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PA design and statistical analysis through X-par driven load-pull and EM simulations

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***Abstract*—Modeling the active device is a key step for the successful statistical analysis of power amplifiers: the nonlinear model must not only depend on the most relevant device fabrication parameters, but should also work accurately in source/load-pull analysis, since variations of the passive embedding network effectively act as a load-pull at the active device ports. We demonstrate that the X-parameter model extracted from physics-based nonlinear TCAD simulations is extremely accurate for load-pull analysis. The X-parameter model is coupled to electromagnetic simulations to assist the variability-aware design of a GaAs MMIC X-band power amplifier (PA): concurrent variations of the active device doping and of the capacitor dielectric layer thickness are considered as the main contributions to PA variability. Two possible output matching networks, with distributed or semi-lumped design, are compared: already for moderate doping variations the PA output power spread is dominated by the active device variability, while passive network variations are always the relevant contribution to PA efficiency.**

***Index Terms*—Device variability, microwave amplifiers, X parameters**

I. Introduction

The statistical analysis of nonlinear circuits as a function of process parameter uncertainty represents a true modeling challenge. In fact, not only the active device nonlinear model must depend on the fabrication parameters, but it also must be accurate enough in case of source- and load-pull analysis, since technological variations of the passive embedding network effectively act load-pulling the active device ports. Technological variations can be incorporated into nonlinear models only when a direct link with the underlying physical process is retained: a unique way is through nonlinear physics-based Technology CAD (TCAD) simulations based on the Harmonic Balance technique, including variability as a function of device process parameters, e.g. device doping or workfunction [1]-[4]. The numerical burden of TCAD, though, is not compatible with circuit design, and calls for the extraction of a CAD-level device model. X-parameters [5] (X-par) are the ideal black-box nonlinear model to translate physical simulations into CAD tools, e.g. Keysight ADS [6], including the technological parameter dependency [7].

The statistical analysis of nonlinear stages also requires accurate modelling of passive network variations as a function of the MMIC fabrication parameters (e.g. the thickness of dielectric, resistive or metal layers). Such variations can be in principle accounted for by electromagnetic (EM) analysis, albeit again at the cost of computationally intensive simulations, especially for full 3D EM models. Following [8], we circumvent the problem by translating parametric EM simulations, into a parametrized S-parameter file (MDIF format) to be used in circuit analysis.

In this paper we discuss how these process-dependent models can assist the variability-aware design of a deep class AB GaAs MMIC power PA at 12 GHz, based on the 1 mm FET device in [8]. The aim is to compare the relative weight of technological variations in the active and passive parts of the PA stage. In particular, concurrent doping variations in the active device and SiN layer thickness of the MIM capacitors are considered as the main contributions to PA variability. We compare two possible output matching networks, with distributed or semi-lumped design strategy, designed using a commercial GaAs foundry design kit (DK). EM simulations are used to extract the parametrized MDIF model as a function of the thickness of the SiN layer. The statistical analysis of the PA stage (including the output matching network only) shows that if the active device doping variations have statistical spread lower that 1%, the two passive matching networks lead to significantly different PA performances while, with higher doping variations, the PA output power spread due to the passives is overcome by the active device variability. On the contrary, efficiency variability is mainly related to passive structures.

II. Modeling approach

In this work, we address the statistical analysis of a tuned load class AB (10% I_{DSS}) PA, based on a 1 mm FET device whose preliminary analysis was introduced in [8]. TCAD simulations based on the Harmonic Balance technique have been used to extract a nonlinear X-par model, as a function of the doping concentration in the active device layer. Although extracted in the conventional 50 Ω environment, the X-par model has been verified against the reference TCAD simulations [9] with several loading condition. The model extends to relative doping variations up to 10% [7]. We now investigate the X-par model with load-pull (LP) simulations [10], to extract the optimum load in compression. Fig. 1 shows the load-pull circles: at 2 dB gain compression the optimum load is found to be $Z_{\mathrm{L,opt}} = (39 + j16)\ \Omega$, which deviates from the values estimated with the load line approach [8], especially concerning the imaginary part. Notice that a validation of the complete load-pull simulation at TCAD level is completely

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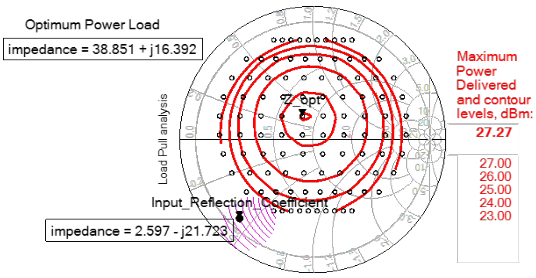

Fig. 1. Load Pull analysis carried out with the X-par model on 50 Ω.

