Unconditional stability test of a 4-port device

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Abstract – **Small-signal unconditional stability versus load terminations must be evaluated for reliable operation of microwave amplifiers. While extensively studied in 2-port devices, extending stability analysis to N>2 port configurations remains challenging due to the lack of streamlined methodologies. Existing tools often necessitate the use of multiple programs to assess intrinsic stability and unconditional stability, adding complexity to the process. This paper introduces an innovative approach by presenting an all-in-one simulation method for evaluating unconditional stability in 4-port devices using exclusively Advanced Design System (ADS) CAD platform. The Ohtomo's method implemented through Winslow probes is used to verify the proviso while parametrized S-parameter simulation data are used for calculating the geometrical μ factor. Obtained simulation results are compared with measured data for a 4-port amplifier prototype.**

I. Introduction

Power amplifiers serve as indispensable components in modern communication systems. Active devices may become unstable under certain load conditions, leading to undesired oscillations. Consequently, small-signal Unconditional Stability (US) is important for reliable operation of the amplifier. The small-signal stability problem under load variations is well-known in 2-port devices and has been discussed through the literature, resulting in analytical expressions (K or μ factors) derived from scattering parameters [1-2]. In the case of 3-port devices, there are computational methods [3-4] and analytical expressions [5] yet, without the straightforwardness and insights of the two-ports. If $N \geq 4$ ports are considered, analytical solutions to verify US do not exist, and numerical methods to solve non-convex optimization problems need to be applied [6]. These techniques make use of external tools that are not integrated in mainstream CAD platforms, requiring of extra software, and ultimately slowing the design process. In addition, before the evaluation of the US, the intrinsic stability of the device loaded with 50 Ω must be verified (Rollet proviso) [7]. Normally, techniques based on pole-zero identification are suggested to verify the proviso [8]. Pole-zero identification techniques are also not integrated into the most popular commercial CAD tools for microwave circuit design.

In this work, the US analysis of a 4-port device performed entirely on a commercial CAD simulator (Advanced Design System — ADS) is presented. The analysis parametrizes the μ stability factor [2] computed at 2 ports for different impedances at the other 2 ports while checking the proviso in the same simulation. Conducting both analyses (proviso and μ factor) in the same simulation simultaneously and within the same platform offers notable advantages, in terms of evaluation speed and ease of use. The procedure is explained through its application to a 4-port amplifier built in microstrip hybrid technology. Two of the ports are the RF in and out accesses. The other two ports are located at the bias lines.

II. Unconditional Stability Test of a 4-port Device

To carry out the stability analysis, an amplifier with two extra ports at the bias lines is considered. The amplifier is based on a FLU17XM GaAs FET transistor and operates at 1.1 GHz, with gate and drain bias conditions set at -2.1 V and 2 V, respectively. This kind of amplifier was used in [9] to achieve a compromise between stability margin and video bandwidth through a characterization of the low-frequency resonances. In this work, the amplifier is used as a test prototype for the US verification since the loads at any of the ports have an impact on the stability of the device. The circuit schematic is shown in Fig. 1.

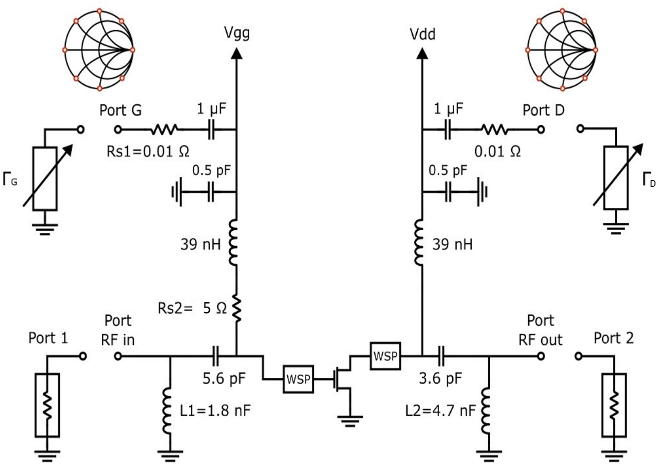

Fig. 1. Schematic of the 4-port FET amplifier. Pure reactive charges are connected at ports G and D to parametrize μ factor.

