A Baseband Feedback Approach to Linearization of a UHF Power Amplifier

William Sear[1], Taylor W. Barton[2]
Department of Electrical, Computer, and Energy Engineering,
University of Colorado, Boulder, 80309, USA
[1]william.sear@colorado.edu, [2]taylor.w.barton@colorado.edu

***Abstract*— This work presents a power amplifier (PA) linearization approach based on baseband feedback. The modulated signal envelope is fed back from the transistor's drain to its gate with an applied amplitude and phase shift selected to reduce the intermodulation distortion (IMD3) product at the output. The design targets IMD3 improvement near the PA's 1-dB compression point (P1dB), enabling linear operation at a higher output power level and therefore improved device periphery utilization and efficiency. This approach offers a potential linearization alternative to digital pre-distortion, which cannot be applied in some systems, without affecting the RF performance. The 850-MHz proof-of-concept prototype based on a 15-W GaN device is characterized with a two-tone measurement with 5-MHz spacing, and demonstrates 9-dB improvement of the lower IMD3 tone near the P1dB point.**

***Keywords*— Distortion reduction, baseband, Gallium nitride, power amplifiers (PA), radio frequency (RF)**

I. Introduction

Modern communications and RADAR transmitters require power amplifiers (PAs) to operate with increasingly high instantaneous bandwidths to meet system demands, while also maintaining linearity and efficiency performance. The most common strategy to simultaneously meet these conflicting requirements is to design for broadband efficiency, sacrificing linearity, and then apply a broadband, memory-based digital pre-distortion (DPD) to linearize the PA. In many applications, however, it is not possible to include DPD. Example scenarios include when the digital baseband signals are not available, as in repeaters operating directly on a modulated signal, or when system complexity limits the ability to sample individual PA outputs, for example for active antennas within phased arrays. Furthermore, because of the oversampling required for digital linearization, the effectiveness of DPD becomes limited as instantaneous bandwidth increases [1]. In cases where DPD is not possible, it is often necessary to "back off" the PA output power to meet linearity requirements, which further degrades efficiency.

The alternative to DPD presented in this work is to employ an analog correction technique in the PA design to improve its linearity without affecting system complexity. Unlike in conventional analog pre-distortion techniques, the approach feeds back the modulated signal envelope from the transistor's drain to its gate. This technique actively corrects linearity through a low-frequency feedback path in the bias networks. Because the feedback is performed at the intermediate frequency (IF) instead of at RF, the fundamental-frequency performance of the PA—including its gain—is largely unaffected.

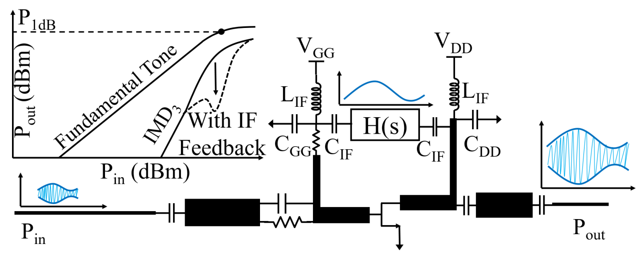


Fig. 1. Block diagram layout of a power amplifier capable of suppressing intermodulation distortion under a high input power, complex modulation excitation through IF feedback.

The prototype 850-MHz PA presented in this work demonstrates proof of concept for the proposed linearization technique. The feedback transfer function is designed to reduce the third-order intermodulation distortion (IMD3) products for an example two-tone case, based on both theoretical analysis and large-signal simulation using a device model that partially captures behavior at the IF [2]. The 15-W prototype is characterized with a 5-MHz tone spacing with and without feedback, and demonstrates a 9-dB improvement in the lower IMD3 tone when baseband feedback is applied. The specific design goal is to lower the IMD3 product near the 1-dB compression point (P1dB), enabling linear operation up to higher output power levels.

II. Baseband Feedback Theory

In the linear region of PA operation under two-tone test, the dominant nonlinear behaviors producing IMD3 products are the nonlinear conductance and nonlinear capacitance of the active device [3]. These nonlinear device parameters relate to IMD3 tone power through the impedance presented to the output of the device at the modulation frequency of the applied signal. The theory underlying the relationship between the IF impedance termination at the drain of the transistor and the resulting intermodulation product strength under two-tone excitation is described in detail in [4] and [5].

