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Author: Tom Sowden, K0GKD

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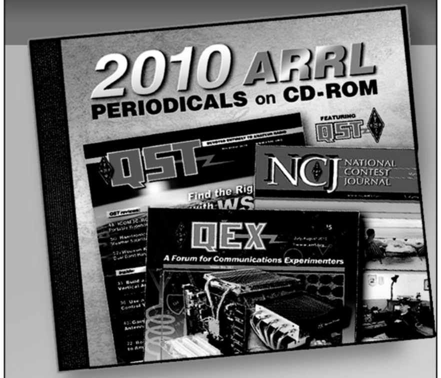

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Homebrew Solid-state 600 W HF Amplifier

Learn how to make an easy-to-build, no-tune, solid-state amplifier to provide that extra 7.8 dB punch.

Tom Sowden, K0GKD

I go along with my wife and daughter to horse shows from time to time; being there to watch them compete is fun and important as a family thing. The time in between their events can best be characterized as "watching paint dry" by those of us who don't share the enthusiasm. It is during these moments that my mind starts wandering toward ham radio, or my golf game. This past summer during such a time I started thinking about building a solid-state linear amplifier.[1] The idea of having a solid state amplifier running on relatively low voltages has always appealed to me. With this in mind I got on the Internet at the motel 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 1980s Motorola developed a line of power field effect transistors (FETs) for amplifiers and other end uses. Helge Granberg, K7ES (SK), one of their circuit engineers, wrote a number of application notes for the use of these power FETs. Over the years his designs have become widely used and to some degree the standard for commercially built solid-state amplifiers. His application note EB104 seemed to me to be the best and most practical design for what I wanted for the upper bands in the HF range.[2] Specification highlights and an excerpt that briefly describes the idea behind the design as indicated in the notes follows:

The RF MOSFET Line MRF150

- N channel enhancement mode.
- Designed primarily for linear large signal output stages up to 150 MHz frequency range.
- Specified 50 V, 30 MHz typical characteristics:
  - Output power — 150 W (per FET).
  - Power gain — 17 dB.
  - Efficiency — 45%.
  - Superior high order IMD, typical at 150 W; third order –32 dB, eleventh order –60 dB.
  - 100% tested for load mismatch at all phase angles with a 30:1 SWR.
  - 600 W RF output from four power FETs per Motorola EB104.

In the Granberg EB104 application paper the following statement summarizes some of the 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.*

Several motivating factors kept my interest moving forward:

- The idea of being able to work with relatively safe voltages (50 V dc) was appealing compared to the dangerous levels present in my Heathkit SB-221.
- The ability to switch bands and not worry about retuning or changing settings was very desirable.
- Topping the list was the fun and challenge of "building my own."

After reading everything I could gather up, the challenges became clear. First, the project would need a high current dc power source at 40 to 50 V; 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 400 W. 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 dissipate the high order products.

Power Supply

The powers supply needs to provide 50 V at 20 A or more. I decided to build a linear supply. I knew that Ameritron had a solid-state amplifier on the market so I downloaded the manual for their power supply. In studying the design I found that they use a multi-wound primary power transformer that allows several voltage selections. With such an arrangement no matter what your line voltage is you can get the exact output required for the amplifier. The Ameritron transformer also had an additional secondary winding that could be used for providing a separate bias supply. 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.[3] The total came to about $87 and change.

A simple full wave rectifier plan was all that was needed for the design. I also needed to think about the metering, as I wanted to monitor both the voltage and the current. The

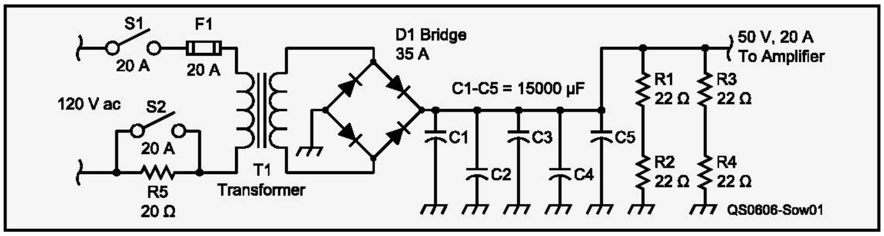

Figure 1 — B+ power supply.