A. μ *factor Parametrization*

In order to perform the US test, a double sweep varying the impedances connected at ports G and D is carried out. For each pair of load terminations (Γ_G, Γ_D) the proviso is checked, and the stability μ factor [2] corresponding to ports 1 and 2 (RF ports) is calculated. More insight on the procedure and criteria used is discussed below.

This parameterization of the μ factor can involve very long simulation times when multiple loads (Γ_G, Γ_D) are swept at the G and D ports for fine coverage of the passive smith chart. This is particularly pronounced because each Γ_G, Γ_D configuration needs the evaluation of the proviso. With N standing for the number of load terminations at one of the ports, the computational demand has a quadratic growth in N^2.

Since we are only concerned with the unconditional stability, the sweep in the load terminations at ports G and D can be restricted to the passivity limit of the Smith chart:

$$\Gamma_G = 1e^{j\varphi_G}\ , \Gamma_D = 1e^{j\varphi_D}$$

The number of load terminations will affect the reliability of the results obtained, however, as stated previously, the simulation time will grow quadratically with the amount of tested loads. Hence, a compromise between speed and reliability must be taken. In this work, N = 64 different phases distributed homogeneously in the limit of the Smith chart are tested for each port G and D. This is a judicious compromise that ensures reasonable simulation times and reliable results when it comes to μ parametrization.

As explained, for each load configuration (φ_G, φ_D), the μ factor is computed at the RF ports for all the frequencies of interest. For the US stability, it is interesting to obtain the minimum μ at each frequency for all φ_G, φ_D in the sweep. This minimum parameter is represented as μ':

$$\mu'(f) = min\big(\mu(f, \varphi_G, \varphi_D)\big) \qquad (1)$$

For unconditional stability, $\mu'(f) > 1$ for all frequencies.

B. Verification of the proviso using Winslow probes

Eq. (1) is only applicable if the Rollet proviso is satisfied for all load configurations implemented in the double sweep φ_G, φ_D. To check the proviso we need a rigorous method that can predict the presence of internal Right Half Plane (RHP) poles in the system. In this work we discard the use of pole-zero identification [8] because it would imply a call to external tools that are not integrated into the CAD simulator (ADS in this case) and data transfer between applications. Another rigorous method was presented by Ohtomo [10]. Ohtomo's classic test involves the sequential use of isolators and circulators placed at the interface nodes between active and passive parts of the circuit. A set of Nyquist plots is obtained and clockwise encirclements of point (1,0) reveals the presence of RHP poles in the circuit. The practical implementation of Ohtomo's test in simulation requires a number of copies of the original circuit equal to the number of analysis nodes [11]. In our circuit, since the amplifier is composed of a single transistor, only two nodes, gate and drain nodes of the active device, have to be considered. This means that two copies of the circuit need to be placed in the same simulation to perform the Ohtomo's stability test. In multi-transistor amplifiers the number of copies of the circuit can increase significantly, escalating complexity and simulation time.

Recently, the practical implementation of Ohtomo's test has been simplified through the use of Winslow probes [11-12]. A Winslow probe connected at a particular circuit branch provide the 2 x 2 Y-parameter matrix of the equivalent circuit seen at that branch. Placing the Winslow probe at the two nodes of interest (gate and drain accesses of the transistor) provides the required information to compute the Ohtomo's Nyquist plots, without needing extra copies of the circuit, thus reducing simulation time and complexity. The Winslow probe and its accompanying equations to implement Ohtomo's test are available in ADS [11]. Therefore, in this work, we use Winslow probes connected at gate and drain ports of the FET transistor (Fig. 1) to verify the proviso. A single S-parameter simulation in ADS serves to compute the proviso from the Winslow probes and the μ factor from the scattering parameters at ports 1 and 2 (Fig. 1).

