Improving the Performance of the EB104 Amplifier with a Transmission Line Transformer

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After coming back to ham radio from a ten year hiatus, one of my first contacts was with a ham in Colorado who was operating Internet remote control. This was a new experience for me and opened my eyes to how I could enjoy ham radio a lot more. I frequently travel as part of my job and as a result have to spend a lot of time in hotel rooms. My wife and I also own a vacation/hunting/fishing cabin in the north woods of Wisconsin, and I try to spend as much time as possible there. Having the ability to use my station from a remote location was a dream come true.

I spent the next year trying out various methods of Internet remote control, which eventually resulted in all new equipment! I ended up with a Kenwood TS480HX, an LDG 600pro auto-tuner, a 40 meter Carolina Windom, and a WaveNode SWR/PWR meter. Everything was working well, but I wanted a little more "punch". I live in a log home on a small lake lot, and don't have room for multiple antennas, and a tower was totally out of the question. My only alternative was to increase my output power.

While I have been a ham for over 51 years, I have always operated "barefooted", so I didn't know much about linear amplifiers. For the Internet remote operation, I knew I was going to have an amplifier that didn't require tuning when I changed bands, could be auto-band switched with either the Kenwood or with Ham Radio Deluxe. I also didn't want to have to replace my auto-tuner or my Carolina Windom, both of which were only rated to 600 watts. With these goals in mind, I began researching what my alternatives were. It quickly became apparent that I needed a solid-state amplifier and one that would support auto-band switching.

While I was evaluating my commercial choices, and trying to identify how I was going to find the funding for one, I read an article in the June 2006 QST, "Homebrew Solid-State 600 W HF Amplifier", by Tom Sowden, K0GKD.[i] I had found what I believed at the time was the "perfect" solution.

This started what turned out to be a year-long project and great education in solid-state MOSFET amplifiers. I have an educational background in electronics and many years ago had a First Class Commercial Radio Telephone License and worked as an electronic technician. What could be so difficult in building the amplifier of my dreams? If I had known then what the true costs to build this amplifier were going to be, I would have been better off buying an Ameritron ALS600! On the other hand, I couldn't have gotten as good of an education in MOSFET amplifiers any other way, and I got to meet a lot of helpful amateur radio experimenters.

The purpose of this article is to share some of my experiences and help other hams who want to take on the challenge of building their own solid-state linear amplifier.

The amplifier that Tom Sowden wrote about in his article was based on a design from the late Helge Granberg, K7ES/OH2ZE, who while an RF engineer at Motorola, wrote Engineering Bulletin EB104[ii]. Granberg introduced the design of a high-powered solid state amplifier, using (4) Motorola MRF-150s in a parallel/push-pull configuration to achieve 600 watts output. EB104 was written in 1983 and Granberg's design principles are still being used today by many commercial Ham radio amplifier manufacturers, including Ameritron and Tokyo HyPower.

Granberg's design was a starting point for experimentation by amateurs and also by commercial Ham radio amplifier manufacturers. The printed circuit board for EB104 has been manufactured by Communication Concepts, Inc.[iii] and a lot of hams have built this amplifier, this author included. There has been a lot written by hams that have built this amplifier and made many improvements to it. If you "Google" EB104 you will find may articles/discussions on how to build an EB104 amplifier, and improvements that have been made by other hams.

I was able to successfully complete my EB104 amplifier, using many of the recommendations that I found on the Internet. I have used it on the air; much of the time via Internet remote control, and it has performed very well, especially on 40 and 20 meters. However like a lot of other hams who have built this amplifier, I was not completely satisfied with its efficiency on the higher bands

There continues to this day to be a lot of discussion about the negatives of Granberg's design. His design was not intended to be a completed project, but rather a starting point for experimenters. People that should know, have commented on Internet forums that the EB104 printed circuit board design is flawed, and that there can be high voltage spikes on the MOSFET drains that can cause harmonic resonance that can under some conditions destroy the MOSFETS.

Other knowledgeable ham experimenters have pointed out that the output transformer, T3, is also a cause of poor efficiency on the higher frequencies. While the "experts" have pointed out the flaws, no one to my knowledge has offered any improvements that could be made, or offered an alternative printed circuit board to the ham community.

Granberg in EB104 identifies that the board had poor RF grounding on the high frequencies due to the close proximity of the parallel MOSFETS. If you carefully examine the PCB, you will also see that there is no direct ground plane on either side of the board on the inside sources of the inner two MOSFETs. Granberg suggests that the RF grounding would be improved by either the use of metal caps over the MOSFETs or by using a solder lug from the mounting screw to the source leads. This would then use the copper heat spreader as part of the RF ground.

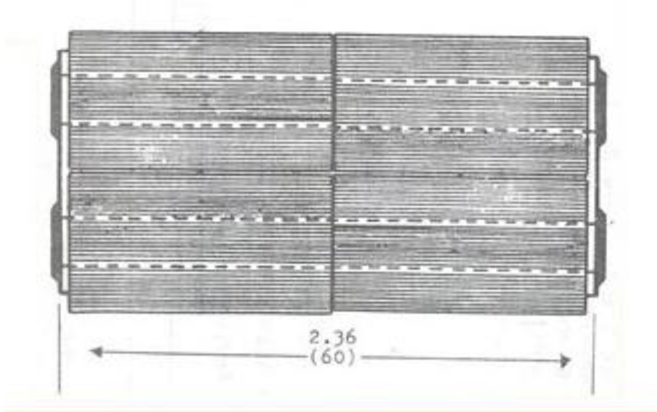
In my search for ways to improve EB104, I met a lot of very knowledgeable hams who had built EB104 and were willing to share their experiences with me. One of these hams is Andreas Duessler, DL6EAT. Andreas build a 1.5KW amplifier combining (4) EB104 boards together.[iv] I exchanged numerous emails with Andreas to get his recommendations for improving EB104. Andreas provided me with a list of around 30 modifications that he had made. He improved the RF grounding of the PCB by constructing metal caps that went over the top of each MOSFET and were soldered to the sources.

This is a photo of Andreas' EB104 amplifier.

While Andreas was able to finish the amplifier, he continued to run in to reliability problems and gave up on the design. He subsequently built a new amplifier using another Granberg design, AR347, which uses (2) MRF 154's. Andreas speaks very highly of this design and did not have the stability problems that he did with EB104.

So it appears that improving the RF grounding by itself does not totally fix the problem with the EB104 design. Another key design deficiency is the output transformer/matching impedance. Let's explore the design of the T3 output transformer.

Granberg ran into problems with heat in the output transformer core, so he connected two transformers in series. The result is a transformer that is really two smaller transformers in series, and also a much shorter transformer than the output transformer that he used in AR347. Both transformers are made by RFPowerSystems[v] and sold by CCI. Compare the ratio of length to width of the RF2000 transformer on the left, which is used in AR347 compared to the T3 transformer on the right that is used in EB104.