C1-C5 — 15,000 µF, 50 V electrolytic. See text.
D1 — 35 A, 200 PIV bridge rectifier.
F1 — 20 A, 250 V fast-blow fuse.
R1, R4 — 22 Ω, 74 W "sand" resistors.
R5 — 20 Ω, 20 W wirewound resistor.
S1 — SPST toggle switch, 20 A, 250 V ac.
T1 — Multitap power transformer, Ameritron 406-3002. See text.

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[1] Notes appear on page 43.

basic full wave rectifier circuit is indicated in Figure 1. The four filter capacitors were selected with the highest capacitance I could find — 15,000 µF at 50 V dc. With five in parallel I would have the 75,000 Ω needed for this current. Resistor R5 limits the initial current. S2 can be closed after a few seconds to bring the output up to full voltage. The specified bridge rectifier (D1) is rated at 35 A at 200 V PIV, and has proven to be more than adequate to handle the current. R1 and R2 were selected since I had two 22 Ω, 75 W "sand" type power resistors in my parts box and I hooked them in series. They get fairly warm drawing about 500 mA, but function well as a bleeder and voltage-regulating resistor.

The other requirement was metering. I purchased a voltmeter and an ammeter. The latter had the matching shunt included, necessary due to the high amperage and reads to 30 A. The voltmeter goes to 100 V dc. In the idle mode the B+ is about 56 V, and drops to 53 during operation. As noted, the primary of the transformer is fused with a 15 A slow blow type. Note that the transformer can be operated from a 240 V ac

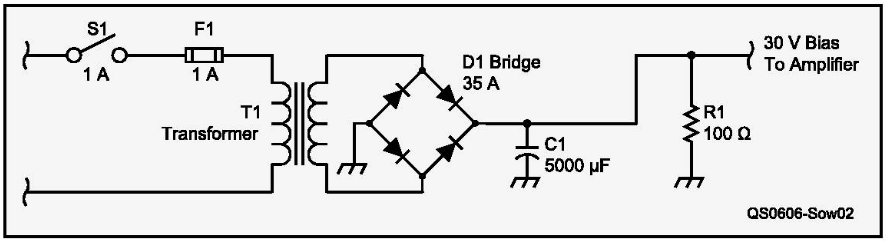

Figure 2 — Schematic of the bias supply.
C1 — 5000 µF, 50 V electrolytic. See text.
D1 — 35 A, 200 PIV bridge rectifier.
F1 — 1 A, 250 V fast-blow fuse.
R1 — 100 Ω, 15 W power resistor.
S1 — SPST toggle switch, 1 A, 250 V ac.
T1 — A winding on T1, Figure 1.

