AM/PM Characterization of Wideband Power Amplifiers

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***Abstract*—This paper presents the linearity assessment of two state-of-the-art wideband power amplifiers, a single stage class AB and a two-way 6 dB Doherty, in terms of amplitude-to-phase-modulation (AM/PM) distortion. The simulated and measured characteristics are shown and discussed. The class AB amplifier maintains AM/PM within 6° from 1 to 4 GHz, i.e. on a 120% bandwidth, while the Doherty amplifier has similar performance from 2.2 to 2.9 GHz, i.e. on a 28% bandwidth. This characterization campaign highlights the superior linearity of the class AB amplifier over relative bandwidths that exceed 100% but, at the same time, the potential of the Doherty amplifier to maintain very limited (within 10°) amplitude-to-phase-modulation distortion over bandwidths up to around 60%. Both power amplifiers are well in line with the state of the art also in terms of linearity, besides output power, gain, and efficiency performance.**

***Index Terms*—Doherty, GaN, high efficiency, linearity, power amplifiers, wideband.**

I. Introduction

Designing power amplifiers (PAs) with high efficiency over wide fractional bandwidths is one of the challenges related to modern wireless communications, mainly for the difficulty of assuring the proper loading conditions for high efficiency operation over multi-octave frequency ranges. Gallium Nitride (GaN) based devices are, in this context, very promising thanks to the favourable optimal loads (around 50 Ω for 1 mm of periphery) [1] that allow a simpler design of wideband matching networks. To further complicate the picture, the adoption of spectrally efficient modulations with very wide instantaneous bandwidths and large Peak-to-Average-Power-Ratio poses stringent requirements not only on the PA efficiency in back-off but also on its linearity that must be preserved on wide bandwidths.

In this framework the Doherty PA (DPA) is one of the most popular techniques based on load modulation [2] that allow for efficient operation also in back-off. Wideband solutions have been demonstrated both with single input [3] and dual input [4], [5] (also referred to as digital Doherty). On the other hand, DPAs typically suffer from a linearity point of view, especially in terms of amplitude-to-phase-modulation (AM/PM) conversion, which results poorer than single-device or combined PAs operating in linear classes.

The AM/PM conversion in PAs has been extensively explored in the literature [6], [7], [8], [9], becoming a key feature when broadband operation is foreseen. This is even more critical in case of DPAs, where it has been demonstrated that the inherent load modulation of this architecture affects in a detrimental way the AM/PM, if not properly counteracted. Recently, in many applications where the radio-frequency (RF) and instantaneous bandwidths are significant, the degree of linearity required from PA is often specified in terms of Noise-to-Power Ratio (NPR) [10], [11], which is evaluated as the ratio between the nonlinear distortion noise and the signal power spectral density at the output of the DPA when Additive White Gaussian Noise (AWGN) with a central notch is applied at the input. There are closed-form relations, that have been experimentally proved [12], to correlate NPR to other linearity figures as inter-modulation distortion (IMD) rejection and AM/PM. For example, under the assumption of weak non-linearity, the NPR is around 7 dB lower than the third-order IMD ratio. This relation, however, can vary significantly if the amplifier presents strong memory effects. Therefore, it is not trivial to predict the NPR during the design phase, and it is currently more practical to use figures of merit such as the AM/PM to estimate the linearity of the PA until the final system level characterization.

In this work, the linearity of two multi-octave PAs, a class AB [13] and a two-way 6 dB DPA [3] is assessed in terms of AM/PM. The AM/PM measurements performed on the manufactured hybrid prototypes, which are state-of-the-art in terms of bandwidth, and efficiency performance, are compared to the corresponding simulations, showing a good agreement, and quite good performance. In fact, the class AB amplifier maintains a measured AM/PM within 6° over a relative bandwidth that exceeds 120% (from 1 to 4 GHz). On the other hand, the DPA demonstrates a very limited (within 10°) AM/PM conversion over bandwidths up to around 60%, suggesting the possible exploitation of this technique also in wideband operation.

