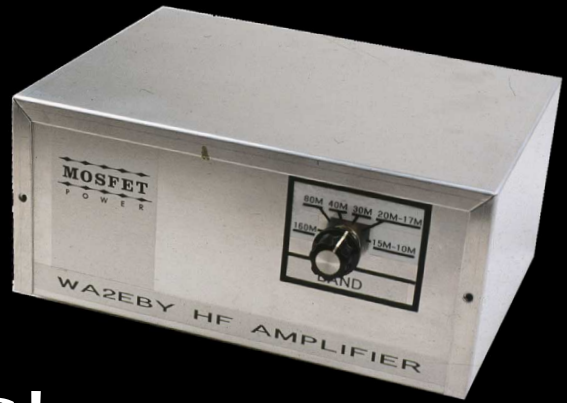


By Mike Kossor, WA2EBY

A Broadband HF Amplifier Using Low-Cost Power MOSFETs



Part 1—With only 1 W of drive, you'll get over 40 W out—from 160 through 10 meters!

Many articles have been written encouraging experimenters to use power MOSFETs to build HF RF amplifiers. That's because power MOSFETs—popular in the design of switching power supplies—cost as little as \$1 each, whereas RF MOSFET prices start at about \$35 each!

Over the years, I tucked away several of these articles, waiting for an opportunity to experiment with them. That opportunity came when I received a call from Al, W2OBJ. Al wanted a low-cost linear amplifier to use with his 5 W QRP transmitter when band conditions got poor. Ideally, the amplifier would generate at least 25 W on all the HF bands. Al's inquiry renewed my interest in the topic and provided the motivation I needed to get my project underway.

Al provided me with an extensive list of RF-amplifier construction articles that use power MOSFETs.¹⁻⁸ These articles provided useful information about MOSFETs and general guidelines for working with them, including biasing, parasitic-oscillation suppression, broadband impedance-matching techniques and typical amplifier performance data. It was clear from the performance data that Al's desire to get 25 W output from power MOSFETs on 1.8 to 30 MHz was going to be a challenge! The RF output power of most of the amplifiers described in the articles drops off to 10 W or less as frequency increases just to 14 MHz.

An Idea Brews

After hundreds of hours of experimentation, I came up with a design that exceeds our original objective: One watt of input power produces over 40 W of output (after harmonic

filtering) from 160 through 10 meters. To the basic amplifier, I added an RF-sensed TR relay and a set of low-pass filters designed to suppress harmonic output and comply with FCC requirements. The amplifier is built on double-sided PC board and requires *no tuning*. Another PC board contains the low-pass filters. Power-supply requirements are 28 V dc at 5 A, although the amplifier performs well at 13.8 V dc.

Several of these amplifiers have been built and exhibit similar performance. Al has been using his amplifier on each of the HF bands, logging well over 500 contacts in 18 months. Signal reports indicate a noticeable improvement in readability (about two S units on average) over his 5 W rig. No indications of instability, CW key clicks or distortion on SSB have been reported. To make it easy for you to duplicate this project, PC boards and parts kits are available, all at a cost of about \$100!⁹

An Overview of MOSFETs

MOSFETs operate very differently from bipolar transistors. MOSFETs are voltage-controlled devices and exhibit a very high input impedance at dc, whereas bipolar transistors are current-controlled devices and have a relatively low input impedance. Biasing a MOSFET for linear operation only requires applying a fixed voltage to its gate via a resistor. With MOSFETs, no special bias or feedback circuitry is required to maintain the bias point over temperature as is required with bipolar transistors to prevent thermal runaway.¹⁰ With MOSFETs, the gate-threshold voltage increases with increased drain current. This works to turn off the device, especially at elevated temperatures as transconductance decreases and $R_{DS(on)}$ (static drain-to-source *on* resistance) increases. These built-in self-regulating actions prevent MOSFETs from being affected