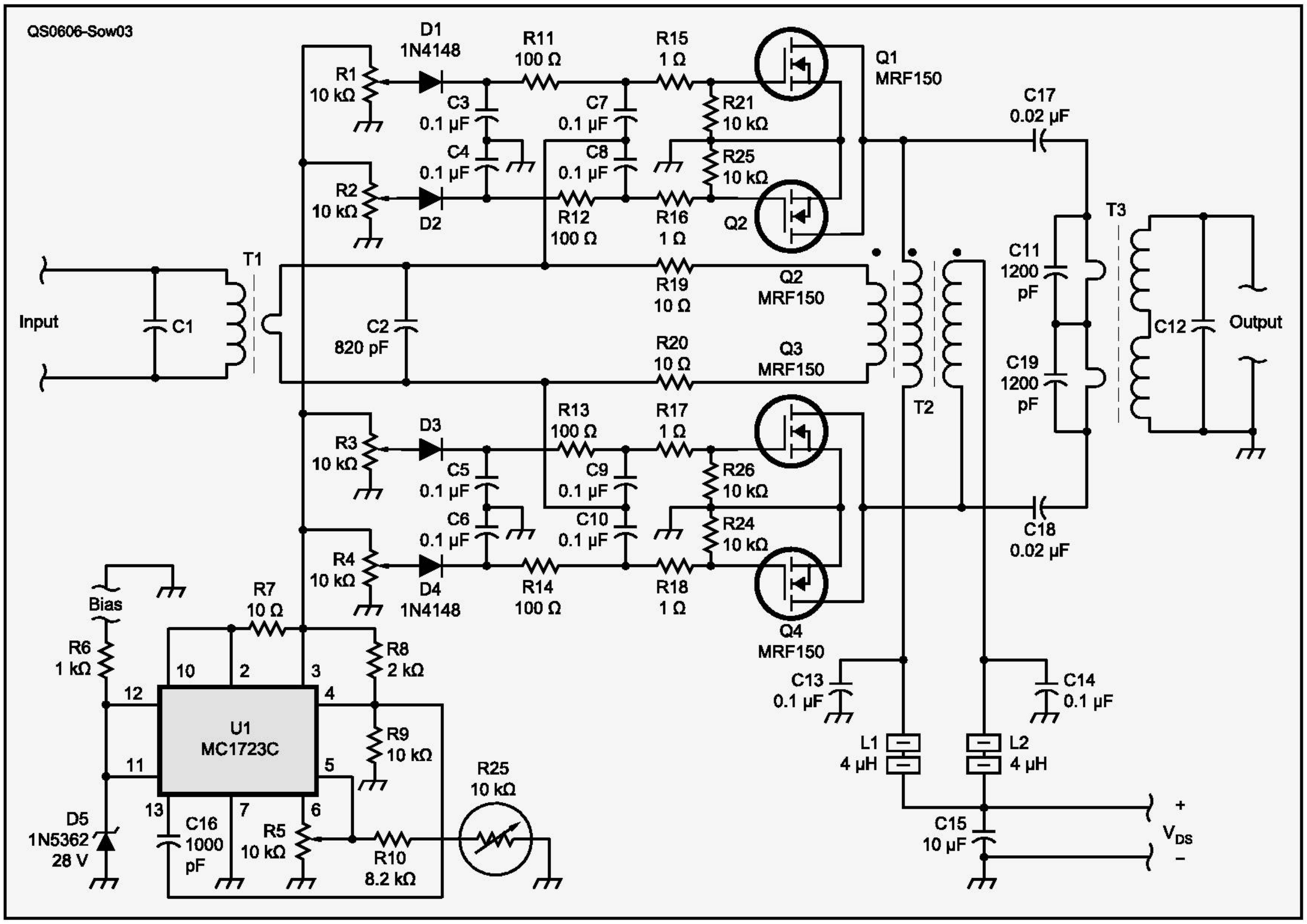

Figure 3 — Schematic of the amplifier main PC board.
C1, C12 — Not used.
C2 — 820 pF ceramic chip capacitor.
C3-C6, C13, C14 — 0.1 µF ceramic.
C7-C10 — 0.1 µF ceramic chip.
C11, C19 — 1200 pF each, 680 pF mica in parallel with an Arco 469 variable or three or more smaller value mica capacitors in parallel. Note this value can be reduced to improve efficiency on the higher bands, at the cost of lower frequency efficiency.
C15 — 10 µF, 100 V electrolytic.
C16 — 1000 pF ceramic.
C17, C18—Two 0.01 µF, 100 V ceramic each in parallel (ATC 200/823 or equivalent).
D1-D4 — 1N4148.
D5 — 28 V Zener. 1N5362 or equivalent.
L1, L2 — 4 µH (two Fair-Rite 26730218001).
Q1-Q4 — Motorola MRF150 transistors.
R1-R5 — 10 kΩ Trimpot.
R6 — 1 kΩ, 1 W resistor.
R7 — 10 Ω, ½ W.
R8 — 2 kΩ, ½ W.
R9, R21-R24 — 10 kΩ, ½ W.
R10 — 8.2 kΩ, ½ W.
R11-R14 — 100 Ω, ½ W.
R15-R18 — 1 Ω, ½ W.
R19-R20 — 10 Ω, 2 W carbon.
R25—Thermistor, 10 kΩ, 25°C; 2.5 kΩ, 75°C.
T1-T3 — See text.
U1 — MC1723C.

