Characterization of Linear Power Amplifiers for LTE Applications

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***Abstract*— This paper compares the performance of and analyzes the linearity metrics with different signals for two linear PAs: a single-ended class-AB PA and a linear Doherty PA (DPA). Both PAs utilize the 6 W GaN HEMT CGH40006P at a design frequency of 3 GHz for the class-AB PA and 3.5 GHz for the DPA. Different linearity metrics are studied for a 5-MHz spaced two-tone signal and a 5-MHz Long Term Evolution signal. The DPA has a power added efficiency of 40% whereas the class-AB PA shows 27% given a -40 dBc linearity constraint on the closest adjacent channel ($ACPR_1$). The class-AB PA, however, exhibits better linearity in terms of $ACPR_2$. It is additionally shown that the trends of the linearity metrics for the different signals differ for the two architectures.**

***Index Terms*— Doherty, AM-AM, AM-PM, class-AB, IMD3**

I. Introduction

To achieve high data rates in wireless communications, spectrally efficient multi-carrier signals are used with high PAPR (Peak-to-Average-Power-Ratio). Power amplifiers (PAs) in mobile base-stations and microwave backhaul applications therefore need to be both efficient and linear over a wide output power dynamic range.

Single-ended class-AB PAs exploiting two-tone third order intermodulation distortion (IMD3) sweet spots are a simple yet effective technique to achieve linear operation [1]. At the same time, this linear class of PA is not efficient over a wide output power dynamic range. To improve average efficiency, particularly for amplifying high PAPR signals, the Doherty Power Amplifier (DPA) has been widely used [2], [3]. Recently, practical trade-off techniques have been introduced for the design of the DPA to achieve simultaneously linear and efficient operation [4], [5], [6]. In the design of both linear class-AB PAs and DPAs, a typical and straightforward approach for linearity is the optimization of continuous wave (CW) gain and phase linearity, and/or IMD3 optimization, even though the intended signal often is a more complicated, high PAPR modulated signal.

This paper draws a comparison between a linear DPA and a single-ended class-AB PA using the same technology, comparable output power levels and frequencies. A study is carried out to determine how different linearity metrics correlate and compare when the optimization of biases is carried out directly on a Long Term Evolution (LTE) signal on the fabricated circuits compared to CW and two-tone tests. As expected, the efficiency of the DPA is found to be superior to that of the class-AB PA when a pre-determined adjacent channel power ratio ($ACPR_1$) and normalized mean square error (NMSE) are optimized for. The $ACPR_2$ of the DPA is significantly degraded when compared to the single-ended class-AB PA.

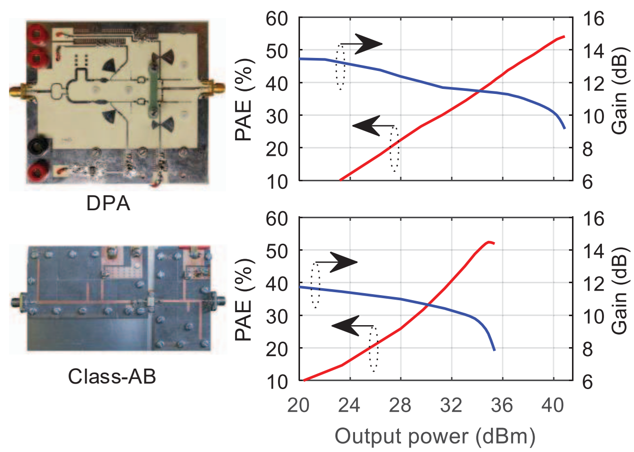

Fig. 1. Photograph of the DPA and the class-AB PA used for the comparison (left) and CW performance after post-optimized biases and supplies (right).

II. Experimental Comparison

The single-ended class-AB and Doherty PAs used in the experiment, shown in Fig. 1, are both designed using the 6 W Wolfspeed GaN HEMT 40006P. The nominal frequencies of operation of the two PAs (3.5 GHz for the DPA and 3 GHz for the class-AB PA) are considered to be sufficiently similar for a direct comparison. The class-AB PA is designed to keep the IMD3 of a 5-MHz spaced two-tone below -30 dBc over the largest possible output power dynamic range. This is achieved using a combination of biasing and harmonic impedance tuning, as described in [1]. The linear DPA is designed using a similar method as in [4], where a good tradeoff between

