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Efficiency Enhancement and Linearization of GaN PAs using Reduced-Bandwidth Supply Modulation

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***Abstract*— This paper demonstrates drain supply modulation for simultaneous efficiency enhancements and linearization. A power-envelope trajectory is used to reduce the slew-rate requirements on the dynamic supply of a supply-modulated PA. The measured 2-GHz PA is a harmonically tuned 10W GaN PA with CW peak output power of 40.3dB and peak PAE of 69%. Six different drain supply trajectories are investigated with a 16-QAM 4MSym/s signal. Envelope tracking (ET) for the peak efficiency trajectory results in an average PAE=42.1%, Pout=30.0dBm, EVM=9.6% with a required tracking bandwidth of 11-24MHz. Using a power-envelope trajectory further enhances PAE by 6 percentage points, increases the output power by 1.9dB, and results in slightly better linearity, with a significantly lower drain supply modulator (DSM) bandwidth of 4.5MHz. Additionally, the strong gain variation with drain supply voltage characteristic of GaN devices is exploited to linearize the amplifier. A constant gain trajectory of 10.4dB results in average PAE=52.7%, Pout=33.7dBm, EVM=4.8% and a DSM bandwidth of 10-35MHz. The corresponding power-envelope trajectory results in the same performance, but requires only 4.5MHz DSM bandwidth. A 10MHz LTE test signal is also evaluated having similar results as the QAM signal.**

Keywords—PA; ET; Sypply Modulation; Linearization

I. INTRODUCTION

Microwave transmitter design usually faces the trade-offs between output power, efficiency and linearity. Common efficiency enhancement techniques are Doherty, Chireix, LINC and envelope tracking (ET) architectures [1]. In ET, a dynamic supply tracks the signal envelope and enables more efficient PA operation over a range of back-off power levels [2]. The PA essentially operates as a mixer in this configuration, implying high nonlinearity. Additionally, the dynamic supply needs to be very efficient at high slew rates, limiting the signal envelope bandwidth that can be efficiently amplified [3], [4]. This paper addresses the above issues of supply-modulated amplifiers by implemented distortion and supply-bandwidth reduction techniques, allowing more linear and efficient amplification for wideband signals. GaN transistors have proven to result in high efficiency and high output power, but the devices also show some unique non-linear behavior, making supply modulated (ET) PAs less efficient, as shown here. A GaN on SiC hybrid S-band PA is measured for the use in supply-modulated PAs using various previously demonstrated trajectories (e.g. in [4]), which are then compared to simple bandwidth limited trajectories. To improve linearity, some of the unwanted nonlinearities of the GaN device are exploited while not sacrificing the efficiency enhancement.

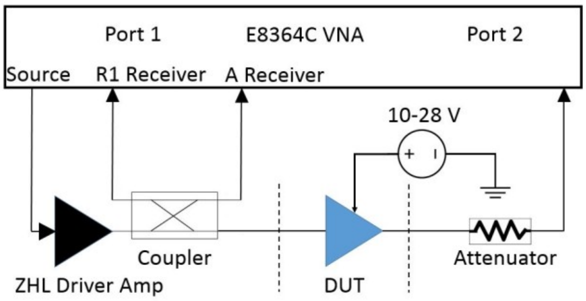

Fig. 1. The PA measurement test bench setup enables power calibration at the PA reference plane.

II. PA CHARACTERIZATION

The PA design uses the CGH40010, 10W GaN on SiC packaged transistor from Wolfspeed. It is biased in class AB with an $I_{d,q}$=150mA at V_{dd}=28V. The output matching network is implemented with harmonic tuning, close to the impedances of an inverse class-F PA. The PA is designed to be unconditionally stable with a low capacitance in the drain circuit, accommodating for supply modulation.

The test setup shown in Fig. 1 allows absolute magnitude and phase measurements referenced to a known input power level. An E8364C vector network analyser is used for the test setup. An external test set created with a bidirectional coupler allowing high-power calibrated measurements at the reference plane of the DUT. Full 2-port S-parameter and source power calibrations are performed at the DUT's plane of reference. No external test set was used on Port 2 which makes the measurement of S_{12} and S_{22} only valid for small signals, and may result in noisy measurements for these parameters.

