Project 738

A 25 watt booster amp for UHF mobile rigs

Ian Thomas

When you're running a UHF mobile rig, you need all the power you can get — repeaters notwithstanding. Most rigs run about 10 W out. This project will boost that to around 25 W, giving your signal quite a 'lift'. It's easy to build and get going and won't break the bank.

THE READY availability and good general performance of compact mobile amateur UHF FM transceivers has led to something of a 'boom' in activity on the 430 MHz band. Repeaters have begun to spring up in increasing numbers and general development of the band is paralleling that of the two metre (144-148 MHz) band in the early 70s. And that's all to the good.

There's just a *little* fly in the otherwise sweet-smelling ointment, though. Most rigs available off the shelf (and that's where most operators start these days) have relatively low power output. That's fine as the designers have to keep down the cost, size and heat output. While gain antennas are available for mobile operation, there's a limit to the size of antenna you can hang off your vehicle. For effective mobile operation, repeaters notwithstanding, you need a modicum of power output, if not as much as you can get! The solution is an add-on 'booster' amp.

With FM operation, a signal increase of 3-6 dB can mean the difference between 'scratchy' reception and virtually noise-free copy. Hence, it makes sense to boost your output by a minimum of, say, 4-5 dB. UHF RF power transistors which take a 10 W input generally have gains in the 4-6 dB region, which suits our purpose nicely. Problem is, the higher the gain, the more money you pay per watt of output power.

Some time ago, your beloved Editor (Roger Harrison, or VK2ZTB to the cogniscenti) indicated he was interested in doing a UHF booster amp project while we were engaged in a discussion about RF design. Cost was a major consideration, so a suitable RF power device had to be found as its cost would be a major part of the overall cost. As it happened, Geoff Wood (of Geoff Wood Electronics fame — see *Over the Counter,* February '84 ETI), had on-hand a large quantity of 25 Watt Motorola UHF transistors and was looking for a project to wrap around them. Great minds think alike, as they say! The devices themsleves weren't your state-of-the-art mickey-mouse transistor, but then, the price tag wasn't in that league either (like $10!). Just what the Editor ordered!

The idea of having a bash at RF power amp design appealed to me, so when I had time I gave the matter some thought. This project is the result.

Samples were duly obtained. They were branded SRF1078 which, with a little research, turned out to be another name for 2N6136s. The appropriate Motorola data book gave a wealth of information on their parameters, so we were away!

After some fiddling with data books, Smith Charts and a heavy duty soldering iron, I came up with a working prototype that virtually performed spot-on first go.

It's a fairly conventional design as far as UHF amps are concerned. 'Stripline' matching sections are used on the input and output to match the transistor to the 50 ohm input and output standard. The base is dc-grounded via a quarterwave stripline section and dc is shunt-fed to the collector via another quarterwave stripline. Trimmers are used on the input and output so that you can adjust the amp for best input and output match. I attached BNC sockets to the input and output, enabling the project to be adapted to a variety of applications.

The project can be used, for example, as a simple 'insertion amplifier' in a power amp chain — its simplest configuration. As a booster amp for an FM mobile, antenna changeover switching needs to be added. Some schemes are suggested later, showing simple amp in/out switching or Tx/Rx switching in conjunction with a low noise preamp. You can please yourself on this score.

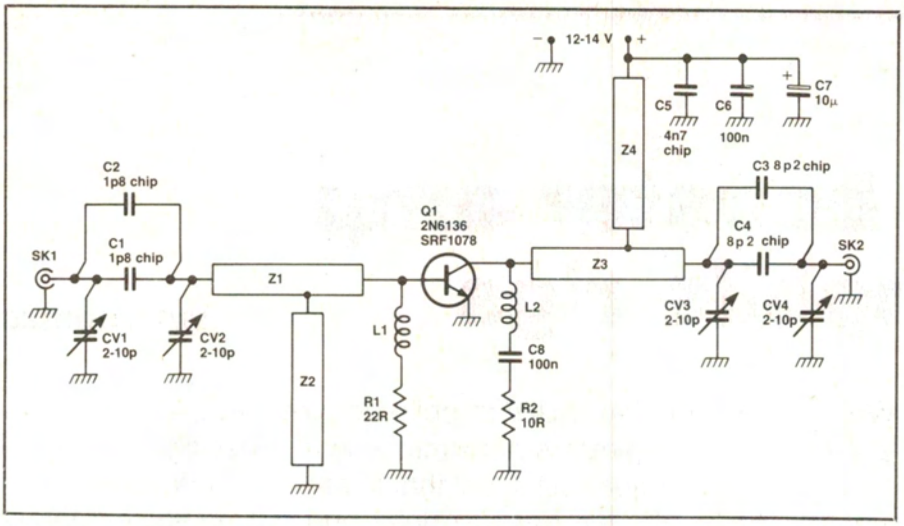
Design considerations

Since the transistors are moderate performance, low-price devices the rest of the design could not use any expensive or exotic components or materials. The SR1078/2N6136 has a guaranteed gain of 4 dB, which means that a transmitter with a 10 Watt output will very nicely drive the transistor to 25 watts output. Since the gain was so low great care had to be taken with the design to minimise losses or the thing would act more as a heater than an amplifier!

At 430 MHz any design must, of necessity, use some form of transmission line approach as one wavelength at 430 MHz is only 69.8 cm in free space. If connections in a circuit are longer than one or two *hundredths* of a wavelength then the effect of their length can no longer be ignored and must be allowed for in the design. Thus, capacitor leads, transistor leads and connections to coax sockets must either be non-existent or taken into account in the design. For this reason, UHF transistors are housed in special packages and components like capacitors are produced having no leads at all!

The transistor comes in a stripline opposed emitter (SOE) package that is specifically intended to be used with microstrip. Since the design was to be cheap, the microstrip had to be fabricated from epoxy-glass laminate rather than the more expensive teflon-glass board (which is nigh on unobtainable because the local agents are only interested in big orders and apparently couldn't care less about providing a service).

Epoxy-glass was really never intended to be used in microstrip circuits and, as a result, its parameters are not controlled. This means both the board thickness and dielectric constant will vary considerably ▶



from sample to sample (and probably across one sample too for that matter) so the design must allow for all possible spreads. With teflon-glass board, both the thickness and dielectric constant are controlled making design much easier.

Also with epoxy-glass board, material dielectric losses are starting to become apparent at 400 Hz-odd. So, the design couldn't contain too-long runs of transmission line that carry the full input and output power in order to minimise line losses. Accordingly, I kept the striplines to around

Designing power amplidiers at RF is mostly an excercise in designing matching networks to transform the 50 ohm input and output impedances into the very low input and output impedances of the transistor itself. In order to get all the input power into the transistor the input matching network must transform the amplifier input impedance (assumed to be 50 ohms) into the complex conjugate of the transistor input impedance given by the manufacturer to obtain maximum power transfer. Exactly the same considerations apply to the output network and in fact the two networks are very similar.

Motorola give the transistor impedances as large signal series equivalent impedances but they can sometimes be given in parallel resistances and capacitances. It doesn't matter how they're specified as they can be converted readily from one form to the other by simple algebra and are entirely equivalent.

