

A Single-Stage 1500 W Amplifier for 160 / 80 / 40 Meters

Do you want lots o' watts per buck? Here's your project!

By Frank A. Garcia, WA1GFZ

This article demonstrates the ease of designing and building a solid-state, high-efficiency power amplifier using inexpensive switching-power-supply FETs. (Use static-protective methods while working with FETs.—*Ed*) Although there is a wide range of possible operating voltages the user may select, the final goal here is to generate 1500 W output from about 50 V dc input. The gates are presently operated at zero bias, but there is provision for a positive bias input to operate the amplifier in class AB modes. This may be tried later, but the present application is for AM and CW modes only. Fifty to

60 W of drive power is required on 80 meters.

The input and output transformers are designed to cover 160 through 40 meters and handle at least 120 V peak input voltage during modulation peaks. The amplifier has been tested with three different output-transformer turns ratios:

- A 1:2 ratio produces about 500 W of output power,
- A 1:3 ratio produced about 800 W,
- A 1:4 ratio produces about 1200 W.

All of these tests were performed in the class E mode. Drain voltage was limited to 40 V during the testing. The shunt-loading control in the tank circuit allows a wide range of output power for each output transformer ratio.

The circuit layout has evolved over 15 years to minimize parasitic reactance. This is an important consider-

ation in low-impedance RF circuitry. This layout has been scaled up from a 160-meter transmitter that I built in 1996 using 14 IRF840 FETs in push-pull parallel running 1500 W peak power on AM. The efficiency of that final is 90%. It has been in constant use since 1997, using PWM amplitude modulation with a two-phase current-mode feedback converter.

The amplifier is built on a 10×11-inch heat sink 3 inches tall with a total surface area of about 1200 square inches to minimize temperature rise. A slot machined in the center allows the output transformer secondary winding to pass between the two halves of the output transformer primary. This heat sink was sized to handle the extra power dissipation if the FETs are to be positive biased to operate in the linear-amplifier mode. A quick analysis of

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temperature rise yields “130°C/W/square inch.” This means there would be about 22°C of temperature rise if the final were dissipating 200 W. Because of the high efficiency of this amplifier, this heat sink has a considerable safety factor even at 1500 W output. Fig 1 shows the finished heat sink with slot and tapped holes for mounting the PC board and components.

Two 3×4×1/8-inch-thick copper heat spreaders connect the FET drains (via the case of each FET) to the 1/2-inch copper tubing of the output-transformer primary. The heat spreaders are silver-soldered to the transformer primary tubes. This arrangement greatly reduces shunt inductance, thereby increasing efficiency.

Class E operation requires a shunt capacitor on each FET drain to store and release energy over the cycle. The heat spreaders form one plate of these capacitors and the heat sink is the other. A sheet of 0.003-inch Kapton serves as the dielectric. The FET mounting screws also attach the spreaders to the heat sink and Nylon inserts are used at each FET to electrically insulate the mounting screw from the heat spreader. The heat spreaders also serve as low impedance connections to the drains and output-transformer primaries and help keep the temperature of each FET constant, so they share the load properly. Fig 2 shows the primary of the output transformer where it connects to the spreaders.

The output capacitance of the FETs plus the distributed capacitance of the heat spreaders provides enough shunt capacitance to operate class E on 80 meters. Although this amplifier could be used on 160 meters, addi-

tional external shunt capacitance would be necessary to limit the peak voltage on the FET drains. Further, the Kapton insulator would need to be thicker if this final was tuned to 40 meters.

The FETs used for this project are Fairchild FQA11N90 rated for 900 V_{ds} (drain-source voltage) and cost about \$3 each in small quantities. Their power dissipation is 300 W at 25 °C, and their current rating is 11.4 A. Operating class E on 80 meters, the peak drain voltage during the “off” part of the operating

cycle is about 175 V at 40 V dc on the final. Twenty-two of these devices are used in the amplifier, which provides a considerable safety factor, and the total cost of these parts was under \$100. The cases of these devices are barely warm after a couple minutes of constant carrier output at 1000 W without a fan on the heat sink. Although I have not tried this amplifier on 40 meters, other amateurs have constructed 40-meter amplifiers using these FETs.

