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10-MHz CLASS-E POWER AMPLIFIERS

200W from a \$6 transistor

A new HF, high-efficiency, class-E, radio power amplifier has recently been developed at Caltech that is smaller and less expensive than existing amplifiers with similar characteristics. This amplifier operates on the 30-meter (10 MHz) band, and is designed with an output power of 200 watts. It is based around the International Rectifier IRFP440 MOSFET, which is a device commonly used in switching power supplies and costs under \$6. We were able to use such a relatively inexpensive, low-power device because of the high efficiency characteristic of the class-E amplifier, typically around 90%. This makes the power dissipated in the switching device small enough to allow operation even without a cooling fan. The 30-meter amplifier requires only 3 to 8 watts of drive power for reliable, efficient operation. We used a modified NorCal-40A low-power radio transceiver to supply this drive.

This new amplifier is a continuation of work done at Caltech by undergraduate and graduate students over the past three years. Last year, a pair of amplifiers was developed specifically for hams operating on the 40-meter band. These amplifiers had output powers of 300 watts and 500 watts. A paper about these amplifiers was published in *QST Magazine*¹. Collections of parts were assembled and sold to people who wanted to try building the amplifiers. It was found that there was much interest among people in amplifiers for other bands. This led to the work done this summer and the development of the new 30-meter, 200W amplifier. Like its predecessors, this new amplifier is easy to build, costs about the same, and has most of the same characteristics and limitations.

BACKGROUND

It is often necessary to amplify weak signals to make them more useful, and there are different methods for carrying out this amplification. Each class of amplifier has advantages and disadvantages which make it more suitable in certain situations. Most conventional amplifiers fall into one of the three classes A, B, or C. The following is a short description of each of these classes:

Class-A: These amplifiers use a single transistor which is always active. An active transistor has considerable amounts of voltage across and current through it. The product of the voltage across the transistor and current through it translates into heat dissipated in the transistor. For this reason, the efficiency of class-A amplifiers is limited to about 30%. However, class-A amplifiers introduce very little distortion in the amplification process. This means that the output of a class-A amplifier looks almost exactly like its input, only larger in amplitude.

Class-B: Class-B builds on Class-A by having two transistors, which take turns amplifying the input signal. One transistor usually handles the positive half of the output, and the other the negative. This way, only one transistor is active at any given time, while the other is off. This doubles the efficiency to around 60%, at the cost of small amounts of distortion at the signal crossover, where one transistor turns off and the other takes over the amplification.

Class-C: The class-C amplifier is known as a switching amplifier. In traditional class-C amplifiers, the switching device is active less than half of the time, making it even more efficient. In modern, transistor-based class-C amplifiers, the transistor often acts like a switch, either completely on or completely off. When on, a large current flows through the transistor, but the voltage across it is small. When off, voltage builds across the transistor, but the current through it falls nearly to zero. This way, there is very little overlap between voltage and current in the transistor, which translates into much less power being wasted in the device, and a higher efficiency. Class-C amplifiers normally have efficiencies reaching 75%-80%. Most of the loss in a class-C amplifier occurs during the actual switching. The transistor does not switch from on to off (or vice versa) instantaneously. As the transistor switches, it goes through an active region, where it has both a current through it and voltage across it. This translates into power wasted as heat in the transistor every time it is switched, and this wasted power increases as the frequency of operation is increased. A disadvantage of the class-C amplifier is that because of its switching mechanism for amplifying signals, it is not linear at all. The output may look nothing like the input. It will be at the same frequency, though with a great deal of harmonic distortion.

Class-E

The Caltech power amplifiers rely on a less well known class of operation, class-E. The class-E amplifier design was first explored in 1964 by Gerald Ewing² and later by Nathan and Alan Sokal in 1975³, who patented it. The use of class-E amplifiers in high-frequency amateur radio transmitters prior to the Caltech designs is unreported. An idealized diagram of a class-E amplifier is shown in Figure 1. It consists simply of a DC current source feeding a switch, followed by a ringing network and the load. A class-E amplifier is very similar to the class-C amplifiers. However, a class-E amplifier achieves even higher efficiency (typically around 90%) by minimizing the current-voltage overlap which occurs during switching in a class-C amplifier. This is done by the addition of the ringing network following the switching device. With the ringing network in place, the voltage across the transistor rises smoothly from 0 to a maximum, and falls smoothly back to zero just

