Parameterized Surrogate Models of Microstrip Structures for Electromagnetic-Based Power Amplifier Design and Statistical Analysis

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Abstract. Integrated circuits operating in the millimetre-wave range require careful electromagnetic optimization of the passive networks to properly account for crosstalk and radiative effects, but also accurate and reliable statistical analysis to assess the impact of process induced variability on chip yield. These two requirements are typically computationally incompatible, since the simulation time required by electromagnetic analysis is too high to allow for multi-trial Monte Carlo statistical analysis. This work presents a parameterized surrogate approach to model the passive networks that allows for an efficient yet accurate electromagnetic-based variability analysis of microwave circuits. As a case study, we report the statistical analysis of a GaN/Si device at 28 GHz evaluating the impact of statistical variations of the matching network, under concurrent variation of two technological parameters, on device performance.

Keywords: Parameterized behavioral models · Process induced variability · Electromagnetic simulation · MMIC statistical analysis

1 Introduction

The adoption of higher frequency bands for both microwave telecommunication and radar systems [1,3,7,15] poses new challenges in the design of monolithic integrated circuits (MMIC) in terms of electromagnetic (EM) coupling, stability issues and sensitivity to process variations, that could instead be neglected, or greatly simplified, at lower frequencies. The high cut-off frequency of the active devices together with the relatively low gain and output power achievable with single transistors/stages makes high-frequency MMICs densely integrated, with unavoidable EM coupling between adjacent structures [11,13], hence making EM-based analysis and optimization a crucial design step.

At the same time, process induced variability (PIV) is a growing concern. Active devices capable of operating at millimetre-wave should feature very short

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gate-lengths, but such technologies are typically less mature and thus affected by larger technological variation. On the other hand, the effect of devices' reactive parasitics become significant at high frequency, hence making the design of the matching networks increasingly challenging and the device performance much more sensitive to load variations. Both aspects increase the impact of PIV on yield, which may drop well below 50%, hence requiring a PIV-aware design approach [9].

Statistical analysis typically relies on the Monte Carlo (MC) approach, requiring accurate but also computationally efficient models for both the active devices and the passive networks [2,5,8]. Focusing on passives, to achieve accurate and reliable statistical results, an EM-based approach must be pursued, as it ensures a direct link between physical process parameters and network performance [4]. However, EM simulations are extremely time-consuming, even when resorting to planar-3D analysis for microstrip structure. Data arrays with several thousands of points should in fact be manipulated to achieve reasonable accuracy, requiring hours of simulation even on multi-core computers. This still widely limit the use of EM simulations in MMIC statistical analysis.

In [12] we proposed a parameterized reduced-order behavioral model as an efficient yet highly accurate approach for EM-based MMIC statistical analysis: few EM simulations, at properly chosen sets of parameter values, are enough to extract a mathematical model of the networks's scattering matrix [6], then translated into an equivalent SPICE circuit [14] to be used within any RF CAD tools. As a case study, we consider the output matching network (OMN) of a commercial GaN/Si HEMT transistor for power amplifier (PA) applications at 28 GHz, presenting in [12] the statistical analysis of its small-signal matching performance. In this work we extend the analysis to the large-signal performance of the matched transistor, confirming model accuracy and showing the impact of OMN variations on the most relevant PA performance.

2 Modeling Approach and Case Study

The EM-simulated S-matrix of the network to be modeled is approximated with a rational barycentric function of the form [6]:

$$\mathbf{S}(j\omega, \boldsymbol{\vartheta}) = \frac{\sum_n \mathbf{R}_n(\boldsymbol{\vartheta})\varphi_n(j\omega)}{\sum_n r_n(\boldsymbol{\vartheta})\varphi_n(j\omega)} \tag{1}$$

The basis functions $\varphi_n(j\omega)$ are used to model the frequency dependence of the S-parameters and are represented by a set of N stable poles q_n [16]:

$$\varphi(j\omega) = \begin{cases} 1 & \text{for } n = 0 \\ \dfrac{1}{j\omega - q_n} & \text{for } n = 1, \dots, N \end{cases} \tag{2}$$

The coefficients are functions of the technological parameters θ_i, through Chebyshev polynomials basis functions ξ_l:

$$\mathbf{R}_n(\boldsymbol{\vartheta}) = \sum_l \mathbf{R}_{ln}\xi_l(\boldsymbol{\vartheta}) \quad \text{and} \quad r_n(\boldsymbol{\vartheta}) = \sum_l r_{ln}\xi_l(\boldsymbol{\vartheta}) \tag{3}$$