The amplifier is characterized by calibrated power sweeps at different drain voltages ranging from 10V to 28V. The results are shown in Fig. 2 and Fig. 3, in grey lines. The grey arrow indicates increasing V_{dd}. Fig. 2 shows output power and PAE vs. input power, while Fig. 3 shows measured gain and phase vs. input power. The measurements clearly show a strong gain dependence on the drain voltage, therefore drain voltages below 10V are not considered. All subsequent calculations are based on these measurements.

III. BANDWIDTH REDUCTION TECHNIQUE AND TRAJECTORIES

In ET, the signal envelope is modulated by the drain supply, which for continuous tracking needs to have a bandwidth that is several times larger than the bandwidth of the signal, and this often limits supply efficiency. To reduce this problem for wideband signals, various bandwidth reduction techniques have been demonstrated, e.g. slew-rate reduction [5], [6]. This paper uses parts of the technique described in [7], which reduces the required tracking bandwidth by choice of the $V_d(V_{in})$ trajectory. One of the common ways to implement a tracking function for the drain supply is to find the highest PAE points at different drain voltages. This results in a function between the drain voltage, V_d, and the input envelope voltage, which in theory has infinite bandwidth. Depending on the tracking function, the practical required bandwidth is between 3 to 10 times the transmitted RF signal I/Q bandwidth, and usually this is accompanied by detroughing of the envelope voltage. The technique from [7], exploits the fact that even if the envelope of the signal has infinite bandwidth, the bandwidth of the transmitted RF power is limited. The drain tracking voltage V_d is approximated by a polynomial with even powers

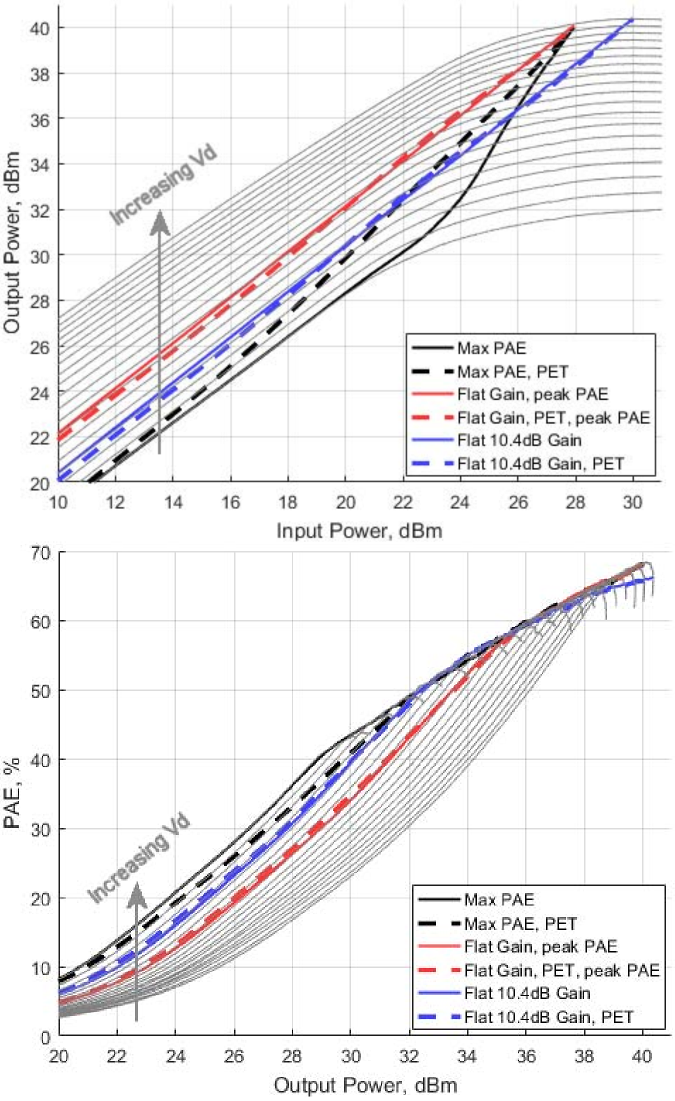

Fig. 2. Measured output power (top) and PAE (bottom) for different drain voltages shown in gray lines. The gray arrow indicates increasing V_d. Colored and black curves are the different trajectories.