Since the design of the matching networks must use, or at least allow for, finite transmission line lengths I chose to do the designs using Smith Chart techniques. The Smith Chart is a device invented by (would you believe) one Mr Smith. It is a graphical technique where all effects of components and transmission lines can be clearly and visually computed. It is an incredibly powerful and effective method and has the great advantage that the whole design can be seen at a glance on a graph rather than being lost in a jumble of mathematics.

I'm not going to go into the derivation of the Smith Chart here as there are plenty of excellent books available on the subject and, to be quite honest, I can't remember it all. I strongly recommend you get a book and read up on it a bit if you want to attempt any designs of your own — it's worth it.

Before any design is attempted it's a good idea to get some idea of what is and isn't possible in terms of realisable components. At 430 MHz we're in an area where parasitic effects can dramatically alter the apparent value of a component. A good example of this is the effect of a piece of wire. If we consider a short length of wire above a ground plane as a lumped inductor then its inductance can be calculated from the formula.

$$L = \frac{\mu}{2\pi}\ \ln\left(\frac{4h}{d}\right)\text{Henrys/metre}$$

This assumes that $h>1.5d$. As the permeability of free space is $\mu_0=4\pi\text{x}10^{-7}$ we can tidy things up a bit and say

$$L = 0.0051n\left(\frac{4h}{d}\right)\text{microhenrys/inch}$$

where 'h' is the spacing of the wire above the ground plane and 'd' is the wire diameter.

That is, a piece of connecting wire ¼" long and ¼" above a groundplane has an inductance of about 5 nH or at 430 MHz, an impedance of *3.5 ohms!* This means that at these frequencies a short circuit is an exceedingly difficult thing to build, about which I will say more later.

The effects of wire inductance don't end with crook short circuits though. If we have a 10 pF capacitor with about ¼" lead length (not hard to have) then the *capacitor* will have an impedance of about −j34 ohms. But, the leads in series with it will have an impedance of +j14.8 leaving a total impedance of −j19.2 ohms for the capacitor plus its leads. This means the capacitor will not look like 10 pF but more like 17.7 pF because of the leads. Also, the length and spacing of the leads is almost impossible to control so our 10 pF capacitor will probably look like something between 15 and 30 pF.

For larger value capacitors (47 pF and greater) the capacitor may be series resonant with its leads and look like a short circuit (one way of building one) or even *inductive.*

Even this isn't the end of the bad news though. Because the capacitor and its leads are forming a partial resonant circuit there are circulating current flowing between the inductance and capacitance which increase the losses in the combination so our 10 pF looks larger and much lossier. As losses don't help gain at all (apart from cooking the capacitor) using capacitors with leads seems to be not on.

This is the reason that the amplifier cannot possibly be built using conventional mounting methods and all UHF circuits are built with components mounted on the wiring side of the board. However, all is not lost and easy solutions are available.

If leads have intolerable effects the answer is to use capacitors that don't have leads. They're called *chip capacitors,* tiny ceramic blocks with solder on each end. A conventional dipped silver mica capacitor would be expected to have a parasitic inductance of about 5 to 10 nH, but chip capacitors have parasitic inductances of about 0.5 nH. Even better, they're readily available in Australia from IRH, who market the Murata range, and from Vitramon, who market their own. Both brands are pretty much the same and are very reasonably priced. Their only disadvantage is that they are so incredibly, fiddlingly *small* — 1¼ x 1¾ mm! You really do have to have care and patience when soldering them in the circuit.

The next problem I had to sort out before commencing the actual design was what trimmer capacitors to use. That there had to be trimmers was a certainty. With the variability of the board material, some adjustment was bound to be necessary. All that I've said about lead inductances for fixed capacitors applies to trimmers as well, but with trimmers, at least the desired capacitance can be set if it's within the range of the capacitor. However, the killer here is the degradation of Q because of circulating currents.

When an amplifier is running at 25 watts out the trimmer doesn't have to get in the way of much of it to be melted to an amorphous blob. There are some truly impressive trimmers available (well not really available in Australia — see my earlier remarks on local agents). Gold-plated, machined from solid brass and works of art, but their price is pretty impressive too! To use them would mean the trimmers in the matching network would cost five times as much as everything else in the amplifier!

Philips however, make a range of very small trimmers that seemed to be OK if they were mounted with their leads bent out sideways and soldered directly onto the board rather than being soldered through the board as they were designed to. They are readily available and quite cheap so they had to be tried. In the final amplifier they probably are a major source of losses but they really are the only cheap alternative.

The last component problem to be cleared up is the form the inductors in the matching networks should take. I've been labouring the point that no matter what is done, if there is a piece of wire in the circuit then it will have a large inductance associated with it. The trick is to make this inductance controllable and predictable. 'U-shaped' pieces of wire could be used as inductors and quite a few amplifiers have been built using them. I liked the idea of using the lengths of transmission line needed to connect into and out of the transistor better so the inductors in the final amplifier are in fact simply tracks on the board with carefully calculated width and length.

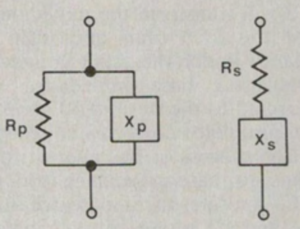
Designing the matching networks

The first point to be considered is the actual mechanical layout for the amplifier. The heatsink for the amplifier is about 110 x 75 mm so I decided to make the microstrip printed board the same size. Since the mounting area for the transistor on the heatsink is in the centre, this automatically placed the transistor in the centre of the board. In fact, for reasons that will be discussed later it was offset to one side slightly from the exact centre but it's still on the centre line of the long axis.

As the input and output connectors were intended to be placed at the two ends of the board, this meant that the tracks connecting the connectors to the transistor base and collector would have to be about 50 mm long. Since these tracks have to carry the full input and output power they should be as wide as possible to minimise ohmic copper losses. The base and collector leads from the transistor are 5.6 mm (0.22″) wide so I decided to make the microstrip leads connecting to them the same width, thereby preserving a constant characteristic impedance along the line (ignoring the change in track metal thickness where the transistor leads are soldered). Taking the actual matching network configuration for granted for the moment, I had to allow about 10 to 12 mm at either end of the board. The space left gave two lengths of microstrip 40 mm long by 5.6 mm wide. These lengths form a major part of the matching networks.

The actual design of the networks starts with the input and output impedances of the transistor itself. We start with the input matching network and, taking a Smith Chart (you can buy a pad of them from Aarque or some technical supply houses but if you do, try to get the ones with both admittance *and* impedance of the one chart — it makes things a hell of a lot easier).

PARALLEL-TO-SERIES AND SERIES-TO-PARALLEL IMPEDANCE CONVERSION



Series to parallel equivalent

$$R_p = R_s \left(1 + \frac{X_s}{R_s}\right)^{2}$$

$$X_p = \frac{R_p.R_s}{X_s}$$

Parallel to series equivalent

$$R_s = \frac{R_p}{1 + \left(\frac{R_p}{X_p}\right)^{2}}$$

$$X_s = \frac{R_s.R_p}{X_p}$$

The large signal input impedance is given as 1.3 − j4.11 ohms at 470 MHz (for the sake of the exercise) so the first thing to do is mark this in on the Smith Chart. As the Smith Chart is in admittances the series impedances can be converted to admittances using the formulas given in the accompanying box. If you're lucky enough to have a chart with both admittances and impedances it can be plotted directly. The input admittance works out to be about 63 — j220 mmho.

