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The Coolest Ideas Under the Sun
SAN DIEGO 2023

X-Parameters: The μ Stability Factor and Its Application to Avoid Oscillation Problems During the Characterization of Power GaN FETs

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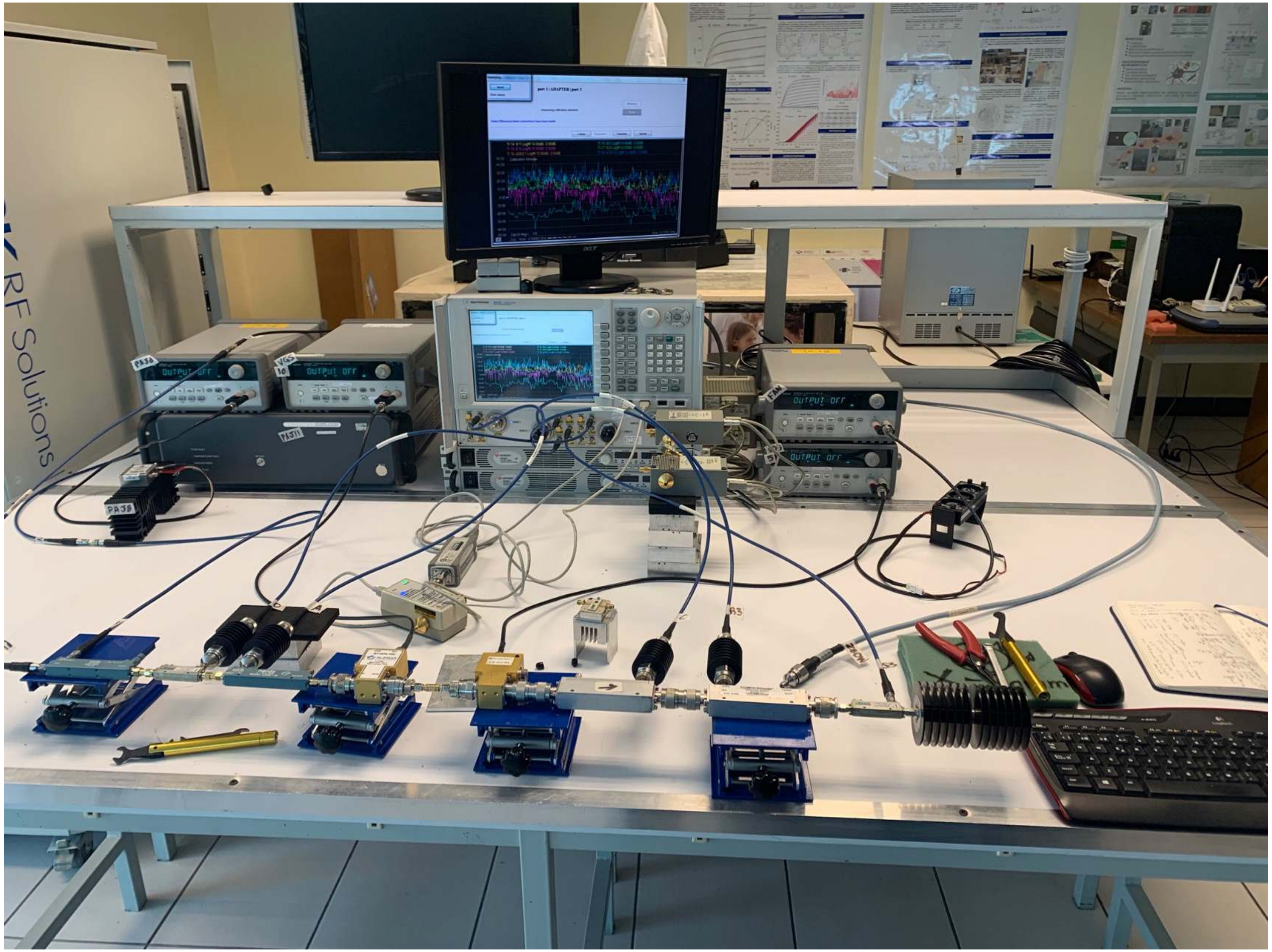
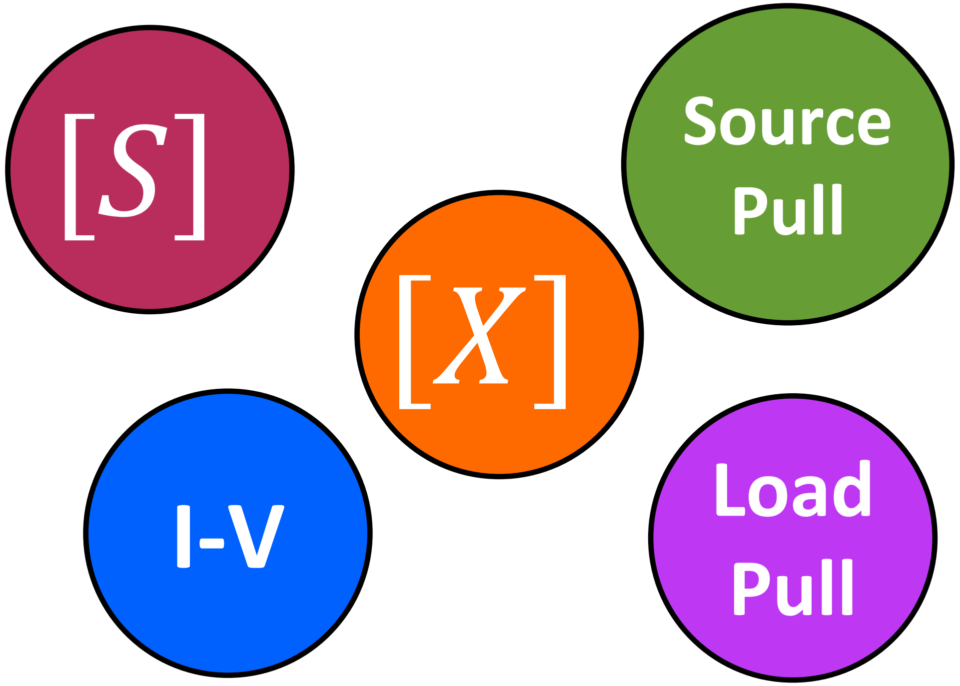
Outline

