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APPLICATION NOTE

A 300W MOSFET Linear Amplifier for 50 MHz

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A 300W MOSFET Linear Amplifier for 50 MHz

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ABSTRACT

In an earlier article, the author described a 50 MHz 125V 250W class C amplifier using the ARF448A/B high voltage MOSFET devices.[1] This paper now describes an improved version of that amplifier which is capable of class AB linear operation. The design changes required and the procedures involved are explained and demonstrated. A complete description of the amplifier and its construction are presented as well as the measured performance.

INTRODUCTION

High voltage, high power MOSFETs have been shown to be very capable RF power amplifiers.[2] The metal gate architecture of the ARF series of devices from Advanced Power Technology has raised the frequency limits for this type of device to 100 MHz. The APT448A/B is typical of the series. It has a 68000 square mil die with a breakdown voltage rating, BVdss, of 450V. The device is packaged in the inexpensive TO-247 plastic package and is available in common source symmetric pairs. Like all MOSFETs, the gate threshold voltage, Vth, has a negative temperature coefficient. This makes operation as a linear amplifier difficult to impossible.

When forward biased with a constant gate voltage, the quiescent drain current will rise as the temperature of the die increases. Operating at the typical drain voltage for these parts, about one third of the rated BVdss, the power dissipation due to the increasing Idq results in "hot spotting" and subsequent thermal runaway. This is an unstable system. The dissipation increases so rapidly that the outside surface of the case does not follow the internal junction temperature. As a result, a bias compensation scheme that uses temperature sensing cannot keep up with the Vth shift and the device is destroyed.

The power dissipation within the die is a direct function of the operating voltage. By lowering the operating voltage the thermal loop gain can be reduced to a point where the gate threshold shift can be compensated for. Thermal stability can be achieved by sensing the case temperature. Linear operation thus becomes practical at 100V and below. While this is less than 25% of the rated BVdss and results in less gain, a very rugged and useful linear amplifier results.

AMPLIFIER DESCRIPTION

These were the design goals for the amplifier:

Frequency range:	50 to 51 MHz
Input VSWR:	< 1.5:1
Gain:	>13 dB
Output Power:	300 W PEP or CW
Efficiency:	> 50%
IMD3:	< -25 dB below PEP

A push-pull topology was chosen for best output power and minimum harmonic output. The previously reported class C design operated form 125V. Since this is too high for reliable class AB operation, 80V was eventually chosen for this design. This is a compromise between gain, efficiency and thermal stability.

In an ideal MOSFET, the input impedance is a pure capacitor. It has no real part. At 50 MHz the ARF448 has an input impedance of just 0.2 + j 0.5. This indicates that the impedance of the bonding wire inductance is slightly larger than the gate capacitance and that there is very little gate loss resistance. It also suggests that careful attention to the design of the input matching network will be necessary to obtain the design goals.

Since the gate input impedance is very low, it magnifies the effects of any stray inductance in the gate matching circuit. In a push-pull design, it is critical to maintain absolute symmetry between the two sides. This fact was demonstrated during the initial design work. One preliminary design had a slight asymmetry in the artwork. The amplifier exhibited low efficiency, hot ferrite in the output transformer balun, and poor distortion characteristics with asymmetrical IMD products. This clearly demonstrates the benefit of having symmetrically packaged devices.

A multiple aperture ferrite bead was chosen for the input transformer. Brass tubing was used for the secondary and the primary was wound inside the brass tubes to provide a very broadband balanced transformer design with minimum leakage reactance. Several cores and construction methods were evaluated and this well-tried design proved best.