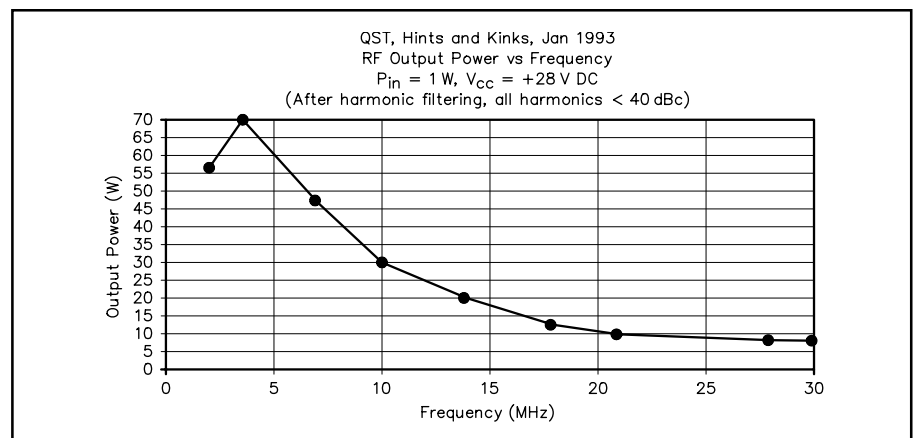


Figure 1—Jim Wyckoff, AA3X, "1 W In, 30 W Out With Power MOSFETs at 80 M," Hints and Kinks, QST, Jan 1993, pp 50-51.

¹Notes appear on page 43.

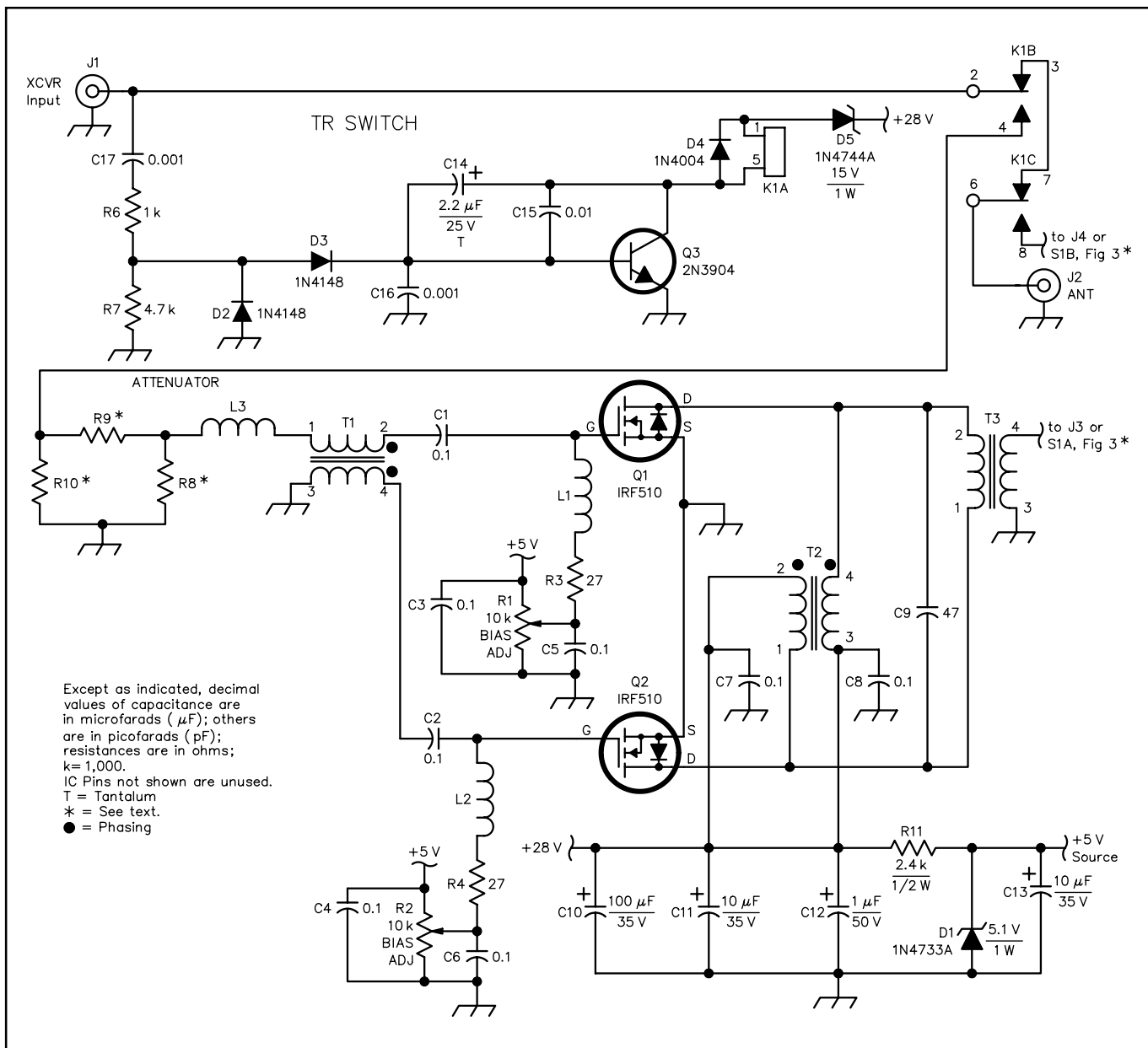
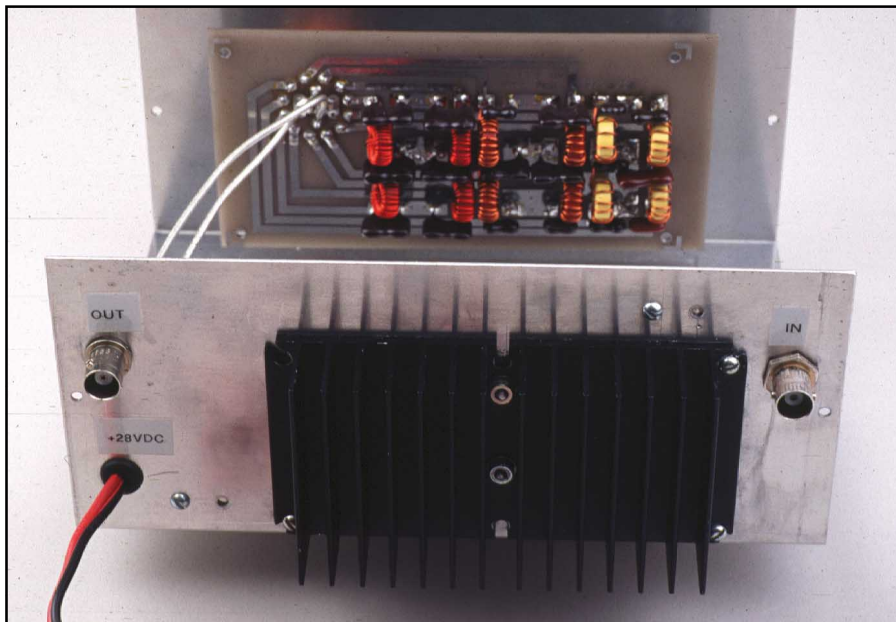


