Solid State Amplifier

High Power Solid State 600 Watts Output

Motorola MRF 150 FETs

K0GKD

Tom Sowden

www.k0gkd.com

(See June QST 2006)

(Updated August 2007 Please note comments at the end!)

See a video of the amplifier in operation at YouTube - K0GKD

Or a video of the inside of the amplifier at **YouTube Inside Amplifier**

I go along with my XYL and daughter to horse shows from time to time, as being there to watch them compete is fun and important as a “family” thing. In between their events can best be characterized as “watching paint dry” by those of us that don't share the same equine enthusiasm. It is during these moments that my mind starts wondering toward ham radio, or my marginal golf game. This past summer during such a time I started thinking about building a solid-state linear amplifier. I have an old Heathkit SB 221 that after a major overhaul and redesign is now working great on 80, 40, 20, and 15; but not 17, 12 and 10. With this in mind I got on the internet at the motel we were staying in and started searching for ideas. One design kept popping up that seemed to be the most popular and offered what seemed to be the best approach.

Back in the early 1980’s Motorola developed a line of “Power FET’S.” for amplifiers and other end uses. Helge Granberg, one of their circuit engineers, wrote a number of application papers for the use of these power FET’S. Over the years his designs have become widely used and to some degree the standard for commercially built solid-state amplifiers. His application EB104 seemed to me to be the best and most practical design for what I wanted for the upper bands in the HF range. Specification highlights that briefly describes the idea behind the design and an exert from his paper follows .

The RF MOSFET Line MRF 150 -N Channel Enhancement Mode Designed primarily for linear large signal output stages up to150 MHz

frequency range. Specified 50 Volts, 30 MHz Characteristics output Power = 150 Watts - Power Gain = 17 dB (Typ) - Efficiency = 45% (Typ)

Superior High Order IMD IMD(d3) (150 W PEP) 32 dB (Typical) - IMD(d11) (150 W PEP) 60 dB (Typical) -

100% Tested For Load Mismatch At All Phase Angles With 30:1 VSWR

600-WATTS RF FROM FOUR POWER FETs Motorola EB104

In the Granberg EB104 application paper the following statement summarizes the main advantages of these types of circuits.

This unique push-pull circuit produces a power output of four devices without the added loss and cost of power splitters and combiners. Motorola MRF150 RF power FET makes it possible to parallel two or more devices at relatively high power levels. This technique is considered impractical for bipolar transistors due to their low input impedance. In a common source amplifier configuration, a power FET has approximately five to ten times higher input impedance than a comparable bipolar transistor in a common emitter circuit. The DC supply voltage and power level determines the output impedance in both cases. The limit to the number of FETs that can be paralleled is dictated by physical, rather than electrical restrictions, where the mutual inductance between the drains is the most critical aspect, limiting the upper frequency range of operation. The magnitude of these losses is relative to the impedance levels involved, and becomes more serious at lower supply voltages and higher power levels. Since the minimum mounting distance of the transistors is limited by the package size, the only real improvement would be a multiple die package. For higher frequency circuits, these mutual inductances could be used as a part of the matching network, but it would seriously limit the bandwidth of the amplifier. This technique is popular with many VHF bipolar designs.

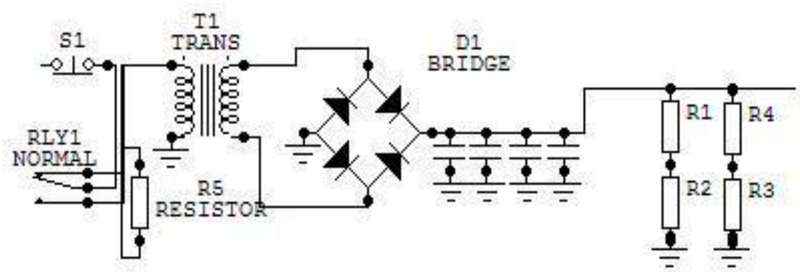
Several motivating factors kept my interest moving forward, namely: (1) the idea of being able to work with safe voltages (50 VDC) was appealing compared to the dangerous levels present in my Heathkit SB221, (2) the ability to switch bands and not worry about retuning or changing settings was very likable, and; (3) the fun and challenge of “building your own” topped off the list.

After reading everything I could gather up the challenges became clear. First, the project would need a high current DC power source at 50 volts; and probably a secondary lower voltage for the bias. Next on the list of issues was the need to dissipate a lot of heat that emanates from the four power FETs. - about 500 watts or so. In addition I wanted the amplifier to be somewhat compact and “presentable” to the rest of my “shack”, so I needed to think of a suitable enclosure. Finally, the one negative aspect of the devices is their harmonic suppression characteristics, and some form of low pass filtering would be needed to deal with the odd order dissipation.

The powers supply considerations centered on the need for 50 volts and 20 plus amps. My first thought was to find a switching supply as the practical solution. In searching around I could not find a reasonably priced unit as most were in the $400 plus range. Since I did not want to start another project that would require a lot of boning up on “switching” technology, I opted to go the linear supply route. Of course the first challenge was to find a transformer that would work. I knew that Ameritron had a solid-state amplifier on the market so I downloaded the manual for the power supply. In studying the design they use a multi-wound primary that allows several selections so that no matter what your line voltages are in your home you can get the exact output required for the amplifier. The Ameritron transformer also had a secondary winding, which could be used for providing a separate bias supply. So I called them up to see if they would sell me one of their transformers. The answer was “of course” if you want to pay $72 plus shipping. All total came to about $87 and change. (Toroids of Maryland also makes a suitable transformer that will work fine for this application which they carry as a stock item - #782-382. You can contact them at 1-888-286-7643 or email to sales@toroid.com. Check with their technical department to make sure you will be getting the right transformer - the specification sheet indicates 38VACRMS at 21.6 amps. Tell their engineering department you will need 50VDC under load at 20-25 amps on peak. I am having them custom make me a much larger transformer for a 1200 watt solid state rig. They have been very professional, informative, and helpful!)

In the Ameritron design they used a “flying choke” for voltage regulation. Although this seemed like a good idea I did not think it necessary providing enough capacitance was built into the supply. Moreover I did not have the room for the choke in the cabinet I wanted to use. A simple full wave rectifier plan was all that was needed for the design. Also I needed to think about the metering, as I wanted to monitor both the voltage and the current. The basic full wave rectifier is indicated below. A good rule of thumb for high current DC power supplies is about 6-7,000ufd for each 'average' amp needed. I found five filter capacitors rated at 15,000ufd and 50VDC (C1-C4 RF Parts No. CGS153U050 Mallory 15,000ufd 50VDC Metal Can 2.0 x 4.2 $12.95 each). After talking to the vendor they confirmed that the peak "surge" voltage rating on the capacitors was 67VDC, and they would probably not breakdown or leak with an idle voltage of 55VDC. I hooked them up in parallel for a total capacitance of 75,000ufd, and in operation this is providing good results. The D1 bridge rectifier is rated at 35 amps at 200V P.I.V. (All Electronics FWB-352 - $2.50), and has proven to be more than adequate to handle the current. R1, R2, R3 and R4 were selected more out of necessity as I had four 22 watt 75 ohm “sand” power resistors on hand. ***(I have since decided that I only needed one pair to keep the heat down so I now only use R1 and R4 to ground - they draw a little over one amp instead of two plus! I also added a fifth 15,000ufd filter capacitor.)*** It is a good idea to keep the bleeder resistors away from the filter capacitors - the latter do not like heat!

