## BACKGROUND

Modern industrial applications for high-efficiency, switch-mode RF amplifiers include laser, plasma, magnetic resonance imaging (MRI), and communications. The power levels and frequency of operation of industrial equipment used in these areas vary greatly. While plasma and heating applications tend to cluster at 13.56 MHz and 27.12MHz, laser and MRI applications tend to migrate towards 40 MHz, 80 MHz, and 128 MHz. Power levels span the gamut from a few watts to hundreds of kilowatts.

The stability, reliability, and low $R_{DS-ON}$ resistance of MACOM high frequency, RF, power MOSFETs make them suitable for switch-mode amplifier applications. The MRF product line, which includes RF power MOSFETS in the 1MHz-1GHz frequency range, has been a communication industry standard for more than 30 years. These devices are also used in many switch-mode amplifier applications and can yield much higher power and efficiency levels than specified in the traditional class AB designs. This application note presents a class E amplifier design based on MRF151A, a single ended power MOSFET, where it yields up to 300 watts at 81.36 MHz with better than 82% efficiency.

Class E amplifiers are well suited to industrial applications due to their simplicity and the high efficiency which can be obtained at a single frequency or over a narrow bandwidth. In this type of amplifier the power transistor operates as an on-off switch and, and in conjunction with the load network, it offsets the current and voltage waveforms in order to minimize power dissipation and maximize efficiency [1].

## THEORY

A simplified schematic of a class E amplifier is shown in Figure 1. It consists of a transistor, a shunt capacitance C, a series LC circuit, a load R, and additional bias and input matching circuitry. The shunt capacitor C can be made up by the internal output capacitance of the transistor or by a combination of internal and external capacitances. The transistor in this case operates as a switch and drives the load network C, $C_o$, $L_o$, R. The design of this load network is done such that the voltage and current through the drain of the transistor are out of phase while power is delivered to the load resistor R. This offset implies that, ideally, no power is dissipated in the transistor thus the efficiency is ideally 100%.

According to [1] the design equations of the load network are given by (1)-(5). The design equations are derived by starting out with the drain voltage waveform equation and imposing a set of constraints peculiar to the ideal class E amplifier circuit. $P_o$ is the output power delivered to the load R given a supply voltage $V_{dd}$. $V_{Dpeak}$ is the peak drain voltage. Reactances X and B take into account the limited Q value of the inductor (Q = $\omega L_o/R$). This Q value is assumed to be in the 3 to 10 range. B is the susceptance of the shunt capacitance C. X is a reactance added to the resonance tuned $L_oC_o$ in order to shape the voltage and current waveforms for optimum class E operation.
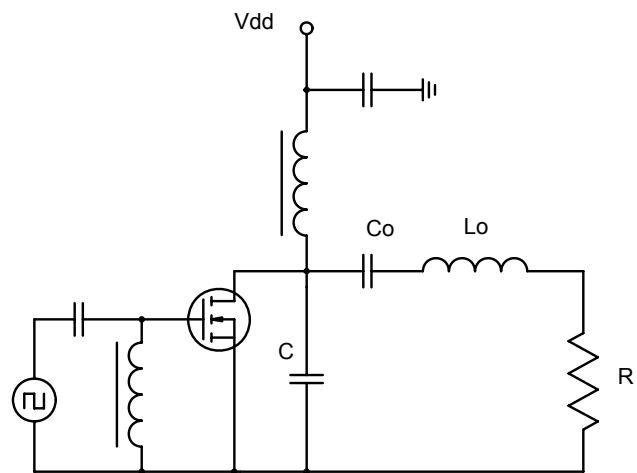


Figure 1. Class E Amplifier Block Diagram

$$P_o \approx 0.577 \frac{V_{dd}^2}{R} \qquad (1)$$

$$I_{dc} = \frac{V_{dd}}{1.734 R} \qquad (2)$$

$$V_{Dpeak} = 3.56 V_{dd} \qquad (3)$$

$$X = \frac{1.110 Q}{Q - 0.67} R \qquad (4)$$

$$B = \frac{0.1836}{R}(1 + \frac{0.81 Q}{Q^2 + 4}) \qquad (5)$$

### DESIGN AND SIMULATION

MRF 151A was chosen for this application because of its 50V operation capability as well as the low $R_{DS-ON}$ (~0.2ohm). Figure 2 shows the Level 1 SPICE model used in conjunction with Agilent's ADS simulation software to optimize the Class E circuit. To ease computations equations 1.0, 4.0, and 5.0 were re-arranged to solve for C, R, $L_o$, $C_o$ as a function of frequency f, output power $P_o$, drain voltage $V_{dd}$, and inductor Q. When these variables are set to 81.36MHz, 300 watt, 48V, and 5 respectively the calculated values are C = 92.4pF, R = 4.4ohm, $L_o$ = 54nH and $C_o$ = 88.3pF. One issue that arises from these results is that the required shunt capacitance C = 92.4pF is smaller than the output capacitance of MRF151A which, per the data sheet, is 220pF. This implies that a class E amplifier would not operate optimally. The maximum frequency of operation for optimal, class E performance, for a particular capacitance value is given by:

$$f_{max} = \frac{0.0292}{RC_{out}} \qquad (6)$$

For a $C_{out}$ = 220pF the maximum frequency for optimal performance is ~30MHz. Since the desired frequency of operation is 81.36 MHz, the ratio $f/f_{max}$ is 2.7. According to [2], the obtainable efficiency for $f/f_{max}$,≈ 2.7 is approximately 82%, which is still an attractive number. The calculated component values were used as a starting point in the simulation and varied in order to maximize output power and minimize DC current. Another constraint used in this optimization was the instantaneous drain voltage which was capped at 125V, which is the breakdown voltage of MRF151A. Figure 3 shows the optimized circuit and Figures 4,5, and 6 show the resulting voltage and current waveforms on the transistor drain, voltage across the load resistor R, and DC current.

On the input side, the gate is matched to 50 ohm using conjugate impedance values. ADS can be used to easily perform this task. A 25 ohm resistor has been added in shunt to improve the bandwidth and stability.

The results suggest a power output of 319 watts and an efficiency of 84.1%. Also, the peak drain voltage is 120.6 V.

A sinusoidal signal has been used to drive the MRF151A circuit. It is possible to shape the drive signal in order to increase efficiency, however, that is beyond the scope of this paper.

## Application Note
## 300 Watt Class E Amplifier Using MRF151A
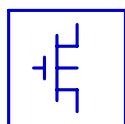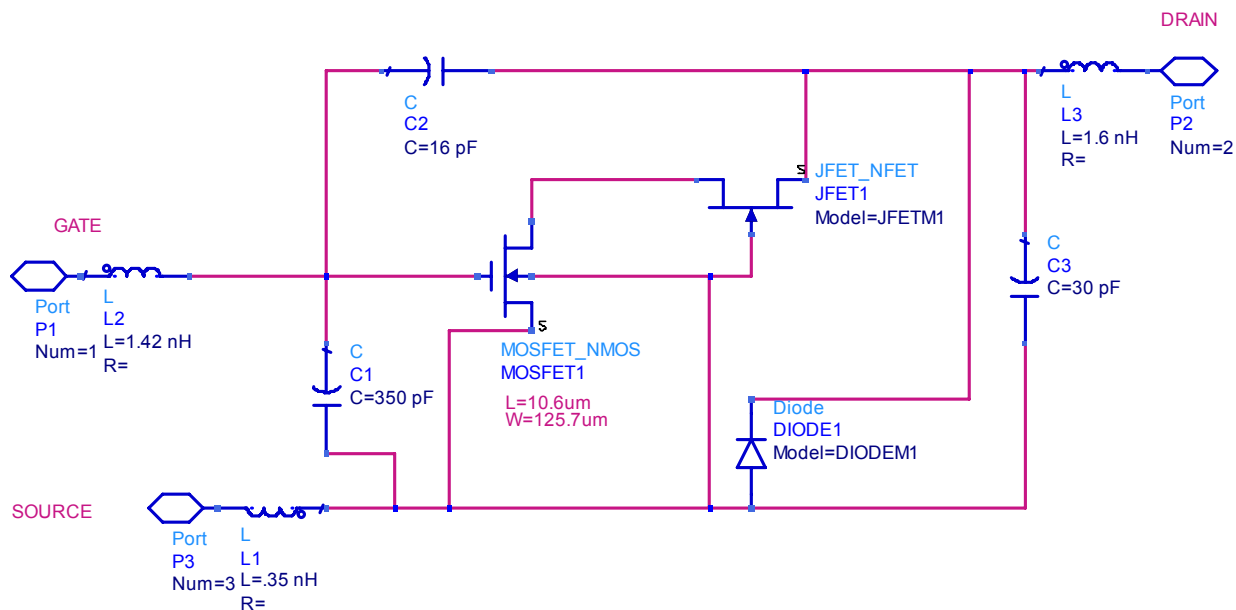
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Figure 2.  MRF151A SPICE Model