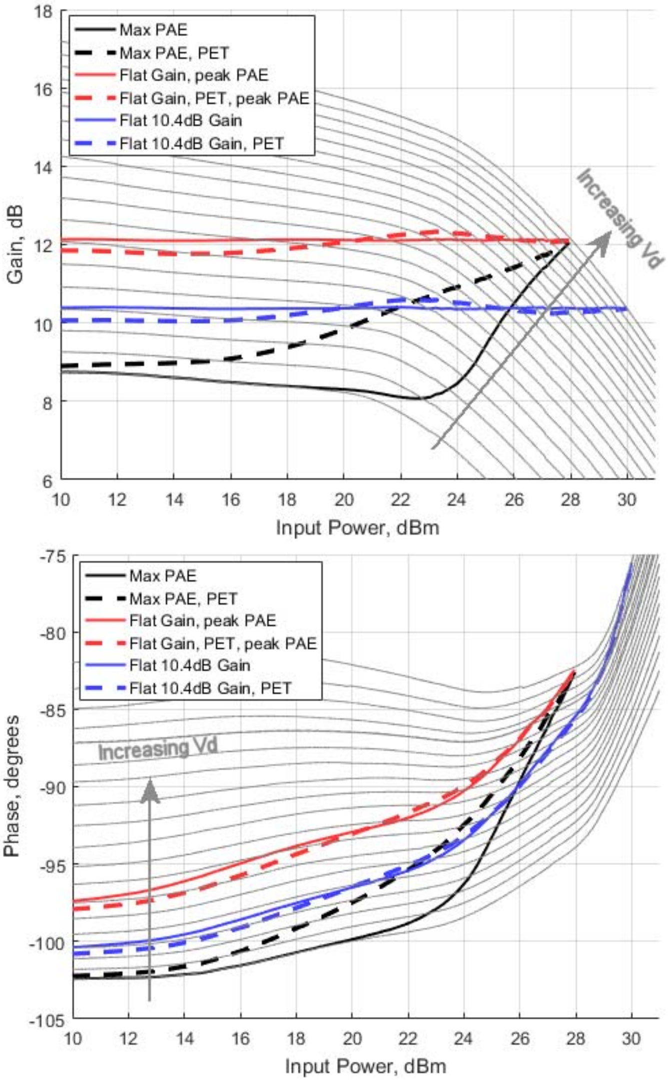

Fig. 3. Measured gain amplitude (top) and phase (bottom) for different drain voltages shown in gray line. Gray arrow indicates increasing V_d. Colored and black curves are the different trajectories.

$$V_d = a_0 + a_2 \cdot V_{i,env}^2 + a_4 \cdot V_{i,env}^4 + \ldots.., \quad V_{i,env} = |V_i(t)| \qquad (1)$$

where $V_{i,env}$ is the envelope voltage, referred to as Power Envelope Tracking (PET) [7]. Limiting the order of the series in (1) to 2nd order, limits the drain tracking bandwidth to the RF signal bandwidth, but results in a derivation of an approximated tracking function that differs from the original tracking function.

IV. TRAJECTORY SELECTION AND SIMULATION RESULTS

This section first investigates the classical maximum efficiency trajectories, and the corresponding approximations with PET, followed by an investigation of the large spread in gain over supply voltage. It is shown that supply modulation can be used for both linearization and efficiency enhancement of the PA.

The various trajectories are shown superimposed on the measured amplifier characteristics in Figs. 2 and 3. Fig. 4 shows the actual drain voltage trajectories vs. normalized input voltage. The chosen trajectories are simulated based on the measured PA model with two different signals, a 16QAM 4MSym/s signal and a 10MHz LTE signal. Fig. 5 and Fig. 6 show the corresponding spectrum of the modulated drain supply voltage for the two test signals. All results are summarized in Table I and Table II.

A. Maximum PAE trajectory

The maximum efficiency trajectory tracks the maximum PAE points for each drive level. This trajectory includes detroughing for voltages 10V - 13V and is shown as a black line in Figs. 2, 3 and 4. The PET trajectory is chosen to match the maximum PAE trajectory as closely as possible, starting and ending in the same points as indicated by the dashed black line in the mentioned figures.

Both trajectories suffer from large gain drop, as shown in Fig. 3, due to the strong dependence of gain on drain voltage in GaN HEMTs. This in turn results in large distortion and low average gain. The loss in gain causes the average PAE to be significantly lower than expected even though the output is following the instantaneous maximum PAE points. The PET trajectory shows similar results in terms of efficiency, linearity and gain, but the required bandwidth is significantly lower, as shown in Fig. 5 and Fig 6. For comparison, the amplifier is also simulated with a fixed drain supply with corresponding average output power shown in Table I and Table II.