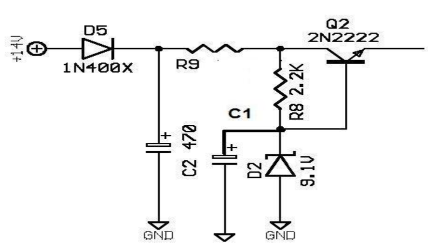
Main Power Supply Schematic



R5=20 ohm 20 watt wire wound resistor; RL1 is a solid state 25 amps w/3.0vdc activation relay ("Hockey Puck" solid state relay with paired SCR output). T1 and the four filter capacitors as noted in the text.

(Note: The secondary windings for the bias supply are not shown on T1)

Surge Delay Circuit



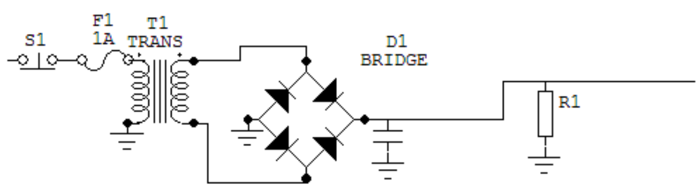
R9=47ohms; C1=2,200ufd @25VDC; D2 = 5VDC to 9.1VDC zener diode @1/2 watt

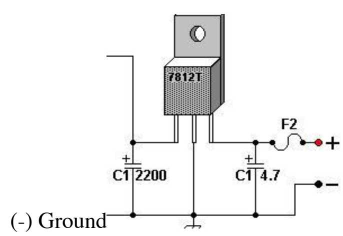
The power supply capacitance of 75,000ufd acts like a direct short on startup so I put together a surge-delay circuit using a solid state relay (Hockey Puck) that is rated at 25 amps, and triggers with a minimum of 3.0VDC. The circuit shown above has about a two second delay before Q2 is turned on. The delay allows R5 (the 20 ohm resistor) that is across the AC leads of the solid state relay ("Hockey Puck" SSR - solid state relay series - w/paired scr output) to conduct when the power is initially turned on feeding the primary of the transformer, and inhibiting the surging current. The reduced power activates the bias supply which is used to feed D5. Current than starts to flow through R8 and R9, pulled by the Zener diode D2. This allows C1 to charge which keeps the voltage on the base of Q2 below its cutoff. Once C1 becomes fully charged the transistor (Q2) turns on sending 7.5VDC via its emitter to activate the "Hockey Puck AC" relay shorting the AC across R5 and allowing full power to T1. (Note: increasing the values of R8 and C1 will further delay turning on Q2.) It works great and you can see the action visually. On power up the B+ voltage hesitates at about 30VDC for nearly two seconds, and then jumps up to 55VDC - its idle state.

The other necessity was for metering. I purchased a volt and an amp meter. The latter had the matching “shunt” included which is necessary due to the high amperage, and reads to 30 amps. The voltmeter goes to 100VDC. As noted, the primary of the transformer is fused with a 15 amp slow-blow type. (If you decide to use a 220VAC source you will have to un-ground the primary, and hook both leads directly to the two "hot" 220VAC feed lines. You will, of course, have to make the necessary change in the secondary transformer options to get the proper voltages out. Make sure the unit is grounded both by the feed ground and the external ground.)

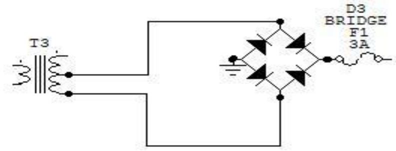
The bias power supply has a full wave rectifier but only one capacitor. The second supply was probably not necessary but I wanted an independent source for the bias and to activate the T/R relay (Note: the schematic below does not show that the secondary windings coming off of the main transformer, as they actually do). I used a second bridge rectifier - a duplicate of the one used for the main supply. The filter capacitor was a 50VDC, 5,000ufd electrolytic, and the bleeder resistor - R1 - is a 22 watt 75 ohm sand power resistor. The secondary voltage measures about 24VDC. This voltage level works fine in the regulation circuit described later. To get 12 volts (DC) for the relay I put together a 7812T voltage regulator (see schematic below), which draws its DC power from the bias supply - the 2712T is commonly available at around $1 or so (I have ten or so in my junk box - email me if you can't find one and I will mail it to you). The metal backing needs to be mounted on the chassis for heat dissipation. The number one lead is connected to the bias B+, and the middle lead is grounded. The outside lead has a 4.7 ufd capacitor, and a one amp fuse for circuit protection.

Bias Power Supply Schematic (28VDC)





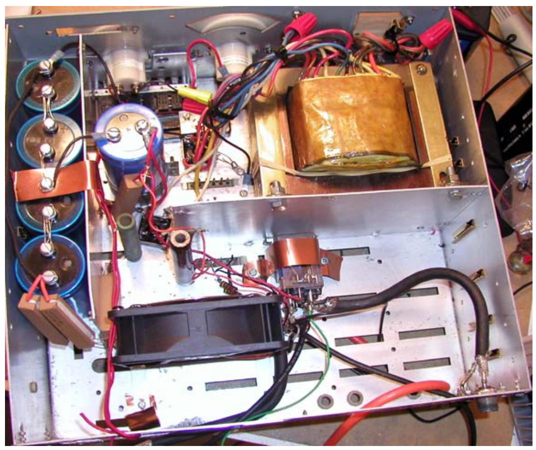
(See text for detail)



Power Supply For Fans - T3 Radio Shack or similar with 12VAC Center Tap.

I constructed a third small power supply for the Chinese fans. I used the center tap of a 12VAC transformer (any model will do with at least three amp secondary capacity) so they would run quieter. The bridge rectifier was the same as used for the other two supplies. The fan B+ is fed from the three amp fuse - I did not use filter capacitors as they are not necessary. The fans were purchased from All Electronics CAT# CF-152 at $5.00 each. F1 should be 3 amps. One is mounted on the heat sink and the second is placed in front of the circuit board.

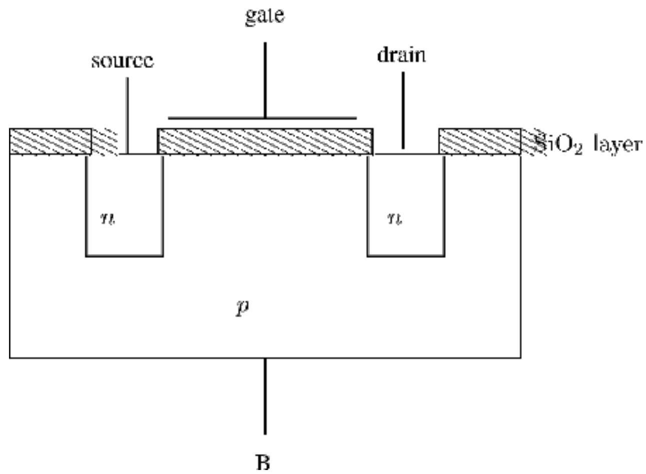
I considered all along using an old chassis from a Heathkit SB104 I bought for parts. Somehow I managed to fit everything into the front of the unit leaving what I hoped was enough room for the circuit board, T/R relay, and the transformer I needed to power the fans.



