Bandwidth-Reduced Supply Modulation of a High-Efficiency X-band GaN MMIC PA for Multiple Wideband Signals

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***Abstract*—This paper introduces bandwidth reduction methods for supply modulation when multiple broadband signals spread over a wide RF bandwidth are simultaneously amplified by a high-efficiency PA. The PA is a GaN on SiC MMIC in the Qorvo 150-nm process with two stages and power combining at the output. With a CW signal at 9.8 GHz, the peak power is 8 W with a peak efficiency of 56% and a saturated gain greater than 23 dB. Three 16QAM signals with bandwidths of 1, 2 and 5 MHz, separated by 70 and 130 MHz and centered around 9.8 GHz have a combined envelope bandwidth of > 800 MHz and a PAR around 9.5 dB, which is too large for an efficient envelope modulator. We show that the tracking bandwidth can be significantly reduced when the envelopes of the individual signals are summed at baseband. Measured results show 42.4% PAE and 18.8% worst-case EVM when tracking is used, compared to 29.7% PAE and 14.4% EVM for a fixed supply with no linearization.**

I. Introduction

Multi-band power amplifiers (PA) for carrier aggregation and multi-function transmitters are in high demand in order to reduce cost and size. This demand, however, is at odds with efficiency requirements, as efficiency enhancement techniques tend to restrict bandwidth. Envelope tracking (ET) is a promising technique [1], but becomes prohibitively challenging as the signal bandwidth increases, due to bandwith expansion of the tracking signal and the tracking amplifier efficiency which decreases as envelope bandwidth increases. Methods for improving the efficiency of ET systems for high-bandwidth signals include slew-rate reduction of the envelope signal, which can be compensated for by the PA drive signal [2], [3],

When multiple signals of arbitrary modulation type and widely separated carrier frequencies are amplified simultaneously, the total signal bandwidth exceeds what can be achieved using conventional ET. Works that have explored Multi-band envelope tracking is explored in [4] for a frequency-tunable PA, but the bands are not used simultaneously. In [5]–[7], ET is demonstrated on two simultaneous signals, and make the important observation that the bandwidth of the *sum of the envelopes* of the two modulated signals is substantially lower than that of the envelope of the total signal. The work in [5]–[7] focuses on 3D linearization of two relatively closely spaced signals, for example for dual-band carrier aggregation.

In this work we instead examine the bandwidth of multiple simultaneous, arbitrarily-spaced signals as might be required for a multi-band, multi-function transmitter. We demonstrate the proposed bandwidth-reduced supply modulation using three modulated signals, but the approach is general and can be extended to additional signals. The technique is implemented on a high-efficiency X-band MMIC PA using a linear tracker.

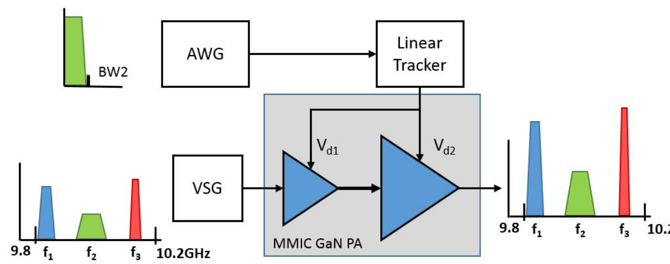

Fig. 1. Block diagram of a supply-modulated PA for multiple signals over a broad RF bandwidth. In this case a two-stage PA is supply-modulated with a linear tracker. Three simultaneous signals with bandwidths of 1,2 and 5 MHz, separated by 70 and 130 MHz within a 9.8 - 10.2 GHz bandwidth are amplified efficiently.

