An Efficient Linearized Octave-Bandwidth Power Amplifier for Carrier Aggregation

Maxwell R. Duffy, Eric Berry, Gregor Lasser, and Zoya Popović
Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, USA
Email: Maxwell.Duffy@colorado.edu, Eric.Berry@colorado.edu, Gregor.Lasser@colorado.edu, zoya@colorado.edu

***Abstract*—In this paper, a single-stage octave bandwidth power amplifier from 2-4 GHz with greater than 10 W output power and drain efficiency ranging from 55-70 % is presented. Input and output networks are synthesized to match the fundamental, 2nd and 3rd harmonics for efficiency, based on load-pull simulations. The amplifier performance is characterized over the entire band for a 20-MHz LTE signal with a PAPR of 8 dB, demonstrating an average efficiency greater than 25 % with a normalized mean square error (NSMR) below -28 dB. Two 20-MHz signals are then simultaneously amplified with a spacing that varies from 200 MHz to 1 GHz, with resulting average efficiencies over 28%.**

***Index Terms*—Power amplifiers, efficiency, GaN, broadband, carrier aggregation.**

I. Introduction

The trend to replace multiple power amplifiers (PAs) with a single component has led to broadband power amplifier development, especially for carrier aggregation. Doherty [1], [2] and other load-modulated PAs [3], [4], as well as envelope tracked PAs [5] designed for improved efficiency at backoff use at least two amplifiers. The goal of this paper is to investigate a compact single-ended broadband PA in the context of multiple, widely-spaced, high PAPR signals.

Multiple methods for single-ended GaN broadband power amplifiers with harmonic tuning have been demonstrated, including a class-J [6], continuous class-F [7], and load-pull optimized [8], [9]. In all cases, the output impedance at the fundamental is matched for efficiency over the entire band, while the harmonics are terminated in various manners, and the device is biased in class AB or B. For maximum efficiency, the saturation level results in the need to linearize the PA.

In this work, an octave bandwidth GaN high power amplifier (HPA) is reported and measured. The Cree CGH40010F GaN-on-SiC HEMT with an available nonlinear model is chosen and the amplifier network is synthesized using stepped impedance transformations with harmonic terminations. In addition to static measurements, the amplifier is tested using a 20-MHz LTE signal with and without digital pre-distortion (DPD). Multi-signal testing is performed using two 20-MHz LTE signals with varying spacing.

II. Broadband Amplifier Design

The broadband amplifier design is based on simulated load-pull for maximum efficiency over 2 to 12 GHz, which takes into account up to the third harmonic of the highest frequency in the band. The sensitivity to the impedance at the fundamental frequency is examined to inform required matching for flat efficiency across the band. Fig. 1 illustrates the procedure that determines the region where the drain efficiency is greater than 65 %. The range from 3.5-4 GHz is, as expected, most affected by impedance variations. A trade-off in the fundamental frequency match sacrifices efficiency in the lower frequency range (2-3 GHz) which reaches over 80% when optimized in load-pull. The matching circuits are designed with a focus on maximizing efficiency and gain in upper part of the band (3-4 GHz), resulting in a flat efficiency and gain response.

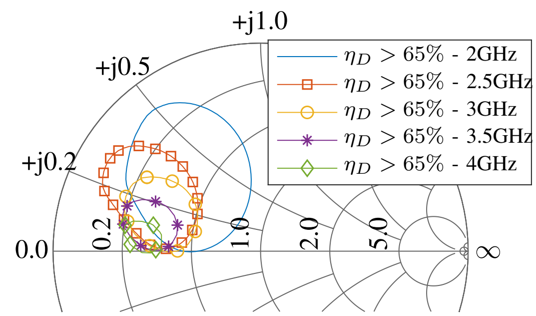

Fig. 1. Maximum drain efficiency contours of the fundamental (2-4 GHz). With increased frequency the efficiency contours shrink.

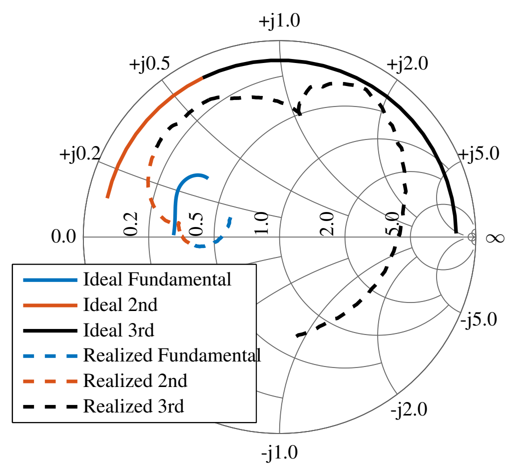

Fig. 2. Output impedance targets of the fundamental (2-4 GHz), second (4-8 GHz), and third harmonic (6-12 GHz) from simulated load pull (solid). Realized impedances of output matching network (striped). Because the second harmonic has a higher impact on efficiency than the third, it takes precedence where the two overlap.

