



QST

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May 1997

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JRC NRD-535D receiver

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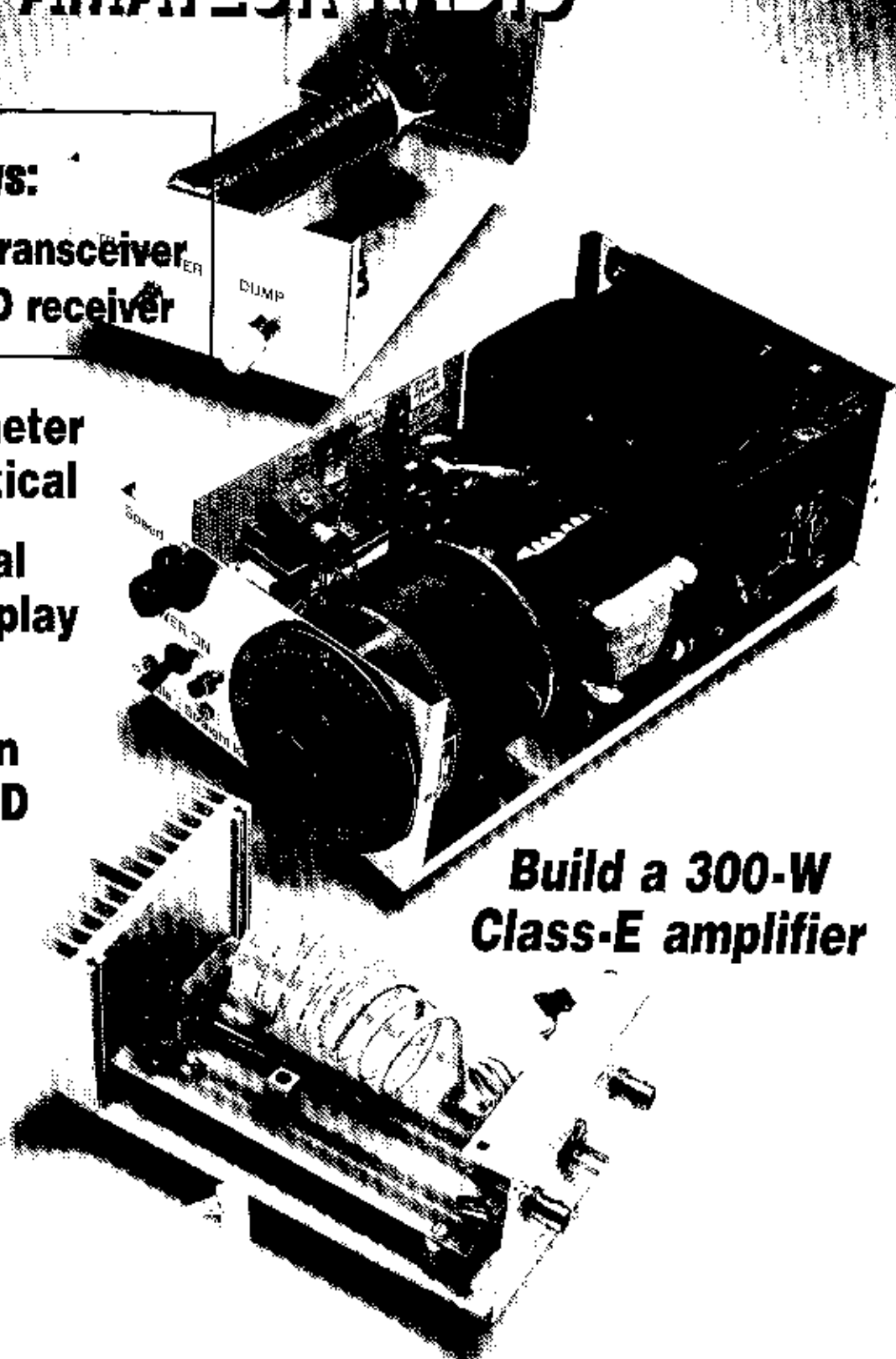
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**Build a 300-W
Class-E amplifier**

High-Efficiency Class-E Power Amplifiers—Part 1

With 3 to 12 W of drive, you can push 300 to 500 W CW out of an \$11 transistor! The trick is to use Class E.

These 300 and 500-W 40-meter amplifiers evolved from a series of undergraduate student projects at Caltech. Our goal was to design an inexpensive amplifier that amateurs can easily duplicate.¹ The amplifiers use inexpensive, readily available power MOSFETs that can be driven by a QRP transceiver; in our case, the NorCal 40A. A block diagram of our setup is shown in Figure 1. The components of the station are shown in Figure 2.

Our 300-W amplifier uses an International Rectifier (IR) IRFP440; the 500-W amplifier employs an IRFP450. These transistors are widely used in switching power supplies, but we have not seen them previously reported for use as RF amplifiers. The MOSFETs have a maximum drain voltage of 500 V, with maximum RMS drain currents of 8.8 A for the IRFP440, and 14 A for the IRFP450. Both transistors are available from Digi-Key: The 440 costs \$8; the 450 costs \$11.

Class-E amplifiers are extremely efficient—about 90%. Because of the low loss, no cooling fan is required. No TR switch is needed; the received signal is piped through the amplifier itself. Even without an external filter, the amplifiers meet the FCC requirements for spurious emissions. They can be built and tuned up with an RF power meter, a multimeter, oscilloscope and a dummy load. Tune-up consists of adjusting an input coil for matching and an output coil to set the power level.

Operational Classes

In addition to the well-known Class A, B, and C operational modes, there are Class D and E.² In Class D and E, the devices operate as switches, half the time completely on, and the other half completely

off. But transistors are not perfect switches. The MOSFETs have a resistance of about 1 Ω when on, and a capacitance of several hundred picofarads when off. Losses are greatly reduced in switching amplifiers, but there is a penalty: The output power no longer depends on the *drive power*, but rather on the *supply voltage*. This means that switching amplifiers are *not* linear amplifiers, and they are *not* suitable for SSB without additional limiting and modulating circuits. However, they are fine for CW, FSK and FM.

In a Class-D amplifier, a pair of transistors switch on and off, out of phase across an output transformer. Fred Raab, WA1WLW, recently developed a Class-D power amplifier that produces 250 W on 40 meters with an efficiency of 75%.³ However, Class-D amplifiers are relatively complex. On the other hand, the Class-E

circuit has significant advantages for the homebrewer because only one transistor, without gate bias or output transformer, is needed, and it can be driven by a low-power transceiver.

