Efficient X-band Switched-Mode Microwave Power Amplifiers

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Abstract

The problem addressed in this paper is reduction of heat dissipation and improvement of dc power usage by increasing the power added efficiency (PAE) and drain efficiency (η) of X-band power amplifiers (PAs) to above 60% and 70%, respectively. Adaptive PAs with dynamic biasing and impedance tuning are also discussed.

INTRODUCTION

Saturated class-A amplifiers can be linear, but have limited efficiencies, usually below 20%. Class-AB PAs reach 50-% efficiencies without sacrificing maximum output power. Class-C PAs can operate at very high efficiencies by sacrificing output power. The efficiency of a PA can be maximized by operating the devices in switched mode [12]. Class-E switched mode of operation has recently gained a lot of attention at different frequency ranges. Switched mode amplifier operation was developed by several Russian authors, e.g. [1,4] and Sokal [14] independently for HF amplifiers, and extended to microwave frequencies in a transmission-line circuit in 1995 [6]. In this class of operation, the transistor is operated as a switch in such a way that the current and voltage time waveforms overlap minimally during a period. The load for this mode of operation needs to be a particular complex impedance at the design frequency, and an open circuit at all harmonics [13], resulting in theoretically 100% efficient amplification. The optimal class-E load impedance [7,13] for the transistor with the given output capacitance C_{OUT} and the operating (switching) frequency f_s can be calculated as

$$Z_E = \frac{0.28}{C_{OUT}\omega_s} e^{j49^\circ} .$$

However, because the microwave transistor has finite resistance during the ON state, and finite switching time, ideal 100% efficiency cannot be achieved. In this case, class-E waveshaping minimizes voltage and current overlapping, providing minimal losses in the active device, compared to linear classes of operation (A, AB, etc.).

The highest frequency at which class-E mode of operation was demonstrated is 10GHz, both with MESFET [3,7,9,16] and HBT devices [8,10,11,15]. Properties of X-band switched-mode PAs found in the literature are summarized in Table 1. The PA in the third column is different than the others in that the load at the output is a non-resonant active antenna which simultaneously matches the fundamental and harmonics. The antenna determines the bandwidth.

It is of interest to find how much current is drawn for a given supply voltage or vice-versa. Taking the time average of the switch voltage over the period for a 50-% duty cycle class-E mode results in a dc power given by $V_{CDC} = I_{DC}/(\pi\omega_s C_{OUT})$. This simple result has important implications for a practical microwave class-E circuit. At a specified frequency, a device with an output capacitance C_{OUT} operating at a supply voltage V_{DC}, must be able to handle the required maximum current. Due to this transistor limitation, approximate maximum frequency of class-E operation can be found for a given device as

$$f_E = \frac{I_{\max}}{56.5 C_{OUT} V_{DC}} .$$

For example, the Alpha general purpose MESFET AFM04P2 for a voltage of 4.2V has the optimal switched-mode frequency equal to 5.5GHz. Above this frequency, this device cannot be used for an ideal class-E circuit, although an approximation to class-E operation may be obtained at higher frequencies with some degradation in maximum achievable efficiency, as in [9]. The bandwidths quoted in the last row are all defined slightly differently and are quoted as in the referenced papers. Note that the large device in the second column has the smallest bandwidth and gain due to the very low input impedance.

Table 1. Summary of demonstrated X-band switched-mode PAs.

f (GHz)	8.4	8.35	10	10	10
device /class	FLK052 class F	FLK202 class E	AFM04P2 class E		DHBT class E*
ref	[3]	[3]	[16]	[9]	[10]
PAE	60	48	62	56	65
Drain	72	69	74	68	72
Pout	685	1700	100	125	125
Gain	7.4	5.3	10	7	10
Bias	7V	7V	4V		4V
f_E (GHz)	1.3	/	5.5		5.9/11
BW*	8%	1%	4%	15%	20%

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In [15], an alternative mode of class-E operation with modified harmonic terminations is presented. In a standard class-E design, the second harmonic is presented with an open circuit, while the alternative harmonic terminations from 9-11GHz are shown in Figure 1. This harmonic termination result in lower peak current, allowing for a higher frequency at which the transistor can still operate in class-E mode. For a HBT device with an output capacitance around 1.5pF, the optimal standard class-E frequency is 6GHz. Using the alternative harmonic termination, it increases to 11GHz [15], with little penalty in output power.