III. Simulation Results

The circuit was initially simulated using the starting values for lumped components depicted in Fig. 1. Frequency has been swept from 10 MHz up to 6 GHz, considering the f_{max} of the transistor. An S-parameter simulation with a nested sweep for the load terminations of ports G and D is launched. As stated, magnitude of the loads reflection coefficients is maintained at 1 while the phases φ_G, φ_D are homogenously swept at N = 64 points each. This nested sweep gives rise to N^2 = 4096 simulations. Two Winslow probes are connected at the transistor's gate and drain (Fig. 1).

First, Ohtomo's test has to be applied to verify the Rollet proviso. Each simulation generates 2 Nyquist plots corresponding to the open loop transfer functions obtained from the Winslow probes. In total we have $2N^2$ = 8192 curves that are plotted on the complex plane (Fig. 2a). We can see that the point (1,0) is encircled clockwise by some of the curves. The curve corresponding to the worst case is drawn alone in Fig. 2b, to clearly observe the encirclement. Consequently, the Rollet proviso is not fulfilled and the circuit is intrinsically unstable. There is no point in computing the μ factor in this case.

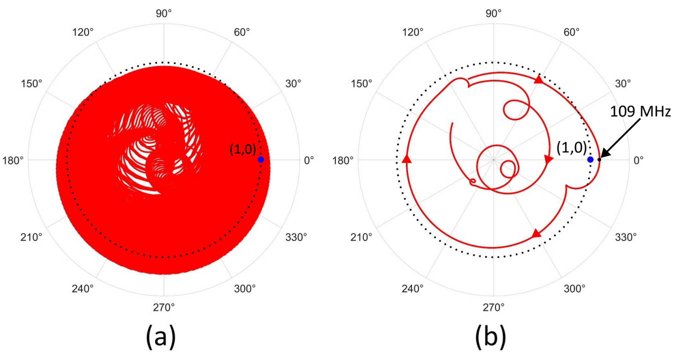

Fig. 2. Checking of the proviso for the original circuit. a) Tracing of the 8192 Nyquist plots obtained with the Winslow probes. b) Tracing of the worst case scenario of the plots in Fig. 2a. Encirclement occurs at about 109 MHz.

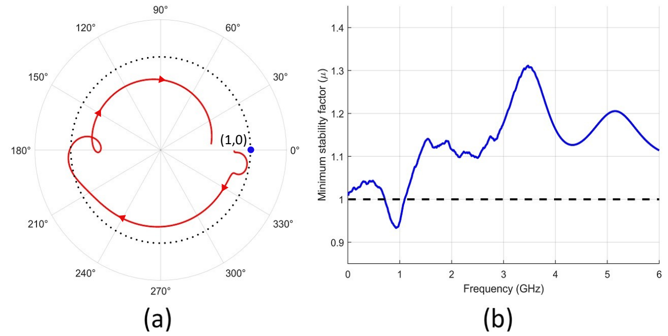

Fig. 3. Simulation results for Ohtomo's test and μ factor using *Rs1* = 10 Ω and *Rs2* = 500 Ω. a) Tracing of the worst case Nyquist plot, now fulfilling the Rollet proviso. b) Stability factor μ' of eq. (1).

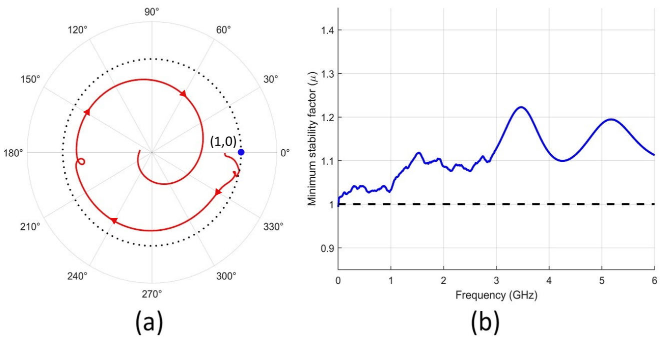

Fig. 4. Final simulation results after modifying gate bias to -2.3 V. a) Worst case Nyquist plot for modified bias. The proviso is once again fulfilled. b) Stability factor μ' of eq. (1). Now μ' is greater than 1 for all frequencies.

