

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

*Original*

Parameterized Surrogate Models of Microstrip Structures for Electromagnetic-Based Power Amplifier Design and Statistical Analysis / Ramella, Chiara; Zanco, Alessandro; De Stefano, Marco; Bradde, Tommaso; Grivet-Talocia, Stefano; Pirola, Marco. - STAMPA. - 1005:(2023), pp. 50-56. (Intervento presentato al convegno SIE 2022 tenutosi a Rende, Italy nel 5-7 September, 2022) [10.1007/978-3-031-26066-7\_8].

*Availability:*

This version is available at: 11583/2976617 since: 2023-04-12T08:40:18Z

*Publisher:*

Springer

*Published*

DOI:10.1007/978-3-031-26066-7\_8

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

Springer postprint/Author's Accepted Manuscript (book chapters)

This is a post-peer-review, pre-copyedit version of a book chapter published in Proceedings of SIE 2022. The final authenticated version is available online at: [http://dx.doi.org/10.1007/978-3-031-26066-7\\_8](http://dx.doi.org/10.1007/978-3-031-26066-7_8)

(Article begins on next page)

# Parameterized surrogate models of microstrip structures for electromagnetic-based power amplifier design and statistical analysis

Chiara Ramella, Alessandro Zanco, Marco De Stefano, Tommaso Bradde,  
Stefano Grivet-Talocia, and Marco Pirola

DET, Politecnico di Torino, 10129 Torino, Italy  
`chiara.ramella@polito.it`

**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 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]:

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

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]:

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

The coefficients are functions of the technological parameters  $\theta_i$ , through Chebyshev polynomials basis functions  $\xi_l$ :

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

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  $50 \Omega$  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 minutes, thus incompatible with a MC analysis, which would demand several days. The considered variable parameters are

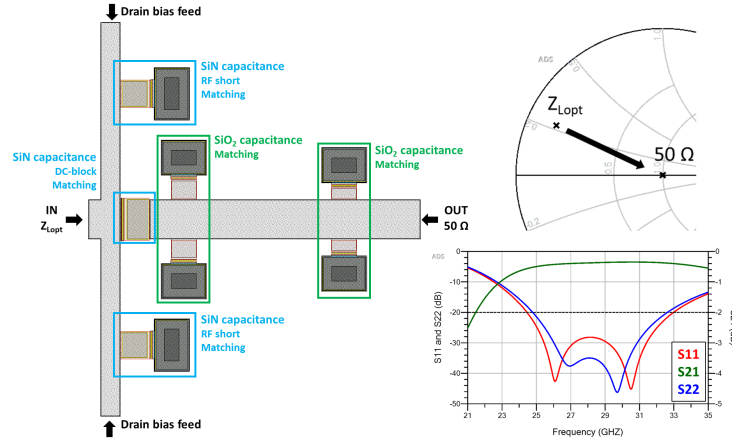


Fig. 1: Output matching network layout and matching performance.

the dielectric layer thicknesses for the two types of MIM capacitors (SiN and SiO<sub>2</sub>) available in the process: based on the available statistical data, we assume a relative variance  $\sigma$  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 percentage points and 0.31 dB, respectively. Fig. 3 illustrates the extrapola-

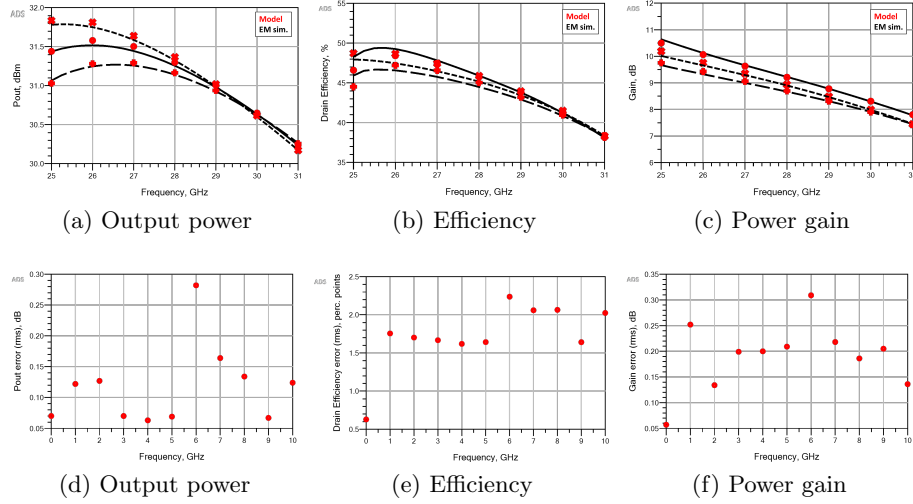


Fig. 2: Model accuracy: (top) comparison between EM simulations and model predictions and (bottom) rms error.

