AMCAD Engineering

White Paper

STAN Tool: A Unique Solution for the Stability Analysis of RF & Microwave Circuits

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Introduction

The next generation of cellular communications (5G) requires communication networks with higher capabilities in bandwidth, speed, and reliability. This fast evolution of connectivity involves developing more complex communication structures to attain the new, highly demanding specifications.

In wireless communication networks, the most restrictive element is the base station, where the power amplifier (PA) is the component that consumes the highest amount of energy. To achieve maximum power efficiency, PAs work near their saturation region, risking the presence of nonlinear distortion [1]. Moreover, power amplifiers at RF and microwave frequencies often present undesired behavior due to the presence of feedback loops, such as frequency division by two, oscillations at incommensurate frequencies, or hysteresis [2]-[4]. This undesired behavior may appear in linear conditions, depending on the device's bias, and in nonlinear conditions where the input power increase may lead to a qualitative change of the solution’s stability.

The detection of instabilities at the design stage enables a reduction of fabrication costs: the circuit can be perfectly characterized without delaying the fabrication process. Moreover, if designs are made for MMIC (Monolithic Microwave Integrated Circuits), the stability analysis gains importance due to the impossibility of adjusting the design after fabrication. Thus, the use of reliable tools allowing rigorous detection of circuit instabilities in both small and large signals is essential at the design stage.

Problematic

Nowadays, the circuit behavior can be predicted using commercial CAD (Computer-Aided Design) Tools, where different simulation methods try to provide more insight into the circuit dynamics. The available methodologies are based on time-domain and frequency-domain integration [5]. When using the time-domain integration, the transient is considered in the analysis. Large time constants are necessary to account for the system dynamics, making it unsuitable at microwave frequencies. On the other hand, frequency-domain methods such as Harmonic Balance (HB) only provide steady-state solutions without giving information about their stability. Note that only stable solutions can be observed physically. Therefore, further analyses are necessary after getting a solution.

Stability Analysis:

Available methodologies in CAD tools are either **not complete** or **too complex** to be practically implemented.

Small-signal stability analysis (K, μ) are widely used. However, **instabilities** may arise in **large signal** when increasing the input power.

Commercial simulators have implemented different tools to simplify the stability analysis of a circuit. In linear conditions, the Rollet factor [6]-[7], *K*, and the μ factor [8] are widely used. However, they are only valid for analyzing a linear two-port network[1], intrinsically stable, that exhibits negative resistance at its ports for any value of passive source or load impedances. Moreover, these methods only provide small-signal stability of a circuit biased in a particular DC steady state. They are not suitable for analyzing multistage PAs with multiple active devices and feedback loops where the internal stability fulfillment is more difficult to ensure. Other methods, more rigorous and suitable for the analysis of more complex structures, have also been developed [10]-[11], but they are not easy to implement when using commercial software.

STAN Tool:

Stability analyses in both **linear** and **non-linear** conditions.

The **pole-zero analysis** provides more insight into the circuit behavior.

The identification methodologies in combination with **parametric**, **multi-node** and/or **Monte Carlo** analyses provide the nature and place of the oscillation.

While small-signal stability analyses may be easier to implement, large-signal stability analysis tools are not typically included in commercial CAD tools. A system may be stable in the small-signal regime, but instabilities may arise from the new steady state given by the input drive's large signal. Different techniques have been developed [12]-[14], but they are either not complete or they are too complex to be easily used in a design flow.

To cope with stability analysis in both linear and nonlinear conditions, STAN Tool [15] proposes a much more powerful approach. Thanks to its unique pole-zero analysis [16]-[21], it provides more insight into the circuit behavior, being able to provide the nature of the oscillation, as well as where it is happening, through parametric, multi-node [19] and/or Monte-Carlo [20] analyses. This approach can help the designer to perform a more reliable stabilization of its circuit by adjusting its components without losing much of its original performance.

The stability analysis using STAN Tool is a two-step process (Fig. 1). First, the frequency response of the circuit, $H_0(j\omega_S)$, under a small-signal perturbation signal is obtained through simulations using commercial CAD tools. The pole-zero map is then identified and plotted in STAN Tool after fitting a transfer function $H_0(s)$ obtained from the frequency domain identification of the frequency response $H_0(j\omega_S)$.

The automatic algorithm and the identification methodologies available in STAN Tool are presented in the next section. Then, the extraction of the frequency response to perform different analyses is described in detail. A new representation scheme for the pole-zero map is also presented. Finally, the analysis of an AMCAD' 35-dBm amplifier design is used to illustrate the stability analysis using STAN Tool.

[1] The extension of the K factor to large-signal analysis is a complex multidimensional problem. A rigorous study is presented in [9].

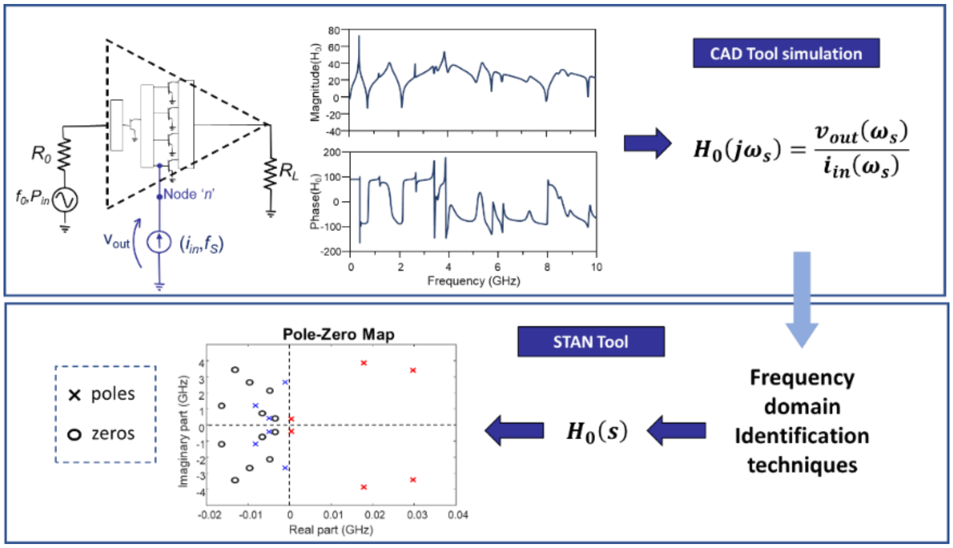

Fig. 1. The stability analysis using STAN Tool is a two-step process.

STAN Tool: Identification Methodologies

In STAN Tool, to obtain a pole-zero map, a transfer function $H_0(s)$ is processed after identifying the frequency response $H_0(j\omega_S)$. This transfer function $H_0(s)$ is a linear model that may suffer from under-modeling/over-modeling effects: some dynamics of the system may be missed or added unnecessarily. The over-modeling can be observed in STAN Tool through couples of poles and zeros located very close in the complex plane, i.e., pole-zero quasi-cancellations. We call these quasi-cancellations "numerical" because they are associated to over-modeling.

There are other type of quasi-cancellations, which we call "physical". They represent an actual physical effect in the amplifier's dynamics that is present in the transfer function with very low sensitivity (poor observability/controllability from the analysis node). To distinguish between "numerical" and "physical" quasi-cancellations is important for a correct interpretation of the stability results. If quasi-cancellations take place on the right-hand side (RHS) of the complex plane, further analyses are necessary to know if the system is actually unstable (numerical quasi-cancellations on the RHS do not imply oscillation while "physical" do).

Identification methodologies

Automatic algorithm that searches for the best possible order of the function with the aid of the phase tolerance parameter.

Moreover, since the order N of the transfer function $H_0(s)$ is unknown a priori, an automatic algorithm that searches for the best possible order of the function has been developed in STAN Tool. This algorithm automatically searches for the transfer function's appropriate order with the phase tolerance parameter's aid facilitating the identification process. This phase tolerance represents the maximum phase error permitted between the frequency response $H_0(j\omega_S)$ and the transfer function $H_0(s)$.

The algorithm tries to fit $H_0(j\omega_S)$ through a number of iterations aiming to keep the phase error under the phase tolerance value defined by the user [18]. A value of the phase tolerance too strict (small) may give raise to numerical quasi-cancellations.

To cope with quasi-cancellations, a new identification method is available in STAN Tool: SISO (Single-Input Single-Output) method. This method, numerically well-conditioned for high-frequency and large band applications, helps the user in easily detecting over-modeling effects with a new analysis parameter, ρ, that provides more insight into the system dynamics.

The SISO method, combined with the existing DACWIN (Divide-And-Conquer With Noise) method and the available analyses in STAN Tool (parametric, multi-node, and/or Monte Carlo), represents an extra tool for reliable and insightful stability analyses of RF and microwave circuits.

SISO (Single-Input Single-Output) method:

In the SISO method, $H_0(s)$ is calculated as a rational function expressed as a sum of partial fractions [21]-[25]:

$$H_n(s) = \sum_{k=1}^{N} \frac{r_{n,k}}{s-p_k} + D_n \tag{1}$$

where $r_{n,k}$ are the residues, p_k are the system poles and D_n is the direct gain of the transfer function.

The solution of (1) is iteratively obtained from a set of initial poles, where the last poles are used as the initial poles for the next iteration. However, this iterative process starting from a small order may make the SISO method a time-consuming option when identifying wideband frequency responses with a high number of resonances.

Residue Analysis

The SISO method enables better control of the undesired effects of over-modeling through a systematic approach with the aid of a new analysis parameter, ρ, extracted from a residue analysis [21]-[25].