I like to test things as I go along to there won't be too many surprises when the final assembly is done. Accordingly, I fired up the power supply and everything seemed okay and the voltages all checked out.

In going over the suggested circuit and description by Helge Granberg, the Motorola engineer it was clear that the bias plays a big role in the manner in which the power FETs operate. A review of some of the factors helped me better understand the design. Metal oxide field effect transistors (MOFETS) offer a lot of advantages over bipolar transistors. Some of the benefits are: (1) higher input impedances allowing for better matching networks and broader bandwidths, (2) superior stability and less likely to self oscillate, (3) sturdier and better able to handle high levels of reflected power, (4) they can handle much higher power levels, and (5) they exhibit exceptional "gains". Also FET's tend to self regulate when they heat up instead of the "out of control" currents that often destroy bipolar devices. The MRF 150's used in the project are enhancement mode N-channel devises.

One might recall that MOSFETs conduct through the same media, P or N material, influenced by the "field effect" created by the stimulation of the opposite material surrounding the conducting media, including the gates. N-channel devices have to have greater positive voltages on the drains than the source as opposed to P-channel devices. Unlike bipolar transistors, the gate to source DC resistance in MOSFET's is extremely high - in the one plus mega ohm range. Accordingly very little current flows through the gate, and the theoretical gains are almost infinite Most power FETs are "enhancement mode" devices for a good reason. They require a positive voltage across the gate or they will not conduct. The term "enhancement" comes from the fact that you have to enhance the media to force it into a conducting status. Think of them like "on-off" switches - when you apply positive voltage on the gates they turn on, and when the voltage goes away they go off. Basically what is happening is that the applied positive voltage on the gates repels the "holes" in the P material around the "doped" area. You can visualize the effect like a two magnets forced together on their same poles, and you can feel the repelling effect. With almost no current, the positive bias forces the "holes" away from the doped area and opens a channel which allows current to flow between the source and the drain.

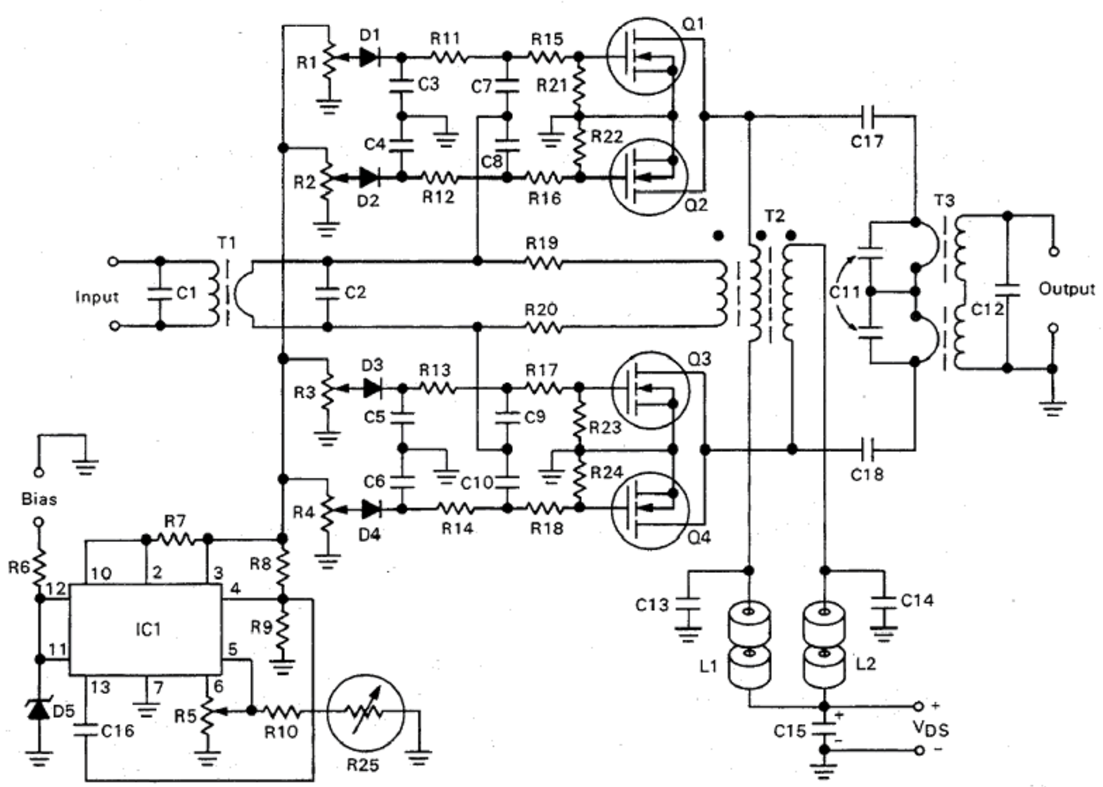


MOSFET transistors have metal gates which are insulated from the semiconductor by a layer of SiO2 or other dielectric. In enhancement type MOSFETs, the application of a gate voltage activates the channel (by inducing a layer of carriers between source and drain under the gate,

One can easily see that the enhancement mode provides the high power designer with a good tool. In short, you can turn the FET on or off with applied bias. With the B+ voltage on the drains during “standby” one does not need to worry about the device conducting or “taking off”. This would not be the case with “depletion” mode FETs.

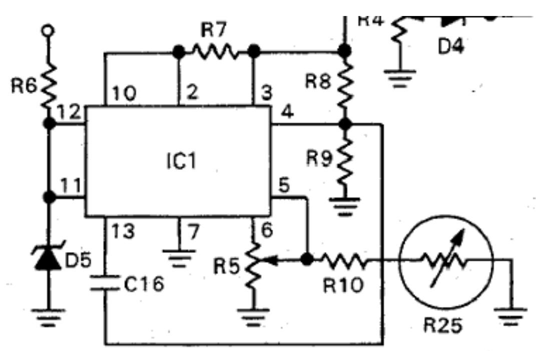
A look at the Motorola application schematic will help as we work our way through the design.