II. Class AB PA

The single stage class AB wideband PA presented in [13] was developed to cover most of the mobile frequencies in the range 0.6-3.8 GHz. The design relied on a strategy based on a

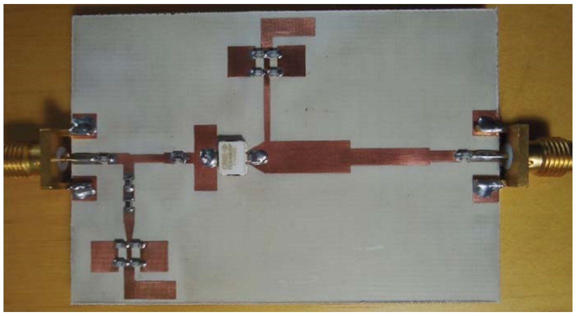


Fig. 1. Picture of the wideband class AB PA [13].

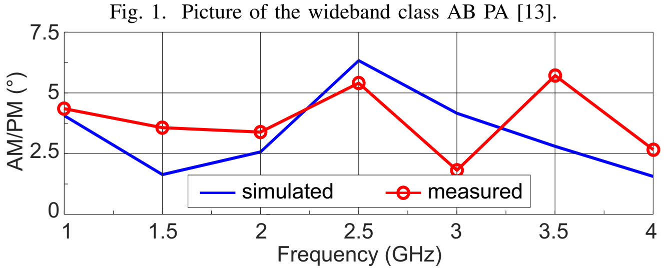
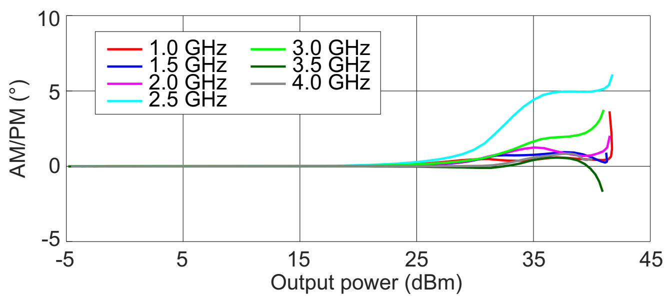
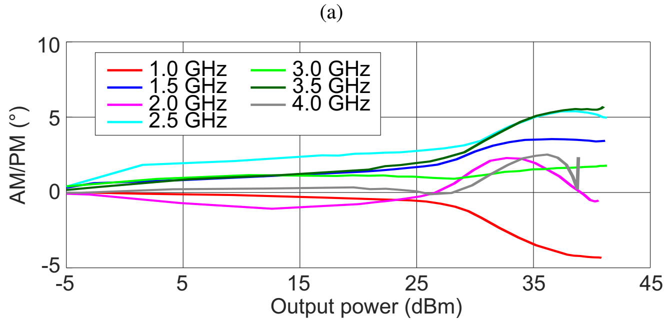


Fig. 2. Simulated (blue, solid) and measured (red, symbols) maximum AM/PM of the wideband class AB PA [13] versus frequency.



(a)



(b)

Fig. 3. Simulated (a) and measured (b) AM/PM of the wideband class AB PA [13] versus output power, from 1 GHz to 4 GHz.

very simple device modelling and matching network synthesis. It adopted the 10 W GaN packaged HEMT CGH40010 from Wolfspeed as active device. It was manufactured on a Taconic substrate with copper metallization (RF35 with $\epsilon_r = 3.5$, 0.76 mm substrate thickness, and 0.035 mm metal thickness) and mounted on a brass carrier, see Fig. 1. It was shown in [13] that under CW excitation in the 0.6–3.8 GHz frequency range (fractional bandwidth of 145.5%), the AB-PA presented more than 40 dBm output power, a gain between 9 and 14 dB and PAE higher than 46%, at saturation.

In the present work, the AB-PA is characterized in terms of AM/PM in the frequency range 1–4 GHz and under the same operating conditions of the original paper. Limitations of the currently available measurement setup have prevented the characterization in the lower portion of the original band, i.e. from 0.6 GHz to 1 GHz. The maximum AM/PM at each frequency is defined as the maximum excursion (difference between maximum and minimum value, hence always positive) of the phase difference between output and input voltage versus input power.

The comparison between simulated and measured results is shown in Fig. 2 in the whole frequency range. The agreement is rather good, considering the wide bandwidth and the reduced discrepancy, that remains lower than 2° between simulations and measurements. This is a very good result, also considering the accuracy of the measured AM/PM, which is affected by uncertainties related to the vectorial computation of the phase of S_{21} and measure of the $\Gamma_{\rm in}$, and which can be estimated to be of the order of 1-2° after calibration. Despite the ultra-wide operating range, the maximum AM/PM is below 6° in the entire frequency range. Fig. 3 shows the simulated and measured AM/PM curves versus output power from 1 to 4 GHz, with 500 MHz steps. The summary of the AM/PM performance of the AB-PA is reported in Table I.

