HIGH-EFFICIENCY L-BAND KAHN-TECHNIQUE TRANSMITTER

F. H. Raab*, B. E. Sigmon, R. G. Myers, R. M. Jackson

*Green Mountain Radio Research, Colchester, Vermont
Motorola Satellite Communications, Chandler, Arizona

ABSTRACT

This paper describes a 20-W PEP linear L-band transmitter based upon the Kahn envelope-elimination-and-restoration technique. A double envelope-feedback loop assures high linearity. The RF power amplifier employs a two stage MMIC driver amplifier and a 20-W PA biased for class-AB operation. The class-S modulator includes a high speed comparator and 1/2 µm HFETs in its output stage. A double envelope-feedback loop assures both high linearity and time-delay equalization for RF bandwidths to 150 kHz. With a two-tone signal the transmitter achieves an efficiency of 56% at full power (40 dBm under QPSK modulation), and 35% at 18 dB in back-off. The third-order IMDs for a two-tone signal vary from -30 dBc to -40 dBc over a 20 dB back-off range.

INTRODUCTION

Pulse shaping in modern digital signals such as QPSK, OQPSK, and CDMA keeps signal energy out of adjacent channels but produces a time-varying envelope. Such signals are transmitted at frequencies from UHF through S-band in applications such as cellular, personal, and satellite communications. Since the transmitters are often portable and battery-operated, there is a need for a linear transmitter that maintains high efficiency over a wide range of power levels.

The Kahn Envelope Elimination and Restoration (EER) technique combines a highly efficient but nonlinear RF power amplifier (PA) with a highly efficient envelope amplifier to implement a high-efficiency linear RF power amplifier. In its simplest form, a limiter eliminates the envelope (accomplished here by saturation of the driver amplifiers in Fig.1), allowing the constant-amplitude phase modulated carrier to be amplified efficiently by class-C, -D, -E, or -F RF PAs. Amplitude modulation of the final RF PA restores the envelope to the phase-modulated carrier creating an amplified replica of the input signal.

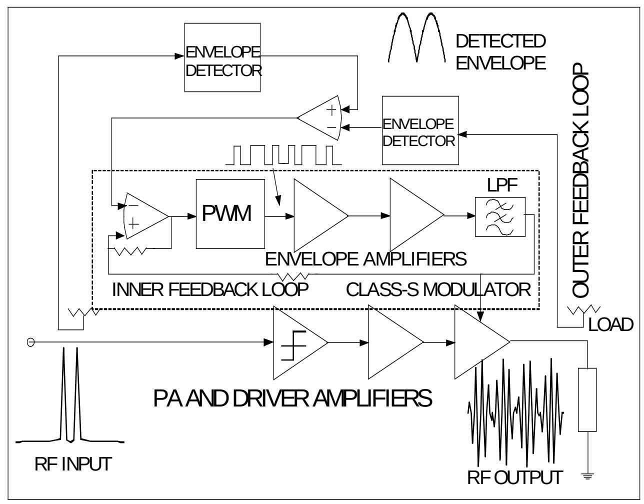


FIGURE 1: BLOCK DIAGRAM OF L-BAND EER TRANSMITTER

The basis for EER is the principle of the equivalence of any narrowband signal to simultaneous amplitude (envelope) and phase modulations:

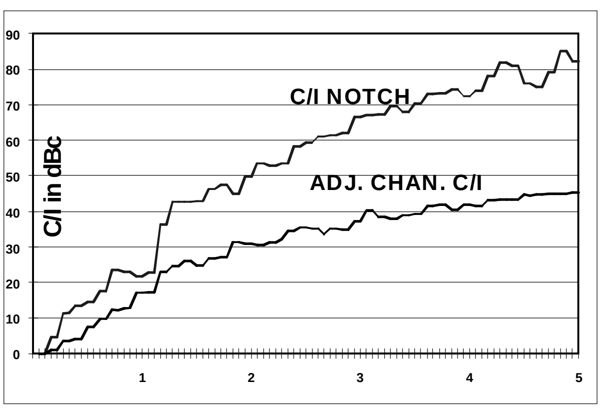
$$V_{RF}(t) = E(t) \cos[(\omega_c t + \phi(t)] \quad (1)$$

The envelope and phase are readily related to the familiar I and Q components (modulations of cosine and -sine carriers) used in signal processing [1].

Kahn [2] developed EER in the 1950s as a means of improving the efficiency of short-wave broadcast transmitters. In contrast to linear amplifiers, a Kahn-technique transmitter operates with high efficiency over a wide dynamic range and therefore produces a high average efficiency for a wide range of signals and power (back-off) levels [3]. Previous applications include short-wave broadcast [4], HF/VHF transmitters [1], [5], VHF amateur-satellite repeaters [6], and cellular transmitters [7].