The Class-E Amplifier

The Class-E amplifier was invented and patented by Nathan Sokal, WA1HQC, and Alan Sokal, WA1HQB, in 1975.⁴ It minimizes heat loss by having as little overlap as possible between voltage and current. Figure 3 shows an idealized Class-E circuit. As the switch opens and closes, the current alternately flows in the switch and in the load network. The switch voltage and

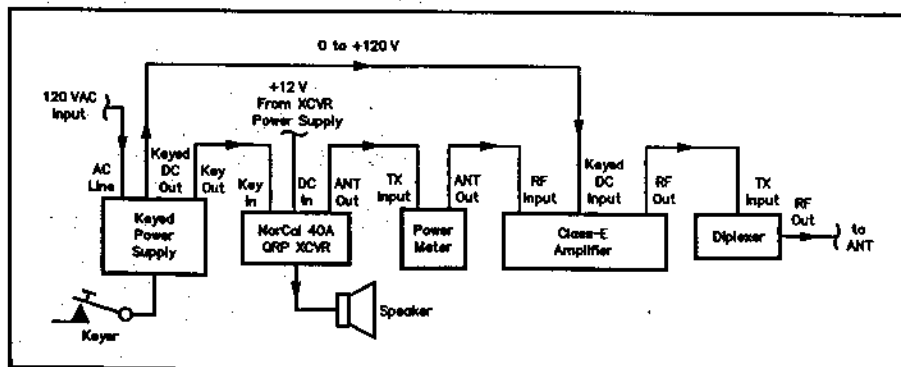
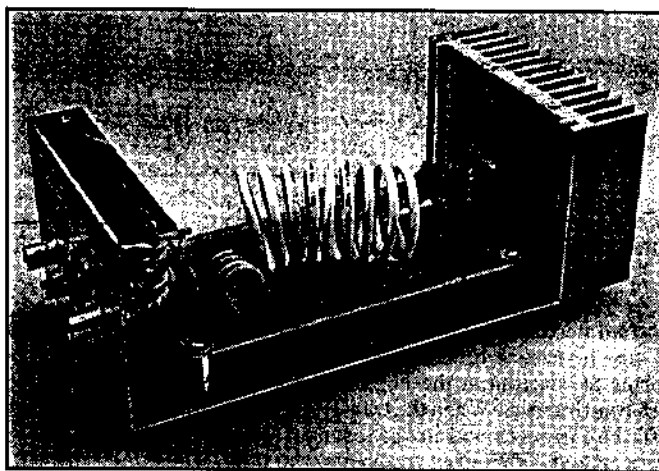


Figure 1—Block diagram of the Class-E amplifier station.

¹Notes appear on page 42.

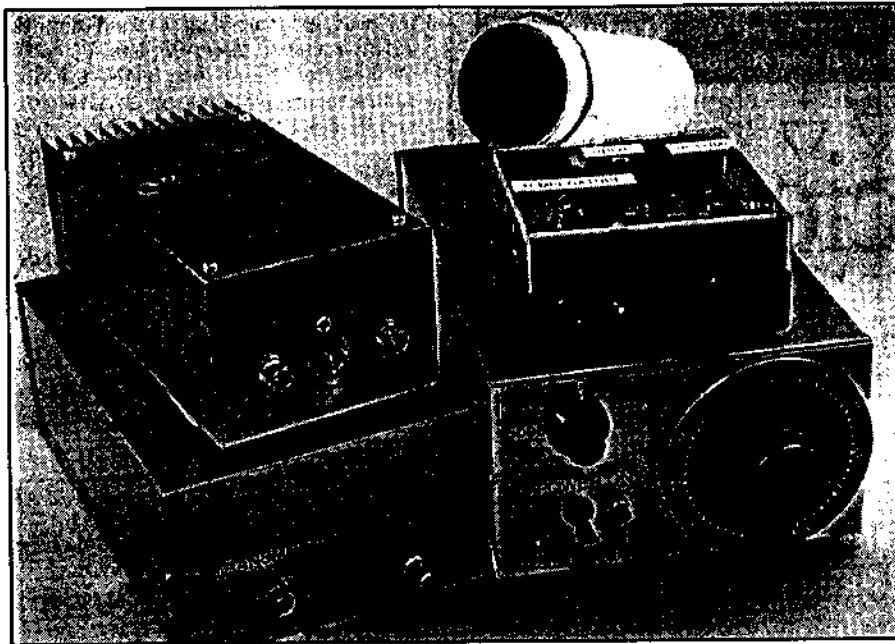


Figure 2—The components of the Class-E amplifier station. Clockwise from bottom left: the diplexer, amplifier, resonant speaker, NorCal 40A and keyed power supply. The latter houses the keyer and a pulse-stretching and shaping circuit.

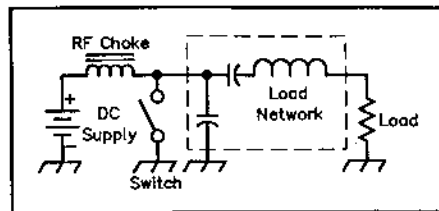


Figure 3—An idealized Class-E amplifier. The transistor is represented by a switch that opens and closes at RF.

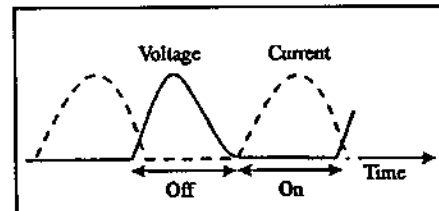


Figure 4—Class-E voltage and current waveforms. Class-E amplifiers reduce loss by keeping the overlap between voltage and current low.

current waveforms are shown in Figure 4. It may be easiest to understand the waveforms by starting at the beginning of the off-time interval. When the transistor turns off, the current flows into the resonant load network, and there is a transient voltage that rises and falls. With a properly designed load network, the voltage returns to zero smoothly with zero slope. The transistor switches on when both the voltage and the current are small, keeping losses low even if the switching is slow or slightly mistimed. Once the transistor turns on, the current rises smoothly until it switches off again, and the cycle repeats. The resonant load network does limit a Class-E amplifier to single-band operation.

For a given dc input power, the power output of a 90% efficient Class-E amplifier is three times greater, and the dissipated power is seven times smaller, than that of a 30% efficient Class-A amplifier. This means that for a given dissipated power, we can get 21 times more power from a Class-E amplifier.

The Caltech Power Amplifiers

Both amplifiers have a common diagram (Figure 5) and PC board, but use components with different values. Several components are added to the basic Class-E circuit for matching and filtering. The MOSFET's gate impedance is rather low, and primarily capacitive, with a reactance of about 4 Ω. There is also a resistive component of about 2 Ω from parasitic series resistance in the gate itself, and the drain on resistance that is capacitively coupled to the gate. T1 reduces the 50-Ω impedance of the drive circuit to about 2 Ω to match the low resistance of the gate and sets the

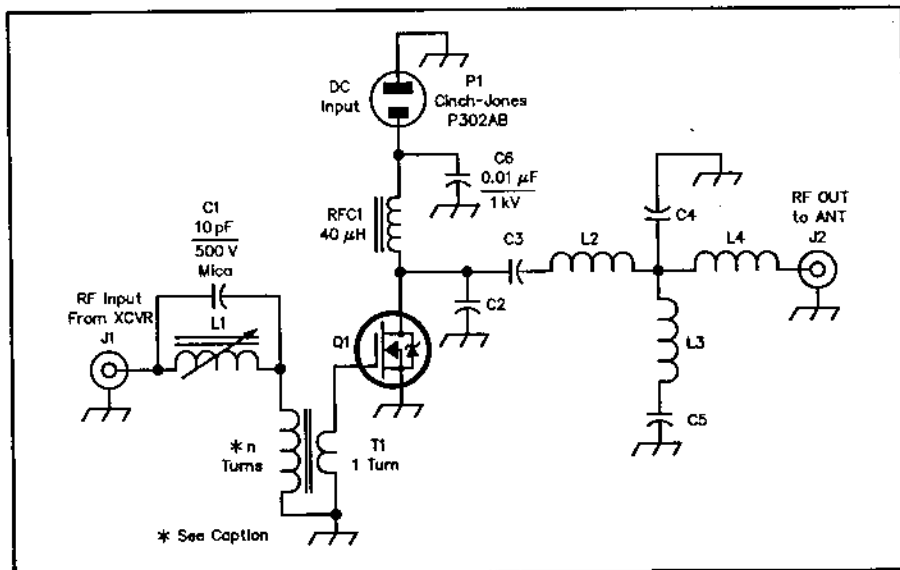


Figure 5—Circuit diagram and parts list for the amplifiers. Mica capacitors are available from Newark. L2, L3 and L4 are made with #10 THWN solid, insulated house wire sold in hardware stores. T1's core is an RF400-0, available from Communications Concepts (see Note 1 for supplier information). L1 is a Toko 10K (2.2 μH), available from Digi-Key. RFC1 is a J. W. Miller type 5240, available from Newark.