To achieve broadband matching, short transmission line sections that approximate lumped elements over the band are implemented, similar to the stepped-impedance networks in [9], [10]. The final topology is generated by constraining the number of transmission line sections to three at the output, and two at the input, with a goal of simplicity and reduced footprint. The range of microstrip line impedances is constrained between 15 and 70 Ω. The ideal terminations found from load-pull and the realized output matching network impedances are shown in Fig. 2. A parallel R-C network is added in series at the gate terminal in the input match to ensure stability, with values resulting from stability analysis. The fabricated amplifier is shown in Fig. 3, and the CW measured results are summarized in Fig. 4. In the operating range of 2-4 GHz, the amplifier maintains a drain efficiency greater than 55%, output power over 40 dBm and large signal gain of 10 dB.

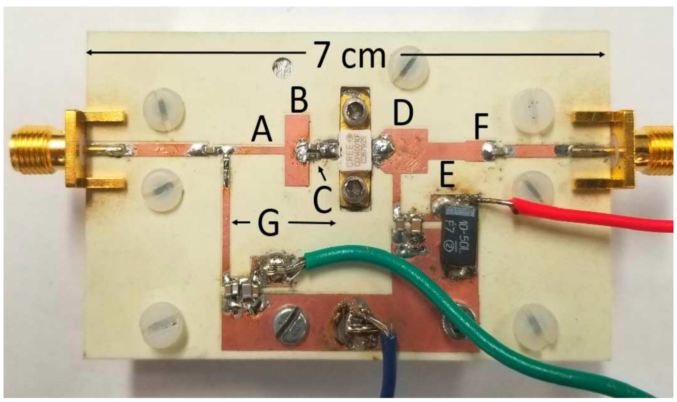

Fig. 3. Fabricated 2-4 GHz power amplifier with stepped impedance line segments of A-66 Ω, B-15 Ω, C-gate stability network, D-21 Ω, E-41 Ω, F-36 Ω, G-1.5 cm. The substrate is a 0.762 mm Rogers 4835.

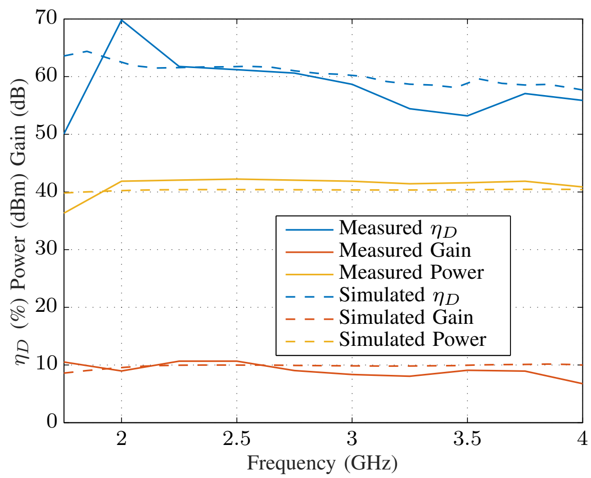

Fig. 4. Amplifier large signal performance at saturation over frequency. Shown are both measured (solid) and simulated (dashed) results.

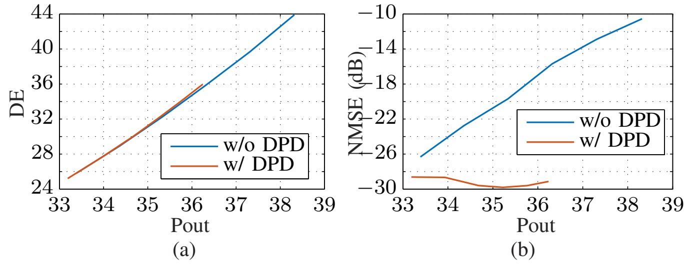

Fig. 5. Amplifier performance vs output power. (a) drain efficiency (b) normalized mean square error with (red) and without (blue) digital pre-distortion. Results are shown at 2.25 GHz.