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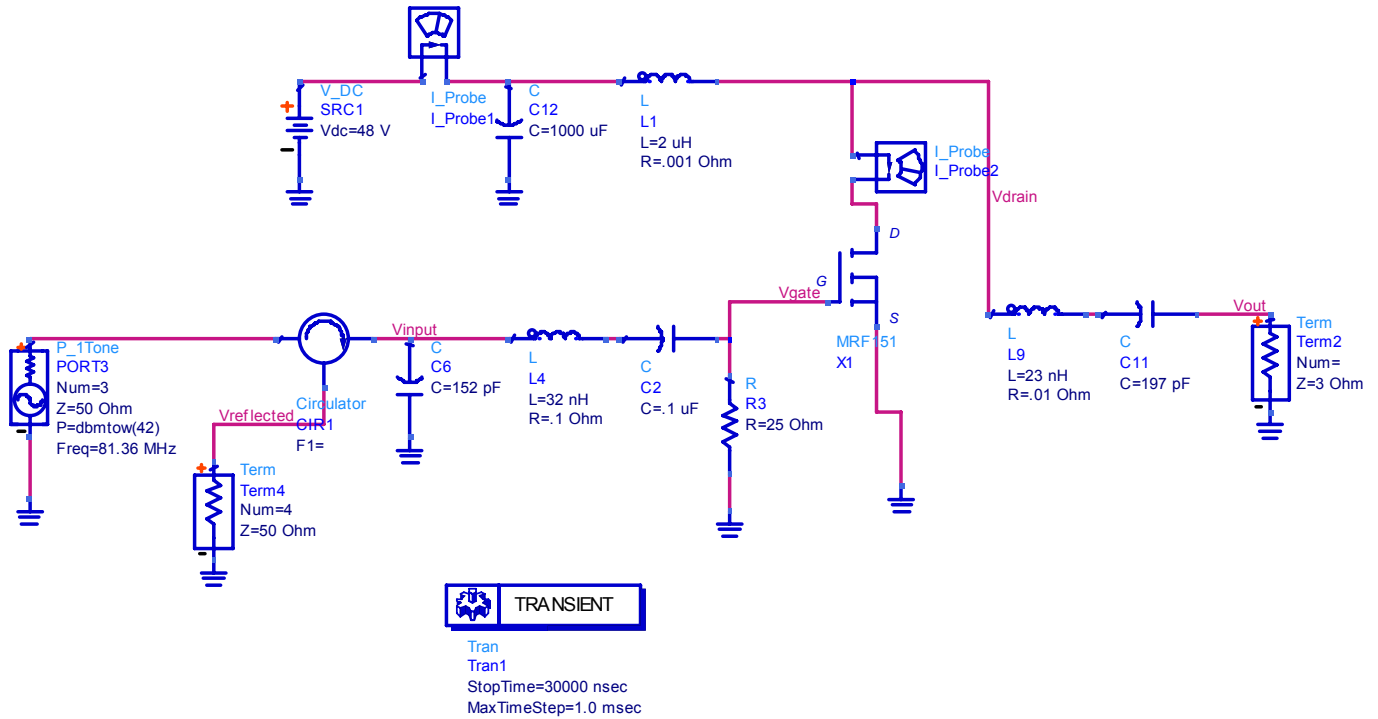
Figure 3.  Class E Amplifier Circuit in ADS
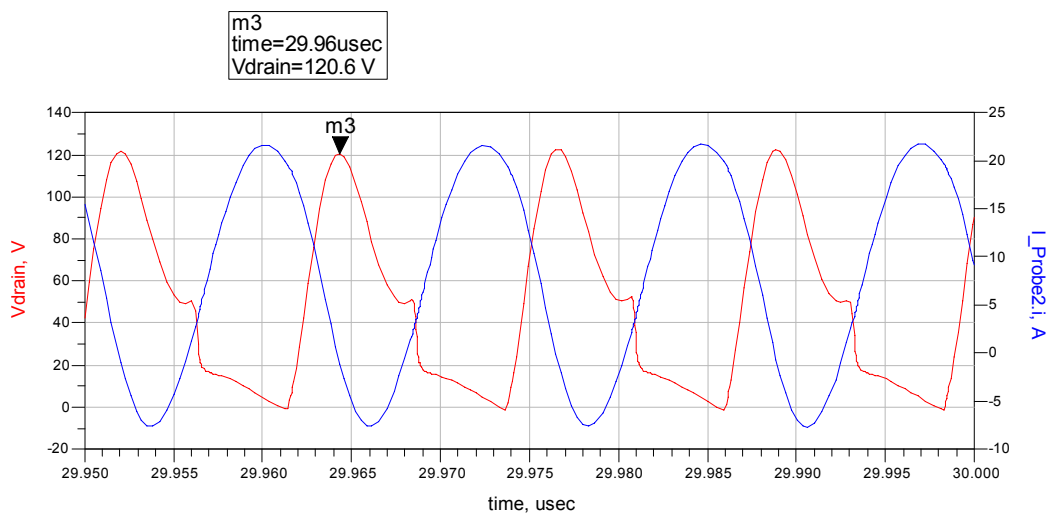