1. Introduction
2. X-Parameters Background
3. The μ Stability Factor in Terms of the X-Parameters
4. Experimental Results
5. Conclusion

Introduction





Transistor characterization is fundamental for developing:

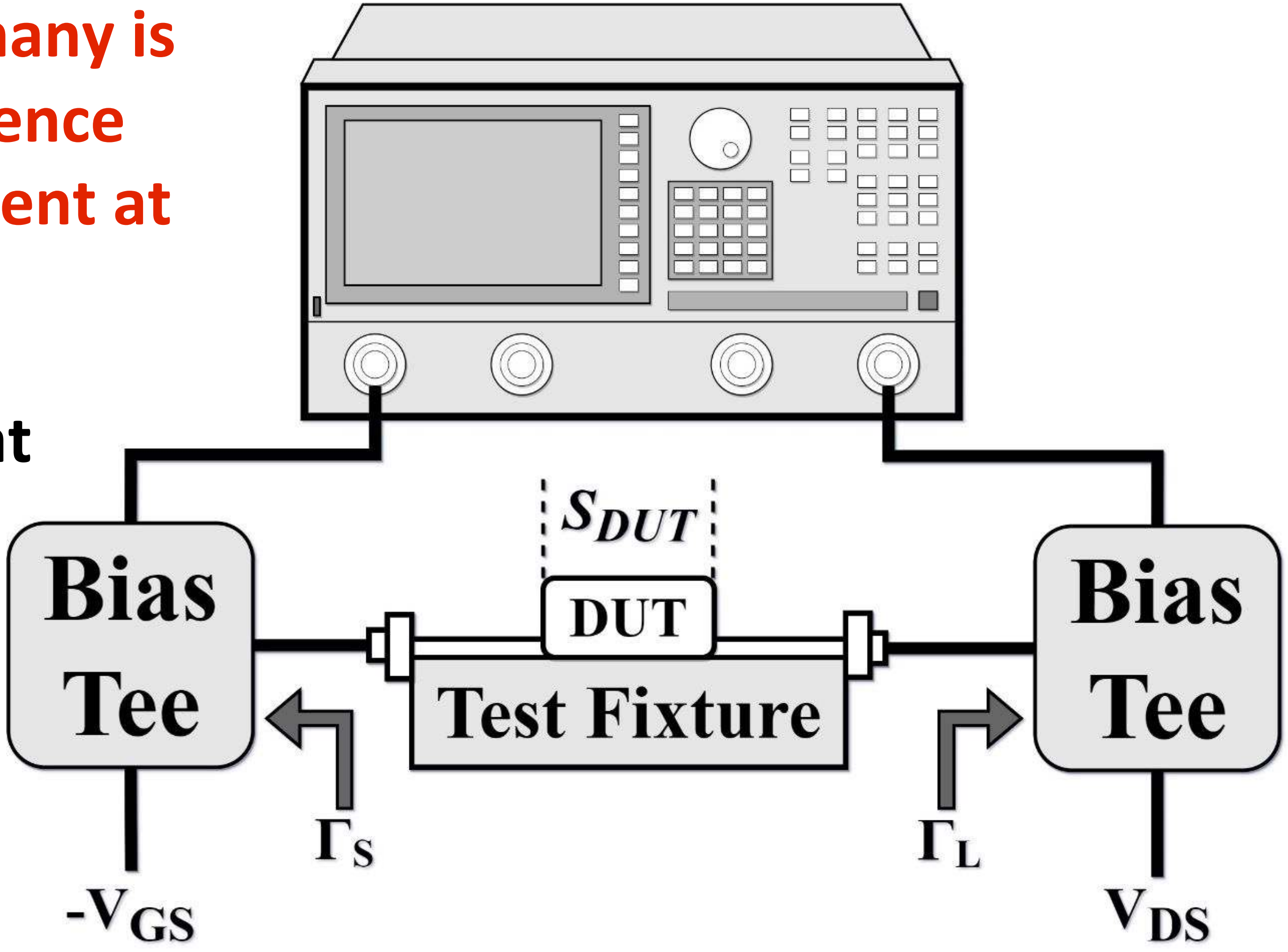
- **Linear Model**
- **Nonlinear Model**
- **Microwave Circuits**

Introduction

The main concern for many is establishing the reference plane of the measurement at the DUT plane

However, there are other things that one should worry about

An instability problem could appear, making it impossible to characterize the FET



Introduction

Instability during the characterization process is something that is not mentioned very often

Transistor Stability Analysis

Linear

<u>S-Parameters</u>

- **Rollet Factor (K)**
- **Stability Circles**
- **Edward-Sinsky Factor (μ)**

★ Simple methodology ★ Frequency domain

★ Easy and straightforward results interpretation

Nonlinear

- **Nyquist**
- **Hopf Bifurcation**

➡ Mathematically more complex

➡ Not easy to interpret the results

★ Time&Frequency domain

Introduction

A simple methodology to analyze the stability of the FET as a function of the frequency and the input power could help to answer the following questions:

- **What causes the instability?**
- **How important is it to analyze the stability of a FET when it is operating in saturation?**
- **How can we stabilize the FET?**

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X-Parameters Background

The X-parameters describe the reflected wave of a Device Under Test (DUT) as a function of the bias (DC) and the input signal as:

$$B_{pk}\left(DC,\left|A_{11}\right|\right)=X^{F}_{pk}\left(DC,\left|A_{11}\right|\right)P^{k}+\sum_{\substack{q=1,l=1\\(q,l)\neq(1,1)}}^{q=N,l=K}\left[X^{S}_{pkql}a_{ql}P^{k-l}+X^{T}_{pkql}a^{*}_{ql}P^{k+l}\right] \quad (1)$$