The input capacitance of the FET gates is about 3000 pF each (resulting in an extremely low-impedance circuit), it is impractical to connect the gate drive with conventional hook-up wire. A PC board was built with two transmission lines on one side (one for each phase) and a ground plane on the other. A small area was left for the driver-transformer secondary center tap. This area is connected to ground but could be used as a point where positive bias is injected. Fig 3 shows the PC board.

The broadband input transformer has a 4:1 turns ratio to match the 50 Ω drive to the amplifier input. The end of the transmission line opposite the drive transformer is loaded with two 50 Ω 10 W non-inductive resistors connected in parallel. This reduces the reactance of the input circuit and presents a more constant load to the driving source. The input SWR is about 1.5:1 across the 80-meter band. Additionally, a small two-turn inductor tunes the gates to peak the drive signal. Although this inductor can be eliminated, the load resistance would need to be lower to match the drive to 50 Ω, with a corresponding increase in drive power requirements. The match would have been better in this configu-

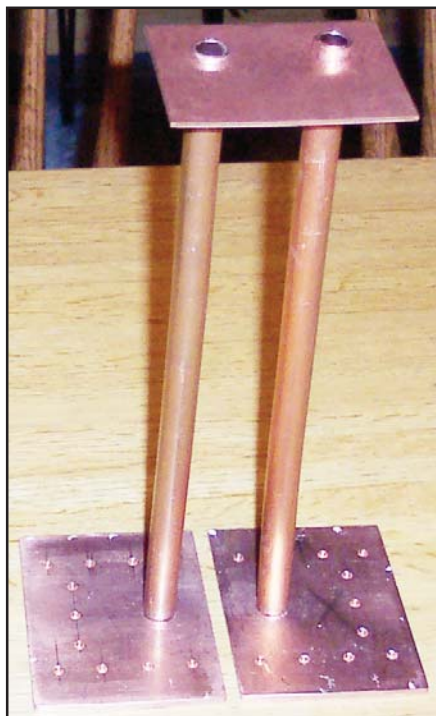


Fig 2—Primary of the output transformer where it connects to the heat spreaders.



Fig 1—Heat sink with slot and tapped holes for mounting the PC board and components.

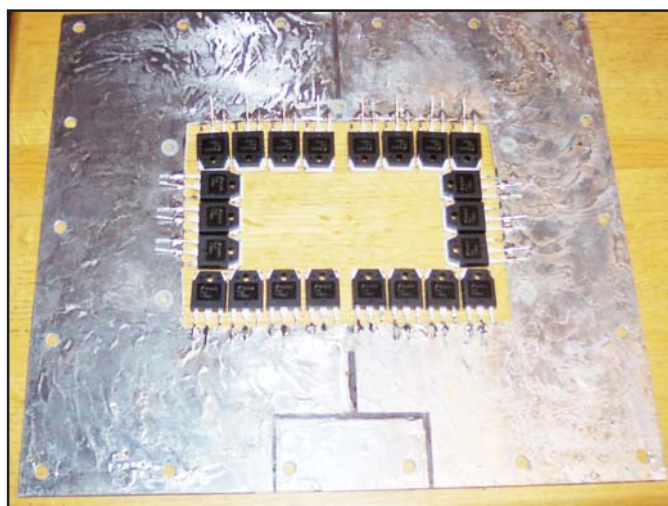


Fig 3—The PC board.

ration if there were a little more inductance between the drive transformer secondary and the PC board.

The gate drive needs to arrive at each FET simultaneously for the devices to share power properly and, furthermore, should have a relatively quick rise time to minimize the time the FET operates in its linear region. The delay between the first and last FET was measured at about 2 ns, which appears to be acceptable. The equal temperature rises of the FETs is an indication that they are evenly sharing the load.

The FET leads are soldered to the PC board with the gate leads on the top layer (transmission line) and the sources on the bottom layer (ground). The drain leads are not used; as mentioned earlier, the FET drain is connected to the heat spreader through its body. Both sides are tinned with 3% silver solder to minimize the resistance. The PC board is attached to the heat sink with #6-32 cap screws and nylon step washers (on the top) to insulate the gate traces. The board is spaced off the heat sink with 24 $\frac{3}{16}$ -inch spacers connecting the source plane to the heat sink. The FETs are attached with 22 #4-40 cap screws. The assembly is aligned by installing four #4-40 threaded rods in the corner holes of the heat sink, so the Kapton is not damaged during assembly. My first insulator failed after a FET mounting screw dug a hole in the insulator while I was trying to find the hole in the heat sink. The threaded rods are replaced with cap screws after the assembly is aligned and the other cap screws are installed. A small amount of thermal grease was used on the heat sink, heat spreaders and FETs to fill any voids. Fig 4 shows the assembled amplifier.

