Linearity of X-Band Class-F Power Amplifiers in High-Efficiency Transmitters

Manoja D. Weiss, *Student Member, IEEE*, Frederick H. Raab, *Senior Member, IEEE*, and Zoya Popović, *Senior Member, IEEE*

***Abstract*—Modern communication signals have time-varying envelopes with significant peak-to-average ratios, resulting in low average efficiency when amplified by commonly used linear power amplifiers (PAs). For linear amplification with increased average efficiency, the Kahn envelope-elimination-and-restoration method uses a highly efficient saturated PA. In this paper, an 8.4-GHz class-F PA with 55% maximum instantaneous efficiency at 610-mW output power, is experimentally characterized in several different biasing modes. Operated in linear mode with constant drain bias, this PA has 10% average efficiency. The suppression of two-tone intermodulation products is 27 dBc when operated at about 0.7 times the peak output power. For the same PA operated in a modified Kahn mode with drive and bias control, a comparable linearity (27.7 dBc) can be obtained at peak output power. Furthermore, the average efficiency increased to 44%, a factor of 4.4 over the linear fixed bias mode.**

I. Introduction

IN MOBILE and satellite communications, the power amplifier (PA) can consume a large fraction of the total system power. For example, about 50% of the total power on a communication satellite can be used up by the PA in the transmitter [1]. Therefore, increased PA efficiency considerably reduces total heat output and prolongs battery lifetime. However, band-limited signals with variable envelopes such as quadrature amplitude modulation (QAM) are typically amplified by linear, but inefficient PAs, such as class A and class AB. In addition, the PA is often operated below its maximum power capability in order to avoid nonlinearities occurring at high output power levels. This further reduces its efficiency. One method of enhancing the PA efficiency is a technique known as envelope tracking, in which the drain bias voltage varies proportionally with the input signal envelope while maintaining the active device in the linear regime [2]–[5]. A class-A or class-B PA can also be maintained in extended saturation and, hence, high efficiency, by providing optimum drain and gate biases [6]. Alternatively, the Kahn envelope elimination and restoration (EER) technique [7] allows the use of saturated high-efficiency PAs in linear transmitter systems. This method, which we refer to as the classical Kahn method, has been successfully demonstrated from HF- through L-bands using saturated class-AB PAs [8], [9].

Manuscript received March 1, 2000; revised December 1, 2000. This work was supported by the United States Air Force, Air Force Material Command, Air Force Research Laboratory, Kirtland Air Force Base under Contract F29601-99-C-0083 with Green Mountain Radio Research, by the National Science Foundation under Special Programs in Networking and Communications Grant NCR 9725778, and by by the Army Research Office under Multidisciplinary University Research Initiative Grant DAAH04-98-1-0001.

M. D. Weiss and Z. Popović are with the Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO 80309 USA.

F. H. Raab is with the Green Mountain Radio Research Company, Colchester, VT 05446 USA.

Publisher Item Identifier S 0018-9480(01)04438-6.

Dynamic power control in the Kahn technique provides increased efficiency by conserving RF power consumption at low-signal envelope levels. This method has been demonstrated at L-band using class-AB PAs [9] and shows promise for use at higher frequencies. This paper presents an experimental overview of the efficiency versus linearity performance of an X-band class-F PA in various different modes of operation, namely, linear with fixed bias, envelope tracking, and Kahn EER with and without dynamic power control. Switched-mode class-E and class-F PAs have a theoretical efficiency of 100% and have been demonstrated with watt-level output powers at 0.5 and 1 GHz with power-added efficiencies (PAEs) of 80% and 73%, respectively [10]. At 5 GHz, 72% PAE was obtained [11], dropping to 61% PAE with the same transistor when scaled to 8 GHz [12]. At 10 GHz, up to 62% PAE was obtained in an active antenna [13]. However, class-E and class-F PAs at higher microwave frequencies typically have lower gain, lower output power [12], and softer saturation characteristics. Furthermore, they are biased in the linear region because they have extremely low gain when biased near pinchoff. Consequently, their efficiency, amplitude modulation (AM) linearity, and amplitude-modulation-to-phase-modulation (AM/PM) conversion characteristics are different, and have to be considered when designing an appropriate dynamic power control scheme. The goal of the measurements presented here is to determine the relationship between drain bias and RF drive level, which gives increased average efficiency without sacrificing linearity of the PA.

