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RF and Microwave Power Amplifier and Transmitter Technologies — *Part 5*

By Frederick H. Raab, Peter Asbeck, Steve Cripps, Peter B. Kenington, Zoya B. Popovich, Nick Pothecary, John F. Sevic and Nathan O. Sokal

Emerging techniques are examined in this final installment of our series on power amplifier technologies, providing notes on new modulation methods and improvements in linearity and efficiency

The ever-increasing demands for more bandwidth, coupled with requirements for both high linearity and high efficiency create ever-increasing challenges in the design of power amplifiers and transmitters. A single W-CDMA signal, for example, taxes the capabilities of a Kahn-technique transmitter with a conventional class-S modulator. More acute are the problems in base-station and satellite transmitters, where multiple carriers must be amplified simultaneously, resulting in peak-to-average ratios of 10 to 13 dB and bandwidths of 30 to 100 MHz.

A number of the previously discussed techniques can be applied to this problem, including the Kahn EER with class-G modulator or split-band modulator, Chireix outphasing, and Doherty. This section presents some emerging technologies that may be applied to wideband, high efficiency amplification in the near future.

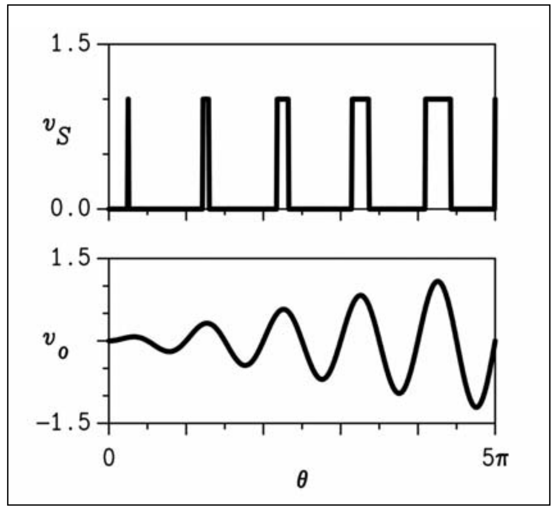

Figure 59 · RF pulse-width modulation.

RF Pulse-Width Modulation

Variation of the duty ratio (pulse width) of a class-D RF PA [112] produces an amplitude-modulated carrier (Figure 59). The output envelope is proportional to the sine of the pulse width, hence the pulse width is varied in proportion to the inverse sine of the desired envelope. This can be accomplished in DSP, or by comparison of the desired envelope to a full-wave rectified sinusoid. The pulse timing conveys signal phase information as in the Kahn and other techniques.

Radio-frequency pulse-width modulation (RF PWM) eliminates the series-pass losses associated with the class-S modulator in a Kahn-technique transmitter. More importantly, the spurious products associated with PWM are located in the vicinity of the harmonics of the carrier [113] and therefore easily removed. Consequently, RF PWM can accommodate a significant RF bandwidth with only a simple, low-loss output filter.

Ideally, the efficiency is 100 percent. In practice, switching losses are increased over those in a class-D PA with a 50:50 duty ratio because drain current is nonzero during switching.

This series of articles is an expanded version of the paper, "Power Amplifiers and Transmitters for RF and Microwave" by the same authors, which appeared in the the 50th anniversary issue of the *IEEE Transactions on Microwave Theory and Techniques*, March 2002. © 2002 IEEE. Reprinted with permission.