- C1—10 pF, 500 V mica
- C2—300 W, 270 pF; 500 W, 390 pF; (For C2 through C5, Cornell Dubilier mica capacitors, type CDV19, 1 kV, 5%)
- C3—300 W, 1500 pF; 500 W, 2000 pF
- C4—300 and 500 W, 100 pF
- C5—300 W, 680 pF; 500 W, 820 pF
- C6—0.01 μF, 1 kV ceramic disc
- J1, J2—BNC or SO-239 connectors
- L1—2.2 μH, Toko 10K; available from Digi-Key.
- L2—300 W, 9 turns; 500 W, 8 turns #10 THWN wound on 1 1/4-inch-OD plastic-pipe form; spread turns to fit holes in PC board.
- L3—300 W, 4 turns; 500 W, 3 turns #14 THWN wound closely spaced on a 1/2-inch-diam drill bit

- L4—300 W, 5 turns; 500 W, 5 turns #14 THWN wound on a 1/2-inch-diam drill bit form, turns spaced to occupy 1 inch
- P1—Cinch-Jones P302AB
- Q1—IRFP440 for 300-W amplifier; IRFP450 for 500-W amplifier; (use International Rectifier transistors only)
- RFC1—40 μH, 3 A
- T1—Pri: 300 W, 5 turns; 500 W 6 turns #26 stranded hook-up wire; wound on RF400-0 core, available from Communications Concepts
- Misc: Berquist K10-104 insulating pad (thermal resistance of 0.2-K/W, 6-kV breakdown rating); available from Digi-Key.

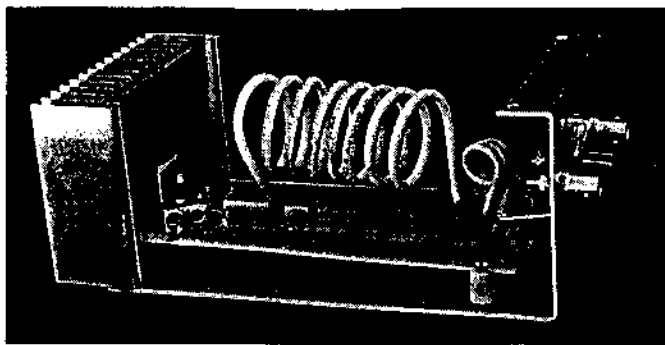


Figure 6—Inside the 500-W amplifier. The large coil is L2; L3 is the small coil. The circuit board is mounted on 1/2-inch standoffs. BNC connectors are used for the RF input and output. No harm is done if the RF input and output are accidentally interchanged.

dc bias to 0 V. L1 is adjusted to cancel the gate capacitance; the input SWR is typically 1.5:1. C1 shunts L1 at high frequencies to reduce ringing in the VHF range. The 0-V gate bias ensures that the transistor is off when it is not driven, because this is far below the threshold voltage, which is about 4 V. We have never seen oscillations in these amplifiers.

C3 and L2 form a resonant network that produces the rising and falling voltage waveform needed for the Class-E amplifier. C5 and L3 act as a notch filter for the second harmonic. Without the notch filter, the second harmonic is typically between -25 and -30 dBc instead of the -40 dBc that the FCC requires on HF. In addition, C5 and L3 transform the 50- Ω antenna impedance to about 10 Ω , the appropriate load for a Class-E amplifier. RFC1 converts the 0 to 120-V dc input from the power supply to a current source, and C6 helps keep RF energy out of the power supply.

C4 and L4 form a low-pass filter to remove VHF harmonics. Without the filter, there are several harmonics at levels from -40 to -60 dBc in the frequency range from 130 to 210 MHz. With the filter, the VHF harmonics are reduced to the -70 to -80-dBc level.

Amplifier Construction

The 500-W amplifier is shown in Figure 6 with its cover removed. The transistor is mounted on a 3x4 1/8-inch heat sink with 1-inch fins (type HS50-3.0 from RF Parts, with a thermal resistance of 2 K/W with no fan) with a #6-32 bolt and nut. The transistor generates most of the heat (about 10% of the dc power) in the amplifier, so it must have good thermal contact to the heat sink. Because the transistor's case reaches high voltages, it must be electrically isolated from the heat sink. We use a Kapton pad manufactured by Berquist that has a thermal resistance of 0.2 K/W and a breakdown voltage of 6 kV. The heat-sink surface must be free of burrs, and the transistor should lie flat on the surface with minimal stress on the leads. If a torque screwdriver is available, International Rectifier recommends a

mounting torque of 10 inch-pounds. The heat-sink baseplate is an aluminum L bracket bent from 0.050-inch-thick aluminum sheet. A U-shaped enclosure cover is made of 0.016-inch-thick aluminum sheet. A hole in the cover allows insertion of a plastic screwdriver for tuning L1.

Solder Q1 and C2 flush to the PC board to reduce VHF ringing on the gate signal. Good electrical contact is needed between Q1's source lead and the heat sink. Use a #6-32 bolt and nut, with washer spacers so that the source lead does not bend. Scope-probe pigtailed soldered to Q1's gate and drain leads poke through holes in the baseplate. Rubber grommets in the holes prevent the pigtailed from shorting to the chassis.

L4, L3 and L2 are made by winding solid insulated wire on pipe and drill-bit forms. Orient the coils at right angles to each other to reduce coupling between them. L2 has a 7-MHz Q of 350; L3 and L4, a Q of about 170. For C2, C3 and C5, use only 1-kV mica capacitors—even 500-V capacitors fail spectacularly with a burst of flame. If a 1-kV, 100-pF capacitor is not available for C4, substitute a series-connected pair of 500-V, 200-pF mica capacitors. For best filtering, mount C4 and L4 directly on the center pin and ground lug of J2. Mount L4 with its axis vertical to reduce coupling to the other coils.