The results presented here are obtained by manually varying the drain bias and RF drive level according to specific relationships. These control schemes may be implemented, for example, by using dc–dc converters [3]. For highest linearity, predistortion techniques derived from the signal envelope can be implemented using digital signal processing (DSP).

II. Background of Kahn EER and Dynamic Power Control

The basic premise of the Kahn method is that any narrow-band signal is equivalent to simultaneous AM and PM of a carrier. As shown in the block diagram of Fig. 1, the envelope is detected and amplified to high power levels by an efficient amplitude modulator, such as a class-S modulator [9]. The class-D, class-E, or class-F PA is operated with high efficiency by correct choice of the fixed-input RF power level. The envelope is restored to the carrier through the drain bias.

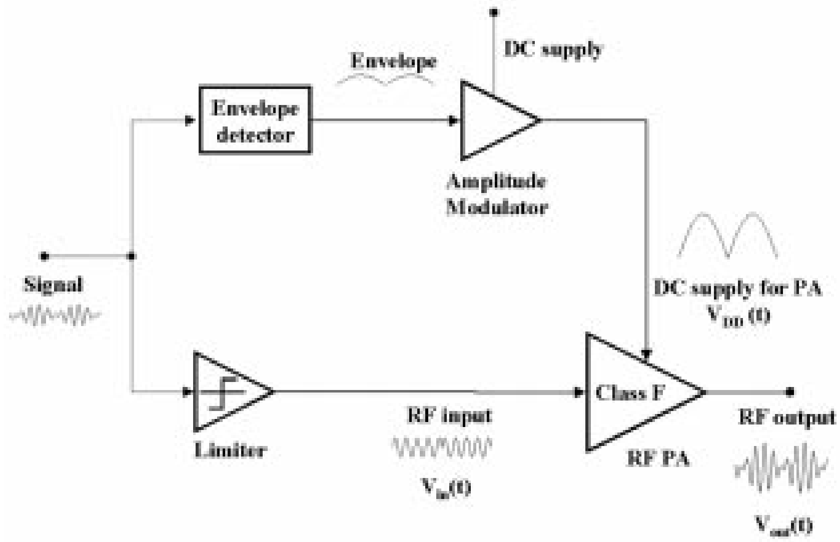


Fig. 1. Block diagram of a classical Kahn EER transmitter system. The signal is separated into envelope and phase data, and the phase-modulated carrier drives the PA. The amplitude is restored by modulation through the drain dc supply.

This gives efficient linear amplification of the RF signal since the PA gain is proportional to the drain bias.

In the classical Kahn method of Fig. 1, the amplitude of the phase-modulated drive signal is kept fixed at a large enough value to ensure optimal PA saturation and high efficiency at the peak envelope level. However, for lower envelope levels, a smaller drive signal is sufficient to cause saturation and high efficiency. Therefore, by regulating the RF drive amplitude in proportion to the signal envelope, the efficiency of the Kahn method can be optimized over all envelope levels. Referred to as Kahn EER with drive modulation, this method conserves RF drive power while keeping the PA saturated and provides linear efficient amplification.

In contrast to the Kahn EER method, conventional linear PAs are not saturated, and the drain bias is kept fixed while the varying-envelope signal drives the PA. This fixed drain bias is large enough to allow maximum linear voltage swing for the highest signal envelope. Since smaller drive levels require less dc power for the same gain, this amplification method is not efficient at low drive levels. To alleviate this problem, the drain bias can be made to track the envelope of the input signal in order to regulate dc power consumption. This dynamic power control method, known as envelope tracking, allows higher efficiencies for all signal levels while keeping the PA in the linear regime.

III. Average Efficiency and Linearity

The instantaneous efficiency of a PA is a function of the instantaneous input and output power and the class of operation. In this paper, the instantaneous efficiency is defined as

$$\eta(E) = \frac{P_{\mathrm{o}}(E)}{P_{\mathrm{i}}(E)} \tag{1}$$

where $P_{\mathrm{o}}(E)$ is the output RF power and $P_{\mathrm{i}}(E)$ is the total input RF and dc power as a function of the signal envelope E. Depending on the class of operation of the PA, the instantaneous efficiency is proportional to the output power or the output voltage (envelope of signal). In practical PAs, the instantaneous efficiency usually achieves a maximum when the gain is compressed by about 3 dB.