The linearity of an EER transmitter does not depend upon the linearity of its RF-power transistors, but upon the accuracy of reproduction of the input signal's amplitude and phase information. The RF PA can be operated at full power and several dB into compression and still achieve the specified IM performance. In contrast, other types of PAs must be operated in back-off (with lower power and lower efficiency) in order to achieve the same IM levels.

In addition to the linearity of the class-S modulator and the amplitude-modulation linearity of the RF PA, the two principal factors that affect linearity are the bandwidth B_S of the class-S modulator and the differential delay between the envelope and phase modulation at the final amplifier [8]. Fig. 2 shows the variation with envelope bandwidth of the worst-case noise-power ratio (NPR) and adjacent-channel IM levels for ten simulated signals (the signals are ramdonly phased tones and occupy nine of ten slots that are evenly spaced in frequency). To keep IM products below -30 dBc (30 dB below the tones), $B_E \geq 1.78\ B_{RF}$.



RATIO of B_E/B_{RF}

FIGURE 2: NPR AND IMD LEVELS AS A FUNCTION OF ENEVELOPE BANDWIDTH

The L-band transmitter (Fig. 1) ensures high linearity by adding to the classical Kahn-technique two features:

- Two envelope-feedback loops, and
- Matched envelope detectors.

The two feedback loops ensure high linearity in both the class-S modulator and modulation of the RF PA. Matched envelope detectors operating at the same signal levels eliminate distortion caused by nonlinearities in the detectors.

RF POWER AMPLIFIER

The RF PA in a Kahn-technique transmitter is always saturated and therefore always operates at maximum efficiency. Hard limiting is performed in the driver amplifier and the drive level to the PA is adjusted to maintain its output 3 dB into saturation for all values of V_{DD}.

The RF chain consists of a two-stage MMIC driver (developed by Motorola for another application) and a Fujitsu 1415-20 final stage in a microstrip package. Other PA types can be successfully used, but the Fujitsu PA is most conveniently integrated with the driver amplifier and class-S modulator. The driver amplifier employs T.I. foundry 1/2 µm HFETs, and the PA employs 1/2 µm epi-MESFETs.

The overall linear gain of the transmitter is 37 dB, 12 dB of which is in the output stage. The final stage is biased class-AB to B in order to achieve a flat gain response. Drain bias voltages were 7 and 10 V dc for the driver and PA, respectively.

The CW efficiency of the PA is 65% at PEP and remains above 60 percent over an 18-dB dynamic range (Fig. 3). In contrast, the efficiency of a conventional class-B PA with the same PEP efficiency drops to 10% at 18-dB back-off.

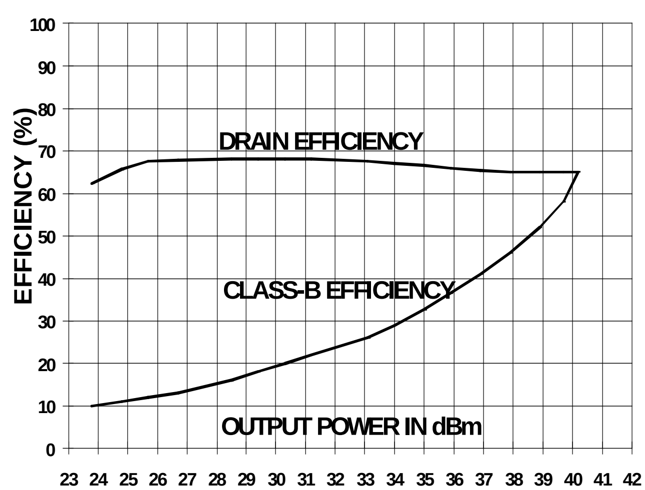


FIGURE 3: SINGLE TONE EER PA EFFICIENCY

CLASS-S MODULATOR

A class-S modulator is a switching-mode envelope amplifier that converts the dc-supply voltage into a time-varying supply voltage that amplitude-modulates the RF PA [9]. Variation of the output voltage is accomplished by varying the pulse width. Class-S modulators are ideally 100-percent efficient.

In the classical EER transmitter, a time delay equal to the group delay of the output filter in the class-S modulator is introduced in the PA arm in order to match the amplitude and phase in the output signal. In this design, the delay compensation is achieved by using a two-loop feedback system (Fig. 4).