The NorCal 40A Driver

For a driver, we use a NorCal 40A,⁵ but its 2-W output is not enough to drive these amplifiers. Fortunately, the NorCal 40A

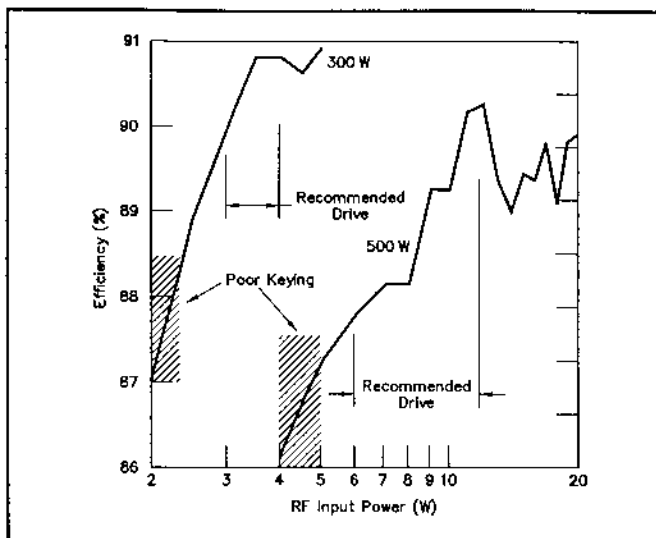


Figure 7—The measured efficiency plotted against RF input power. These measurements were taken with the heat sink at room temperature. In operation, the heat-sink temperature rises and the on resistance increases, so that the efficiency drops somewhat. Recommended drive power for the 300-W amplifier is 3 to 4 W; for the 500-W amplifier, 6 to 12 W. The dc input power was calculated from voltage and current measurements made with Fluke 87 multimeters; the RF output power was determined with a Bird 43P wattmeter using a 500-W element. Bird lists the accuracy of this wattmeter as ± 25 W, but we were able to improve the accuracy of the measurement to an estimated 1% by thermal calibration. RF input power was measured with a Diamond SX-200 wattmeter.

can be modified to deliver greater power output.⁶ We recommend 3 to 4 W drive for the 300-W amplifier, and 6 to 12 W for the 500-W amplifier. These drive levels give an efficiency in the 90% range (Figure 7). Drive levels lower than these give poor efficiency; higher drive levels increase the dissipated power without improving efficiency. Don't drive the 300-W amplifier with less than 2.3 W, and the 500-W amplifier with less than 5 W. At these low power levels, the transistor may not turn on fully at all supply voltages, subharmonic spurious components may be generated, and the amplifier may not key properly.

The recommended drive powers produce peak gate voltages of between 15 and 20 V. International Rectifier specifies a maximum peak gate voltage of 20 V to avoid rupturing the gate. Although the drive levels are close to this limit, experience shows them to be quite safe. The 20-V limit is more appropriate for the low frequencies used in power supplies than for RF voltages. In controlled tests, we've pushed the 300-W amplifier to 60-V gate-voltage peaks, *three times* the manufacturer's voltage limit, without damage.

Next month, we'll discuss the keyed power supply, keying waveform shaper and tune-up. Join us!

Notes

¹A package of amplifier parts *only*, including PC board, components, connectors, heat sink and chassis is available at cost from Puff Distribution, Department of Electrical Engineer-

ing, MS 136-93, Caltech, Pasadena, CA 91125. Price: \$50 for US orders, \$60 for foreign orders. The price includes tax and shipping by surface mail. Make payment by check or money order only to "Caltech-Puff Distribution." Foreign checks must be drawn on a bank with a US branch office. Please provide your Amateur Radio call sign and specify which amplifier (the 300 or 500 W unit) you want. For more information, contact Dale Yee by e-mail at yee@systems.caltech.edu, fax 818-395-2137, or you can download an order form from: <http://www.systems.caltech.edu/EE/Faculty/rutledge/poweramp.html>. We do not offer power-supply components. Those parts are available from Communication Concepts, 508 Millstone Dr, Beavercreek, OH 45434-5840, tel 513-426-8600; Digi-Key, PO Box 677, Thief River Falls, MN 56701-0677, tel 800-344-4539, <http://www.digikey.com>; Newark Electronics, (many branches throughout the US; check your telephone book for a branch near you); main office: 4801 N Ravenswood Ave, Chicago, IL 06040-4496, tel 800-463-9275, 312-784-5100, fax 312-907-5217; RF Parts, 435 South Pacific St, San Marcos, CA 92069, tel 800-737-2787; Mouser Electronics, 2401 Hwy 287 N, Mansfield, TX 76062, tel 800-346-6873, 817-483-4422, fax: 817-483-0931 e-mail sales@mouser.com; <http://www.mouser.com>.

A template package is not available from the ARRL.

²Historically, amateurs have built high-power amplifiers with vacuum tubes rather than transistors to avoid complicated power-combining networks and many low-power transistors. See Dick Ehrhorn, W4ETO, "RF Power Amplifiers and Projects," *The 1996 ARRL Handbook*, Chapter 13. Exceptions to this are the elegant designs by Helge Granberg, K7ES/OH2ZE (SK). *RF Application Reports*, published by Motorola Inc, in 1995, contains over 20 Application Notes and Engineering Bulletins written by Helge Granberg on amplifiers with output powers of 20 to 1200 W. Communication Concepts sells the boards and components for these amplifiers. *Radio Frequency Transistors*, by Norm Dye and Helge Granberg, published by Butterworth-Heinemann, Boston, 1993, is recommended reading. Joel Paladino, N6AMG, adapted one

of Granberg's transistor amplifiers (see "An Experimental Solid-State Kilowatt Linear Amplifier for 2 to 54 MHz," *QST*, Sep 1992, pp 19-23). However, the power transistors alone cost \$900! This led us to look for a less-expensive way to make transistor power amplifiers.

³Fred Raab, WA1WLW, "Simple and Inexpensive High-Efficiency Power Amplifier," *Communications Quarterly*, Winter 1996, pp 57-63.

⁴Nathan Sokal, WA1HQC, and Alan Sokal, WA1HQB, "Class-E, A New Class of High-Efficiency Tuned, Single-Ended Switching Power Amplifiers," *IEEE Journal of Solid-State Circuits*, Vol SC-10, Jun 1975, pp 168-175. This paper by father and son is a classic in the radio engineering literature, and is still the basic reference for the Class-E amplifier.

⁵The NorCal 40A designed by Wayne Burdick, N6KR, is available in kit form for \$129 from Bob Dyer, KD6VIO, at Wilderness Radio, PO Box 734, Los Altos, CA 94023-0734, tel 415-494-3806, <http://www.flx.net/~jparker/wild.html>. The NorCal 40A Web address is: <http://www.flx.net/~jparker/norcal.html>.

⁶A number of NorCal 40 modifications were published in *QRPp*, the magazine of the Northern California QRP club that first made the NorCal 40 kit available. For information on subscriptions to *QRPp* and back issues, contact Jim Cates, 3241 Eastwood Rd, Sacramento, CA 95821. Wayne Burdick, N6KR, suggests increasing the supply voltage for more power. If you do this, increase the voltage rating of Zener diode D12 to accommodate a larger peak collector voltage. For 3 W output, we use an MRF237 at Q7, the PA. To further increase the power to 7 W, we reduced L7 from 18 turns to 11 turns, and L8 from 18 turns to 14 turns. We replaced C45 and C47 with 560-pF, 300-V mica capacitors, and C46 with a 1500-pF, 100-V mica capacitor. For other approaches to raising the output power, see Dave Meacham, W6EMD, "5 Watts from your NorCal 40A," *QRPp*, Mar 1995, pp 6-7, and Ron Manabe, KN6VO, "Increasing the Output Power of the NorCal 40," *QRPp*, Jun, 1994 pp 42-45. Ron reports an output power of 7 W.

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David Rutledge, KN6EK, has been a professor in Electrical Engineering at Caltech since 1980. His research is in microwave circuits and antennas. He is the winner of the 1997 Distinguished Educator Award of the Microwave Theory and Techniques Society, and is a Fellow of the Institute of Electrical and Electronic Engineers (IEEE). Q57

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High-Efficiency Class-E Power Amplifiers—Part 2

Class-E operation permits low-cost MOSFETs to develop considerable power.