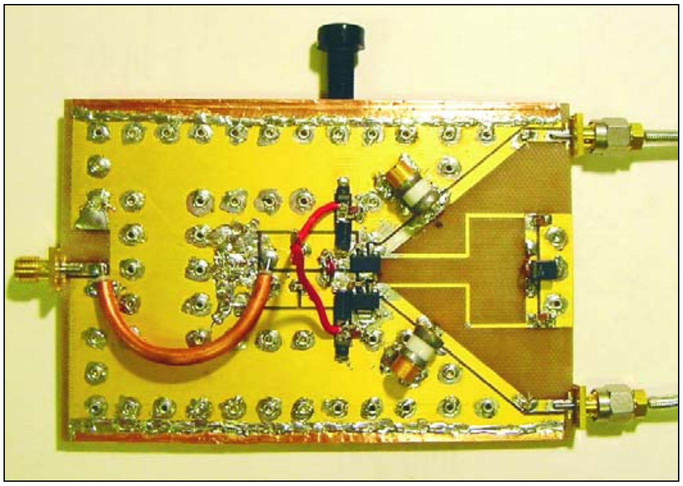

Figure 60 · Current-switching PA for 1 GHz (courtesy UCSD).

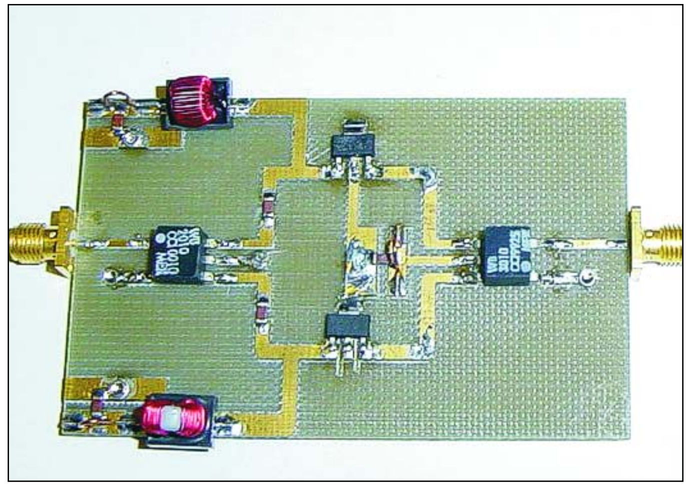

Figure 61 · Prototype class-D PA for delta-sigma modulation (courtesy UCSD).

Previous applications of RF PWM have been limited to LF and MF transmitters (e.g., GWEN [114]). However, the recent development of class-D PAs for UHF and microwave frequencies (Figure 60) offers some interesting possibilities.

Delta-Sigma Modulation

Delta-sigma modulation is an alternative technique for directly modulating the carrier produced by a class-D RF PA (Figure 61) [PA8],[PA9]. In contrast to the basically analog operation of RF PWM, delta-sigma modulation drives the class-D PA at a fixed clock rate (hence fixed pulse width) that is generally higher than the carrier frequency (Figure 62). The polarity of the drive is toggled as necessary to create the desired output envelope from the average of the cycles in the PA. Phase is again conveyed in pulse timing.

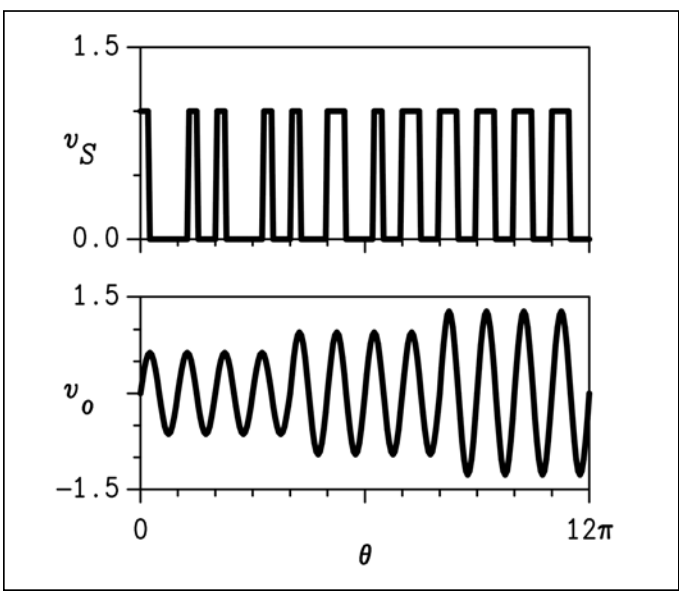

Figure 62 · Delta-sigma modulation.

