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# Linearity-aware design of Doherty power amplifiers

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**Abstract**—The linearity is a crucial requirement of power amplifiers. At design level, it is typically assessed by means of AM/AM, AM/PM and IMR, which are extracted from 1- and 2-tone characterization. These however are not fully representative of the actual behaviour under modulated signal excitation, for which purpose other system-level metrics such as the NPR have been successfully introduced. In this paper, different linearity estimations are used to compare two GaN-on-Si Doherty MMIC power amplifiers for Ka-band space applications. One of the two amplifiers shows an AM/PM reduction of more than 30% with respect to the other. However, it is observed that this does not always lead to a reduction in NPR. The reasons for this disagreement between metrics are analysed and discussed.

**Index Terms**—Doherty, power amplifier, linearity, NPR

## I. INTRODUCTION

The need for linearity in high frequency transmitters, especially when operated with advanced non-constant envelope modulations, strongly constrains the power amplifier (PA) design, often penalizing the power efficiency performance. Different solutions have been proposed in the past to optimize the linearity/efficiency trade-off in PAs. Among them, the Doherty power amplifier (DPA) [1], is today very popular due to its high efficiency over a wide power range. Furthermore, being a purely-RF technique, in principle it does not require any additional digital signal processing, making it less critical, compared to other efficiency enhancement techniques, when used in very high throughput applications, e.g. 5G. However, in practice, DPAs still suffer from poor linearity requiring the use of linearizers to achieve compliance with communication standards. As a consequence, the development of low-distortion DPAs is crucial to enable the adoption of this architecture for standards like the 5G mobile, where antenna arrays are based on a large number of low-power integrated PAs working at microwave (sub-6 GHz bands) or millimetre-wave frequencies (28/39 GHz) [2]. Amplitude-to-amplitude modulation (AM/AM) can be compensated by simple memoryless digital pre-distortion (e.g. look-up table) because it can be considered almost static, whereas a significant effort is required to minimize amplitude-to-phase modulation (AM/PM) [3], which results strongly non-linear thus requiring non-static linearizers.

In this paper, the linearity of DPAs is evaluated comparing the Figures of Merit (FOMs) typically used by designers, such as the 1-tone AM/AM and AM/PM modulation, and system-level metrics like the Noise Power Ratio (NPR). Two GaN-on-Si microwave monolithic integrated circuit (MMIC) DPAs for Ka-band medium-power applications are presented. The first

one targets high efficiency over a wide bandwidth, the second is expressly conceived to reduce the AM/PM with a minimum effect on the performance achieved by the first one on the same band. Considerations on the linearity of the two designs are made and conclusions are drawn on the effectiveness of the different metrics.

## II. LINEARITY FOMS

Linearity must be evaluated and enforced during PA design. Memoryless systems are completely characterized by AM/AM and AM/PM curves obtained from 1-tone simulations. Weak-memory systems are mostly described by the Inter-Modulation Ratio (IMR) obtained from 2-tone characterization. Additionally, by spanning the tones separation, long-term memory effects can also be captured. If memory effects are significant and the adopted modulated signals are wideband, more complete metrics such as the NPR are required to fully estimate the system linearity. While AM/AM, AM/PM and IMR are easily computed in real-time from standard harmonic balance simulations during PA design, the NPR requires system-level characterization based either on Additive White Gaussian Noise (AWGN) or multi-tone excitations and proper filtering. In simulation, the required computational effort is such that real-time evaluation of these FOMs becomes unfeasible. An extrapolation of the NPR from 2-tone harmonic balance simulations is possible [4]:

$$\text{NPR}|_{\text{dB}} = \text{IMR}|_{\text{dB}} - 7.8 \text{ dB}. \quad (1)$$

However, (1) does not fully account for long-term memory effects and is formally valid only when the non-linearity can be approximated by a third order polynomial. When the curve deviates from this approximation, e.g. when the amplifier approaches the 1 dB compression point, (1) is no longer valid. Therefore, a complete envelope simulation over the baseband frequency range of operation is required to estimate correctly the linearity of amplifiers operated near saturation. In this work, the NPR is computed by an envelope simulation that considers a baseband AWGN excitation around the RF carrier, and compared to the extrapolated 2-tone approximation.

## III. CASE STUDY

Two two-stage Doherty amplifiers for space applications are presented. The employed technology is GaN-on-Si, targeting a saturated output power of the order of 5 W in the 17–20 GHz bandwidth. The reference topology adopted for the design of the two MMICs is illustrated in Fig. 1. The output

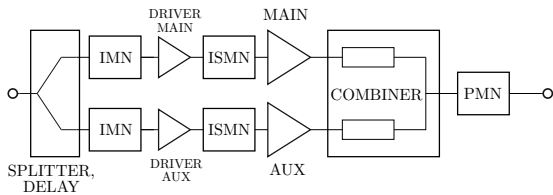


Fig. 1: Block diagram of the adopted 2-stage DPA topology.