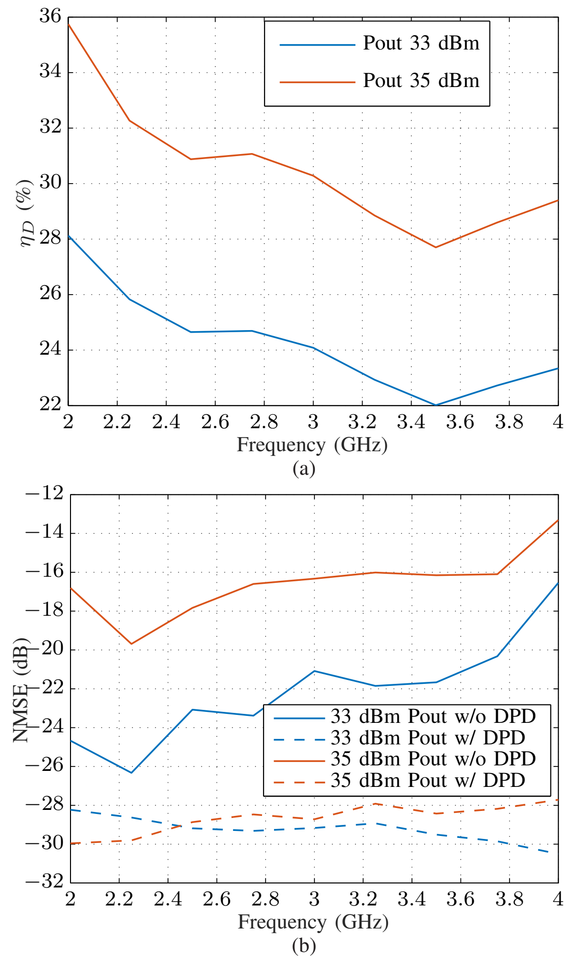

Fig. 6. Amplifier performance is shown with 35 dBm (red) and 33 dBm (blue) average output power vs frequency. (a) Drain efficiency and (b) normalized mean square error with (dashed) and without (solid) digital predistortion.

III. LTE Signal Results

Linearity testing of the amplifier is performed using a 20-MHz LTE downlink signal, with an 8.2 dB PAPR, generated in MATLAB. Measurements are first done with the original signal, and subsequently with DPD applied. The amplifier is linearized using the model shown in [11] with a 7th order polynomial and 7 memory taps.

The amplifier is tested by stepping output power in 1 dB intervals from 33 to 38 dBm. At each of these steps a DPD

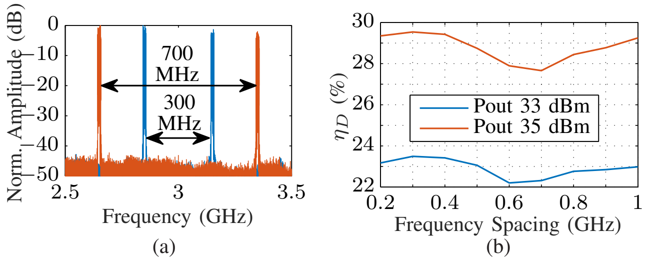

Fig. 7. (a) The input spectrum for two 20 MHz LTE signals with 300 MHz (blue) and 700 MHz (red) spacing. (b) Amplifier drain efficiency with 35 dBm (red) and 33 dBm (blue) output power vs. frequency spacing.

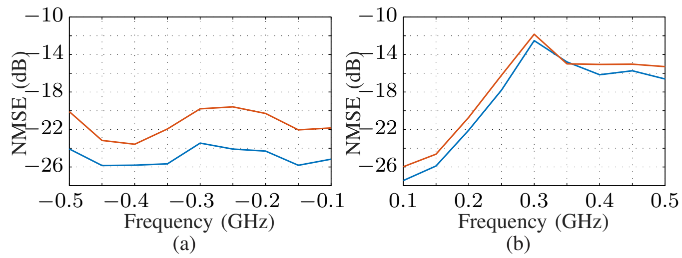

Fig. 8. Amplifier linearity performance with 35 dBm (red) and 33 dBm (blue) output power vs frequency. (a) The lower band normalized mean square error and (b) the upper band normalized mean square error.

model is generated and applied. In Fig. 5a it is shown that amplifier output power and drain efficiency remain the same with and without DPD. The DPD reduces the output power but does not affect efficiency for that output power. In Fig. 5b, we see the improvement in normalized mean square error (NMSE) that results from using DPD for a given output power. At $P_{out} = 36$ dBm we see a 15 dB improvement in NMSE with no degradation in efficiency. This is interesting because it shows that power and efficiency do not need to be sacrificed for linearity up to a point.

Signal testing is done from 2-4 GHz and results gathered with and without DPD for $P_{out} = \{33, 35\}$ dBm. Fig. 6a shows variation in average η_D for the two output power levels using our LTE signal. In Fig. 6b we see that DPD improves the NMSE by 15 dB for the the higher power case and 7 dB for the lower power case. It can be seen that linearity performance degrades as frequency increases.