FIGURE 2 — Detailed Schematic



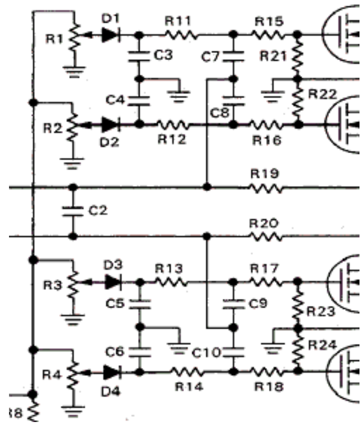
R1–R5 — 10 k Trimpot
R6 — 1.0 k/1.0 W
R7 — 10 Ohms
R8 — 2.0 k
R9, R21–R24 — 10 k
R10 — 8.2 k
R11–R14 — 100 Ohms
R15–R18 — 1.0 Ohms
R19–R20 — 10 Ohms/2.0 W Carbon
R25 — Thermistor, 10 k (25°C), 2.5 k (75°C)
C1 — Not used
C2 — 820 pF Ceramic chip
C3–C6, C13, C14 — 0.1 μF Ceramic
C7–C10 — 0.1 μF Ceramic chip
C11 — 1200 pF each, 680 pF mica in parallel with an Arco 469 variable or three or more smaller value mica capacitors in parallel
C12 — Not used
C15 — 10 μF, 100 V Electrolytic
C16 — 1000 pF Ceramic
C17, C18 — Two 0.1 μF, 100 V Ceramic each, (ATC 200/823 or equivalent)
D1–D4 — IN4148
D5 — 28 V Zener, IN5362 or equivalent
L1, L2 — Two Fair-Rite 2673021801 ferrite beads each or equivalent, 4.0 μH
T1–T3 — See text
Q1–Q4 — MRF150
IC1 — MC1723CP
All resistors 1/2 W carbon or metal film unless otherwise designated.

Lets start with the bias voltage regulation part of the circuit. I have sectioned it out for better focus.



The Zener diode (D5) is used to reduce the bias voltage below the maximum allowed by IC1 of 40VDC. Since the bias supply only provides 24VDC the diode does not draw current and is not necessary unless you plan on using the B+ for the source. The regulated output comes out of the divider at 3 and 4. The thermistor R25 should be in physical contact with the copper spreader described later. It is in the circuit to change value with temperature, and lower the bias voltage output if heat starts to be a factor. In theory it would drop the bias to a level that would automatically reduce the output of the amplifier if the devices became too hot. R5 regulates the output voltage, and is set for about 7VDC as the source bias for the amplifier.

The bias should be individually set using R1,2,3, and 4 for each of the MRF150s so they draw 100 to 150miliamps each as noted below.

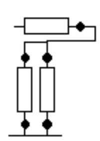


The four diodes (D1-D4) act as blocking mechanisms in case one of the FETs goes bad and shorts the B+ from the drains back through the bias network. R1, R2, R3, and R4 control the bias for each individual FET. Initially the potentiometers should be set so the variable output tap is shorted to ground. This will insure that when B+ is applied to the drains the devices will not conduct, or over conduct! When setting the bias (later) put a high-resolution amp meter between the B+ and the circuit board. Than adjust each potentiometer so that its FET conducts about 100 to 150 milliampere, or collectively 600 milliampere. It is sort of a progressive thing…the first one brings the amp meter to 150, the next to 300 and so on. I routed the bias supply through the T/R relay. This insures that when the relay goes into the receive mode the bias is cut off immediately to the FETs.

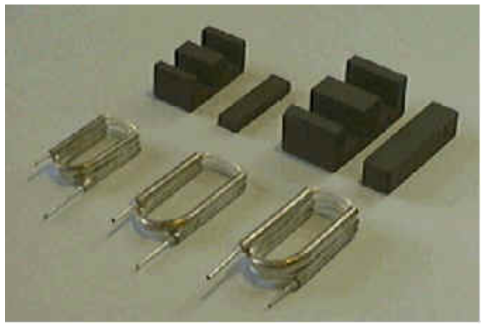
On the input for the excitation drive I added three two-watt 120 ohm carbon resistors in parallel to ground, and two-one watt 24 ohm resistors (in parallel) feeding T1 in series. These were chosen based on my available inventory. I am trying to source five watt 30 ohms ones for the series connection, and 50 ohms for the ground. This would improve the attenuation to a safer level. The basic idea is to protect the gates of the MRF150's from excessive RF, which will "fry" them in a second. It takes about 20 to 25 watts to drive the amplifier to 600 watts with existing combination. The ideal drive level would probably be 50 watts or so, with more attenuation in the circuit. This would work even if the drive level reached 100 watts! One can experiment with different combinations to achieve a safer circuit to better protect the gates.

To input on circuit the circuit board at junction between the series resistor and the grounding resistor.

To T1->

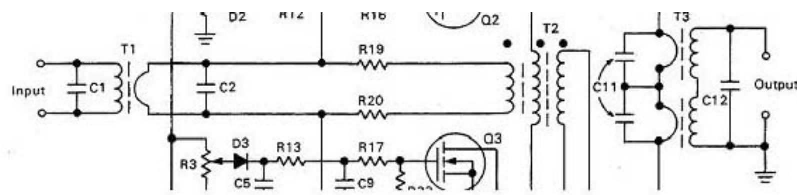


Working through the problems with the impedance matching transformers in the circuit is probably best left to engineers with experience in this area. The whole area of “ferromagnetic-core materials” is a study into itself. Regardless of what form the coils or transformers take the core permeability is critical and must provide sufficient reactance at the low end of the operating frequency range. The rule of thumb is that it should be at least four times the reactance that the winding is designed to look into at the lowest frequency to be used. The four input and output broadband transformers in the Motorola applications are probably the most critical components in the amplifier. Typically the primaries of the “binocular” type transformers consist of brass or copper tubes inserted into ferrite sleeves. The tubes are shorted together at one end of the circuit board to make the "primary". The secondary “high temperature” wire is threaded through the tubes. Since the “tubes” act as a single winding, the transformation ratio is limited to the squares of the secondary - 1, 4, 9, 16 etc. The cores must be large enough so the material will not saturate at the designed power level. This can cause many problems including extreme heat, transformer non-linearity, distortion products etc.



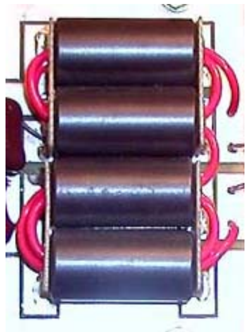
Binocular Transformers

In the schematic T1 and T3 have a 9:1 impedance ratio, and are wound on “binocular” cores (T1 should have 3 turns of "high temperature wire" on the secondary - don't make the mistake of using four turns as the first turn on ferrite transformers looks like 1/2 of a turn). T1 is looking at a 5.5 ohm secondary from the 50 ohm or so driving excitation, while T3 is the opposite taking a 5.5 ohm load to a 50-ohm output. T3 uses two “binocular” cores hooked up in series. According to Granberg excessive heat resulted with the use of only one core so he hooked up two cores in series with a lower permeable material to reduce losses and heat generation. The two cores in combination provided the necessary reactance at the lowest operating frequency of 2.0MHz for the design. (The resulting ratio worked out as the square of the primary in series is 4, or 2 squared, and the secondary at 36, or 6 squared, which calculates to the 9:1 ratio).