The next thing to be worked out is the characteristic impedance of the 0.22″ wide microstrip. To do this we use the somewhat daunting formula

$$Z_0 = \frac{377h}{\sqrt{e_r x W[1+1.735\epsilon_r^{-.0724}(\frac{W}{h})^{-.836}]}}$$

where

W = the width of the microstrip line

h = the dielectric thickness

ϵr = the dielectric constant of the board material

Also, a correction factor must be applied for W when the conductor has a finite thickness and is:

$$W_{eff} = W + \frac{t}{\pi}(\ln\frac{2h}{t} + 1)$$

where t is the thickness of the conductor. For normal one ounce copper it is 1.4 thou and the fibreglass is about 0.060″ thick.

Cranking through all this we get W_{eff} = 0.222 so for very wide conductors the correction factor is negligible but for narrow lines it is not, as we will see when working out the bias stub lengths. Finally, we plug in the value for W_{eff} in the first formula and using a value of 4.5 for ϵ_r we get the Z_0 of the line to be 31.6 ohms. As I mentioned earlier, this value will vary a bit from board to board so there's not a great deal of point in working it out to 17 significant figures.

Once we know the Z_0 of the line we can, using the Smith Chart, work out the effect of the transmission line. As the Smith chart is normalised for 20 millimho (50 ohms) it is necessary to denormalise it to the 31.6 ohms of the transmission line. The centre of the Smith Chart corresponds to exactly 50 ohms so if we redefine this point to be 31.6 ohms then all other impedances must also be multiplied by 50/31.6 before they are plotted on the redefined chart. Thus the 1.3 + j4.11 (input Z) on a 50 ohm chart becomes 2.06 + j6.5 on a chart normalised to 31.6 ohms. This is marked in as point "B" on Chart A. Next we need to know the electrical length of the 40 mm of transmission line. This is worked out by first calculating the wavelength in free space from

$$\lambda_0 = \frac{c}{freq} = \frac{3 \times 10^8}{4.7 \times 10^8} = 0.638 \text{ metre}$$

where c is the velocity of light in free space

Next, the wavelength, assuming all the ▶

power in the microstrip is carried in the dielectric in the TEM mode (which it isn't) from the formula

$$\lambda_{TEM} = \frac{\lambda_0}{\sqrt{\epsilon_r}} = \frac{0.638}{2.12} = 300.8\ \mathrm{mm}$$

or near enough to 300 mm

Finally, a correction factor must be worked out to allow for the increase in propagation velocity because some of the energy is carried in air and is

$$K = \left[\frac{\epsilon_r}{1+0.63(\epsilon_r-1)[\frac{W}{h}]^{.1225}}\right]^{½}$$

evaluating with $\epsilon_r = 4.5$ we finally get K = 1.120, therefore the actual wavelength in the microstrip is

$$\lambda_{real} = \lambda_{TEM} \times K = 300 \times 1.120 = 336\ \mathrm{mm}$$

Therefore, our 40 mm of line is equal to 40/336 or 0.1191 of a wavelength.

From point B on the Smith chart we must draw a constant VSWR circle in the direction towards the generator (the transistor base impedance represented by point B is the load) for 0.1191 of a wavelength to give point C on the chart. This point is still normalised to 31.6 ohms so to convert back to 50 ohms read off the impedance and multiply it by 31.6/50. Then replot the point on the chart, which is now back to a normal 50 ohms, to give point D.

I made the 31.6 ohm normalised impedance after rotation 5 + j60 ohms or 1.3 − j16.7 millimho. Therefore, after normalising back to 50 ohms the impedance is 3.16 + j37.9 ohms or, as admittance, 2.05 − j26.4 mmho. This is the actual admittance at the end of the input transmission line.

Next we consider the effects of the input trimmer capacitor CV2. As this capacitor is adjusted the impedance at its circuit node will follow a circle of constant conductance along the curve marked D-E'-E. When the amplifier is being tuned we can place E' anywhere we want on the circle within the constraint that the trimmer capacitor is a 2-10 pF device, so the minimum rotation is given by 2 pF and is 5.9 mmho (marked as E'). The maximum rotation is given by 10 pF and is 29.5 mmho (marked as E).

Next, we turn our attention to the input connector which is (hopefully!) exactly 50 ohms and is represented by the point in the exact centre of the chart. This is the impedance of the pin sticking out of the connector but there is a piece of copper ribbon connecting it to the board which has a series impedance that it would be prudent to allow for.

If we say the inductance of the connecting ribbon is somewhere between 0 and 10 nH, then there is a series Z of +j0 to +j30 ohms. This is plotted on the chart as curve F F' which is a constant reactance circle and we know the impedance on the board is somewhere in this arc.

Other aspects

As the transistor is operated in class C its base must be connected to ground for dc. All that is needed is a quarter wave line from the input microstrip to ground. As the input dc currents aren't all that large I chose to use microstrip line 1.3 mm wide. For bias stubs like this it isn't all that important what the characteristic impedance is as it's a short circuit at one end and an open circuit at the other (if we get the length right).

First we work out the effective width of the line using the formula given earlier to get

$$W_{eff} = 0.050 + \frac{0.0014}{\pi}\left(1n\frac{.12}{.0014}+1\right) = 0.0524''$$

The correction factor for the increase in propagation velocity must also be worked out again and is

$$K = \left[\frac{4.5}{1+0.63(4.5-1)[\frac{0.0524}{0.06}]^{0.1225}}\right]^{½} = 1.192$$

so finally, we get a wavelength for 1.3 mm wide track as 300 x 1.192 or 358.5 mm. Therefore, the quarter wave bias stub is 89.6 mm long.

This is too long to be included as a straight run so it's folded into a meander line. The golden rule here is to make sure that the meanders are at least three dielectric thicknesses apart to avoid interaction and to mitre the corners to avoid reflections at the bends.

The same process is repeated for the collector dc feed stub, except that I chose a 1.8 mm track here because the earth end has to be ac earth but the positive rail for dc. The chip capacitors I had for bypassing were 0.1" long by 0.070" (2.5 x 1.8 mm) wide so the chip capacitor that ac-earthed the end of the stub was the same width as the stub and (more or less) preserved its characteristic impedance to ground.

Repeating the calculation for K, we get K = 1.176 and hence one wavelength = 353.6 mm or a quarter wavelength of 88.4 mm.

This completes the electrical design and all that remains to be done is to lay out the board following the calculated dimensions. The tuning microstrips were continued almost to the ends of the board and gaps cut in them 1.3 mm (0.050") wide where the four tuning chip capacitors were to go.

As much of the board was left covered with 'earth plane', as it can't be emphasised too much how important a good solid earth is for the transistor. The SOE transister package has two emitter leads on opposite sides of the device and both must be soldered massively to huge solid areas of ground plane. You can see on the layout that the ground is taken all along one side of the board to earth the emitter to the trimmer capacitors of the matching networks and on the other side a 20 mm wide strip of ground ties the transistor to the earth for the base and collector stubs.

