastic bobbin (from P26/16 potcore or similar); 5 A fuse (speaker fuse, not mounted on pc board); fuse holder; 1 m of 0.8 mm enamel-covered copper wire; 155 mm length of aluminium extrusion, 40 mm x 12 mm, for use as the heatsink bracket; assorted nuts and bolts, hookup wire, etc; two solder lugs.

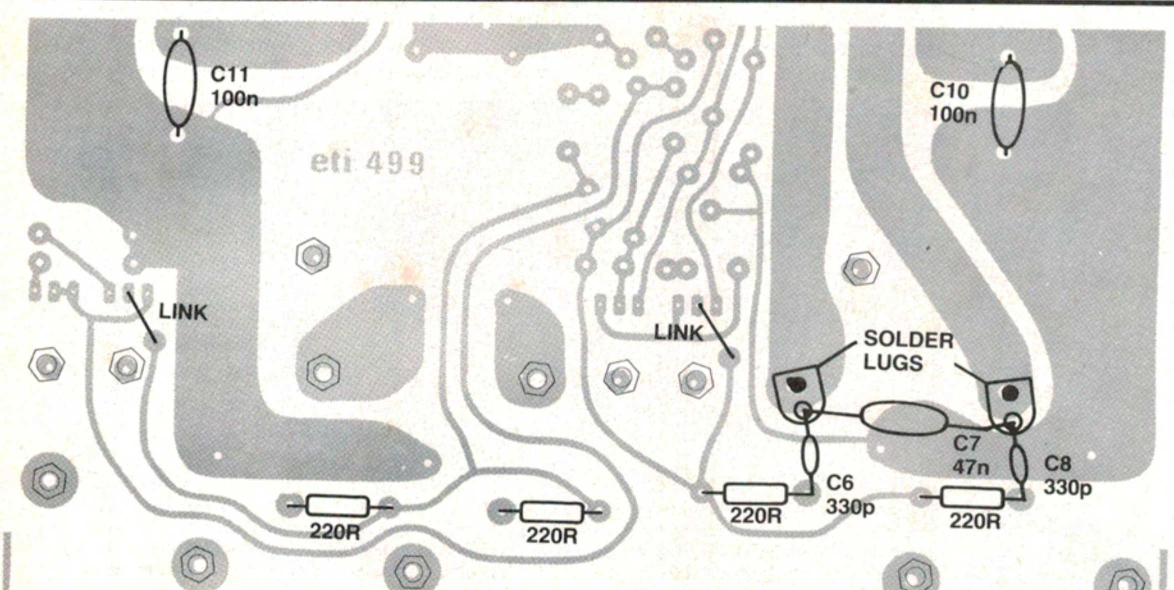
Price estimate

We estimate the cost of purchasing all the components for this project will be in the range:

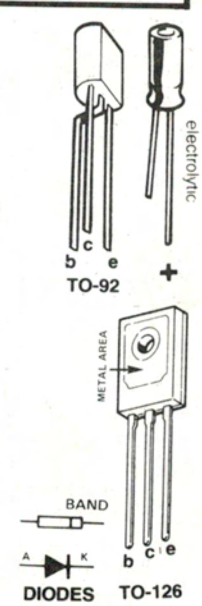
$75-$85

(heatsink & transformer extra)

Note that this is an **estimate** only and **not** a recommended price. A variety of factors may affect the price of a project, such as — quality of components purchased, type of pc board (fibreglass or phenolic base), type of front panel supplied (if used), etc — whether bought as separate components or made up as a kit.