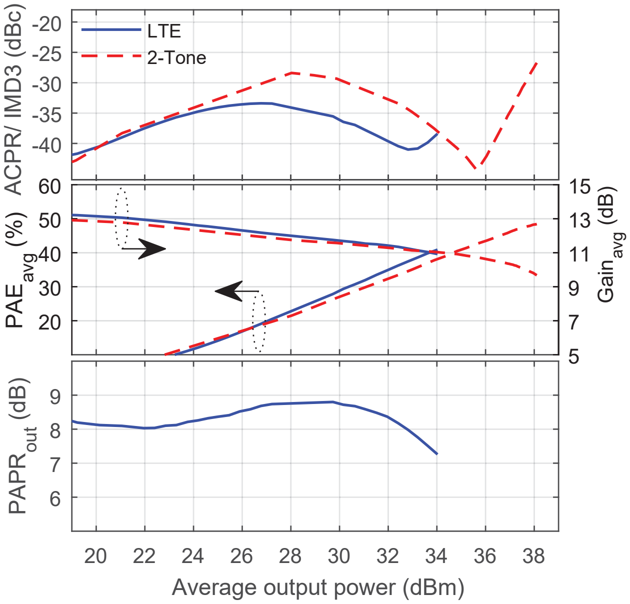

Fig. 2. ACPR/IMD3, average PAE and gain, and output PAPR vs. average output power for a 5-MHz 8.5-dB PAPR LTE signal and for a 5-MHz spaced two-tone for the DPA at 3.5 GHz.

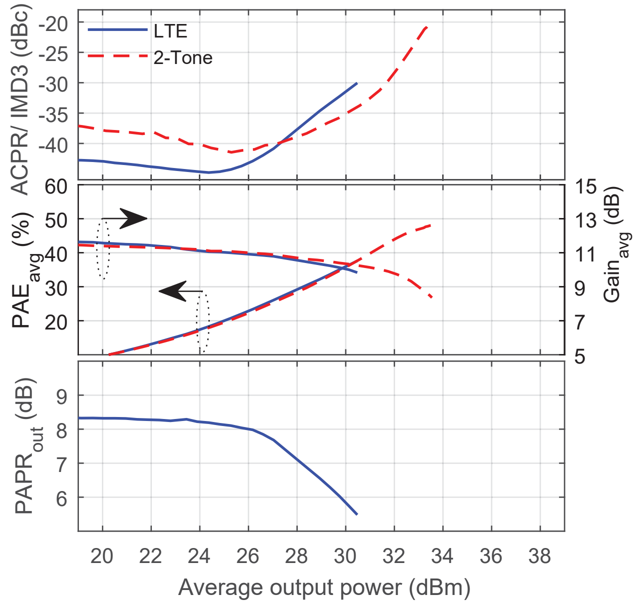

Fig. 3. ACPR/IMD3, average PAE and gain, and output PAPR vs. average output power for a 5-MHz 8.5-dB PAPR LTE signal and for a 5-MHz spaced two-tone for the class-AB PA at 3 GHz.

efficiency and linearity is found, and using a generalized black box approach for the design of the combiner [7].

Both amplifiers' gate biases and drain supplies are post-optimized to achieve the highest PAE when fed with a 8.5-dB PAPR 5-MHz LTE signal, while still maintaining linear operation. Linearity of operation is defined here using common metrics for distortion evaluation of modulated signals: ACPR and NMSE. Average PAE is maximized by sweeping gate biases and drain supplies while enforcing an ACPR_1 of -40 dBc and NMSE of -30 dB. These values are selected based on the state of the art of what can be achieved with current technology without the aid of digital pre-distortion techniques [4]. A Matlab-controlled measurement setup is used for the bias optimization. The baseband signal from a Keysight (N8241A) waveform generator is up-converted by a Keysight (E8267D) vector signal generator. Output power and spectrum are obtained using Keysight USB power sensors (U2000A) and a PXA Signal Analyzer (N9030A).

For the class-AB PA, the optimization results in a quiescent current $I_{DS,q} = 40$ mA ($V_{GS} = -2.85$ V), which is the same bias found in [1] for optimal two-tone IMD3 suppression. The supply voltage, however, decreases to $V_{DS} = 21$ V. In the DPA case, the main transistor's $I_{DS,q} = 120$ mA ($V_{GS,m} = -2.62$ V), the auxiliary's gate voltage is $V_{GS,a} = -3.7$ V and the drain supply voltages are $V_{DS,m} = 23$ V and $V_{DS,a} = 28$ V.

Fig. 1 shows the CW measurement resulting from the post-optimization of biases and supplies for the two PAs. Both amplifiers present comparable efficiency (>50% PAE) at their saturated output power (40.9 dBm for the DPA and 35.4 dBm for the class-AB PA). At a 8 dB output power back-off (OPBO) the CW PAE is 34% and 25% for the DPA and class-AB PA, respectively. It should be noted that the CW gain compression characteristic of the DPA is less steep than that of the single-ended PA due to the power contribution of the auxiliary transistor.

III. Two-Tone and Modulated Signal Analyis

The measurement results for a 8.5-dB PAPR 5-MHz LTE signal and a 5-MHz spaced two-tone signal are presented for the DPA in Fig. 2 and for the class-AB PA in Fig. 3. For the DPA, the two-tone sweet spot occurs at the average output power of 35.7 dBm and the LTE sweet spot occurs at 32.8 dBm – a difference of 2.9 dB. For the class-AB PA on the other hand, the two-tone sweet spot occurs at 25.3 dBm and the LTE sweet spot occurs at 24.4 dBm – a difference of 0.9 dB. It is important to note that the LTE sweet spot occurs much closer to the intended operating point (at $\mathrm{ACPR}_1 = -40$ dBc), and closer to the maximum output power for the DPA than for the single-ended PA. Regarding the two-tone performance at IMD3 $= -30$ dBc, the DPA and the class-AB PA have 48% and 43% PAE, respectively.