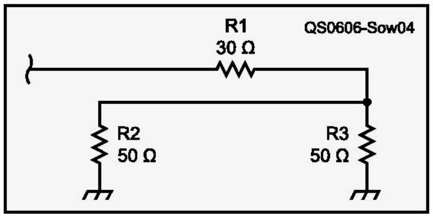

Figure 4 — Input circuit on the circuit board at the junction between the series resistor and the grounding resistor. R1-R3, see text.

source instead. You will have to un-ground the primary, and hook both leads directly to the two "hot" 240 V ac feed lines. You will, of course, have to make the necessary changes in the secondary options to get the proper voltages out. My preference was to keep 240 V out of the picture. Make sure the unit is grounded both by the feed ground and the external ground. It might be a good idea to fuse the B+ feeding the amplifier (25 A would be safe), although I did not. Also shunting the filter capacitors that are hooked up in series with 5 kΩ, 2 W resistors might help equalize the voltage across the capacitors. The conservative capacitor working voltage rating of 50 V allowed me to hook them up in parallel to obtain a total capacitance of 75,000 µF.

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 TR relay (Note: The schematic in Figure 2 does not show 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 selected was a 5000 µF, 50 V dc electrolytic. The secondary supply output voltage measures about 30 V dc.

I considered 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, TR relay, and the transformer I needed to power the fans.

I like to test things as I go along so 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. See Figure 2 for a schematic of the complete power supply.

Amplifier Design

In going over the suggested circuit and description by Helge Granberg, the Motorola engineer, it was clear that the bias level 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.

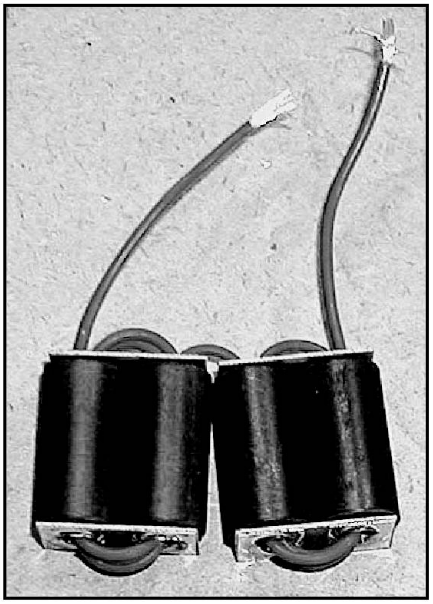

Figure 5 — T3 made as a double binocular core.

Metal oxide field effect transistors (MOSFETS) offer a lot of advantages over bipolar transistors. MOSFETs provide higher input impedances allowing for better matching networks and broader bandwidths. They offer superior stability and thus are less likely to go into potentially damaging oscillation. They are sturdier and better able to handle high levels of reflected power. Finally, they can handle much higher power levels. FETs also tend to self regulate when they heat up instead of the out of control currents that often destroy bipolar devices at high temperatures. The MRF150s used in the project are enhancement mode N-channel devices.

A look at the Motorola application schematic, Figure 3, will help as we work our way through the design.

Design Details — Bias Design

Let's start with the bias voltage regulation part of the circuit. In simple terms the Zener diode (D5) reduces the voltage from the source — in my case 28 V dc — and provides the input to regulator IC1. The regulated output comes out of the divider at pins 3 and 4. Thermistor R25 is placed in the circuit to change value with temperature, and lower the bias voltage output if the temperature rises. 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 7 V dc as the source bias for the amplifier.

The bias should be individually set for each of the four MRF150s so they draw 100 to 150 mA each no signal, 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 at the ground end. This will ensure that when B+ is applied to the drains the devices will not conduct. When setting the bias (later) put a high-resolution ammeter between the B+ and the circuit board. Then adjust each potentiometer so that its FET conducts at 150 mA, or collectively 600 mA. It is a progressive thing — the first one brings the ammeter to 150, the next to 300 and so on. I routed the bias supply through the TR relay. This ensures that when the relay goes into the receive mode the bias to the FETs is immediately cut off.