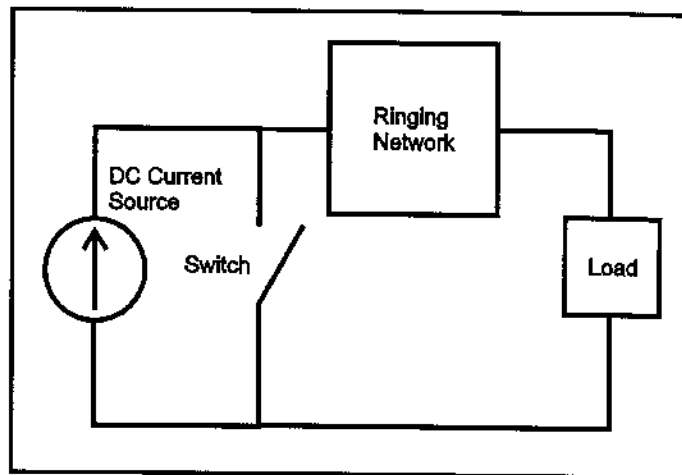


Figure 1. Block diagram of class-E amplifier

before the transistor switches on again. A complete cycle of the class-E switching amplifier can be broken down into the following four phases (see Figure 2):

Device On: Transistor conducts current through itself to the ground. The voltage across the transistor is very small, keeping power dissipation in the device low.

Switching On to Off: Voltage across transistor rises smoothly as current is redirected from the device into the resonant load network. While the switching is occurring, power dissipation is kept low because the voltage across the device rises slowly and remains small during the short switching period.

Device Off: Voltage rises smoothly to a maximum, then falls smoothly back to zero.

Switching Off to On: Since there's near-zero voltage across the transistor, little power is wasted as current is again directed into the device instead of the load network.

In this way, the class-E amplifier achieves efficiencies of around 90%, which allows us to operate with a relatively small, inexpensive transistor. Power dissipated in the transistor is small enough that heat can be removed with a simple heat-sink. No fan is required for low duty cycle use. Because of the relationship between efficiency, dissipated power, and output power, an amplifier running at 90% efficiency can output 21 times more power (at a given dissipation level) than a 30% efficient amplifier¹. However, there are some disadvantages to the

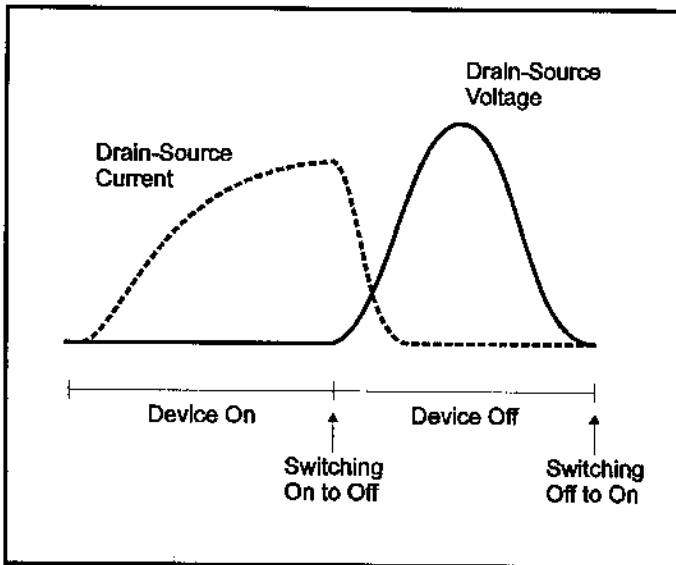


Figure 2. Ideal class-E waveforms

class-E design. The amplifier must be driven with enough power to reliably switch the transistor on and off. The gates of the MOSFET's are capacitive and present a low impedance at high frequencies. The drive must be powerful enough to switch the transistor on and off quickly and completely. If the transistor is not switched on and off reliably, or if it is switched too slowly, inefficient operation results which can cause a buildup of heat in the transistor, leading to its failure. The class-E amplifier is completely non-linear, and its operation is limited to a single band by the ringing circuit on its output. The power output of the amplifier (assuming it is driven properly)

depends almost exclusively on the DC supply voltage. This makes it unsuitable for use in SSB transmitters, without external circuitry^{4,5}. However, it works very well in CW, FM, and FSK applications, where information is transmitted either by turning a carrier on and off completely (CW) or by changing the frequency, not amplitude, of the carrier by small amounts (FM, FSK).

THE 30-METER AMPLIFIER

The newly developed 30-meter, 200W amplifier is very similar in design to the existing 40-meter amplifiers. For the most part, only the component values were changed to operate at the higher frequency. See Figure 3 for a circuit diagram of the amplifier, and Appendix 1 for a more detailed description of the components used. Components L1 and T1 match the input of the transistor to the output of the driving transceiver. The impedance of the gate of the MOSFET is low and mostly capacitive (though there is a small parasitic resistive component, as well). The transformer matches this low impedance to the nominal 50Ω impedance of the driver. The variable inductor L1 is tuned to cancel the capacitance of the gate at the operating frequency. The input SWR is typically below 1.4. Capacitor C1 is a high frequency bypass of L1 to reduce VHF ringing.