A ferrite two-hole balun type core was used for T2 whose primary function is to provide a load balance for T1 and feedback to the gates of the four FETs for stability. Low permeable ferrite was used to reduce heat and still provide proper reactance levels. The application note has a more detailed analysis of the matching transformers and their impedance and load issues. (**You can download the EB104 application note from the Communication Concepts web site - www.communications-concepts.com**)

T3 - Double "Binocular" Core



As a non-engineer type it seemed to me that buying the transformers pre-wound on the properly engineered material was the best way to go. Communication Concepts offers the whole package with the ready-made circuit boards, pre-wound impedance transformers, and all of the hard to find parts for a reasonable dollar amount. Alternatively, winding your own would not be that difficult but you would have to make sure you had the proper core, wire etc. (RF Parts carries high temperature wire, and a good selection of ferrite transformers).

***Note: I received the following email from Bruce Meyer regarding the ferrite ratings: Dear Tom, Without getting too technical, 43 material has a perm of 850. 61 material 125. The 43 material will have basically 8 times the inductance of the 61 material. This is optimum for 2-30 Mhz. Although the 61 will work it won't perform as good as the 43 material. If power levels get much higher then the 61 material may be a better choice since it will not saturate as easily as the 43 material. For the EB 104 though 43 material is optimum. For the EB 104 our RF 1000 w/43 material is the one Helge used and recommended.* He later wrote "*For T1 an RF 400 is used. This transformer uses 43 material (850 perm). Fair-Rite part # 2643006301 beads. It is wound 9:1, three turns with *22 gauge Teflon wire Type E. T2 uses 2 RF 1000,s This transformer also uses 43 material. Fair-Rite part # 2643540001 beads. Both have 9:1 impedance ratios wired in series. Wire is # 18 gauge Teflon wire Type E. Both of these transformers are manufactured by RF Power Systems and available through Communication Concepts. By the way I used to work with Helge at Motorola. His son Mike works with me now.*" Bruce's company can be found on the web at [www.rfpowersystems.com.](http://www.rfpowersystems.com)**

Selection of the proper "perm" material for the transformers is somewhat of a conundrum. If you select a relatively high "perm" material so you will have the necessary reactance at the lower frequencies, you will likely have problems due to the rise in reactance with higher frequencies. At some point the transformers will saturate due to the increased reactance. Accordingly, the design engineer has to come up with a compromise based on the range of frequencies wanted. For example, if you do not operate on 160 meters you may be able to lower the "perm" material in T3 which would lower the reactance, especially at the higher frequencies, and you may be able to achieve full output on 10 or 12 meters. The way the amplifier is set up I can only get about 400 watts on 12 meters, and 350 on 10 meters. Since I run "barefoot" on these bands keeping the 160 meter option is preferable.

Armin Sturm (DK9PY) did some very productive testing on the circuit and was able to get good power out on 12M and 10M with a change in component values. Armin sent me the following email, which will be of interest to everyone building this project:

Dear Tom,

I wanted to update you on the EB104 PA project and what I have done in the mean time. The PA works fine now and after a lot of experimenting without any damage (hi), I am now in a position to install everything into the housing and get it operational. As reported before, the DC input power in relation to the PA output power was not good, meaning that the efficiency was not acceptable for operational use. So I experimented with the output transformer and different impedance ratios, but had no success, as only 1 : 16 or 1:4 were easily possible. The best appears the 1:9 ratio. However, when increasing the voltage to 52 or even 54 Volts, the PA drew exactly the same current as before and there was no noticeable increase in output power. This means that the efficiency becomes even worse. So I tried to reduce the voltage and ended at 41 Volt. The DC current did not noticeable change and the output power stayed still the same. This means that the efficiency became better. Compare the 52 Volts (or even the 54 V) 20 A to 41 Volts 20 A and still achieving the same RF output power.... Result: First, 41 Volt seems a good voltage to operate the PA with, as with this voltage, the output impedance of the MOSFET circuit with the 1:9 transformer matches the output impedance closer to 50 Ohms, hence more RF power is coupled out. Unfortunately I cannot reduce the switching PS voltage to a value lower than 41 Volt. Secondly, the capacitors C11 (1200 pF) are far to high to meet the upper frequencies of the specified bandwidth of 1.5 to 30 MHz. With 1200 pF, the output power drops dramatically above 22 MHz. At 28 MHz they become hot or even dies (when using CW). Without the C11 capacitors the PA works still fine, the 1 dB bandwidth is from 1 MHz to >40 MHz, however the efficiency on 160 and 80 and in the mid range around 14 MHz could be increased by adding a C11 with a value of approx. 850 pF. Above 30 MHz the output power starts to drop. The final result now is:

Band U A P in P out P in DC eff.

Amplification

160 41 25 4,5 550 1025 54% 20,87

80 41 25 4,8 500 1025 49% 20,18

40 41 24 5 500 984 51% 20,00

30 41 22 5,5 500 902 55% 19,59

20 41 20 5,3 500 820 61% 19,75

17 41 20 6 450 820 55% 18,75

15 41 18 7,5 500 738 68% 18,24

12 41 17 8 480 697 69% 17,78

10 41 15 10 450 615 73% 16,53

You can reach Armin via his web page at http://dk9py.myvnc.com/index.htm

A brief description of the relay circuit follows. It might be important to note that a lot of engineers and hams do not believe in combining the antenna relay switching functions with the bias switching. The fear is that rf will work its way into the bias and cause problems. Heathkit engineers did not subscribe to this for years, and most of their amplifiers have the bias and the antenna switching combined into one relay. I followed this example with the thought that I could always change it if there were problems. Just to be safe I added a small toroid wound with six turns between the relay bias connections and the MRF-150 board. An rf choke would work as well. I used an inexpensive three pole relay I bought from All Electronics - CAT# RLY-632 - $3.00.