Figure 4.  Voltage and current waveforms on the drain of MRF151A

## PROTOTYPE

Before a prototype can be tested, the low value load resistor must be matched to 50 ohm for use with standard test equipment. A simple way of doing this is by using a lumped element quarter wave as described in [3] and shown here in Figure 7. The characteristic impedance of this quarterwave section is given by:

$$Z_o = \sqrt{Z_{in} Z_{out}} \qquad (7)$$

For a load resistor R = 3 ohm the characteristic imped-ance would be 12.25 ohm. For f = 81.36 MHz the com-ponent values are L = 24 nH and C = 160 pF.

The prototype is shown in Figure 8. The load inductors are the hair-pin type and are made of AWG10 copper wire. The inner diameter are 0.35" in both cases and the lengths are 0.63" for 23nH and 0.97" for 24nH. A vector network analyzer was used to measure the inductance values and the length of the inductor was adjusted until the desired values of 23 and 24 nH were achieved. The recommended reactance value for the drain RF choke is at least 10R or 30 ohm. This trans-lates into $L_{RFC}$ > 60nH. This inductor has been built using 12 turns of AWG 16 copper wire wound on an Amidon T-157-6 iron powder torroid which provides about 13uH of inductance. This is more than enough to eliminate any contribution from the biasing network. Some optimization of the load network was necessary due to PCB parasitic capacitances and inductance er-ror. The final value of the series resonant capacitor was 174.1pF.

The performance of the prototype is shown in Table 1 and Figure 9. At $P_{out}$ = 300 watt, Eff = 82.1. These numbers correlate well with simulated results of 319 watts with 84.1% efficiency. Power gain, on the other hand is 13dB in the simulation but only 10.9dB when tested. Since the SPICE model does not incor-porate thermal effects a faster gain compression of the prototype is to be expected. If higher gain is required it can be achieved by a tradeoff in power and efficiency as shown in Table 1. For example at $P_{out}$ = 250 watt, Gain = 14.2dB and Eff = 78.1, which is still a relatively good number.

At $P_{out}$ = 300 watt and $P_{in}$ = 24.3 watt, power added efficiency (PAE) is 77%. Dissipated power in this case is 89.6 watts. Since the thermal resistance of MRF151A is $R_{\theta JC}$= 0.42 ºC/W the rise in junction tem-perature is 37.6 ºC. Even with a case temperature of 85 ºC the junction temperature would be only ~123 ºC.
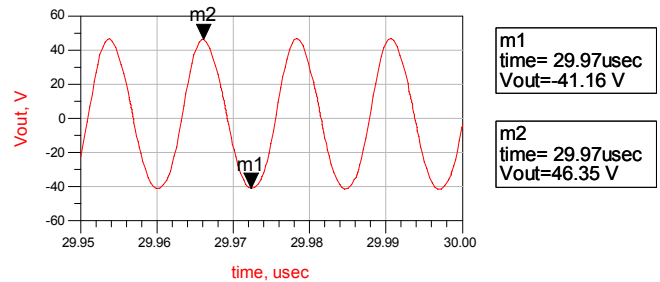


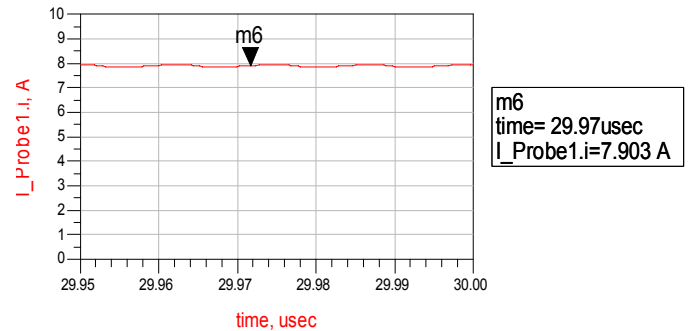Figure 5. AC voltage across the load resistor

| m1 |
| --- |
| time= 29.97usec |
| Vout=-41.16 V |

| m2 |
| --- |
| time= 29.97usec |
| Vout=46.35 V |



| m6 |
| --- |
| time= 29.97usec |
| I_Probe1.i=7.903 A |

Figure 6. DC current drawn from the power supply.
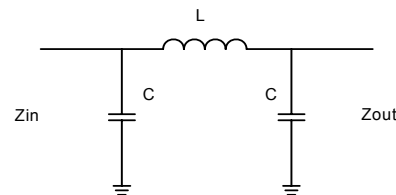