The harmonic of the output voltage (first term)

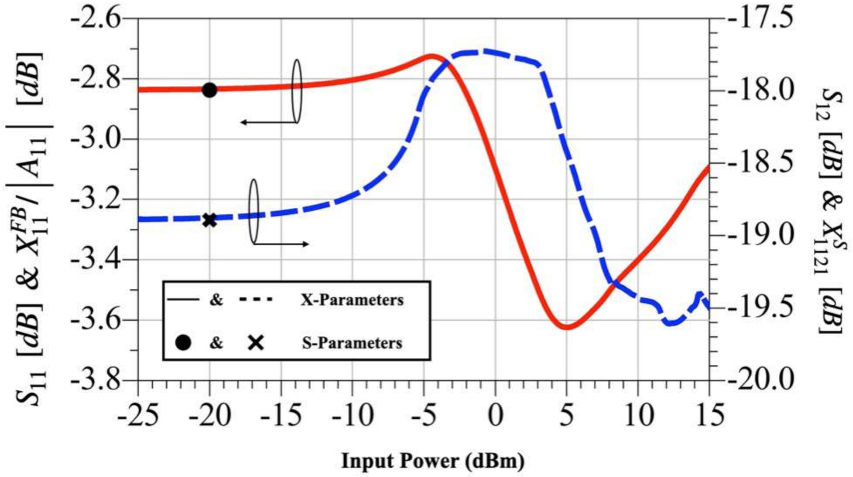
Describe the change in the traveling wave between the ports p and q at the hamonics k and l (bracketed sum term)

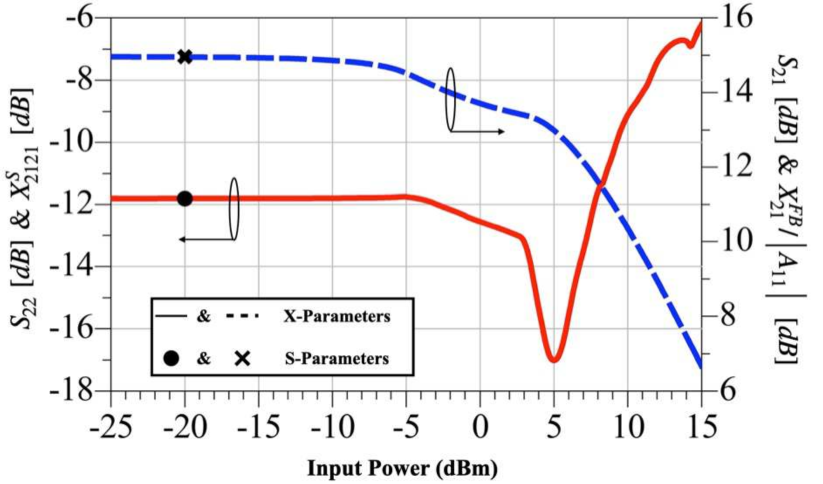
Where:

- p ➡ **the output port**
- q ➡ **the inputport**
- k ➡ **harmonic of the output port**
- l ➡ **harmonic of the input port**

X-Parameters Background

At low input power the X^S term converge with the S-Parameters





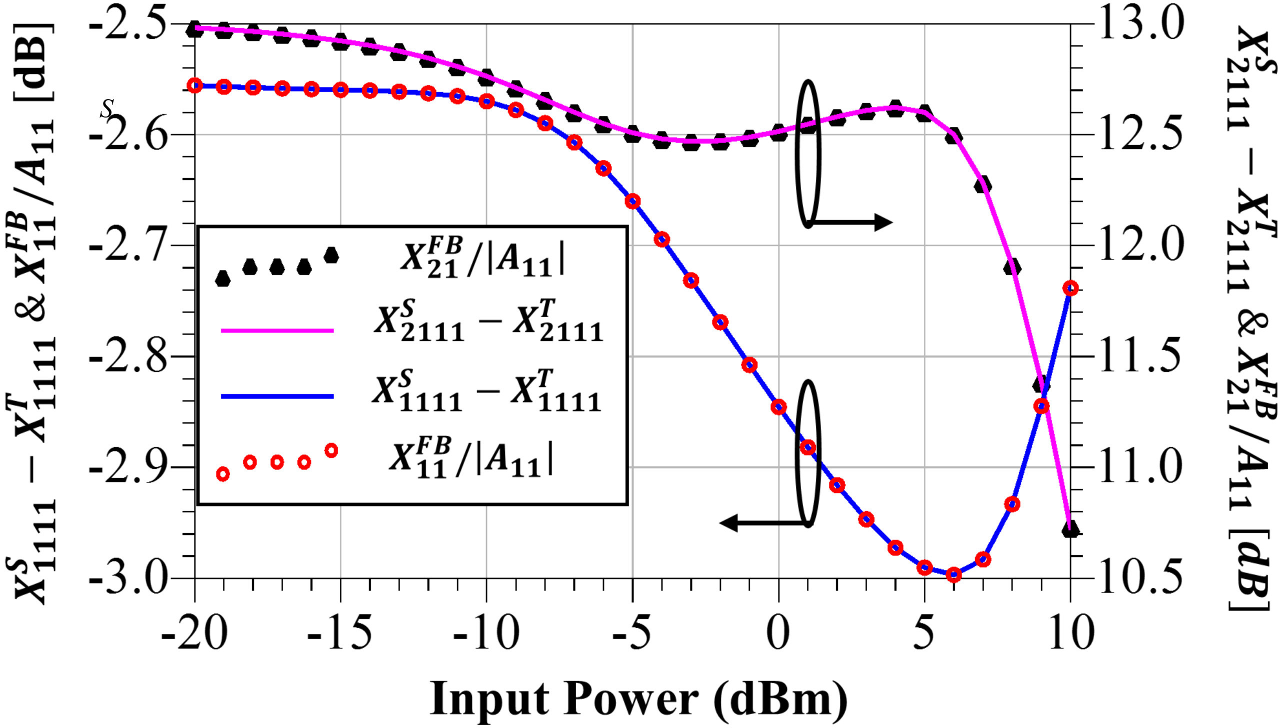
Whereas the Large-Signal (LS) behavior can be described by:

$$S_{11}^{LS} \rightarrow X_{1111}^{ST} = \frac{X_{11}^{F}}{|A_{11}|} \quad (2a)$$

$$S_{12}^{LS} \rightarrow X_{1121}^{ST} = X_{1121}^{S} - X_{1121}^{T} P^{2} \quad (2b)$$

$$S_{21}^{LS} \rightarrow X_{2111}^{ST} = \frac{X_{21}^{F}}{|A_{11}|} \quad (2c)$$

$$S_{22}^{LS} \rightarrow X_{2121}^{ST} = X_{1121}^{S} - X_{2121}^{T} P^{2} \quad (2d)$$



Outline

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3. **The μ Stability Factor in Terms of the X-Parameters**
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The μ Stability Factor in Terms of X-Parameters

The μ stability factor is defined as:

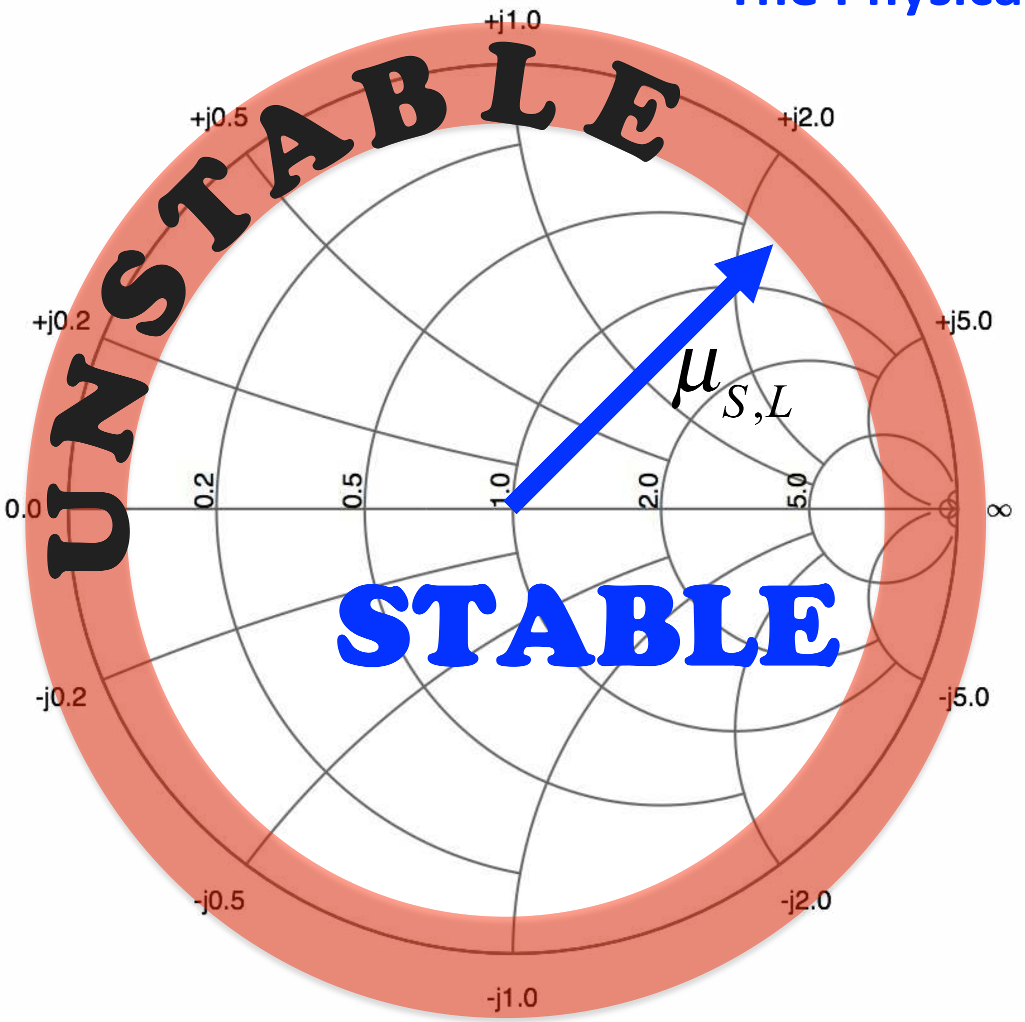
$$\mu_S = \frac{1-|S_{22}|^2}{|S_{11}-\Delta S_{22}^*| + |S_{21}S_{12}|} \quad (3)$$

$$\mu_L = \frac{1-|S_{11}|^2}{|S_{22}-\Delta S_{11}^*| + |S_{21}S_{12}|} \quad (4)$$

Where:

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (5)$$

The Physical Interpretation



The μ stability factor indicates the minimum distance from the center of the Smith chart to the possible Γ that makes unstable the transistor

If $\mathbf{\mu_{S,L}} > \mathbf{1}$, the FET is **UNCONDITIONALLY STABLE**, otherwise, the FET is **CONDITIONALLY STABLE**

The μ Stability Factor in Terms of X-Parameters

Since S-parameters are for linear regimen,

the question is....

¿What happened in the nonlinear regimen of the FET?