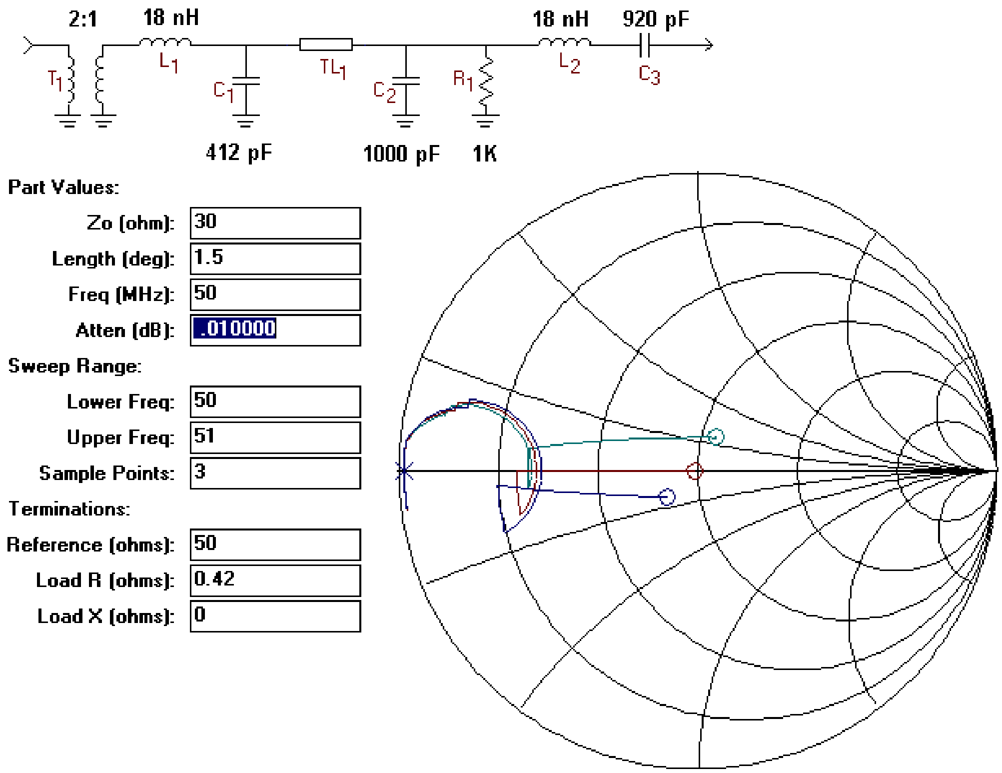

Figure 1 Input Match Calculation

The typical HF push-pull amplifier employs a bifilar choke to decouple the drain voltage feed. As the frequency and power increases, this feed method becomes less practical due to the contradiction between the need to reduce the number of windings to offset the stray capacity and requirement not to saturate the core. In this design, a powdered iron toroid was chosen for the feed choke core. This proved far superior to any of the ferrite cores evaluated. It is inexpensive and easy to reproduce.

DESIGN

There are three main areas to be addressed. The input matching needs to provide a balanced feed to a low impedance pair of gates. The output impedance must be matched to a suitable load impedance and that transformed to a 50Ω single-ended load. The bias must be thermally compensated to track the negative temperature coefficient of the gate bias threshold.

The input is reasonably straightforward. Each gate input is 0.2 +j0.5, as estimated from the data sheet. The push-pull topology puts these two impedances in series which makes the matching less difficult. A Smith Chart[1] program makes the actual design easy. The program used here is winSmith.[2] The two gates impedances are added in series and a network synthesized to transform the resulting impedance up to 50Ω. The Smith Chart program only works with single ended circuits so the center tap was added later. See Figure 1 Input Match Calculation.

The input transformer design was chosen for its simplicity and relative ease of construction. Of several attempts using different material permeability, multiple beads, and different conductor types, this proved to be the best performing and most consistent. The core is a Fair-Rite[5] "multi-aperture core," part number 2843010402. The type 43 material has a μ_i of 850. At 50MHz, type 61 material (μ_i of 125) would also be satisfactory. This transformer is essential in providing balanced drive to the gates of the MOSFETs. 3/16" diameter brass tubing was used for the secondary winding. Copper shim stock forms the connections to the brass tubing at each end of the transformer secondary. The two turn primary winding is wound inside the tubing. This construction provides a very reproducible transformer with minimum leakage reactance and a very broad frequency response. It would be a suitable input transformer for a broadband amplifier covering 1 to 100 MHz.

The leakage reactance of the input transformer, referred to the secondary, is about 18 nH and is represented as L1 in the simplified input schematic in Figure 1. The gate load is represented by the "Load R", L2, and C3. Using all three parts of the gate impedance allows proper evaluation of the network bandwidth. A pi-network consisting of C1, TL1, and C2 is used to step up the gate load to the 12.5Ω needed by the transformer and it compensates for T1's leakage reactance. Notice that the net stray inductance of the gate is almost enough to effect a match with a single shunt capacitor. This has actually been done but it was not easy to fit all the parts in the available space and was thus judged unacceptable. To transform the network into the required balanced configuration, the series TL1 is split into two equal parts, the shunt capacitors remain the same, and a neutral center tap is provided at the transformer secondary.