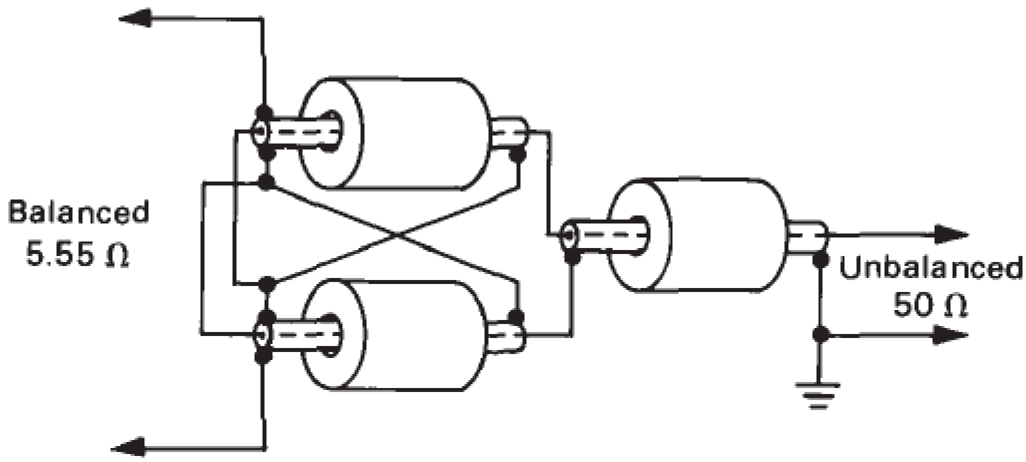
Dye/Granberg in their book, Radio Frequency Transistors, advises that the form factor, the length to width ratio is important. With a short transformer, like T3 in EB104, the coupling between the windings is lower and leakage inductance is increased. This could be why the amplifiers that are using the RF2000 transformer have higher matching efficiency than EB104. FAR circuits created a printed circuit board (PCB), "the extended HOG (Helge O Granberg)" that increases the length of the board under the output transformer to enable using the RF2000 transformer. I have been unable to find any feedback on the Internet on the success of this board/transformer design.

The other ham who gave me a tremendous amount of help is Baruch Zilbershatz, 4Z4RB. Baruch custom builds solid-state amplifiers which he sells internationally on his EBay store.[vi] Baruch built several "EB104" amplifiers, using the CCI boards and the original EB104 output transformer. He later switched to a PCB of his own design. Baruch's PCB has more spacing between the MOSFETS and considerably larger drain traces. The bottom side of Baruch's board is a solid ground plane. Baruch also improved the RF grounding by using solder lugs from the MOSFET mounting screws to the sources.

Baruch has also moved away from using the conventional tube and sleeve design output transformers, which are used in EB104, and later in AR347, the ALS600, ALS1300, and the Tokyo HyPower, to a Transmission Line Transformer (TLT). His experience has been very positive; providing improved efficiency and output on the higher frequencies, and also making the parallel/push-pull amplifier design much more stable. Baruch has told me that since switching to the TLTs, he has not destroyed a single MOSFET, while before he lost many.

Baruch kept pushing me to use a TLT in my EB104 amplifier. When I first met Baruch I had no idea what a TLT was and I wasn't convinced that this was the answer to improving the design. Baruch's discussion got me very interested and I started researching everything that I could find on the Internet on TLTs, and I also ordered several books on this topic and RF amplifier design.

Granberg briefly discusses an alternative of using the TLT in EB104, but then goes on to further discuss the tube and sleeve transformer, which he used in EB104, and which CCI still provides in their kits. Granberg in other writings[vii] pointed out the inherent inefficiency in the tube and sleeve transformer and how much more efficient a TLT is. Since Granberg passed away at an early age, in 1996, we will never know why he didn't use a TLT in EB104. This is the design of the TLT that Granberg talked about in EB104:



This is a 1:9 transformer, with a 1:1 balun on the right. The 1:9 TLT has a balanced output so the 1:1 balun is used to match the output to the 50 ohm unbalanced antenna. Other authors have indicated that if the two halfs of the TLT are wound on separate cores then a balun isn't needed.

While Granberg did not use a TLT in EB104, he did use one in AN758. This engineering bulletin contains a very good discussion on the construction of a TLT. Granberg also wrote a Motorola Application Note, AN749, "Broadband Transformers and Power Combining Techniques for RF".[viii] This application note discusses a variety of broadband output transformers. Granberg in this application note states that the transmission line transformer is superior in bandwidth and power handling capability.

Doug DeMaw, W1FB, in his book "Practical RF Design Manual", also has a detailed discussion of TLT construction. DeMaw points out the importance of using trimmer capacitors to compensate for leakage inductance. He also points out that the shield of the coax carries the high current, which contributes to the high efficiency of the TLT.[ix]

Larry Sevick, W2FMI, in his book Transmission Line Transformers states, "Accurate loss measurements have shown that only a limited number of ferrite materials are useful in power applications, where high efficiency is an important consideration." He goes on to say, "nickel-zinc ferrite cores with permeabilities in the moderately low range of approximately 50 to 300, yield efficiencies in excess of 98%. No conventional transformer can approach this performance."[x]

Material 43 ferrite cores have a permeability of 850, while material 61 cores have a permeability of 125.

Sevick also writes that people misunderstand how the TLT works and attempt to think of them like conventional transformers. "Because of the canceling effect of the transmission line currents, little flux is generated in the core. Since losses with certain ferrites are only on the order of 20 to 40 millidecibels, very small transmission line transformers can handle surprisingly high power levels." Furthermore, the power capability is determined more by the size of the conductors than the size of the cores. Very small structures can handle amazingly high power levels. Sevick reported that “a torroid with a 1” OD and 14 turns of no. 18 wire successfully handled 1kw of peak power in single-side band operation over an extended period of time. It became warm to the touch but did not over-heat”.

Sevick wrote that with the proper core material bandwidths of about 100 MHz and matching efficiency approaching 99% was possible.[xi]

Matti Hohtola, OH7SV, the designer of the LUMA 1 KW amp, has written, “I think that the harmonics are related to incorrectly operating RF PA transformer. You probably know the problem related to class-AB operation. During the non-conducting half cycle, the MOSFET is in high impedance state. If you use a popular type of a transformer, that end of transformer is not connected anywhere and the voltage bounces releasing high frequency energy to the output. I have also tried a popular type of a transformer and it resulted in a breakdown of one low-pass filter (LPF) capacitor. This confirms that there were lot of harmonics with the bad transformer and the first LPF capacitor could not stand that high RF current.” It is my assumption that Hohtola is talking about a conventional tube and sleeve transformer.

High harmonic content could explain the high voltage spikes that destroyed MRF150s on the EB104 rather than the EB104 PCB design being true root cause.

After a lot of reading and several conversations with Baruch, I became convinced the “problem” with EB104 design, might not be the printed circuit board, but rather the T3 output transformer design.

Ken Holland, K9FV, and I met on the Internet and began an email “conversation” on MOSFET amplifiers and TLTs. Ken is building an EB104 design amplifier, using SD2933s instead of MRF150s, and he is designing his own printed circuit board. Ken and I both began testing different TLTs using our SWR analyzers. We both found that we could get surprisingly high efficiency matching with the TLTs. Before I replaced the EB104 T3 conventional transformer with a TLT, I wanted to run a comparison test, so I ordered a new T3 transformer from CCI. With the tube and sleeve transformer, I found that by using ARCO variable capacitors instead of the 1200 pf capacitors that are shown in EB104, I was able to tune out some of the leakage reactance of the transformer on the higher bands and get better performance. I was not however able to get close to the efficiency provided by the TLTs. I also ran some tests on the T1 input transformer and found that this transformer provided very efficient matching. I suspect the problem with the T3 output transformer is related to the use of two transformers in series.