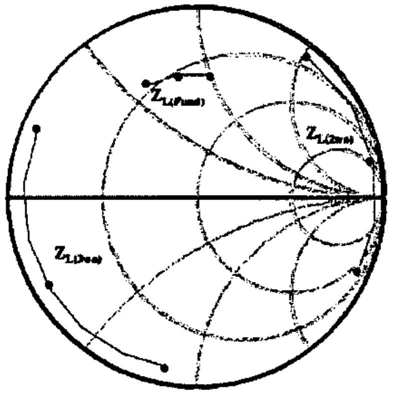

Figure 1. Fundamental and 2nd and 3rd harmonic terminations for a HBT alternative class-E PA from 9 to 11GHz.

10-GHz MESFET AND HBT POWER AMPLIFIERS WITH OVER 60% PAE

Class-E PAs designed around a commercial GaAs MESFET device [9] and an InP HBT Northrop-Grumman device [11] are compared. The relevant parameters of the two devices are similar: the maximum output power is around 125mW, the output capacitance is around 1.5pF, the dc bias around 4V, and the optimal class-E frequency 6GHz. The MESFET PA is a hybrid circuit, while the DHBT PA is monolithically integrated.

The measured data for the 10-GHz MESFET PA is shown in Figure 2. The circuit is fabricated on a Rogers$^{@}$ TMM6 substrate ($\varepsilon_r = 6$; thickness = 0.635μm), Fig.2. The discrete active device and RF decoupling capacitor are mounted on a machined copper base connected to the ground plane with conductive epoxy. The device pads are wire-bonded to the microstrip circuit, resulting in additional parasitics and loss. Figure 3 shows the measured frequency response, indicating a 15% bandwidth for a drain efficiency over 60%.

It is interesting to investigate the repeatability of the hybrid amplifier, since parasitics and device-device variations will have a large effect for switched-mode operation. Over 20 PAs were fabricated using the same technique and then characterized, yielding a spread in characteristics as presented in Table 2.

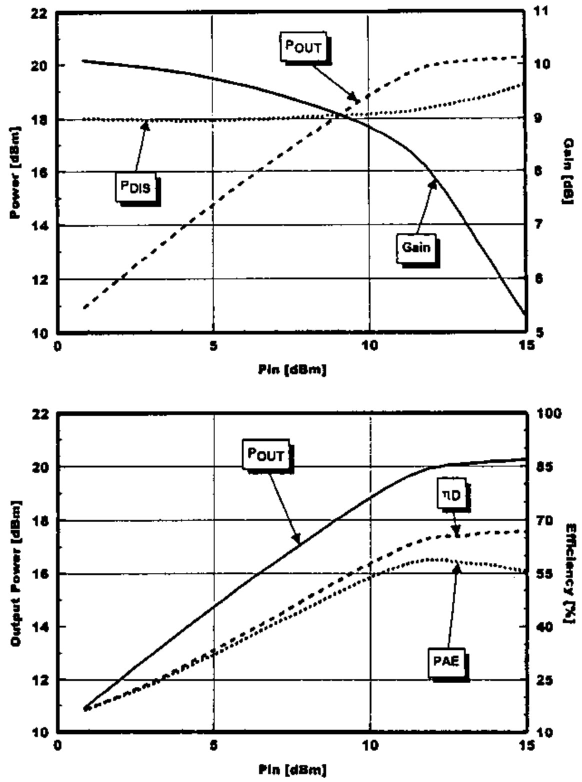

Figure 2. (a) Measured efficiency and power for the class-E hybrid MESFET PA. (b) Measured efficiency and power for the class-E hybrid MESFET

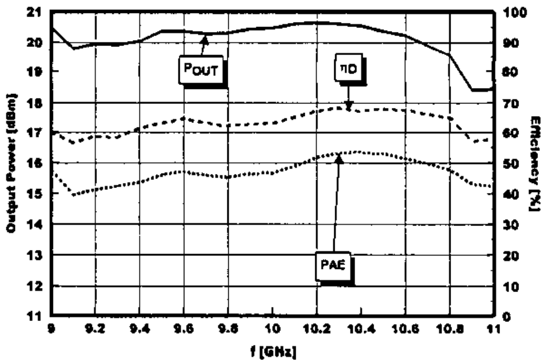

Figure 3. Measured frequency response of the class-E hybrid MESFET PA.