Because of the high currents circulating in the input network, it is imperative that C2 be a larger sized class 1 dielectric (COG or NPO) capacitor. It must be a leadless SMT chip type or the required value will need to be adjusted. The input tuning capacitor, a 900 pF mica compression trimmer, is mounted directly to the end of the input transformer.

The output network is straightforward. The proper load impedance for class AB is calculated from the formula $R_L = (.98Vdd^2)/2P_o$. This is the load for each device and Po is one half of the total in a push-pull circuit. It is shunted by the output capacitance, Coss. As was done for the gate circuit, both output impedances are seriesed to represent the total output impedance. The result for both devices in push-pull, is 30.7Ω in parallel with 75pF (half the output capacitance of a single device). Though the design goal was 300W PEP, the amplifier was actually designed for a 400W load line. This gives a good compromise between efficiency and linearity.

In a classical design, a suitable transformer would be used to set the load impedance and either the output power or the operating voltage would be adjusted to fit the available turns ratio. Normally, in a low voltage low frequency hf design, the output capacitance is ignored because it is shunted by a much smaller load resistance. At 50 MHz the effects of the output capacitance must be compensated for so a slightly different approach was taken in this circuit.

WinSMITH was used again to design the output matching. See Figure 2. The output impedance of 30Ω is rotated south by the effect of the shunt output capacitance, C2. There are two options. Some additional shunt capacitance could be added to further reduce the equivalent series real part to 12.5Ω, a series L used to resonate the resulting series C, then a 4:1 transformer used to go to 50Ω. However, building a reproducible low loss 4:1 balanced transformer was very difficult, and compensating its leakage reactance further complicates the design. A second option was used. The equivalent series output capacitance was resonated first and then more series inductance was added to rotate the load all the way up to the 1/50Ω admittance circle. Then a shunt capacitor was used to resonate the added X_L. The extra L and shunt C form an L-network which transforms the 20Ω equivalent series output impedance up to 50Ω. This results in an easily duplicated design with a smooth, low-Q match.

The DC feed to the drains is provided through a shunt bifilar choke. At this frequency, most ferrite materials exhibit too high a loss to be used at this impedance level. A powdered iron core works famously here.

The balun (balanced-to-unbalanced) transformation function is provided by a simple coax and wire transformer. Two of the windings are provided by the 50Ω Teflon coax and the third balancing winding by an additional single wire.

The bias network requires some understanding. Power MOSFETs have normal lot-to-lot variations in gate threshold voltage, Vth, the forward transconductance, Gfs, and other parameters. A number of devices were checked for Vth and they were all very close. They were all from the

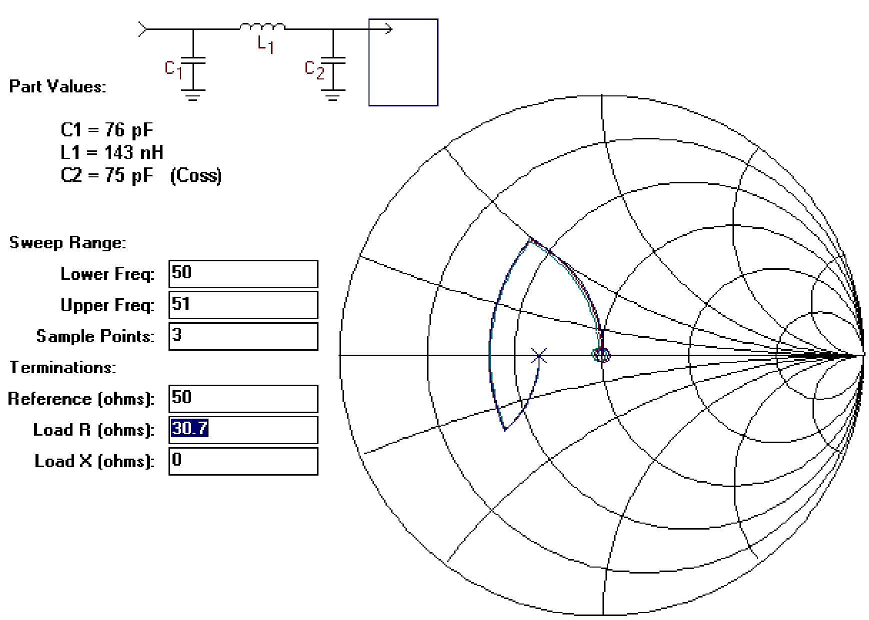

Figure 2 Output Network Calculation

same die lot. The die lot number is marked on the package. For comparison, devices from another lot were checked and were uniformly a half a volt lower. If this were the case for the devices to be used in the amplifier, a DC block should be added in each side at the transformer and the bias feed