From Fig. 2b, the encirclement occurs at a frequency of about 109 MHz. To avoid this low-frequency oscillation, the two stabilization resistors in the gate bias path, *Rs1* and *Rs2*, are increased to 10 Ω and 500 Ω, respectively. The simulation has been repeated with the updated values of the two resistances. In this case, none of the curves encircles the (1,0) point. Fig. 3 (a) presents the curve for the worst case (the closest to the encirclement) showing an intrinsically stable circuit, fulfilling the proviso. Consequently, we can move on to compute the μ factor for the 4096 simulations to test the unconditional stability. Fig. 3 (b) shows the parameter μ', defined in (1), versus frequency. We can observe that $\mu' < 1$ for the frequency interval from 795 MHz to 1.08 GHz. Therefore, US is not guaranteed for the amplifier in these conditions.

Certain loads connected to ports G and D may lead to negative resistance in the input and output RF ports, increasing the likelihood of oscillations. Moreover, stabilization resistors *Rs1* and *Rs2* have no significant impact on factor μ' at the critical frequencies. Unconditional stability can be attained if the gain of the amplifier is reduced varying the transistor bias point. This has been done here as an easy way to test the analysis procedure. Fig. 4 shows the results for the stabilized amplifier at a lower gate bias (V_{GS} = -2.3 V). The circuit demonstrates intrinsic stability for all loads connected to ports D and G, as evidenced by the absence of clockwise encirclement of point (1,0) in the worst-case scenario, as depicted in Fig. 4a. Furthermore, μ' remains greater than 1 for all possible combinations at all frequencies, as illustrated in Fig. 4b, ensuring unconditional stability for any load impedance connected to any of the four ports.

IV. Measurement Results

A 4-port prototype based on the schematic of Fig. 1 has been used to verify simulation results. The main objective is to corroborate, at least qualitatively, the results obtained in simulation. The specific values of the utilized lumped components are those indicated in Fig. 1. A picture of the fabricated amplifier is shown in Fig. 5.

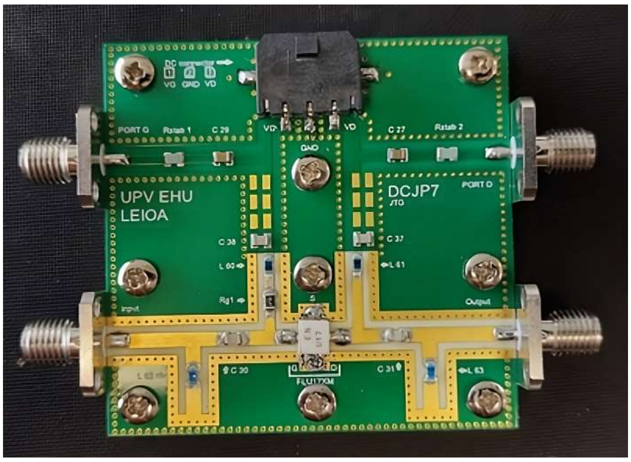

Fig. 5. 4-port amplifier based on a FLU17XM GaAs FET transistor.

A first measurement is performed with the original values of *Rs1* and *Rs2* (Fig. 1). Ports G and D are terminated with open circuits, and the RF input and output ports are loaded with 50 Ω. A directional coupler is connected at the output RF port, with its coupled path connected to a spectrum analyzer (SA) to monitor the possible oscillations. Measurements obtained reveal a low-frequency oscillation, as depicted in Fig. 6. Note that the oscillation frequency is about 60 MHz, lower than expected. Considering that the steady-state oscillation frequency will shift from the startup value and the limited accuracy of non-linear transistor models, this oscillation corroborates the intrinsic instability of the amplifier deduced from the simulation results of Fig. 2.