The function of RFC1 is to convert the 0-150 VDC from the power supply into a current source. RFC1 also helps, in conjunction with

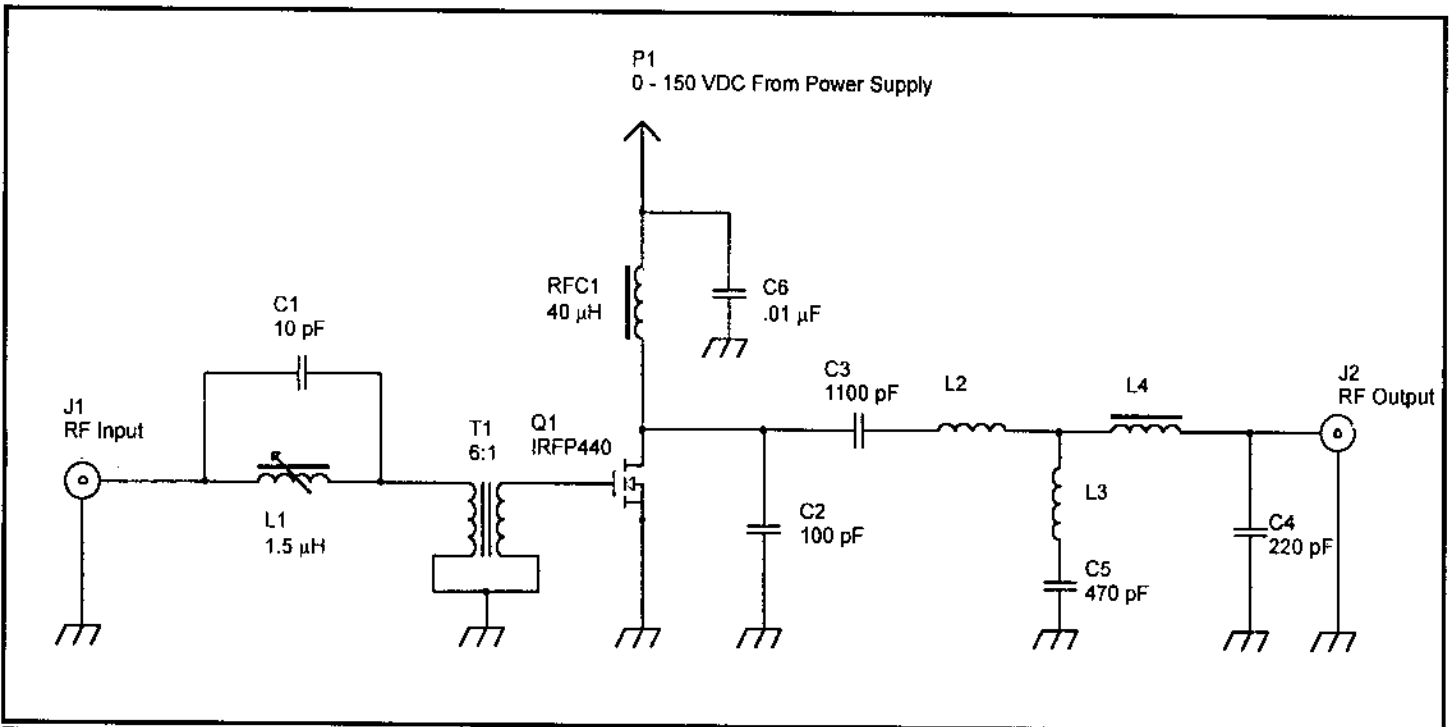


Figure 3. Circuit diagram of 30-meter, 200W amplifier

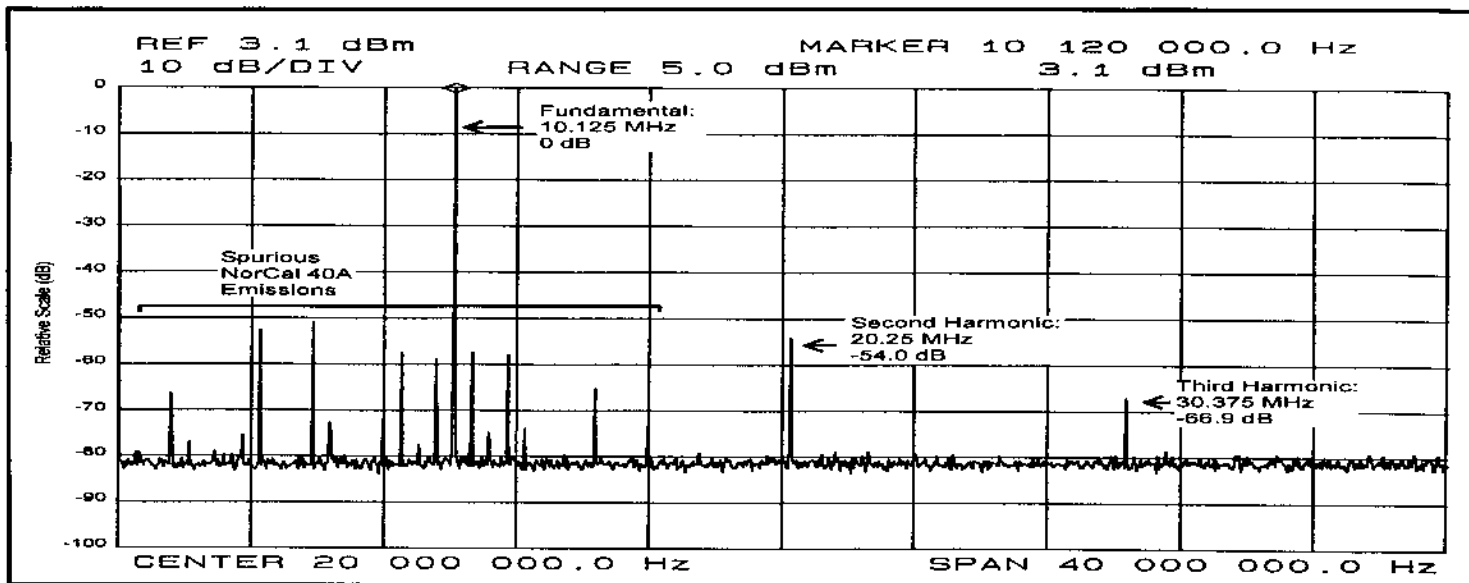


Figure 4. HF spectrum of 30-meter amplifier driven with modified NorCal 40A transceiver

C6, to keep RF voltages away from the power supply. C3 and L2 form the main resonant circuit. They cause the voltage at the drain to rise smoothly to a maximum and return to zero before the transistor turns on again. C5 and L3 serve two purposes. The first is to form a notch filter for the second harmonic. Together, C5 and L3 resonate at twice the operating frequency (around 20 MHz) and therefore provide a direct path to ground for the second harmonic. Their second function is to transform the 50Ω impedance of the antenna down to around 10Ω, a better match for the transistor in this type of circuit.

C4 and L4 form a low-pass filter. They ensure that all of the harmonics fall well below -40dB of the carrier, the limit set by the FCC. Figures 4 and 5 are the HF and VHF spectra of the amplifier's output, respectively. These

spectra were taken with the amplifier output set to 200W. The driver was a modified NorCal 40A transceiver, which will be discussed in the next section. The drive level was 4.8W.

Figure 6 shows a picture of the MOSFET gate and drain waveforms.

The 30-meter amplifier requires from 3 to 8 watts of drive power for optimal operation. See Figure 7 for a plot of efficiency vs. drive power. We have noticed problems with keying the amplifier at levels below approximately 4 watts, so drive powers exceeding this amount are recommended. The drain efficiency is found by dividing the output RF power by the input DC power. A better indicator of how much power is being dissipated in the transistor, however, is the total efficiency. The total efficiency is defined as the RF output power divided by the sum of the input DC power and RF drive power. As can be