X-Parameters can describe the nonlinear behavior of the FET

Thus, the μ stability factor in terms of the X-parameters is proposed to write as:

$$\mu_S^{ST} = \frac{1 - \left|X_{2121}^{ST}\right|^2}{\left|X_{1111}^{ST} - \Delta\left(X_{2121}^{ST}\right)^*\right| + \left|X_{2111}^{ST} X_{1121}^{ST}\right|} \quad (6)$$

$$\mu_L^{ST} = \frac{1 - \left|X_{1111}^{ST}\right|^2}{\left|X_{2121}^{ST} - \Delta\left(X_{1111}^{ST}\right)^*\right| + \left|X_{2111}^{ST} X_{1121}^{ST}\right|} \quad (7)$$

The μ Stability Factor in Terms of X-Parameters

The advantages of using X-parameters in the stability analysis are:

- **Allows to analyze the stability of the FET in frequency and input power.**
- **The interpretation of the stability analysis is straightforward.**
- **The analysis time is reduced compared with other methods.**

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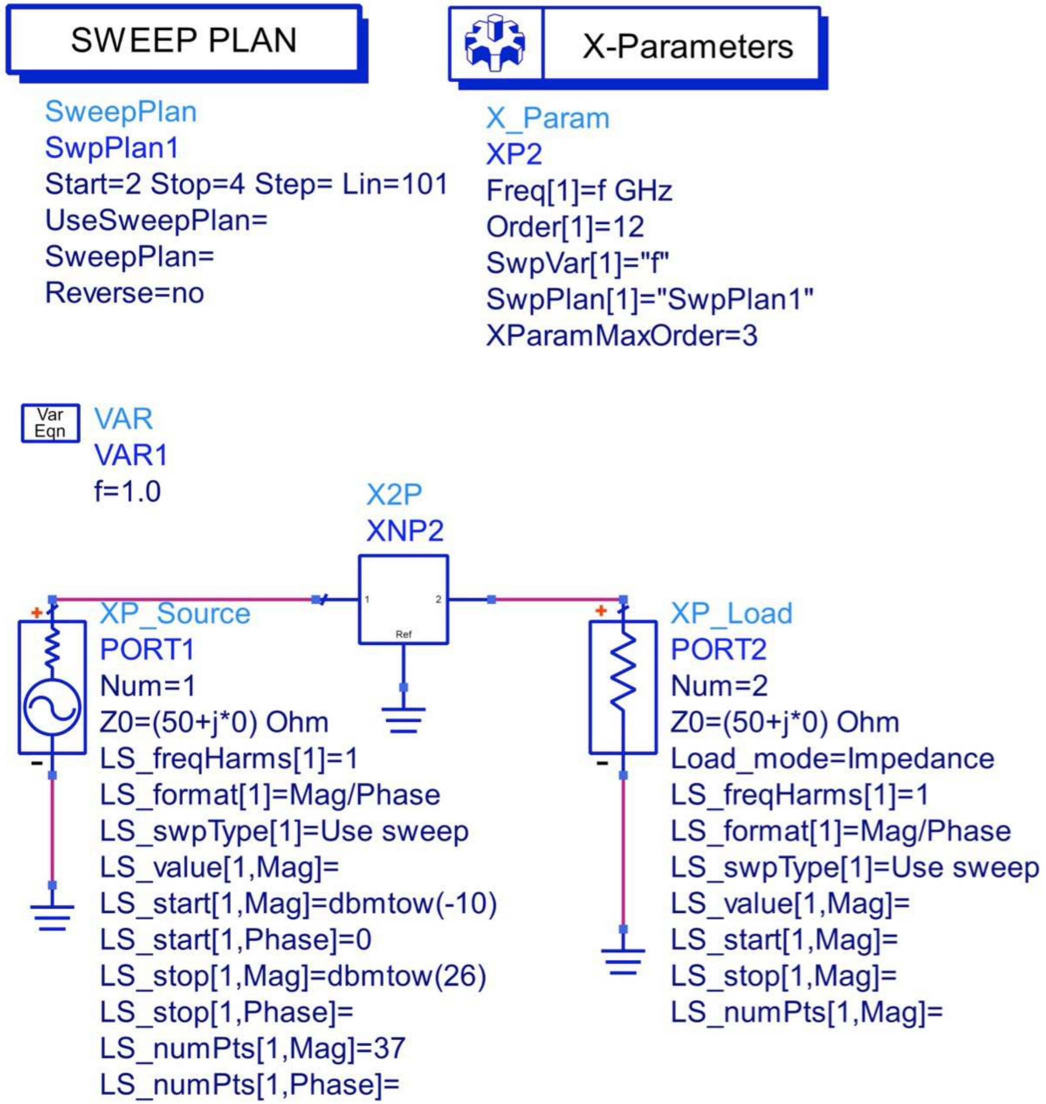
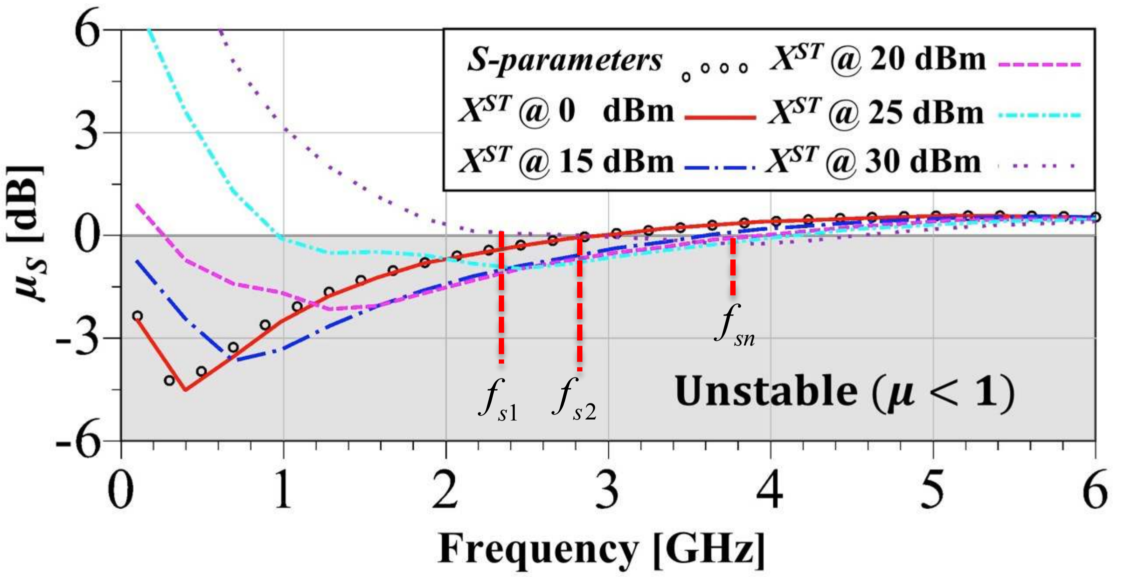
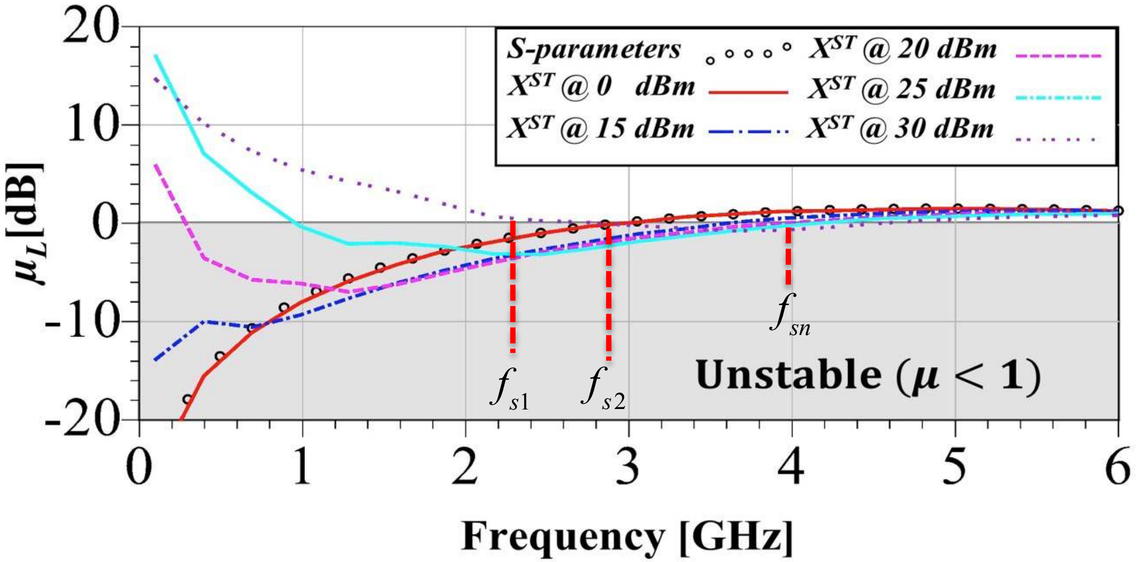
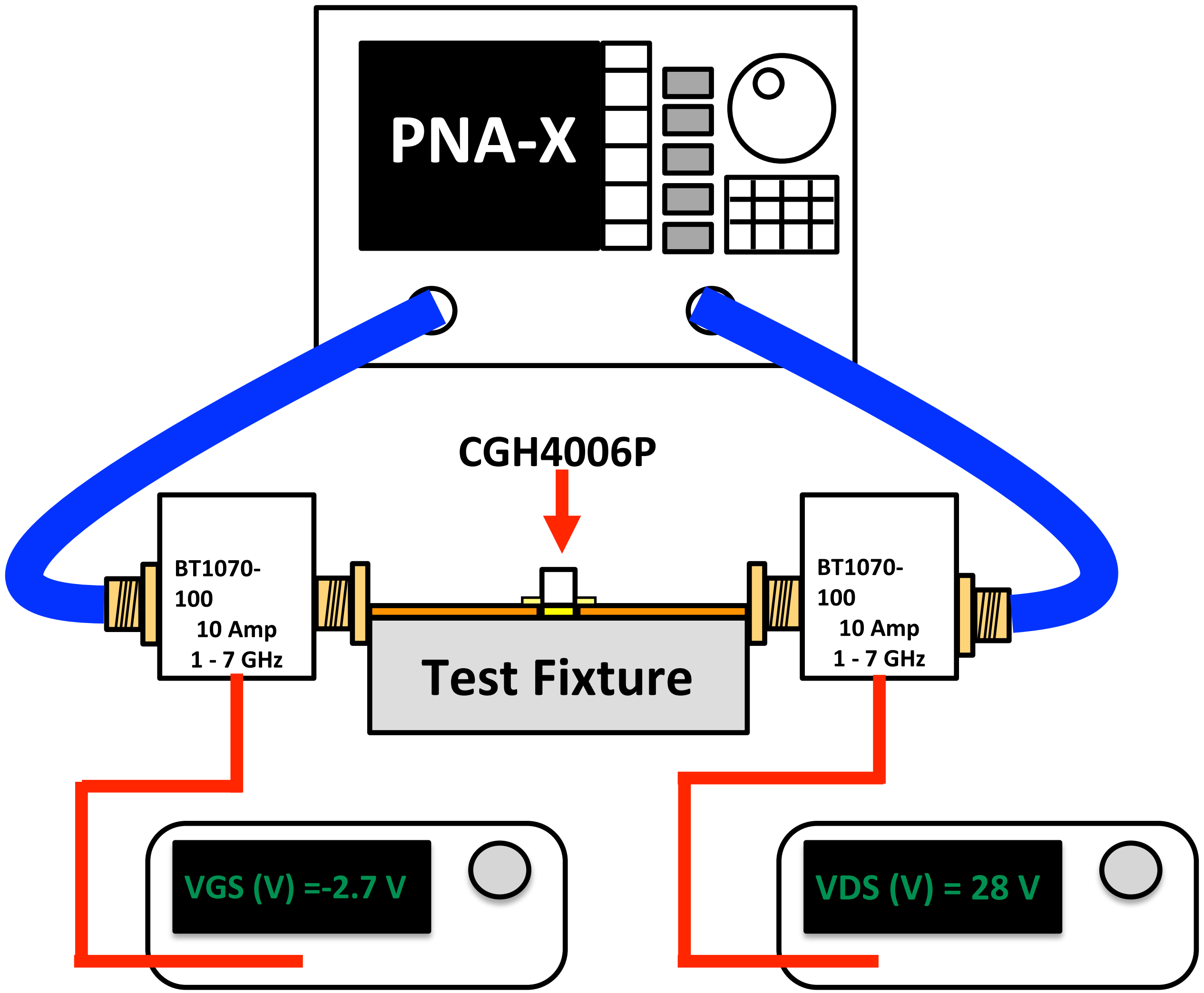
Experimental Results