Last month⁷ we talked about Class-E amplifier fundamentals and began construction of a 40-meter unit. Now we'll tackle the power supply, keyed-waveform shaper and develop some power.

A Keyed Power Supply

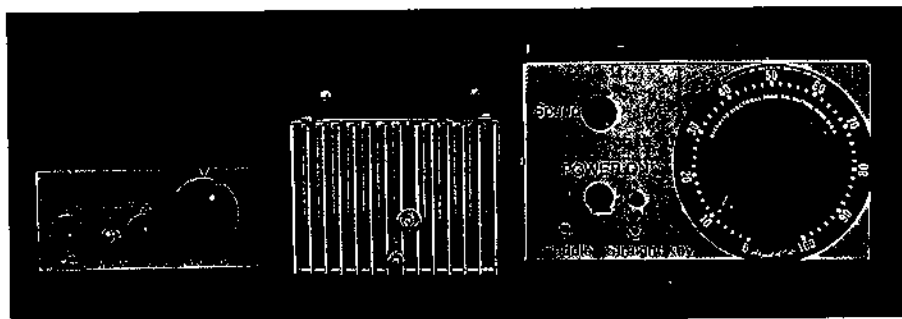
Nonlinear Class-E operation sharpens the CW keying envelope, causing annoying key clicks. To prevent this, we key the power supply to shape the supply voltage. A separate 4×7×12-inch (HWD) enclosure houses the dc supplies, a stretcher circuit that delivers a stretched pulse to the driver and a shaper that produces the shaped pulse for the amplifier. Figure 8 shows how these circuits connect.

So that the RF drive does not end before the shaping pulse, the keying pulse to the NorCal 40A driver is stretched a few milliseconds. The stretcher (Figure 9) takes a keyer's CMOS logic signal and provides a buffered keying waveform to the shaper and a stretched keying waveform to the NorCal 40A driver. Dc supplies (Figure 10) provide 12 V dc to run the ICs and 0 to 120 V dc for the amplifier. A wave shaper (Figure 11) gives this 0 to-120 V dc supply voltage a controlled rise and fall time to avoid key clicks. Figure 12 shows the keyed power supply with its cover removed.

There are other advantages to using a keyed power supply to control the output power. The amplifier power dissipation is low at all supply voltage levels, so that loss is kept low throughout a keying pulse. Because the keyed power supply also acts as a solid-state TR switch, a relay is not needed. This is because the supply voltage is zero except during key down. (This feature works well with the NorCal 40A, because it, too, does not use a relay for switching.) At zero voltage, the drain-to-gate capacitance in a MOSFET is quite large, and the signal from the antenna is fed through the amplifier with a loss of only about 7 dB. The NorCal 40A receiver sensitivity is excellent,⁸ and a 7 dB

signal loss does not hurt reception at all. A 7-dB loss degrades the MDS to -130 dBm, still far below typical 40-meter antenna noise levels of -90 to -110 dBm. On the positive side, with 7 dB attenuation, the receiver is less susceptible to intermodulation

distortion from other signals in the 40 meter band. In addition, the amplifier reduces AM broadcast signals by about 20 dB. The 7-dB loss does need to be made up at the audio end. For this, we mount a 2-inch-diameter speaker in a cardboard mailing tube cut to



Transceiver, amplifier, and power supply for a 40-meter, 500-W station. The NorCal 40A transceiver driver is on the left, a 500-W amplifier is in the center and the power supply on the right. The amplifier's heat sink and transistor mounting screws are visible. The large dial controls the variable autotransformer, varying the RF output power.

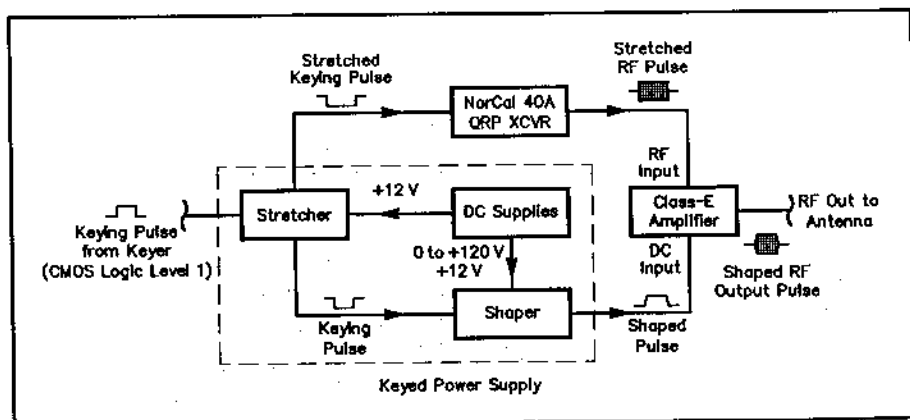


Figure 8—Block diagram showing the connections between the stretcher, dc supplies, shaper, NorCal 40A and the Class-E Amplifier. The stretcher, the dc supplies, and the shaper are in the keyed power supply. Power supply keying is done by a Curtis keyer IC (not shown) that provides a CMOS logic-level 1 during key down. The Curtis keyer IC and application note are available from MFJ Enterprises Inc, Box 494, Mississippi State, MS 39762, tel 800-647-1800, 601-323-5869, fax 601-323-6551; e-mail mfg@mfjenterprises.com; WWW <http://www.mhjenterprises.com>. (Keyer circuits using Curtis ICs can be found in recent editions of *The ARRL Handbook*.—Ed.)

⁷Notes appear on page 42.

resonate at 650 Hz for CW reception. This gives a sound level that is quite adequate.⁹

The Diplexer

For greater reduction of spurious emissions, we recommend following the amplifier with a band-pass diplexer (see Figure 13) to terminate out-of-band spurious components in a 50 Ω load.¹⁰ Our diplexer (in a 3.5×6×10-inch [HWD] box) uses the equivalents of a 100-pF series capacitor, an 1800-pF shunt capacitor and air-wound inductors. Stretch or compress L2 to achieve minimum SWR. The measured loss of 40-meter signals

was extremely low, only 4%. Our experience shows that a diplexer can reduce all spurious components to more than -55 dBc.

Tune-Up

Refer to Figure 3 in Part 1. There are two amplifier coil adjustments. First, with the cover on and the dc input off, L1 is set for minimum input SWR with full RF input. Typically, the SWR can be reduced to 1.5:1. If it cannot be brought below 2:1, try adding or subtracting a turn from L1.

Output power is peaked by stretching or squeezing L2. Note: For safety, the ampli-

fier's cover should always be attached when the RF drive is applied. The cover also significantly lowers the inductance of L2. Be sure to turn off the supply voltage before you touch any amplifier parts! A high RF voltage will burn the skin. RF burns are deep and heal slowly. Having a keyed power supply helps here, because the amplifier supply voltage is zero except during key down.