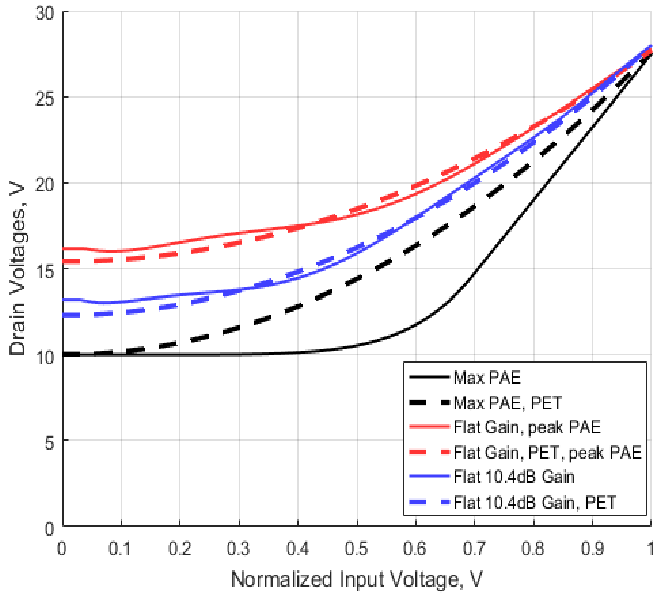

Fig. 4. The different trajectories for the different cases in solid lines. The approximated PET trajectories in dashed lines.

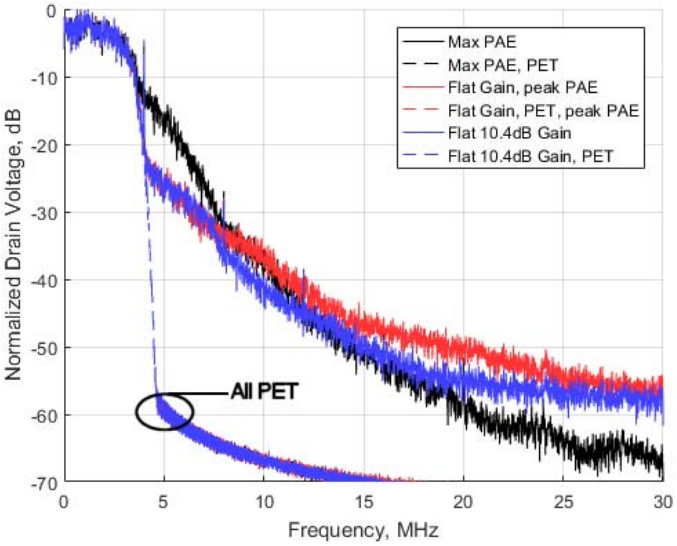

Fig. 5. Spectral content of the drain voltage for all trajectories and approximate PET trajectories for an applied 16QAM 4MSymb/s signal.

B. Constant Gain Trajectories

The large unwanted drop in gain vs. drain voltage can be exploited to improve linearity: choosing a trajectory for constant gain instead of the maximum efficiency results in a more linear PA with higher average gain. Two test cases are presented. The first trajectory is chosen for a gain of 12.1dB which hits the peak PAE point at the maximum drain voltage. The second trajectory follows a gain of 10.4dB. The resulting trajectories for the two cases are shown in solid red and blue lines in Figs. 2, 3 and 4, respectively. The PET trajectories are chosen to fit the corresponding average gains as closely as possible, and are again shown as dashed blue and red lines in the same figures.

Fig. 4 shows the previously discussed trajectories in terms of input drive voltage. Note that the tracking voltage (V_d)