Average efficiency is a good indicator of average power consumption in most communication systems with time-varying envelopes. By increasing the average efficiency of a PA from 30% to 50% (a factor of 1.7), for the same average output power, the average input power is reduced 1.7 times, and the battery lifetime is increased 1.7 times. On the other hand, the average heat output is reduced by a factor of 2.3. Higher average efficiency [14] is obtained by having increased efficiency over a large range of signal envelopes and is defined as

$$\overline{\eta} = \frac{\overline{P}_{\mathrm{o}}}{\overline{P}_{\mathrm{i}}} \tag{2}$$

where $\overline{P}_{\mathrm{o}}$ is the average output power and $\overline{P}_{\mathrm{i}}$ is the average total input power. The average input power is calculated as the expected value of $P_{\mathrm{i}}(E)$, and the output power is calculated similarly. If the probability distribution function (PDF) of the envelope $p(E)$ is known, where E is the envelope, the average input and output power can be calculated as

$$\overline{P}_{\mathrm{i}} = \int_0^{E_{\max}} P_{\mathrm{i}}(E)p(E)dE \tag{3}$$

and

$$\overline{P}_{\mathrm{o}} = \int_0^{E_{\max}} P_{\mathrm{o}}(E)p(E)dE. \tag{4}$$

In order to measure the average efficiency of different amplifier modes, we measure $P_{\mathrm{i}}(E)$ and $P_{\mathrm{o}}(E)$ for a sinusoidal input signal with amplitude E. From this measured data, the average input and output power is then calculated for a signal with any type of modulation with a known PDF. Note that for the Kahn modes, E is the drain voltage, and for the linear modes, E is the amplitude of the RF input signal.

The PDF of the envelope is a measure of the relative time corresponding to different levels. The PDFs of some common

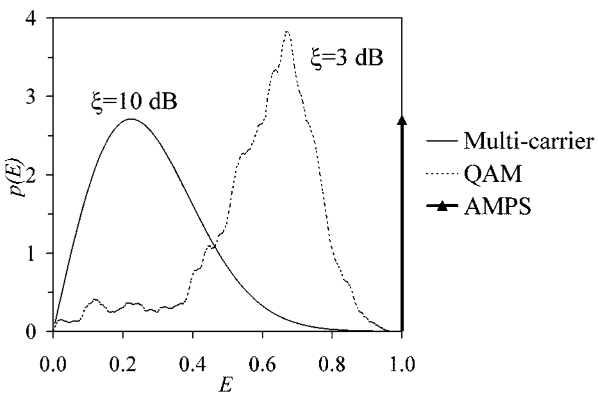


Fig. 2. PDFs $p(E)$ of some common signals. The Rayleigh distribution is for OFDM (multicarrier) signals and the constant amplitude signal used in the AMPS is always at peak power. E is the normalized time-varying signal envelope. ξ is the peak-to-average ratio, given in decibels.

signals are shown in Fig. 2. For frequency modulated (FM) and other constant-amplitude signals such as the Advanced Mobile Phone Service (AMPS), the signal is always at peak output. Shaped-pulse data signals such as QAM have PDFs with peak-to-average power ratios of 3–6 dB [15]. Multicarrier signals such as offset frequency division multiplex (OFDM) have Rayleigh PDFs [16] with typical peak-to-average ratios from 7 to 13 dB. Such signals are used in cellular communications, multibeam satellite systems, and digital broadcasting.

Varying signal envelope levels give rise to AM and AM/PM effects, which cause intermodulation distortion (IMD) in the output signal. In this paper, linearity is represented by the amount of IMD for a two-tone input signal. Since two high-power sources at X-band were not available to measure the peak-power IMD, it was calculated based on measurements of gain compression and phase distortion for a single-tone excitation to the PA. This input RF signal can be written as $V_{\text{in}}(E) = E\cos(\omega t)$. The output signal as a function of this input signal amplitude (envelope) is then given by

$$V_{\text{out}}(E) = A_{\text{out}}(E)\cos\left(\omega t + \phi(E)\right) \tag{5}$$

where $A_{\text{out}}(E)$ is the AM characteristic and $\phi(E)$ is the AM/PM, both of which are measured for each PA mode. Using this data, a behavioral model of each PA mode can be formulated, which is then analyzed under a two-tone excitation. For the linearity calculation, a two-tone signal such as

$$V_{\text{in,two-tone}} = \frac{E}{2}\cos(\omega_1 t) + \frac{E}{2}\cos(\omega_2 t) \tag{6}$$