Figure 2—Schematic of the MOSFET all-band HF amplifier. Unless otherwise specified, resistors are $\frac{1}{4}$ W, 5% tolerance carbon-composition or film units. Equivalent parts can be substituted. Part numbers in parentheses are Mouser (Mouser Electronics, 968 N Main St, Mansfield, TX 76063; tel 800-346-6873, 817-483-4422, fax 817-483-0931; sales@mouser.com; <http://www.mouser.com>); see Note 9.

C1-C8—0.1 μF chip (140-CC502Z104M)
 C9—47 pF chip (140-CC502N470J)
 C10—100 μF , 35 V (140-HTRL35V100)
 C11, C13—15 μF , 35 V (140MLR35V10)
 C12—1 μF , 50 V (140-MLRL50V1.0)
 C14—2.2 μF , 35 V tantalum (581-2.2M35V)
 C15—0.01 μF chip (140-CC502B103K)
 C16, C17—0.001 μF chip (140-CC502B102K)
 D1—1N4733A, 5.1 V, 1 W Zener diode (583-1N4733A)
 D4—1N4004A (583-1N4004A)
 D2, D3—1N4148 (583-1N4148)
 D5—1N4744A, 15 V, 1 W Zener diode (583-1N4744A)
 J1, J2—SO-239 UHF connector (523-81-120)