From (1), the analysis of the residue $r_{n,k}$ provides quantitative information on the contribution of the pole p_k to the transfer function: the residues obtained at a sensitive node have large values, while the residues corresponding to pole-zero quasi-cancellations identified at a node with poor observability are very small.

From the residues $r_{n,k}$, and taking into account the resonance frequency ω_r, the normalized factor $\rho_{i,k}$ is defined as [21]-[25]:

$$\rho_{i,k} = \frac{|H^{i,k}(j\omega_r)|}{|H^{i}(j\omega_r)| - |H^{i,k}(j\omega_r)|} \tag{2}$$

where $\omega_r = \sqrt{b^2 - a^2}$ is the resonance frequency of the pole $p_k = a \pm bi$. This factor quantifies the relative effect of the pair of resonant complex-conjugate poles on the transfer function, i.e., it can be used to quantify quasi-cancellations, and it provides a tool to detect numerical poles resulting from over-modeling. The detected poles through the SISO method can be classified into three groups:

- High-sensitivity poles, ρ > 1: these poles are the resonant poles that contribute the most to the frequency response, to the circuit dynamics. If the resonant poles with ρ > 1 are placed on the RHS of the complex plane, they are unstable physical poles. Therefore, the circuit is unstable.
- Low-sensitivity poles, 0.01< ρ < 1: these poles may be physical or numerical. If they are physical, they may then correspond to circuit dynamics far from the observation node. Therefore, when low sensitivity poles are placed on the RHS of the complex plane, further analyses (e.g., parametric, multi-node) are required to determine their nature.

- Very low-sensitivity poles, $\rho < 0.01$: these poles are most likely numerical, and they are not important for the analysis of the circuit dynamics.

Residue analysis

***ρ* factor:** quantifying the relevance of critical poles to avoid the undesired effects of over-modeling.

Unstable poles with **ρ > 1** -> No doubt, the system is **unstable.**

If poles and zeros are located very close in the pole-zero map, their nature, physical or numerical, can be deduced by looking at their ρ value. In the case of poles with $\rho < 1$ located on the RHS of the complex plane, if they follow a consistent path in a parametric analysis (versus input power or bias) and cross to the left-hand side (LHS) of the complex plane (when input power or bias are swept), they are physical poles in all likelihood.

DACWIN (Divide-And-Conquer With Noise) method:

In the DACWIN method, $H_0(s)$ is calculated applying standard frequency domain identification techniques for linear systems based on quotient of polynomials [16]-[21]:

$$H_0(s) = \frac{\prod_{i=1}^{N_Z}(s-z_i)}{\prod_{i=1}^{N_\lambda}(s-p_k)} \tag{3}$$

where z_i are the zeros and p_k are the poles of the system.

When fitting frequency responses at microwave frequencies using this kind of algorithms, transfer functions $H_0(s)$ with high orders N are often required, resulting in possible ill-conditioned identification processes.

To cope with these effects, the automatic algorithm of DACWIN divides the frequency band into smaller sub-bands that use smaller orders to fit the frequency response $H_0(j\omega_S)$ perfectly, avoiding sub-bands too small to account for noise [18].

DACWIN algorithm is focused on the reliable detection of unstable poles, but it does not guarantee the production of a single and complete model of the system because of the division in shorter sub-bands.

STAN Tool: extraction of the frequency response $H_0(j\omega_S)$

The frequency response $H_0(j\omega_S)$ to be fitted using STAN Tool corresponds to the linearization of the circuit's steady-state solution under the influence of a perturbation signal in the given frequency bandwidth. A small-signal current source plays the role of the perturbation and is connected to a circuit's sensitive node (Fig. 2). The frequency response $H_0(j\omega_S)$ is then obtained as the ratio between the node voltage and the current in the perturbation branch (Fig. 2).

$$H_0(j\omega_s)\frac{v_{out}(\omega_s)}{i_{in}(\omega_s)} \tag{4}$$

- DC or small-signal stability analysis. An AC simulation, sweeping the frequency of the perturbation source, f_s, is carried out.
- Large signal stability analysis. In the large-signal stability analysis, the system has two frequencies: the frequency of the input drive, f_{in}, and the frequency of the perturbation source, f_s. Therefore, a mixer-like HB analysis (using a conversion matrix algorithm, available today in most popular commercial simulators), sweeping the frequency f_s, is performed.

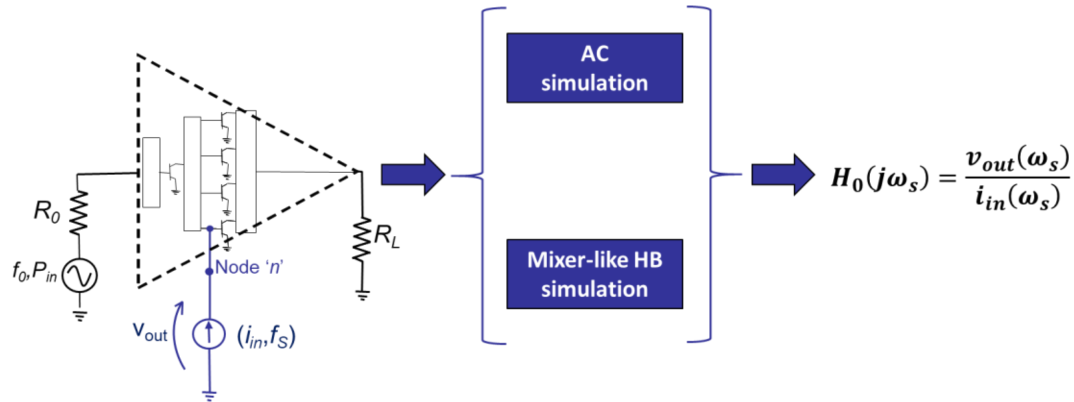

Fig. 2. Extraction of the frequency response $H_0(j\omega_S)$: AC simulation (small-signal stability analysis), mixer-like HB simulation (large-signal stability analysis).

STAN Tool Analyses

Besides the simple small-signal or large-signal analysis, STAN Tool offers additional analyses that aim to provide more insight into the circuit dynamics: parametric, multi-node, and/or Monte-Carlo analyses. The extraction of the frequency response $H_0(j\omega_S)$ to perform these analyses is explained in the following:

- Parametric analysis (Fig. 3). Parametric analyses can be performed to observe the evolution of poles when varying a circuit parameter or a combination of them. It is useful to achieve optimal stabilization or discard numerical quasi-cancellations. Here, a collection of transfer functions are obtained for each combination of the parameters. The STAN Tool will later read the transfer functions and provide the evolution of poles and zeroes with those parameters.

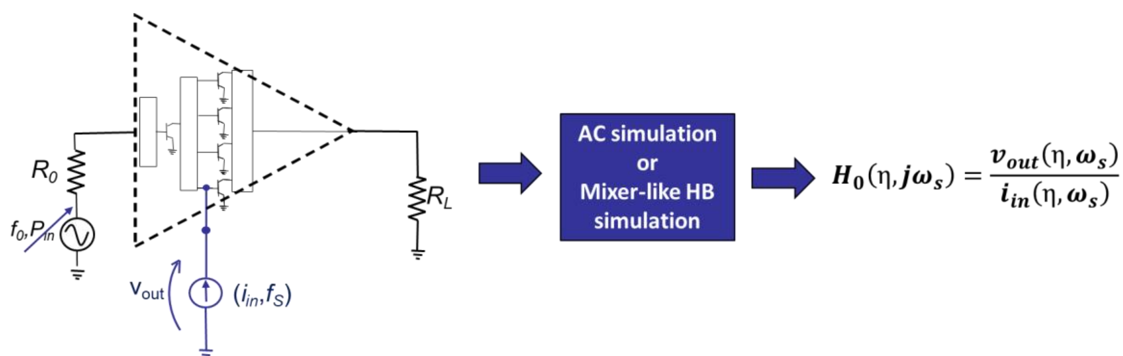

Fig. 3. Extraction of the frequency response $H_0(j\omega_S)$ to perform a parametric analysis.

- Multi-node analysis (Fig. 4). The stability analysis of multistage PAs with many active devices and feedback loops may be difficult because of several active devices and feedback loops. Moreover, amplifiers with power-combining structures often present oscillation at the fundamental frequency divided by two ($f_0/2$) that are generally odd mode: one branch of the circuit oscillates 180° out of phase with the other branch. As a result, the combination nodes represent a virtual ground for the odd-mode oscillation, and it will not be detected. Therefore, the node selected to perform the analysis may not detect instabilities taking place at other stages. A multi-node analysis can be used to detect where in the circuit the oscillation is taking place to cope with this problem. The multi-node analysis can be easily performed using STAN Tool (Fig. 4). A transfer function corresponding to each node is obtained by sequentially injecting the perturbation source at each one of them, where one node par stage is usually sufficient.

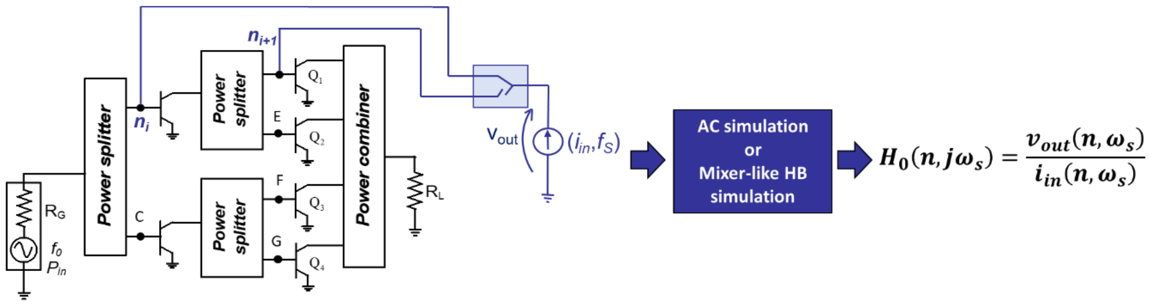

Fig. 4. Extraction of the frequency response $H_0(j\omega_S)$ to perform a multi-node analysis.