Attach a dummy load and power meter to J2. With the RF input applied continuously, slowly increase the dc input voltage, while monitoring the gate and drain voltages using an oscilloscope with 10× high-impedance

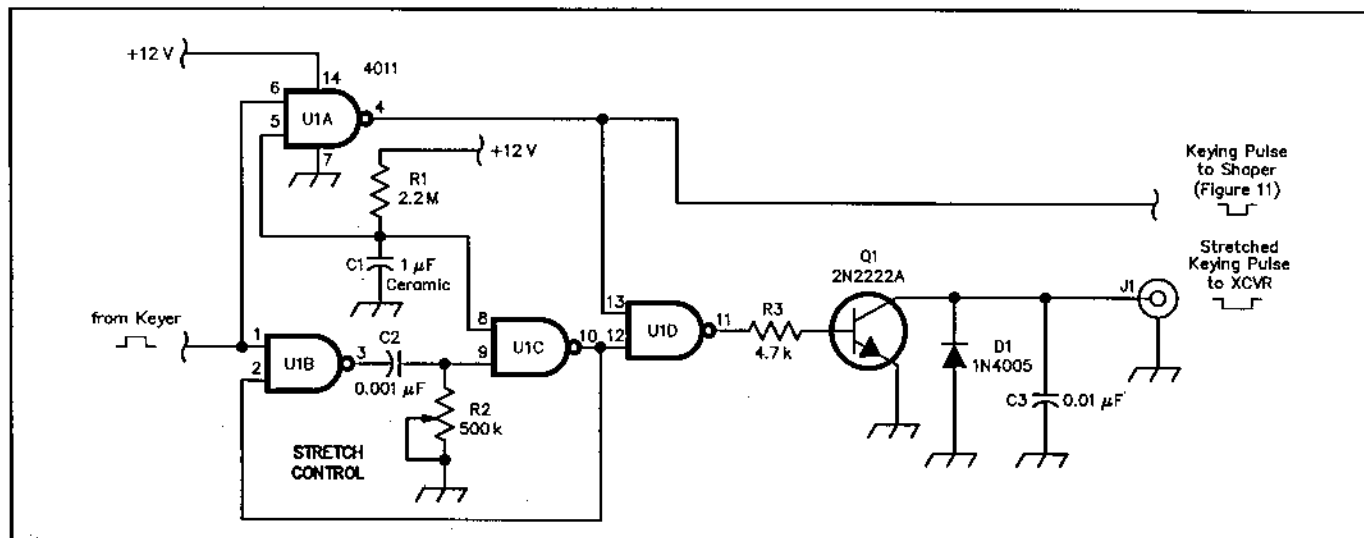


Figure 9—Stretcher circuit diagram. NAND gate A acts as a buffer and produces a keying pulse for the shaper. One input has an RC delay to prevent keying glitches when the power is turned on. Gates B and C are connected by an RC network that causes a pulse to be triggered on a falling edge. R2 is adjusted to ensure that the RF output from the NorCal 40A lasts longer than the shaping pulse. The components are assembled on perboard.

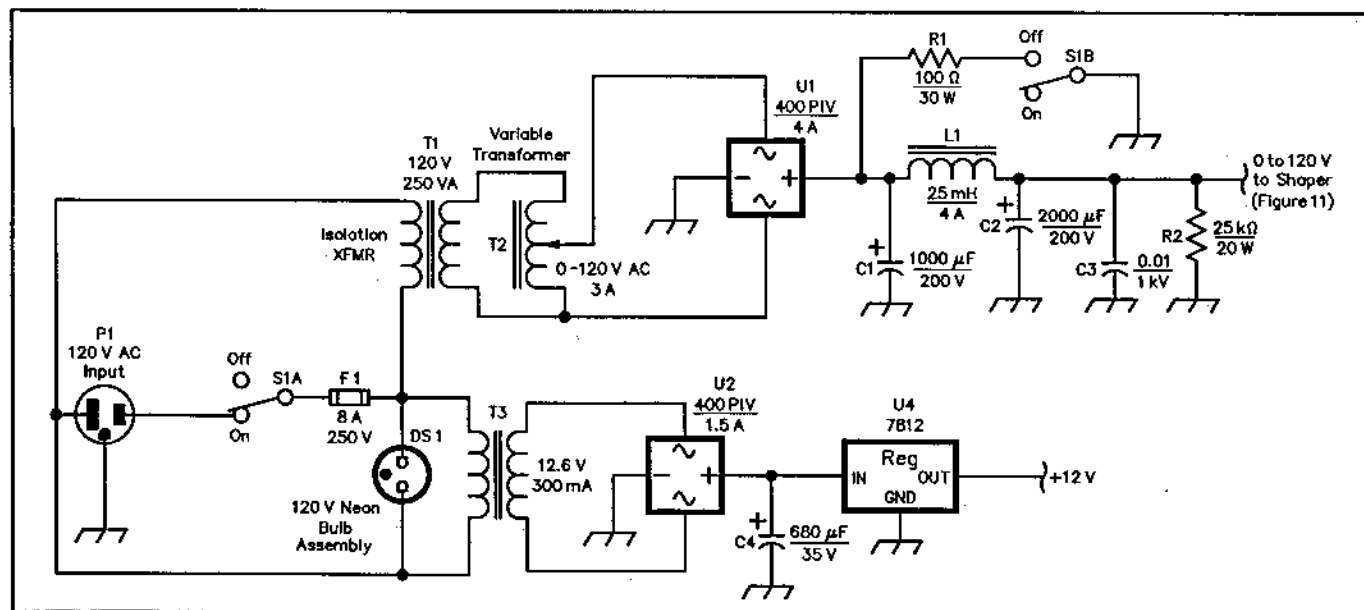


Figure 10—Dc supplies diagram. There are two isolated supplies: one with an unregulated 0 to 120-V output controlled by an autotransformer, and another with a +12-V regulated output. Two bleeder resistors help keep capacitor voltages at safe levels when the supply is turned off or its output reduced. The 4-A bridge rectifier is an RS404LR by Diodes, Inc, available from Digi-Key. The Panasonic 1000 and 2000-μF electrolytics in the filter are available from Digi-Key. The Stancor C-2686 25-mH choke is available from Newark. We scrounged the isolation transformer and variable autotransformer from old equipment. Look for them at swap meets, or purchase equivalents from Newark (Magnetek N55M 250-VA isolation transformer and the Staco 291 3-A variable autotransformer).

probes. (You should see waveforms similar to those in Figure 15, although the peak drain voltage should be about half of that in the figure.) The RF output should begin to rise. Increase the dc input until the forward RF output power is 25% of full power. Make sure the output SWR is 1.5:1 or less. Measure the dc input voltage, and adjust L2 to give 25% power at 60 V dc. Stretching L2 reduces its inductance and increases the output power, but usually lowers the amplifier's efficiency. Squeezing L2 reduces the output power and usually increases amplifier efficiency.

Increase the dc input voltage until the

amplifier reaches maximum output power. The dc voltage should now be between 115 and 120 V, and the peak drain voltage of the RF-stage MOSFET should be between 380 and 420 V. Larger peak drain voltages run the risk of transistor failures. Lower voltages may indicate an excessive drain current, which can lead to a failure. If the voltage is too high, stretch the coils a bit more. If the voltage is too low, squeeze the coils. Check the RF drive and input SWR again. You may find that they have changed somewhat and that readjustment is needed. Measure the dc supply current and voltage, and

calculate the amplifier efficiency to ensure that it is 85% or above. Use a 0.001- μ F capacitor to bypass the voltmeter terminals because an RF voltage there can cause a significant measurement error. (In addition, you should realize that RF power meters often have error factors as high as 10%.)