Great care is required to protect the Kapton dielectric of the shunt capacitor during assembly. It is also very important to remove all burrs and dirt to prevent damaging the Kapton as the FETs are tightened down. Kapton has a 7,000 V/mil voltage rating, and the insulator in the 160-meter rig has never failed running at about 80 V peak dc input. The peak positive voltage has been measured at about 400 V during testing with the amplifier mistuned. High voltage is also present on the secondaries of the step-up output transformers. The output transformer's secondary lead is #10 (AWG) Teflon insulated wire, which provides sufficient, if not optimum, insulation. The final configuration will have a sleeve of Kapton on the inside of the transformer primary tubes to

provide better voltage insulation.

A quick test was performed to determine if it was worth the time to package the amplifier into a chassis. The test verified that the design would work well and was worth the investment of material and time to complete the project. Fig 5 shows the test set up. Gratifyingly, the amplifier worked very well under these sub-optimum conditions. Several CW contacts and good reports provided the motivation to continue the project. No test is complete without a failure of some sort, and true to tradition, the series tuning capacitor failed during these tests, so a vacuum-variable cap was installed to complete the tests. The circulating current is quite high in the tank circuit, so the final design uses vacuum caps for both the tuning and the loading capacitors.

The next logical test step was to try a larger dc power source, because my test supply was severely overloaded. This amplifier was tested in the presence of several hams after the 2003 Marlboro, Massachusetts hamfest. Al, K1JCL, contributed a large dummy load and RF power meter and Tom, K1JJ, brought his peak-reading Bird 43 meter. Steve, WA1QIX, provided the test shack and modulator. We modified Steve's modulator by disabling his overload interlocks so we could see what this amplifier would dish out. My goal was to see how much power could be extracted from the amplifier with 50 V on the drains and the peak power under modulation.

We found the amplifier would make 1000 W at 50 V but required additional shunt caps for 80-meter operation. The class E drain waveform was cleaned up when four 1000 pF doorknob capacitors were added between the drain busses and ground, so as to increase the shunt capacitance of each phase by 2000 pF. This

increased shunt-capacitor value allowed lower-impedance operation.

The result of this test proved that the amplifier would easily produce 1000 W of carrier. This was the threshold of stability for the tank component values because of the output-transformer ratio. The heat sink temperature was warm but not hot during these tests. We had no way of accurately measuring the dc input current, the heat sink didn't get warm enough to worry about.

This test indicated that a bit of work on the output network was necessary. The 1:4 turns ratio of the output transformer introduced too much leakage inductance and was later reduced to 1:2 which, in turn, requires a change in the output-tank component values. In this case, the inductor value decreases while the capacitor values must increase to maintain the proper class E wave-

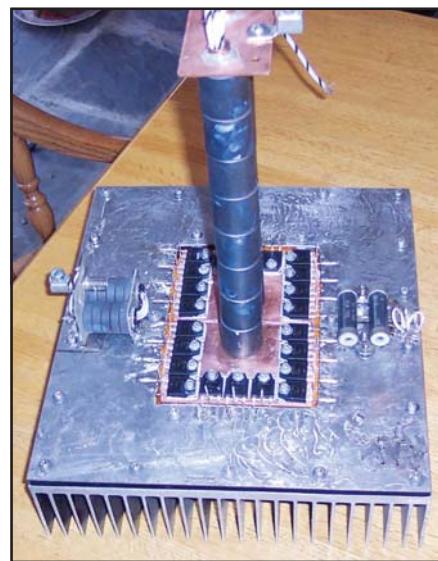


Fig 4—The assembled amplifier.



Fig 5—The amplifier test setup.

form. The new total shunt-capacitor value is about 8000 pF per phase, to allow a push-pull dc operating impedance under 2 Ω. The $R_{DS\ ON}$ of each bank of FETs is about 0.09 Ω; efficiency will decrease if the operating impedance is decreased further.