The delta-sigma modulator employs an algorithm such as that shown in Figure 63. The signal is digitized by a quantizer (typically a single-bit comparator) whose output is subtracted from the input signal through a digital feedback loop, which acts as a band-pass filter. Basically, the output signal in the pass band is forced to track the desired input signal. The quantizing noise (associated with the averaging process necessary to obtain the desired instantaneous output amplitude) is forced outside of the pass band.

The degree of suppression of the quantization noise depends on the oversampling ratio; i.e., the ratio of the digital clock frequency to the RF bandwidth and is relatively independent of the RF center frequency. An example of the resultant spectrum for a single 900-MHz carrier and 3.6-GHz clock is shown in Figure 64. The quantization noise is reduced over a bandwidth of 50 MHz, which is sufficient for the entire cellular band. Out-of-band noise increases gradually and must be removed by a band-pass filter with sufficiently steep skirts.

As with RF PWM, the efficiency of a practical delta-sigma modulated class-D PA is reduced by switching losses associated with nonzero current at the times of switching. The narrow-band output filter may also introduce significant loss.

Carrier Pulse-Width Modulation

Carrier pulse-width modulation was first used in a UHF rescue radio at Cincinnati Electronics in the early 1970s. Basically, pulse-width modulation as in a class-S modulator gates the RF drive (hence RF drain current) on and off in bursts, as shown in Figure 65. The width of each burst is proportional to the instantaneous envelope of the

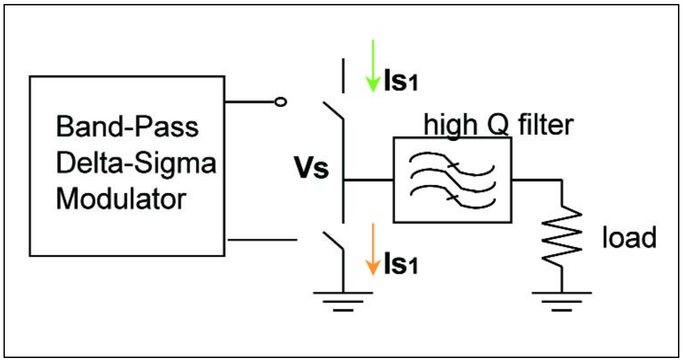

Figure 63 · Delta-sigma modulator.

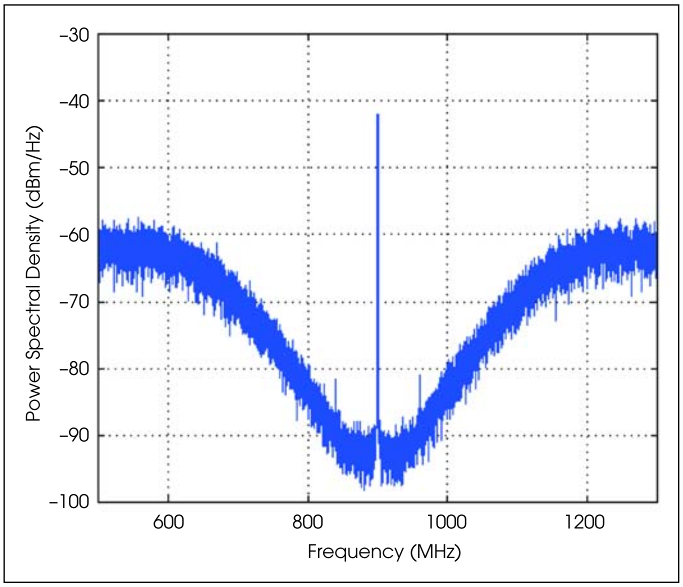

Figure 64 · Spectrum of delta-sigma modulation.