Figure 7. Lumped element quarter wave section



Figure 8. Prototype of class E amplifier

At 300 watts, second and third harmonic levels are –39dBc and –57dBc respectively. If necessary the harmonic levels can be improved further by including additional filter stages.

The drain voltage was also measured using an oscilloscope and it is shown in Figure 10. Although the limited frequency response of the probe and EM interference are masking some of the higher frequency components it can be seen that the simulated voltage waveform shown in Figure 4 is a reasonable prediction of the measured waveform.

| Pout (Watts) | Pout (dBm) | Pin (Watts) | Pin (dBm) | Gain (dB) | Id (Amps) | Eff (%) | Vd (Volts) | H2 (dBc) | H3 (dBc) |
|---|---|---|---|---|---|---|---|---|---|
| 300 | 54.8 | 24.3 | 43.9 | 10.92 | 7.61 | 82.1 | 48.0 | -39 | -57 |
| 250 | 54.0 | 9.5 | 39.8 | 14.19 | 6.67 | 78.1 | - | -39 | -56 |
| 200 | 53.0 | 6.1 | 37.9 | 15.15 | 5.75 | 72.5 | - | -38 | -57 |
| 150 | 51.8 | 4.3 | 36.3 | 15.43 | 4.74 | 65.9 | - | -37 | -59 |
| 100 | 50.0 | 3.1 | 34.9 | 15.07 | 3.75 | 55.6 | - | -35 | -57 |
| 50 | 47.0 | 1.9 | 32.7 | 14.29 | 2.47 | 42.2 | - | -34 | -56 |
| 5 | 37.0 | 0.6 | 27.8 | 9.21 | 0.71 | 14.6 | - | -32 | -46 |

Table 1. Performance of Class E amplifier with MRF151A MOSFET



Figure 9. Performance of Class E amplifier with MRF151A MOSFET

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It would be possible to measure the current waveform as well, however, this is a challenging task as it requires measuring a very small voltage across a current sensing resistor in the presence of large EM interference. From Figure 4, the current swing expected in the drain circuit is about 30 A.

### CONCLUSION

A class E power amplifier operating at 81.36 MHz has been designed and built using MACOM MRF151A power MOSFET. Using a 48V power supply, the amplifier yielded 300 watts of output power with better than 82% efficiency and approximately 11dB gain. At 250 watts of output power, better than 78% efficiency with more than 14dB gain were obtained. At 300 watts, second harmonic levels were –39dBc and third harmonic levels were –57dBc.



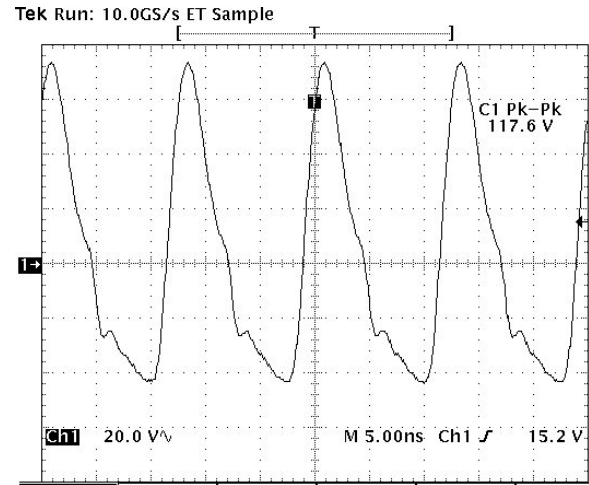Figure 10. Drain voltage at Pout = 300 watt

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[1]     H.Krauss, C. Bostian, F. Raab, *Solid State Radio Engineering*, John Wiley and Sons, 1980.
[2]     A. Grebennikov, N. O. Sokal, *Switchmode RF Power Amplifiers*, Elsevier, 2007.
[3]     G. Hiller, *Designing With PIN Diodes*, MACOM Application Note AG312.

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