This amplifier was scaled to use larger output transformer cores than I had in my junk box. The next larger size of commercially-available core (1.5-inch OD, shorter, and having a lot more core area) would be a much better design choice. Using these larger cores, the height of the output transformer could be reduced by 50% with a corresponding reduction in leakage inductance with a better aspect ratio. However, the tall stack of cores never changed case temperature during testing.

An applications engineer suggested A material should be operated under 150 gauss at 4 MHz to keep losses low, which seems like a very conservative number. Type-43 material has similar performance with a little higher permeability. The A637 cores used were flea market loot. They are older switching-power-supply cores that work well up to 80 meters. Type-43 comes in the same size: 1.125×1.125 inches.

Fig 6 shows the schematic of the

final amplifier. The parts count is quite low but the layout is very critical to insure power sharing of the FETs. Figs 7 and 8 show the amplifier module mounted into a chassis for additional testing.

The amplifier will produce a lot more power at higher voltages, but the goal was to operate at 50 V on the drains to provide a comfortable safety margin on the voltage rating of the FETs, shunt capacitor insulation and output transformer insulation. This amplifier can be scaled to operate on 40 meters without additional shunt capacitors, but half as many cores should be used in the output transformer. The amplifier can also be modified to operate on 160 meters with additional shunt capacitors and/or a larger heat spreader to increase the distributed capacitance value. This amplifier would also make an efficient CW transmitter final if a slope-controlled series switch were to be included in the dc power source. It cannot be used as a CW linear amplifier because key clicks will be generated as the driver turns on and off. AM is also possible with this amplifier using a series modulator.

The adjustment of a Class E amplifier is somewhat different than for other modes, and efficient operation

depends largely on obtaining a clean waveform. An oscilloscope should be used to monitor the drain waveform and the gate drive until the user is comfortable operating a class E final. The gate drive should be at least 24 V_{P-P} , which corresponds to 50 to 60 W of RF input power on 80 meters.

This amplifier was operated without a load by mistake without any protection or failure. There is at least a 2:1 voltage safety factor in the drain waveform while running 1200 W output at 50 V input. After the initial tank capacitor failure, no other components have failed after extensive testing over a one-year period.

Conclusion

This amplifier will produce 1500 W output at 50 V on the drains, but the efficiency will be lower than expected. Sixty or 70 V would be a better choice. Steve, WA1QIX, set a rule of thumb at 50 W carrier per device as a good choice for high efficiency. My testing agrees with this choice. A few more FETs would allow 1500 W at 50 V. My next design will use a larger heat spreader to eliminate the doorknob caps added to this configuration.

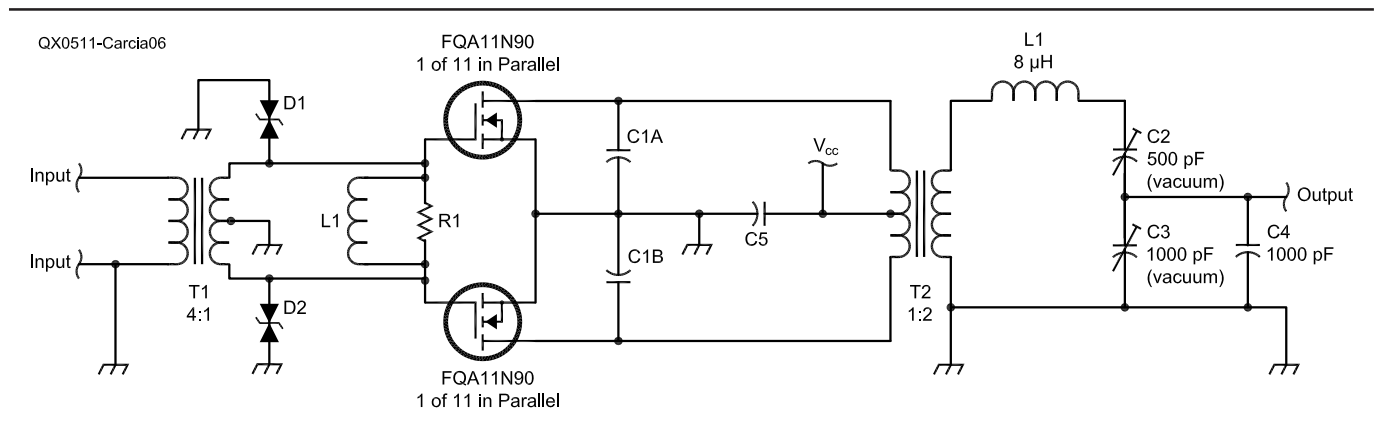


Fig 6—A partial schematic of 80-meter class-E amplifier (FQA11N90). One of 11 parallel connected circuits shown. Unless otherwise specified, use 1/4 W, 5%-tolerance carbon composition or film resistors.