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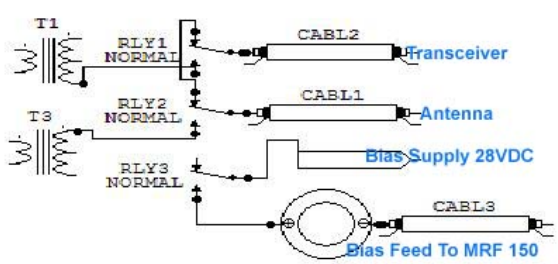
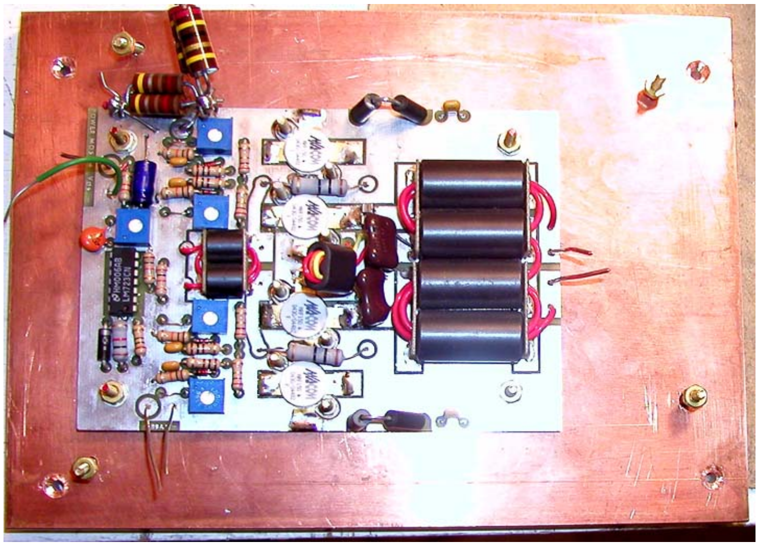
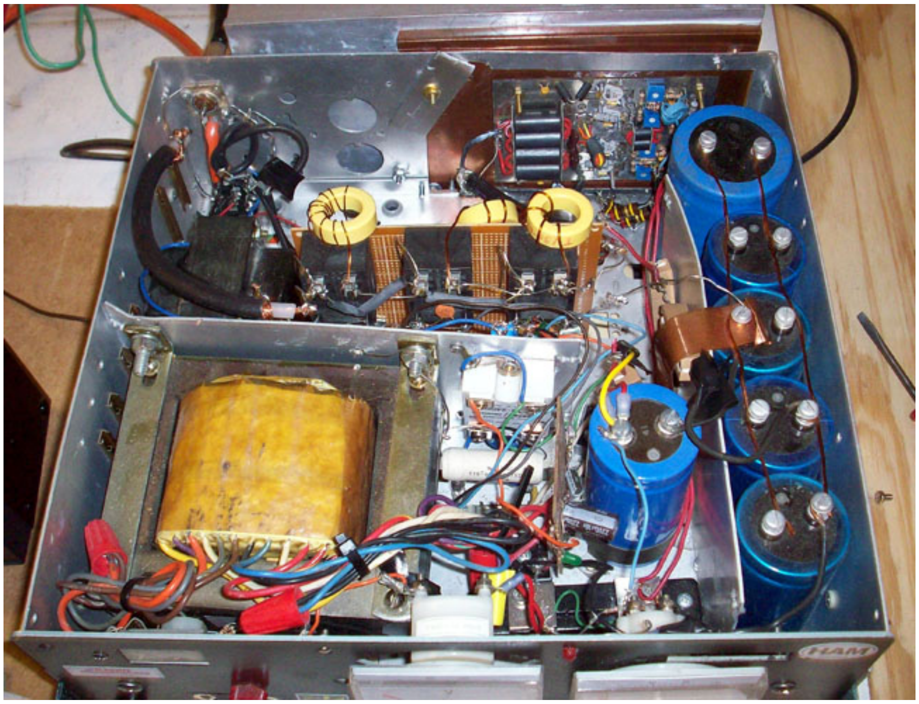


The relay circuit is shown above. The 12VDC is fed to one side of the relay coil and the ground (return) line on the coil is fed outboard to the transceivers "amplifier" relay control - push to talk on SSB (this connection is not shown). On activation by the transceiver to the transmit function the 12VDC is grounded and the relay is activated. This routes the transceiver output to the resistors feeding T1 on the MRF-150 circuit board, and places the output from the MRF-150's to the antenna. Concurrently the third pole routes the 24VDC bias to the MRF-150 where it turns the FET's 'on' with the preset voltages discussed earlier. Coax cables are used for all connections, and the toroid is wound with six turns of wire as shown and as discussed earlier in the above text. There have been no problems with this setup since I first put the amplifier on the air in late 2004 - no sign of any "rf" problems. Those that are worried about this setup can easily add a second relay for the bias. It works good in that the bias is cutoff concurrently with the "driving" rf from the transceiver, and the MRF-150's stop conducting immediately. The change is instantaneous and there is no need for a "delay" circuit to protect external equipment.

The next hurdle that was clearly a potential problem was the 500 watts, or so, of heat energy that had to be dissipated. Just about everything I read indicated that the MRF150s have to be mounted on a copper spreader in order to remove the heat away from the devices. Communication Concepts offered both the copper spreader and a suitable heat sink so I bought both items. The resulting assembly went together a lot easier than I had envisioned. To make sure that the FET's are lined up I placed the blank circuit board on top of the copper spreader, lined up with the way I wanted it to be bolted. Placing all four FET's in their respective sockets allowed me to mark their mounting holes on the copper. At the same time I marked the four mounting holes for the circuit board. I then drilled the holes based on the markings. (I counter sunk the copper on the opposite side so all of the bolt heads would be flush with the copper thereby allowing it to be flush mounted later to the aluminum heat sink. Feeding the bolts from the bottom up insures that they will not protrude on the bottom.). The next step was to mount the FET's onto the circuit board. Temporarily placing the screws you intend to use for their mounting into the FET's and through the holes will align them for soldering (don't secure them). I then soldered the leads to the board in a manner that allows for the flanges on the FET's to be slightly below the circuit board. At this point the FET's (soldered to the circuit board) can be bolted to the copper. Use a small dab of "heat transfer" grease on the bottoms of each FET. Be careful to use small enough screws and bolts so that the nuts will clear the plastic covers on the FET's. Once the FET's are secured the circuit board can be bolted to the copper. You will need to use small spacers to keep the bottom of the board from shorting out on the copper. After the board is secured to the copper it is a good idea to check and make sure the connections are not touching the copper. A secondary check with a volt-ohm meter should show high resistance when reading the power input connection to ground. The copper is now ready to mount on the aluminum heat sink. Once again use "heat transfer" grease between the two surfaces. The whole process seems somewhat daunting but when you practice it a couple of times you will get the idea and it will go together easily.



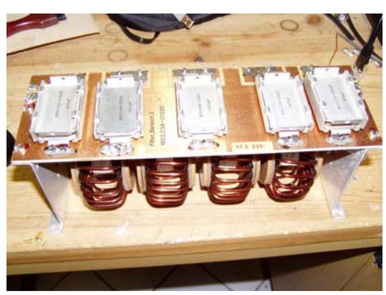
Attaching the heat sink, and than bolting the assembly to the SB104 chassis was a job! Finally I got it all together.



The "Solid State 600 Watt Output Amplifier" ready to go. Starting at the upper left corner and moving clockwise- the t/r relay, the circuit board, filter capacitors, full wave rectifier, soft start module, power transformer, and the relay switched low pass filter in the middle. One can easily see that I am not a contruction artist! The separate low pass filters (80M, 40M and 20/17M) are switched from the front with push bottons - led's light up under the buttons to confirm that the relay has engaged. Now it is very easy to change bands by just pushing the respective band button.

Granberg's analysis of the harmonic amplitude indicated -30 to -40 dB for the 2nd harmonic, and the highest 3rd amplitude at only -12dB at 6.0 to 8.0 MHz carrier frequencies. This obviously is a problem. The FCC mandates that harmonic output needs to be at least -40dB! Since I planned on using the unit on 80, 40, 20, 17, 15, 12 and 10, I would need separate filters for each band. A low pass filter I had in my inventory that had a cutoff of 30MHz would work okay for 12 and 10 meters since the second harmonic would easily be eliminated.