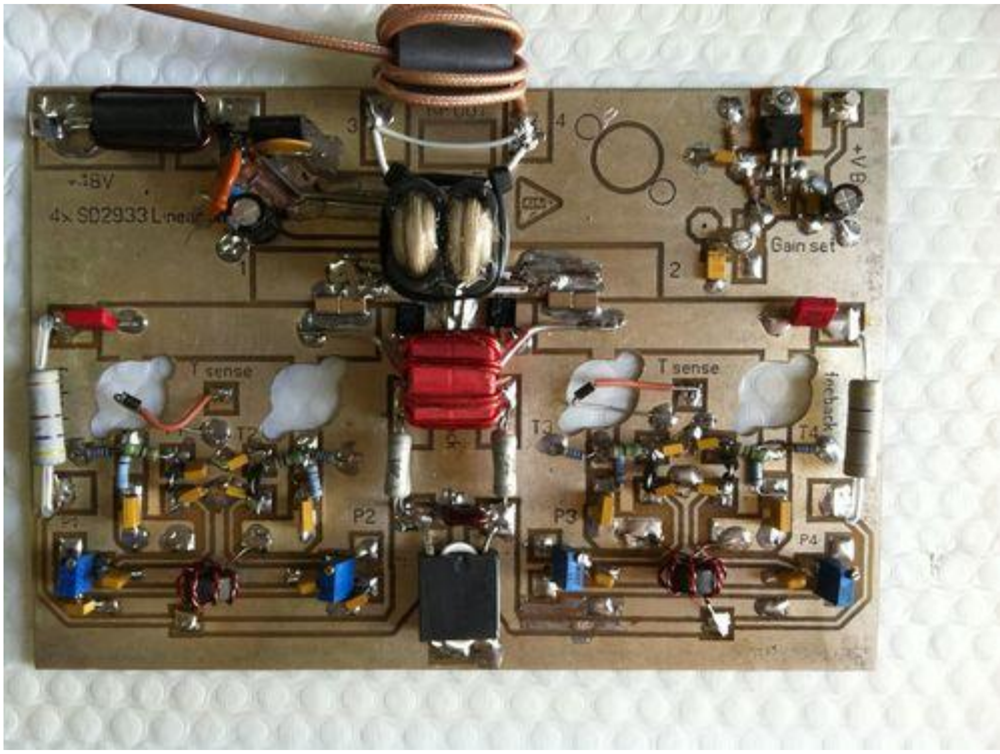
Building a 9:1 TLT is not complicated. I built them using a variety of cores and coax cables. Since I had no plans on ever operating on 160 meters, and I wanted to see if I could get EB104 to work on 6 meters, I settled on #61 material cores. The optimum coax impedance for a 600 watt amplifier with a 50 volt DC supply is 16.5 Ω. I was able to get 18 ohm coax from CCI, it is expensive at $5.50 per foot but you only need a couple of feet. Baruch recommended 25 ohm coax, which is available at lower cost. The loss in efficiency is minimal. He is also building TLTs using twisted pairs of enameled magnet wire, which is very low cost.

The length of the transmission line is not critical. Baruch recommended 10 ½" but when I explained that I did not operate 160 and would like to try to get to 6 meters, he recommended 9". Baruch recommended either #43 or #61 cores.

I also found that I needed a capacitor across the input (low impendance) port to cancel out the leakage reactance on the higher bands. Using the #61 cores with 18 ohm coax and an ARCO 469 variable capacitor on the input, I was able to get virtually a perfect match from 160-6 meters!

I got the best matching efficiency using ferrite tubes, since this resulted in the shortest interconnect distance. The 9:1 TLT has two interconnects, cross connected from one output transmission line back to the input of the other line, this is what changes it from a 4:1 to a 9:1 transformer. This distance is much shorter when using tube ferrites. My original plan was to use this transformer in EB104, but I ran into mounting problems when I tried to install it. I would have had to route two new output pads on the board and I didn't want to do that with a board that was already populated for fear the vibration could cause problems. (If you are starting with a new, unpopulated board this is the way that I would go. With the tube ferrite TLT, I was able to get a much better match on 6 meters, and you might be able to raise the upper limit of EB104 to 6 meters with this TLT.)

This is a photo of one of Baruch's amplifiers using the this type of ferrite tube TLT. I purchased these TLT cores from Baruch, so I don't know the source for them. This photo also shows the high quality of the printed circuit boards that Baruch has designed as a replacment for the EB104 board. Baruch's board accomodates either MRF150s or SD2933s. Baruch sells a populated board, minus the MOSFETs on his Ebay store http://stores.ebay.com/4z4rb?_trksid=p4340.l2563



I then investigated the use of a Fair-Rite #61 multi-aperature core, part number 2861010002. This core is available at Mouser. http://www.mouser.com/ProductDetail/Fair-Rite/2861010002/?qs=TibuvmyplOfyocW6Cak6iFs0ERjbVW9q

This core was used in the 250 watt solid state amplifier in Chapter 17 of the 2011 ARRL handbook, A New 250-W Broadband Linear Amplifier. [xii] That amplifier used a 4:1 TLT so there were no cross connects needed. The design of my 1:1 balun and my amplifier control circuit came from that article.

This is a photo from the ARRL Handbook that shows the 4:1 TLT:

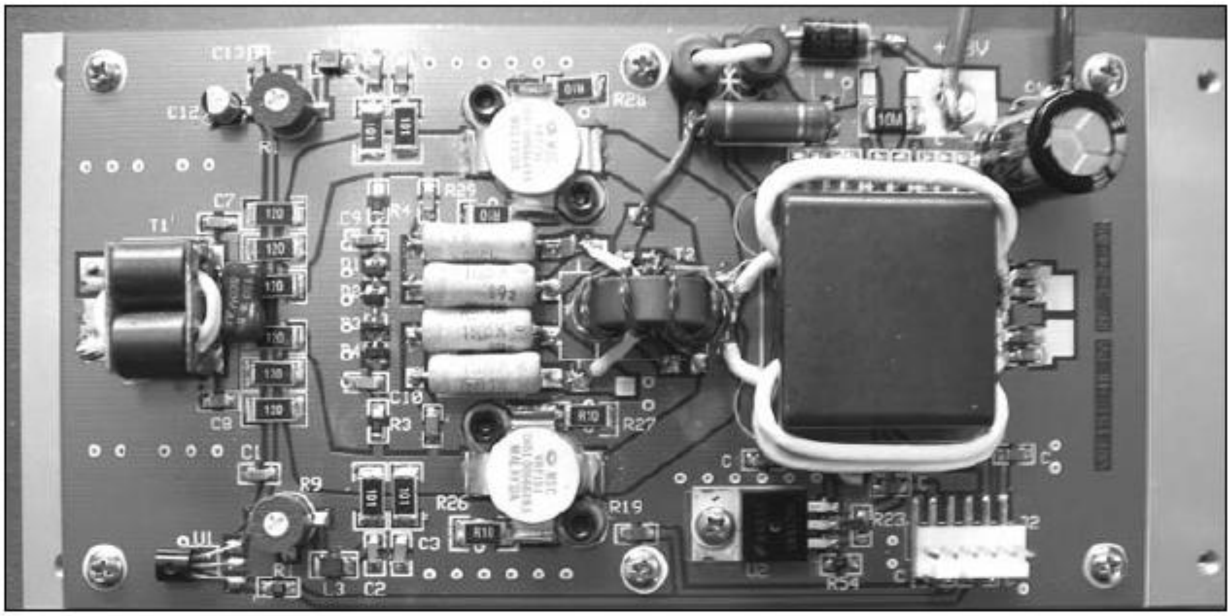
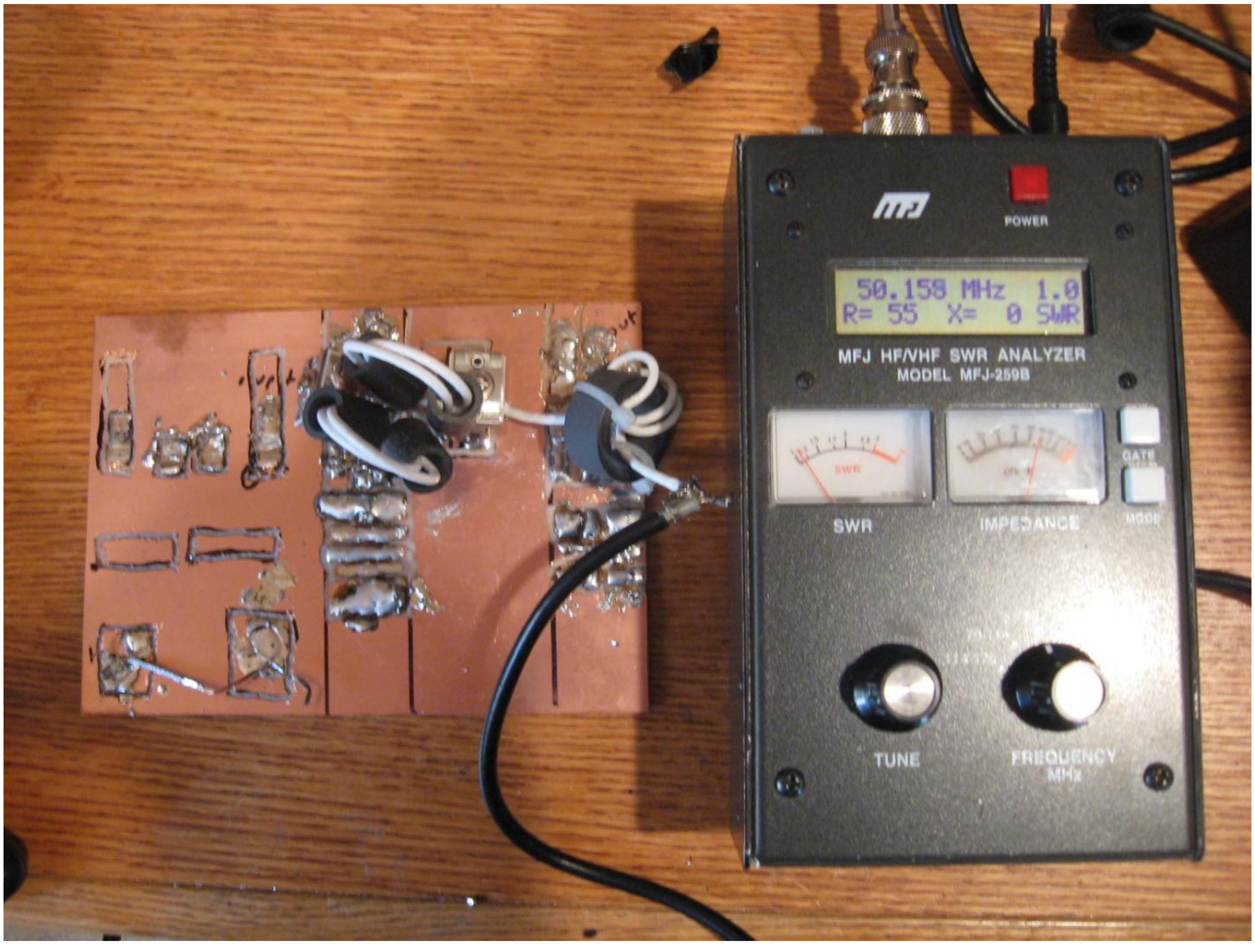


Fig 17.47 — The power amplifier module PC board assembly mounted on the heat sink.

This circuit is very similar to that of the new Elecraft KPA500 amplifier, which is also using a TLT.

I ran a test using this core, configured as a 9:1 TLT and while the cross connect lengths were longer, the matching efficiency was almost as good as the TLT I had built with ferrite tubes.

Here is a photo of the test jig that I used to test the various TLTs and the EB104 T3 tube and sleeve transformer. There is a 5.5 ohm resistor on the input of the TLT, and I am feeding the output with my MFJ-259B SWR analyser. As you can see in the photo below, I ran a test all the way up to 50 mhz and got a near perfect match!



Here are the test results of the TLT with the Fair-Rite multi-aperature core and 18 ohm coax, with the ARCO 469 adjusted for lowest SWR and highest match efficiency across 80-10 meters. As you saw in the previous photo, I was able to get a very good match all the way up to 6 meters when I used Baruch's ferrite tubes, but the results weren't as good with the multi-aperature core. I am sure this was due to the much longer interconnect with this core.

Test with ARCO 469 (215-790Pf)

MHZ	Z	X	SWR	Match Efficiency
1.8	89	0	1.1	99.00%
3.5	83	0	1.1	99.00%
7.15	83	0	1.1	99.00%
14.15	89	0	1.2	98.00%
18.12	85	0	1.2	98.00%
21.2	80	0	1.2	99.00%
24.93	74	0	1.1	99.00%
28.3	49	21	1.1	99.00%
50.11	26	20	2	87.00%

Contrast these results with the test results of the T3 tube and sleeve transformer used in EB104:

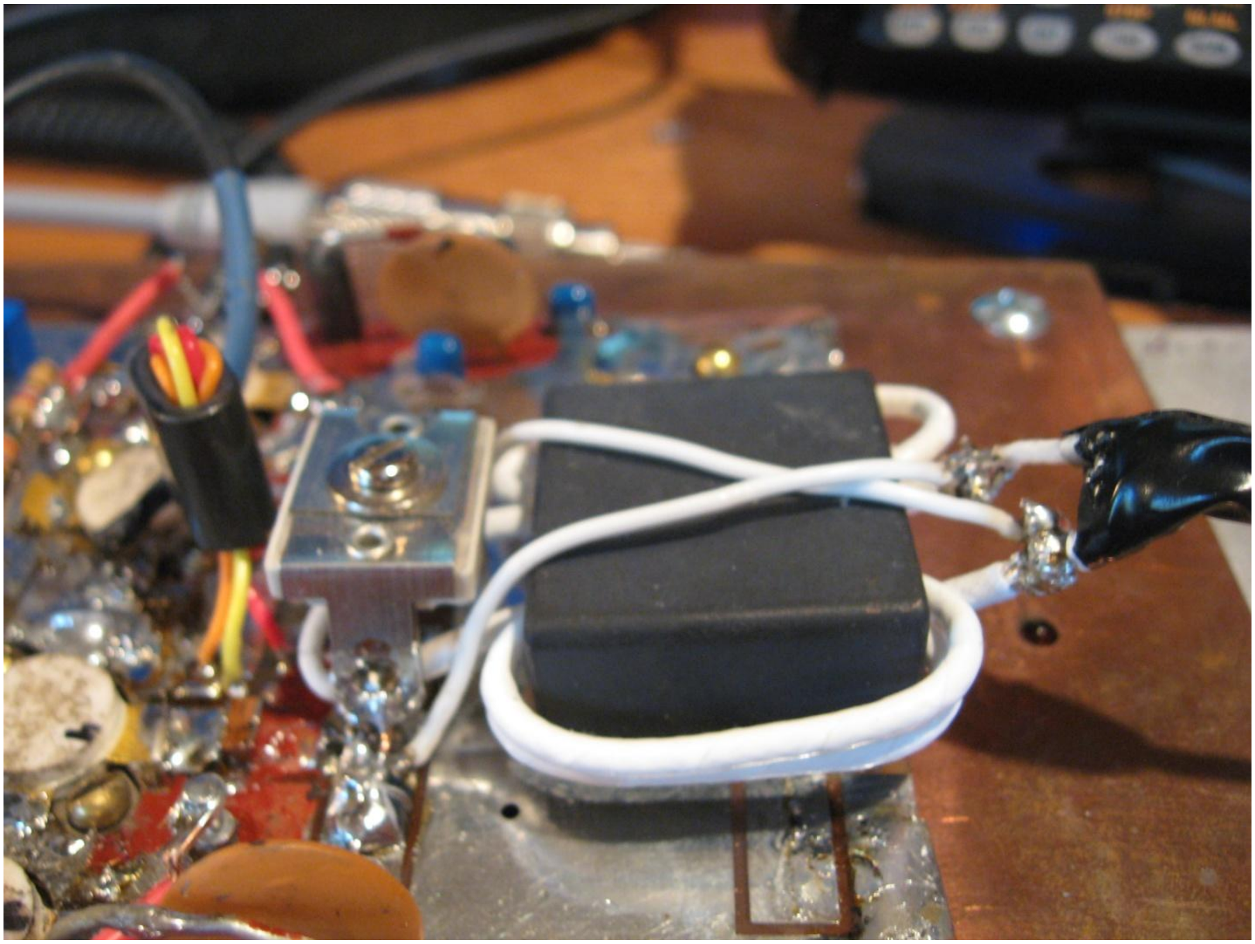
9:1 "T3" output with 820 pf in parallel with ARCO 469

MHZ	R	X	SWR	Match Efficiency
1.8	53	2	1	99.00%
3.5	59	7	1.2	98.00%
7.15	89	0	1.5	95.00%
14.15	126	0	2.5	81.00%
18.12	68	49	3.2	72.00%
21.2	37	44	3.8	65.00%
24.93	23	27	4.2	61.00%
28.3	17	15	5	55.00%
50.11	42	67	6.1	47.00%

These test results are consistent with the on-air performance that I had been experiencing with my EB104 amplifer. Based on these test results and with the encouragement of Baruch and Ken, I elected to take apart my amplifer and replace the output transformer with this TLT.

At first glance this output transformer looks like a conventional transformer and it was very easy to mount on the EB104 board. I used a small amount of silicon to physically mount the core to the PCB. I soldered the output of the TLT directly to the coax going in to the balun and then insulated all of the connections with liquid electrical tape.

I wound 3 turns of 18 ohm coax on each side of the multi-aperture core. This is about 10 inches of coax for each side. I used 3 turns of RG-188 coax on a Fair-Rite 2643665802 core for the 1:1 balun. (I have gotten feedback from early reviewers of this article that the Fair-Rite core number may no longer be valid. Any #61 material ferrite cores, such as an Amidon FT-114 can be used for the 1:1 balun)

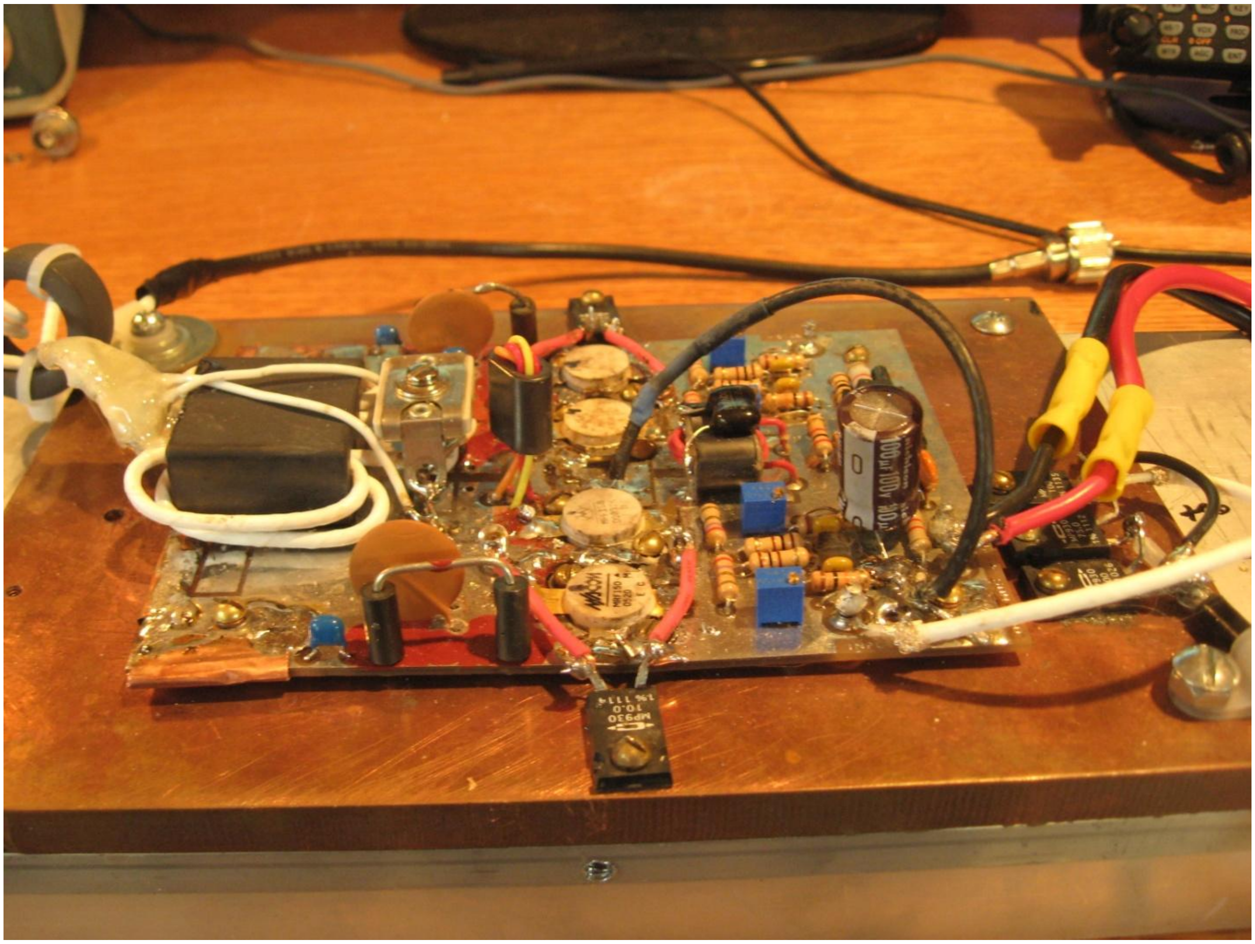


In this photo you can see the ARCO 469 on the input side of the TLT, the cross connects are on top of the TLT, and the 1:1 balun is out of the photo on the right side. This photo was taken before I insulated the output connections using liquid tape.