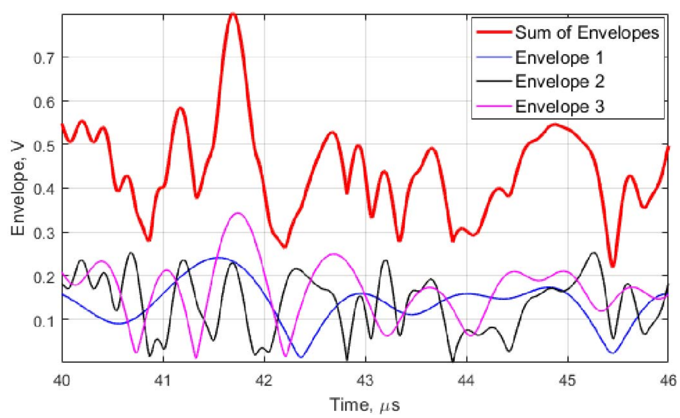

Fig. 2. Three signal envelopes in baseband showing the sum of the envelopes (red, thick) used for tracking.

II. Theoretical Background

The supply-modulated transmitter in which three modulated signals at carrier frequencies f_1, f_2, and f_3 are amplified by a MMIC PA with linear supply tracker is shown in Fig. 1. The total bandwidth of the input signal is approximately $(f_3 - f_1)$, assuming the modulation bandwidth is substantially smaller than the signal separation. Using a conventional ET approach, the bandwidth expansion of the nonlinear envelope

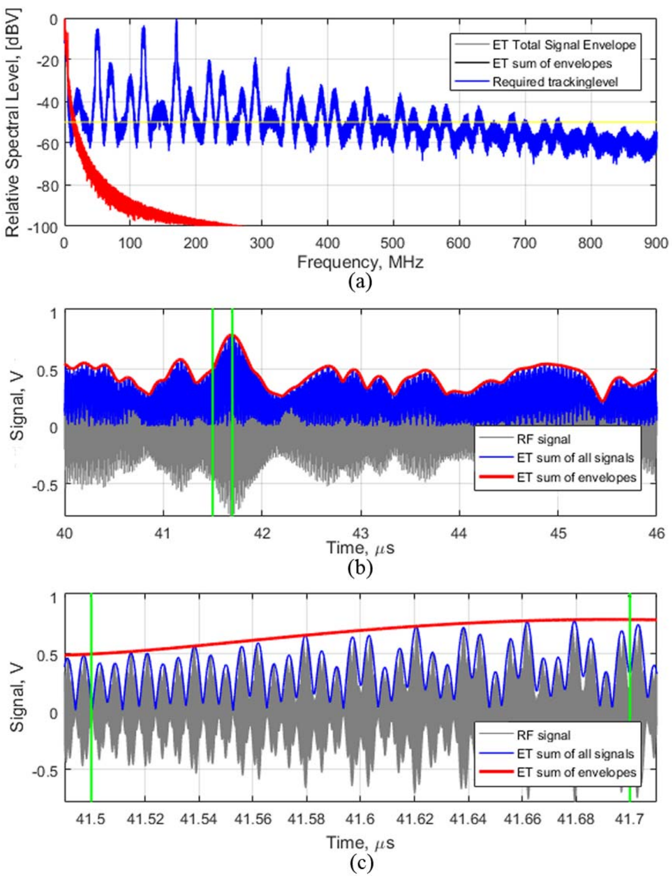

Fig. 3. (a) Ideal spectra of combined envelope (blue) and summed envelopes (red). (b) Time domain waveforms of the same and (c) Zoomed in time domain waveform showing the carrier, combined envelope and summed envelope.

computation means that a bandwidth of at least $5 \times (f_3 - f_1)$ is required for the tracker. For our example signals separated by up to 200 MHz, an efficiency 1 GHz tracker would be needed, which has not been demonstrated to date. The fastest integrated trackers in 150-nm GaN switch at 200 MHz and are able to track 40 MHz signal bandwidth [8].

To reduce the tracker bandwidth requirements, we investigate tracking based on the sum of the envelopes of the multiple signals:

$$E_{\text{track}}(t) = \Sigma_i^N |E_i(t)| \tag{1}$$

where $E_i(t)$ is the envelope of one of the N multiple signals to be amplified. Conceptually, this approach treats the multiple signals as time-varying vectors, and tracks the amplitude of the worst-case envelope, i.e. the condition when all vectors add constructively. In this way, the composite signal is never clipped by the tracker. A time-domain simulation of the resulting signal is shown in Fig. 2. Qualitatively, the sum of envelopes has dynamics dominated by that of the fastest-varying signal. Note that it is only the modulation bandwidth, not the separation of the carrier frequencies, that affects the tracking signal as this computation is performed on the baseband signals.