It is commonly understood that presenting a perfect short-circuit impedance to the device at the IF will minimize IMD3 effects, by eliminating self-modulation at the drain of the transistor. In fact, it has been demonstrated that if it is possible to present a negative IF impedance to the drain, the IMD3 tone powers can be substantially canceled [6]. In [6], this negative impedance improvement on IMD3 is demonstrated experimentally using an active IF load-pull test bench.

Equivalent performance can be achieved by introducing a feedback loop between the input and output of the amplifier at the IF. Conceptually, instead of injecting an externally generated tone, we are using the tone generated by the nonlinear response of the transistor, and injecting that signal back into the drain through a signal path that includes the IF gain of the transistor. This loop is designed such that it modifies the effective IF impedance to minimize the IMD3 tones' power without affecting the fundamental tones' output power. This approach is illustrated in Fig. 1, in which an IF feedback path is inserted between the drain and gate bias lines at the RF short nodes but before the baseband choke. The transfer function $H(s)$ is generalized as (1) and represents an arbitrary gain and phase shift to the signal in the IF range.

$$H(s) = G(s)e^{j\theta(s)} \tag{1}$$

The optimal values of G and θ depend on both frequency and on the strength of the IF tone generated by the nonlinear response of the transistor, which in turn is a function of input signal power. In other words, for a given tone spacing the transfer function can be designed to improve IMD3 at a particular input power level. The baseband feedback concept was originally reported in [7] using a controlled laboratory feedback path applied to a GaAs device and at relatively low input power levels. Here, we present an on-board passive circuit capable of realizing an IMD3 improvement in a GaN device at high RF output powers near compression.

III. Prototype Design

The proof-of-concept prototype is designed for operation around 850 MHz using the Wolfspeed CGH27015F (15W) packaged GaN device. The PA is designed to exhibit conventional class-AB performance with a saturated output power of 42 dBm. The goal of the baseband feedback design is to target the PA's 1-dB output power compression point, which occurs at 24 dBm input power. By improving IMD3 near compression, then, the PA can in principle be driven at a higher input power level.

Initial design was performed in simulation using a large-signal model. The model described in [2] was selected for this work because it has additional modeling of the IF response compared to the manufacturer-provided model of this device, although our usage is not the intended application. The information available in simulation, even with the additional IF information, is not sufficient for an accurate model of the IMD3 response of the device under compression conditions. As a result simulation results will be used only to approximate the trends in the upper and lower IMD3 tones as a function of G and θ.

The need to feed back low-frequency signals also imposes the constraint on the gate and drain capacitances (C_{GG} and C_{DD}) that they cannot be so large as to short the envelope signal. This introduces the potential for low-frequency oscillations in the gate and drain bias lines. These oscillatory conditions are also not fully captured by the device model. In practice the amount of capacitance at each node is determined experimentally to stabilize the PA with the smallest possible capacitance value, so as to minimize the perturbation of the low frequency feedback path.

To determine the optimum baseband transfer function its

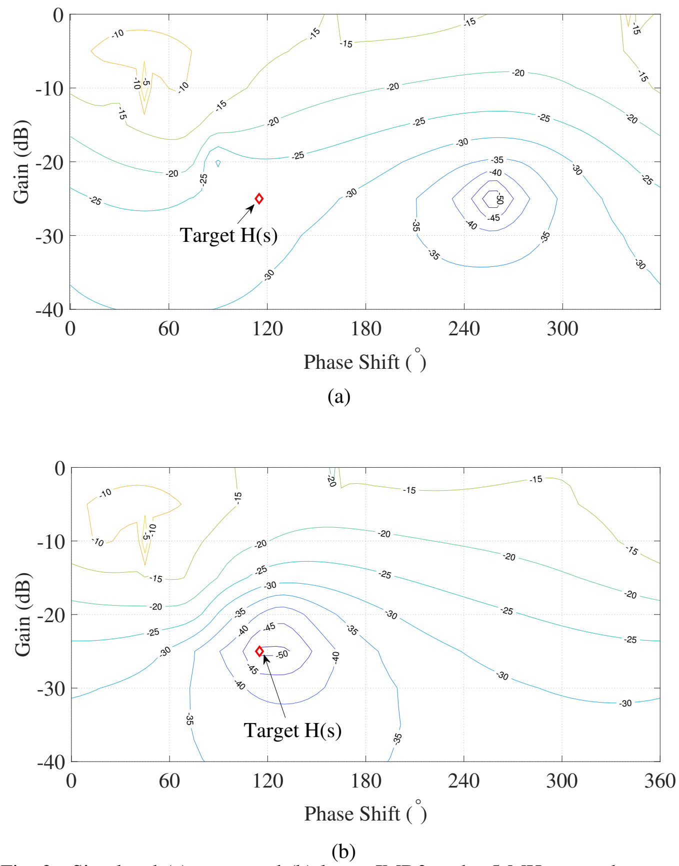


Fig. 2. Simulated (a) upper and (b) lower IMD3 under 5-MHz spaced tones with 24-dBm input tone power as a function of baseband feedback transfer function at 5 MHz.