TRACK SIDE OVERLAY DIAGRAM

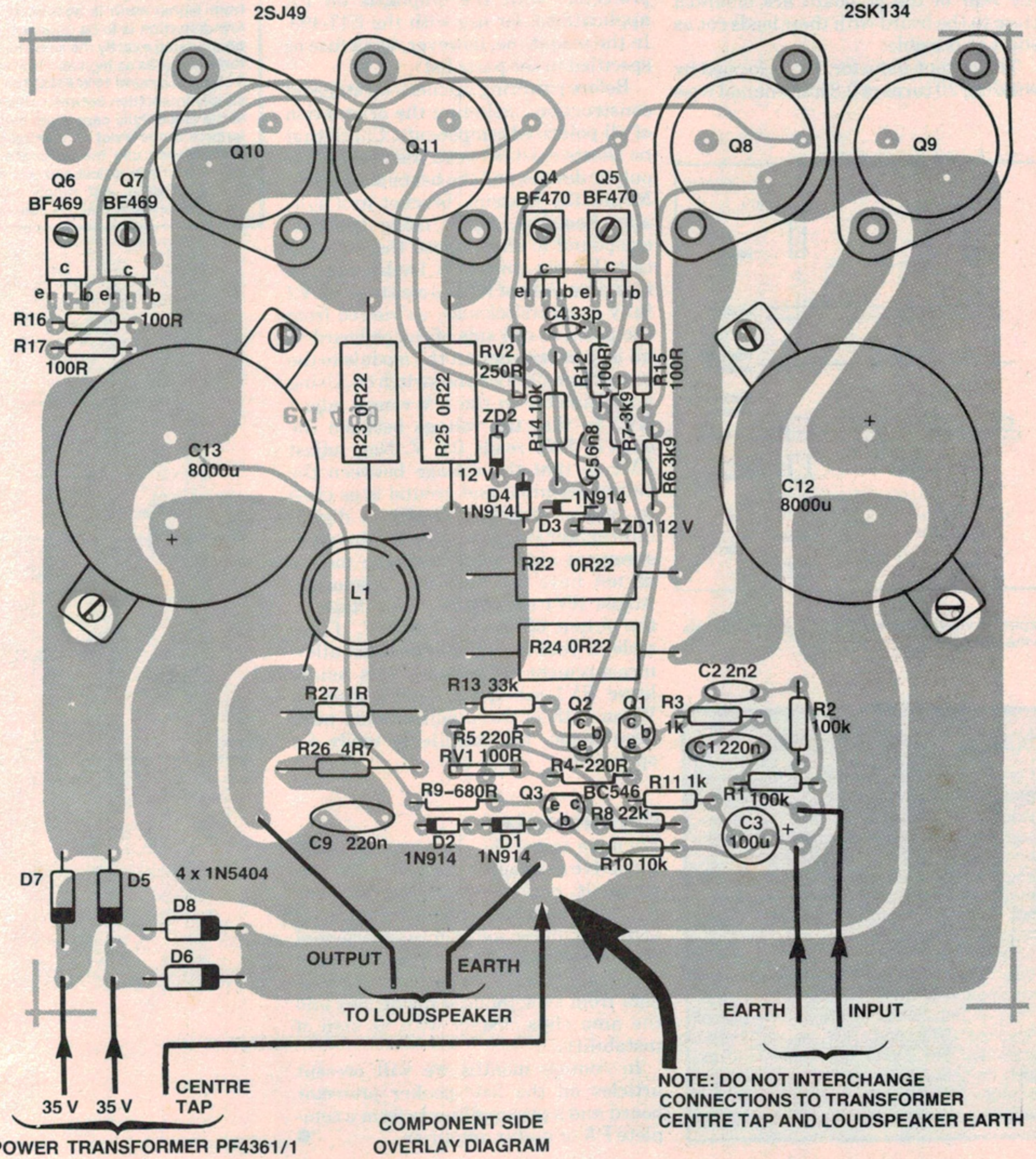


ule in kit form from one of the kit suppliers who support our projects, this bracket should be supplied drilled, ready to mount the transistors. If not, drill all the necessary holes before proceeding further. Make certain the holes are free of burrs or shavings that might otherwise cut through the transistor insulating washers. This is best done with a couple of twists of an oversize drill (i.e: around 13 mm diameter).

The bolts holding the MOSFETs in place also serve to make electrical connections to the cases of the devices. These bolts must be insulated from the heatsink bracket, which will be at earth potential. This is done with the use of short insulating sleeves cut from a length of 'spaghetti' insulation. Use a small quantity of heatsink compound on both sides of the transistor insulating washers to ensure good thermal contact. Insert the sleeves in the holes of the heatsink bracket and mount the four MOSFETs as shown in the accompanying diagram.

The four driver transistors can now be mounted. Again, use transistor insulating washers between the metal sides of the transistors and the heatsink bracket, although insulating sleeves are not necessary.

Once all the transistors have been mounted on the heatsink bracket use a multimeter to check for any short circuits to the heatsink bracket by measuring the resistance from the case of each MOSFET, and from the centre lead of each driver transistor, to the bracket. The measurements should show open circuit on all transistors. If a short does exist the transistor should be ▶

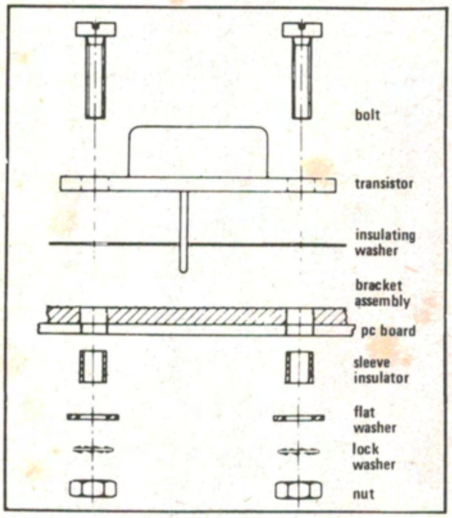


COMPONENT SIDE OVERLAY DIAGRAM

removed and remounted, possibly with a new insulating washer. Finally, solder the leads to the transistors.