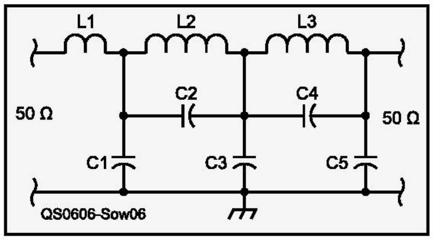

Figure 6 — Granberg's low pass filter design. Standard value capacitors have been placed in parallel to obtain non-standard values where required. For example, 2 × 47 + 10 pF means two 47 pF and one 10 pF capacitor in parallel. Wire type for all inductors is 14 gauge enameled. Capacitors are RMC 3 kV disk ceramic except those above 390 pF are 2 kV units. See Table 1 for values.

I added several 2 W carbon resistors, one in series with T1 and another two to ground. (Note: Figure 4 does not show the series connection with the resistor and the input of T1.) The former was about 30 Ω, and the two to ground were about 50 Ω. I wanted to attenuate the drive so that if I was running the exciter at 100 W and forgot to drop it prior to using the amplifier I would not burn out the MRF150s. They can blow it in a minute with too much excitation. It provides about 5 dB of attenuation. Without the resistors the drive required would only be about 10 to 15 W.

Design Details — Impedance Matching

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 unto 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 impedance 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, made of 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. Saturation can cause many problems including extreme heat, transformer non-linearity and excessive distortion products.

In the schematic T1 and T3 have a 9:1 impedance ratio, and are wound on binocular cores. T1 should have three 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 ½ of a turn). T1 is looking at a 5.5 Ω secondary from the 50 Ω or so driving excitation, while T3 is the opposite taking a 5.5 Ω load to a 50 Ω output. T3 uses two binocular cores hooked up in series. According to Granberg, excessive heat resulted from the use of only one core so he hooked up two cores in series with a lower permeability material to reduce losses and heat generation. The two cores in combination provided the necessary reactance at the lowest operating frequency of 2.0 MHz for the design. The resulting ratio worked out as the square of the primary in series as 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. The primary functions of T2 are to provide a load balance for T1 and feedback to the gates of the four FETs for stability. Low permeability 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.

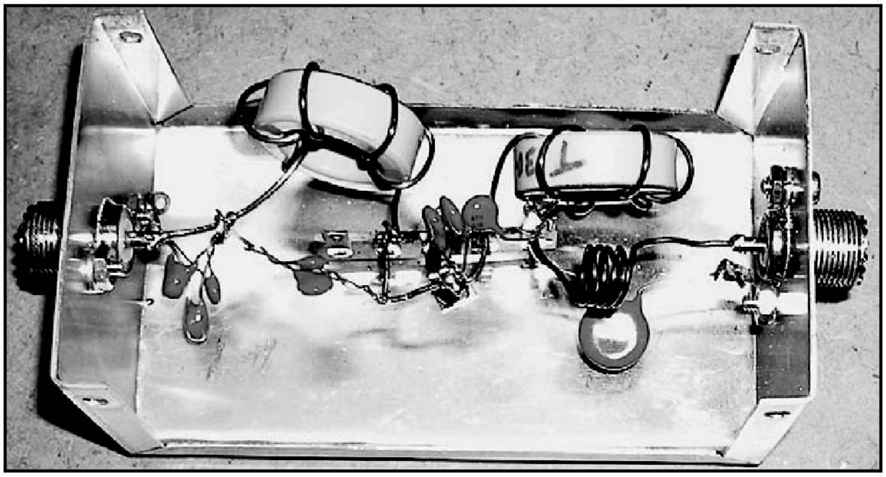

Figure 7 — Granberg low pass filter for 20 meter operation.

Granberg noted that the stability of the amplifier was tested into a 3:1 load mismatch at all phase angles, and was found to be completely stable.