When I replaced the T3 output transformer with a TLT, I also took advantage of having the board off the heatsink to make some other improvements to the amplifier. This included replacing the single turn bias pots with 12 turn pots. (This is an absolute mandatory change, and makes it much easier, and safer, to adjust the idle bias). I replaced the two decoupling capacitors, C13 and C14, with four .047 µf capacitors, and two .001 µf capacitors. I also replaced C15, with a 100 µf, 100 volt capacitor.

Helge Granberg in EB104 made recommendations for improving the RF grounding of the board. I tried the metal caps on two different occasions and each time I had a flash under the cap and I destroyed a pair of MOSFETS! I have no idea what I may have done wrong but after the second time and having to replace six MOSFETS, I gave up on that idea. I tried Granberg's other recommendation of putting solder lug on the MOSFET mounting screws and soldering them to the sources. This sounds easy but due to the very limited space around the MOSFETS, I was not able to do this on all of them. I was able to ground some of them. At Ken's suggestion, I wrapped the portion of the PCB under the output transformer with thin copper foil. This bonded the grounds on both sides of the board together.

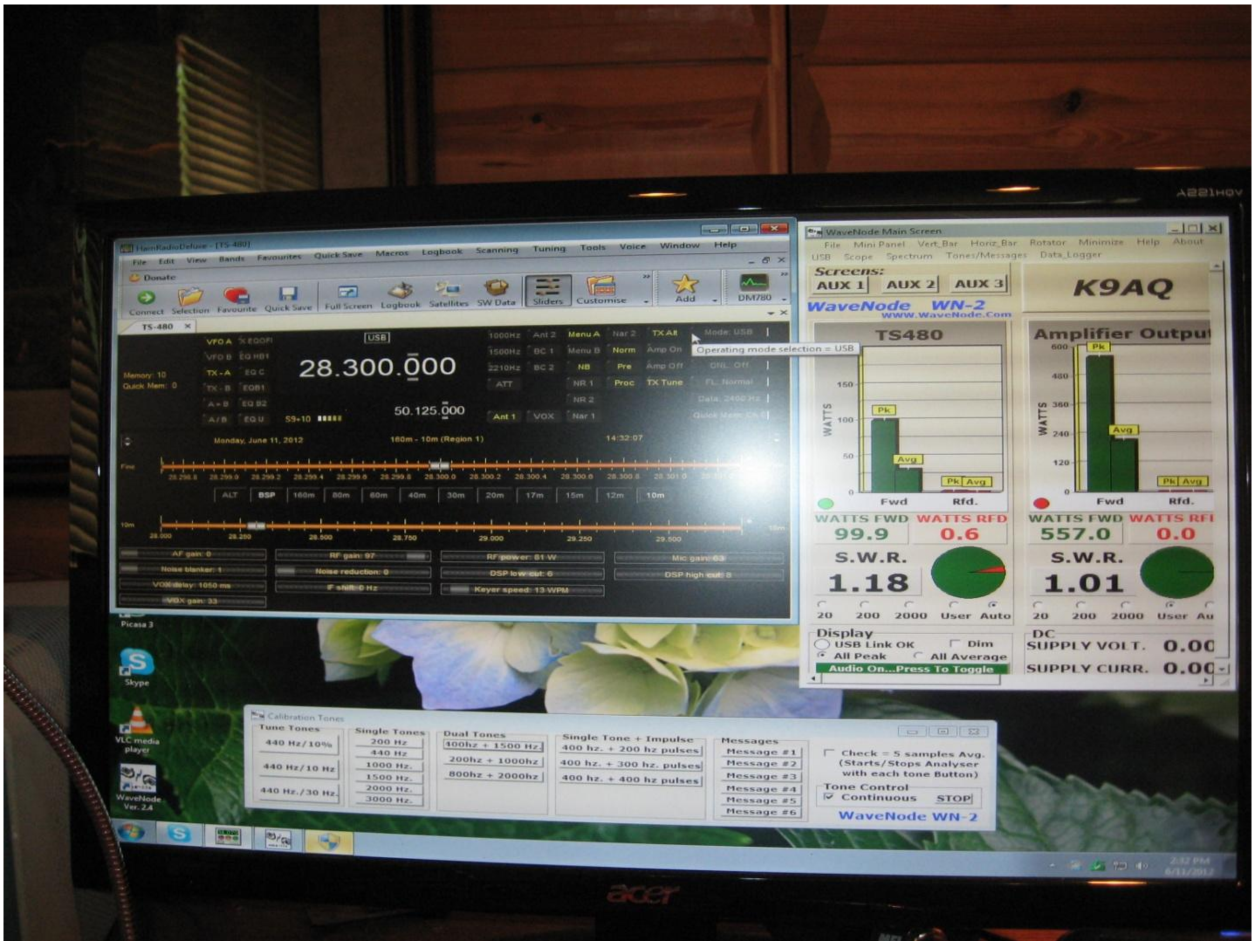
Here is a photo of the board after all of the changes:



From the left side of the photo you can see the 1:1 balun, the 9:1 TLT, copper foil bonding the two sides of the board together for better RF grounding, the replacement decoupling capacitors, an ARCO 469 variable capacitor on the TLT input, insulating varnish under L1/L2, Caddock 10 ohm,10 w resistors on the heatsinks for R19/R20, a 470 pf capacitor across T1 replacing C2 (820 pf ceramic chip capacitor), 12 turn bias pots, a 100 µf/100v capacitor for C15, and a 10 dB Pi section attenuator on the input.

What the photo doesn't show, but is also very important, is the work that I did with a Dremel tool and a grinding bit, to increase the clearance around each of the MOSFETS. I found that without that extra clearance, you could very easily short out the MOSFET drains to ground. (If I was starting with a new board, I would have made the clearances even greater so that I could more easily have put grounding lugs under the MOSFET screws.) You MUST check for shorts before you power up your amplifier for the first time. Also start your testing with a 3 amp fuse. Use a low value fuse until you get all of your MOSFET bias adjustments made. With the original 1-turn bias pots, it is VERY difficult to adjust the bias and it is very easy to have the MOSFET over biased to the point of oscillation. Multi-turn potentiometers are the solution for this.

So does it work? Absolutely! I am now getting a true 600 watts from 80-12 meters, and 557 watts on 10 meters.   (I don't operate 160, so I didn't do any testing on this band. My off-board tests of the TLT indicated that there was a very good match on 160. If this band is important to you, you could also consider changing the core mix to #43) Here is a photo documenting the 10m test:



I am driving the amplifier with a two tone test signal from WaveNode[xiii] and measuring both the input and output power and SWR. You can see that I am driving it with 99.9 watts. My attenuator is probably providing a little more than 10 dB of attenuation. I found that my Kenwood TS480, like most transceivers, has a considerable leading-edge power spike when you have reduced the power output; running it at "full" power eliminates that spike while also eliminating the possibility of over-driving the amplifier. The 10 dB input attenuator also provides a very low SWR to the transceiver.