Some final remarks on the design of the layout before going on to he construction: The transistor is operating in class C and as such generates quite a bit of power at higher harmonics. Since the output is assymetric it is to be expected that a fair bit of this power would be at the second harmonic. However, not coincidentally, the dc feed stubs are a high impedance for the fundamental but at the second harmonic are half wavelength long and look like a short circuit again. This means that they act to suppress the generation of second harmonic power and this was one of the major reasons for their choice. The second thing that should be mentioned is that all the rather awesome formulae that have been invoked only deal with the effects that we want and I've tacitly ignored all sorts of bad things that can happen (and do!).

All the practical notes on this type of amplifier mention that they're prone to oscillation at 20-80 MHz and this little beast proved no exception. To suppress these oscillations it's necessary to add on networks in both the collector and base circuits that're high impedance at 70 cm but are lossy as the lower frequencies. This is another good reason to keep the impedances low around the transistor ports — we can add on oscillation suppression components without worrying too much about changing the matching conditions.

I found it necessary to put damping on both the collector and base (although either is enough, both seemed a good idea) and, fortunately, only a few turns of air-spaced inductor give a nice high Z at the operating frequency. However, if you find that your amplifier draws a couple of amps for no drive power you have joined those who've been blessed with a 30 MHz oscillator instead of a 440 MHz amplifier! But more of this in the construction section.

Next, we consider how the input trimmer CV1 will modify the impedance arc F-F'. Once again, the trimmer is a 2-10 pF capacitor so the parallel admittance is 5.9 to 29.5 mmho. If the series inductance is zero, (unlikely) then varying CV1 will trace out a constant conductance arc H-G. If it is the maximum 10 nH, varying CV1 will trace out an arc H'-G'. This defines an area on the chart H-G-G'-H, which is the impedance on the board under the input connector that we want to transform to the impedance E'-E at the end of the input microstrip.

to do this, we add in the series capacitors C1 and C2. Two capacitors in parallel are used to try and distribute the current and lower losses, although it may not be necessary. The two capacitors are each 1.8pF so we have a total capacitance of 3.6 pF, or an impedance of 94 ohms.

Adding in series capacitors causes the impedance from E'-E to be rotated along arcs of constant reactance to I'-I. Thus, if CV1 is adjusted to the correct value then C1 and C2 will transform the impedance at he end of the 31.6 ohm microstrip to the impedance under the input connector and the transistor base impedance will be transformed to the desired 50 ohms.

The complete, correctly adjusted transformation process is: The microstrip rotates the transistor base impedance from point A to D, CV1 rotates the impedance from D to E", C1 and C2 rotates it to I", where correctly adjusting CV1 changes it to F". Finally, the parasitic input inductance transforms the impedance to F, the 50 ohm input impedance.

When designing matching networks like this there are really almost infinite possible combinations of network configurations that can be chosen. I chose this one for three main reasons. The first was that I didn't want to have components close to the transistor as, on the microstrip, impedances are low and currents are high. This means that voltages are low and as the dielectric loss of the epoxy glass board can be represented as a parallel resistance to ground from the microstrip, preserving low impedance minimises this loss. Also, adding in ▶

Values shown on both charts are 'normalised' to 1.0 at the chart centre. For plotting the input impedance, chart centre represents 50 ohms. For calculations involving the input and output striplines (Z1 and Z3 on the circuit), the chart centre has been 're-normalised' to 31.6 ohms. All values should be multiplied accordingly.