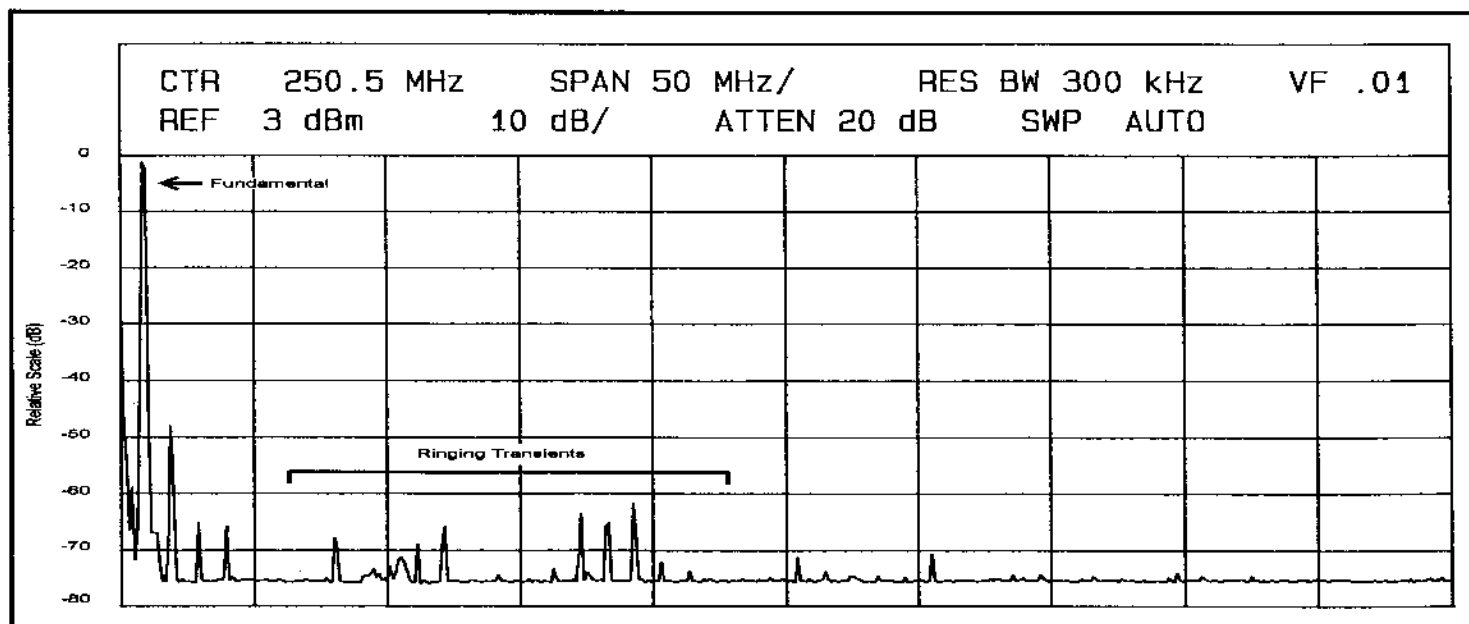


Figure 5. VHF spectrum of 30-meter amplifier driven with modified NorCal 40A transceiver

THE NORCAL 40A MODIFICATIONS

Because the 30-meter amplifier was aimed at an audience of amateur radio operators, one of our goals was to find a suitable transceiver for driving the amplifier that would be commonly available to hams. We tried using a modified NorCal 40A (NC40A) as the driver. The NC40A is a 40-meter (7 MHz) transceiver. However, Ed Burke outlines a way of modifying the NC40A to change its operating frequency from 7 MHz to 10 MHz⁶. At the heart of this modification is the changing of the IF from 5 MHz to 8 MHz. Both the original and modified NC40A's have a local oscillator at 2 MHz. In the original, 2 MHz is mixed with 5 MHz to give the operating frequency of 7 MHz. In the modified NC40A, 2 MHz is mixed with 8 MHz, and the resulting radio works at 10 MHz.

The modified NC40A, though functional on the 30-meter band, suffered some losses in performance. The MDS went from -132dBm to -126dBm, the gain (RF input to audio output) from 104dB to 96dB, and the output power from 2.5W to 1.4W. To solve these problems, the following changes need to be made to Ed Burke's list of modifications. All component numbers refer to the Wilderness Radio NorCal 40A.

- 1: A 15pF capacitor is added in series with C2. This decreases C2's capacitance enough so that it can resonate with the secondary of T2 at 10 MHz.
- 2: C4 is left at 5pF

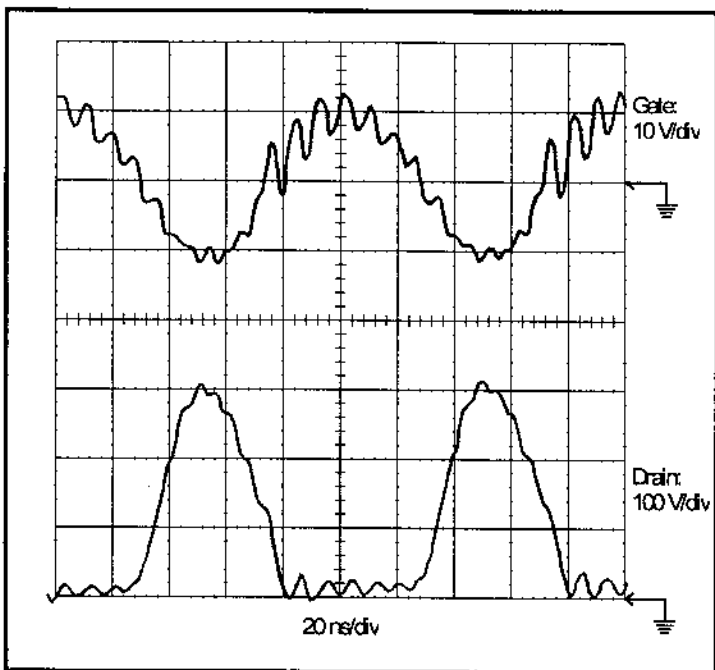


Figure 6. Gate (top) and drain (bottom) waveforms of 30-meter amplifier, being driven at 4.78W with a modified NorCal 40A transceiver. The output power is 204W. The gate is at 10 V/div, and the drain at 100 V/div. The time scale is 20 ns/div. Note the ringing on both waveforms.

seen from Figure 7, though the drain efficiency continues to increase, the total efficiency drops for drive powers above approximately 8 watts. This happens because the drive power does not couple to the output, but is dissipated in the transistor as heat. Therefore, once the drive power is high enough that the transistor is switching optimally, further increasing the drive power only increases the amount of power dissipated in the transistor, and does not benefit the total efficiency of the amplifier.

An interesting feature of this amplifier, which it shares with the existing 40-meter amplifiers, is the way in which signals couple backwards from the output to the input. When the supply voltage is at 0 volts (this occurs during reception), there is a large capacitance between the gate and drain of the transistor. Therefore, in-band signals couple backwards through the amplifier, including the transistor, with a measured loss of only 8.5dB. Because of the high sensitivity of the modified NorCal 40A driver (we measured its MDS to be -133dBm), even with this 8.5dB of attenuation placed before the antenna, the transceiver is still limited by atmospheric noise. This way, no additional transmit/receive switch circuitry is required for the amplifier. The amplifier operates nearly transparently with the driving transceiver.