The average gains for the two-tone and LTE signals follow the CW performance for both PAs, however they are smoother than the CW gain due to the effect of the variable signal envelope. The average efficiencies for the two signals are very similar for the class-AB PA. For the DPA, the average PAE of the LTE signal is higher when compared to the two-tone. This could be explained by the enhanced back-off efficiency of the DPA compared to the class-AB PA (see Fig. 1) and the higher PAPR of the

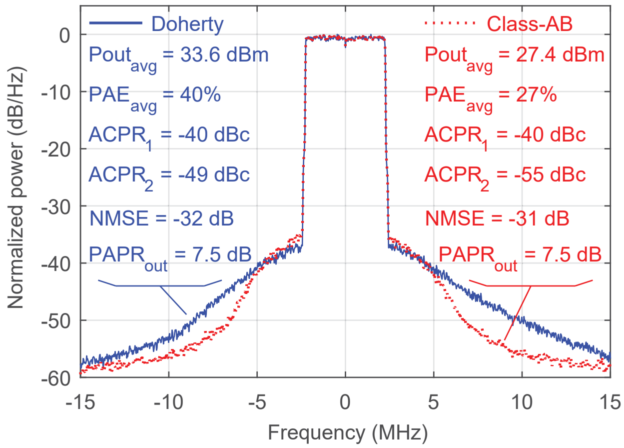

Fig. 4. Normalized power spectral density for a 5-MHz 8.5-dB PAPR LTE signal at 3.5 GHz for the DPA and at 3 GHz for the class-AB PA.

LTE signal. Both PAs present higher PAE compared to CW measurements. We note that the biases and supplies are kept fixed for all measurements. In [4], [8], [9], it was reported that different biasing can be used in CW to achieve a closer behavior to modulated measurements.

Figs. 2 and 3 also present the output PAPR of the LTE signal. The output PAPR remains similar to the input PAPR for a large dynamic range for the DPA, whereas it compresses severely at high powers levels for the class-AB PA. The spectrum and corresponding AM-AM and AM-PM at the intended operating points for both PAs are shown in Figs. 4 and 5, respectively. In Fig. 4, a summary of the performance for both PAs is also included. Both PAs present similar ACPR_1, NMSE and output PAPR. The DPA performs at 13 percentage points higher average PAE compared to the class-AB PA. However, the class-AB PA presents 16 dB lower ACPR_2 compared to the DPA. As expected from Fig. 2, reducing the output power of the DPA degrades both ACPR_1 and ACPR_2 until deep back-off ($\sim$20 dBm) is reached.

The AM-AM for the DPA compresses around 1.5 dB, which is less than the CW compression. Lower compression for modulated measurements compared to CW were also reported in [4], where the biases also had been optimized differently for the two signals. The AM-AM for the class-AB PA compresses around 1 dB. Both PAs present around 5 degrees of AM-PM distortion. Overall, the class-AB PA presents a smoother AM/AM and AM/PM compared to the DPA, which is also reflected in ACPR_2.

IV. Conclusion

It is demonstrated that a Doherty PA optimized for a trade-off between linearity and efficiency presents higher efficiency compared to a linear single-ended class-AB PA, for a given ACPR_1 constraint. On the other hand, the DPA never exhibits as good linearity as the class-AB PA in terms of ACPR_2. Given relaxed linearity requirement

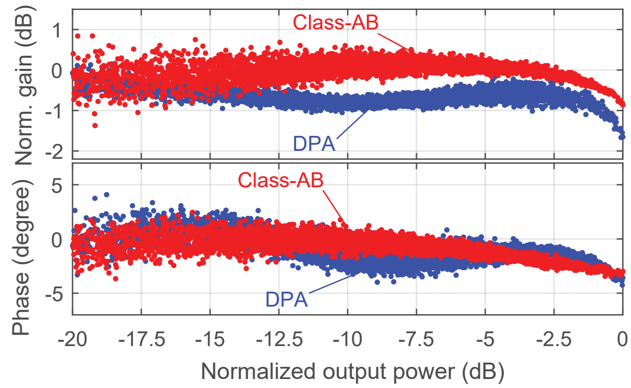

Fig. 5. AM-AM and AM-PM for the DPA and the class-AB PA for a LTE signal summarized in Fig. 4.

in future wireless systems, both the DPA and the class-AB PA present different advantages. It is also shown that two-tone IMD3 performance follows LTE performance more closely for the class-AB PA compared to the DPA. This result underscores the importance of PA design and characterization using the desired signal in the case of complex PA architectures such as Doherty.

Acknowledgment

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