K1—12 V DPDT, 960 Ω coil, 12.5 mA (431-OVR-SH-212L)
 L1, L2—9 $\frac{1}{2}$ turns #24 enameled wire, closely wound 0.25-in. ID
 L3—3 $\frac{1}{2}$ turns #24 enameled wire, closely wound 0.190-in. ID
 Q1, Q2—IRF510 power MOSFET (570-IRF510)
 Q3—2N3904 (610-2N3904)
 R1, R2—10 k Ω trim pot (323-5000-10K)
 R3, R4—27 Ω , $\frac{1}{2}$ W (293-27)
 R6—1 k Ω chip (263-1K)
 R7—4.7 k Ω chip (263-4.7K)
 R8—130 Ω , 1 W (281-130); for 7 dB pad (5 W in, 1 W out)
 R9—43 Ω , 2 W (282-43); for 7 dB pad (5 W in, 1 W out)
 R10—130 Ω , 3 W (283-130); for 7 dB pad (5 W in, 1 W out)

R8, R10—300 Ω , $\frac{1}{2}$ W (273-300); for 3 dB pad (2 W in, 1 W out)
 R9—18 Ω , 1 W (281-18); for 3 dB pad (2 W in, 1 W out)
 R11—2.4 k Ω , $\frac{1}{2}$ W (293-2.4K)
 T1—10 bifilar turns #24 enameled wire on an FT-50-43 core.
 T2—10 bifilar turns #22 enameled wire on two stacked FT-50-43 cores.
 T3—Pri 2 turns, sec 3 turns #20 Teflon-covered wire on BN-43-3312 balun core.
 Misc: Aluminum enclosure 3.5 \times 8 \times 6 inches (HWD) (537-TF-783), two TO-220 mounting kits (534-4724), heat-sink compound (577-1977), amplifier PC board (see Note 9), heat sink (AAVID [Mouser 532-244609B02]; see text), about two feet of RG-58 coax, #24 enameled wire and #20 Teflon-insulated wire.



A rear panel view of the amplifier showing the heat sink.

by thermal runaway. MOSFETs do not require negative feedback to suppress low-frequency gain as is often required with bipolar RF transistors. Bipolar transistor gain increases as frequency decreases. Very high gain at dc and low frequencies can cause unwanted, low-frequency oscillation to occur in bipolar transistor RF amplifiers unless negative feedback is employed to prevent it. Low-frequency oscillation can damage bipolar transistors by causing excess power dissipation, leading to thermal runaway.

MOSFET Limitations

Of course, MOSFETs do have their limitations. The high gate impedance and the device structure make them susceptible to electrostatic discharge (ESD) damage. Some easily applied precautions prevent this: Use a soldering iron with grounded tip; use a wrist strap connected to ground through a 1 M Ω resistor to bleed off excess body charge while handling MOSFETs and do all work on an anti-static mat connected to ground via a 1 M Ω resistor.

The sensitivity of a MOSFET's gate to static and high-voltage spikes also makes it vulnerable to damage resulting from parasitic oscillation. This undesired self-oscillation could result in excessive gate-to-source voltage that permanently damages the MOSFET's gate insulation. Another MOSFET limitation is gate capacitance. This parameter limits the frequency at which a MOSFET can operate effectively as an RF amplifier. I recommend reviewing the referents of [Notes 1, 2 and 3](#) if you are interested in more detailed information about MOSFETs.

Power MOSFET RF Amplifiers

Of the several power MOSFET amplifiers I built to check their performance, the one providing the best performance is the push-pull design described by Jim Wyckoff, AA3X, in *QST* (see [Note 3](#)). I used IRF510 power

MOSFETs rather than the IRF511s specified. The performance of this power MOSFET amplifier design is summarized in [Figure 1](#); its basic design is very similar to another amplifier described in the referent of [Note 4](#), written 10 years earlier. That amplifier uses a pair of more-expensive MRF138 MOSFETs designed specifically for RF applications.

As [Figure 1](#) shows, the Hints and Kinks amplifier performance is excellent from 1.8 MHz to 7 MHz and far exceeds the published figure of 30 W output on 3.5 MHz. As frequency increases above 10 MHz, however, output drops off rapidly, falling below 10 W above 21 MHz. (These levels were measured after harmonic filtering.)