Getting the Pieces

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 enchilada" with the etched and drilled circuit boards, pre-wound impedance transformers, and all of the hard-to-find parts for a reasonable dollar amount.[4] A properly wound transformer is shown in Figure 5. Alternatively, winding your own would not be that difficult, but you would have to make sure you had the proper core material and high temperature wire. RF Parts carries high temperature wire as well as a good selection of ferrite transformers.[5]

Keeping the FCC at Bay

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

Fortunately, Granberg provided the filter design shown in Figure 6 to provide the required attenuation. Even though the Granberg filters worked okay in some recent experiments, an alternative with fewer parts can be constructed using the five-element Chebyshev low-pass filters described in Figure 12-20 of the 2006 edition of *The ARRL Handbook*. For example, for a

Table 1
Values for Granberg Low Pass Filters as Shown in Figure 6

(Meters)	*C1 (pF)*	*C2 (pF)*	*C3 (pF)*	*C4 (pF)*	*C5 (pF)*	*L1*	*L2*	*L3*
80	2 × 82 + 390	2 × 82	2 × 390 + 3 × 82	2 × 220	2 × 220 + 82	not used	1.8 µH, 12 turns on T130-2	1.6 µH, 11 turns on T130-2
40	2 × 100 + 2 × 47	2 × 39	2 × 150 + 2 × 100 + 47	150 + 39	2 × 100 + 47	0.85 µH, 8 turns air wound 0.6″ ID, 0.6″ long	0.9 µH, 9 turns on T130-6	0.82 µH, 8 turns on T130-6
20	3 × 47 + 10	39 + 10	4 × 39 + 100	56 + 68	2 × 47 + 10	0.39 µH, 6 turns air wound 0.6″ ID, 0.6″ long	0.41 µH, 7 turns on T130-6	0.32 µH, 6 turns on T130-6
17	47 + 39 + 15 + 10	2 × 15	4 × 39 + 47	2 × 39	2 × 39 + 10	0.28 µH, 5 turns air wound 0.6″ ID, 0.6″ long	0.33 µH, 12 turns on T130-0	0.27 µH, 10 turns on T130-0

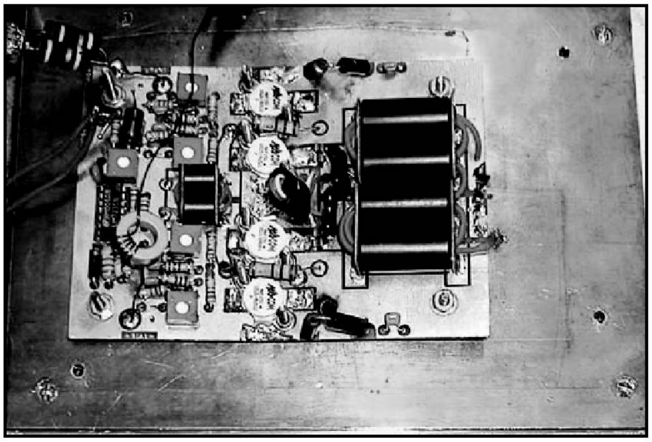

Figure 8 — Fully assembled amplifier PC board.

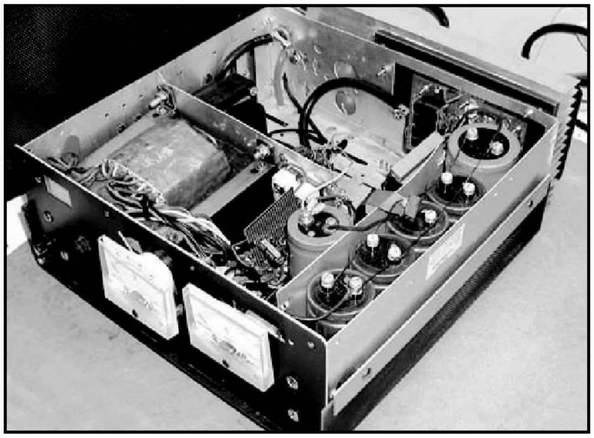

Figure 9 — The inside of the 600 W amplifier.