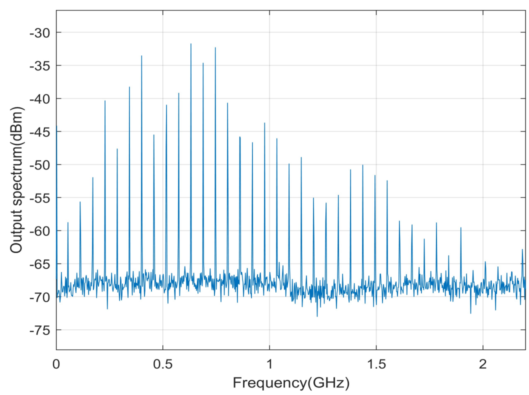

Fig. 6. Measured output spectrum for the intrinsically unstable amplifier. Stabilization resistances values of Rs1 = 0.01 Ω and Rs2 = 5 Ω are used. Ports D and G are loaded with open circuits and RF ports are loaded with 50 Ω.

In order to stabilize the circuit, the resistance values *Rs1* and *Rs2* were adjusted to simulated values of 10 Ω and 500 Ω, respectively. Load conditions at each port were replicated from the previous measurement scenario. In these conditions (50 Ω terminations at RF ports and open circuits at ports G and D) the amplifier is stable, and no low-frequency oscillation takes place. The resulting measured spectrum is represented in Fig. 7. The same stable result was obtained with other terminations at ports G and D.

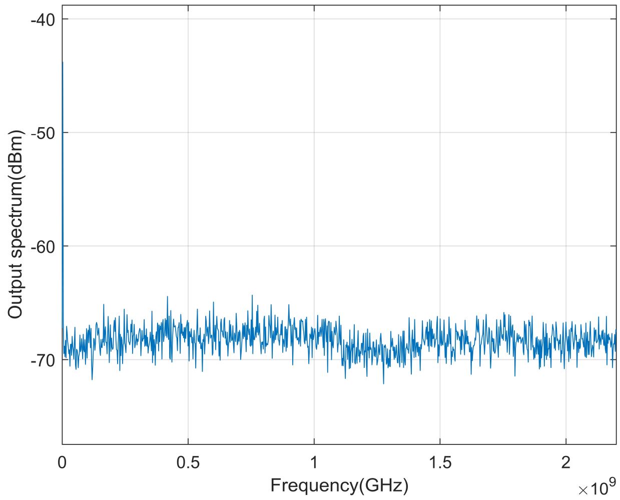

Fig. 7. Measured output spectrum for the intrinsically stable amplifier. Stabilization resistance values of Rs1 = 10 Ω and Rs2 = 500 Ω are used. Ports D and G are loaded with open circuits. RF ports are terminated with 50 Ω.

However, when the RF input and output ports approach open-circuit termination, oscillations are detected around 900 MHz (Fig. 8). This is consistent with the simulation results of Fig. 3b, since $\mu' < 1$ at that frequency. These experimental results confirm that US is not assured and the circuit has the possibility of oscillation under specific load conditions.