Keyed-Waveform Shaping

The keying envelope is controlled by the three potentiometers in the shaper and stretcher circuits. R3 in the shaper circuit sets the rise time, R4 sets the fall time. R3 also helps control the power supply droop as

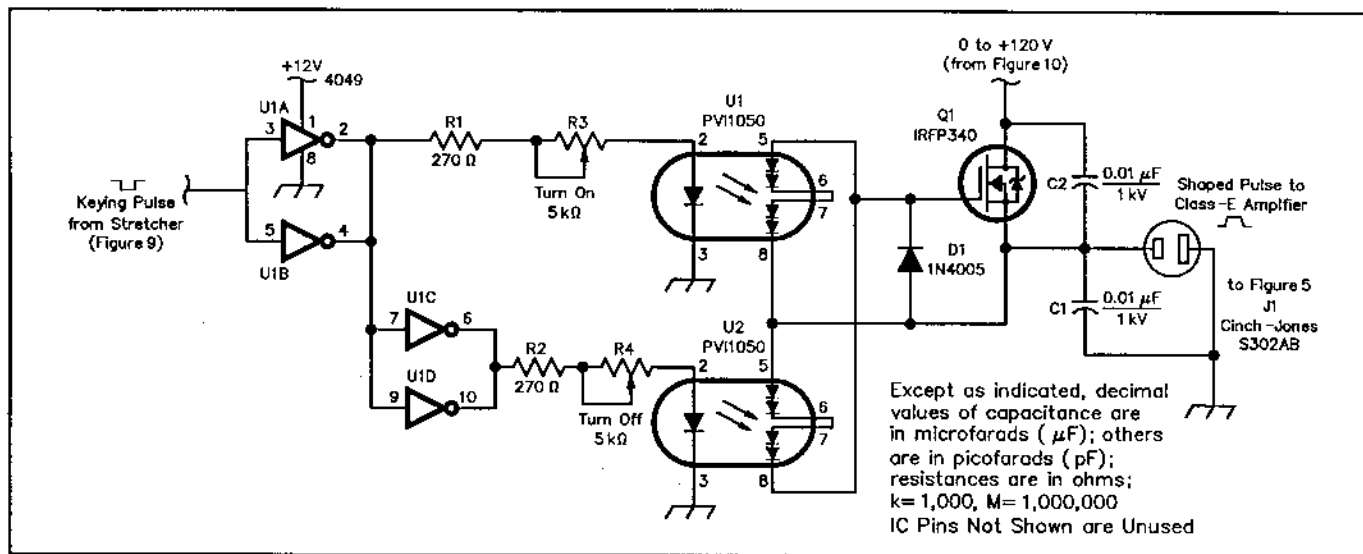


Figure 11—Shaper circuit diagram. A pair of optically isolated MOSFET drivers (type PVI1050) turn Q1 on and off to bring the supply voltage up and down. Keying waveform rise and fall times are adjusted by R3 and R4, which control the current to each MOSFET driver. The 270- Ω resistors limit the LED current to a safe level. The TURN-ON potentiometer is also used to keep the overshoot from the unregulated power supply to a reasonable level. D1 prevents Q1's gate voltage from drifting negative. C1 and C2 are RF bypasses. To keep the supply voltage from appearing across exposed contacts, a female socket is used at J1. All components are available from Digi-Key. Point-to-point wiring on perboard is used.

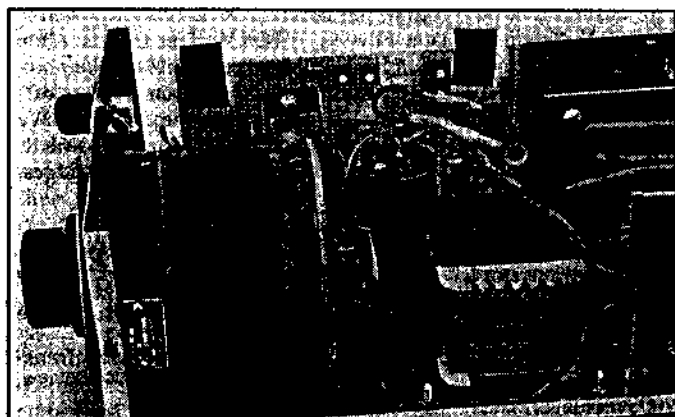


Figure 12—The keyed power supply with the cover removed, viewed from the side. T1 is mounted on the back plate, along with the fuse and connectors for the dc output, a keying line to the NorCal 40A and the ac line input. The TUNE switch keys the amplifier for testing. The variable autotransformer is on the left, mounted to the front panel. In the center foreground, mounted to the base plate, is L1, the 25-mH choke. Mylar sheets are taped to the perboards for electrical isolation. The large components are attached directly to the box. The IRFP340 is mounted on the bottom of the box using a Berquist K10-104 Kapton insulating pad, #6-32 screw and a torque of 10 inch-pounds. The other shaping circuit components are mounted on perboard. Layout is not critical.

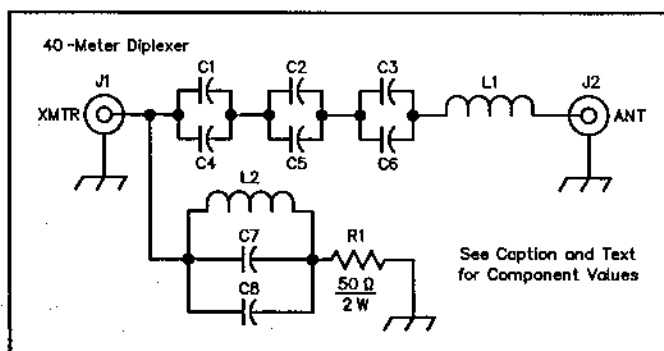


Figure 13—Schematic of our diplexer. It uses six 150 pF capacitors, two 910-pF capacitors and air-wound inductors made of $\frac{3}{16}$ -inch-wide copper tape (see Note 1).

C1-C6—150 pF, 1 kV mica 5%-tolerance (Cornell Dubilier type CDV19; available from Newark Electronics, see Note 1)
C7, C8—910 pF (same type as above)
L1—24 turns of $\frac{3}{16}$ -inch-wide copper tape, 1 $\frac{3}{8}$ inch ID; see Note 1.
L2—4 turns of $\frac{3}{16}$ -inch wide copper tape, 1 inch ID; see Note 1.
R1—50- Ω , 2-W (approx) termination, Jameco part number 71458; available from Jameco Electronics, 1355 Shoreway Rd, Belmont, CA 94002, tel 415-592-8097; fax 415-592-2503 and 415-595-2664)

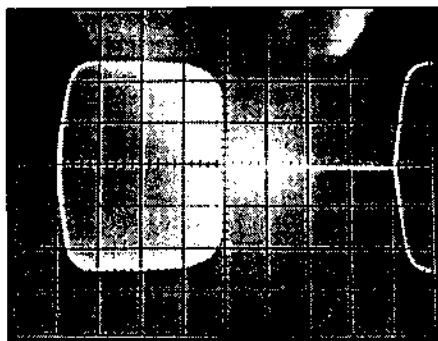


Figure 14—Keying waveform of the 500-W amplifier at 30 WPM. The horizontal axis is 10 ms per division. The rise and fall times are about 3 ms.

the amplifier is keyed. R2 of Figure 9 determines the stretch in the pulse that keys the NorCal 40A, so that it does not stop transmitting before the end of the shaped pulse. We recommend using a keyer with adjustable weighting to offset the pulse stretching. The potentiometer settings interact somewhat, and there are variations at different sending speeds, so it is best to set them at the speed you commonly use. Adjust the controls for rise and fall times between 2 and 5 ms, and for a smooth keying envelope. Figure 14 shows keying at 30 WPM with rise and fall times of about 3 ms.