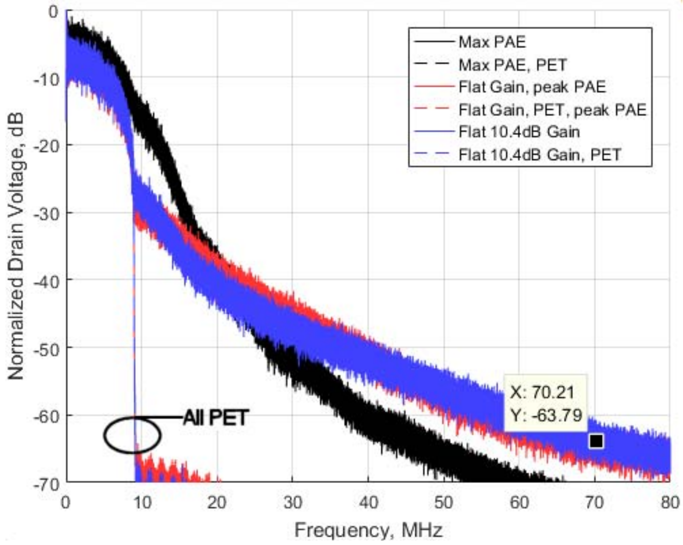

Fig. 6. Spectral content of the drain voltage for all trajectories and approximate PET trajectories for an applied 10MHz LTE signal.

range is smallest for the flat gain trajectories. This will lead to a lower slew rate requirement of the dynamic drain supply. One might expect that this would give a lower average PAE for the PA, but this is not the case. The gain is much higher for most of the input power range, the average output power is also higher, resulting in higher average efficiency of the constant gain case relative to the maximum PAE case. The linearity is comparable or better than the non-tracked amplifier at the same average output power, and significantly better than for maximum efficiency tracking.

The PET trajectories for constant gain show the same results regarding efficiency, linearity and gain, but the required bandwidth is again significantly lower, as shown in Fig. 5 and Fig. 6.

V. CONCLUSIONS

The conclusion of this paper is twofold. First, a greatly reduced bandwidth requirement of V_d is shown with the application of an approximate tracking function, PET. Using PET with only two coefficients, gives almost the same result as ET and is by nature detroughed. Second, a linearity improvement can be achieved by exploiting the strong gain dependence on the drain voltage. Choosing constant gain trajectories results in the best average PAE, with superior linearity compared to standard maximum PAE trajectory.

ACKNOWLEDGMENT

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TABLE I

Result for All Drain Voltage Trajectories, both ET and PET, using a 16-QAM, 4 MSym/s, α=0.22 Test Signal:

	Maximum Efficiency			**Flat Gain from Fig. 3**				
	Const.	**PAE**		**Const.**	**Peak PAE (G=12.1dB)**		**G = 10.4dB**	
	V_d=28V	**ET**	**PET**	**V_d=28V**	**ET**	**PET**	**ET**	**PET**
Po, dBm	30.5	30.0	31.9	33.6	33.5	33.5	33.7	33.7
PAE, %	23.0	42.1	48.1	37.7	49.2	49.7	**52.7**	**52.9**
EVM, %	3.1	9.6	6.6	4.3	**2.6**	**3.1**	4.8	4.6
ACPR_L, dBc	-37.9	-29.5	-30.9	-35.0	-39.1	-37.3	-34.6	-34.4
ACPR_U, dBc	-37.6	-29.2	-30.6	-34.8	-38.8	-37.1	-34.4	-34.2
Avg. Gain, dB	16,8	8.6	10.6	15.9	12.1	12.1	10.4	10,4
Required V_d Bandwidth, MHz	-	11 - 24	**4.5**	-	12 - 35	**4.5**	10 - 35	**4.5**

TABLE II

Result for All Drain Voltage Trajectories, both ET and PET, using a 10MHz LTE Test Signal:

	Maximum Efficiency			**Flat Gain from Fig. 3**				
	Const.	**PAE**		**Const.**	**Peak PAE (G=12.1dB)**		**G = 10.4dB**	
	V_d=28V	**ET**	**PET**	**V_d=28V**	**ET**	**PET**	**ET**	**PET**
Po, dBm	25.4	25.4	26.8	29.2	29.1	29.0	29.3	29.3
PAE, %	9.0	23.2	27.3	19.3	29.3	29.5	**35.0**	**35.6**
EVM, %	3.6	4.9	8.9	5.2	**3.2**	**4.4**	4.6	5.3
ACPR_L, dBc	-38.1	-34.3	-30.2	-34.6	-38.7	-36.1	-35.9	-34.4
ACPR_U, dBc	-37.7	-33.9	-29.8	-34.2	-38.4	-35.7	-35.5	-34.0
Avg. Gain, dB	17.1	8.4	9.8	16.6	12.1	12.0	10.4	10,4
Required V_d Bandwidth, MHz	-	24 - 45	**9.1**	-	28 - 64	**9.1**	25 - 70	**9.1**