High-Efficiency Linear Amplification by Dynamic Load Modulation

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Abstract – **Load modulation is a new technique in which amplitude-modulated signals are produced with high efficiency by dynamic variation of the load impedance of the power amplifier. The prototype MOSFET PA operates in class E and produces a peak output of 19 W at 30 MHz with an efficiency of 66 percent. Load modulation is accomplished by a T network with a pair of high-voltage MOSFETs that act as a voltage-variable capacitor. The envelopes of a variety of different signals are successfully generated. For a Rayleigh (multi-carrier) envelope with a 10-dB peak-to-average ratio, the average efficiency is twice that achieved in linear operation of the same PA.**

I. INTRODUCTION

Linear RF power amplification is required in many modern applications that use shaped-pulse data modulation (e.g., square-root raised-cosine) or simultaneously transmit multiple carriers. The efficiency of conventional linear RF power amplifiers (PAs) varies with the signal amplitude (envelope), resulting in relatively low average efficiencies, especially when the peak-to-average ratio is high. For example, for a Rayleigh-envelope (multicarrier) signal with a 10-dB peak-to-average ratio, the average efficiencies of ideal class-A and -B PAs are only 5 and 28 percent, respectively [1]. Various techniques for high-efficiency linear amplification (e.g., Kahn, Chireix, and Doherty [2]) have been developed, but all are subject to limitations in bandwidth or the dynamic range over which the efficiency is improved.

An electronically tuned RF PA can be configured for frequency agility, adaptation to a variable load, or amplitude modulation [3],[4]. The basic configuration for producing an amplitude-modulated signal is shown in Figure 1. Time-varying bias or control signals are applied to the electronically tunable output filter, resulting in a time-varying drain-load impedance and in turn a time-varying signal amplitude. Phase information is passed through the driving signal to allow the synthesis of any bandlimited signal. High efficiency is achieved by judicious choice of the impedance locus used during modulation.

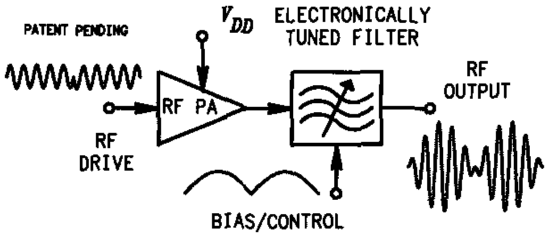

Figure 1. Load-modulated transmitter.

II. LOAD MODULATION

The load-modulation (LM) process varies the instantaneous load impedance presented to the RF PA along a locus. The impedance locus is selected to provide good dynamic range and good efficiency with a variable output network of reasonable complexity. The ideal locus depends upon the type of PA, and load-pull contours of output power and efficiency are useful in determining the preferred locus.

For ideal saturated PAs of classes A, B, C, D, and F [2], the output power is inversely proportional to the parallel component of load resistance and the efficiency decreases as the load becomes more reactive. The ideal locus is therefore a line from the nominal load (full output) along the pure-resistance line on the Smith chart (intermediate output) to infinite impedance (zero output).

The power and efficiency "load-pull" characteristics of an ideal class-E PA are shown in Figure 2 [5]. Output amplitude decreases as the impedance moves from the nominal load to the upper right. The efficiency remains 100 percent along a line oriented at 65° and decreases as the impedance moves away from this line. The ideal LM locus is therefore a line that runs from the nominal load at the center of the chart (full power) along the $\eta=1$ line (intermediate outputs) to the outer edge of the chart (zero output). Such a locus maintains a 100-percent efficiency at *all* output amplitudes.

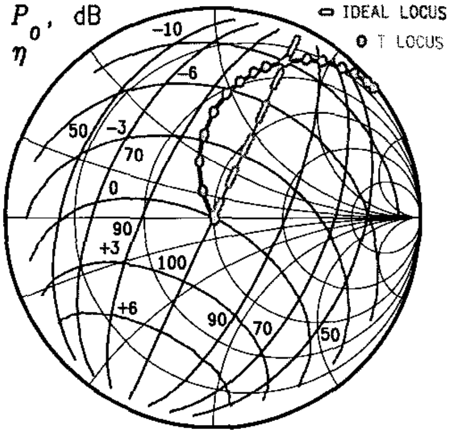

Figure 2. Load pull for ideal class E.