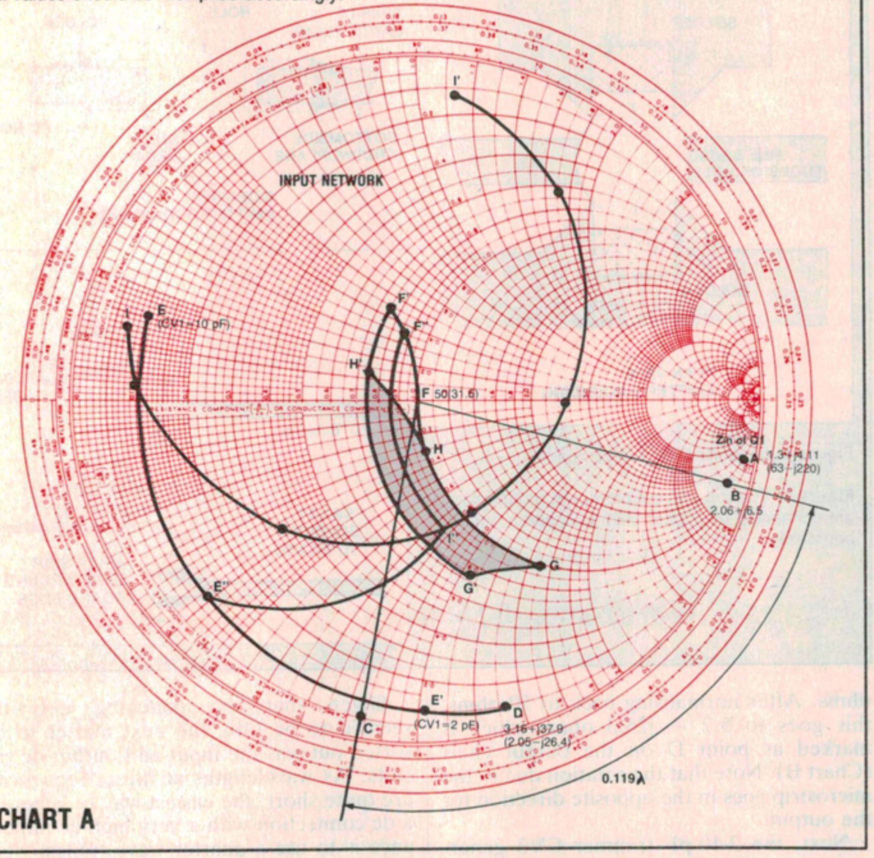


CHART A

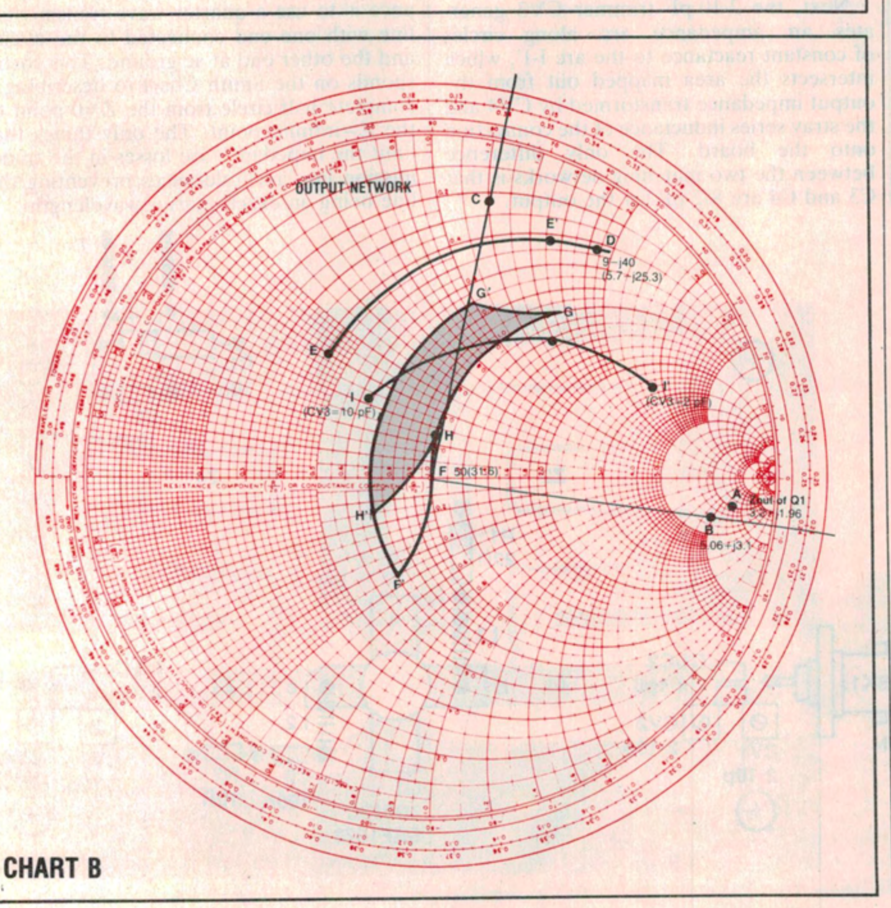


CHART B

capacitors near the transistor base would make grounding problems that much harder.

The second reason for the chosen network was that I wanted all trimmer capacitors to have one end at earth potential so they could be adjusted without the adjustment tool changing things. A very common matching network is to have C1-C2 a trimmer and delete CV1. It would work just fine but then both sides of the trimmer would be 'hot' and tuning it up would be a pain.

PARTS LIST — ETI-738

Resistors	all ½W, 5%
R1	22R
R2	10R
Capacitors	
C1, C2	1p8 ceramic monolithic chip capacitors, Murata type GR39 or Vitramon type VJ0805A1R8D.
C3, C4	8p2 ceramic monolithic chip capacitors, Murata type GR39 or Vitramon type VJ0805A8R2D.
C5	4n7 ceramic monolithic chip capacitor, Murata or Vitramon.
C6, C8	100n radial lead monolithic or disc ceramic capacitor.
C7	10µ/20 V tant., radial leads.
CV1,2,3,4	1p8-10p Philips film trimmers, type 2222-809-05002.
Semiconductors	
Q1	Motorola SRF1078 (2N6136)
Miscellaneous	
L1, L2	4½ turns self-supporting, 0.020" diameter enamelled copper wire wound 0.1" (2.5 mm) inside diameter.

ETI-738 pc board (double-sided); suitable heatsink (e.g: D.S.E. no. H-3460 or H-3422); BNC chassis mount sockets — two off; four 4BA bolts and eight nuts; coaxial changeover relay(s) as required; chassis to suit (if required), etc.

Price estimate: $28-$35

(less chassis and relays)

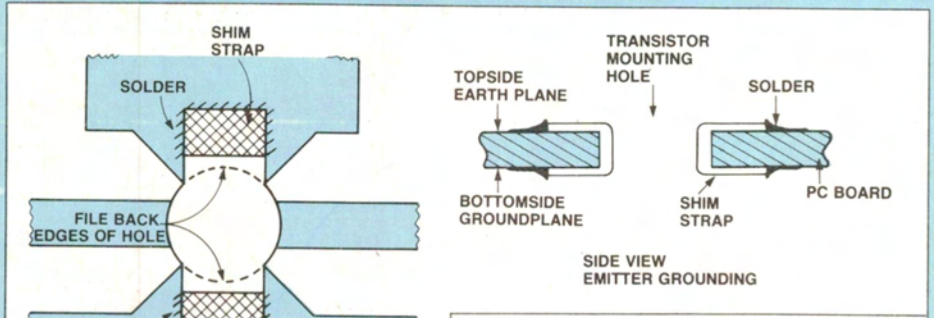


Figure 1. Grounding the emitter leads.

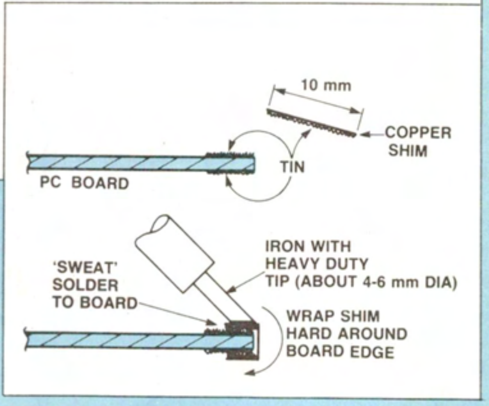


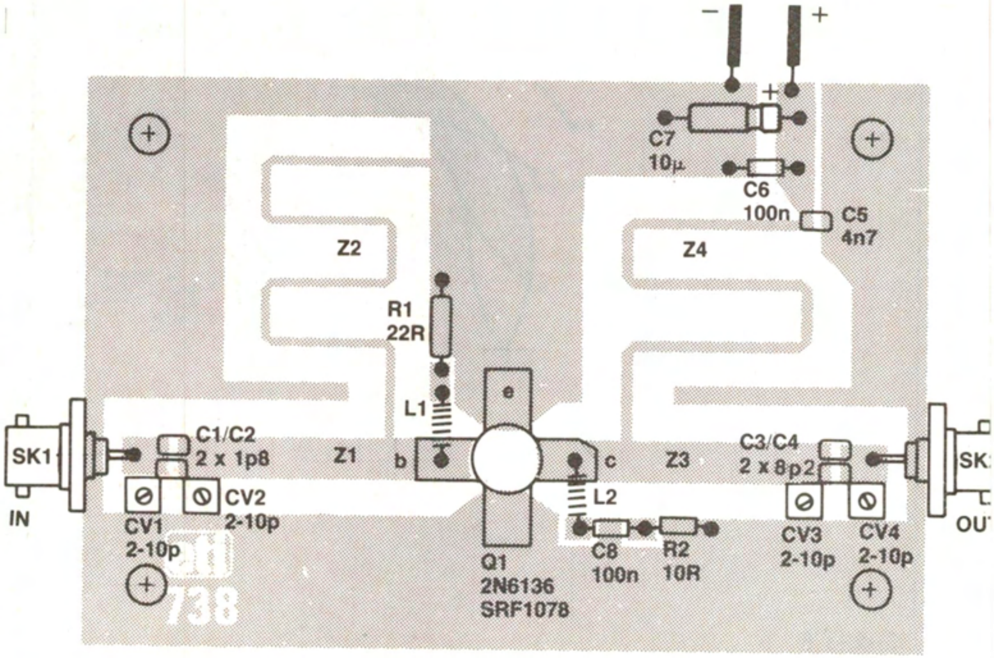
Figure 2. The top and bottom board groundplanes are connected by copper shim wrapped around the board edge.