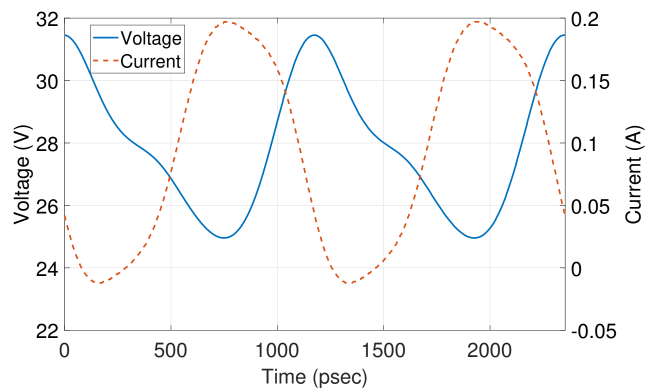


Fig. 3. Small-signal intrinsic drain voltage and current waveforms showing a signficant second harmonic component.

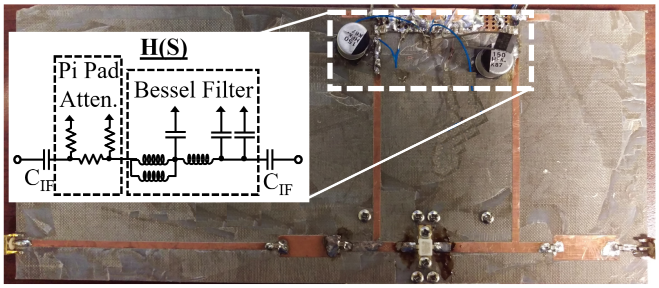


Fig. 4. The 215.9 mm by 88.9 mm baseband feedback power amplifier.

gain and phase are swept in simulation while the amplifier is under 5 MHz spaced two-tone signal excitation at the 1-dB output power compression point. The resulting upper and lower IMD3 contours in the (θ, G) plane are reported in Fig. 2. From these results it is clear that the upper and lower IMD3 tones for this particular device, bias point, and IF drain termination each exhibit different feedback network minima, situated at the same gain level but with different phases. In a class-AB amplifier with a perfect second harmonic short the upper and lower IMD3 minima should, according to theory, occur at the same gain and phase point [6]. The separate upper and lower minima points observed in Fig. 2 indicate a reactive second harmonic termination causing the IMD3 minima to separate when a negative IF impedence is presented. This effect of reactive harmonic termination has also been experimentally demonstrated in [8]. The presence of a second harmonic component can clearly be seen in the simulated small-signal intrinsic drain voltage and current waveforms reported in Fig. 3. In order to simultaneously improved both the upper and lower IMD3 tones, then, the PA's second harmonic termination should be adjusted to present a short circuit at the intrinsic plane.

For this prototype the lower IMD3 minimum at -25 dB gain and 115 degrees of phase shift was selected as the initial transfer function due to its greater potential IMD3 suppression and smaller required phase shift compared to the upper IMD3 tone minimum. This target point, shown in Fig. 2, is expected to improve the lower IMD3 tone while not substantially degrading the upper tone relative to its nominal case, i.e., zero feedback gain.

IV. Measurement

A photograph of the baseband feedback amplifier implemented on Taconic TLY-5 substrate is shown in Fig. 4. The RF signal path flows from left to right along the bottom of the figure while the baseband feedback network is implemented along the top of the figure at the end of the quarter-wavelength bias lines. Fig. 4 also shows the cascaded four-pole Bessel filter and pi-pad attenuator that form the baseband feedback network.