tion capabilities of the model. Fig. 3(a) reports the output power at extrapolated parameter values, namely  $+3\sigma$  (solid/circles) and  $-3\sigma$  (dash/crosses): the agreement with EM simulations is still excellent. Fig. 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 than any other built-in ADS extrapolation algorithms applied to narrow-band (18 GHz-38 GHz) EM simulations (blue curves).

Fig. 4 reports the results of a 500-trial Monte Carlo simulation with uncorrelated variations of the two parameters, both featuring a gaussian distribution with  $\sigma$  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 percentage 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.

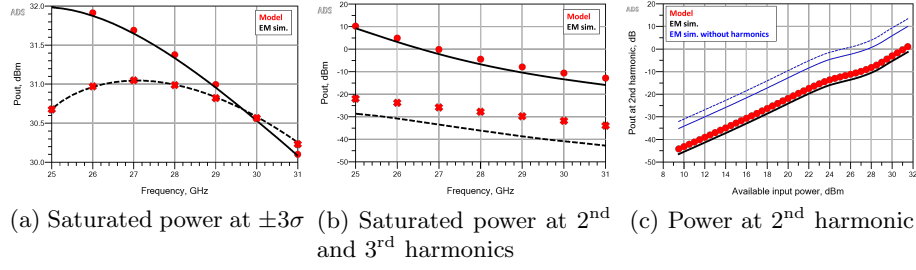


Fig. 3: Results at extrapolated (a) parameters and (b)-(c) frequency values.

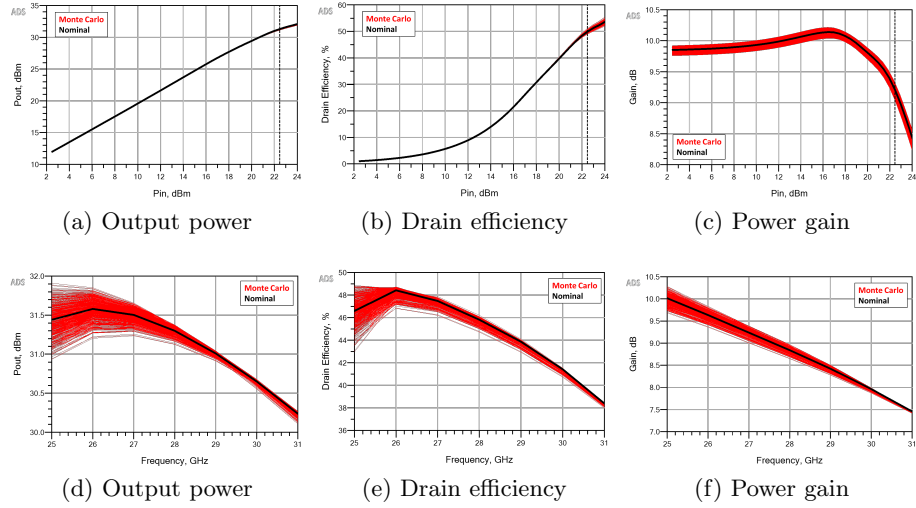


Fig. 4: Statistical analysis results.

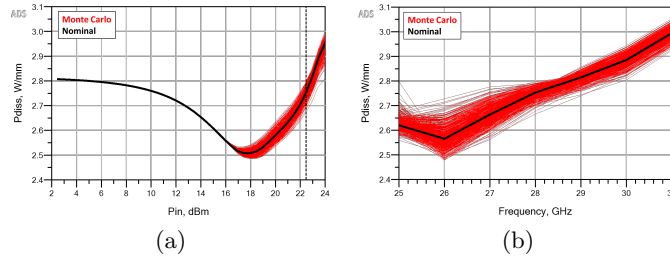


Fig. 5: Statistical analysis results: dissipated power density.