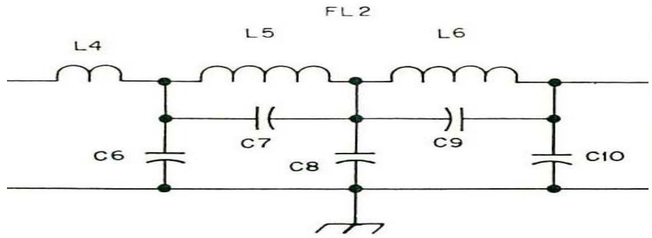
In the original model I built the filters in small Radio Shack aluminum boxes with coax connectors used for the input and output. This was just too cumbersome when changing bands as it was awkward screwing them in and out. Accordingly I had Far Circuits make a circuit board for the five filters I needed. To switch them in and out I used relays which are activated from the front panel. To make sure they are powered there are LEDs under each push button indicating that the relay is powered "on". The end result has been very good.



Armin Sturm's (DK9PY) Filters With Vacuum Relays

While the Granberg filters detailed below worked well I later switched to Chebyshev filters as they were easier to construct.

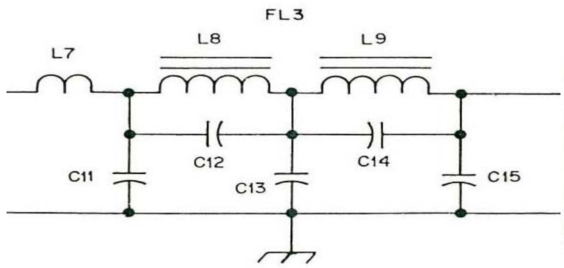
17 **Meter Low Pass Filter**



FL2 (18 - 22 MHz)

L4 — 0.28 μH, 5 ts airwound, 0.6" ID, 0.6" long.
L5 — 0.33 μH, 12 ts on T130-0 toroid.
L6 — 0.27 μH, 10 ts on T130-0 toroid.
C6 — 47 + 39 + 15 + 10 pF.
C7 — 2 × 15 pF.
C8 — 4 × 39 + 47 pF.
C9 — 2 × 39 pF.
C10 — 2 × 39 + 10 pF.

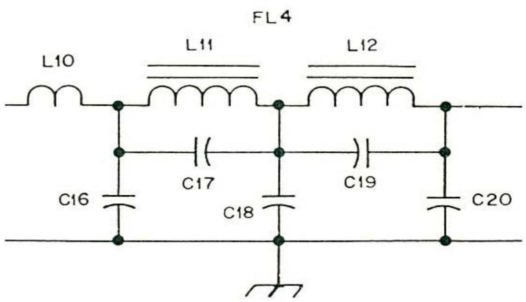
20 Meter Low Pass Filter



FL3 (10 - 15 MHz)

L7 — 0.39 μH, 6 ts airwound, 0.6" ID, 0.6" long.
L8 — 0.41 μH, 7 ts on T130-6 toroid.
L9 — 0.32 μH, 6 ts on T130-6 toroid.
C11 — 3 × 47 + 10 pF.
C12 — 39 + 10 pF
C13 — 4 × 39 + 100 pF.
C14 — 56 + 68 pF.
C15 — 2 × 47 + 10 pF.

40 Meter Low Pass Filter



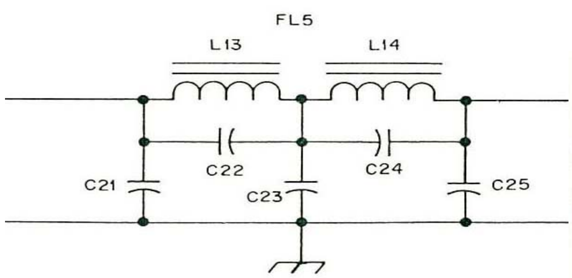
FL4 (7.0 - 8.0 MHz)

L10 — 0.85 μH, 8 ts airwound, 0.6" ID, 0.6"
L11 — 0.90 μH, 9 ts on T130-6 toroid.
L12 — 0.82 μH, 8 ts on T130-6 toroid.
C16 — 2 × 100 + 2 × 47 pF.
C17 — 2 × 39 pF.
C18 — 2 × 150 + 2 × 100 + 47 pF.
C19 — 150 + 39 pF.
C20 — 2 × 100 + 47 pf.

FL5

L13 L14

80 Meter Low Pass Filter



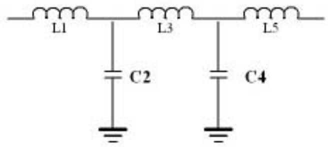
FL5 (3.5 - 4.0 MHz)

L13 — 1.80 μH, 12 ts on T130-2 toroid.
L14 — 1.6 μH, 11 ts on T130-2 toroid.
C21 — 2 × 82 + 390 pF.
C22 — 2 × 82 pF.
C23 — 2 × 390 + 3 × 82 pF.
C24 — 2 × 220 pF.
C25 — 2 × 220 + 82 pF.

- Low-pass filter circuit and component values for 1.6-30 MHz operation. Standard capacitor values have been placed in parallel to obtain nonstandard values. Toroid cores are Amidon, Palomar or Micrometals Corp. powdered-iron units. The designator "×" means "times," E.g., 2 × 47 + 10 pF means two 47- and 10-pF capacitors, all in parallel to provide 114 pF. Wire type for all inductors is no. 14 enameled. Capacitors are RMC 3-kV disc ceramic, except those units that are 390 pF and higher, which are RMC 2-kV units. Relays are Deltrol 20693-83/405 with 12-V coils.

The filter calculations you find you are experiencing noticable attenuation on the output from the filters you can spread out the wires on the transformers somewhat and see if that helps. Another trick is to reverse the input/output leads. One of the problems with the high voltage capacitors specified are the available tolerances.

Even though the Granberg filters work okay in more recent experiments the Chebyshev filters worked better for me. They are easy to design. Using the ARRL Handbook you can do the math easily, as follows:



Inductive Filter Layout

Using the following table you can calculate the components:

No.	Fcc	-3db	-20db	L1 - L5 uH	C2 - C4 pF	L3 uH
1	0.74	1.15	1.69	5.6	4700	13.7
2	0.901	1.26	1.81	5.6	4300	12.7
3	1.06	1.38	1.94	5.6	3900	11.8

For a 40 meter filter I chose a cutt-off frequency of 9.01mHz - No. 2. This will provide plenty of attenuation for both the even and odd harmonics. All you need to do is multiply the Fcc by 10 and divide the component values by 10. Therefore you get 9.01mHz, L1/L5=.56uH, C2/C4=430pF, and L3=1.27. I used Amidon toroids for the inductance; T-130-6 for L1 and L5, and T-130-2 for L3. Their formula for calculating the number of turns follows:

$$N = 100\sqrt{\frac{\text{desired 'L' } (\mu h)}{A_L\ (\mu h/100 \text{ turns})}} \qquad L(\mu h) = \frac{A_L \times N^2}{10{,}000} \qquad A_L(\mu h/100 \text{ turns}) = \frac{10{,}000 \times \text{'L' } (\mu h)}{N^2}$$

N = number of turns L = inductance (μh) A_L = inductance index (μh)/100 turns)

AL for the T-130-2 is 110, and for the T-130-6 is 96. Doing the math results in 7.63 (8) turns for L1 and L5, and 10.7 (11) turns for L3. In practice this worked out right on the money. Of course, different toroids have different formulas so you will just have to research the factors in order to achieve the correct inductance.