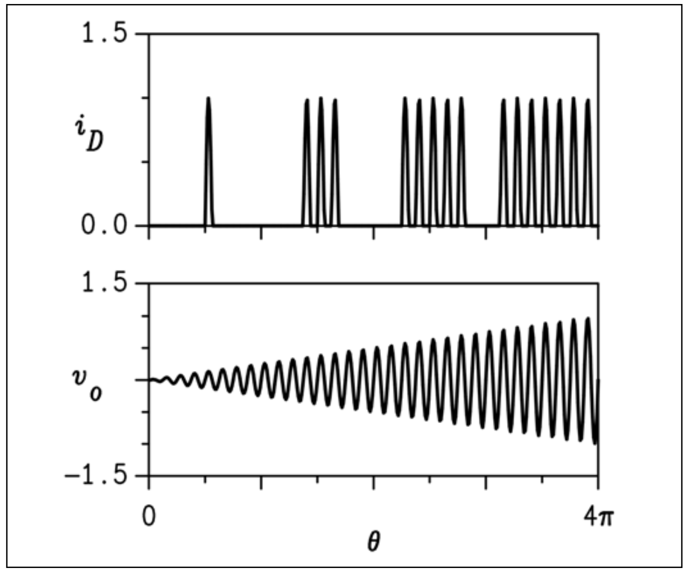

Figure 65 · Carrier pulse-width modulation.

desired output. The amplitude-modulated output signal is recovered by a band-pass filter that removes the sidebands associated with the PWM switching frequency. The PWM signal can be generated by a comparator as in a class-S modulator or by delta-sigma techniques.

As with RF PWM and delta-sigma modulation, the series-pass losses and bandwidth limitations of the high-level modulator are eliminated. The switching frequency in carrier PWM is not limited by capabilities of power-switching devices and can therefore easily be tens of MHz, allowing large RF bandwidths. A second advantage is that carrier PWM can be applied to almost any type of RF PA. A disadvantage is that a narrow-band output filter with steep skirts is required to remove the switching-frequency sidebands, and such filters tend to have losses of 1 to 2 dB at microwave frequencies. Nonetheless, the losses in the filter may be more than offset by the improvement in efficiency for signals with high peak-to-average ratios.

Power Recovery

A number of RF processes result in significant RF power dissipated in "dump" resistors. Examples include power reflected from a mismatched load and dumped by a circulator and the difference between two inputs of hybrid combiner dumped to the balancing resistor. The notion of recovering and reusing wasted RF power was originally applied to the harmonics (18 percent of the output power) of an untuned LF class-D PA [117].

More recently, power recovery has been applied to outphasing PAs with hybrid combiners [118, 119]. The instantaneous efficiency of such a system depends upon both the efficiency of the PA and that of the recovery system. Since the two PAs operate at full power regardless of the system output, inefficiency in the PA has a significant impact upon the system efficiency at the lower outputs. Nonetheless, a significant improvement over conventional hybrid-coupled outphasing is possible, and the PAs are presented with resistive loads that allow them to operate optimally. Typically, 50 percent of the dumped power can be recovered.

The power-recovery technology can also be used to implement miniature DC-DC converters. Basically, a high-efficiency RF-power amplifier (e.g., class-E) converts DC to RF and a high-efficiency rectifier circuit converts the RF to DC at the desired voltage. Implementation at microwave frequencies reduces the size of the tuning and filtering components, resulting in a very small physical size and high power density. In a prototype that operates at C band [120], the class-E PA uses a single MESFET to produce 120 mW with a PAE of 86 percent. The diode rectifier consists of a directional coupler with two Schottky

