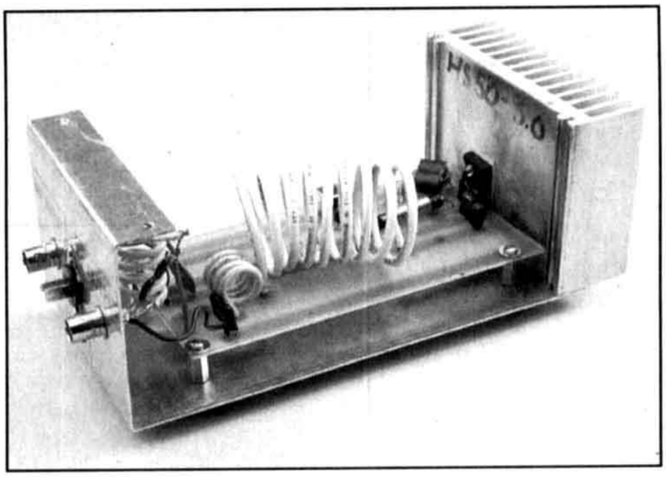
By Eileen Lau, KE6VWU; Kai-Wai Chiu, KF6GHS; Jeff Qin, KF6GHY; John Davis, KF6EDB; Kent Potter, KC6OKH; and David Rutledge, KN6EK

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

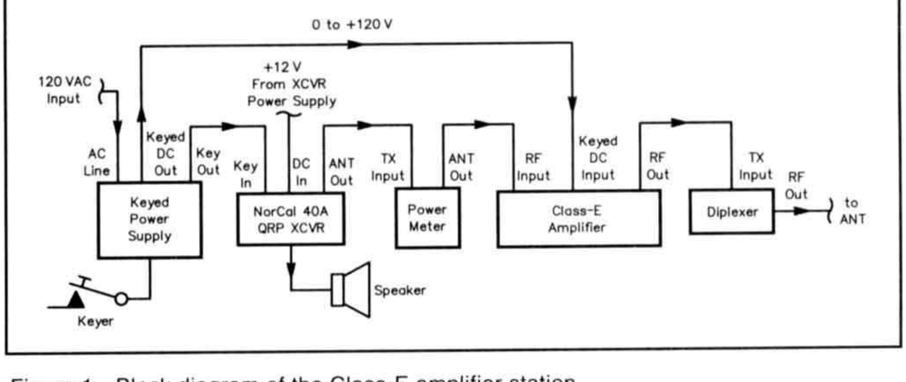


Figure 1—Block diagram of the Class-E amplifier station.

[1]Notes appear on page 42.

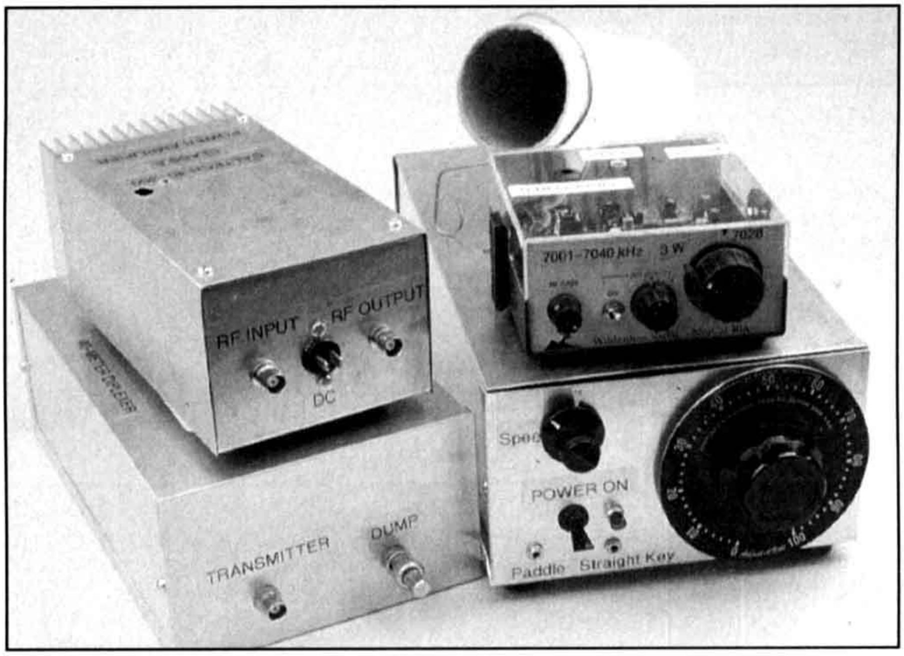


Figure 2—The components of the Class-E amplifier station. Clockwise from bottom left: the diplexer, amplifier, resonant speaker, NorCal 40A and keyed power supply. The latter houses the keyer and a pulse-stretching and shaping circuit.

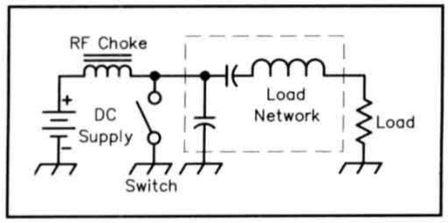


Figure 3—An idealized Class-E amplifier. The transistor is represented by a switch that opens and closes at RF.