- Monte Carlo analysis. Models of electronic components present a tolerance value that, when fluctuating, may give rise to a change in the solution. Evaluate the circuit's stability, taking into account variations around a nominal value can be done following a Monte Carlo analysis. STAN Tool can deal with the high number of frequency responses obtained from Monte Carlo analysis, where a frequency response is obtained at each of the iterations and provides a sensitive stability analysis.

Representation Scheme: Plotting the Resonant Poles

Poles within the identification band are usually plotted, as the user needs to analyze the circuit behavior properly. However, resonant poles are easier to identify and, since unstable poles are typically resonant poles, plotting the resonant poles adds clarity to the solution's analysis. Moreover, physical unstable poles are highly resonant while varying a circuit parameter, enabling their easy detection. Therefore, in STAN Tool, poles are plotted (Fig. 5) taking into account the next two considerations [25]:

- Complex-conjugate poles present different damping factors depending on their resonance: resonance peaks are greater in second-order transfer functions with low damping factors. Therefore, by calculating the poles' damping ratio most resonant poles can be determined. In STAN Tool, only resonant poles, $p_i = a + jb$, with magnitude peaks greater than 0.5 dB are plotted:

$$mag(H)_{\omega=\omega_r} = 20log\left(\frac{\omega_n^2}{2ab}\right) > 0.5 \text{ dB} \tag{5}$$

  where ω_n is the natural frequency defined as $\omega_n = \sqrt{a^2 + b^2}$.

- The resonant poles with $mag(H)_{\omega=\omega_r} > 0.5\ dB$ are plotted only if their resonance frequency, ω_r, is within the analysis band:

$$\omega_{min} \leq \omega_r \leq \omega_{max} \tag{6}$$

However, since all poles' representation may be of interest to the user depending on their system, the possibility of plotting all poles is available in STAN Tool by choosing the *display all Poles* option.

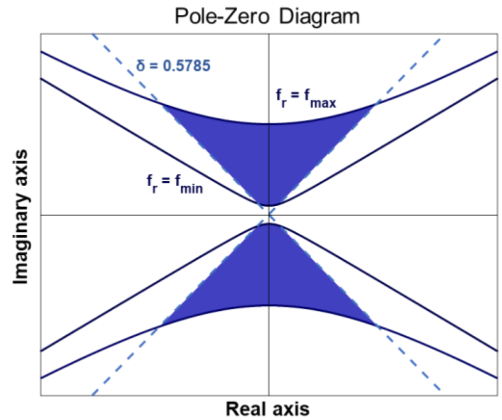

Fig. 5. Area of the complex plane where the resonant poles fulfilling the two conditions will be located.

SISO method and DACWIN method may provide different solutions for the less resonant poles, i.e., the poles that are further from the $Re = 0$ axis. However, both methods provide the same solution for the critical resonant poles.

Stability analysis using STAN Tool

The stability analysis using STAN Tool will be illustrated through the analysis of a 35-dBm amplifier design based on an AMCAD GaN transistor compact model that considers traps and thermal effects (Fig. 6). This amplifier is expected to operate at f_0 = 4 GHz, with a PAE = 63.3 % , a P_{out} = 34.3 dBm and a gain of 14.1 dB at the 3-dB-compression point.

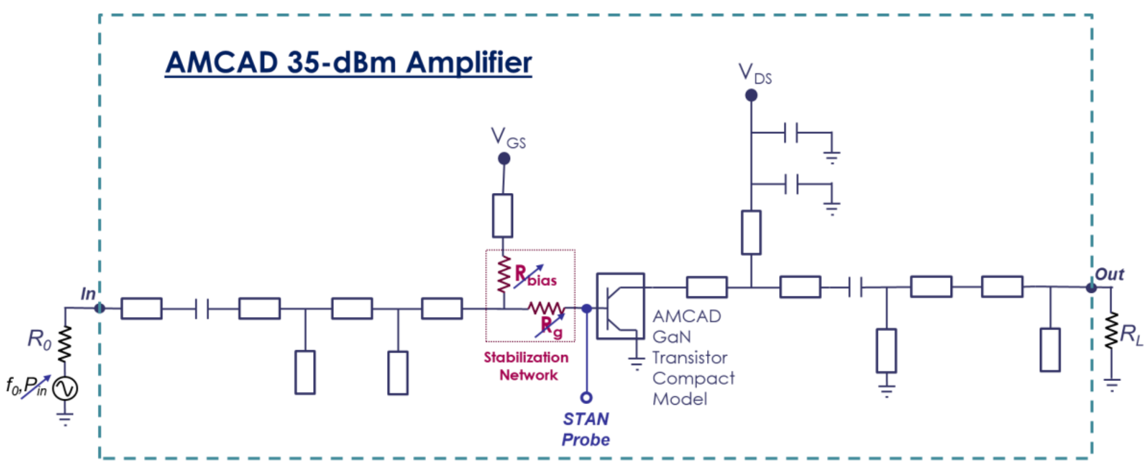

Fig. 6. 35-dBm amplifier design based on an AMCAD GaN transistor compact model that considers traps and thermal effects.

As stated, STAN Tool allows small-signal and large-signal stability analyses. The two analyses in combination with parametric and Monte Carlo analyses will be described in the next sections.

Small-signal stability analysis

To perform the small-signal stability analysis, the frequency response is first obtained using a commercial CAD Tool as was illustrated above. In this AMCAD design example, the frequency f_S will be swept from 0.01 GHz to 10 GHz (Fig. 7), but it can be swept throughout the whole operation band of the active device.

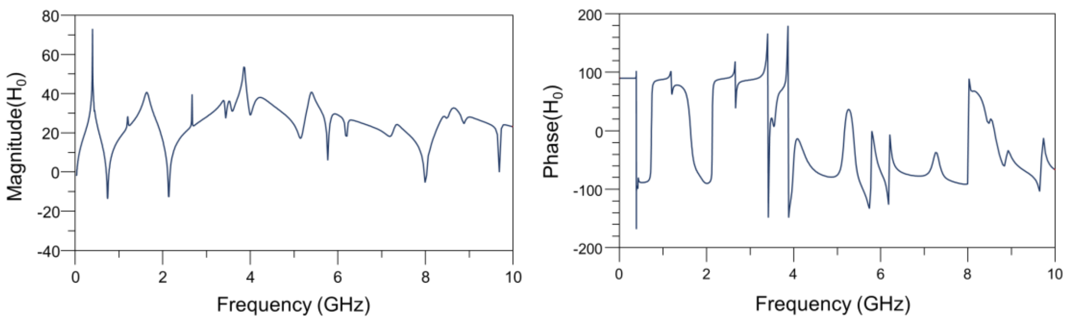

Fig. 7. Magnitude and phase of the frequency response obtained using a commercial CAD tool to perform the small-signal stability analysis.

The frequency response in Fig. 7 will be exported and directly read by STAN Tool without being processed. The identification will be performed using the automatic algorithm of the SISO method (by default) with a phase tolerance of 0.5°, in the whole bandwidth of the simulation.

The identification results are shown in Fig. 8. The two graphs on the left display the magnitude and phase of the frequency response $H_0(j\omega_S)$ where the original data is represented in circles and the identified function in red solid line. The phase-error plot highlights the accuracy of the solution and it should be smaller than the phase tolerance value defined by the user, 0.5° in this case.

From the poles/zeros plot in Fig. 8, the circuit presents instabilities at 386 MHz, 3.4 GHz and 3.8 GHz. The frequency of the poles and zeros is given by their imaginary part.

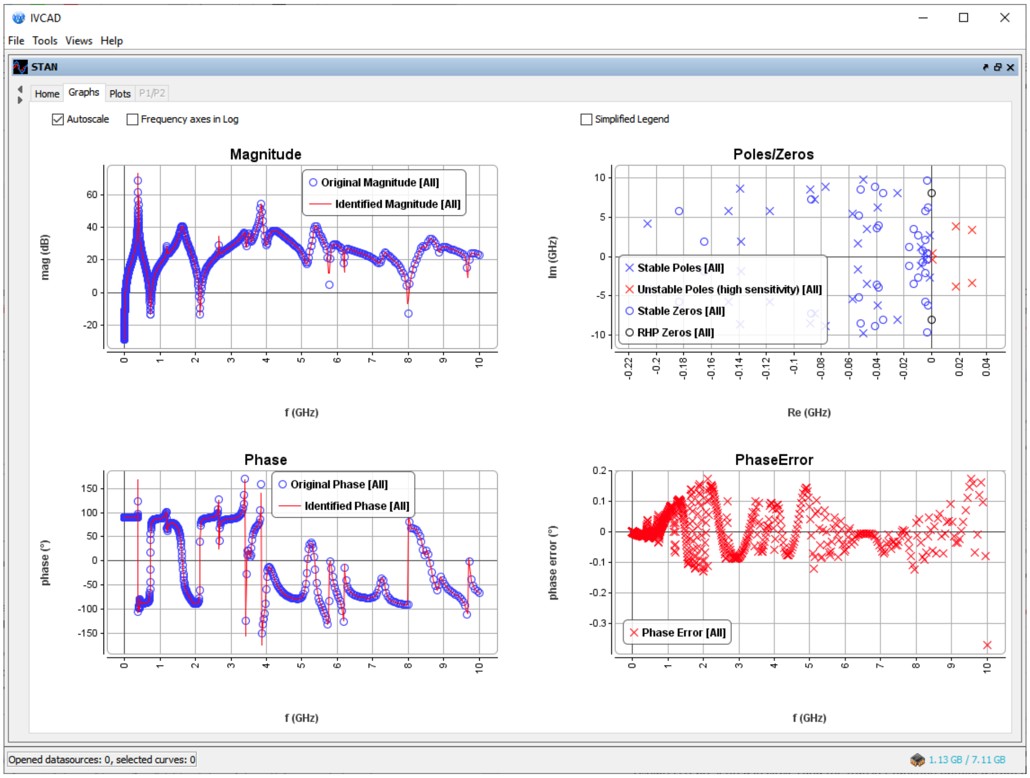

Fig. 8. Results obtained from the identification of the frequency response $H_0(j\omega_S)$. Original data from $H_0(j\omega_S)$ is represented in circles and the data from $H_0(s)$ is represented in red solid line.