A T network (two inductors with a variable capacitor from center to ground) is a convenient output filter for use with switching-mode PAs. Its inductive input prevents harmonic currents and only single adjustment is required to change frequency [3]. For an ideal class-E PA, the impedance locus of a simple T network (Figure 2) maintains a 90-percent efficiency over a 12-dB dynamic range of amplitude (Figure 3). Even with a single variable element, load modulation has considerable potential to improve the efficiency at lower output amplitudes.

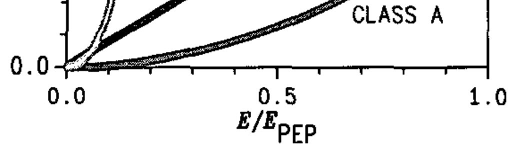

Figure 3. Efficiencies of ideal PAs.

The electronically variable element can be a semiconductor, ceramic capacitor, or MEMS device. Semiconductors offer good power-handling capability, can be retuned rapidly, and in this application offer the largest range of variation of capacitance (Figure 4). As the bias voltage is reduced, the capacitance increases and the RF voltage decreases. The the bias voltage can therefore be reduced all the way to zero, resulting in a large range of amplitude control.

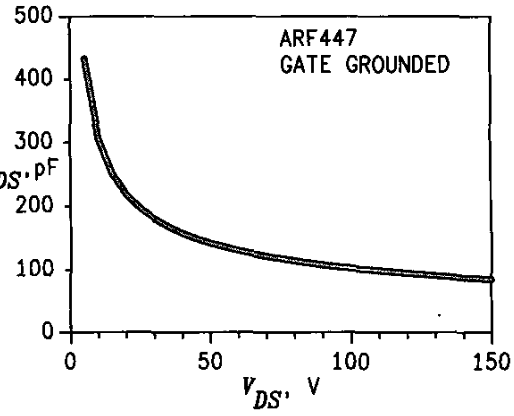

Figure 4. Semiconductor capacitance.

The envelope bandwidth must be at least twice the RF bandwidth, as in an EER system [2]. However, in an EER system real power must be modulated over this bandwidth. In the load-modulation technique, only the bias voltage on the tuning device must be varied.

III. PROTOTYPE AMPLIFIER

A simplified circuit of the prototype load-modulated PA is shown in Figure 5. The PA operates from 25 V and has a 12.5-Ω load. MOSFET Q1 is a Polyfet SQ741 with both sides connected in parallel. It has an on-state resistance of about 1 W and a breakdown voltage of 120 V. The SQ741 is biased on the verge of conduction and driven with a square wave to promote fast switching. Trimmer C1 adds about 30 pF to the 34 pF of the drain capacitance to achieve optimum class-E operation at the peak-envelope power (PEP) output at 30 MHz.

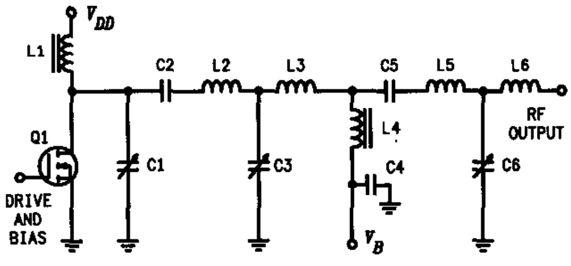

Figure 5. Simplified circuit of prototype.

The first T network (L2-C3-L3) provides load-impedance modulation as well as the inductive reactance for class-E operation and high impedance to the harmonics. It has input and output impedances of 12.5 Ω and Q = 3.5. Voltage-variable capacitor C3 is a parallel pair of APT ARF446/447 high-voltage MOSFETs with grounded gates. The roughly 200-pF capacitance required for PEP output (Figure 4) is achieved with a bias voltage of about 100 V. At zero bias, the capacitance increases to 5400 pF.

The second T network (L5-C6-L6) is fixed tuned. It transforms the 50-Ω load to the 12.5-Ω output of the first T network and attenuates the second harmonic produced in the voltage-variable capacitor C3.

The bias is supplied by Apex PA84 high-voltage op-amp and fed to C3 through a large inductor L4 and tuning inductor L3. In addition to C3, a total of 3000 pF due to the blocking and bypass capacitors C2, C4, and C5 must be charged and discharged during bias modulation. The bias system has a small-signal bandwidth of about 450 kHz, but is slew-rate limited by a maximum op-amp current of 40 mA.