The third reason for preserving a low impedance in the microstrip is that it makes the design of bias networks for the transistor that much easier. As the transistor must have correct dc conditions applied to it as well as the correct matching conditions, we have to be able to make dc connections to the base and collector that don't disturb the RF conditions. If we are connecting to a low impedance point then a merely moderate parallel bias impedance at RF is OK. If the microstrip were a moderate impedance then we would have to expend some effort to make bias circuits that were very high impedance or allow for the bias impedance in the design. But more about bias later.

The design of the collector matching network follows exactly the same procedure as the input except that the source and load are reversed so all the arcs on the Smith Chart go in the opposite direction. The collector impedance is 3.2 + j1.96 ohms which, after denormalising to 31.6 ohms goes to 5.06 + j3.1 ohms. Rotating this impedance by 0.1191 (the length of the 40 mm output stripline) gives an impedance of 9 – j40 ohms. After normalising back to 50 ohms, this goes to 5.7 – j25.3 ohms which is marked as point D on the output chart (Chart B). Note that the rotation due to the microstrip goes in the opposite direction for the output.

Next, the 2-10 pF trimmer CV3 generates an impedance arc along circles of constant reactance to the arc I-I', which intersects the area mapped out from the output impedance transformed by CV4 and the stray series inductance of the connection onto the board. The only difference between the two matching networks is that C3 and C4 are 8.2 pF for the output.

Given that the matching networks seemed to be OK, the next matter to be sorted out was the input and output dc circuits. As wavelengths at these frequencies are quite short, the easiest way to generate a dc connection with a very high ac impedance is to use a quarter wave transmission line with one end connected to the circuit and the other end at ac ground. This corresponds on the Smith Chart to describing a complete half circle from the Z=0 point to the Z=infinite point. The only things that limit the impedance are losses in the transmission line and tolerances preventing the line being an exact quarter wavelength.



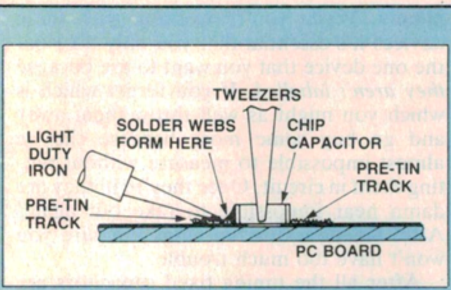


Figure 3. How to solder the chip capacitors in place.

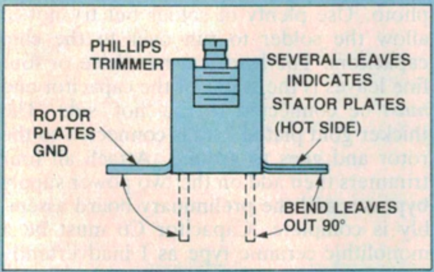
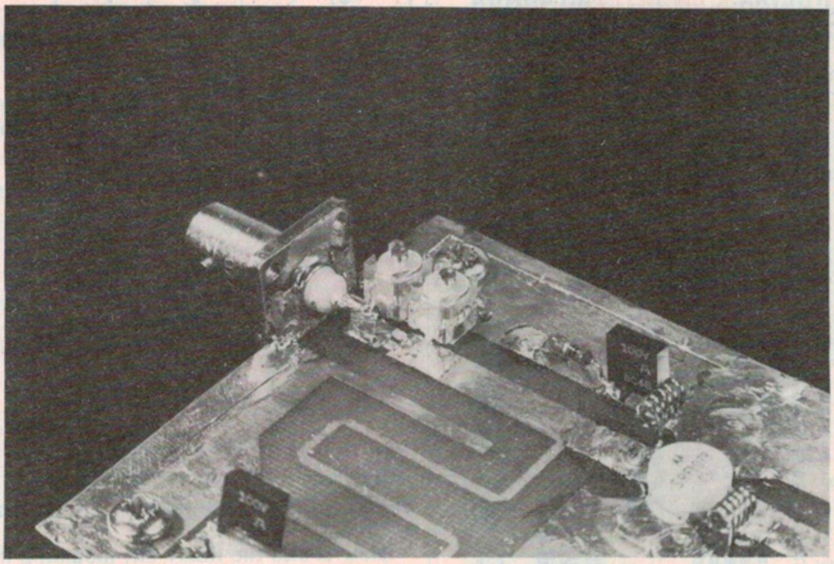


Figure 4. Bending the trimmer leads



Output line. View of the amp's output stripline section, showing the link to the BNC socket, the two trimmers and chip caps. Note the collector dc feed stripline.

Construction

The first thing to make is the printed board. The dimensions of all the critical tracks are given as components so if you want, you can tape up your own artwork. Try to stick as close as possible to the dimensions given or use the artwork provided but make the board two or three mm longer than the heatsink you intend to use so you can mount the input and output connections. The other side to the board *must absolutely* be solid, uninterrupted copper. Apart from being a good ground it is an essential part of the microstrip transmission lines! Make sure the two rectangular pads for the hot ends of CV1 and CV4 are big enough for the trimmers to be mounted without fouling CV2 and CV3 but no bigger. Also make sure that the two gaps that're bridged by C1/C2, and C3/C4 are exactly 1.3 mm wide so the chip capacitors can be mounted correctly. The same applies to the collector bypass capacitor C5, but the spacing of the other two collector bypasses, C6 and C7, is less important. Alternatively you could buy a ready-made board.

Once the board is etched trim it off neatly to the corner marks and drill a small hole where the transistor goes. Then, carefully locate it where it is to be finally mounted on the heatsink and clamp it firmly with a couple of G clamps. Next, drill the four mounting holes using a 2.4 mm drill right through the board and the heatsink making absolutely sure that you miss the heatsink fins and go into the spaces between them. The holes should be about 5 mm from the sides of the board and about 12 mm from the ends, but this will depend on the heatsink you use. Remove the board from the heatsink and open out the mounting holes to 3.6 mm. Next, open out the hole in the pc board for the transistor to a neat 10 mm. If you have a drill to do this, so much the better but probably you'll have to use a rat-tail file. However, if you do it make sure it is centred correcty. Next, carefully cut out the two sides of the transistor mounting hole where the emitter leads are soldered according to the sketch in Figure 1 so the emitter leads can be earthed to the back of the board solidly. Cut two bits of copper foil about 5 mm wide by 10 mm long so they neatly fit into the two flats you've just cut for the emitter grounds. Form them tightly around the edge of the hole and solder them into position using lots of solder to be sure they're completely connected, but not so much that there's excess solder all over the board. This part is quite important as it connects the emitters to both the upper and lower groundplanes.

Next, attach the input and output connectors to the board. I didn't want to get involved with fancy mounting brackets so I simply soldered the connectors directly to the edge of the board using lots of solder.

The usual electronics soldering iron really isn't hot enough to do this so I clamped the connector in a vyce with the flange side where the board is to be attached on top. After pre-tinning the connector, I held the board against it in the spot where it was to be mounted and applied a fine gas glame to the flange of the connector. This should be done with excruciating care as you only have to touch the flame to the board or the connector dielectric to, at best, make a hell of a mess and, at worst, ruin things completely.

When things are hot enough, pour in heaps of solder to make two good solid webs on both the ground-plane and wiring sides of the board then hold the board *exactly* vertical until the solder sets. The connector output pin should be over the edge of the pad on the board so it doesn't foul the trimmer capacitors.