Once instabilities have been detected, a stabilization of the circuit can be carried out varying a circuit parameter. To cope with instabilities at high frequency, a series resistor R_g will be connected to the gate of the transistor (Fig. 6). This resistance will reduce the amplifier's gain, thus a trade-off between stability and performances will be necessary.

The value of R_g that will stabilize the circuit and still maintain good performances can be obtained through a parametric analysis. In this analysis, a collection of frequency responses $H_0(\eta,j\omega_S)$ (Fig. 9) will be obtained from the simulator for each parameter value, where R_g will be swept from 1 Ω to 15 Ω in the same frequency band than in Fig. 7.

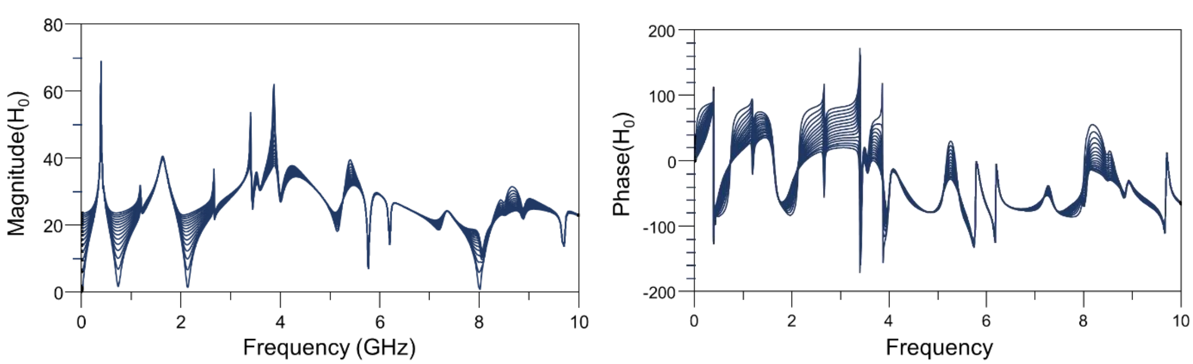

Fig. 9. Magnitude and phase of the frequency response obtained using a commercial CAD tool for the parametric small-signal stability analysis.

STAN Tool is able to identify each one of the frequency responses (Fig. 9) and show the evolution of poles with the parameter (Fig. 10): high-frequency unstable poles will cross to the LHS of the complex plane when increasing R_g.

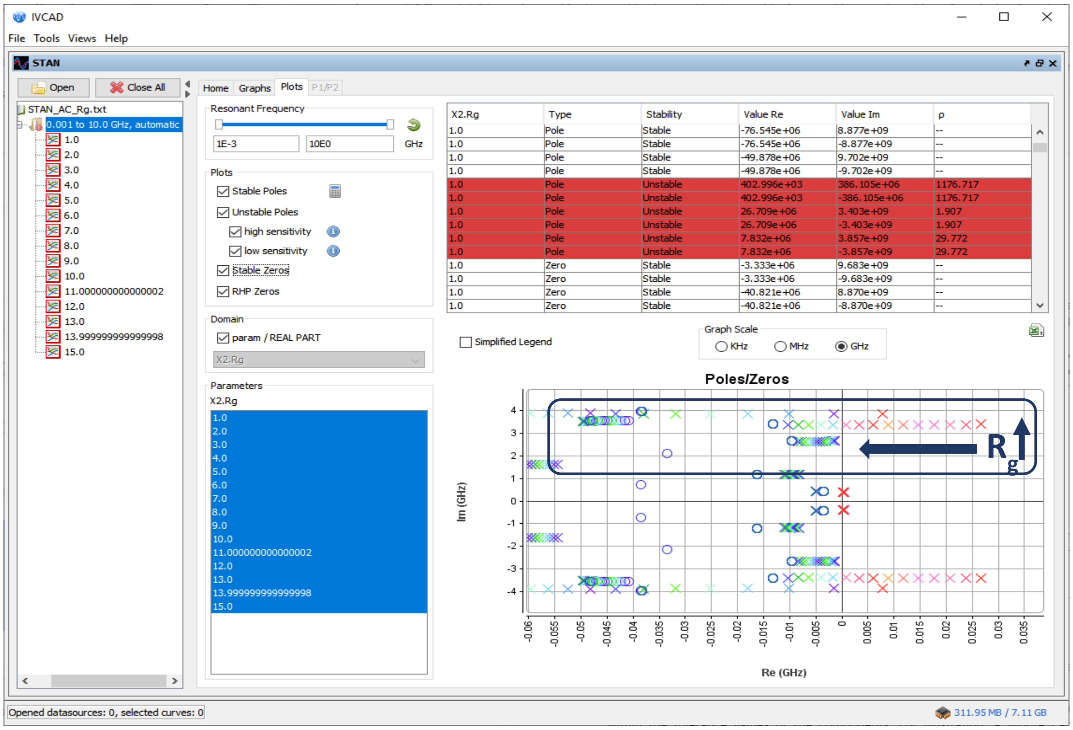

Fig. 10. Results of the parametric small-signal stability analysis using STAN Tool.

Moreover, plotting the real part of poles versus R_g (Fig. 11) using the option *param/REAL PART* allows an easier detection of the start-up of the oscillation (bifurcation point). From Fig. 11, the high-frequency instabilities disappear if a series resistor R_g > 11 Ω is connected at the gate terminal of the transistor. The low-frequency instabilities will be discussed later.

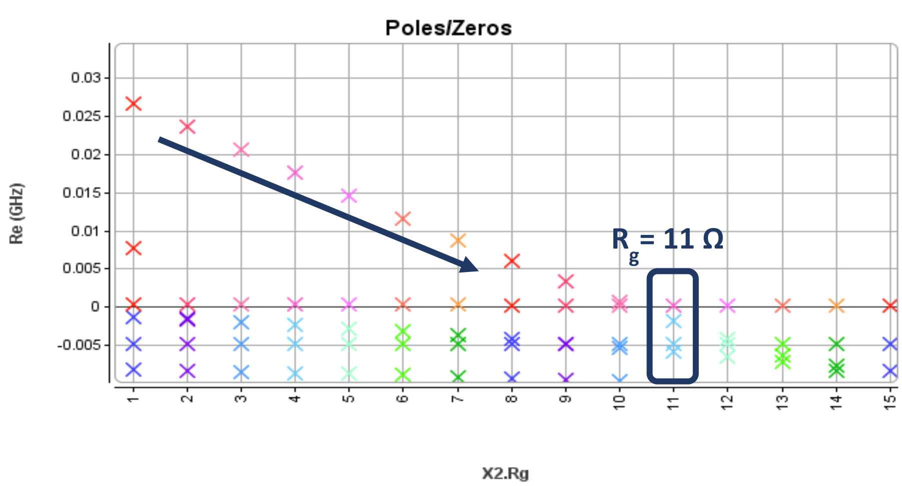

Fig. 11. Real part of poles versus the parameter R_g. The high-frequency instabilities disappear for $R_g \geq 11$ Ω.

The small-signal stability analysis of Fig. 7 has been repeated with the R_g = 11 Ω and no instabilities around 4 GHz have been obtained (Fig. 12). In practice, a designer will not choose the R_g value right at the bifurcation point, here this value will be used for the illustration of the capabilities of STAN Tool.