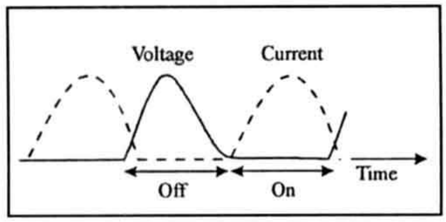


Figure 4—Class-E voltage and current waveforms. Class-E amplifiers reduce loss by keeping the overlap between voltage and current low.

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

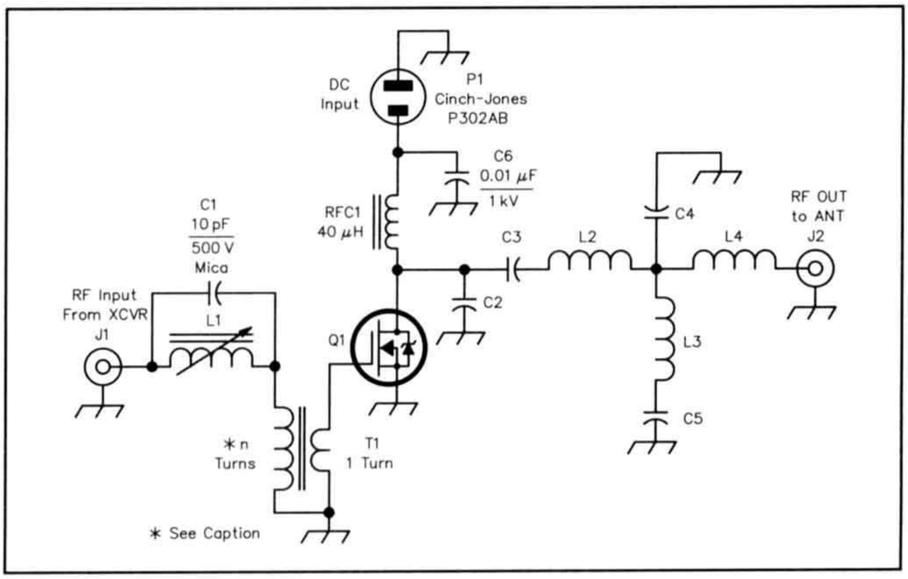


Figure 5—Circuit diagram and parts list for the amplifiers. Mica capacitors are available from Newark. L2, L3 and L4 are made with #10 THWN solid, insulated house wire sold in hardware stores. T1's core is an RF400-0, available from Communications Concepts (see Note 1 for supplier information). L1 is 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 1¼-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 ½-inch-diam drill bit
L4—300 W, 5 turns; 500 W, 5 turns #14 THWN wound on a ½-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.

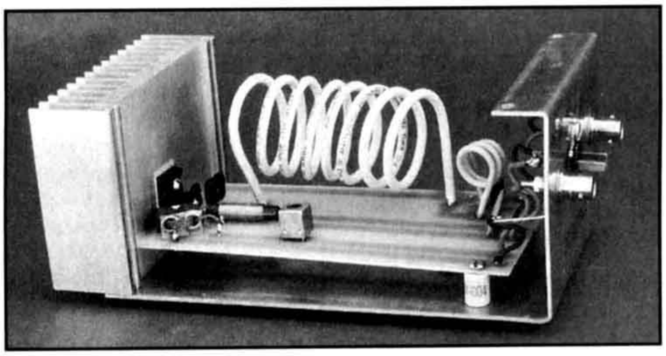


Figure 6—Inside the 500-W amplifier. The large coil is L2; L3 is the small coil. The circuit board is mounted on 1/2-inch standoffs. BNC connectors are used for the RF input and output. No harm is done if the RF input and output are accidentally interchanged.

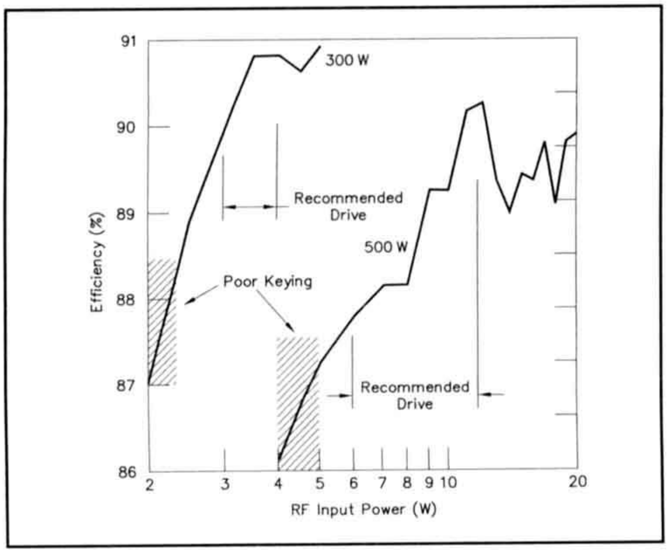


Figure 7—The measured efficiency plotted against RF input power. These measurements were taken with the heat sink at room temperature. In operation, the heat-sink temperature rises and the *on* resistance increases, so that the efficiency drops somewhat. Recommended drive power for the 300-W amplifier 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.

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 3×4 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 pigtails soldered to Q1's gate and drain leads poke through holes in the baseplate. Rubber grommets in the holes prevent the pigtails 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 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

[1]A 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.

[2]Historically, 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-Heineman, 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.

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

[4]Nathan 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.

[5]The 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.fix.net/jparker/wild.html**. The NorCal 40A Web address is: **http://www.fix.net/~jparker/norcal.html**.

[6]A 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).

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