Table 2. Summary of average performance for over 20 hybrid PAs using a commercial MESFET.

Pout [dBm]	Gain [dB]	η_D [%]	PAE [%]	ρ [dB]
20-20.5	7-7.5	60-71	48-57	<-13

Pout – output power, η_D – drain efficiency, PAE – power added efficiency, ρ - large-signal input reflection coefficient.

The monolithic class-E DHBT PA was fabricated with the Northrop-Grumman InP process, which has many attractive properties that result in high-efficiency performance [8,10]. The wider bandgap InP collector forms the base-collector heterojunction, which results in a high breakdown voltage (BVceo>18V). The double heterojunction with the InP collector/subcollector reduces the offset voltage to less than 50mV and knee voltage to less than 1V at a 53kA/cm^2 current density. Using a 1.5μm x 30μm x 4 finger device, monolithic circuits in standard and alternative class-E mode were analyzed using harmonic balance simulations, and the comparison with measurement is shown in Figure 4, which also demonstrates PAE improvement when harmonics are appropriately terminated. This example is an excellent illustration of the importance of 2nd and 3rd harmonic terminations for achieving ultra high efficiency at microwave frequencies.

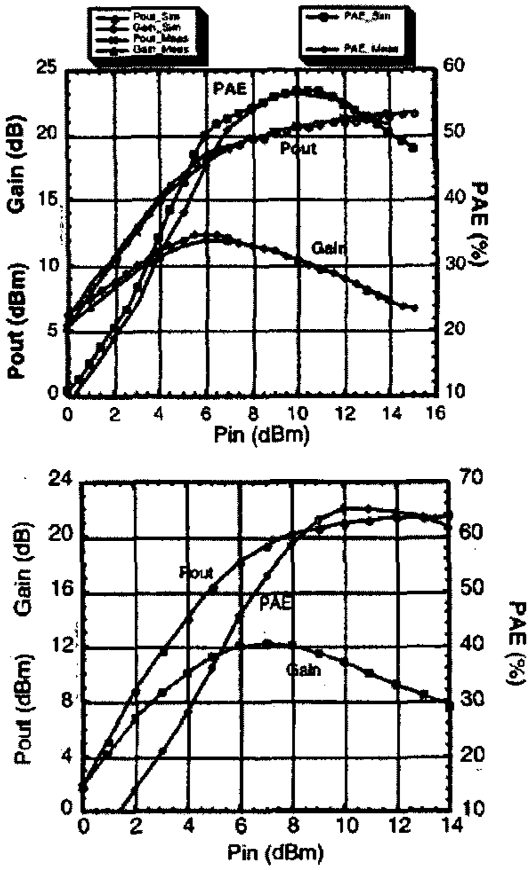

Figure 4. Measured performance of monolithic class-E DHBT PA with open-circuit harmonic termination (top) and modified harmonic termination (bottom) [10].

In [8] the same DHBT device was used in a hybrid circuit and a very high efficiency of 71% PAE was achieved with a 2-finger (two times smaller) device at 54mW.

ADAPTIVE CLASS-E 10-GHZ AMPLIFIERS

Dynamic Biasing for Power Control

High-efficiency power amplifiers are designed to operate in the saturated regime. As a consequence, when a range of output power levels is required, the efficiency suffers at the lower power levels. The idea of dynamic control of the bias supply is brought up to increase the efficiency for low output power levels by optimally varying the bias supply. For example, in [5] a dynamic control circuit using a boost DC-DC converter demonstrated an increase in average efficiency by a factor 1.64 (from 3.89% to 6.38%) for a 1-MHz bandwidth CDMA signal input to a 950-MHz HBT class-A power amplifier.

The hybrid MESFET PA presented in the previous section was characterized w.r.t. drain bias current and voltage over a range of output power levels, and this information provides the reference signal for the design of the dynamic power control feedback loop shown in Figure 5. To sense the output power, a 20-dB coupled line coupler and a single diode detector follow the output PA matching circuit and provide the signal V_{sense}. In the feedback loop, this signal is compared with a reference V_{ref}. The loop is closed through the DC-DC converter that adjusts the drain bias to the PA such that the measured output power signal matches the command power signal.