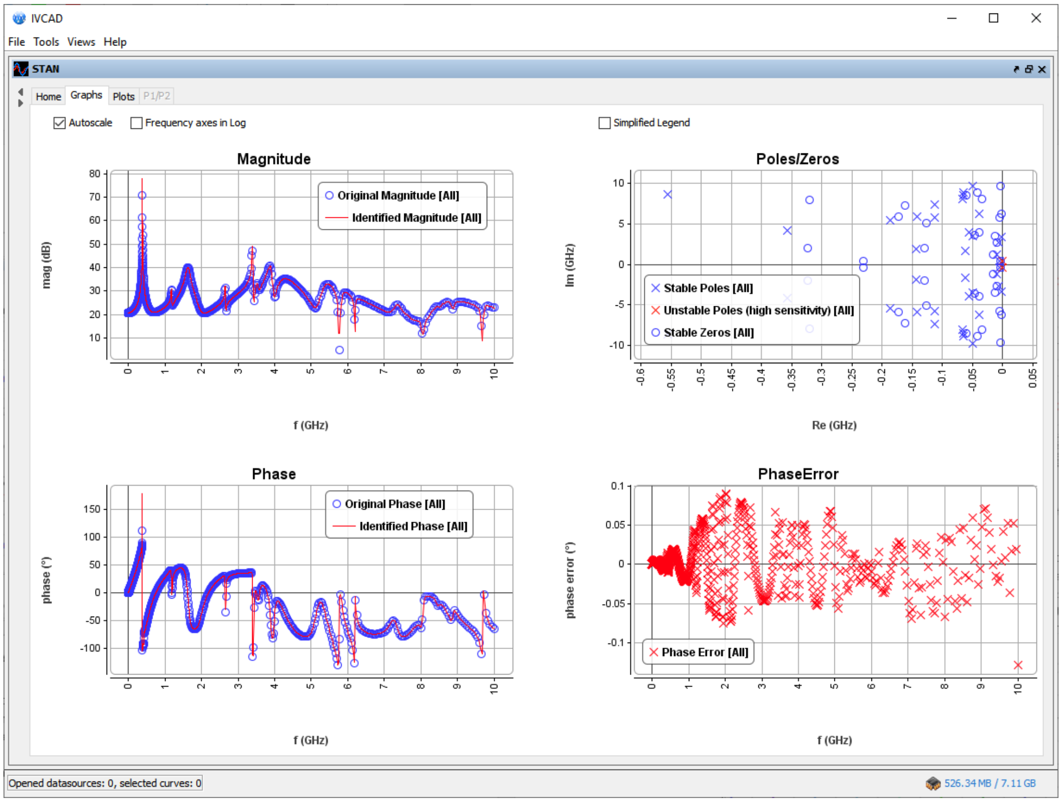

Fig. 12. Small-signal stability analysis when considering R_g = 11 Ω. Instabilities around 4 GHz have disappeared.

However, with the presence of this gate resistance, the performances of the amplifier have changed: PAE = 55 %, P_{out} = 34.5 dBm and gain of 9.8 dB. Since the PAE has degenerated while the P_{out} remains around the same values, the selection of this parameter at the design state is critical for high-efficiency applications. STAN Tool enables the adjustment of this component without losing much of original performances. The analysis of other circuit parameters such as bias voltages, or the implementation of more complex stabilization networks to achieve stabilization can be easily done using STAN Tool.

In the previous parametric analysis, while the high-frequency unstable poles move to the LHS of the complex plane, the low-frequency poles remain on the RHS (Fig. 10). These unstable poles have a quite small real part and they will eventually cross to the LHS when increasing the R_g value. However, because of their slow movement with the variation of the parameter, a R_g = 27 Ω would be necessary to fully stabilize the circuit. With R_g = 27 Ω the circuit presents a PAE = 47.8 % and a P_{out} = 37.8 dBm, for a gain of

Stabilization

Stabilization techniques have an impact on the circuit's performances.

A **reliable** stability-analysis tool as **STAN Tool** is necessary to obtain **high-performance stable** designs.

7 dB at the 3-dB-compression point. Because of the degradation of the performances, using R_g = 27 Ω has been discarded.

Therefore, since low-frequency instabilities are associated to the polarization networks, the low-frequency unstable poles will be eliminated by introducing a series resistance, R_{bias}, in the gate polarization branch (Fig. 5) that will affect less the amplifier's performances. Thus, the previous parametric analysis is now repeated for the R_{bias} parameter, while maintaining R_g = 11 Ω. Since the real part of poles is quite small, R_{bias} is swept from 0.01 Ω to 0.1 Ω. From Fig. 13, the circuit becomes fully stable for R_{bias} ≥ 0.03 Ω.

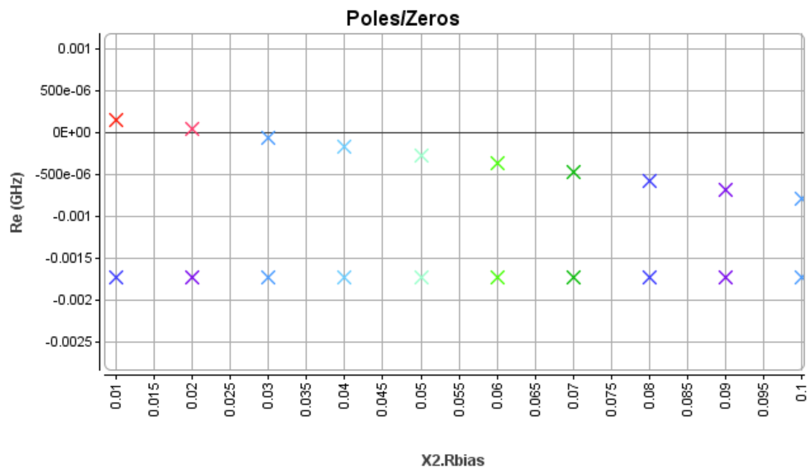

Fig. 13. Real part of poles versus the parameter R_{bias}. The circuit is stable for R_{bias} ≥ 0.03 Ω and R_g ≥ 11 Ω.

The circuit will be stable when considering R_g = 11 Ω and R_{bias} = 0.03 Ω (Fig. 14), with PAE = 55 %, P_{out} = 34.5 dBm and gain of 9.8 dB. The R_{bias} = 0.03 Ω is quite small and stabilization can be achieved from small parasitic effects. Since this component does not affect too much the circuit's performances, a designer may use an actual resistor of 2 Ohm to be sure of the stabilization, for instance. Here R_{bias} = 0.03 Ω will be considered for illustration purposes.

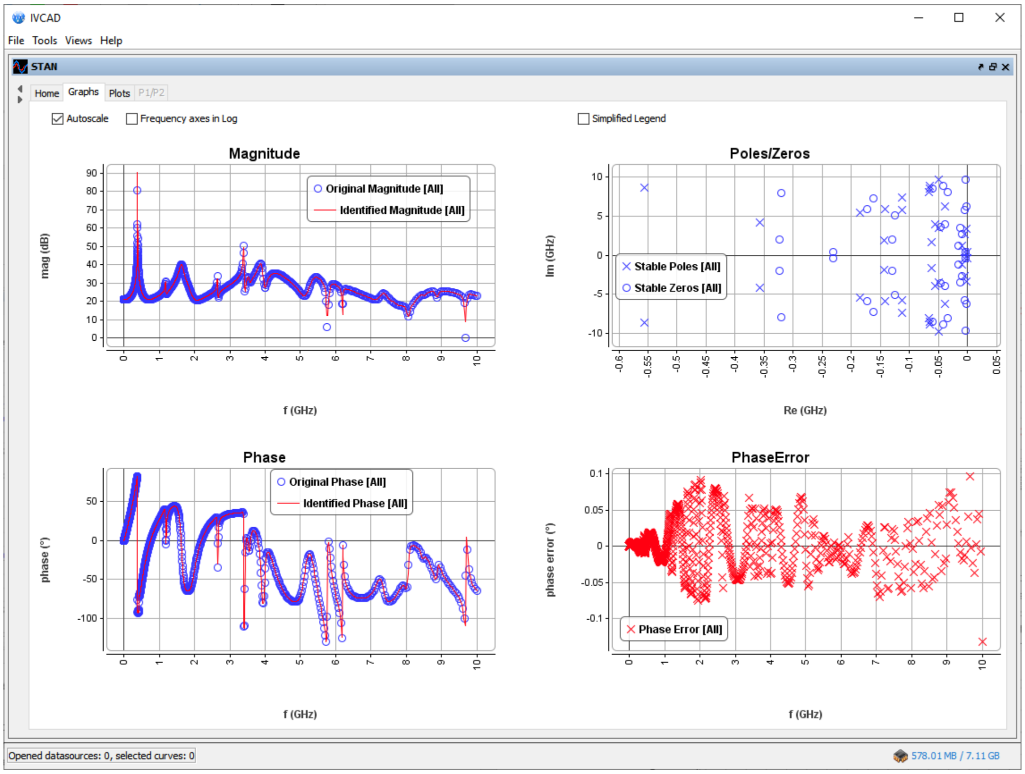

Fig. 14. Stable results obtained after stabilization using a small-signal and parametric-small-signal analyses in STAN Tool.

Large-signal stability analysis

The 35-dBm amplifier has been stabilized in small-signal operation using small-signal and parametric small-signal analyses in STAN Tool. However, as stated in the introduction, undesired behavior may appear in large-signal conditions.

A large-signal stability analysis will next be performed. In this analysis, the stabilized circuit with R_g = 11 Ω and R_{bias} = 0.03 Ω will be analyzed for different input power, P_{in}, values and frequency f_0 = 4 GHz. Thus, an HB parametric analysis is first used to obtain the frequency responses. As it was done in the parametric small-signal analysis using the R_g parameter, a collection of frequency responses corresponding to the different P_{in} values will be obtained. The frequency band will be selected to account for the low and high frequency instabilities, considering the possible presence of instabilities at f_0, in this case from 0.1 GHz to 5 GHz.

From the identification of the frequency responses (Fig. 15), unstable poles have been detected for P_{in} values between 10 dBm and 21 dBm, with the circuit presenting instabilities also at 26 dBm. Therefore, the circuit is stable in small signal, but it becomes unstable for several values of the input drive.