VHF Ringing

In many Class-E amplifiers, ringing in the VHF range can be seen on the gate and drain waveforms (Figure 15). This ringing can be quite pronounced, with bumps several volts high on the gate or drain or both. The bumps disappear when the RF input is removed, and that is why we refer to this as *ringing* rather than *oscillation*. We have compared measured spectral plots with PSpice simulations and believe that the waves are driven by the sudden turn-on and turn-off of the transistor, acting rather like the gong of a bell.

We notice two distinct time periods and frequency ranges for the ringing. During the time the transistor is on, the ringing frequency is about 80 MHz. This appears to be a resonance of the external drain capacitor combined with the internal inductance of the capacitor and the transistor and may indicate a mismatched load. The on-ringing is usually small if the load is matched so that the drain voltage comes smoothly to zero before the transistor turns on.

The ringing while the transistor is off covers a broad range of frequencies—from 130 to 210 MHz. If the output low-pass filter is removed, the ringing can be seen easily on a spectrum analyzer at levels between -40 and -60 dBc. The off-ringing appears to be caused by a resonance of the external drain capacitor and its internal inductance, together with the transistor's internal drain capacitance and its inductance. The internal drain capacitance varies greatly with the drain voltage, so that the frequency is modulated as the drain voltage rises and falls. The

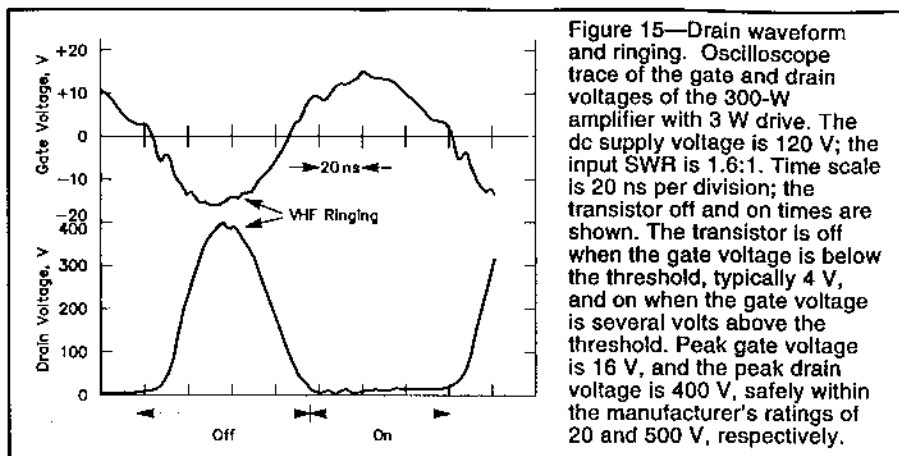


Figure 15—Drain waveform and ringing. Oscilloscope trace of the gate and drain voltages of the 300-W amplifier with 3 W drive. The dc supply voltage is 120 V; the input SWR is 1.6:1. Time scale is 20 ns per division; the transistor off and on times are shown. The transistor is off when the gate voltage is below the threshold, typically 4 V, and on when the gate voltage is several volts above the threshold. Peak gate voltage is 16 V, and the peak drain voltage is 400 V, safely within the manufacturer's ratings of 20 and 500 V, respectively.

low-pass filter reduces these harmonics to the -70 to -80 dBc range.

On the Air

The amplifiers meet the FCC requirements for spectral purity [confirmed in the ARRL Lab—Ed.]. NorCal 40A designer Wayne Burdick, N6KR, emphasizes that it is important to correctly tune the band-pass filter following the transmit mixer to minimize spurious emissions from the NorCal 40A.¹¹

These amplifiers are excellent for chasing DX, schedules and "ragchews," particularly at this low point of the sunspot cycle. The amplifiers require no warm-up, no tune-up, and produce no fan or relay noise. We can vary the power from 1 W to full power via the variable autotransformer. The antenna SWR should be 1.5:1 or better because the amplifier is not protected against large mismatches. With a high SWR, the transistor will probably overheat. Check the dc voltage when the amplifier is delivering full power to the antenna to ensure that it remains between 115 V and 120 V. Readjust the coils if the voltage is too high or too low.

Our most common problem has been a poorly mounted PA transistor. If the transistor is not flat against the heat sink, heat transfer is poor and the transistor becomes quite hot; efficiency suffers (becoming usually less than 85%) and the amplifier may not reach full power. The output power may also drift downward, a sign that the transistor temperature is increasing and that the transistor is under stress.

Component temperature can be a good diagnostic tool. For the 500-W amplifier, our experience is that for CW QSOs longer than 30 minutes, the temperature of C3, C5 (Figure 5) and the heat sink rises to about 60° C. For the 300-W amplifier, the heat-sink temperature is about 50° C. This is hot to the touch, and it can be checked with a lab thermometer. The temperature will vary according to your operating style, and if the temperature is higher than you like, you can add a fan.

The Future

We see room for improvements: pro-

tection against antenna mismatches and employment of an inexpensive keyed switching power supply that is as lightweight as the amplifiers. Finally, it would be interesting to develop Class-E amplifiers for the other bands. We have built a 250-W amplifier for the 20 meter band that exhibits an efficiency of 88% with 10 W drive. We believe that Class-E amplifiers provide amateurs with good building challenges and operating fun at modest cost.

Acknowledgments

This work began as senior theses by Joyce Wong and Meng-Chen Yu at Caltech, and many of their ideas appear here. John Davis was supported by a scholarship from the James Irvine Foundation and the Army Research Office. Eileen Lau, Kai-Wai Chiu, and Jeff Qin received Caltech Summer Undergraduate Research Fellowships funded by the ETO Corporation and the Caltech Gates Grubstake Fund. We appreciate the help from all the people at the ETO Corporation, particularly Dick Ehrhorn, W0ID; Don Fowler, W1GRV; Tim Coutts; Chip Keen and Frank Myer. Mitsu Sakamoto, JA4FVE, of Kurashiki, Japan, sent us off-the-air recordings over the Internet. We would like to thank Wayne Burdick, N6KR; Wes Hayward, W7ZOI; and Bill Bridges, W6FA, for their advice.

Notes

- ⁷Eileen Lau, KE6VWU, et al, "High-Efficiency Class-E Amplifiers—Part 1," *QST*, May 1997, pp 39-42. The amplifier enclosures are 3 1/2 x 4 1/2 x 7 1/2 HWD.
- ⁸Rick Lindquist, KX4V, "Low-Power Transceiver Kits You Can Build," *Product Review*, *QST*, Jun 1996, pp 45-50.
- ⁹See J. B. and R. V. Heaton, "An Electro-Acoustic CW Filter," *QST*, Apr 1983, pp 35-36; Wally Millard, K4JVT, "A Resonant Speaker for CW," *Hints and Kinks*, *QST*, Dec 1987, p 43; and Richard Clemens, KB8OAB, "More on Resonant Speakers," *Hints and Kinks*, *QST*, Jan 1989, p 37.—Ed.
- ¹⁰David Newkirk, WJ1Z (now W9VES), and Rick Karlquist, N6RK, "Mixers, Modulators, and Demodulators," *The 1996 ARRL Handbook*, Chapter 15, p 15.22.
- ¹¹Telephone conversation with Wayne Burdick. This tuning is done by carefully adjusting C50 to peak the output power.