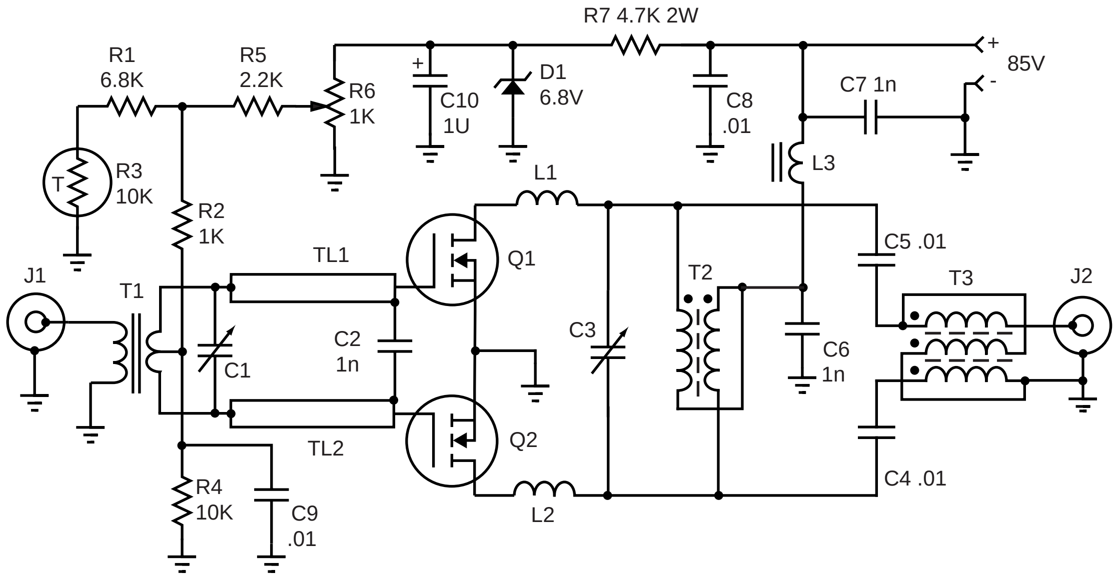

Figure 3 50MHz Amplifier Schematic

network duplicated for each device. Since these devices were quite uniform, for simplicity it was decided not to provide for individual gate bias adjustment in this design.

Because the gate bias voltage required to maintain a particular value of idling drain current decreases as the temperature of the die increases, it is necessary to thermally compensate the gate bias source or the devices will "run away". A commonly available NTC resistor tracks the temperature of the case. Refer to Figure 3. This bias circuit has been in the literature for many years.[6] The ratio of R1 to R3 in part determines the rate of compensation. A smaller value of R1 or a lager value of R5 will increase the thermal sensitivity. A drop of thermally conductive glue keeps the thermistor in contact with the case. Proper operation is indicated when the set value of Idq does not change after the heatsink is hot from prolonged operation.

CONSTRUCTION

Refer to Figure 4 for the parts layout. A photomaster of the artwork is shown in Figure 5. The original size of the artwork is 3.25 x 7 inches. The circuit board is 1 oz. copper double sided 1/16-inch G-10 printed circuit board material. All our sides of the board and three sides of the two rectangular cutouts for the transistors are wrapped with copper foil tape and soldered in place to provide a low