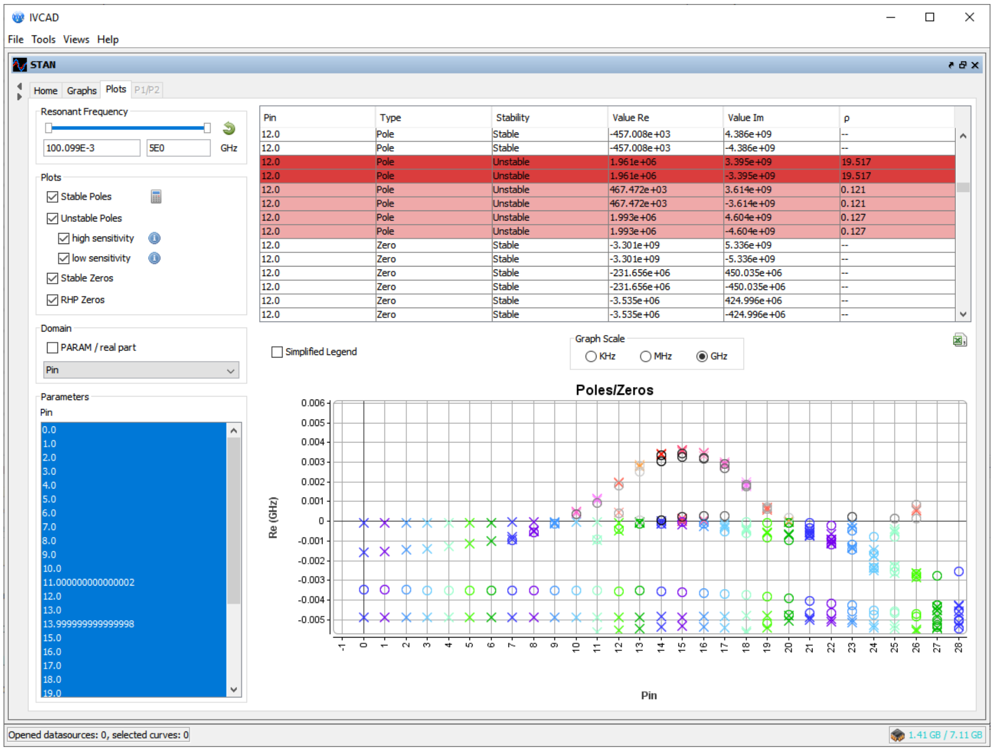

Fig. 15. Parametric large-signal stability analysis showing unstable poles between 10 dBm and 21 dBm.

Unstable poles are detected around 3.4 GHz. To cope with this problem, STAN Tool enables an analysis that considers two parameters, i.e., in this case, a parametric analysis considering a double sweep in R_g and P_{in} can be performed. This analysis will provide the R_g value at which the circuit is stable for all the P_{in} values.

Analyzing the results presented in the *P1/P2* tab in STAN Tool (Fig. 16), the circuit will be stable in large signal when $R_g \geq 15\ \Omega$. Therefore, a small-signal stability analysis is not sufficient to declare a circuit stable, a large-signal parametric analysis would be required.

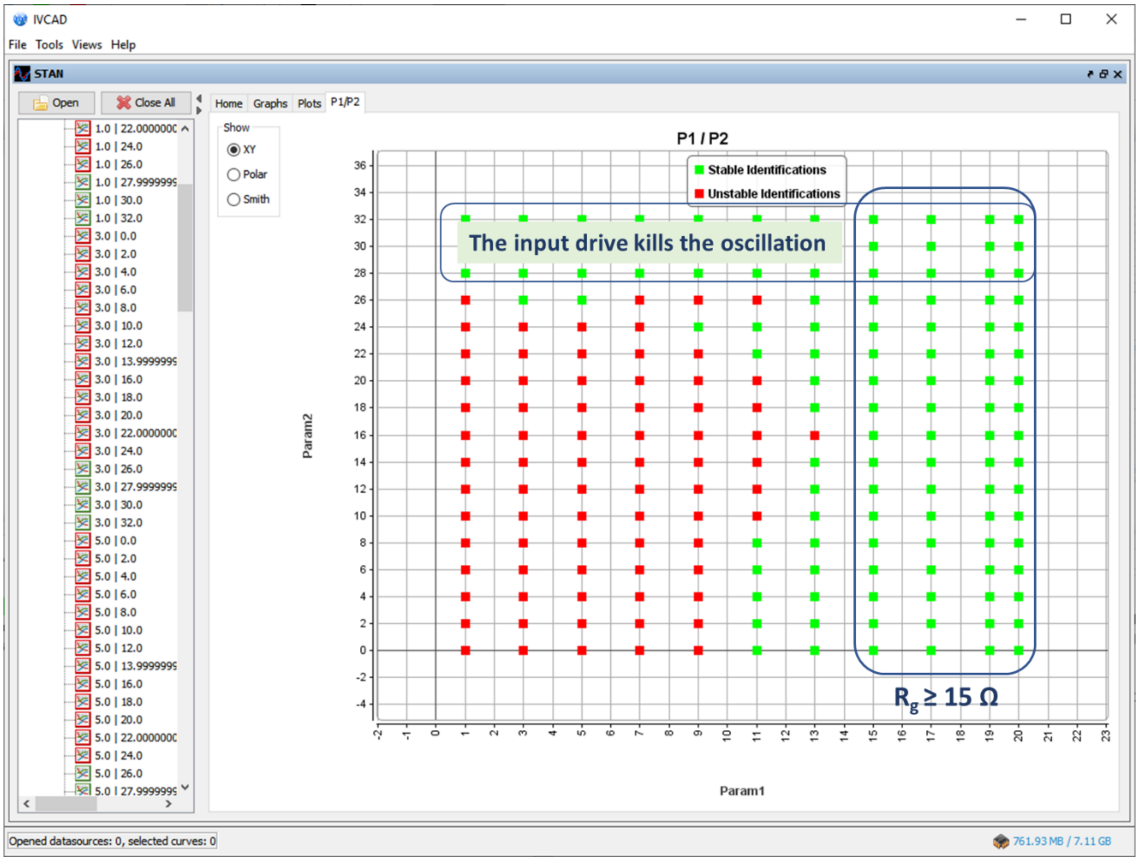

Fig. 16. Parametric analysis with two parameters in STAN Tool. The circuit will be stable for all input-power values when $R_g \geq 15\ \Omega$.

To validate the results from Fig. 16, the parametric large-signal stability analysis will be repeated for a $R_g = 15\ \Omega$ and $R_{bias} = 0.03\ \Omega$. As can be gathered from Fig. 17, the circuit is now stable and it presents a PAE = 52.4 %, a P_{out} = 34.5 dBm and a gain of 9 dB.

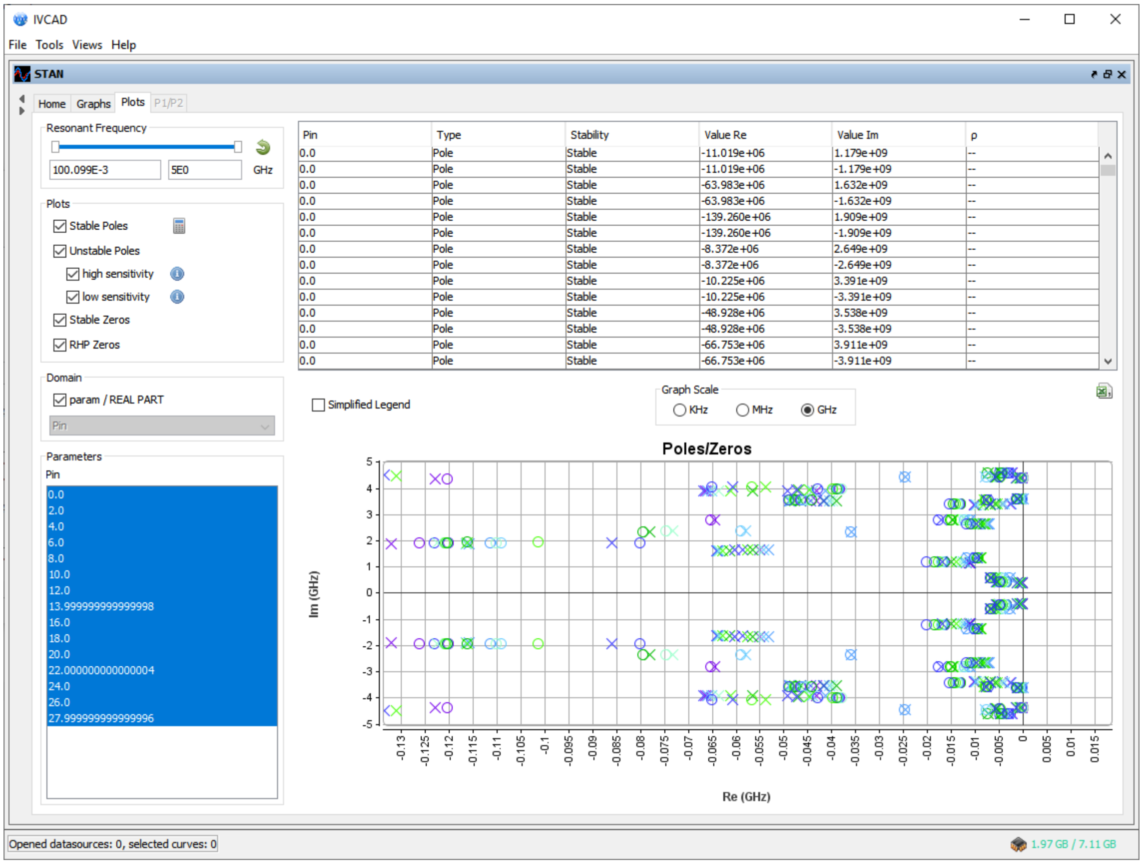

Fig. 17. Parametric large-signal stability analysis. The circuit is stable for all the input-power values when considering R_g = 15 Ω and R_{bias} = 0.03 Ω.