is input to the behavioral model. This two-tone signal can also be represented as

$$V_{\text{in,two-tone}} = E\cos\left(\frac{\omega_1 - \omega_1}{2}t\right)\cos\left(\frac{\omega_1 + \omega_1}{2}t\right) \tag{7}$$

which is a signal of frequency $(\omega_1 + \omega_2)/2$ modulated by a slowly varying envelope $E\cos((\omega_1 - \omega_1)t/2)$. This expression can be written as

$$V_{\text{in}}(E) = A_{\text{in}}(t)\cos(\omega t). \tag{8}$$

Thus, $V_{\text{out}}(t)$ can be calculated using (5) and (8). Using a discrete Fourier transform, the spectrum of the output signal V_{out} can then be analyzed. The power ratio between the carrier and the highest of the third and fifth IMD products is defined as the IMD. The IMD at peak output power is calculated for the Kahn modes. For the linear modes, the IMD is calculated at peak output power and at backed-off power. An acceptable value for IMD for communication applications is 30 dBc.

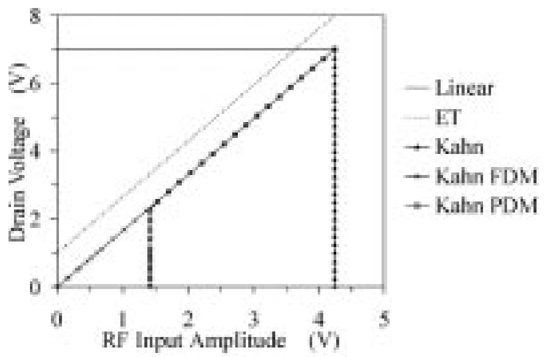
IV. Definition of PA Modes

A single PA is characterized for operation in five different biasing modes in order to determine the best method of dynamic bias control for high efficiency and linearity. Two linear modes of operation, one with fixed and the other with dynamic drain bias (envelope tracking), are compared with three modes of saturated PA operation, one being the classical Kahn method described in Section II, and the other two being modified Kahn methods with drive modulation. The following five PA modes represent specific relationships between the drain voltage and RF signal amplitude, and are shown graphically in Fig. 3(a).

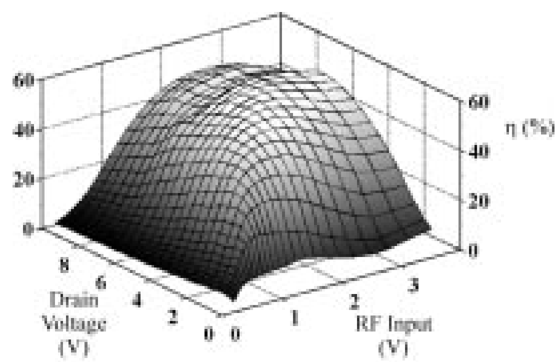
1) *Linear*: the signal is fed directly into the RF input and the drain voltage is fixed. This mode is called the linear mode because the amplifier is unsaturated.
2) *Envelope tracking (ET)*: linear operation with the dynamic drain voltage proportional to the signal envelope.
3) *Kahn*: classical Kahn operation, as shown in Fig. 1, with fixed RF drive.
4) *Kahn full-drive modulation (FDM)*: modified Kahn mode with dynamic RF input amplitude proportional to the signal envelope.
5) *Kahn partial-drive modulation (PDM)*: another modified Kahn mode, which is similar to the Kahn FDM mode, but has a minimum value for the drive, to increase efficiency at low envelope levels.

The fixed-bias linear and Kahn modes are not dynamic in that either the drain is kept fixed or the drive is kept fixed, as can be seen in Fig. 3(a). The envelope tracking, Kahn FDM, and Kahn PDM modes are dynamic since both the drain and drive amplitudes change simultaneously. Fig. 3(b) shows the instantaneous efficiency of the PA used in this study as a function of drain bias and drive amplitude. It is apparent from this graph that dynamic control of both values is necessary for maintaining high instantaneous efficiency.