## References

1. Bao, M. et al.: A 24–28-GHz Doherty Power Amplifier With 4-W Output Power and 32% PAE at 6-dB OPBO in 150-nm GaN Technology. *IEEE Microw. Wireless Compon. Lett.* **31**(6). 2021. <https://doi.org/10.1109/LMWC.2021.3063868>
2. Beleniotis, P. et al.: Statistical Modeling of GaN HEMTs by Direct Transfer of Variations to Model Parameters. *EuMIC* 2021. <https://doi.org/10.23919/EuMIC50153.2022.9783780>
3. Cidronali, A. et al.: System Level Analysis of Millimetre-wave GaN-based MIMO Radar for Detection of Micro Unmanned Aerial Vehicles. *PIERS-Spring* 2019. <https://doi.org/10.1109/PIERS-Spring46901.2019.9017681>
4. Donati Guerrieri, S. et al.: Efficient sensitivity and variability analysis of nonlinear microwave stages through concurrent TCAD and EM modeling. *IEEE J. Multiscale Multiphys. Comput. Tech.* **4**, 2019. <https://doi.org/10.1109/JMMCT.2019.2962083>
5. Donati Guerrieri, S., et al.: Bridging the gap between physical and circuit analysis for variability-aware microwave design: Modeling approaches. *El.* **11**(6), 2022. <https://doi.org/10.3390/electronics11060860>
6. Grivet-Talocia, S., Trincherio, R.: Behavioral, parameterized, and broadband modeling of wired interconnects with internal discontinuities. *IEEE Trans. Electromagn. Compat.* **60**(1), 2018. <https://doi.org/10.1109/TEM.2017.2723629>
7. Ishikawa, R. et al.: A 28-GHz-Band GaN HEMT MMIC Doherty Power Amplifier Designed by Load Resistance Division Adjustment. *EuMIC* 2021. <https://doi.org/10.23919/EuMIC50153.2022.9783948>
8. Manfredi, P., Canavero, F.G.: Efficient statistical simulation of microwave devices via stochastic testing-based circuit equivalents of nonlinear components. *IEEE Trans. Microw. Theory Techn.* **63**(5), 2015. <https://doi.org/10.1109/TMTT.2015.2417855>
9. Mao, S. et al.: A Yield-Improvement Method for Millimeter-Wave GaN MMIC Power Amplifier Design Based on Load—Pull Analysis. *IEEE Trans. Microw. Theory Techn.* **69**(8), 2021. <https://doi.org/10.1109/TMTT.2021.3088499>
10. Ramella, C. et al.: Thermal-aware GaN/Si MMIC design for space applications. *COMCAS* 2019. <https://doi.org/10.1109/COMCAS44984.2019.8958104>
11. Ramella, C. et al.: Electro-magnetic Crosstalk Effects in a Millimeter-wave MMIC Stacked Cell. *INMMiC* 2020. <https://doi.org/10.1109/INMMiC46721.2020.9160341>
12. Ramella, C. et al.: Efficient EM-based variability analysis of passive microwave structures through parameterized reduced-order behavioral models. Accepted for publication in *EuMIC* 2022.
13. Sangwan, V. et al.: High-Frequency Electromagnetic Simulation and Optimization for GaN-HEMT Power Amplifier IC. *IEEE Trans. Electromagn. Compat.* **61**(2), 2019. <https://doi.org/10.1109/TEM.2018.2820202>
14. Triverio, P. et al.: A parameterized macromodeling strategy with uniform stability test. *IEEE Trans. Adv. Packag.* **32**(1), 2009. <https://doi.org/10.1109/TADVP.2008.2007913>
15. Wohler, D. et al.: 8-Watt Linear Three-Stage GaN Doherty Power Amplifier for 28 GHz 5G Applications. *BCICTS* 2019. <https://doi.org/10.1109/BCICTS45179.2019.8972750>
16. Zanco, A. et al.: Uniformly Stable Parameterized Macromodeling Through Positive Definite Basis Functions. *IEEE Trans. Compon. Packag. Manuf. Technol.* **10**(11), 2020. <https://doi.org/10.1109/TCPMT.2020.3012275>