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APT9903
By: Richard Frey, P.E.

APPLICATION NOTE

500W, CLASS E 27.12 MHz AMPLIFIER USING A SINGLE PLASTIC MOSFET

500W, Class E 27.12 MHz Amplifier Using A Single Plastic MOSFET

Richard Frey, P.E.
Advanced Power Technology, Inc.
Bend, Oregon 97702 USA

ABSTRACT

In this paper, we report on the design and evolution of a 500W, 27 MHz Class E amplifier. It doubles the operating frequency of previous high efficiency amplifiers using MOSFET transistors in the TO-247 package. Device criteria, circuit design, and amplifier performance characteristics are presented and compared to a HEPA computer model.

INTRODUCTION

As the semiconductor industry moves to larger size wafers to raise its productivity, they need more control of the processing. This translates into the need to produce a “harder” and more uniform plasma in vapor deposition and etching operations that rely on RF plasma. Typical operation is at 13.56 MHz but 27.12 MHz produces better results and is gaining increased popularity.

One of the challenges facing designers is finding devices suitable for service at the higher frequency. Around 1990, plasma equipment designers discovered that some of the inexpensive plastic high voltage MOSFETs they used in their switchmode power supplies were capable of operating in high efficiency Class E service at 13.56 MHz. Since the switchmode devices operate at high voltage and cost much less than the alternative purpose-built RF parts, acceptance was almost immediate.

Purpose-built RF devices operate on supply voltages below 50 Vdc. Suitable switchmode devices with drain breakdown voltage of 1 kV can run on supply voltages up to 300 Vdc. They also demonstrated system level benefits operating at higher voltage. Power Combining and matching are easier since the drain impedance is higher. Lower RF current is less stress on the series elements and enables the power supply design to be more efficient, smaller and lighter.

This RF application challenges most standard switchmode devices due to their packaging and die layout. The drain of the MOSFET is connected to metal back heat spreader, used for heat sinking the device. This requires either an insulator between the package heat spreader and the heat sink or grounding the drain and changing the circuit topology to accommodate it. Either method adds assembly cost of the PA and increases the potential for failures due to incorrect installation not to mention the poor thermal transfer characteristics of the insulator.

The package construction results in high source inductance, limiting the frequency response of these devices. In some cases, the circuitous gate metallization layout caused gate signal propagation delay, limiting the frequency response and reducing the effective power dissipation of the device.

Raising the bar to 27 MHz reduces the number of suitable switchmode parts. This is primarily due to resistive losses associated with the polysilicon gate structure in the closed cell geometry used in most switchmode devices. Input capacitance is essentially fixed by the device's power rating. Doubling the operating frequency quadruples the gate dissipation. If the ESR of the gate capacitor is large, it cannot carry the RF current required to drive the device.

The use of metal gate conductors dramatically reduces gate ESR. It is not unusual to reduce the gate resistance by a factor of 100 -- from 4 to 0.04 ohms -- on devices of equal power rating. This complicates RF matching to the gate, but it is now rugged enough to operate reliably.

At 13 MHz, the device C_{OSS} is combined with an external capacitor to obtain the required shunt output capacitance needed for proper class E operation [1]. At 27 MHz, the C_{OSS} is typically larger than that required for optimum Class E service. This compromises optimum Class E efficiency and output power capability. However, this would be a design consideration for any RF device, not just switchmode MOSFETs.

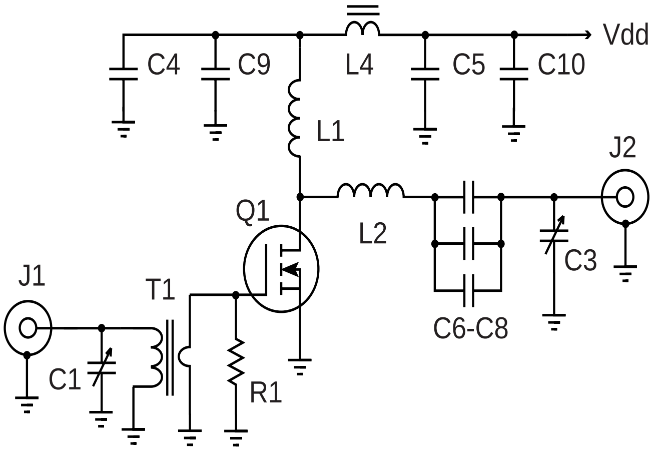

Figure 1: 27 MHz Class E Amplifier Schematic

High voltage MOSFETs are now available that combine the best practices from the RF world with the economy of the switchmode devices and packaging. They are available in mirror image pairs and the heat spreader of the plastic TO-247 package is connected to the source. They operate up to 300V V_{dd}, at frequencies up to 100 MHz.