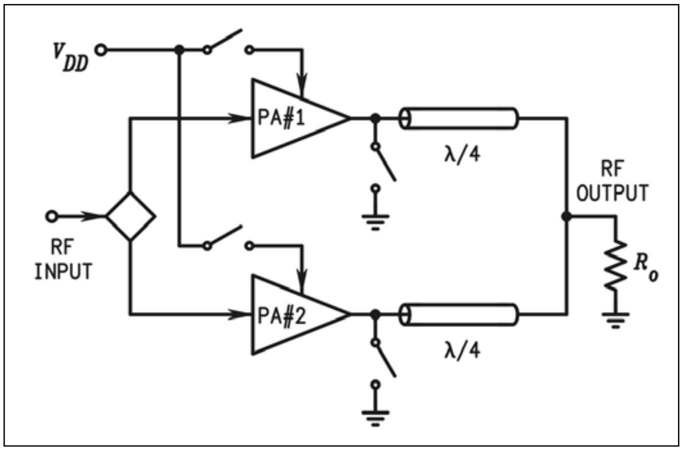

Figure 66 · Switched PAs with quarter-wavelength transmission line combiner.

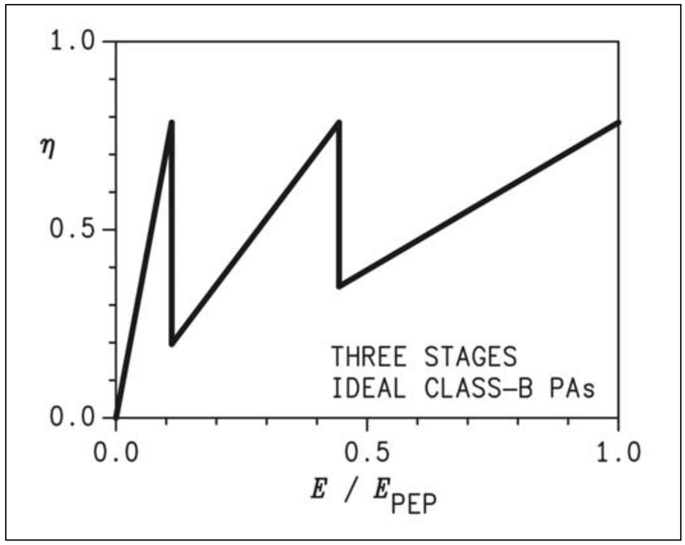

Figure 67 · Instantaneous efficiency of switched PAs.

diodes connected at the coupled and through ports and has a 98-percent conversion efficiency and an overall efficiency (including mismatch loss) of 83 percent. For a typical DC output of 3 V, the DC-DC conversion efficiency is 64 percent.

Switched PAs with Transmission-Line Combiners

RF-power amplifiers cannot simply be connected in series or parallel and switched on and off to make a transmitter module that adapts to variable peak envelope power. Attempting to do so generally produces either little effect or erratic variations in load impedance, sometimes leading to unstable operation and destruction of the transistors. Systems of microwave PAs that are toggled on and off are therefore connected through networks of quarter-wavelength transmission lines. The Doherty transmitter (discussed in part 4 of this series) is a classic example of this sort of technique.

An alternative topology (Figure 66) uses shorting switches and quarter-wavelength lines to to decouple off-state PAs [121, 122]. The inactive PA is powered-down (by switching off its supply voltage), after which its output is shorted to ground. The quarter-wavelength line produces an open circuit at the opposite end where the outputs from multiple PAs are connected together to the load. This technique may be more easy to implement (especially for multiple PAs) than Doherty because a short is more readily realized than an open.

If PA #1 is the only PA active, its load is simply R_0. If both #1 and #2 are active, the combination produces an effective load impedance of 2Ro at the load ends of the lines. Inversion of this impedance through the lines places loads of $R_0/2$ on the RF PAs. Consequently, the peak power output for two active PAs is four times that with a single PA. As in discrete envelope tracking, the RF PAs operate as linear amplifiers. The number of PAs that are active is the minimum needed to produce the current output power. The peak power is thus kept relatively close to the saturated output, eliminating most of the effects of operating in back-off. The efficiency can therefore reach PEP efficiency at a number of different output levels, as shown in Figure 67.