Analogously, variation of the gate bias (quiescent current) in an RF PA also results in significant savings of dc-input power. However, minimum drive and gate bias levels are often required to ensure proper operation of the RF final amplifier and modulator [17]. The minimum drive/gate-bias level ensures saturation of the PA in spite of gain reduction and/or reduces amplitude-to-phase conversion by decreasing the degree of saturation so that nonlinear capacitance variations are reduced. All five PA modes listed above were measured with various gate-biasing schemes. However, there was almost no change in average efficiency between these PA schemes, and the linearity proved to be low. Therefore, for all measurements described in the following section, the gate bias is kept fixed.



(a)



(b)

Fig. 3. (a) Five modes of PA operation compared in this paper. Each mode represents a specific relationship between the drain bias and instantaneous envelope of the RF input. Two linear modes are compared with three Kahn modes where the PA is saturated. (b) Instantaneous efficiency as a function of drain bias and RF input amplitude. By varying both voltages in a dynamic manner, the efficiency can be optimized for all input envelope levels.

V. Measurements

The PA used for this study is an 8.4-GHz class-F PA [12] designed with a Fujitsu FLK052WG MESFET. At the fundamental frequency, the transistor load impedance $R_{\rm eq}$ is chosen in order to maximize power transfer to the load [18], [19], and is given by

$$R_{\rm eq} = \frac{V_{\rm DS}}{I_{\rm DSS}}. \quad (9)$$

$V_{\rm DS}$ is the maximum drain voltage and $I_{\rm DSS}$ is the maximum drain current. The load presents the second harmonic at the switch with a short to increase efficiency by making the switch voltage waveform approximately a square wave. Higher harmonics are not considered since the gain decreases with frequency and is negligible beyond about 30 GHz. The load filters out the third harmonic, producing a sinusoidal output. The switch voltage waveform was measured using time-domain optical sampling and class-F operation was confirmed by observing an approximately square waveform at the drain [20]. The microstrip circuit is fabricated on a 0.508-mm RT5880 Duroid ($\epsilon_r = 2.2$) substrate. This PA provides a maximum instantaneous efficiency of 55% for 610-mW output power and 5.3-dB saturated gain with $V_{\rm GS} = -0.9$ V and $V_{\rm DS} = 7$ V.

Each PA mode is implemented by manually changing the drain voltage and drive signal amplitude according to the relationships shown in Fig. 3(a). By monitoring the RF and dc power levels and the phase of the output signal, $P_{\rm i}(E)$, $P_{\rm o}(E)$, $V_{\rm out}(E)$, $\phi(E)$, discussed in Section III, are measured for each PA mode. E is the RF signal amplitude for the linear modes and the drain voltage for the Kahn modes. The power and phase are measured using an HP70820A Transition Analyzer. An HP83020A preamplifier is used to amplify the power levels from an HP83650A synthesized sweeper so as to saturate the class-F PA. From this data, the average efficiency and linearity are calculated for each mode, as described in Section III.

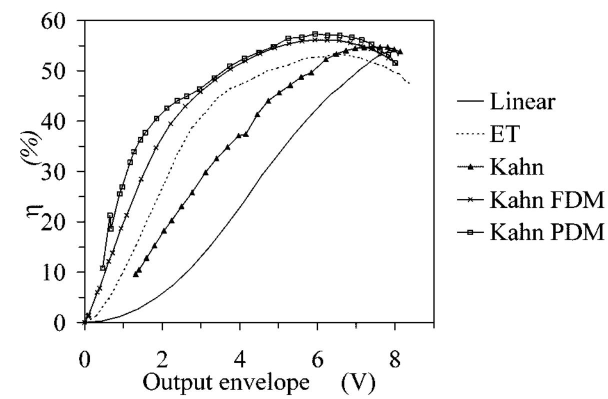


Fig. 4. Measured instantaneous efficiency of the PA modes. The efficiency is decreased for low signal levels.

VI. Comparison of Modes

The effect of dynamic biasing on average efficiency can be shown by comparing the measured instantaneous efficiency as a function of output signal amplitude, as illustrated in Fig. 4. The linear amplifier with fixed bias has very low efficiency at low power levels. The Kahn method, where the RF drive level is fixed, has higher efficiency on average than the linear case due to PA saturation. However, the dynamic biasing schemes (envelope tracking, Kahn FDM, and Kahn PDM) have much higher efficiency over the entire range of output levels. Kahn PDM has the best efficiency performance over all other modes. Based on measurements of $P_{\rm i}(E)$ and $P_{\rm o}(E)$ and the PDFs given in Fig. 2, the predicted average efficiency for multicarrier and QAM signals is calculated as shown in Table I.