AMPLIFIER DESIGN

The device used for this amplifier is an APT ARF448A. It has a BV of 450V and $R_{\theta JC}$ of 0.55°C/W. The class C gain is more than 25dB at 27 MHz. C_{OSS} is 125 pF at V_{dd}=125V. $R_{D(ON)}$ is 0.4Ω. These data sheet parameters were entered in the HEPA [1]

```
*    PSPICE MODEL RF N-CHANNEL POWER
     MOSFET
*    ARF448A/B           27 July 1998
**                          G D S
*    .SUBCKT ARF448      6  4  1
CISS      3  5  1450P
CRSS      5  2  65P
LG   7 6  4  6N
M 8 5 3 3 125-050M L=2U W=1.4; DGSB LEVEL 1
J1  8  3  2  125-050J
D  3  2  125-050D
LS  1  3  2  3N
REGATE  7  5  .29
LD  4  2  4  5N
.MODEL 125-050M NMOS (VTO=3.4 KP=14u
          Lambda=1m Gamma=.2 RD=130m RS=13m)
.MODEL 125-050J  NJF (VTO=-25.5 BETA=.01
          Lambda=.5)
.MODEL 125-050D D (BV=550 RS=230M CJO=422P
          VJ=670M  M=330M)
.ENDS
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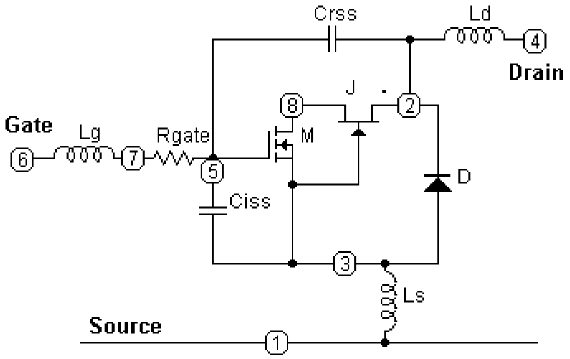

Figure 2. SPICE model for ARF448 MOSFET

C1,C3	75-380 pF mica trimmer, ARCO 465
C4-C8	.01 uF 1 kV disc ceramic
C9,C10	.1 uF 500V disc ceramic
L1	6 uH. 25t #24 ga.enam. 0.5" dia.
L2	210 nH. 4t #8 ga. .75" id, 1" long
L4	2t #20 PTFE on .5" ferrite bead μ=850
Q1	APT ARF448A
R1	25Ω 5W non-inductive
T1	Pri: 4t #20 PTFE, Sec: 1t brass tube on 2 hole balun bead Fair-Rite #2843010302 μ=850

Table 1: 27 MHz Class E Amplifier Part Values

Class E design program and it generated starting design values for the circuit. The circuit is common to most Class E amplifiers. [2] See Figure 1. In Class E amplifiers there is a capacitor shunted across the drain to source. There is none used here because the output capacitance of the device is slightly larger than the optimum value for that component. This defines the upper frequency limit for efficient Class E operation of a particular device. The 3Ω ESR of C_{OSS} is one of the primary loss mechanisms in the circuit. However, C_{OSS} exhibits little of the parasitic inductance that caused VHF ringing in the circuit described by Davis. The output circuit values were adjusted slightly for maximum efficiency at an output power of 490 W but basically, it worked "as advertised" right off the bat.

While this description of the output circuit sounds straightforward, it was not reduced to practice very easily. The problem was providing enough rf voltage to the gate to drive the drain into saturation. The input impedance of the gate at 27 MHz is 0.1 -j2.7. C_{iss} is 1400 pF. If 10V of peak gate drive is needed, a reasonable match between the drive source and gate is required. There is approximately 9 nH of parasitic gate inductance. This is enough inductance to make it impossible to observe the actual voltage applied to "the gate" with an oscilloscope.

SPICE was used to model the gate drive circuit. A SPICE macro model for the device is shown in Figure 2. The goal was to design a network to match the gate impedance sufficiently to permit sine wave drive as in reference [2]. A circuit using a 4:1 transformer and an L-network was designed using winSmith. [3] This worked, but the circuit was not stable. The parallel equivalent of the gate is 2200 pF in parallel with 210 ohms. A 25 ohm 5W padding resistance was placed across the gate. This raises the effective input impedance to 0.38 -j2.6, lowers the network Q, and makes it much easier to match and drive properly.