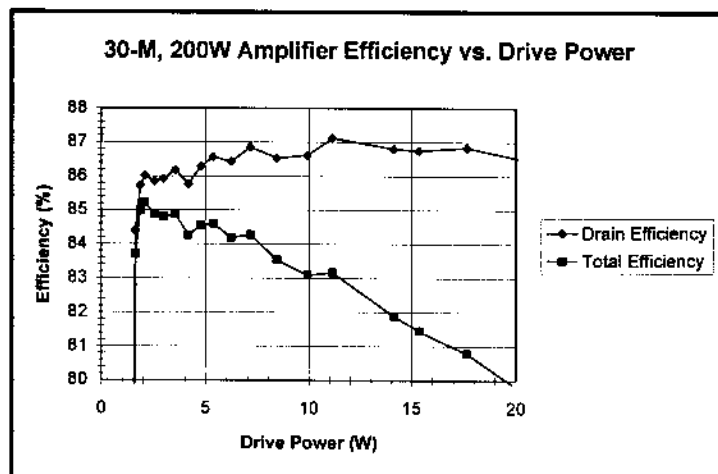


Figure 7. Efficiency vs. drive power for 30-meter amplifier

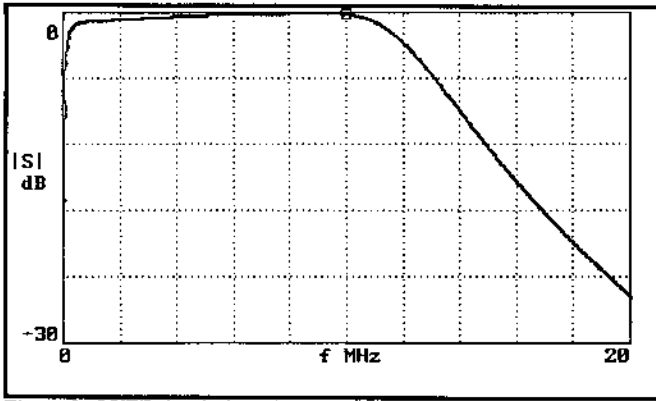


Figure 8. PUFF simulation of modified NorCal 40A low-pass filter

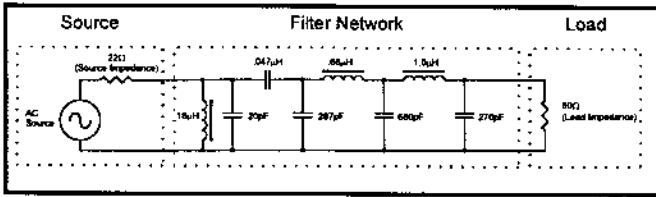


Figure 9. The modified NorCal 40A low-pass filter

The above two steps bring the gain and sensitivity of the modified NC40A back close to their original values. In our NC40A's, the sensitivity after the modifications was -133dBm , and the gain was 102dB .

- 3: T1 is wound with 21 turns for the primary, 4 turns for the secondary
- 4: The output transistor Q7 is changed to a Motorola MRF237
- 5: L7 is wound with 13 turns
- 6: L8 is wound with 16 turns
- 7: C45 and C47 are replaced with 270pF capacitors
- 8: C46 is replaced with a 680pF capacitor

These steps greatly improve the power output of the NC40A. Step 3 matches the output of the driver stage of the transmitter to the input of the power amplifier. Steps 5 through 8 lower the impedance of the low-pass filter, increasing the current and therefore the power from the power amplifier. The values for these components were determined through computer simulations of the low-pass filter using PUFF⁷. See Figure 8 for the low-pass filter's (Figure 9) simulated profile. The output powers of the two NC40A's that we modified were increased to 5.5W and 6.5W , making the modified NC40A perfect for driving the amplifier.

- 9: C18 is replaced with a 680pF capacitor

This last change, though not essential, gives an audio frequency of around 600Hz . Using the 200pF capacitor suggested in Ed Burke's modifications gives a higher pitched audio tone, and may be desirable to some.

DIPLEXERS

To keep spurious emissions from the NorCal 40A driver and the 30-meter amplifier low, two diplexers were built. A diplexer is a band-pass filter which has an impedance of 50Ω at all frequencies, terminating out-of-band spurious emissions in a 50Ω dummy load⁸. See Figures 10 and 11 for schematic diagrams of the diplexers that we used. The smaller of our two diplexers, designed to handle low powers, is placed between the NorCal 40A driver and the