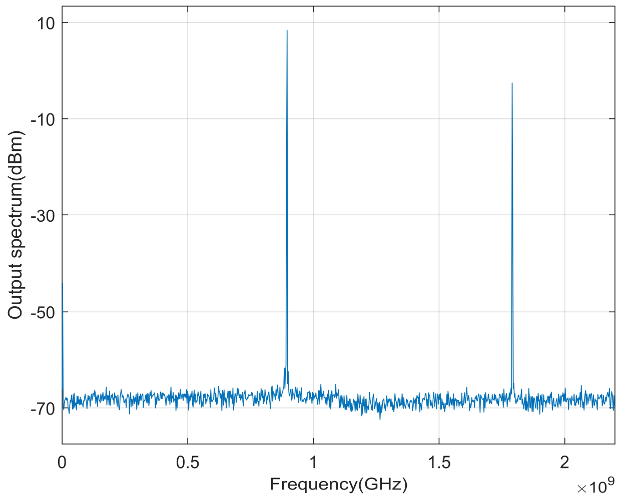

Fig. 8. Measured output spectrum for the amplifier fulfilling the proviso. Ports D and G are short circuited while RF input and output ports are loaded with highly reflective loads (close to open circuit). An oscillation at 900 MHz is measured.

As it was done in simulation, we have reduced the gate bias to V_{GS} = -2.3 V as a way to reduce the gain of the device. Various load conditions were examined, revealing no instabilities across the entire frequency spectrum. In addition to short and open terminations, a double-stub tuner was employed to provide additional load terminations at the ports. None of the tested configurations exhibited unstable behavior in agreement with the simulations results from Fig. 4.

V. Conclusions

In this work, the unconditional stability test of a 4-port device has been performed using integrally the CAD platform of ADS. This is beneficial to streamline stability simulations without the need of external tools required for N > 3 devices. The μ factor at two ports is parametrized with respect to the other two ports, while at the same time Winslow probes have been used to check Rollet's proviso using Ohtomo's method. The whole process is carried out in an all-in-one simulation. Obtained results have been compared with experimental measurements with reasonable agreement.

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References

[1] J. Rollett, "Stability and Power-Gain Invariants of Linear Twoports," in *IRE Transactions on Circuit Theory*, vol. 9, no. 1, pp. 29-32, March 1962.

[2] M. L. Edwards and J. H. Sinsky, "A new criterion for linear 2-port stability using a single geometrically derived parameter," in *IEEE Transactions on Microwave Theory and Techniques,* vol. 40, no. 12, pp. 2303-2311, Dec. 1992.

[3] S. Colangeli, W. Ciccognani and E. Limiti, "Algorithmic Test of the Unconditional Stability of Three-Port Networks," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 12, pp. 5197-5205, Dec. 2018.

[4] B. Aja, E. Artal, M. L. De La Fuente, J. P. Pascual and J. L. Cano, "Three Port Stability Analysis of Broadband Millimetre Wave MMIC Amplifier," *2006 European Microwave Integrated Circuits Conference, Manchester*, UK, 2006, pp. 399-402.

[5] R. -F. Kuo and T. -H. Chu, "Unconditional Stability Boundaries of a Three-Port Network," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 2, pp. 363-371, Feb. 2010.

[6] S. Colangeli, W. Ciccognani, P. E. Longhi and E. Limiti, "A Test for Unconditional Stability Based on Polynomial Convexification," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 10, pp. 4177-4187, Oct. 2020.

[7] M. Ohtomo, "Proviso on the unconditional stability criteria for linear twoport," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 43, no. 5, pp. 1197-1200, May 1995.

[8] A. Anakabe, N. Ayllón, J. M. Collantes, A. Mallet, G. Soubercaze-Pun and K. Narendra, "Automatic pole-zero identification for multivariable large-signal stability analysis of RF and microwave circuits," *The 40th European Microwave Conference*, Paris, France, 2010, pp. 477-480,

[9] J. Pelaz, J. -M. Collantes, N. Otegi, A. Anakabe and G. Collins, "Combined control of drain video bandwidth and stability margins in power amplifiers for envelope tracking applications," *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*, Tampa, FL, USA, 2014, pp. 1-4.

[10] M. Ohtomo, "Stability analysis and numerical simulation of multidevice amplifiers," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 6, pp. 983-991, June-July 1993.

[11] Keysight, Designing for Stability in High Frequency Circuits, Appl. Note.

[12] T. A. Winslow, "A Novel CAD Probe for Bidirectional Impedance and Stability Analysis," *2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia*, PA, USA, 2018, pp. 1032-1035.