IV. EXPERIMENTAL RESULTS

During the modulation process, the PA operates in suboptimum class E most of the time, resulting in peak drain voltages as high as $4V_{DD}$. The supply voltage is therefore set at 25 V to ensure safe operation. The PA produces a peak output of 19 W with 66-percent drain efficiency. The second harmonic is 50 dB below the fundamental at PEP output and all other harmonics are 60 dB or more below the signal.

The output voltage varies almost linearly with the tuning voltage V_B (Figure 6). At zero bias, the output drops to 15 mW, corresponding to a 41-dB dynamic range. The phase varies more or less steadily over a range of 83°. The AM nonlinearity and phase variation are easily removed by predistortion.

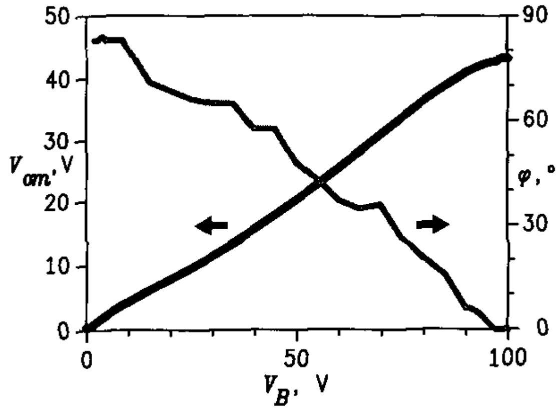

Figure 6. Variation of output with bias.

Signals with a variety of different envelopes (Figure 7) including AM, triangle, two-tone, ten-tone, and pulse are generated with good accuracy. The full modulation range is achievable at frequencies up to 50 kHz and pulses with rise times as short as 10 μs can be produced. At higher frequencies, the modulation range decreases with frequency because of the slew-rate limit of the bias op-amp.

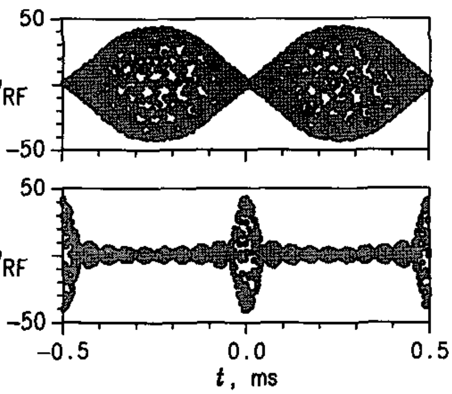

Figure 7. Example envelopes.

The efficiency at lower amplitudes (Figure 8) is significantly better than that of class-B linear amplification with the same efficiency at PEP (1.7 times at half-PEP output voltage). The measured average efficiencies are compared in Table 1 to those predicted for class B. Moderate improvements are observed for signals with lower peak-to-average ratios. However, for the 10-tone signal (10-dB peak-to-average ratio), the average efficiency is more than doubled.

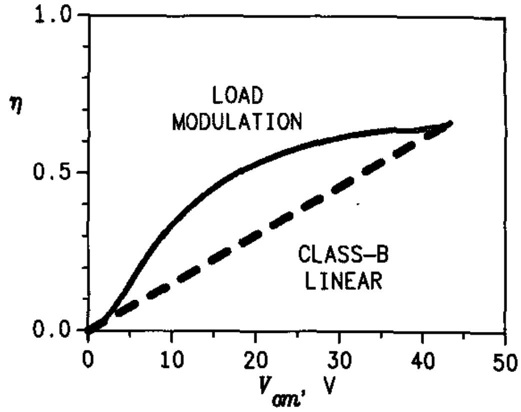

Figure 8. Instantaneous efficiency.

TABLE I
AVERAGE EFFICIENCIES

Signal	ξ, dB	η_B	η_{LM}	η_{LM}/η_B
CW	0	0.658	0.658	1.00
AM	4.3	0.492	0.617	1.25
Triangle	4.8	0.439	0.610	1.39
Two-Tone	3.0	0.517	0.634	1.23
Ten-Tone	10.0	0.235	0.492	2.10
Pulse	∞		0.600	

V. CONCLUSIONS

The capability of load modulation to produce high-efficiency linear power amplification has been demonstrated in a simple prototype amplifier with a single variable element. Further increases in the efficiency at low signal levels can be achieved by using an electronically tunable network with two or more variable elements. The modulation bandwidth can be increased by decreasing the blocking capacitances and by designing a bias modulator especially for this purpose. The load-modulated PA is therefore a promising candidate for applications such as base stations and satellite repeaters that require wideband, high-efficiency linear amplification.

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