This is the setup that I use for Internet remote operation. All of my band-switching and monitoring is done with the computer. My amplifier has no manual band-switch, or metering. Ham Radio Deluxe (HRD) controls the band switching. In the amplifier I have a band decoder board from Unified Microsystems http://www.unifiedmicro.com/decoder.html , connected to the parallel port on my host computer. As long as HRD is running, its band monitor will provide the correct band information to the Unified Microsystems board even if you make the band change on the TS480. I am using WaveNode to also monitor the PA temperature, PA voltage, and PA current. I run the PTT line through a relay on WaveNode that will open when the SWR exceeds a configurable threshold. I am in the process of implementing some additional controls with WaveNode. It provides the ability to control for analog outputs, which can be used to drive relays. I am going to use a pair of silicon control relays to turn the 220 volts AC on/off to the power supply, and another relay to disconnect and ground my antenna when thunderstorm conditions are present.

If the TLT offers so many advantages, why are some commercial amplifiers still using the tube and sleeve transformer? The September/October 2006 issue of QEX contains an article, "Get 1.5KW from a New RF MOSFET: A Legal Limit HF Linear, Tokyo Style"[xiv] According to the designers of the Tokyo Hy Power amplifiers, the best broadband performance and efficiency is obtained with a TLT. They state that the only reason conventional "bead and tube" transformers are used is lower cost. Dye/Granberg wrote that the conventional transformer is inferior in performance to a transmission line transformer, in power handling, loss factor, and bandwidth. According to them the only factor in favor of the tube and sleeve transformer is its simple construction, which makes it inexpensive and easily mass-producible.[xv] Elecraft is using a TLT in the KPA500, and according the article referenced above, it appears Tokyo HyPower is using it in their new HL-2.5Kfx amplifier. In looking at photos of the Yaesu Quadra and the Icom PW-1, they both appear to be using TLTs, but I haven't found a schematic to confirm this.

The cost difference is truly very minimal, but when a commercial vendor is building equipment in volume, every dollar saved goes directly to the bottom line. The only "expensive" component in the TLT is the coax. For optimal results with a 9:1 TLT, the coax impedance should be 16.5 ohms. The closest that I could find to this was 18 ohms, and the cost was about $5.50 per foot. Since you only need two feet of coax, the total cost for the coax and the Fair-Rite core is around $15. For a ham building his own amplifier, the cost difference is negligible.

So why are we still using them in home-brew construction? The only answer is that we take the easy way and copy what has been done by others year after year, and don't keep up with the best practices in the industry. At first the TLT seems like magic and it is hard to understand why it works. It works and it is very easy to build and install in EB104.

Low Pass Filters. When I first built my EB104 amplifier I ordered four filter boards from CCI. I build filters for 40-10, replacing the 500 volt capacitors provided by CCI with 1KV capacitors, and mounted a pair of these boards on to a perf board, where I added the relays for switching the filters. Two of these "motherboards" were stacked on top of each other for mounting in the cabinet. As I mentioned earlier, I then used the band decoder board, BCD-10, from Unified Microsystems and HRD to provide auto-band switching. Since I had long-term plans to build a 1KW solid state amplifier, I thought that this would also be a perfect time to redo my filter/relay board and upgrade it for higher power.

In Tom Sowden's EB104 article, he mentioned that he had FAR Circuits design a printed circuit board for his filters. I called Fred at FAR Circuits and found out that Tom's board only accommodated the filter components and that it did not have relays for band switching. Fred and I then worked together to redo this board. The components were upgraded to be able to handle a 1KW class amplifier and the board was redesigned for Zettler relays for band switching. Fred did a really good job of thinking ahead. The board can be changed for either high or low side relay switching. It can use either through hole or surface mount capacitors. The board is now available on the FAR web site as the "Tom Sowden High Power Harmonic Filter Board", and the cost is $35.

Unfortunately for me my cabinet was designed around the stacked CCI boards, so I had to move a lot of stuff around to get the much larger FAR board to fit in my cabinet. I now have the cabinet set up so that in the future I can replace the EB104/MRF150 PA module with a four SD2923 power amplifier (PA) board. I found a really low cost source for SD2933s, so now I have the itch to build a new amplifier!

Amplifier Control. When I started the amplifier project, one of the first things I build was the amplifier monitoring and control circuit from the 2011 ARRL Handbook, "250 Watt Broadband Linear Amplifier". This control board monitors PA current, Temperature, SWR, and wrong band filter selection. I build this control board using a Radio Shack universal board. I almost got it completed but then got side tracked with the more fun project of building the amplifier board. Since I use WaveNode for SWR protection and for monitoring, I just never got around to finishing the control board. A word to the wise, build the control board first and ALWAYS use it. Especially when you have the PA module on the bench for testing. I didn't and over time have had to replace six MRF150s. That's the one really good thing about MRF150s; you get them for a very reasonable cost on EBay. I have become an expert on testing and replacing MOSFETs. I found this very helpful MOSFET test information on the Internet http://www.4qdtec.com/mostest.html#simple I have found that it pays to test the MOSFET before you install it. I have gotten good results with this test.

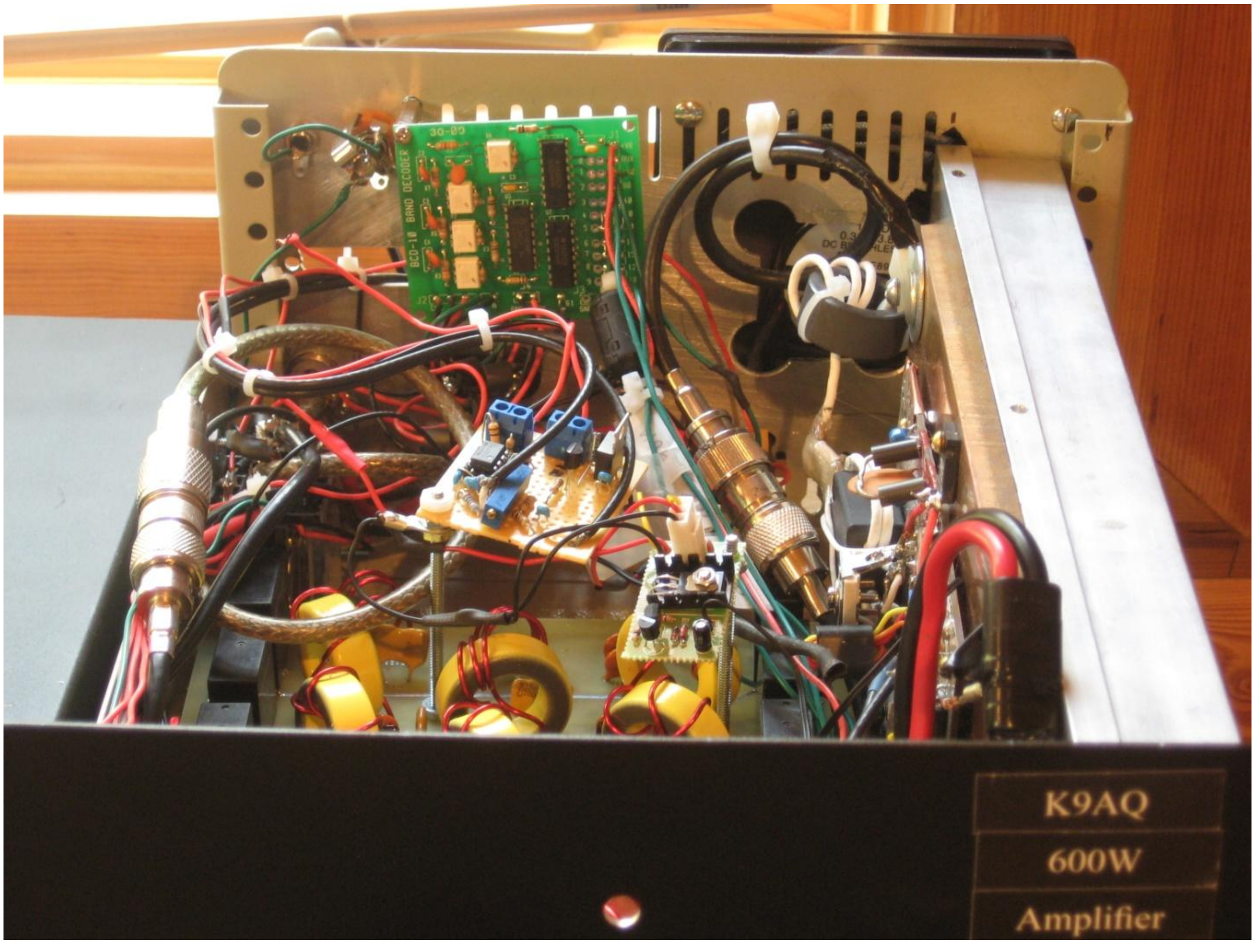
I don't know if the control circuit would have prevented the loss of these MOSFETs but it may have. In the future, I will always use a control board.