Each of the techniques, however, exhibits different AM/PM characteristics $\phi(E)$, as shown in the measured data in Fig. 5. The classical and PDM Kahn methods have a large increase in AM/PM, due to deep saturation of the PA at low envelope levels.

The measured AM linearity, given by the input–output transfer characteristic $V_{\rm out}(E)$, is shown in Fig. 6. The peak output level for all modes is about 8 V. The linear modes saturate at high envelope levels and, therefore, must be operated in backoff for high linearity. The Kahn modes, on the other hand, have input–output characteristics, which are approximately straight lines over the entire envelope range. However, the classical Kahn and Kahn PDM modes suffer from *feedthrough*, which occurs in an amplifier when a zero-input signal envelope on the drain results in a nonzero output due to the feedback capacitance of the device. This degrades the linearity and also reduces dynamic range of the output. The Kahn FDM technique gives no feedthrough and gives the highest AM linearity.

TABLE I
COMPARISON OF AVERAGE EFFICIENCY AND LINEARITY RESULTS. THE PREDICTED VALUES ARE OBTAINED BY ANALYZING PA MODELS FORMED BY MEASURING THE CHARACTERISTICS OF EACH MODE UNDER A SINGLE-TONE EXCITATION

Power amplifier modes 8.4 GHz	Predicted IMD ratio (dBc)	Predicted average efficiency Multi-carrier -10 dBPEP	QAM -3 dBPEP	Peak Power (W)
Kahn	23.8	26.4%	43.8%	0.66
Kahn-FDM	27.7	43.7%	53.4%	0.66
Kahn-PDM	26	46.7%	54.4%	0.62
Linear (fixed drain)				
Full power	17	9.5%	28.7%	0.61
0.67 of full power	27			0.41
Envelope tracking				
Full power	23.1	36.1%	49.5%	0.72
0.7 of full power	24.6			0.50

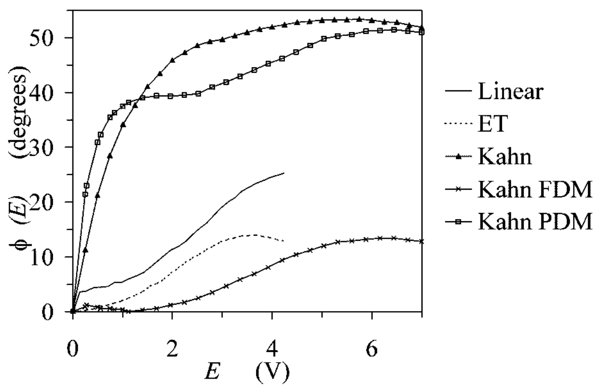


Fig. 5. Measured AM/PM of the PA modes. For the Kahn modes, the envelope is the drain voltage (0–7 V), and for the linear modes, it is the amplitude of the RF input (0–4.24 V).

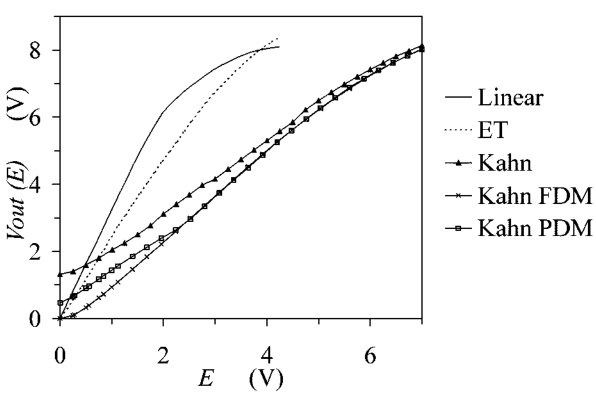


Fig. 6. AM linearity of the PA modes. $V_{\rm out}$ is the amplitude of the output signal, which has a peak value of about 8 V. For the Kahn modes, the envelope is the drain voltage (0–7 V), and for the linear modes, it is the amplitude of the RF input (0–4.24 V).

The predicted linearity and average efficiency of the various techniques are summarized in Table I. The presented data includes the average efficiency for multicarrier signals with a 10-dB peak-to-average ratio, and for QAM signals with a 3-dB peak-to-average ratio. Peak power for all modes is about 0.6 W, corresponding to a maximum output envelope of about 8 V. The PDFs of both these signals are shown in Fig. 2. The overall amplifier linearity is obtained from a combination of the measured AM and AM/PM effects, as described in Section III. One would expect the linear mode in backoff to have the highest linearity, i.e., 27 dBc, with low efficiency, i.e., less than 10%. The FDM Kahn technique, in contrast, gives the same linearity with a significantly improved average efficiency of 44% (at least a factor of 4.4 improvement).