Once the MOSFETs and drivers have been mounted, the remainder of the components can be mounted on the pc board, including the small signal transistors and the components on the rear of the pc board. Mount the two 8000u electrolytic capacitors last; be sure to bolt the capacitors down, however, before soldering the lugs. Mount the four 0R22 resistors now, leaving around 5 mm between the resistor and the board. Ensure that all components mounted on the rear of the pc board are mounted close to the board with their leads cut as short as possible.

The output inductor, L1, is formed by winding 20 turns of 0.8 mm enamel wire



Exploded view of how to mount the output devices to the bracket and pc board.

SOME CAPACITORS AREN'T . . .

For the R26-C29 network to provide an effective high frequency load to the output stage it is imperative that C9 (220n greencap) have low self inductance. From experience, we have found Elna type greencaps and Philips polycarbonates meet this requirement. High frequency instability, if not outright oscillation, may result if this requirement is not met.

To a lesser extent, the same applies to C7, C10 and C11. Note that C7 ac-couples the sources of Q8 and Q9 together, so that the self inductance of the source ballast resistors R22 and R24 is no longer important, preventing high frequency instability in this section of the output stage brought about by the inductance of the wirewound ballast resistors.

around a 14 mm former. The plastic bobbins supplied for use with the P26/16 potcores are ideal for this purpose.

Powering up

Supply fuses have not been included on the pc board because the resulting resistance necessitates the use of a second set of electrolytic capacitors close to the output devices. To protect the loudspeakers in the case of failure of the power amp a fuse should be used in series with the loudspeaker cable. We will shortly be publishing a loudspeaker protector, with the emphasis on PA applications, for use with the ETI-499. In the meantime, however, use a fuse as specified in the parts list.

Before powering up check all stages of construction, including the orientation of all polarised components. Check that no shorts exist between the cases of the output devices and the heatsink bracket. Mount the heatsink bracket to a suitable heatsink, again using heatsink compound to ensure good thermal contact. Do not connect a loudspeaker at this time. Adjust RV1 to centre and RV2 fully counterclockwise, as viewed from the positive rail side of the pc board. If all is in order, connect the module to the power transformer and switch on. Using a multimeter on the 1 V range, adjust RV2 so that the voltage between the ends of RV2 reads 0.8 V. Now adjust RV1 so that the voltage between the output terminal and ground is as close to zero as possible. Ideally, a digital multimeter should be used for this measurement since most analogue meters do not have the necessary resolution. Adjust RV1 to achieve a dc voltage on the output of less than 10 mV, if possible. If your multimeter does not allow measurement of voltages this small, leave RV1 set at the centre position. When both of these adjustments have been made, the module is ready for operation.

Performance

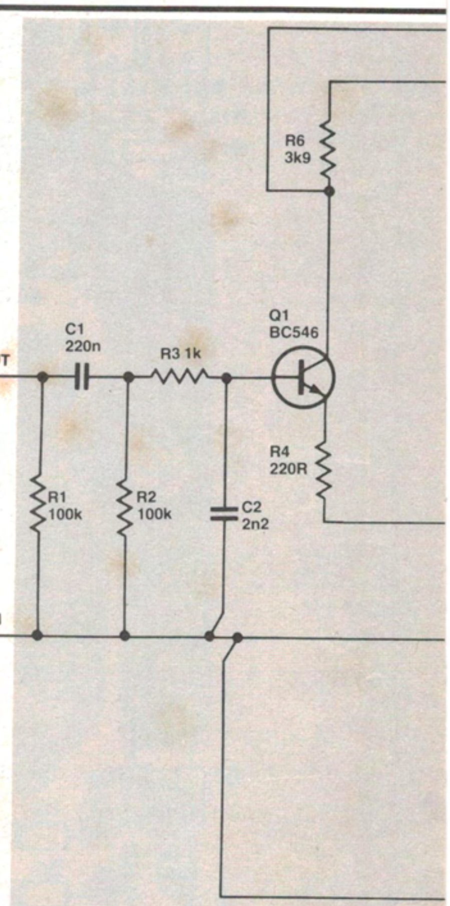
We have tested the prototype into both inductive and capacitive loads and at all times *it performed impeccably.* The sound is clean and smooth with no sign of the harshness sometimes experienced with transistor power amps. The high speed of MOSFETs helps to ensure freedom from slew-induced distortions and the amp clips cleanly with no sign of instability.