As a case study, we consider a $6 \times 100\,\mu\text{m}$ GaN/Si HEMT device matched at output for maximum power at 28 GHz. The adopted technology is the 100-nm process from OMMIC [3]. The device is biased in shallow (25%) class AB and the optimum drain termination is $Z_{Lopt} \approx (6+j11)\,\Omega$, allowing for an output power in excess of 31.7 dBm with associated gain and efficiency better than 8.8 dB and 44%, respectively. The matching network, shown in Fig. 1, transforms the standard 50 Ω load into Z_{Lopt} on a broad frequency range. The network is EM simulated in the 18 GHz-38 GHz range with 100 MHz frequency sampling: the simulation time is roughly 15 min, thus incompatible with a MC analysis, which would demand several days.

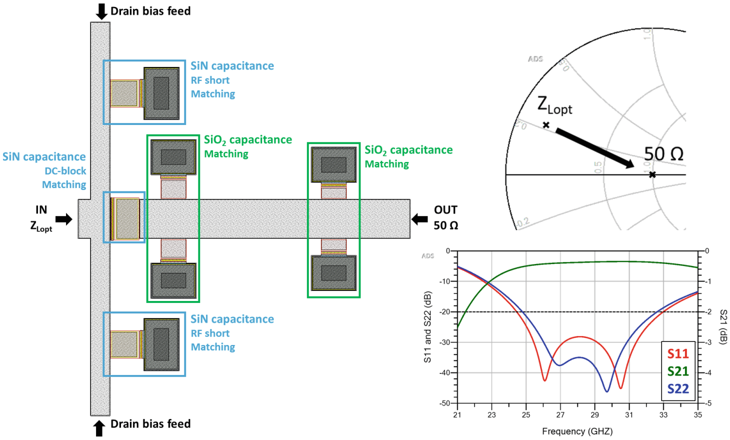


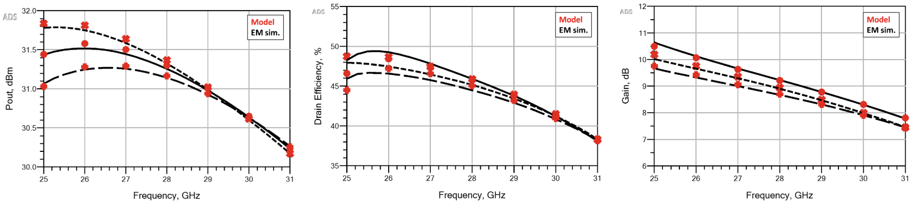
Fig. 1. Output matching network layout and matching performance.

The considered variable parameters are the dielectric layer thicknesses for the two types of MIM capacitors (SiN and SiO_2) available in the process: based on the available statistical data, we assume a relative variance σ of 5% for the nitride thickness and 3% for the oxide thickness. The parameter space boundaries are set to $\pm\sigma$ for both parameters: a deliberately reduced limit with respect to the classical $\pm 3\sigma$ to assess the model extrapolation capabilities under larger variations during MC analysis. Only 10 EM simulations were required to extract the model coefficients with residual error less than 10^{-3} [14]. As detailed in [12], the model demonstrates remarkable robustness against port impedance change, maintaining an accuracy within $4 \cdot 10^{-3}$ when simulating the S-parameters with Z^*_{Lopt} at the input port.

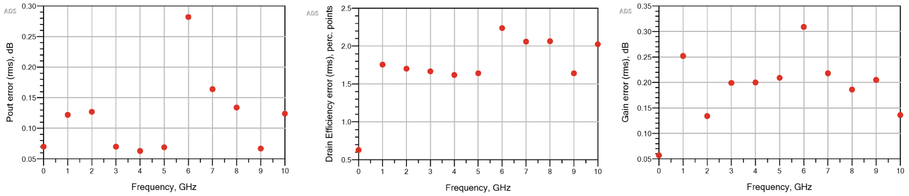
3 Results

The large-signal performance of the matched device is analyzed under continuous-wave excitation in the 25 GHz to 31 GHz range (1 GHz step), sweeping the input power from small-signal to saturation. The comparison between

EM simulations (black lines) and model predictions (red symbols) are reported in the following figures: Fig. 2-top reports the performance at saturation over frequency for nominal (solid/circles) and two random (dash/crosses) parameter values. The accuracy is very good, as confirmed by the results shown in Fig. 2-bottom, reporting the rms errors at 10 randomly selected test points. The maximum errors in predicting the output power, drain efficiency and gain are lower than 0.28 dB, 2.3% points and 0.31 dB, respectively.