For QAM signals, the classical Kahn method gives better efficiency than the linear fixed-bias mode, but the dynamic biasing schemes (envelope tracking, FDM, and PDM Kahn) have much higher average efficiencies and are all comparable. This is because the PDF for the QAM signal is only 3 dB below the peak envelope level, where all the dynamic biasing schemes have similar performances.

A comparison of efficiency and linearity results from the measurements described in the previous section is summarized in Table I. The following observations should be pointed out:

1) Kahn EER can be used to linearize highly nonlinear amplifiers such as saturated class-F and E;
2) average efficiency and linearity of Kahn EER can be increased by drive modulation;
3) average efficiency and linearity of a fixed-bias class-F amplifier can be increased by dynamic drain biasing (envelope tracking);
4) dynamic modes have higher average efficiency and linearity;
5) for approximately the same output power, the saturated dynamic modes (Kahn FDM, PDM) give higher efficiency and linearity than the dynamic linear method ET;
6) Kahn EER with FDM gives the highest linearity at the peak output level, while increasing the average efficiency of the PA by a factor of 4.4 over the case of the unlinearized fixed-bias PA.

VII. DISCUSSION

In summary, this paper has discussed the average efficiency and linearity of an 8.4-GHz class-F nonlinear X-band PA intended for use in transmitters with time-varying signal envelopes. The class-F amplifier has a high instantaneous efficiency for high signal amplitudes, but low efficiency for smaller signals, yielding a poor efficiency when averaged over time. We show experimentally that several different dynamic power control techniques can be used to improve the average amplifier efficiency, and that among these techniques, the best simultaneous efficiency and linearity are obtained by a modified Kahn EER technique. For example, the average efficiency for a Rayleigh distribution of signal amplitudes (multicarrier OFDM) was improved to 44% for this amplifier at a peak output power of 0.6 W, with IMD products suppressed to 28 dBc. The same amplifier when operated in linear fixed bias mode has only 10% average efficiency, with 17-dBc distortion at the same output power. The techniques we discuss in this paper are not specific to class-F and class-E amplifiers or to the signal amplitude distributions we have investigated here.

They are quite general and can be used in conjunction with any amplifier and a variety of modulation schemes for which the envelope varies.

The total efficiency of the Kahn method depends not only on the PA, but also on the amplitude modulator used to amplify the envelope signal (Fig. 1). The class-S amplitude modulator at L-band [9] has an efficiency of 90% at switching speeds on the order of 100 kHz. If a 1-MHz dc–dc converter is used instead of a class-S modulator, approximately 90% efficiency can be obtained [21]. Future work in this area will include design and integration of the drive and bias control circuits with the microwave PA.

REFERENCES

[1] G. D. Gordon and W. L. Morgan, *Principles of Communications Satellites* . NY: Wiley, 1993.

[2] A. A. M. Saleh and D. C. Cox, "Improving the power-added efficiency of FET amplifiers operating with varying-envelope signals," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 51–55, Jan 1983.

[3] G. Hanington, P. Chen, V. Radisic, T. Itoh, and P. Asbeck, "Microwave power amplifier efficiency improvement with a 10 MHz HBT DC–DC converter," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1998, pp. 589–592.

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

[5] F. H. Raab, "Efficiency of envelope-tracking RF power-amplifier systems," in *Proc. RF Expo East'86*, pp. 303–311.

[6] B. Geller, F. Assal, R. Gupta, and P. Cline, "A technique for the maintenance of FET power amplifier efficiency under backoff," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1989, pp. 949–952.

[7] L. Kahn, "Single sideband transmission by envelope elimination and restoration," *Proc. IRE*, vol. 40, pp. 803–806, July 1952.

[8] F. Raab and D. J. Rupp, "High-efficiency single-sideband HF/VHF transmitter based upon envelope elimination and restoration," in *Proc. 6th Int. HF Radio Syst. Tech. Conf.*, July 1994, pp. 21–25.

[9] F. Raab, B. Sigmon, R. Myers, and R. Jackson, "L-band transmitter using Kahn EER technique," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2220–2225, Dec 1998.