The advantage of this technique is the ease in design associated with relying on short circuits rather than open circuits to isolate the off-state PAs. A possible disadvantage is operating individual PAs from multiple load impedances without retuning and a limited number of power steps available (e.g., 9/9, 4/9, 1/9 for a three-PA system).

Electronic Tuning

The performance of virtually all power amplifiers is degraded by load- impedance mismatch. Mismatched loads not only reduce efficiency, but also create higher stresses on the transistors. Because high-efficiency PAs generally require a specific set of harmonic impedances, their use is often restricted to narrow-band applications with well-defined loads.

Electronic tuning allows frequency agility, matching of unknown and variable loads, and amplitude modulation. Components for electronic tuning include pin-diode switches, MEMS switches, MEMS capacitors, semiconductor capacitors, ceramic capacitors (e.g., BST), and bias-controlled inductors. To date, electronic tuning has been applied mainly to small-signal circuits such as voltage-controlled oscillators. Recently demonstrated, however, are two electronically tuned power amplifiers. One operates in class E, produces 20 W with an efficiency of 60 to 70 percent, and can be tuned from 19 to 32 MHz (1.7:1 range) through the use of voltage-variable capacitors

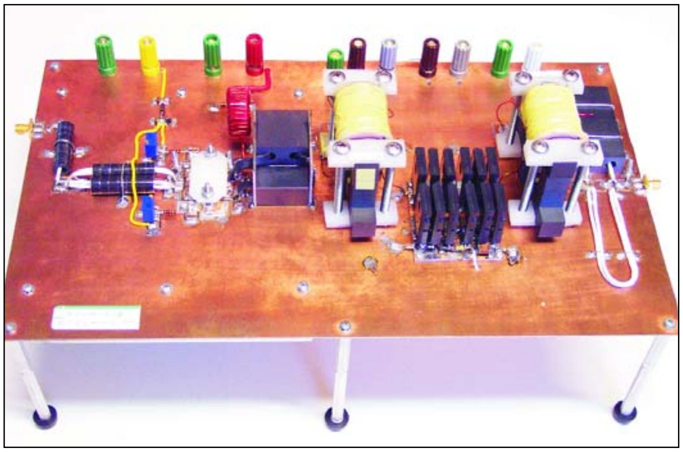

Figure 68 · Electronically tunable class-D PA (courtesy GMRR).

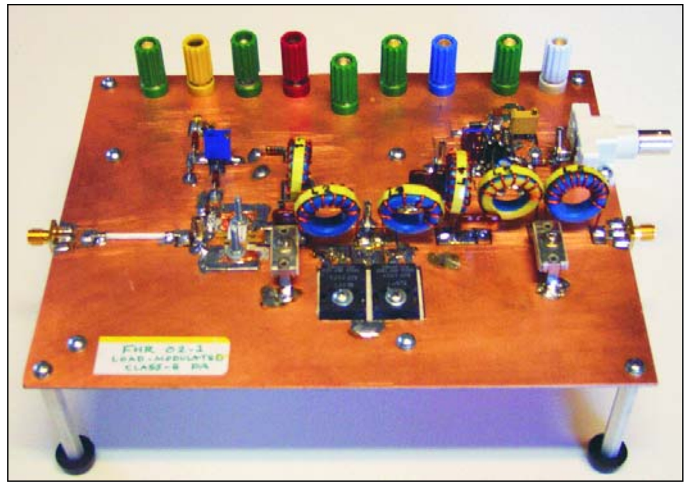

Figure 70 · Load-modulated class-E PA (courtesy GMRR).

[123, 124]. The second (Figure 68) operates in class D, produces 100 W with an efficiency of 60 to 70 percent, and can be tuned from 5 to 21 MHz (4.25:1 range) through the use of electronically tunable inductors and capacitors [125].