40 meter filter I chose a cut-off frequency of 9.01 MHz. Filter No. 2 in the table will provide plenty of attenuation for both the even and odd harmonics. All you need to do is multiply the F_{co} by 10 and divide all the component values by 10. Therefore you get 9.01 MHz, L1 and L5 are 0.56 µH, C2 and C4 are 430 pF and L3 is 1.27 µH. I used Amidon toroids for the inductors — T-130-6 for L1 and L5, and T-130-2 for L3. The other filters can be scaled in the same way.

Since I did not have room in the cabinet for the filters, I built them in small RadioShack aluminum boxes with coax connectors for the input and output as shown in Figure 7. The connecting coax to the amplifier is about one foot long. It is somewhat awkward to screw them in and out when changing bands but it really is not much worse than changing antennas. If I had built the amplifier in a slightly larger case I would have had room for the filters, and could have added a band switch.

Keeping Cool

The next hurdle that was clearly noted as a potential problem was the 400 W 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. The FETs are bolted directly to the copper and the circuit board is set on top of the board with small spacers to keep the underside from short circuiting to ground. The FETs are then soldered to the circuit board, and the whole assembly is attached to a heat sink. It sounded rather daunting when I first thought about how all of this could go together.

Communication Concepts offered both the copper spreader and a suitable heat sink so I bought both items. The resulting board went together a lot easier than I had envisioned. Attaching the heat sink, and then bolting the assembly to the SB104 chassis was a job! Finally I sort of got it all together. Figure 8 shows the completed board.

The last chore was to hook up the two fans. I used a pair of 12 V dc imported high output fans that I purchased for a bargain. To power them I used an old 12 V filament transformer with its own bridge rectifier. After firing them up, I decided that they were making too much noise so I wired the center tap of the transformer in place and dropped the voltage to about 7 V. They now run much quieter and move more than enough air to keep everything cool Figure 9 shows the inside of the amplifier.

Firing it Up

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, routed the output through my 20 meter low pass filter, and then into my 11 element log periodic multiband antenna. With the transceiver set for 10 W on 20 meters I keyed the amplifier and started increasing the drive until my output wattmeter indicated 600 W. The SWR was flat and 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. Holy cow — it works!

I guess the thing I like the most is switching bands and not worrying about changing the amplifier. When I decide to use the amplifier on other bands, I will, of course, have to use a different low pass filter.

I found out that a slight increase in drive power increases the output to 800 W. Running at the rated output, however, will keep everything cool. You may notice a slight increase in resting current as the FETs heat up. This is normal. The voltage regulation circuit, with the thermistor mounted on the copper, will reduce the idle current by dropping the bias voltage. If the heat is being removed properly the resting current will not go much higher than 1.5 A from its cold state at 0.75 A. If this becomes a problem you can always speed up the fans or drop the power back a notch. I can talk away with peak output of 600 W and the copper spreader and aluminum heat sink stay remarkably cool.

Notes

[1] The FCC rules concerning homebrew amplifiers can be found at 97.315.

[2] **www.communication-concepts.com/appnotes/EB104Sharp300.pdf**.

[3] ALS-600 transformer T2, Part Number 406-3002. Ameritron, 116 Willow Rd, Starkville, MS 39759, **www.ameritron.com**, 662-323-8211.

[4] **www.communication-concepts.com/eb104.htm**.

[5] **www.rfparts.com/**.

Tom Sowden, K0GKD, received his General class license at age 15 in a small town in Kansas where he grew up. He graduated from Northwestern University in Evanston, Illinois with a degree in Investment Management and first worked in New York as a trainee for Standard & Poor's Corporation. He then joined the Navy and served on a minesweeper off the coast of Viet Nam.

He has had several careers including 20 years in the flour milling business, and 20 years in the bag business. He is still involved with the latter in the Kansas City area where he owns and manages his own company.

He dropped out of ham radio in the early 1980s and let his ticket expire. The events of 9/11 got him thinking about this hobby and he got his ticket back three years ago. Through the vanity program he was able to obtain his original call sign.

Tom has three children and four grandchildren and lives in the Kansas City area. You can reach Tom at 4450 W 188th St, Stilwell, KS 66085 or at **k0gkd@arrl.net**. *His Web site is at* **www.k0gkd.com**.