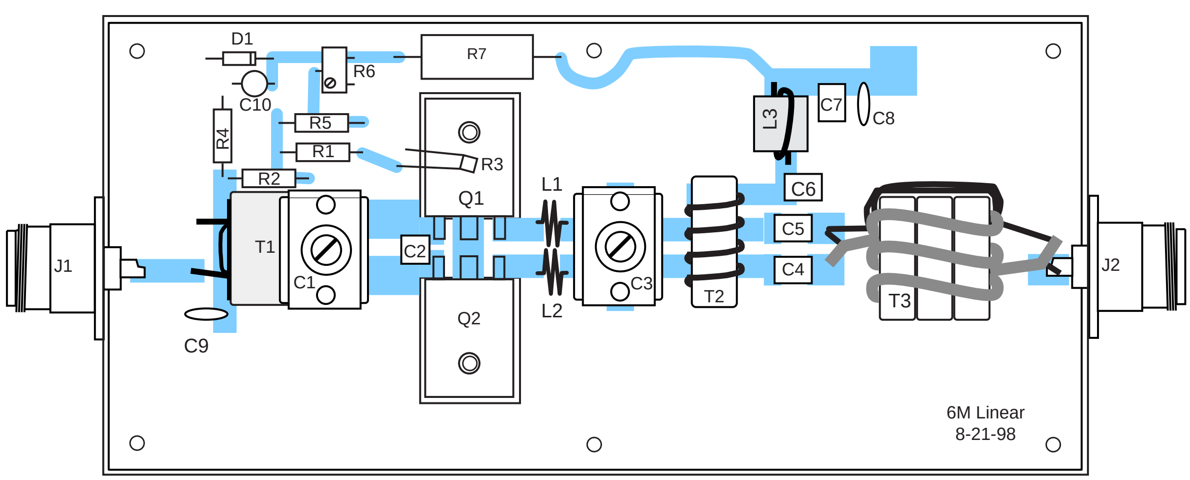

Figure 4 Amplifier Parts Layout

impedance continuous ground plane. The two cutouts for the transistors and six mounting holes are the only holes in the board. All of the parts are surface mounted which permits the board to be mounted directly to the heatsink.

This amplifier was built on a 7 inch length of AAVID #60765 heat sink extrusion.[1] It is 3.25 inches wide, 1.5 inches deep, and has nine fins. With 50CFM of air blown across it, the devices will easily maintain thermal stability in a 30°C environment. The heatsink is not big enough for anything but very intermittent use without a fan to assure adequate air flow across the fins. The input and output connectors are each secured by two 4-40 screws tapped into the base of the heatsink. For safety, a cover is recommended as fairly high rf voltages are present.

POWER SUPPLY

Power for the amplifier needs to be fairly well regulated since any ripple will show in the output signal as undesired 120 Hz amplitude modulation. For on-air testing at the author's home, a very simple power supply was constructed using a 500W 120-240V isolation transformer to drive a full wave center tapped rectifier with 50,000 uF of filtering. Under SSB conditions, this is adequate. For CW it needs some better regulation or the output power will sag over the length of a dash and there will be some detectable hum. A regulated supply capable of providing 80Vat 6A is needed.

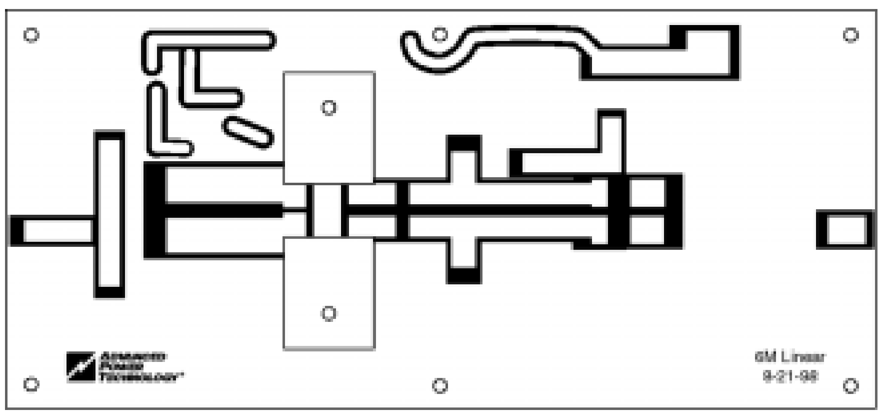

Figure 5 Printed Circuit Artwork (not to scale)

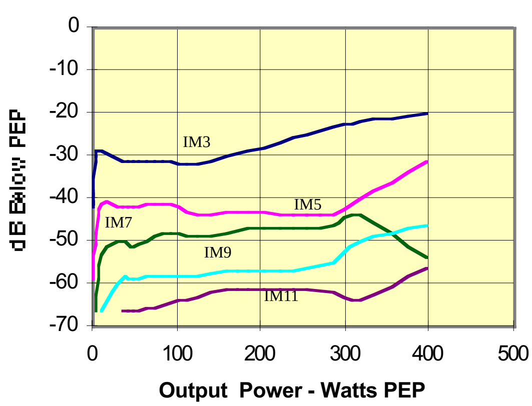

Figure 6 SSB Performance

PERFORMANCE

This is the first known class AB application of the ARF448 parts. Until now the only other linear application is in a pulsed-mode linear amplifier for magnetic resonance imaging. The SSB performance was encouraging since these devices were developed to serve the ISM plasma generation market and no attention to linear performance was given in their design. The IMD performance with 200 mA of quiescent bias was better than expected. See Figure 6. The amplifier was tested with up to .5A of Idq. While the IMD performance improves somewhat, the efficiency degrades significantly.