III. Doherty PA

The wideband DPA presented in [3] was developed building on the results of the wideband class AB discussed in Sec. II, which was used as a starting point for the Main stage. The DPA design was supported by a bandwidth estimation method which allowed to estimate the non-linear performance in terms of output power, efficiency and AM/AM, using linear simulations only. This method consists in representing the whole matching and power combining output network, including the load, by means of a frequency dependent 2-port impedance matrix $\mathbf{Z}$ that connects the Main and Auxiliary

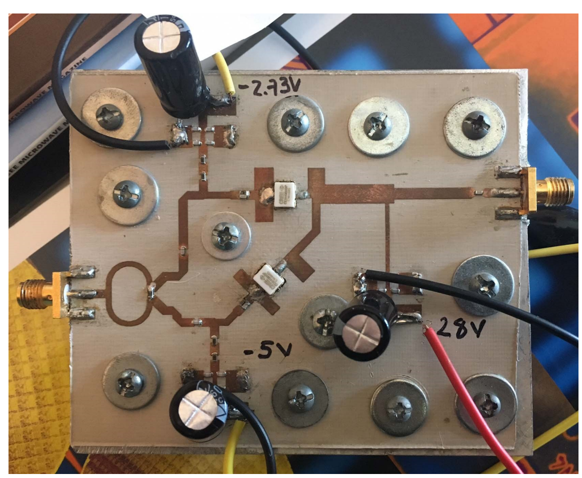


Fig. 4. Picture of the wideband DPA [3].

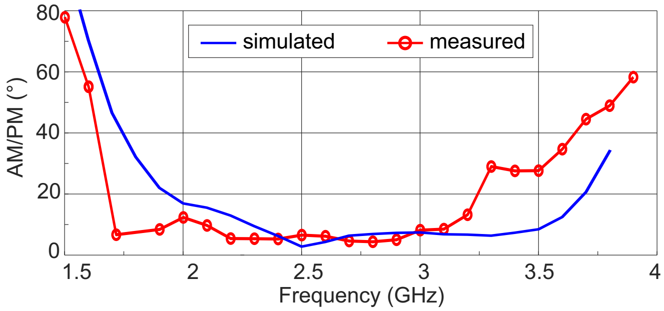


Fig. 5. Simulated (blue, solid) and measured (red, symbols) maximum AM/PM of the wideband DPA [3] versus frequency.

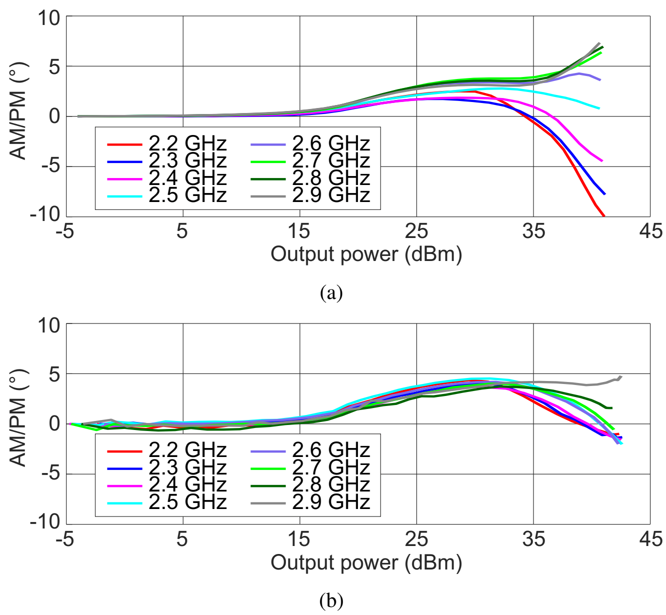


Fig. 6. Simulated (a) and measured (b) AM/PM of the wideband DPA [3] versus output power, from 2.2 GHz to 2.9 GHz.

devices, represented as current sources. The input section of the DPA, including the power splitter and the input stabilization and matching networks, is not considered in this simplified analysis. As such, the method does not allow to estimate the AM/PM, which would require direct access to the load node as well as to the RF input of the DPA.