IV. Multiple Signal Results

The amplifier is tested with two concurrent 20 MHz LTE signals which are moved in 100 MHz steps from a center frequency of 3 GHz. The composite PAPR of this signal is 10.3 dB. The input spectrum for two of these cases is shown in Fig. 7a. Results are presented for $P_{out} = \{33, 35\}$ dBm. Fig. 7b shows drain efficiency as a function of signal spacing. The drain efficiency of the amplifier stays practically constant over spacing (+/- 1 percentage point).

In Fig. 8 we can see the NMSE of the upper and lower band as a function of signal spacing. The lower band has a more constant NMSE with signal spacing whereas the upper band peaks up to a -12 dB NMSE error with 600 MHz signal separation. The results from Fig. 6b showed a degradation in linearity in the upper frequency band of the amplifier, so this is expected.

V. Conclusion

In summary, an efficient broadband PA for carrier aggregation is demonstrated. The design method, using stepped impedance matching, is successful in synthesizing an efficient high power amplifier (55-70 % drain efficiency > 10 W output). A comparison of these results with other published works in shown in Table I. LTE signal testing with DPD shows high average efficiency (28-36 %) for a 20 MHz signal across the band. Testing with two modulated signals shows high efficiency, and ongoing linearization efforts for the multiple signal case will be reported in the final paper.

TABLE I
Comparison of Broadband PA Performance

Reference	Type	BW(%),CF(GHz)	η_D(%)	PSAT(dBm)
[6]	CJ	60, 2	60-70	40
[7]	CCF	170, 1.35	55-70.3	43.7-46.9
[8]	HT	77, 3.1	57-72	40-41.7
[9]	SI	55, 2.75	64-76	40.5-42
This Work	SI	67, 3	55-70	40-42
CJ:class-J, CCF:Continuous class-F, HT:Harmonic Termination, SI:Stepped Impedance				

Acknowledgment

This work was funded by Lockheed Martin award #4102673517.02.

References

[1] M. Abadi, H. Golestaneh, H. Sarbishaei, and S. Boumaiza, "Doherty power amplifier with extended bandwidth and improved linearizability under carrier-aggregated signal stimuli," *IEEE Microwave Wireless Compon. Lett.*, vol. 26, no. 5, pp. 358–360, May 2016.

[2] R. Darraji *et al.*, "Generalized theory and design methodology of wideband doherty amplifiers applied to the realization of an octave-bandwidth prototype," *IEEE Trans. Microwave Theory Tech.*, vol. 65, no. 8, pp. 3014–3023, Aug 2017.

[3] D. J. Shepphard, J. Powell, and S. C. Cripps, "An efficient broadband reconfigurable power amplifier using active load modulation," *IEEE Microwave Wireless Compon. Lett.*, vol. 26, no. 6, pp. 443–445, June 2016.

[4] P. H. Pednekar and T. W. Barton, "Rf-input load modulated balanced amplifier," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, June 2017, pp. 1730–1733.

[5] P. L. Gilabert and G. Montoro, "3-d distributed memory polynomial behavioral model for concurrent dual-band envelope tracking power amplifier linearization," *IEEE Trans. Microwave Theory Tech.*, vol. 63, no. 2, pp. 638–648, Feb 2015.

[6] P. Wright, J. Lees, J. Benedikt, P. J. Tasker, and S. C. Cripps, "A methodology for realizing high efficiency class-j in a linear and broadband pa," *IEEE Trans. Microwave Theory Tech.*, vol. 57, no. 12, pp. 3196–3204, 2009.

[7] H. Huang *et al.*, "Design of multioctave bandwidth power amplifier based on resistive second-harmonic impedance continuous class-f," *IEEE Microwave and Wireless Components Letters*, vol. 27, no. 9, pp. 830–832, Sept 2017.

[8] P. Saad, C. Fager, H. Cao, H. Zirath, and K. Andersson, "Design of a highly efficient 2-4-ghz octave bandwidth gan-hemt power amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 7, pp. 1677–1685, July 2010.

[9] J. Xia, X. W. Zhu, and L. Zhang, “A linearized 2 - 3.5 ghz highly efficient harmonic-tuned power amplifier exploiting stepped-impedance filtering matching network,” *IEEE Microwave Wireless Compon. Lett.*, vol. 24, no. 9, pp. 602–604, 2014.

[10] M. Olavsbraten, T. Mathiesen, and E. Berry, “Design of an efficient wideband (1-5ghz) 10w pa in gan technology using harmonic tuning,” in *2017 IEEE 18th Wireless and Microwave Technology Conference (WAMICON)*, April 2017, pp. 1–5.

[11] L. Ding *et al.*, “A robust digital baseband predistorter constructed using memory polynomials,” *IEEE Trans. Commun.*, vol. 52, no. 1, pp. 159–165, Jan 2004.