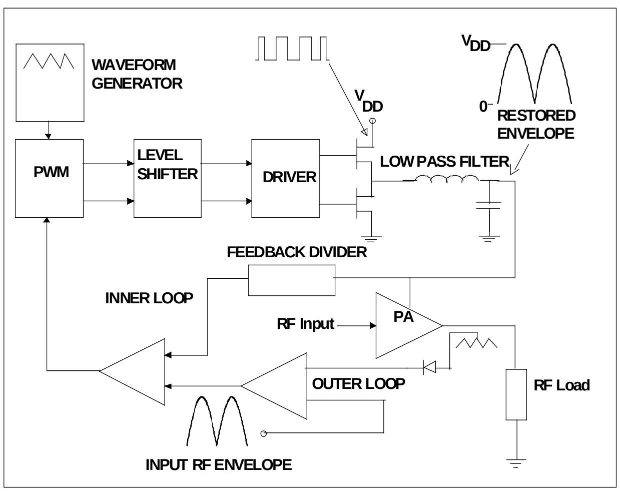


FIGURE 4: BLOCK DIAGRAM OF THE CLASS-S MODULATOR

The closed loop class-S modulator is similar to a buck topology dc-dc switching power converter. The major difference is the class-S modulator operates with a variable reference signal (the RF envelope).

The RF output of the PA is detected and fed back to the outer loop error amplifier (Fig. 4), which compares the detected signal to the RF input envelope. The difference between these two signals is amplified to produce an error signal, which is fed to one input of the inner loop error amplifier. The inner loop error amplifier feeds its control signal to one input of a high speed Pulse Width Modulator (PWM).

A 3.3 MHz triangle wave drives the other input to the PWM. The resultant output of the PWM is a train of pulses whose width varies with the amplitude of the envelope of the RF input signal. The use of a triangular waveform produces symmetrical, double-sided pulse-width modulation.

The output of the PWM is level-shifted to drive a totem pole arrangement of 16-mm GaAs HFETs designed by Motorola and fabricated by the T.I. GaAs foundry. Three devices are connected in parallel in the upper arm and three more in the lower arm to minimize the "on-state" resistance of the output stage. A two pole low pass filter removes the switching frequency and its harmonics to produce the high-level envelope signal.

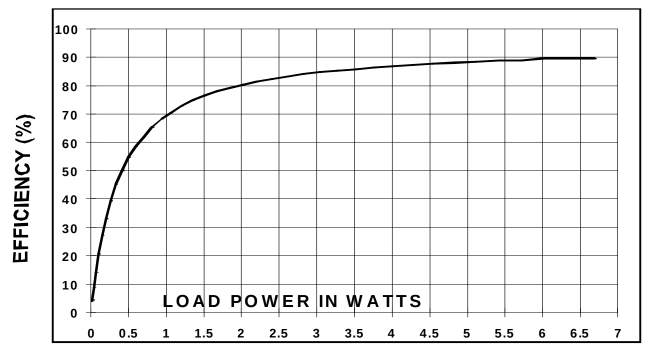


FIGURE 5: CLASS-S MODULATOR EFFICIENCY

The efficiency of the class-S modulator operating into a dummy load is 90 percent at PEP and better than 80 percent over a 10-dB back-off (Fig. 5). The transfer function of the modulator is virtually a straight line over a 26-dB dynamic range (Fig. 6). The frequency response is essentially flat from dc through 150 kHz. Fig. 7 shows that a 150-kHz sinusoid is reproduced both linearly and with correct timing (offset is added to facilitate visualization).

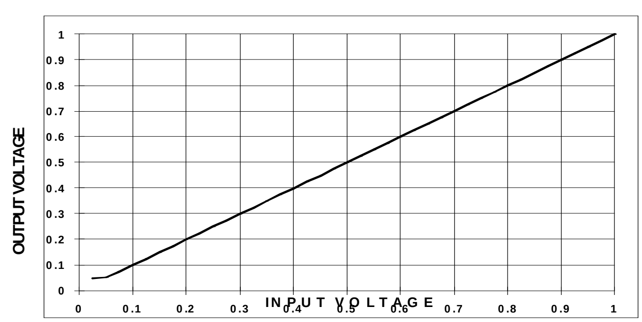


FIGURE 6: CLASS-S MODULATOR TRANSFER FUNCTION (NORMALIZED)

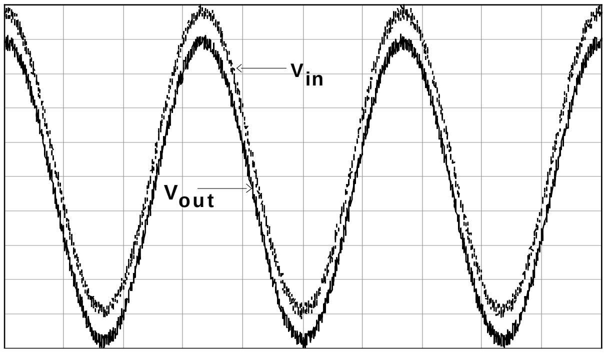


FIGURE 7: FREQUENCY RESPONSE OF THE CLASS-S MODULATOR, F=150kHz.