(a) Output power (b) Efficiency (c) Power gain

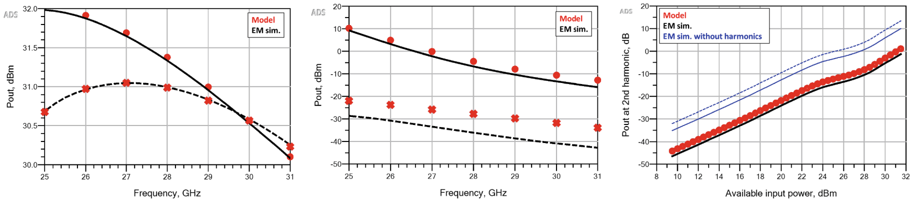


(d) Output power (e) Efficiency (f) Power gain

Fig. 2. Model accuracy: (top) comparison between EM simulations and model predictions and (bottom) rms error.

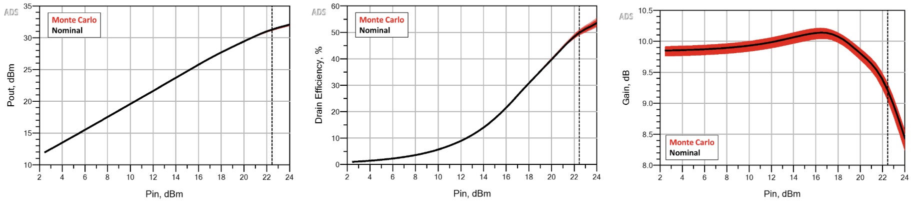
Figure 3 illustrates the extrapolation capabilities of the model. Figure 3(a) reports the output power at extrapolated parameter values, namely $+3\sigma$ (solid/circles) and -3σ (dash/crosses): the agreement with EM simulations is still excellent. Figure 3(b) shows instead the output power at second (solid/circles) and third (dash/crosses) harmonics. Considering the small absolute value of these quantities, the agreement is still good. Remarkably, as detailed in Fig. 3(c), the proposed model extrapolates in frequency much better that any other built-in ADS extrapolation algorithms applied to narrow-band (18 GHz-38 GHz) EM simulations (blue curves).

Figure 4 reports the results of a 500-trial Monte Carlo simulation with uncorrelated variations of the two parameters, both featuring a gaussian distribution with σ relative variance. Except for gain, affected by constant symmetrical spread at all power levels, PIV most affects the performance at saturation where up to 1 dB of power/gain spread and 6% points of efficiency spread can be observed in the lower portion of the band. The dissipated power density, which determines the device temperature [10], is also reported in Fig. 5: at high power levels the spread reaches 250 mW/mm.

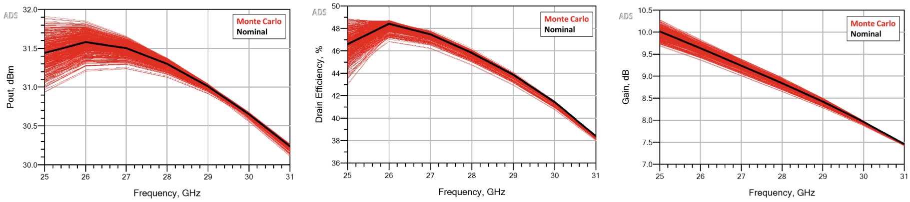


(a) Saturated power at ±3σ (b) Saturated power at 2$^{\text{nd}}$ and 3$^{\text{rd}}$ harmonics (c) Power at 2$^{\text{nd}}$ harmonic

Fig. 3. Results at extrapolated (a) parameters and (b)-(c) frequency values.

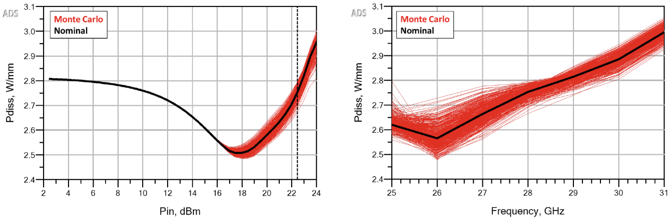


(a) Output power (b) Drain efficiency (c) Power gain



(d) Output power (e) Drain efficiency (f) Power gain

Fig. 4. Statistical analysis results.



(a) (b)

Fig. 5. Statistical analysis results: dissipated power density.

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