C1A—3×4-inch copper plate 1/8-inch thick. FET drains and primary of output transformer common point. This plate is isolated from the heat sink with a 0.003-inch thick Kapton sheet.
C1B—Same as C1A. A capacitor is formed by the two heat-spreader plates and the heat sink. The value of each capacitor is about 3000 pF. This is in parallel with about 3000 pF of output capacitance from the 11 parallel connected FETs. This is the class-E shunt capacitance. Later 4000 pF was added to the shunt value by connecting two 1000 pF doorknob capacitors across C1A and C1B.

CR1, CR2—15-V, 1500 W Transorbs for FET gate-transient protection.
C4—Parallel combination of film and disc capacitors providing a low-impedance dc bypass.
L1—2 turns #14 AWG bare copper wire 1/2-inch ID, tuned to peak the drive signal on 80 meters.
L2, C2 and C3 are typical values for 80 meters. Double them for 160 meters and halve them for 40 meters. (C2 and C3 are vacuum-variable capacitors.)
R1—(2) 50 Ω, 10 W non-inductive resistors connected in parallel.

T1—Broad bandwidth input transformer with 4:1 impedance, with center tapped secondary. (Source: Communication Concepts, Inc; www.communication-concepts.com or an old solid-state amplifier transformer.)
T2—16 Chrometrics A637 cores (type-43 is a good substitute). Turns ratio is 1:2, 1:3 or 1:4. 1 turn 1/2-inch OD copper tubing primary and #10 AWG Teflon insulated wire secondary. This is sized to work on 160 meters with 120 V dc (peak) input voltage.



Fig 7—A view of the amplifier module mounted into a chassis for additional testing.



Fig 8—Views of the amplifier module mounted into a chassis for additional testing.



This amplifier is a work in progress, and the present configuration provides 1000 W of CW carrier at around 46 V, with an efficiency of 88%. The output inductor runs hot. An inductor of lower value wound with copper tubing would improve efficiency. An AM modulator providing 100 V peak voltage would easily produce 1500 W peak power with plenty of safety factor. The output power was pulsed to 5 kW peak output using a perfect 50 Ω load with 130 V on the drains as a final test. There was no sign of problems, but the output inductor was too small for this power level.

I recently found a six-meter linear using power FETs that used TO220 FETs. There was about a dozen configured in push-pull parallel with positive bias on the gates. This proves linear amplification is possible. A bank of RF FETs with over 5000 W of dissipation would not be possible for \$100 in parts.

Nathan Sokal, WA1HQC, has provided several *QEX* articles covering the design of class-E power amplifiers (*QEX* Jan/Feb 2001, p 9; Mar/Apr, p 60; May/June, p 60).

Steve, WA1QIX, has a Web site covering several Class E projects others have built and he helps to simplify Nathan's design choices. This is a good reference for determining final tank component values. There is also good information on tuning class E amplifiers (www.classeradio.com). Steve has links to Nathan's information and design software.

The Class E FORUM (<http://classe.monkeypuppet.com>) is another good Web site for finding information and contacting amateurs building solid-state transmitters. It is normal to measure close to 90 % efficiency on a class E amplifier. This is very nice during the summer when the heat from a tube amplifier wants to chase you out of the shack after a short time.

Thanks to the Following

Edited by John, W3JN
Tests: Steve, WA1QIX; Al, K1JCL;
Tom, K1JJ

Frank Carcia, WA1GFZ, has been a licensed amateur since 1966. He has been an avid homebrewer for 40 years building receivers, transmitters, linear amplifiers and beam antennas. He is mainly interested in high-performance receivers.

Frank worked in communications and control electronics for 30 years doing design and testing. □□

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