The frequency-domain analysis is shown in Fig. 3(a) and confirms the bandwidth benefits of this approach. The envelopes of three 16QAM signals centered around 9.8 GHz with bandwidths of 1, 3, and 5 MHz and with various spacings (as detailed in Table I), are combined. Conventional ET requires 800 MHz tracking, while tracking the sum of envelopes requires only 17 MHz, a reduction by approximately a factor of 50 in bandwidth. Fig. 3(b) compares the combined RF signal (grey), its envelope (blue), and the sum of envelopes signal (red). In the zoomed in section of Fig. 3(c), it can be seen that the sum of envelopes tracks the peak of the conventional envelope signal at much lower bandwidth, but does not deviate into the troughs of the signal. When an ideal class-B PA is assumed, the simulated efficiency when the sum of the envelopes is tracked is 52%, whereas linear class-B operation at peak output power results in only 23% efficiency.

III. Measurement Results

To verify the sum of envelopes tracking approach, we constructed a test bench based on an X-band MMIC and a hybrid linear tracker. The approach is demonstrated for three signals with varying spacing and relative power levels. Details of the experimental setup and measurements are described below.

A. MMIC PA and Hyrbid Linear Tracker Test Bench

The PA is a two-stage MMIC implemented in the Qorvo 0.15 μm GaN-on-SiC HEMT technology. It is designed to be stable with no external capacitors on the bias network, since the drain bias network needs to pass broadband signals from the dynamic supply. The first driver stage of the PA is composed of two $8 \times 50\,\mu$m devices, while four $10 \times 90\,\mu$m devices are combined in the second stage, with a saturated gain greater than 20 dB at 2-3 dB gain compression. The maximum drain supply voltage is $V_{DD} = 20\,$V, for a total class-AB quiescent drain current $I_D = 310\,$mA. Both stages are supply-modulated for the measurements presented here.

Off-chip bypass capacitors are added to all but the second stage drain bias line to ensure PA stability. No capacitance is added to the second stage drain pad to enable fast supply modulation. The only bypass capacitance to this node is provided by the on-chip integrated MIM (Metal-Insulator-Metal) capacitors, for a total value of 30 pF. The connection between the supply modulator and the PA is kept as short as possible to reduce inductance. The PA is soldered on a CuMo carrier and the input/output RF pads are wire-bonded to 50-Ω microstrip lines on alumina. The PA frequency sweep shows a bandwidth from about 9 to 10.5 GHz, with peak efficiency at 9.7 GHz. The PA measured dependence on supply voltage and frequency is summarized in Fig. 4.

The linear tracker is designed around the Analog Devices ADA4870 Current Feedback operational amplifier, chosen for its superior current drive, slew rate, and bandwidth. The ADA4870 can source a maximum of 1A, requiring just two opamps in parallel to drive the RFPA to its peak drain current of 1.5 A. The slew rate specification of $2500\,V/\mu s$ suggests