I used BNC connectors as any minor mismatch they may cause can be tuned out with the matching networks. But unfortunately, BNC connectors are normally used with RG58C/U coax which is becoming lossy at these frequencies. If you intend to use longish runs of coax into and out of the amplifier you may choose to use type N or some other connectors which suit less lossy cable. Whatever you use, I think the direct soldering method has a lot to recommend it, as you get about the best possible electrical connection to the grounds on both sides of the board.

In order to complete the earthing on the board, cut long strips of copper foil about 10 mm wide and neatly tin one side all over. Next, work your way all around the edges of the board, tinning and groundplane and wiring side grounds in to about 5 mm from the edge. Next, cut the strip of copper foil so it's the same length as the board and hold the soldered side so it overlaps the edge of the board about 4 mm. Apply a soldering iron to sweat the foil onto the board (See Figure 2). If you line things up right you should be able to simply slowly run the iron along the foil to solder it to the board. Next wrap the foil *hard* around the edge of the board and repeat the process on the other side. The foil then solidly connects the groundplane side to the earth on the wiring side and gives the best earth I could come up with.

Repeat this process all round the edges of the board leaving a gap for the power supply where it comes to the edge of the board and taking the foil right up to the sides of the connectors. When you've finished, the only edge of the board that should be visible is about 10 mm where the +12 volts comes out. Once everything seems to be stuck down nicely it's a good idea to run around all the joints with a bit more solder to make ▶

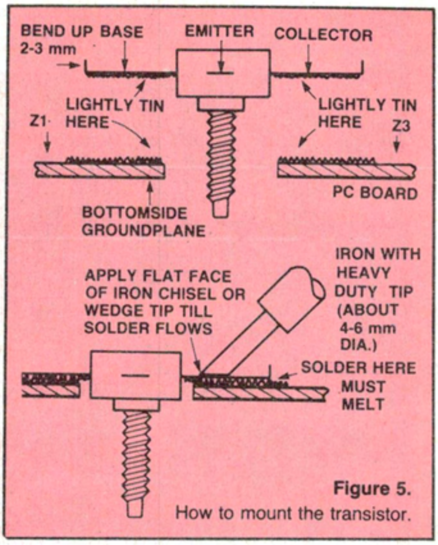


Figure 5. How to mount the transistor.

sure; there's no such thing as too good an earth!

Now comes the fiddly bit; mounting the chip capacitors. First, tin all the areas where any components are to be attached but don't leave great waves of solder — it isn't necessary and can do harm. Then, using a fine pair of tweezers, pick up the chip capacitity to be mounted and hold it firmly in place over the gap in the track on the board. The two tinned ends of the capacitor should neatly overlap the tracks and it should be held hard down against the board.

Touch a soldering iron tip firmly against he track right next to the end of the capacitor to be soldered *but don't try to touch the end of the actual capacitor* (See Figure 3). The idea is to melt the solder tinning and carry the heat to the capacitor that way. As the track gets hot enough a neat little web of solder should form around the tinned end of the capacitor. Immediately remove the heat and allow things to cool. Solder the other end by just touching the iron next to the end but *don't* press down on the body of the capacitor or you may damage it.

With chip capacitors too much heat for too long *must* be avoided as you can cause the solder tinning to leach off the end completely. When you're working with these devices it's essential that you only take out the one device that you want to use because *they aren't labelled.* If you forget which is which you might as well throw them away and go buy some more because they're almost impossible to measure without putting them in circuit. Once they're in they are damn near impossible to take out again! After all these dire warnings I'm sure you won't have too much trouble.

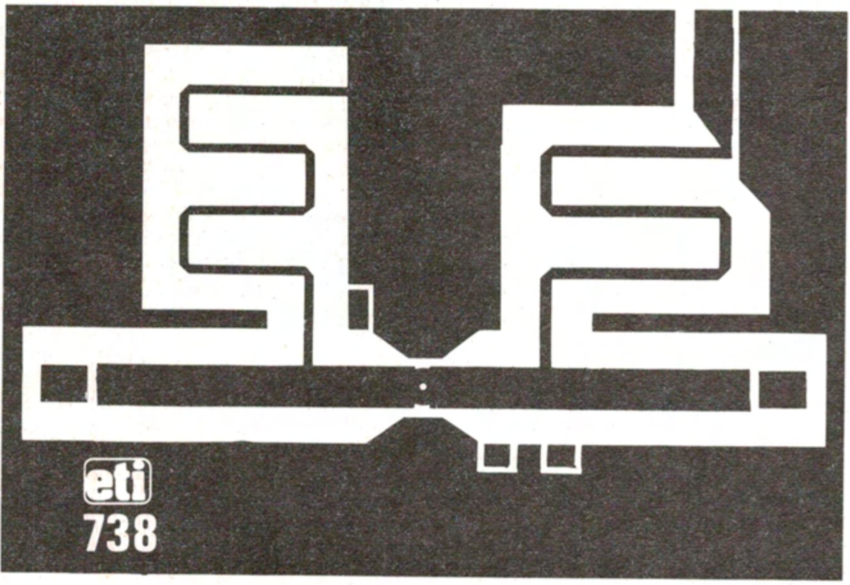
After all the tuning fixed capacitors are attached, do the 4.7 nF collector bypass capacitor the same way and that's the fiddling finished.

Next attached the four trimmers by bending their leads hard out from the body (Figure 4) and mounting them as seen in the photo. Use plenty of solder but try not to allow the solder to run over to the chip capacitors. The lead that has three or four fine leaves is the stator of the capacitor and *must* be connected to the 'hot' side. The thicker gold plated lead is connected to the rotor and goes to ground. Attach all four trimmers then add on the two power supply bypasses and the preliminary board assembly is complete. Capacitor C6 must be a monolithic ceramic type as I inadvertently used a tantalum in the first model (once) and the RF currents blew it to pieces. Dramatic!

Next, the board has to be mounted on the heatsink. I tapped the four mounting holes with a 4 mm tap for the mounting screws. If you have one, this is a nice way to do it but self-tappers could be used as the screws carry no heat or power. Screw down the board component side up with spacers exactly 2.5 mm wide between the board and the heatsink. This space is absolutely critical as if the spacers are too high you will neatly pop off the top of the transistor when you bolt it in and if they're too thin you can't get smooth connections between the transistor and the microstrip. I actually rummaged around in my junk screw box and found four nuts the right thickness and drilled the threads out of the centre. You could use several washers instead, but however you do it, it must be right.

Screw down the board then drill the hole

NOTE: Double-sided board, reverse side all copper.



for the transistor if you didn't do it when you drilled the mounting holes. The transistor mounting hole must be exactly in the centre of the hole in the board and have no burrs that interfere with heat conduction. Drop the transistor into its hole and make sure all the leads align nicely with the earth and microstrip. Bend up the end of each lead about 2 mm. If all is well remove it. Lightly tin the underside of each lead and smear the mounting base with heatsink compound. Pre-tin the striplines. Bolt the transistor in position with the base and collector leads exactly aligned (the collector is the lead with one corner clipped off at 45°). *Don't overtighten it* as the stud is only copper and painfully easy to strip.