Although the amplifier is identified as stable, my first attempt at duplicating the amplifier resulted in oscillations that destroyed one of the IRF510s. I was puzzled by this. At first, I thought the problem was caused by my substitution of the slightly more robust IRF510 MOSFETs for the called-for IRF511s. That idea proved wrong when my second attempt to power up the amplifier with IRF511 MOSFETs installed also resulted in a blown IRF511. (Thank goodness these are \$1 power MOSFETs, not \$35 RF MOSFETs!) I finally achieved good stability when I added a small amount of inductance in series with the MOSFET source to ground (just two turns of #24 wire, 0.125 inch diameter). With this added inductance, I was able to remove the ferrite beads from the circuit without any sign of instability. I believe the substitution of the IRF510 and minimizing source lead inductance are the reasons I obtained significantly higher RF output power and wider bandwidth than described in the referent of [Note 3](#). This experiment underscores the need to observe *exact* construction techniques and physical layout if similar performance is to be expected. Even though I used PC board construction, I got significantly different

results because my layout was not the same as the author's.

Modifying the Design

Although the amplifier performed better than expected, its bandwidth was significantly less than desired. Considerable experimentation (and I do mean considerable!) resulted in the circuit shown in [Figure 2](#). This amplifier consists of two power MOSFETs operating in push-pull and employs an RF-sensed TR relay.

During receive, TR relay K1 is deenergized. Signals from the antenna are connected to J2 and routed through K1 to a transceiver connected to J1. (This path loss is less than 0.3 dB from 1.8 MHz through 30 MHz.) In transmit, RF voltage from the transceiver is sampled by C17 and divided by R6 and R7. D2 and D3 rectify the RF voltage and charge C16. Q3 begins conducting when the detected RF voltage across C16 reaches approximately 0.7 V. This energizes K1, which then routes the transmitted RF signal from J1 to the input of the amplifier and sends the output of the amplifier to the antenna at J2. RF-sensed relay response is very fast. No noticeable clipping of the first CW character has been reported.

I made provisions to include an RF attenuator (consisting of R8, R9 and R10) to enable adjusting the amplifier input power to 1 W. (The parts list contains resistor values to reduce the output of 2 or 5 W drivers to 1 W.) The 1 W signal is then applied to the primary of T1 via an input impedance-matching network consisting of L3. T1 is a 1:1 balun that splits the RF signal into two outputs 180 degrees out of phase. One of these signals is applied by C1 to Q1's gate. The other signal is routed via C2 to Q2's gate. The drains of Q1 and Q2 are connected to the primary of output transformer T3, where the two signals are recombined in phase to produce a single output. T3 also provides impedance transformation from the low output impedance of the MOSFETs to the 50 Ω antenna port. Dc power is provided to the drains of Q1 and Q2 by phase-reversal choke, T2. This is a very effective method to provide power to Q1 and Q2 while presenting a high impedance to the RF signal over a broad range of frequencies. The drain chokes for Q1 and Q2 are wound on the same core, and the phase of one of the chokes (see the phasing-dot markings on T2) is reversed. C9 increases the bandwidth of impedance transformation provided by T3, especially at 21 MHz.

The 5 V bias supply voltage is derived from 28 V by Zener diode D1 and current-limiting resistor R11. Bypass capacitors C3, C4, C5, C6 and C13 remove RF voltages from the bias supply voltage. Gate bias for Q1 and Q2 is controlled independently. R1 adjusts Q1's gate-bias voltage via R3 and L1. R2 works similarly for Q2 via R4 and L2.

At low frequencies, the amplifier's input impedance is essentially equal to the series value of R3 and R4. L1 and L2 improve the input-impedance match at higher frequencies. The low value of series resistance provided by R3 and R4 also reduces the Q of