[10] T. B. Mader and Z. B. Popović, "The transmission line class-E amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 290–292, Sept. 1995.

[11] T. B. Mader, M. Marković, E. Bryerton, M. Forman, and Z. B. Popović, "Switched-mode high-efficiency microwave power amplifiers in a free space power-combiner array," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1391–1398, Oct. 1998.

[12] E. Bryerton, M. Weiss, and Z. Popovic, "Efficiency of chip-level versus external power combining," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1482–1485, Aug. 1999.

[13] M. Weiss and Z. Popovic, "A 10 GHz high-efficiency active antenna," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1999, pp. 663–666.

[14] F. H. Raab, "Average efficiency of power amplifiers," in *Proc. RF Technol. Expo'86*, pp. 474–486.

[15] L. Sundstrom, "The effect of quantization in a digital signal component separator for LINC transmitters," *IEEE Trans. Veh.Technol.*, vol. 45, pp. 346–352, May 1996.

[16] R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*. Norwood, MA: Artech, 2000.

[17] F. H. Raab, "Drive modulation in Kahn-technique transmitters," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, June 1999, pp. 811–814.

[18] S. C. Cripps, "A theory for the prediction of GaAs FET load–pull contours," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Boston, MA, June 1983, pp. 221–223.

[19] H. L. Krauss, C. W. Bostian, and F. H. Raab, *Solid State Radio Engineering*. New York: Wiley, 1980, ch. 14, pp. 432–476.

[20] M. Weiss, M. Crites, E. Bryerton, Z. Popović, and J. Whittaker, "Time-domain optical sampling of switched-mode amplifiers and multipliers," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2599–2604, Dec 1999.

[21] D. Maksimovic, private communication.

Manoja D. Weiss (S'97) was born in Colombo, Sri Lanka. She received the B.S.E.E degree from the Grove City College, Grove City, PA, in 1993, the M.S.E.E degree from the Pennsylvania State University, University Park, in 1995, and is currently working toward the Ph.D. degree in electrical engineering at the University of Colorado, Boulder.

Her research interests include microwave and millimeter-wave high-efficiency amplifiers, distributed transmitters, active antennas, and microwave semiconductor devices.

Frederick H. Raab (S'66–M'72–SM'80) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University (ISU), Ames, in 1968, 1970, and 1972, respectively.

He is Chief Engineer and Owner of the Green Mountain Radio Research Company (GMRR), Colchester, VT, a consulting firm that he founded in 1980. He co-authored *Solid State Radio Engineering* (New York: Wiley, 1980) and over 80 technical papers. He holds seven patents. His professional activities include RF PAs, radio transmitters, and radio-communication/navigation systems. He is an extra-class amateur-radio operator W1FR, licensed since 1961.

Dr. Raab is a member of Eta Kappa Nu, Sigma Xi, the Association of Old Crows (AOC), the Armed Forces Communications and Electronics Association (AFCEA), the Radio Club of America (RCA), and the Institute of Navigation (ION). He was program chairman of RF Expo East'90. He was the recipient of the 1995 ISU Professional Achievement Citation in Engineering.

Zoya Popović (S'86–M'90–SM'99) received the Dipl.Ing. degree from the University of Belgrade, Belgrade, Yugoslavia, in 1985, and the Ph.D. degree from the California Institute of Technology, Pasadena, in 1990.

She is currently a Professor of electrical engineering at the University of Colorado, Boulder. She co-authored *Introductory Electromagnetics* (Englewood Cliffs, NJ: Prentice-Hall, 2000) and co-edited *Active and Quasi-Optical Arrays for Solid State Power Combining* (New York: Wiley, 1997). Her research interests include microwave and millimeter-wave quasi-optical techniques, microwave and millimeter-wave active antennas and circuits, RF photonics, high-efficiency microwave circuits, smart antenna arrays, and antennas and receivers for radio astronomy.

Dr. Popović received the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Microwave Prize, the International Scientific Radio Union (URSI) Young Scientist Award, and the National Science Foundation Presidential Faculty Fellow Award in 1993. She was also the recipient of the URSI Isaac Koga Gold Medal in 1996, the Eta Kappa Nu Professor of the Year Award from her students in 1998, and the Humboldt Research Award in 2000 presented by the Alexander von Humboldt Foundation.