In coming months we will present articles on the loudspeaker protector board and a preamplifier to form a complete PA or guitar amplifier. ●

HOW IT WORKS — ETI-499

The circuit is a development from one published in Hitachi's application notes for these MOSFETs. The original circuit uses driver transistors designed by Hitachi for use as MOSFET drivers. Unfortunately these devices are not available in Australia at the present time, so most of the differences are to ensure stability and low distortion with a more readily available driver. We have used the BF469, BF470 complementary video output pair as used in the 477 module. These transistors provide the necessary speed so as not to degrade the performance of the output transistors.

One of the most difficult stages in the development of an amplifier module of this type is the pc board design. Separation of the large currents flowing to the electrolytic capacitors from signal earth is absolutely imperative if low distortion is to be obtained. An earlier pc board using exactly the same circuit gave distortion figures as high as 1% when driven into 8 ohms at around 10 W RMS! The problem was simply interaction between charging currents to the electrolytic capacitors and the earth reference to the input differential pair. For best performance use the pc board design published with this article and pay special attention to all earth and supply connections. In particular ensure that the connections to the



centre point of the transformer and the loudspeaker earth are soldered into the correct positions on the pc board. Although these two points are immediately adjacent on the pc board they are *not* equivalent electrically due to the slight resistance of the board. If these wires are connected the wrong way around the distortion will be increased possibly by as much as 20-30 dB!

Transistors Q1 and Q2 form an input differential pair. Their function is to compare the output signal with the input signal and drive the voltage amplifier transistors in the driver stage with the necessary correction signal, sometimes called the error voltage or error signal. The base of Q1 is held at ground potential by resistor R2. Capacitor C1 in conjunction with R2, R3 and C2 forms an input filter, which defines the upper and lower 3 dB points of the amplifier. This filter therefore restricts the maximum possible signal slope capable of being driven to the input of the differential pair. This is an essential function since it eliminates slew-induced distortions such as TIM, provided that the rest of the power amp has a slew rate in excess of this limit. For a more detailed description of slew-induced distortions and their remedies see the articles on the 477 MOSFET module published in January, February and March 1981.

The gain of the differential pair is around 17, so most of the open loop gain is done by the driver transistors Q4 and Q5, and their associated current mirror formed by Q6 and Q7. The series RC network C4, R12 ensures stability of the amplifier by decreasing the gain of the driver stage at very high frequencies, while keeping the phase shift produced within 90°.

As stated above, transistors Q6 and Q7 form a current mirror. The purpose of these devices is to ensure the current through the two driver transistors remains identical. At the same time the very high impedance represented by Q7 on the collector of Q5 ensures high open loop gain, and consequently low distortion through the relatively large amount of negative feedback available. RV2 varies the voltage between the gates of the output MOSFETs and therefore the amount of bias current through the output transistors. If the voltage across this preset is set to around 0.8 V the bias current will be approximately 80 mA, which is about right. If the bias current is decreased completely by turning RV2 fully away from the MOSFET end of the board, the MOSFFTs will remain off until a signal is fed to the input. This is pure class B operation and results in the coolest operation of the power amplifier. The disadvantage, however, is that a slight increase in distortion, called crossover distortion, will result. In PA or guitar applications this is not a problem, so the amplifier can be used in this mode without hesitation.

The diodes D3, D4 and the zener diodes ZD1 and ZD2 ensure that the voltage between the gates of the FETs and their sources never exceeds 12.6 V, the most common cause of MOSFET failure.

Capacitors C6 and C8 equalise the capacitive input characteristics of the MOSFETs and make it considerably easier to correctly stabilise the output stage. Capacitor C7 brings the sources of the two 2SK134 MOSFETs to the same potential at high frequencies, and overcomes possible problems that might otherwise be caused by inductance in the source resistors R22 and R24.

The four resistors R22-R25 help to match the differences between the characteristics of the different output devices.

The passive filter network formed by R26, C9 ensures that the module always has a load at high frequencies. If the amplifier is tested with large high frequency sinewaves this resistor will become extremely hot, but this does not indicate a fault condition. The inductor L1 and the resistor R27 help to ensure total stability into capacitive loads, such as when driving extremely long loudspeaker leads.