Load Modulation

The output of a power amplifier can be controlled by varying the drive, gate bias, DC supply voltage, or load impedance. "Load modulation" uses an electronically tuned output filter (Figure 69) to vary load impedance and thereby the instantaneous amplitude of the output signal. The modulation bandwidth can be quite wide, as it is limited only by the bias feeds to the tuning components.

A key aspect of load modulation is a diligent choice of the impedance locus so that it provides both good dynamic range and good efficiency. For ideal saturated PAs of classes A, B, C, and F, the optimum locus is the pure resistance line on the Smith chart that runs from the nominal load to an infinite load. For ideal class-E PAs with series inductance and shunt susceptance for optimum operation with the nominal load, the optimum locus is the unity-efficiency line running from the nominal load upward and rightward at an angle of 65° [126]. For real PAs, the optimum locus is found by examination of load-pull contours.

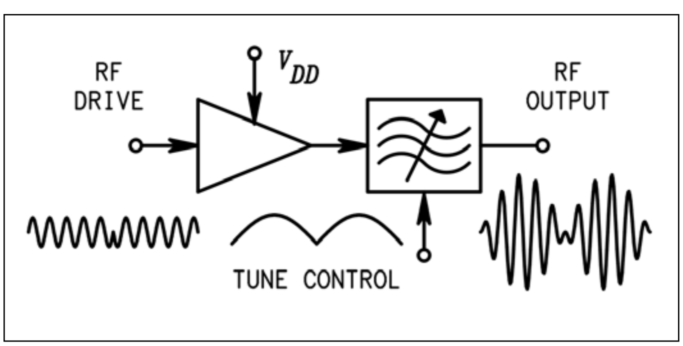

Figure 69 · Load modulation by electronic tuning.

The simple T filter has a single electronically variable element, but provides an approximately optimum locus for class E over the top 12 dB of the dynamic range. The experimental 20-W, 30-MHz [124, 126] shown in Figure 70 achieves a 41-dB range of amplitude variation. The measured instantaneous-efficiency curve (Figure 71) corresponds to a factor of 2.1 improvement in the average efficiency for a Rayleigh-envelope signal with a 10-dB peak-to-average ratio.

A load-modulated PA for communications follows the electronically tuned filter with a passive filter to remove the harmonics associated with the nonlinear elements. Predistortion compensates for the incidental phase modulation inherent in dynamic tuning of the filter. Variation of the drive level can be used to conserve drive power and to extend the dynamic range.

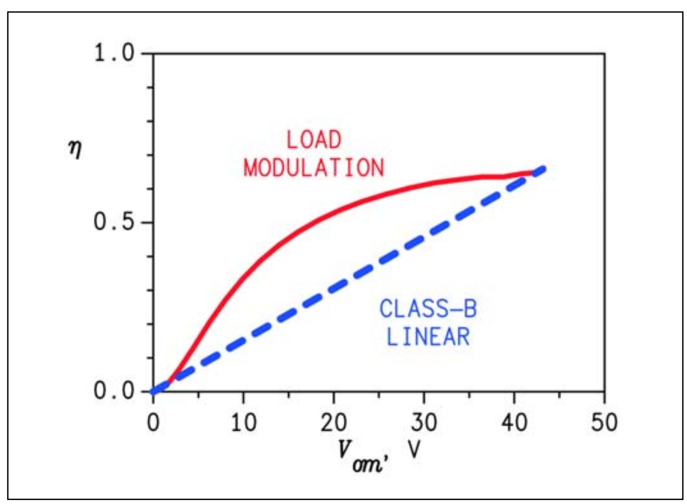

Figure 71 · Instantaneous efficiency of load modulation compared to class-B linear amplification.

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Correction

In Part 4 of this series (Novermber 2003 issue), Figures 45, 52, 55, 56, 57 and 58 should have been credited as "Courtesy Andrew Corporation" instead of "Courtesy WSI."

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Acronyms Used in Part 5

BST	Barium Strontium Titanate
GWEN	Ground Wave Emergency Network
PWM	Pulse-Width Modulation