TRANSMITTER PERFORMANCE

The efficiency and linearity of the complete EER PA are shown in Fig. 8. Power-added efficiency for production of a two-tone signal is 57 percent at PEP and drops to about 35 percent at 18 dB into back-off. In contrast, a class-B PA that is 65-percent efficient for CW at PEP is only about 6.5-percent efficient for a two-tone signal 18 dB into back-off. The IMD levels vary between -30 and -39 dBc for an RF bandwidth of 150 kHz.

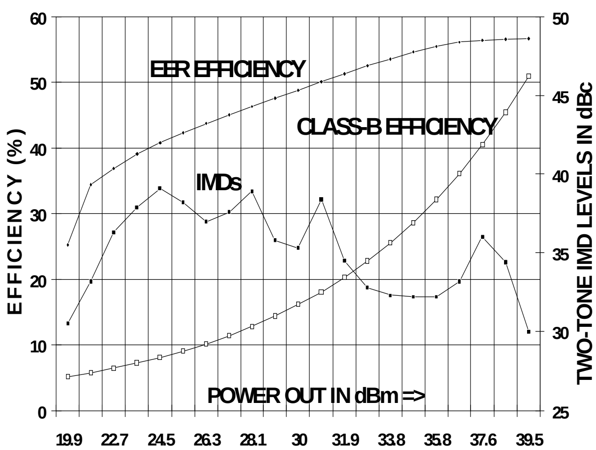


FIGURE 8: MEASURED PERFORMANCE OF THE TRANSMITTER

PHYSICAL DIMENSIONS

The breadboard EER PA consists of three discrete functional stages:

- MMIC driver amplifier with 25 dB gain
- Packaged PA with 12 dB gain
- Class-S modulator.

The class-S modulator is fabricated by wire-bonding chips and occupies a board area of 1.5 in x 1.5 in. Full integration and packaging of the design will yield a size of approximately 1.35 in x 1.0 in x 0.5 in.

CONCLUSION

The Kahn EER technique dates from the 50s. This paper presents the application of todays technology to yesterday's techniques. Implementation of a Kahn EER transmitter improves PA efficiency and linearity. The next step is to employ DSP technology to replace many of the analog functions presented here.

REFERENCES

[1] F. H. Raab and D. J. Rupp, "High-efficiency single-sideband HF/VHF transmitter based upon envelope elimination and restoration," Proc. Sixth Int. Conf. HF Radio Sxstems and Techniques (HF '94) (IEE CP 392), York, UK, pp. 21 - 25, Jul. 4 - 7, 1994.

[2] L. R. Kahn, "Single sideband transmission by envelope elimination and restoration,"Proc. IRE, vol. 40, no. 7, pp. 803 - 806, Jul. 1952.

[3] F. H. Raab, "Average efficiency of power amplifiers,"Proc. RF Technology Expo. '86, Anaheim, Ca., pp. 374 - 486, Jan. 30 - Feb. 1, 1986.

[4] B. Weaver, "A new, high efficiency, digital, modulation technique for AM or SSB sound broadcasting applications," Proc. Int. Symp. Broadcasting Technol., Zhuhai, 1991.

[5] A. Bateman, P. Kennington, J. P. McGeehan, and M. Beach, "Multi-mode transceiver design," Proc. RF Expo West '94, San Jose, CA, pp. 327 - 331, Mar. 22 -24, 1994.

[6] K. Meinzer, "A linear transponder for amateur radio satellites," VHF Communications, vol. 7, pp. 42 - 57, Jan. 1975,

[7] T. Sowlati, Y. Greshishchev, C. Angre, T. Salama, G. Rabjohn, and J. Sitch, "Linear transmitter design using high efficiency class E power amplifier," Proc. Int. Symp. Personal, Indoor, and Mobile Radio Commun., Toronto, pp. 1233 - 1237, Sept. 1995.

[8] F. H. Raab, "Intermodulation distortion in Kahn-technique transmitter," IEEE Trans. Microwave Theory and Techniques., vol. 44, no. 12, part 1, pp. 2273 -2278, Dec. 1996,

[9] F. H. Raab and D. J. Rupp, "Class-S high-efficiency amplitude modulator," RF Design, vol. 17, no. 5, pp. 70 - 74, May 1994.