The smallest-valued capacitance on the gate that ensures stability was experimentally found to be 240 pF. This capacitance is not large enough to ideally short the baseband signal components (by design), and therefore makes the

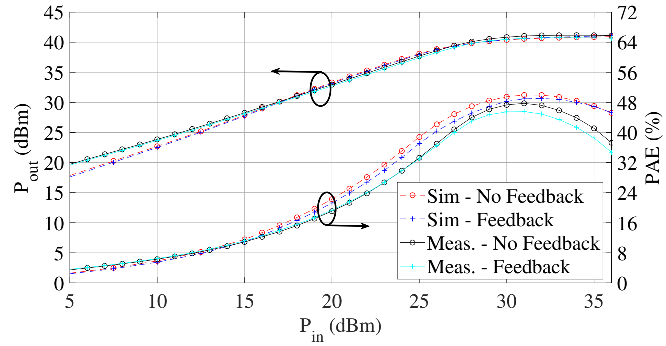
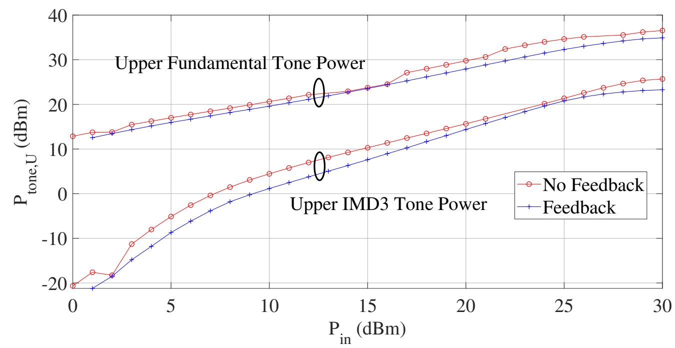
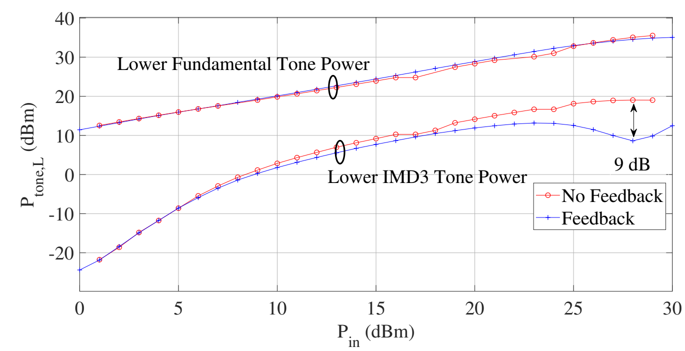


Fig. 5. Simulated and measured CW output power and PAE of PA with and without IF feedback at 5MHz present.



(a)



(b)

Fig. 6. Measured fundamental and IMD3 tone power under 5 MHz tone spacing for (a) upper and (b) lower tones compared with and without feedback.

overall linearity dependent on the transfer function. In this purely proof-of-concept design the transfer function is optimized for one tone spacing only, and presents non-optimal terminations to all other baseband frequencies. The performance in backoff of the fabricated PA is therefore degraded compared to an ideally passively terminated design, but it demonstrates lower IMD3 at the designed input power and tone spacing.

The power amplifier is first characterized under CW excitation at 850 MHz. Fig. 5 reports the output power and power-added-efficiency (PAE) of the amplifier and compares the measured results to simulation. The measured results compare favorably with simulated results for both output power and PAE in all cases. The introduction of a baseband feedback network does not degrade output power in any meaningful way and results in at most a three percentage point degradation in PAE compared to the amplifier without baseband feedback.

Fig. 6 reports the measured output power per tone for the fundamental and IMD3 products of the power amplifier under two-tone excitation. As expected the baseband feedback network does not introduce any power loss in either upper or lower fundamental output tones compared to an amplifier without baseband feedback. The addition of baseband feedback does not perturb the upper IMD3 tone while suppressing the lower IMD3 by 9 dB at the P1dB point as designed. No predistortion was applied to any of the reported measurements.

V. Conclusion

The baseband feedback technique presented in this work offers an analog linearization method that is implementable with simple analog circuits at the modulation frequency of the signal without perturbing the RF PA design. In this proof-of-concept prototype the baseband feedback network is successfully demonstrated to suppress the lower IMD3 term under a 5-MHz tone spacing around the P1dB point of the PA as designed. The capability to suppress IMD3 in gain compression prevents the need for operating the PA in backoff, thus allowing for higher efficiency operation, while maintaining linearity under a complex modulation envelope. Although it incurs a small penalty in terms of design complexity, the approach does not affect complexity at the system level.

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