The input transformer has been used before [4]. It is made from a two hole ferrite "binocular" bead balun. The secondary winding consists of two 7/8" pieces of 3/16" diameter brass tubing connected with copper shim stock.

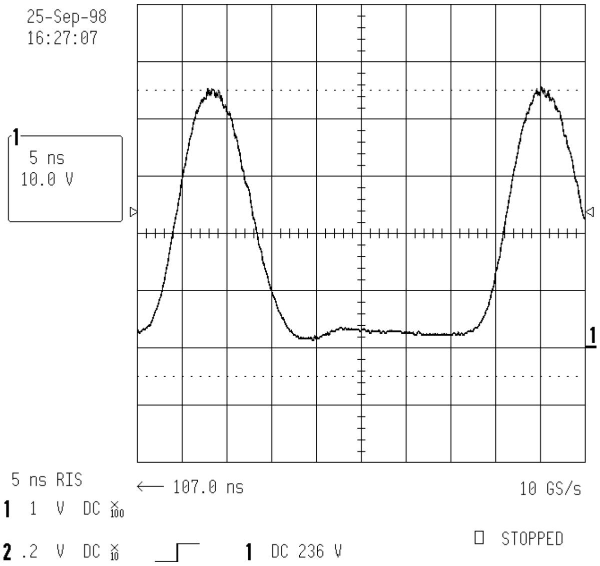

Figure 4: Drain voltage waveform of 500W Class E amplifier

The four turn primary is wound inside the tubes for maximum coupling and minimum leakage which measured 19 nH referenced to the secondary side.

High quality passive components are required in the output network. Most important of these is L2. It was wound from #8 ga. bare copper wire, its Q measured 375, and the calculated dissipation is 4.2 W. This coil is not capable of continuous duty operation unless it is attached with high temperature solder and/or separate mechanical termination support is used. It was necessary to parallel three 10 nF Z5U ceramic coupling capacitors to carry the rf current.

COMPUTER SIMULATION

A simple SPICE model of the amplifier, similar to that used by Davis in [2], was compared with HEPA results and the measured results of the operating amplifier. Overall, the agreement was good, especially between HEPA and the ideal circuit SPICE model. Attempts to insert the SPICE macro model of the transistor into the amplifier was not successful. A much more sophisticated model is needed to adequately simulate the effects of the nonlinear capacitances of the MOSFET. However, the SPICE model was very useful for understanding the gate drive problem mentioned earlier.

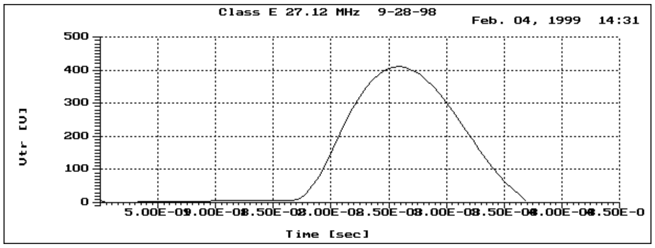

Figure 3. Drain voltage waveform from HEPA

HEPA assumes that the device is being driven into saturation, the only input parameter it considers is input drive power -- used for the overall efficiency calculation. The gate drive was the biggest problem in the design because a large RF-capable power MOSFET has a very small input impedance.

One of the best tests for reliability of an amplifier is mismatch load testing. Called "load pull" in some circles, it is a test which describes what the amplifier does when operating into a load other than 50 ohms. The ARF448 has about 175 watts of available dissipation in the test amplifier with its air cooled heat sink. The performance at eight points around a 2:1 VSWR mismatch circle was calculated using HEPA. Then the same test was run on the amplifier itself with the drive duty cycle reduced to 50%. The various loads were obtained using a variable L-network and adjusting each load impedance with a vector impedance meter. The differences between the calculated and measured results were very small.

The measured load pull results are shown in Figure 5. The most obvious conclusion is that there is a region in the high impedance inductive quadrant that should be avoided. Protection would be required to keep the transistor within its safe operating area if operated in this region.

Without protection, the output power soared to 750 W and the drain current was almost twice normal. The efficiency stayed quite constant, never losing more than 11% at any load angle. Some form of current foldback would be needed in the power supply of a practicable amplifier.