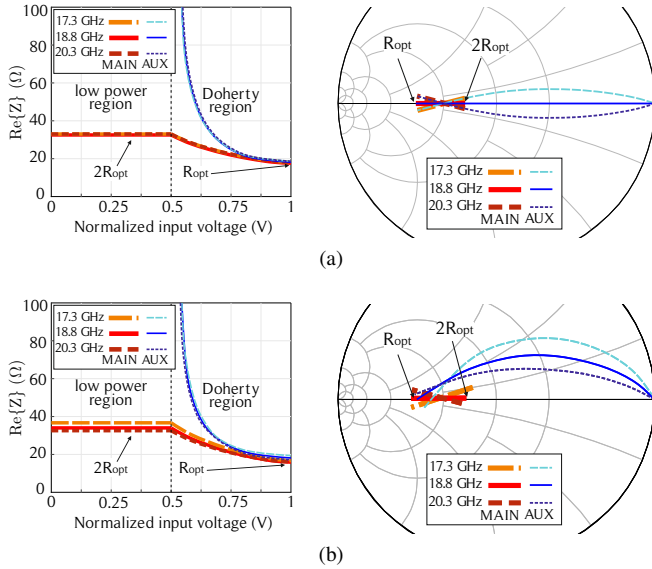


Fig. 2: Load modulation of the standard (a) and linearized (b) DPAs, real part cartesian (left) and complex Smith chart (right) representations.

section consists of a real-to-real post-matching network (PMN) that transforms the output impedance into the real impedance that is presented to the common node of the Doherty power combiner. This is based on a  $\lambda/4$  line section on the Main path and a  $\lambda/2$  line section on the Auxiliary [5]. The power stage, which is made up by two devices having the same periphery ( $8 \times 100 \mu\text{m}$ ), is driven by two separate drivers ( $6 \times 50 \mu\text{m}$  periphery), one on each branch. Adopting separate drivers on the two branches has an advantage in terms of efficiency [5]. The load modulation presented at the intrinsic drain plane of the active devices, which are modelled as ideal current sources, is shown in Fig. 2 (a). A purely real load trajectory is maintained throughout the Doherty region at the design frequency of 18.8 GHz, whereas a relatively small reactive component is present at all other frequencies. This corresponds to a null output phase distortion only at the design frequency. However, the AM/PM is given by both output and input phase distortion, the latter always present when load modulation occurs [3], [6], [7]. Hence, nulling the output phase distortion might not be the best strategy to cancel AM/PM.

The design of the linearized DPA is based on the strategy proposed in [8], which assumes a 1-tone stimulus and therefore relies on AM/PM estimations. The original DPA combiner is modified to intentionally introduce an output phase distortion,

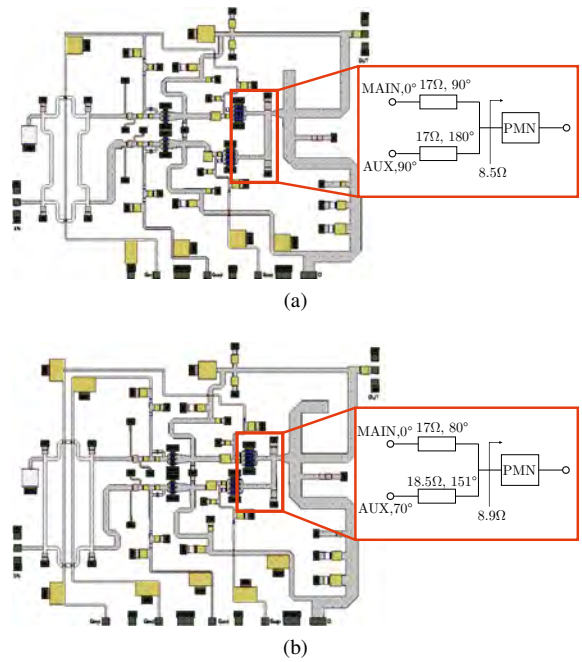


Fig. 3: Layouts of the standard (a) and linearized (b) DPAs with a detail of the corresponding output combiner schematic.

which is selected to compensate the phase distortion due to the load modulation. In this way, the overall AM/PM can be ideally eliminated, or at least significantly reduced. This partial compensation is achieved by modifying the auxiliary branch, in such a way that the auxiliary load impedance maintains a significant reactive component in the whole Doherty region. The power and efficiency performance of the linearized DPA is minimally affected by this modification because the load modulation of the Main is practically unaltered compared to the original DPA, and the load impedance of the Auxiliary at saturation is also maintained. The load modulation presented at the intrinsic drain plane of the active devices by the modified combiner is shown in Fig. 2 (b). The layouts of the two DPAs are reported in Fig. 3, together with a detail of the corresponding output combiners.