The last chore was to hook up the fans - one on the inside directed at the board, and the other on the heat sink. After firing them up the fans they were making too much noise so I wired the center tap of the transformer in place and dropped the voltage to about 7VDC. They now run much quieter and move more than enough air to keep everything cool. I decided later to move the inside fan to the heat sink as it was really not doing much meaningful work blowing on the circuit board.

With everything ready to go I hooked up a dummy load and set the bias. Surprisingly there were no problems. I decided to “go for it” and hooked up the amplifier and my 11-element log periodic multi-band antenna. With the transceiver set for 10 watts I keyed the amplifier and started increasing the drive until my output wattmeter (on voice peaks) indicated 600 watts (note: the 600 watts was achieved on SSB voice peaks as measured with a Autek WM1 computing meter which captures peak output). The SWR was where it usually runs so I made a call. It took a nanosecond for someone to report a 20 over signal with very clear audio. Holly Cow - it works!

I found out that a slight increase in drive power increases the output to 800 watts. However, running at the rated output will keep everything cool. You may notice a slight increase in 'resting' current as the FET's heat up. This is normal and the voltage regulation circuit with the thermistor mounted on the copper will mitigate this increased idle current somewhat by dropping the bias voltage. If the heat is being removed properly the resting current will not go much higher than 1.5 amps compared to its cold state of about .75 amps. If this becomes a problem you can always speed up the fans or drop the power back a notch. With a low SWR on most of my antennas I can talk away with peak output of 600 watts and the copper spreader and aluminum heat sink stay remarkably cool. This is one COOL DUDE! To hear and see the amplifier in operation go to YouTube - K0GKD.

Updating comments: There are some very good suggestions and modifications noted in the technical correspondence of the October 2007 QST of interest to anyone wanting to build this unit. If I get the authors permission I will post his comments here.

My amplifier has been running with weekly use for about two years - not without incidents. During the winter of 2007 the amp quit suddenly. When I opened it up one of the FETs had burned through the circuit board. On examination it had worked lose from its mounting and the heat did the rest. In rebuilding the circuit board I found some very tiny lock washers that would just fit between the FET casing and over the bolts. Now the FETs are secured so they can not work lose and hopefully this will not be a problem going forward.

The other modification was to incorporate the low pass filters inside of the unit. The filters are switched by relays that are controlled from the front panel. This is really a great improvement when changing bands. Now I just push the appropriate button and an LED comes on indicating the relay has engaged and the amp is ready to go on the changed band. I asked Far Circuits to produce a circuit board for the filters and it is now available. When I get the part number I will add it to this web page.

I received the following letter from Colin Darby M0OTT which were published in the October 2007 issue of QST:

Dear ARRL

I read with interest the construction article “Homebrew Solid-state 600 W HF Amplifier” by K0GKD published in the most recent copy of QST.

Having recently constructed the same Motorola design from a set of components from the US based company Communication Concepts I do have a number of extra construction hints (in no particular order) that may aid future builders.

1. The generic diagram shown in the QST article from the EB104 Engineering Bulletin differs slightly from the actual circuit used when constructed on the PCB supplied. Also the EB104 Bias Configuration as redrawn by Communication Concepts is slightly in error.

2. The value of R15-R18 has been changed to 2.7 ohms (supplied by Communication Concepts). R19 and R20 may have to be up rated for heavy key down applications

3. Due to the very close spacing between the PCB and the copper heat spreader, ensure that all solder joints are cropped to within 2mm on the lower side of the PCB board.

4. C17 and C18 are the four physically thickest 0.1 chip capacitors and sit on the top surface of the PCB. Only thin chip capacitors are fitted to the underside.

5. M3 bolts and nuts can be used to mount the PCB to the copper spreader. M3 nuts used as spacers provide the correct clearance between the two surfaces.

6. Fit a socket for IC1 to allow easy replacement.

7. The four-ferrite beads (L1, L2) are electrically conductive and must be mounted so that they do not touch the earth plane, otherwise you will have a fire on your hands!

8. The phasing on T2 is critical; the red and orange leads need to be on opposite sides at the top and bottom of the transformer. If in any doubt phone Marlis at Communication Concepts for advice before proceeding with the construction.

9. Trim pots R1-R4 need to be fitted slightly up in the air to ensure clearance for other components.

10. When all components are fitted to the PCB, double test that there are no shorts on the 50-volt rail. You may have to remove a very small section of the PCB copper in close proximity to the MRF150 FET'S etc to avoid this problem.

11. Only use silver loaded heat sink compound to ensure maximum heat transfer and, fit two large diameter (120mm) 1400-RPM fans to provide adequate cooling and low noise.

12. The current bias stability of the MRF150 FET'S is greatly improved if the out put of the voltage regulator (IC1) is reduced from 7volts to 5-5.5volts (via R5) and the thermistor (R25) is mounted in close thermal contact with one of the MRF150 transistors. I clamped the lead of one end of the thermistor close to its body under an extra nut on one of the securing bolts of the output transistors.

13. The Motorola data sheet suggests 0.25 amps per device as a suitable bias current.

14. The bias voltage for the amplifier may be derived from the 50volt supply and, any relays and control circuitry powered by the existing 13.8volt power supply used by your transceiver.

15. For those in Europe a suitable toroidal mains transformer (40 v + 40 v @ 12.5 amp each winding 1000VA) can be sourced at a very reasonable sum from Clairtronic Ltd in the UK sales@clairtronic.co.uk on +44 (0) 1234 330775. Use 63volt capacitors in the power supply, as the supply will be approximately 57 volts without a load.

16. Provide a suitable 20-25 Amp fuse in the +50 volt lead and, fit a rectifier diode (of adequate surge rating) with its cathode connected to the amplifier side of the fuse and its anode to earth to protect the amplifier from reversed power supply leads.

17. When testing for the fist time ensure that pots R1-R4 have their sliders at earth potential, and that a low current fast blow fuse (2 Amp) is substituted for the normal one during the initial test phase. If the fuse blows at turn on, test for shorts, however, if it blows when setting up the bias current you may have the phasing of T2 incorrect, turning the amplifier into a high powered oscillator!

18. Do not forget that due to the high power gain you will require only around six watts or so to drive the amplifier to 600watts output.

19. Extra circuitry for ALC control etc may be required depending on usage. A 50-ohm input attenuator (5-7dB) feeding the amplifier is desirable, and can be protected from gross overload by a suitable fuse. A peak reading power meter needs to be incorporated either internally or externally to the amplifier.

20. If the RF unit and power supply are constructed as separate units (my preference), the power supply will sit very neatly under the bench alongside the transceiver supply. The Solid State Amplifier with output filters is small and light enough to stand on the back of the average transceiver if required.

21. Communication Concepts also supply suitable LP output filters at reasonable cost that are simple to construct. These appear to be perfectly satisfactory at least up to the 400-watt legal limit imposed in the UK.

22. Have fun!

Colin Darby…M0OTT

Email M0OTT at ColinDarby@FatRose.fsnet.co.uk