The DPA adopted the same active device and was fabricated on the same substrate as the AB-PA (Fig. 4). The CW characterization from 1.5 GHz to 3.8 GHz (fractional bandwidth of 87%) of the DPA in terms of output power, efficiency and gain was presented in [3], together with system-level characterization using a WiMAX signal at 2.6 GHz. The DPA showed more than 42.3 dBm saturated output power, linear gain higher than 10 dB and efficiency higher than 42% in saturation and 33% at 6 dB output power backoff.

The DPA has been now characterized in terms of AM/PM in the same frequency range and under the same operating conditions. The results are shown in Fig. 5, where they are compared to the simulations. The agreement is rather good,

TABLE I
COMPARISON WITH OTHER STATE-OF-THE-ART PAS.

Ref.	Arch.	Freq. (GHz)	P_{MAX} (dBm)	η_{SAT} (%)	η_{OBO} (%)	AM/PM (°)
[13]	**AB**	**0.6-3.8**	**40**	**50-75**	**-**	**2-6**
[15]	DPA	2	42	70	56 (*)	17
[9]	DPA	4.7-5.3	39	52-57	30-33 (*)	2-5.5
[14]	DPA	2.3	22.4	39	19 (*)	4.7
[3]	**DPA**	**1.5-3.8**	**42.3**	**42-63**	**33-55 (†)**	**4-77**
		1.7-3.1	**42.3**	**45-63**	**39-45 (†)**	**4-10**
		2.2-2.9	**42.3**	**47-55**	**40-45 (†)**	**4-6.5**

(*) at 9 dB OBO
(†) at 6 dB OBO

considering the wide bandwidth, except for a slight shift of the measured results towards lower frequencies.

Given the multi-octave operating range, the AM/PM is quite high at the band edges, staying below 60° from 1.6 to 3.8 GHz and reaching around 80° at the lower band edge (1.5 GHz). However, there is a quite wide frequency range where the AM/PM is very limited, which is an impressive result for a DPA. From 1.7 to 3.1 GHz (58% fractional bandwidth) the AM/PM is below 10°, while from 2.2 to 2.9 GHz (28% fractional bandwidth) the AM/PM is below 6.5°. Fig. 6 shows the simulated and measured AM/PM curves versus output power from 2.2 to 2.9 GHz, with 100 MHz steps. Notably, the agreement is rather good in this range.

The presented DPA is compared to others found in the literature for which AM/PM measurements are available. Some of the considered ones, such as [9] and [14], have been expressly conceived to minimize AM/PM. The DPA in [9] exploits a specific design strategy that was not available at the time our DPA was designed. However, despite the impressive results and challenging operating frequency, it can only maintain a very low AM/PM (below 5.5°) in a quite narrow (12%) relative bandwidth. The DPA in [14] relies on a built-in phase compensation strategy aimed at minimising AM/PM, succeeding in keeping it lower than 5° but only at a single frequency (2.3 GHz). The DPA presented here compares well with the state of the art, considering that it shows a comparable linearity figure over a relative bandwidth close to 30%, while maintaining high output power and good efficiency, both at saturation and at 6 dB OBO. To the best of the authors' knowledge, the question as to whether specific AM/PM minimization strategies can be effectively applied to realize octave-bandwidth DPAs with competitive performance still remains open.

IV. CONCLUSION

This paper has presented the linearity assessment of two state-of-the-art wideband PAs in terms of AM/PM conversion. The simulated and measured AM/PM characteristics of the two PAs have been presented, compared, and discussed with a focus on the relative bandwidth of operation. AM/PM below 6.5 ° has been measured on the class AB PA over a 120% fractional bandwidth. The DPA, despite the well known

AM/PM conversion due to load modulation, demonstrates a similar behaviour in a 58% bandwidth, presenting a AM/PM below 10°. These characterization results highlight from one hand the superior linearity of the class AB amplifier over multi-octave bandwidths but, at the same time, the potential of the Doherty amplifier to maintain very limited AM/PM, namely below 10°, over bandwidths up to around 60%. Both power amplifiers result well in line with the state of the art also in terms of linearity, besides output power, gain, and efficiency. Future work will include the system level characterization of the PAs also in terms of NPR, with different signal bandwidths, to estimate the strength of their memory effects and to correlate the NPR and AM/PM linearity measures.

ACKNOWLEDGMENT

The authors would like to thank Prof. Nuno B. Carvalho and Ricardo Figueiredo of the Instituto de Telecomunicações, Aveiro, Portugal, for the fruitful discussions.

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