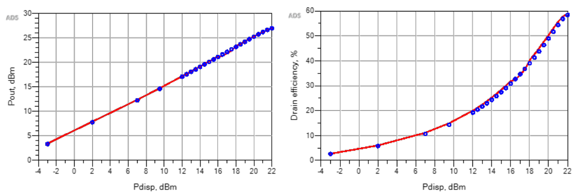

Fig. 2. $P_{\mathrm{in}} - P_{\mathrm{out}}$ (left) and drain efficiency (right) on $Z_{\mathrm{L,opt}}$ with X-par (red solid lines) and reference TCAD analysis (blue symbols). Doping is 90% of the nominal value. Harmonics are shorted.

unfeasible, due to the number of loads and input power levels to be analyzed. Limiting the validation to the optimum load found, Fig. 2 shows how the model compares with TCAD analysis with doping equal to 90% of the reference value: the accuracy for $P_{\mathrm{in}} - P_{\mathrm{out}}$ and efficiency is excellent.

Passives designed to match $Z_{\mathrm{L,opt}}$ will also be affected by a considerable spread due to technological variability. The synthesized loads are thus subject to uncertainty, effectively load-pulling the device output port around the nominal value, even at the harmonics. These variations add to the ones originating from the active device *per se*. The aim of this work is to compare the two contributions in a realistic case. Therefore we proceed to the design of the passive structure for the output matching network, using a commercial GaAs foundry DK suitable for X-band applications, with 3 μm-thick gold micro-strip transmission lines, and a $T_{\mathrm{SiN}} = 100$ nm-thick SiN insulating layer for MIM capacitors (resulting in about 600 pF/mm^2 capacitance). A preliminary layout is based on conventional microstrip transmission lines, then converted into a semi-lumped circuit, heavily exploiting MIM capacitors to shorten both the stubs and the series lines and including the output DC-block capacitance. The obtained layouts are fine tuned with EM simulations, to achieve proper loads up to the fifth harmonic. Fig. 3 shows the two layout solutions: in M1 (left), distributed lines prevails, while in M2 (right), a more aggressively scaled layout uses larger capacitances. Following the DK specifications, T_{SiN} may undergo statistical variations with $\sigma = 2$ nm standard deviation, i.e. 2% of the nominal value. To grasp the dependency of the matching network on MIM variations, we perform different EM simulations and store the port S-par as a function of T_{SiN} into an MDIF file, e.g. as in Fig. 4.

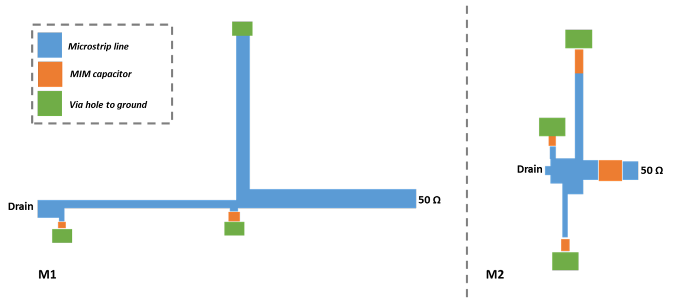

Fig. 3. Two possible layouts of the output matching network.

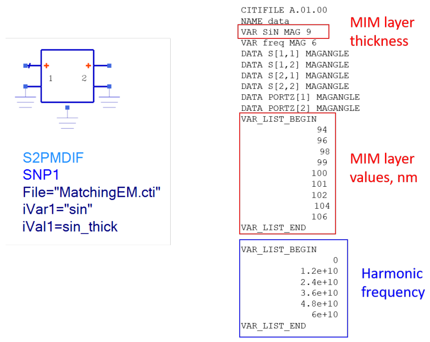

Fig. 4. MDIF file used for passive structures as a function of T_{SiN}. Left: circuit symbol; right: relevant part of the ADS *.citifile* used.

Once the parametrized models are assessed, the complete statistical analysis of the PA stage (here limited to the output port matching) can be readily addressed fully at circuit level [8], circumventing the need for statistical physical analyses.