The ARRL board was available through ExpressPCB, but you have to order boards for the entire amplifier, and the cost was more than I felt was reasonable for a control circuit.

(11/26/12 - I have changed direction with the amplifier control. Instead of using an analog controller, I have built one using an Arduino micro controller. I have it working "bread-boarded" and am making some final changes. When it is done, I will update the article with information about the controller.)

I have finally put my amplifier back together in the cabinet after all of the changes. This turned out to be more of challenge than I anticipated. I had laid out the interior of my cabinet based on the area that was taken up by the stacked boards with the CCI filters. The new filter/relay board from FAR Circuits takes up a lot more room. This would not have been a problem if I had laid out the cabinet so that the PA module was on the floor of the cabinet, with the filter/relay board stacked on top of it, and then with the control boards on top of that. Redoing the layout of my cabinet would have meant moving the relays and the fan, in addition to drilling and tapping holes in the PA module, which I didn't want to do. I was able to get everything back in the cabinet, but it was a tight fit. There is a lesson to be learned here, take your time in laying out the inside of your cabinet and take into consideration being able to easily remove subcomponents for repair or modification. It is easier to have a little more room than you need than to have to use a shoe-horn to get everything to fit!

This is a photo of the inside of my amplifier:



The board on the back wall is the BCD-10 band decoder module. There are two smaller control boards that are temporarily mounted on the screws that mount the filter/relay board. One of these is smart fan speed controller with a temperature sensor that I found on eBay.[xvi] The other small experimenter's board contains the circuitry to allow WaveNode to monitor my amplifier temperature and voltage. These boards will be combined on a motherboard with the amplifier control circuit when it is completed. This will be stacked on top of the filter/relay board.

This is photo of the front of the amplifier:

As you can see there is a hole for a band switch, but I never implemented this. I do all of my band switching from my computer. The other blank holes are reserved for “fault” display from the amplifier control board when it is installed.

If you are not using WaveNode or something similar to monitor the critical conditions of the amplifier, you will need to install meters for PA voltage, current, SWR, and output power.

Power Supply. I originally build the same linear power supply that Tom Sowden described in his article, using the power transformer from the Ameritron ALS 600. I never was totally satisfied with the lack of voltage regulation, and large voltage swings from no load to full load. These voltage swings generated RFI which got into my computer monitor. I had found a switched power supply on EBay that was originally used in HP Proliant server racks. The power supply is rated at 51V at 57 amps. I was able to purchase this for under $50 including shipping, and my plan was that I would put this on the shelf and use it when I build a 1KW amplifier. Instead I ended up using this as my power supply for EB104 and it works great.

These power supplies were used in the Proliant servers from both Compaq and HP, and have a model number of 226519-001. The power supply was built by Astec. The Astec model number is HPS3KW. I just did a search on EBay and found seven suppliers for these power supplies.

I have been using it for over six months and have never found any RFI generated by the power supply. It will easily handle a 1KW amplifier. My only objection is that the fan noise is greater that I would like, but I have learned to live with it.

Where do we go from here? There has never been a better time for a ham to build a MOSFET linear amplifier. Power supplies are inexpensive and easily obtained. The EB104 style amplifier with a few modifications and a TLT is great starting point for the amplifier, and will provide years of trouble free service. MRF150s are inexpensive from numerous EBay suppliers. The low cost makes this the best choice for a first-time solid state amplifier builder; it doesn't hurt so much when you destroy your first MOSFET! There is now a good filter/relay board available from FAR Circuits, and there soon will be a control board. If you are looking for an alternative to a commercial solid-state linear, this is a great choice.

If you are looking for a little more power, SD2933s are a much newer and better MOSFET than the MRF150s. They are more expensive at around $100 a piece list price, but lower cost sources for used/tested SD2933s are now available. I was able to purchase eight of them for $250, which included the shipping cost, and recently I found them for an even cheaper price on EBay. The SD2933s are now the MOSFET of choice for many builders, including Baruch (4Z4RB), Tokyo Hy Power, and Elecraft. Hams in Russia have built EB104 amplifiers using the larger SD2933s, by enlarging the openings for the MOSFET. It is a tight fit but it works. [xvii] FAR Circuits has the Extended HOG board which should work very well with the SD2933s and the TLT that I used in my EB104 amplifier. You can build an amplifier just as good as the Tokyo HyPower for a lot less cost.

EB104 has been around for a very long time and it really is time for a new printed circuit board design. Baruch has a very nice board that will work with either MRF150s or SD2933s. He can supply you with a pre-populated board, minus the MOSFETs which you have to provide, for less cost that getting the same components from CCI. For many hams this would be a better alternative that totally starting from scratch.

Baruch has also graciously offered to put his amplifier design and printed circuit board into the public domain. I have plans to build this amp with SD2933s, but it will be a while before I have time for that project. My EB104 is working beyond expectations and for me to take advantage of a 1KW amplifier; I will have to replace my antenna. Upgrading my antennas and selling my wife on the "need" for a tower and a Hexbeam is my next priority. Maybe I can move my station to my North Woods Cabin where I have a lot more room, and operate Internet remote control all the time. After that I will work on the new amplifier.

I would like to express my thanks again to Baruch, 4Z4RB, for his help. He spent hours with me on Skype telephone calls from Israel to Wisconsin, and many back and forth emails. He really is the leader in experimenting with TLTs in parallel/push-pull MOSFET amplifiers and he has been happy to share his experience with others. Without him pushing me in this direction, I would never have considered using a TLT in EB104. It has been a great learning experience. I would also like to thank Ken, K9FV for his help. Ken and I spent hours on email comparing notes and sharing experiences. Finally I would like to thank Fred Reimers, KF9GX, at FAR Circuits for all of his help with the filter/relay board, and his encouragement.

73 de K9AQ, Don Solberg

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