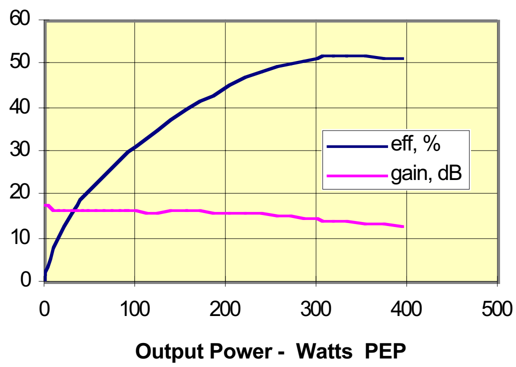

Figure 7 Amplifier Performance

The gain and efficiency objectives have been met as shown in Figure 7. The gain is 14.3dB at 300W PEP. The efficiency peaks at 51% at the same power. Under single tone conditions, the drain efficiency is 61% at 250W. The bandwidth of the amplifier is determined by the input network. The Smith chart of the input network, Figure 1, shows the tracks for 50, 50.5 and 51 MHz. With the network adjusted for best match at 50.5MHz, the SWR at the ± 0.5MHz bandwidth points is 1.3. It would be difficult to increase this SWR bandwidth enough to cover the full 4 MHz of the amateur 6M band without resorting to resistive loading which would then reduce the available gain.

CONCLUSION

This paper has presented a 50 MHz 300W PEP linear amplifier using plastic packaged high voltage MOSFET transistors. This is the first known implementation of a full duty cycle class AB amplifier using these transistors. The design challenges, the approaches to their solution, and the resulting amplifier performance are shown. The parts used, construction and mechanical layout all have been described in sufficient detail to permit duplication. The new line of plastic packaged RF power transistors from APT offer the designer a new cost effective solution for efficient layout and effective performance.

Table 1: Amplifier Parts List

C1	215-790 pF Arco[8] #469 mica compression trimmer
C2,6,7	1000 pF 500V NPO chip cap, KD[9] 2020N102J501P
C3	20-180 pF Arco #453 mica compression trimmer
C4-5,8-9	.01 uF 500V chip
C10	1 uF 35 V electrolytic
D1	6.8 V 1W Zener diode
L1-2	~70 nH, 3t #18 enam. .31" dia. .25"L
L3	2t #20 on Fair-Rite Prod. #2643006302 bead µi = 850
Q1	ARF448A
Q2	ARF448B
R3	10K NTC Fenwal[10] #140-103LAG-RB1
R6	1K .5W ten turn trimmer
T1	Pri: 2t #20 PTFE, Sec: 3/16" brass tube on Fair-Rite #2843010402 balun core
T2	6t bifilar #20 PTFE on Amidon #T-94-2 toroid µi = 10
T3	3t RG-316 coax, 3t #20 PTFE on three Fair-Rite #5961001801 toroids µi = 125
TL1-2	30Ω printed line .6"L

[1] Frey, R.B.: *A 50 MHz, 250W Amplifier using Push-Pull ARF448A/B*, APT9702, Advanced Power Technology, Inc.
[2] Frey, R. B.: A Push-Pull 300 Watt Amplifier for 81.36 MHz, *Applied Microwaves and Wireless*, April 1998.
[3] Smith™ Chart is a trademark and property of Analog Instruments Co., new Providence, NJ.
[4] WinSMITH, copyright Eagleware Corp., 1995, available through Noble Publishing, Inc.
[5] Fair-Rite Products Corp., PO Box J, One commercial Row, Wallkill, NY 12589.
[6] Granberg, H. O., Wideband RF Power Amplifier, *R.F. Design*, February 1988.
[7] AAVID Thermal Technologies, Inc., Box 400, Laconia, NH 03247
[8] Arco Electronics, 5310 Derry Ave., Agoura Hills, CA 91301
[9] KD Components, Inc., 2151 Challenger Way, Carson City, NV 89706
[10] Fenwal Electronics, Inc., 450 Fortune Blvd., Milford, MA 01757

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