The circuit is now stable in small-signal and large-signal conditions. However, further analyses may be necessary to ensure the circuit's stability when working in real conditions: a Monte-Carlo analysis can be performed to be sure that the system will remain stable within the tolerance value of the components. For illustration, the Monte Carlo analysis will be performed for an input-power P_{in} = 18 dBm, i.e., at the input-power value where the poles are nearer the Re = 0 axis. Components have been varied ± 5% and 100 iterations have been considered. From Fig. 18, the circuit will be stable within the tolerances considered.

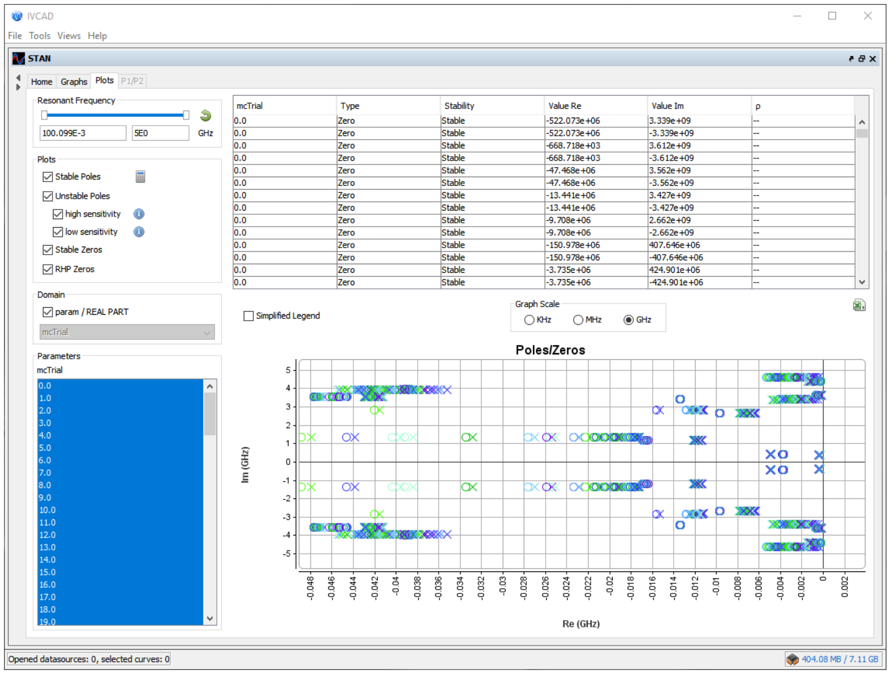

Fig. 18. Monte Carlo analysis of the stabilized circuit varying the circuit's components ± 5% with 100 iterations.

The circuit performances throughout the stability analysis using STAN Tool are summarized in the table. After stabilization, the amplifier has lost a 10 % de PAE and it presents a gain reduction of 5 dB, thus a reliable stability-analysis tool as STAN Tool is necessary to obtain high-performance stable designs.

	PAE @ 3 dB	P_{out} @ 3 dB	Gain @ 3 dB
Unstable Amplifier	63.3 %	34.3 dBm	14.1 dB
Stable in small signal: R_g = 11 Ω, R_{bias} = 0.03 Ω	55 %	34.5 dBm	9.8 dB
Stable in large signal: R_g = 15 Ω, R_{bias} = 0.03 Ω	52.4 %	34.5 dBm	9 dB

Understanding the Pole-Zero map through the analysis of the ρ factor

The new analysis parameter, the ρ factor, enables the quantification of over-modeling effects.

To illustrate the use of the ρ factor in STAN Tool, the small-signal and large-signal stability analysis presented above will be used. In STAN Tool, the value of the ρ factor can be observed, in the tab *Plots,* in the last column of the table (Fig. 19). Unstable poles are divided in high-sensitivity and low-sensitivity poles.

High-sensitivity poles ($\rho > 1$) will always be physical. In the small-signal stability analysis (Fig. 19), the unstable high-sensitivity poles present a ρ factor of ρ = 1056.381, ρ = 1.75 and ρ = 14.044 at f = 386.11 MHz, f = 3.406 GHz and f = 3.853 GHz respectively, where all of them are physical poles. To help the user with a better identification of the unstable physical poles, those with $\rho > 1$ will be colored in red when the circuit is unstable and stabilization solutions are required.

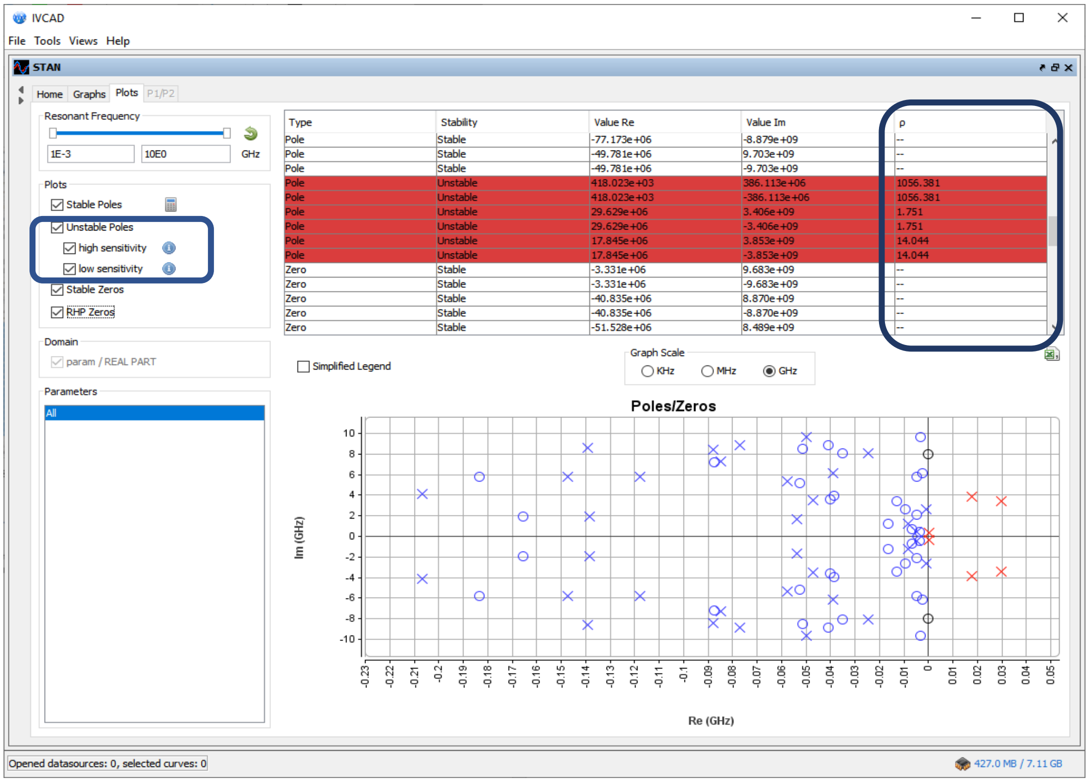

Fig. 19. Unstable high-sensitivity poles ($\rho > 1$) detected from the small-signal stability analysis.

Analyzing now the results of the large-signal stability analysis for P_{in} = 12 dBm, high-sensitivity unstable poles have been detected at 3.395 GHz, and low-sensitivity unstable poles have been detected at 3.61 GHz and 4.60 GHz (colored in pale red in Fig. 20).

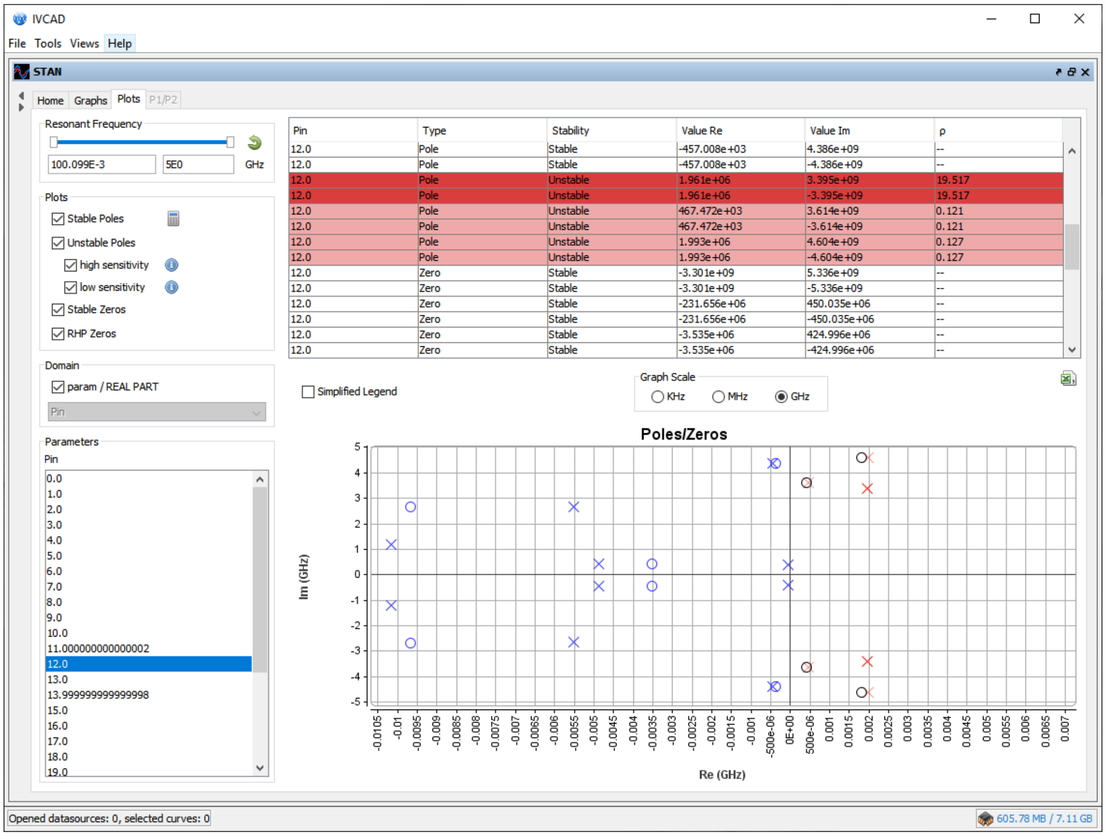

Fig. 20. Unstable low-sensitivity ($\rho < 1$) and high-sensitivity ($\rho > 1$) poles from a large-signal stability analysis at $P_{in} = 12$ dBm.