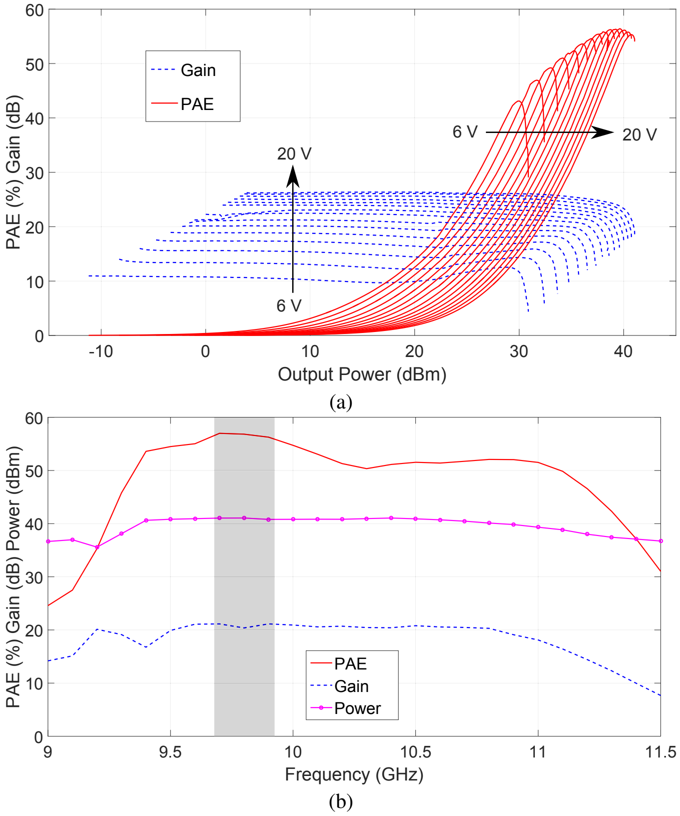

Fig. 4. CW measurements of the supply modulated PA; (a) – Measured CW performance of the MMIC PA at 9.8 GHz, (b) – performance across frequency. The frequency range used for the modulated testing is highlighted in grey.

TABLE I
SUMMARY OF PERFORMANCE FOR SEVERAL SIGNAL SCENARIOS

f_1,f_2,f_3 (GHz)	P_1,P_2,P_3	Drain	PAE (%)	EVM (%) 1	2	3
9.7, 9.83, 9.88	0.33, 0.33, 0.33	Track	42.4	13.8	16.7	18.8
		Fixed	29.7	8.7	11.3	14.4
9.7, 9.83, 9.9	0.2, 0.5, 0.3	Track	41.6	17.2	20.2	24.8
		Fixed	29.4	10.9	6.8	15.3
9.73, 9.85, 9.9	0.33, 0.33, 0.33	Track	41.1	12.3	16.4	19.1
		Fixed	29.8	9.4	10.8	13.9
9.73, 9.85, 9.9	0.2, 0.5, 0.3	Track	40.1	14.1	18.5	19
		Fixed	28.8	9.2	10.6	12.1

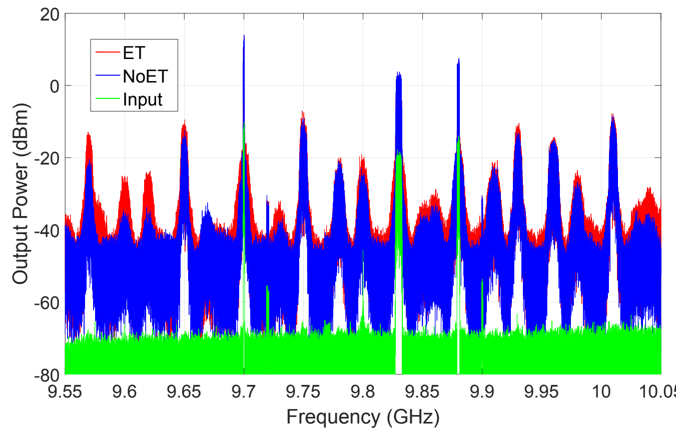

Fig. 5. Measured spectrum of signals at the PA output with and without reduced-bandwidth supply modulation.

that the circukt is capable of distortion-free tracking of singals with bandwidths up to 28 MHz for an output voltage swing of 6-20 V (14 V_{p-p}). A 200 mΩ series resistor, R_s, is added to each of the amplifier outputs to help stabilize the op amps from capacitive loading under various biasing conditions of the RFPA. During construction and testing of the linear tracker, it was found that an additional 200 mΩ resistor was necessary at the combined output of the linear tracker.

B. Supply Level Modulation PA Performance

The PA test bench is characterized in CW across different supply levels and frequencies as shown in Fig. 4. Because the signal is received with a vector signal analyzer with limited bandwidth, the frequency range of operation is down-selected to the 9.7 – 9.9 GHz range highlighted in grey. Within this frequency range, the PA is measured with several different signal scenarios, in which the relative spacing and average power levels are varied. A summary of these measurements is given in Table I. For each signal scenario, the PA is measured with and without reduced-bandwidth supply modulation. The PAE values in Table I do not include the efficiency of the linear amplifier. Supply modulation improves the PA PAE by approximately 11 percentage points in each case.