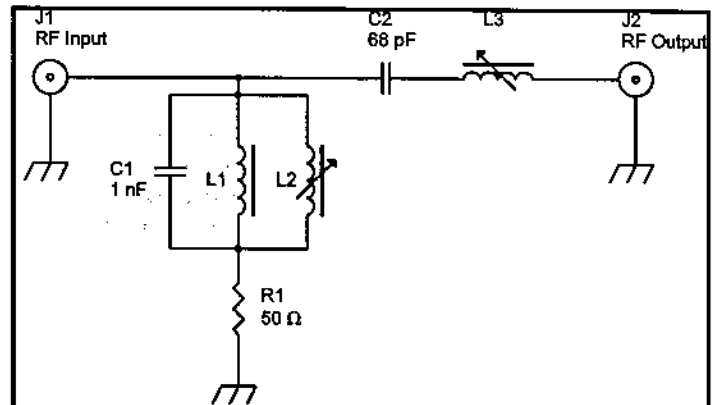


Figure 10. Circuit diagram of the small, low power diplexer. C1 and C2 are silver micas. L1 is 12 turns of magnet wire wound on a T37-2 core. L2 and L3 are $.68\mu\text{H}$ and $4.7\mu\text{H}$ Toko variable inductors, respectively. R1 is a $\frac{1}{4}$ watt precision resistor.

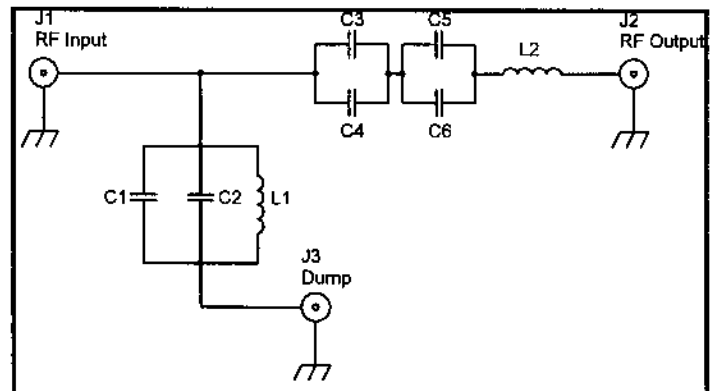


Figure 11. Circuit diagram of the large, high power diplexer. C1 and C2 are both 560pF . C3-C6 are 150pF . All six capacitors are Cornell Dubilier mica, 1000V . L1 is 3 turns of copper tape with inner diameter of $1''$. L2 is 12 turns of copper tape with inner diameter of $1\frac{3}{8}''$. For the dump, a 5-watt BNC 50Ω load is used.