III. Power Amplifier Statistical Analysis

The PA statistical analysis has been carried out within Keysight ADS with concurrent, fully uncorrelated, random gaussian variations of doping of the active device (standard deviation $\sigma = 2.5\%$ and 5% of the nominal value) and of T_{SiN} ($\sigma = 2\%$). Simulations with no doping variations (only T_{SiN}) are also used for comparison, to monitor the relative weight of passives and active device variations. The two matching networks M1 and M2 are compared in terms of the stage output power and efficiency spread. The sensitivity analysis of the passive structures is considered crucial for PA design, as no optimization is possible when the active device variability, that depends only on the foundry and cannot be modified by the user, is dominant. Figs. 5-7 show the distribution of the output power at three input power levels, i.e. fully in back-off, at 6 dB Output Power Back-off (OBO) and in saturation. P_{out} spread always presents a significant skew in back-off [7], while it is more symmetric at higher power drive. The overall spread is highest around 6 dB OBO. Notice that the two matching networks behave differently (see the MIM variations only, left in the three figures) and generally M2 is worse than M1, especially in saturation, due to the role of MIM capacitors. Figs. 5-7 show that increasing doping

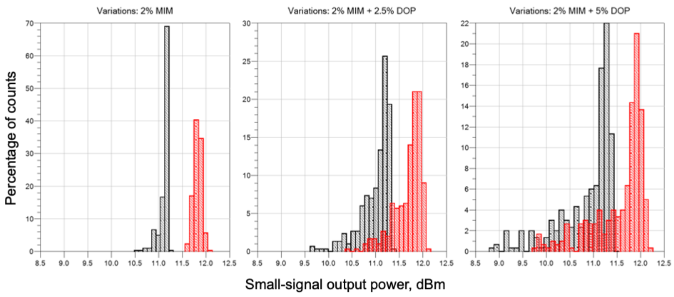

Fig. 5. Output power distribution of the PA stage in back-off, subject to concurrent T_{SiN} and: no doping variations (left); 2.5% variations (center); 5% variations (right). Red: M1; black: M2.

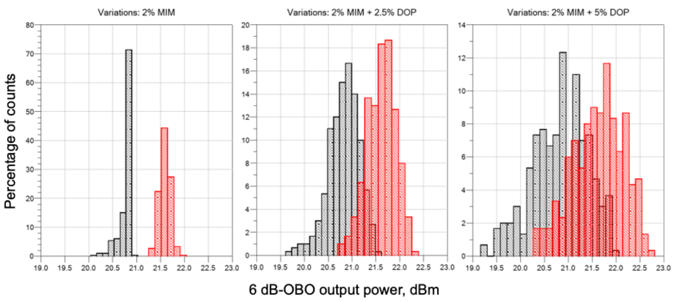

Fig. 6. Output power distribution of the PA stage at 6 dB OBO, subject to concurrent T_{SiN} and: no doping variations (left); 2.5% variations (center); 5% variations (right). Red: M1; black: M2.

variations (from left to right) obviously worsens the overall spread, while the relative importance of the MIM variations is significantly reduced, effectively de-sensitizing the PA with respect to passive variations. When the gaussian distributions corresponding to M1 and M2 are partially or significantly overlapped, as e.g. at 6 dB OBO even with only 2.5% doping variations, the differences of the two passive layouts are smeared out by the active device variations, and are effectively equivalent in terms of the overall PA power distribution. In these conditions, the design of the passive matching network is not an issue for variability. At saturation, instead, M1 and M2 lead to markedly different PA behavior, even with the highest doping variations. When it comes to other PA performances, though, the situation is different: Fig. 8 shows for example the distribution for the efficiency in saturation: the role of doping variations in this case is negligible, since they affect both the DC and harmonic FET currents, making the overall efficiency spread dominated by passive components variations.

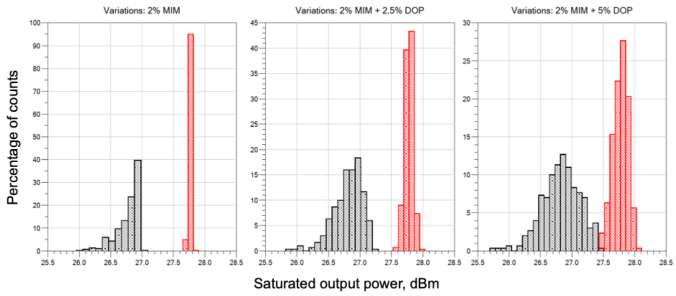

Fig. 7. Output power distribution of the PA stage at saturation, subject to concurrent T_{SiN} and: no doping variations (left); 2.5% variations (center); 5% variations (right). Red: M1; black: M2.

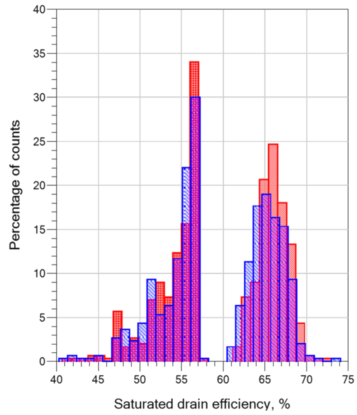

Fig. 8. Efficiency of the two layout solutions M1 (left) and M2 (right) at saturation. Red: T_{SiN} variations only. Blue: T_{SiN} and 5% doping variations.

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