Fig. 5 shows the full measured spectrum at the PA with and without supply modulation for the first scenario in Table I. Significant mixing products can be seen due to the nonlinearities of the PA, even with a fixed supply. Supply modulation exacerbates this nonlinearity, as is expected from the supply-dependent gain seen in Fig. 4. The normalized individual signal spectra are shown in Fig. 6. It is expected that the nonlinearities can be corrected using predistortion techniques such as those described in [5], [6].

IV. CONCLUSION

When multiple arbitrarily spaced signals are amplified by a single PA, conventional ET results in bandwidths too large for an efficient envelope modulator. We show that the tracking bandwidth can be significantly reduced when the envelopes of the individual signals are summed at baseband. Experimental validation shows that this approach results in 12.7 percentage points higher PAE in an X-band PA operating on three equal-power 16QAM signals within a 200 MHz bandwidth centered around 9.8 GHz.

V. ACKNOWLEDGEMENTS

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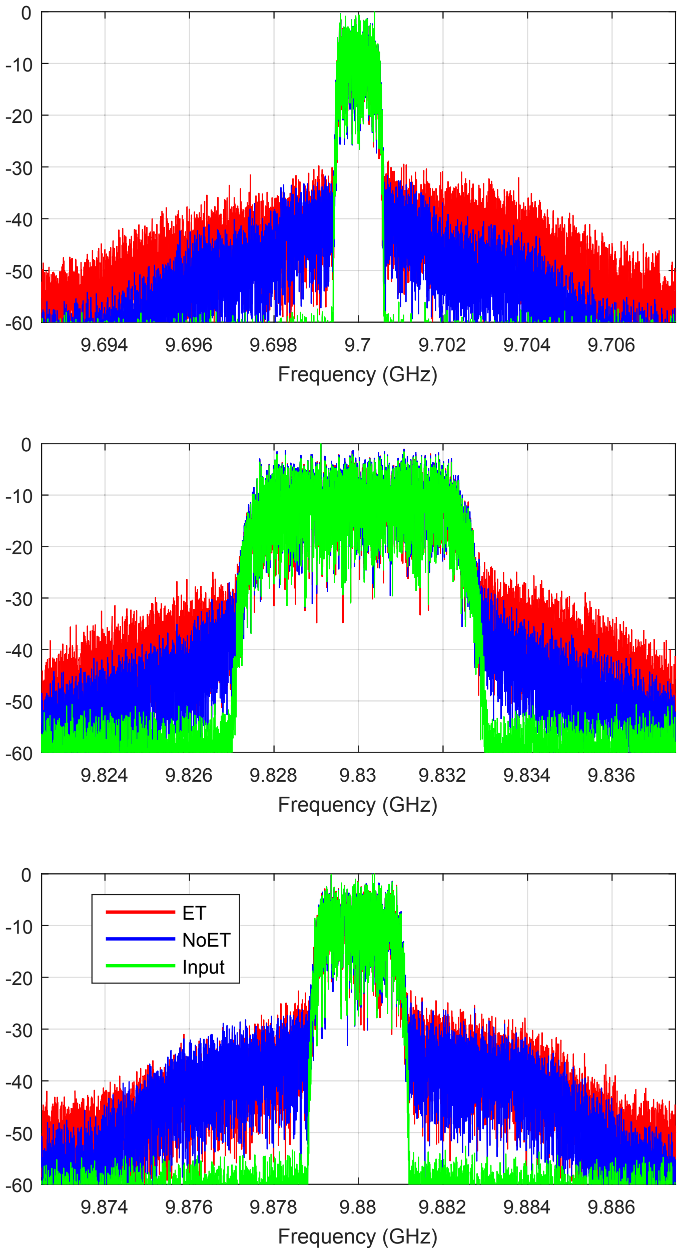

Fig. 6. Measured normalized individual signal spectra at the input of the PA (green), output of PA with no supply modulation (blue) and output of PA with reduced bandwidth supply modulation (red).

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