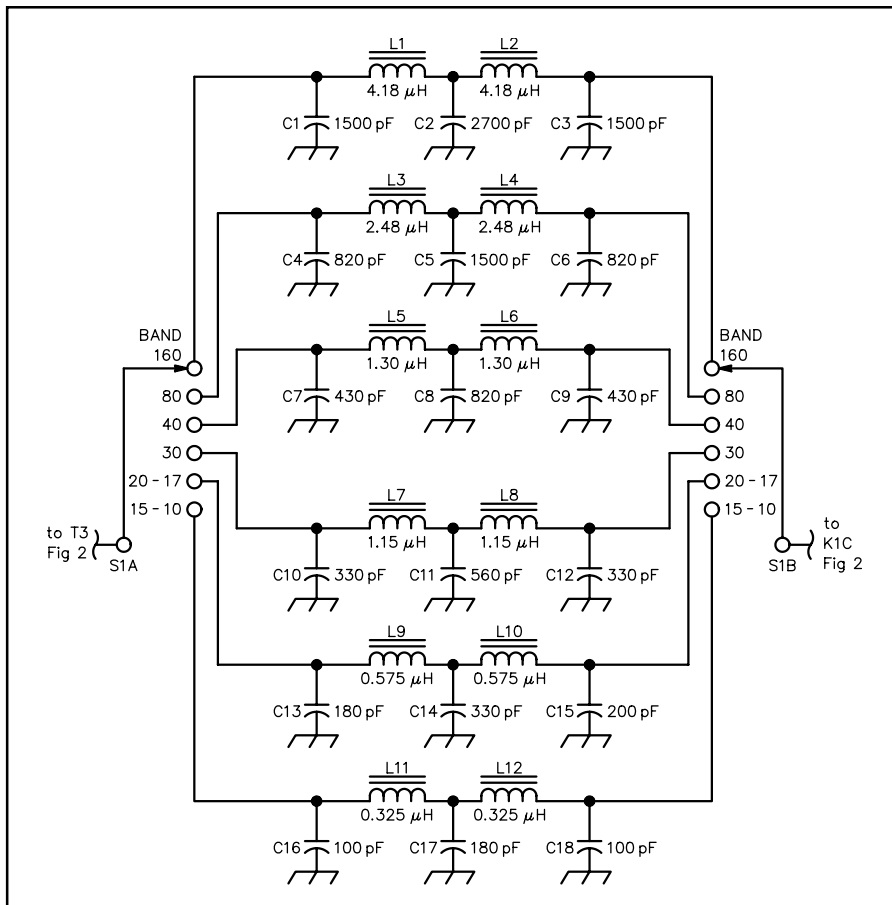


Figure 3—Low-pass filter schematic. In some cases, the actual filter component values differ from the calculated values of a standard 50 Ω -input filter. Such differences improve the impedance matching between the amplifier and the load. Capacitors are all dipped mica units.

- C1, C3, C5—1500 pF (5982-19-500V1500)
 C2—2700 pF (5982-19-500V2700)
 C4, C6, C8—820 pF (5982-19-500V820)
 C7, C9—430 pF (5982-15-500V430)
 C10, C12, C14—330 pF (5982-19-500V330)

- C11—560 pF (5982-19-500V560)
 C13, C17—180 pF (5982-15-500V180)
 C15—200 pF (5982-15-500V200)
 C16, C18—100 pF (5982-10-500V100)
 S1—2 pole, 6 position rotary (10YX026)
 Misc: low-pass filter PC board (see Note 9)

impedance-matching inductors L1 and L2, which improves stability. Dc blocking capacitors C1 and C2 prevent loading the gate bias-supply voltage.

C14 keeps transistor Q3 conducting and K1 energized between SSB voice syllables or CW elements. Without C14, K1 would chatter in response to the SSB modulation envelope and fast keying. Increasing the value of C14 increases the time K1 remains energized during transmit. The reverse voltage generated by K1 when the relay is deenergized is clamped to a safe level by D4. D5 drops the 28 V supply to 13 V to power 12 V relay K1. D5 can be replaced with a jumper if K1 has a 28 V dc coil or if you intend to operate the amplifier with a 13.8 V dc supply.

Harmonic Filtering

Although biased for class AB linear operation, this amplifier (like others of its type) exhibits some degree of nonlinearity, resulting in the generation of harmonics. This push-pull amplifier design cancels even-order harmonics (2f, 4f, 6f, etc) in the output transformer, T3. Odd-order harmonics are

not canceled. Second-order harmonics generated by the amplifier are typically less than 30 dBc (30 dB below the carrier) whereas third-order harmonics are typically only 10 dBc. FCC regulations require all HF RF-amplifier harmonic output power to be at least 40 dBc at power levels between 50 to 500 W. To meet this requirement, it is common practice for HF amplifiers to use low-pass filters. Separate low-pass filters are needed for the 160, 80, 40 and 30 meter bands. The 20 and 17 meter bands can share the same low-pass filter. So, too, the 15, 12 and 10 meter bands can share a common low-pass filter; see Figure 3.