Low-sensitivity unstable poles may be physical or numerical. To better detect their nature, further analyses are required. First, to analyze the low-sensitivity poles at 3.61 GHz, the frequency band of the identification will be reduced to the interval 3.4 GHz to 3.8 GHz, where the center frequency will be the frequency of the unstable low-sensitivity poles. With the reduction of the frequency band a better fit is more easily obtained facilitating the detection of numerical unstable poles.

In the new analysis with a smaller frequency band using the automatic algorithm, the unstable poles with $\rho = 0.121$ at 3.61 GHz are not present (Fig. 21). Therefore, they were numerical poles.

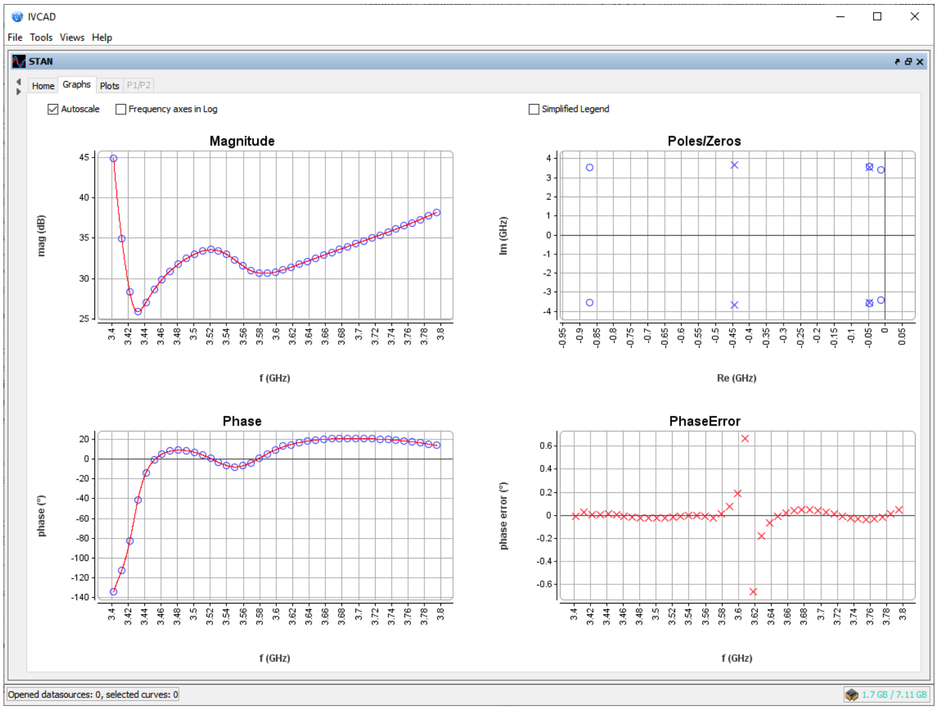

Fig. 21. Unstable low-sensitivity poles (ρ = 0.121) detected at 3.61 GHz for P_{in} = 12 dBm have disappeared when considering an identification bandwidth from 3.4 GHz to 3.8 GHz.

The above procedure will be also applied to the low-sensitivity unstable poles at 4.60 GHz. Actually, we know these poles are physical because they correspond to Floquet repetitions of the main instability at 3.4 GHz [26]. They will be used here to illustrate the behavior of low-sensitivity unstable physical poles.

After reducing the frequency band, the unstable poles remain on the RHS of the complex plane. To check if low-sensitivity unstable poles are actually physical, another method can be used: as previously stated, if poles follow a consistent path in a parametric analysis and cross to the left-hand side (LHS) of the complex plane, they are physical poles. Thus, looking at the parametric large-signal analysis from Fig. 15, where the poles are plotted on the complex plane, low-sensitivity poles at 4.60 GHz follow a consistent path with the input power and eventually cross to the LHS of the complex plane (Fig. 22), as expected. Therefore, they are low-sensitivity physical unstable poles.

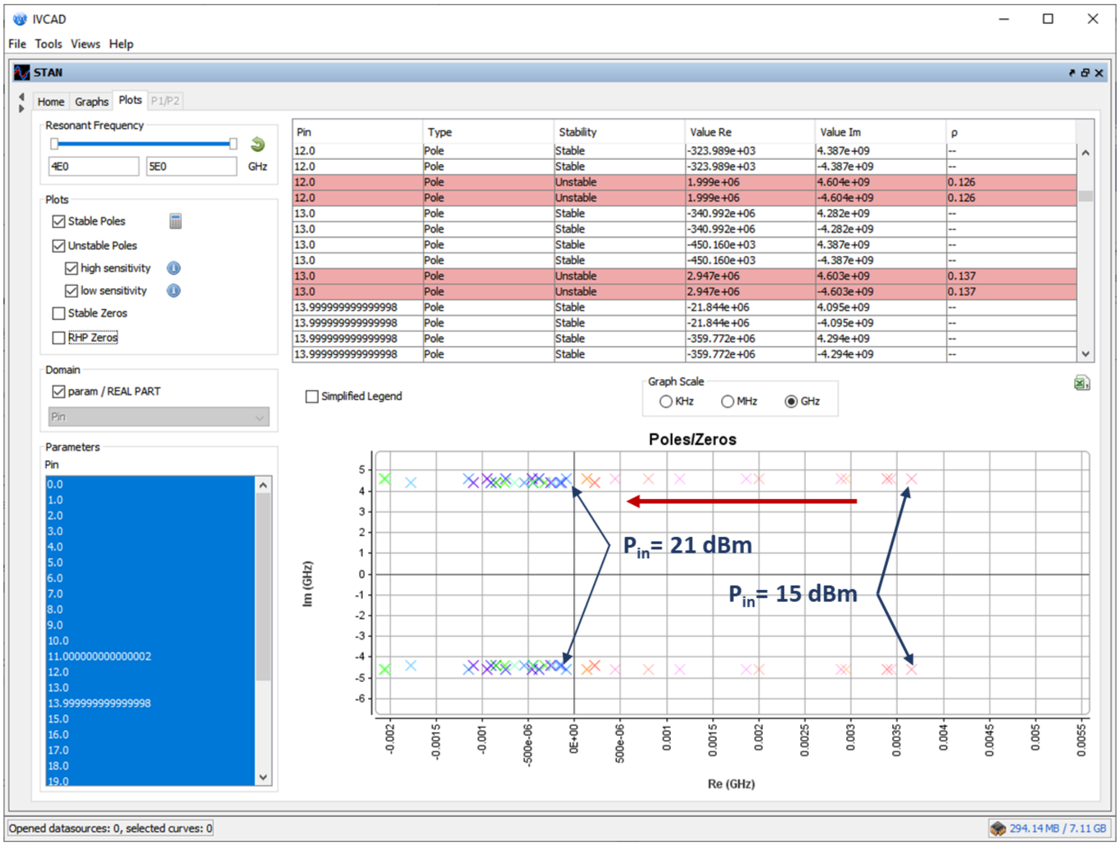

Fig. 22. Evolution of the low-sensitivity unstable poles (4.6 GHz) with P_{in}. They follow a consistent path with the variation of the parameter: they are physical poles.

The analysis of the ρ factor helps to minimize the undesired effects of over-modeling in the identification process, where physical poles will always have a $\rho > 1$ and the nature of poles with $\rho < 1$ can be easily detected with the aid of the analyses available in STAN Tool.

Conclusion

In this paper, an overview of STAN Tool characteristics has been presented. A new identification methodology available in STAN Tool, conceived to help the user with over-modeling effects, has been described. From this new method, the user is provided with an additional tool, the ρ factor, which helps to discard numerical quasi-cancellations and control over-modeling effects.

STAN Tool is a unique utility to perform stability analyses in both linear and nonlinear conditions. Its two identification methods in combination with the parametric, multi-node and Monte Carlo analyses provide more insight into the system dynamics helping the user to fully characterize its design.

STAN Tool capabilities have been illustrated through an AMCAD' 35-dBm amplifier based on an AMCAD transistor compact model that considers traps and thermal effects, where analyses in both small-signal and large-signal conditions, in combination with parametric and Monte Carlo analyses, have been presented.

Stabilization has also been illustrated and it has been easily accomplished using STAN Tool, where the intuitive interpretation of the pole-zero map eases the selection of the place and values of components without sacrificing the circuit's performance.

STAN Tool is a unique solution for the stability analysis of RF and microwave circuits that provides insightful information of the system and helps the designer to get the best performance of his design.

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