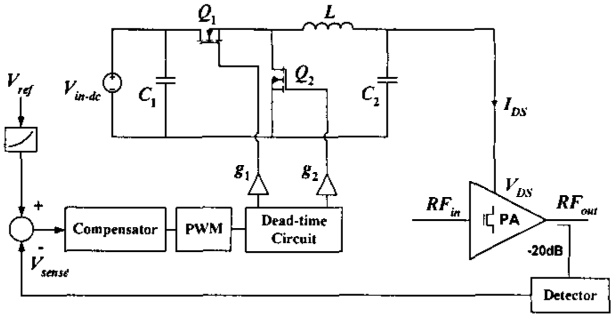

Figure 5. Block diagram of dynamic bias control loop for 10-GHz hybrid MESFET class-E PA.

Changes in the output power induce changes in the duty cycle of the converter and hence the drain bias and the output power is regulated to the specified reference value. The efficiency of the PA with the closed-loop power control and with constant input power of 12dBm is measured and is shown in Figure 6 over the output power range of 15dBm to 20dBm. The gate bias voltage is kept at –1V. The curve with the lowest overall efficiency is measured for constant drain bias while the output power is varied. The highest efficiency curve, with an average drain efficiency of 62.3% is measured for the PA alone where the drain bias is varied manually. The solid line with an average efficiency of 60.4% is obtained with the loop closed and the bias varying adaptively. The loss due to the connectors and coupler is calibrated out in this case. The average efficiency over the power range is increased by a factor of 1.46 when efficient dynamic biasing is used in an efficient feedback loop.

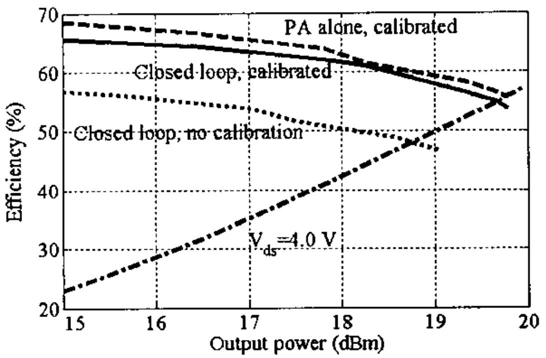

Figure 6. Measured efficiency for the PA with constant drain bias (dash-dot line), the PA with manual drain bias control (dashed line), and the entire closed loop system (solid and dotted lines).

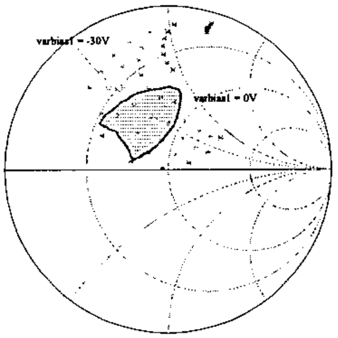

Figure 7. Simulated range of dual-MEMS varactor tuner when bias is varied from 0 to 30V. The shaded are shows the measured range of class-E impedances due to device and parasitic variations.

Tuning for Efficiency Optimization

Another type of adaptation can be accomplished by providing adaptive tuning of the input and output matching circuits. In [9] it is shown that the load impedance phase in a class-E PA has a large effect on the efficiency and output power. Table 2 conveys in part the same message – the variations in parasitics due to hybrid integration and the variation in output capacitance of the different discrete devices produces a desired range of output impedances, Figure 7. A tuner is designed to cover this range and in the process of being implemented using MEMS varactors with a linear tuning range from 0.5-1.5pF [2]. The MEMS varactor is shown in Figure 8a, and the micro-machined 15-GHz 15-nH resonant frequency air inductor used for the self-assessment circuit and the bias lines for the PA in Figure 8b. The tuner results will be presented at the conference. In addition, a number of applications for class-E PAs will be discussed.

ACKNOWLEDGMENTS

The work done by the authors presented in this paper was funded by Wright Paterson Air Force Base, a DARPA IRFFE contract and an NSF ITR project. We thank Prof. Maksimovic at the Univ. of Colorado for insight and help in the dynamic biasing circuit.