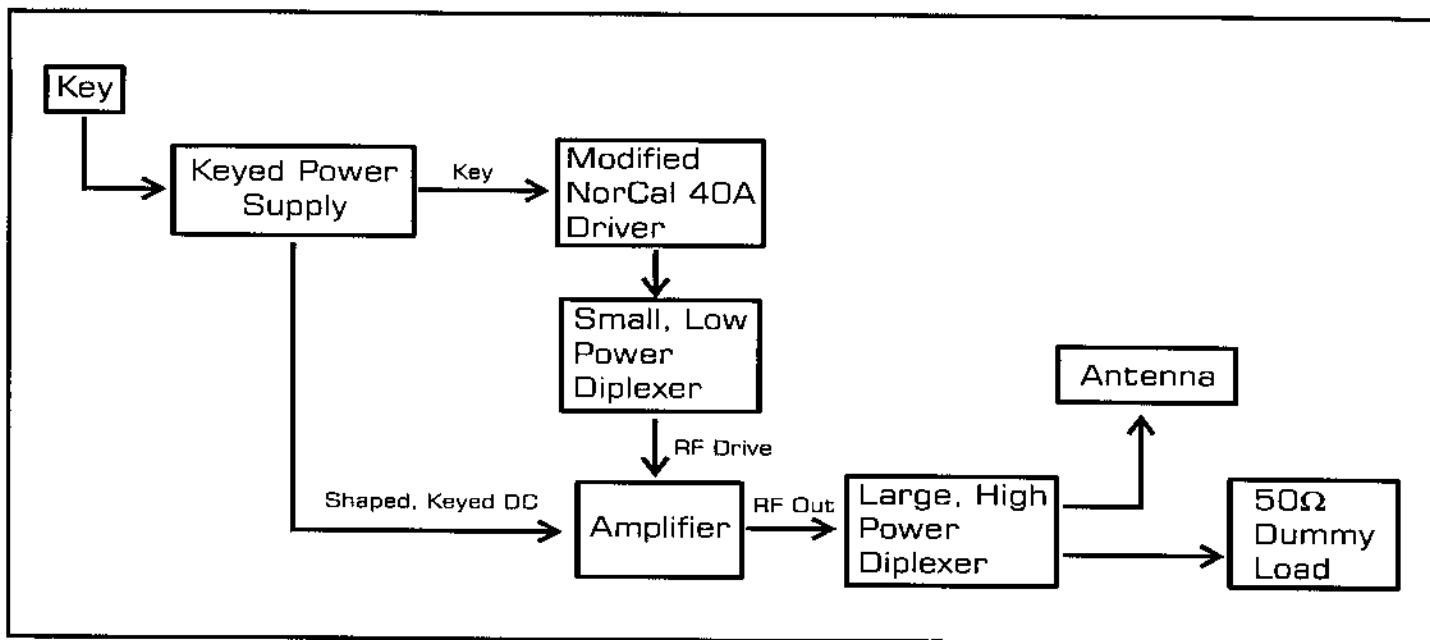


Figure 12. Block diagram showing complete 30-meter CW radio station

power amplifier. This diplexer is constructed with the same type of variable inductors that are found in the power amplifier's input network. The capacitors are small silver micas. The case is a small metal box, manufactured by Pomona Electronics, measuring 2.25x1.4x1.1 inches, with female BNC connectors at either end. This diplexer ensures that the power amplifier is driven with a clean signal at the correct frequency. It attenuates the spurious emissions from the driver which would otherwise be amplified by the power amplifier. The larger, high power diplexer is placed after the output of the power amplifier, and helps in attenuating spurious emissions generated by the power amplifier. It is constructed with the same types of air-core inductors and 1000-V mica capacitors found in the power amplifier, and is housed in a 3.5x6x10-inch box. **Figure 12** shows a block diagram of the complete 30-meter CW radio station.

FUTURE WORK

There is still much room for improvement on these class-E power amplifiers. One possibility is a built-in pre-amp, which would allow the amplifiers to be driven with smaller amounts of power, allowing their use with low power QRP transceivers without modification. Another useful addition would be a TR switch of some sort, which would allow for better reception by allowing incoming signals to bypass the amplifier. A small, switching power supply could be developed to replace the current one,

which is very large and expensive. It may even be possible to use the RF drive, perhaps divided in frequency, as an oscillator for such a power supply. Finally, it would be interesting to develop class-E amplifiers for other bands and higher powers. Work is already underway for developing a 15-meter class-E amplifier.

ACKNOWLEDGEMENTS

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APPENDIX 1

Name	Component	Notes
Q1	IRFP440	Use International Rectifier only
C1	10 pF	Cornell Dubilier mica, 500V, 5%
C6	.01 μ F	Ceramic disc, 1000V
C2	100 pF	Cornell Dubilier mica , type CDV19, 1000V, 5%
C3	1100 pF	Cornell Dubilier mica , type CDV19, 1000V, 5%
C4	220 pF	Cornell Dubilier mica , type CDV19, 1000V, 5%
C5	470 pF	Cornell Dubilier mica , type CDV19, 1000V, 5%
L1	1.5 μ H	Toko variable inductor
RFC1	40 μ H	Radio frequency choke
L2	9 turns	.2" copper tape wound on 1/4" O.D. pipe, spread 2.6" to fit holes on the PC board
L3	5 turns	18-gauge wire, closely spaced on a 7/32" drill bit
L4	10 turns	20-gauge wire, wound on T80-2 type toroidal core
T1	6 turns	26-gauge, stranded hookup wire

References

¹ E. Lau, K.-W. Chiu, J. Qin, J.F. Davis, K. Potter, D.B. Rutledge, "High-Efficiency, Class-E Power Amplifiers," *Part 1, QST*, pp. 39-42, May 1997; *Part 2, QST*, pp. 39-42, June 1997. Packages of amplifier parts *only*, including PC board, components, connectors, heat sink and chassis for both 40-meter (300W and 500W) and 30-meter (200W) amplifiers are available at cost from Puff Distribution, Department of Electrical Engineering, MS 136-93, Caltech, Pasadena, CA 91125. Contact Dale Yee by email at yee@systems.caltech.edu or by fax at (626) 395-2137 for more information. Visit <http://www.systems.caltech.edu/EE/Faculty/rutledge/powcramp.html> for an order form.

² G.D. Ewing, "High-Efficiency Radio-Frequency Power Amplifiers," Ph.D. Dissertation. Oregon State University, Corvallis, Oregon, 1964.

³ N.O. Sokal and A.D. Sokal, "Class E - A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of Solid-State Circuits*, Vol. SC-10, pp. 168-176, June 1975.

⁴ D. Freedman, "Signal Envelope Elimination and Restoration," *QST*, p. 82, October 1997.

⁵ N.O. Sokal, "Signal Envelope Elimination and Restoration in Class-E, High-Efficiency Linear RF Power Amplifiers," *QST*, p. 80, January 1998.

⁶ E. Burke, "NC40 to N30 Conversion," *QRPP*, Vol. III, Number 4, p. 63, December 1995.

⁷ PUFF is a program developed at Caltech for design and simulation of microwave integrated circuits, but is very useful for RF circuits, as well. It is available from Puff Distribution, Department of Electrical Engineering, MS 136-93, Caltech, Pasadena, CA 91125. The cost is \$10. See <http://www.systems.caltech.edu/EE/Faculty/rutledge/puff.html> for more information.

⁸ D. Newkirk and R. Kariquist, "Mixers, Modulators, and Demodulators," *The 1996 ARRL Handbook*, Chapter 15, p 15.22.