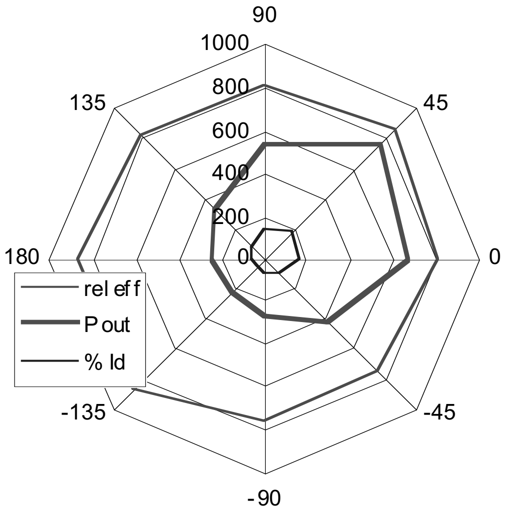

Figure 5: Load pull result for 500 W nominal output at 2:1 VSWR. Efficiency is displayed as % x 10.

Class E amplifiers are used commercially in RF sources of plasma generators and as exciters for CO_2 lasers. In plasma generator applications it is known that the load varies over a particular range. The feed line length is chosen so the load presented to the amplifier does not enter the +45° quadrant. Other plasma generators have some form of active matching network between the amplifier and the load to handle the load pull issue. The drive or the drain voltage is reduced until a reasonable match is achieved. In CO_2 lasers, the drive is pulse width modulated and under high VSWR conditions, the pulse width is reduced until the load stabilizes.

EXPERIMENTAL RESULTS

The efficiency of the Class E amplifier is 13% better with 30% more output power than was obtained from an initial Class C amplifier designed by classical methods using the same components. [5] The schematic did not change, only the values of L2 and C3 are different.

The performance of the amplifier is summarized in the table below along with the calculated values from HEPA. The results are fairly close.

	Measured	HEPA	Units
RF Output Power	490	494.93	W
Drive Power	10	10	W
Drain Voltage	125	125	V
Drain Current	4.72	4.47	A
Peak Drain Voltage	430	410.25	V
Peak Drain Current		27.27	A
Loss in L2		4.2	W
Second Harmonic	-24		dB
Third Harmonic	-57		dB
Drain Efficiency	83	88.45	%

The drain voltage waveform is shown in Figure 4 and the gate waveform in Figure 6. The peak drain voltage measures 430V. The approximately 10 nH of parasitic inductance between the "drain" and the scope probe prohibits a true measurement. This is a problem similar to that already mentioned for the gate. It is as high as prudent design will allow. The achieved efficiency is 5.5% below the model. This could be due to the C_{OSS} being higher than the data sheet value, or its ESR being higher than 3 ohms or the switching times being longer than the values used, Clearly, the device is operating somewhere past the point where C_{OSS} provides the right value for optimum Class E operation. There are tradeoffs to be made between efficiency and maximum output power. The goal was 500W. 83% was the highest efficiency obtainable.

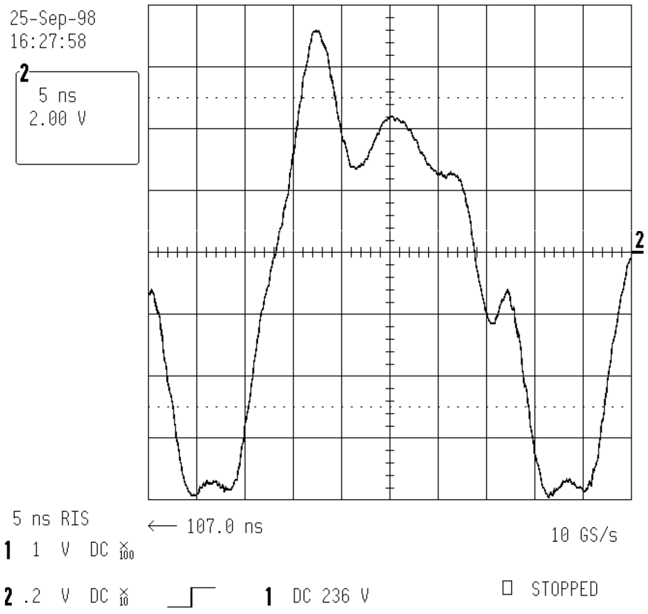

Figure 6. Measured gate voltage waveform at Po=490W

SUMMARY

This article has presented the design of a 27 MHz Class E amplifier using a high voltage RF MOSFET. The initial circuit values were obtained using HEPA, a commercial Class E design program. 27 MHz was chosen because it represents a frequency above that deemed optimum for the parameters of the device. A comparison of the measured and calculated performance is presented along with several practical design issues and application caveats.

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ADVANCED POWER TECHNOLOGY®

405 S.W. Columbia Street
Bend, Oregon 97702 USA
Phone: (541) 382-8028
Fax: (541) 388-0364

Parc Cadera Nord - Av. Kennedy BAT B4
33700 Merignac, France
Phone: 33-556 34 34 71
Fax: 33-556 47 97 61

Printed -June 1999