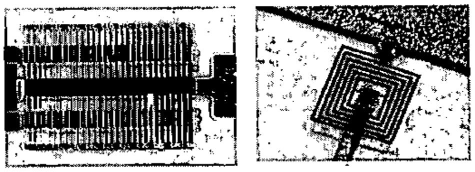

Figure 8. Photograph of MEMS varactor used in tuner (top) and air micromashined inductor used for the bias lines and self-assessment circuit (bottom).

REFERENCES

[1] A. D. Artym, "Switching mode of high frequency power amplifiers," *Radiotekhnika*, vol. 24, June 1969, (In Russian).

[2] P. Bell, N. Hoivik, V. Bright, Z. Popovic, "A Frequency Tunable Half-Wave Resonator using a MEMS Variable Capacitor," *35th International Symposium on Microelectronics Digest*, Denver, CO, Sept 2002

[3] E. W. Bryerton *et al.*, "Efficiency of chip-level versus external power combining," *IEEE Trans. MTT*, vol. 47, pp. 1482–1485, Aug. 1999.

[4] A. Grebennikov, "Class E high efficiency power amplifiers: historical aspects and future prospects," *Applied Microwave and Wireless*, pp. 64–71, July 2002.

[5] G. Hanington, P. Chen, P. Asbeck and L. Larson, "High-efficiency power amplifier using dynamic power-supply voltage for CDMA applications," *IEEE Trans. MTT*, vol. 47, pp. 1471-1476, Aug. 1999.

[6] T. B. Mader, Z. Popovic, "The transmission-line high efficiency class-E amplifier," *IEEE Microwave and Guided Wave Letters*, vol. 5, Issue: 9, pp. 290–292, Sept. 1995.

[7] T. B. Mader, *et al.*, "Switched-mode high-efficiency microwave power amplifiers in a freespace power-combiner array," *IEEE Trans. MTT*, vol. 46, Issue:10, Part: 1, pp. 1391–1389, Oct. 1998.

[8] W. Okamura, *et al.*, "An HBT PA module with 70% PAE for X-band applications," *2003 GOMAC conference digest*, Tampa, FL, Apr. 2003.

[9] S. Pajic, Z. Popovic, "An Efficient X-band 16-element Spatial Combiner of Switched-Mode PAs," *IEEE Trans. MTT*, vol.51, No.7, July 2003.R

[10] T. Quach, P. Watson, W. Okamura, E. Kaneshiro, A. Gutierrez-Aitken, T. Block, J. Eldredge, T. Block, T. Jenkins, L. Kehias, A. Oki, D. Sawdai, R. Welch, R. Worley, "Ultrahigh-Efficiency Power Amplifier for Space Radar Applications," IEEE Journal of Solid State Circuits, Vol. 37, No. 9, Sep 2002, pp. 1126-1134.

[11] T. Quach, P. Watson, T. Jenkins, L. Kehias, R. Welch, R. Worley, A. Gutierrez-Aitken, E. Kaneshiro, D. Sawdai, J. Eldredge, T. Block, W. Okamura, and A.K. Oki, "Broadband Class-E Power Amplifier for Space Radar Application," 2001 IEEE GaAs IC Symposium, pp. 209.

[12] F. Raab, P. Azbeck, S. Cripps, P. Kenington, Z. Popovic, N. Pothecary, J. F. Sevick, and N. O. Sokal, "Power amplifiers and transmitters for RF and microwave," *IEEE Trans. MTT*, pp. 1527–1530, Mar. 2002.

[13] F. H. Raab, "Idealized operation of the class-E tuned power amplifier," *IEEE Transactions on Circuits and Systems*, vol. CAS-24, pp. 725–735, Dec. 1977.

[14] 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. SSC-10, pp. 168–176, June 1975.

[15] P. Watson, R. Neidhard, L. Kehias, R. Welch, T. Quach, R. Worley, M. Pacer, R. Pappaterra, R. Schweller, and T. Jenkins "Ultra-High Efficiency Operation Based on an Alternative Class-E Mode," 2000 IEEE GaAs IC Symposium, pp. 53-56.

[16] M.D. Weiss, Z. Popovic, "A 10-GHz high-efficiency active antenna," *IEEE MTT-S International Microwave Symp. Digest*, pp. 663–666, 1999.