Switching among the six filters can be a messy wiring problem, especially on the higher-frequency bands where lead lengths should be kept short for optimum performance. This problem is solved by mounting all six low-pass filters on a PC board. A two-pole, six-position rotary switch (S1) mounted directly on the same PC board manages all filter interconnections. One pole of S1 connects the amplifier output to one of the six filter inputs, while S1's other pole simul-

taneously connects the corresponding filter's output to the TR relay, K1. Only two coaxial-cable connections are required between the RF amplifier and the low-pass filter board.

Next Month

In Part 2, I'll wrap up with amplifier construction and adjustment, and discuss the amplifier's overall performance. See you then!

Notes

- Doug DeMaw, W1FB, "Power-FET Switches as RF Amplifiers," *QST*, Apr 1989, pp 30-33. See also Feedback, *QST*, May 1989, p 51.
- Wes Hayward, W7ZOI, and Jeff Damm, WA7MLH, "Stable HEXFET RF Power Amplifiers," Technical Correspondence, *QST*, Nov 1989, pp 38-40; also see Feedback, *QST*, Mar 1990, p 41.
- Jim Wyckoff, AA3X, "1 Watt In, 30 Watts Out with Power MOSFETs at 80 Meters," Hints and Kinks, *QST*, Jan 1993, pp 50-51.
- Doug DeMaw, W1FB, "Go Class B or C with Power MOSFETs," *QST*, March 1983, pp 25-29.
- Doug DeMaw, W1FB, "An Experimental VMOS Transmitter," *QST*, May 1979, pp 18-22.
- Wes Hayward, W7ZOI, "A VMOS FET Transmitter for 10-Meter CW," *QST*, May 1979, pp 27-30.
- Ed Oxner, ex-W9PRZ (SK), "Build a Broadband Ultralinear VMOS Amplifier," *QST*, May 1979, pp 23-26.
- Gary Breed, K9AY, "An Easy-to-Build 25-Watt MF/HF Amplifier," *QST*, Feb 1994, pp 31-34.
- Parts for this project are available in five modular kits. The following three kits are available from Mouser Electronics (Mouser Electronics, 958 N Main St, Mansfield, TX 76063; tel 800-346-6873, 817-483-4422, fax 817-483-0931; sales@mouser.com; <http://www.mouser.com>): Amplifier components (Mouser P/N 371-HFAMP1) consisting of the amplifier PC board and all PC-board-mounted components (except for the ferrite cores). Price: \$35, plus shipping. Amplifier hardware kit (Mouser P/N 371-HFAMP2) consisting of the aluminum enclosure, two UHF connectors, two TO-220 mounting kits, AAVID heat sink and one container of heat sink compound. Price: \$30 plus shipping. Low-pass filter kit (Mouser P/N 371-HFAMP3) consisting of the low-pass filter PC board, rotary switch and all PC-board-mounted capacitors (inductor cores are not included). Price: \$35, plus shipping. Part-placement diagrams accompany the PC boards. PC boards only are available from Mouser Electronics: HF amplifier board (#371-AMPPWB-2); filter PC board (#371-LPPWB-2). Price \$15 each, plus shipping.
- The following two kits are available from Amidon Inc (Amidon, Inc, 240 Briggs Ave, Costa Mesa, CA 92626; tel 1-800-898-1883, 714-850-4660, fax 714-850-1163): Amplifier ferrite kit (Amidon P/N HFAFC) containing the ferrite cores, balun core and magnet and Teflon wire to wind the transformers for the HF amplifier. Price: \$3.50 plus shipping. Low-pass filter cores kit (Amidon P/N HFFLT) containing all iron cores and wire for the low-pass filters. Price: \$4.50 plus ship.
- See Motorola Application Reports Q1/95, HB215, *Application Report AR346*.

Thermal runaway is a condition that occurs with bipolar transistors because bipolar transistors conduct more as temperature increases, the increased conduction causes an increase in temperature, which further increases conduction, etc. The cycle repeats until the bipolar transistor overheats and is permanently damaged.

Mike Kossor, WA2EBY, was first licensed in 1975. He earned his MSEE degree in 1987 from Stevens Institute of Technology in Hoboken, New Jersey. Mike has been employed by Lucent Technologies for 15 years, where he designs high-linearity RF amplifiers for PCS and cellular base stations. You can reach Mike at 244 N 17th St, Kenilworth, NJ 07033; mkossor@lucent.com. 