With the transistor screwed down, the four leads should lie dead flat against the board; if the soldered copper foil for the emitter earths causes the emitter leads to stand proud remove the transistor and remove excess solder from the emitter earthing and try again. When all is perfect, carefully flow solder all around and under all four leads. (See Figure 5).

All that remains to be done now is to make and connect the two oscillation supresion networks and the amplifier is finished. To wind the inductors I used a #42 drill shank as a mandred (a complete set of number drills is an invaluable asset when winding inductors at these frequencies). Anything hard and round with a diameter of about 2-2.5 mm will do fine. The collector inductor has about 3½ turns of 0.5 mm wire but almost any wire will do so long as it's strong enough to be self supporting.

Bend the ends of the coil so one end sits nicely right in the middle of the collector lead and the other sits on the pad cut in the groundplane and solder it in. Next, bend the leads of the 100 nF bypass capacitor out hard against the body and cut them off about 2 mm long. Solder the capacitor in and bend the leads of a 120 ohm resistor with a slight kink in them so when they are soldered onto the board the resistor body is about 1 mm from the board, and solder in the resistor.

The same process is repeated with the inductor and resistor for the base but the base has no capacitor as both ends are at the same dc potential. The base inductor is the same in all respects as the collector but the base resistor is 22 ohms. When all this is done you're ready to power the thing up and make it work!

Tuning and adjusting

This process is always fraught with tension and drama as if you slip up it isn't too hard to wipe out the whole thing so be careful where you poke your screwdriver! Adjust all trimmers to about the mid-position, connect up your output load and signal source (turned off!) and finally the power supply set to about 12 volts. If at all possible, adjust the signal source to a lower power setting than the full 10 watts and arrange for the supply current to be monitored. Turn on the dc power then apply input power for just a few seconds then turn it off again. The amplifier should draw one or two amps when the input power is on but none when it is off. If it continues to draw dc power when the input is shut down then congratulations, you've built an oscillator! If all is well, apply power again and adjust CV3 and CV4 for maximum power into the load.

At this stage it is assumed that some power is getting into the transistor but if no power comes out at all it may be necessary to adjust CV1 and CV2 until there is some output. I found that CV2 was by far the most sensitive and adjusting this should get results. Finally, adjust up CV1 and CV2 for maximum power then re-adjust CV3 and CV4. Go to maximum input power and repeat the whole process and you should then be getting a full 25 watts out of the booster.

Some helpful hints are as follows if the amp oscillates: L1 may be reduced to 2½ turns and this will stop almost anything but you will lose 0.2 or 0.3 dB of gain as the 22 ohms robs the base of input power. Likewise, L2 may also be reduced but here the problem tends to be that the 10 ohm resistor burns. You may have to use a larger resistor. I haven't included a ferrite bead in the power supply lines as it didn't seem to be necessary, but if you're having trouble, give it a shot. Lastly, if the 10 ohms in the collector tends to disappear in a cloud of smoke, but everything else seems to go OK, then you almost certainly have oscillation trouble. The only way enough power can get through L2 to do the deed is for there to be a lot of power at the lower frequencies.

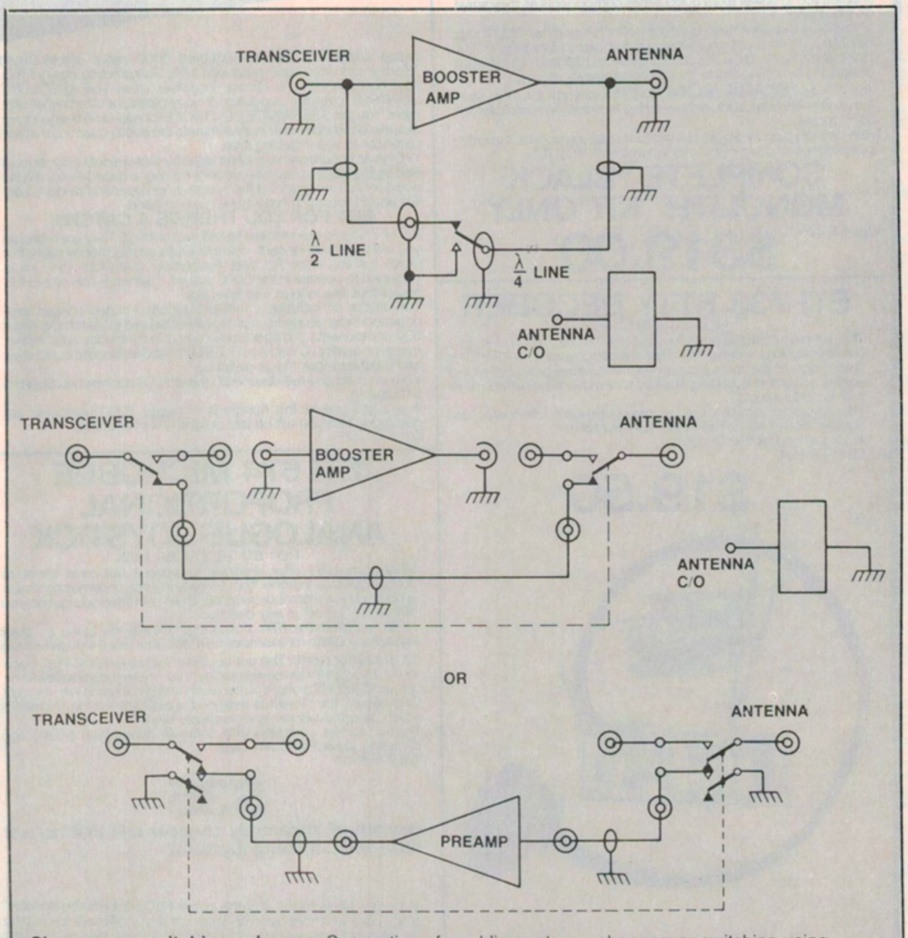
Test results and conclusions

After the original model was built and checked at dc it was tested at over the range 435 MHz to 475 MHz. All the original testing was at 470 MHz which is where the transistors are specified. After the routine amount of trouble with instabilities, everything worked fine and serious testing began. At the higher frequencies I was never able to get the full 4 dB gain given by the manufacturer and had to settle for a bit over 3.5 dB or about 22.5 watts for a fixed 10 watts in with no reflected power. However, at 438 MHz the gain was up to 4.1 dB to give nearly 26 watts out for ten in. The slightly off performance at 470 MHz was attributed to dielectric losses on the board and probably the trimmers were contributing too. It's rather hard to tell as when the amplifiers running everything gets a bit hot.

As far as amplifier bandwidth is concerned I was able to achieve 10 MHz virtually deat flat, and 36 MHz at the −1 dB output level.

Because of the quarterwave bias stubs, the second harmonic rejection was excellent at about −60 dB, but the third was not so good at −26 dB. Perhaps a filter may be needed if the antenna rejection is not enough.

Finally, the amplifier seemed to pretty well meet all requirements. The best one of all is the price; if you shop around a bit you should get all the bits for about $1/watt! ●



Changeover switching schemes. Suggestions for adding antenna changeover switching using coaxial changeover relays. The top scheme requires accurate cutting of the lines.