#### IV. RESULTS

Fig. 4 reports the linearity comparison of the two architectures in terms of AM/PM (1-tone) and NPR (envelope, 100 MHz bandwidth around 18.8 GHz carrier). The former is reduced by up to 35% by the linearized DPA, in the whole Doherty region, as predicted by the adopted design strategy. The NPR significantly improves (by up to 10 dB) in the low-to-medium power region, due to more convenient harmonic loading conditions. However, as power increases towards saturation, the two designs tend to the same NPR performance. This might be due to similar nonlinear behaviour of the Main transistor at high compression levels, but further investigations are ongoing to better address this phenomenon. The comparison suggests that a design performed relying on the estimation of AM/PM alone does not guarantee the

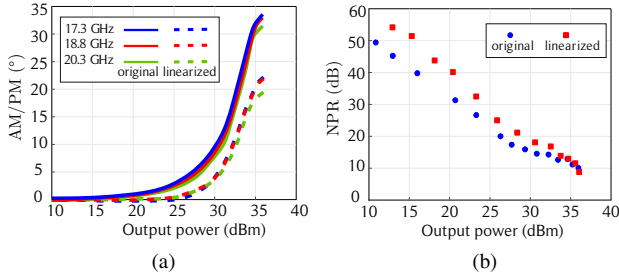


Fig. 4: DPAs linearity in terms of AM/PM (a) and NPR (b).

desired linearity improvement when the targeted baseband signal bandwidth is of the order of 100 MHz, as in the present case. Therefore, it is interesting to understand whether a 2-tone estimation of the NPR could be used as an additional design tool. As anticipated in Section II, this estimation is only accurate when the PA presents little or no memory effect. To rapidly assess the existence of memory effects in the PA under design, 2-tone simulations with different tone spacing can be performed. Fig. 5 shows this procedure for both DPAs, highlighting the existence of long-term memory effects which cause the 2-tone NPR estimation to vary with tone spacing. The significant memory effects may be ascribed to the reactive behaviour of the matching and bias networks at baseband frequencies. One way to minimize these effects is to design networks that present a very low impedance to the drain of the active devices at low frequency. The existence of non-negligible memory effects suggests that the 2-tone NPR approximation will not be very accurate, especially at high power levels. Fig. 6, which compares the NPR estimation using 2-tone (red) and envelope (blue) simulations for the two DPAs, both analysing a 100 MHz bandwidth around a 18.8 GHz carrier, confirms this prediction. As it can be seen, results are in good agreement for small-signal excitations but differ as power increases. This happens because the IMR is mostly determined by third-order intermodulation products. Therefore, 2-tone NPR approximations do not consider higher-order of non-linearity and memory that become dominant at high input power. However, a similar trend can be noticed: the 2-tone simulation underestimates (by roughly 8 dB) the NPR in both cases. Therefore, while the absolute NPR value can only be extracted by accurate envelope simulations, the relative linearity improvement can effectively be estimated by 2-tone simulations. As a consequence, the presently available DPA design strategies to optimize linearity can be complemented by computationally light NPR estimations.

## V. CONCLUSION

The presented simulations (fabrication now ongoing) show that it is possible to reduce the AM/PM of a DPA by more than 30% without negatively affecting its performance. At the same time, the NPR suggests that a reduction of the AM/PM does not necessarily lead to a significant improvement of the linearity of the amplifier in the presence of complex modulated

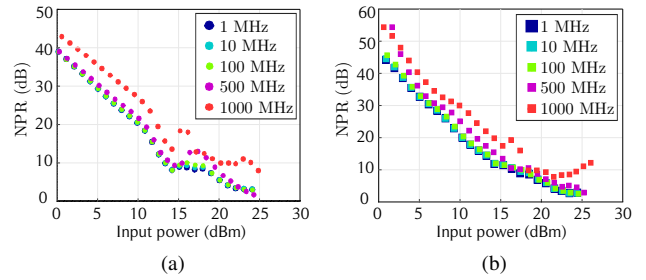


Fig. 5: NPR estimated using 2-tone simulations with different tone spacing for the original (a) and linearized (b) DPAs.

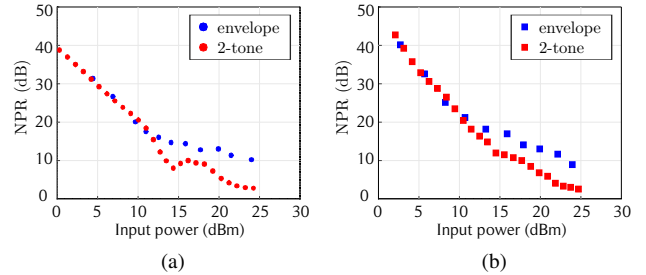


Fig. 6: Comparison of NPR estimated using 2-tone (red) and envelope (blue) simulations for the original (a) and linearized (b) DPAs.

signals. The possibility to extract NPR estimations from 2-tone characterization, as long as its validity limits are taken into account, offers the possibility to aid the circuit design with an almost real-time monitoring of a system-level FOM.

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