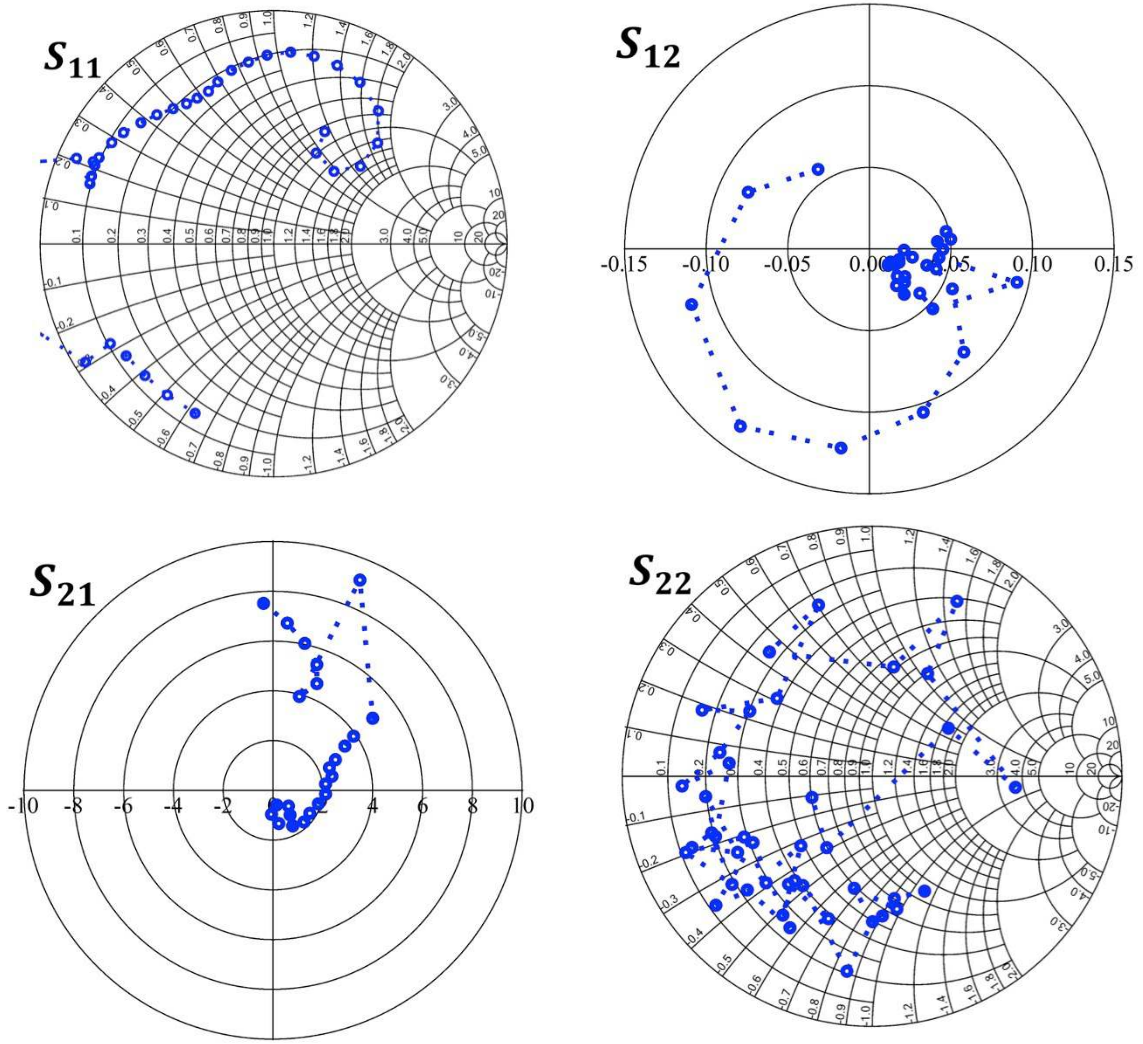






Experimental Results

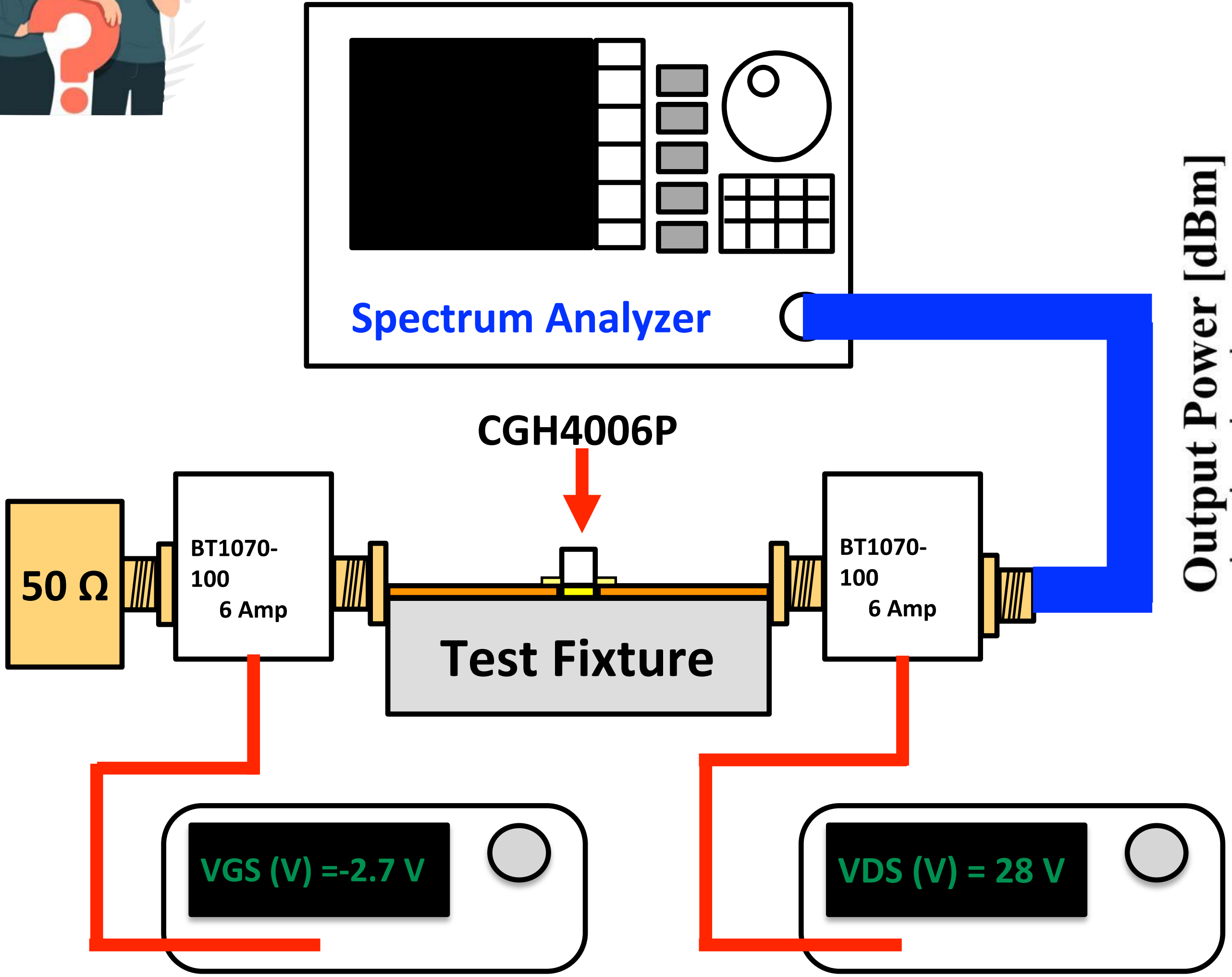




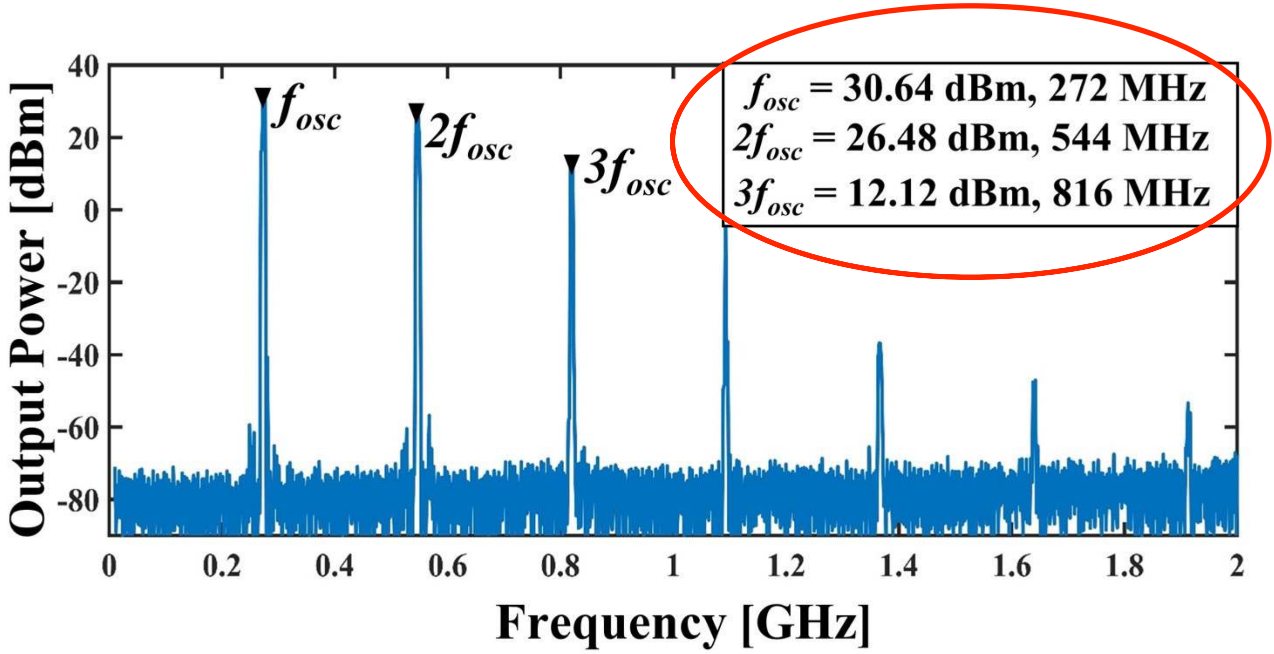
It does not look like a typical S-Parameters measurement

Experimental Results

The question is, **WHAT HAPPENED**?

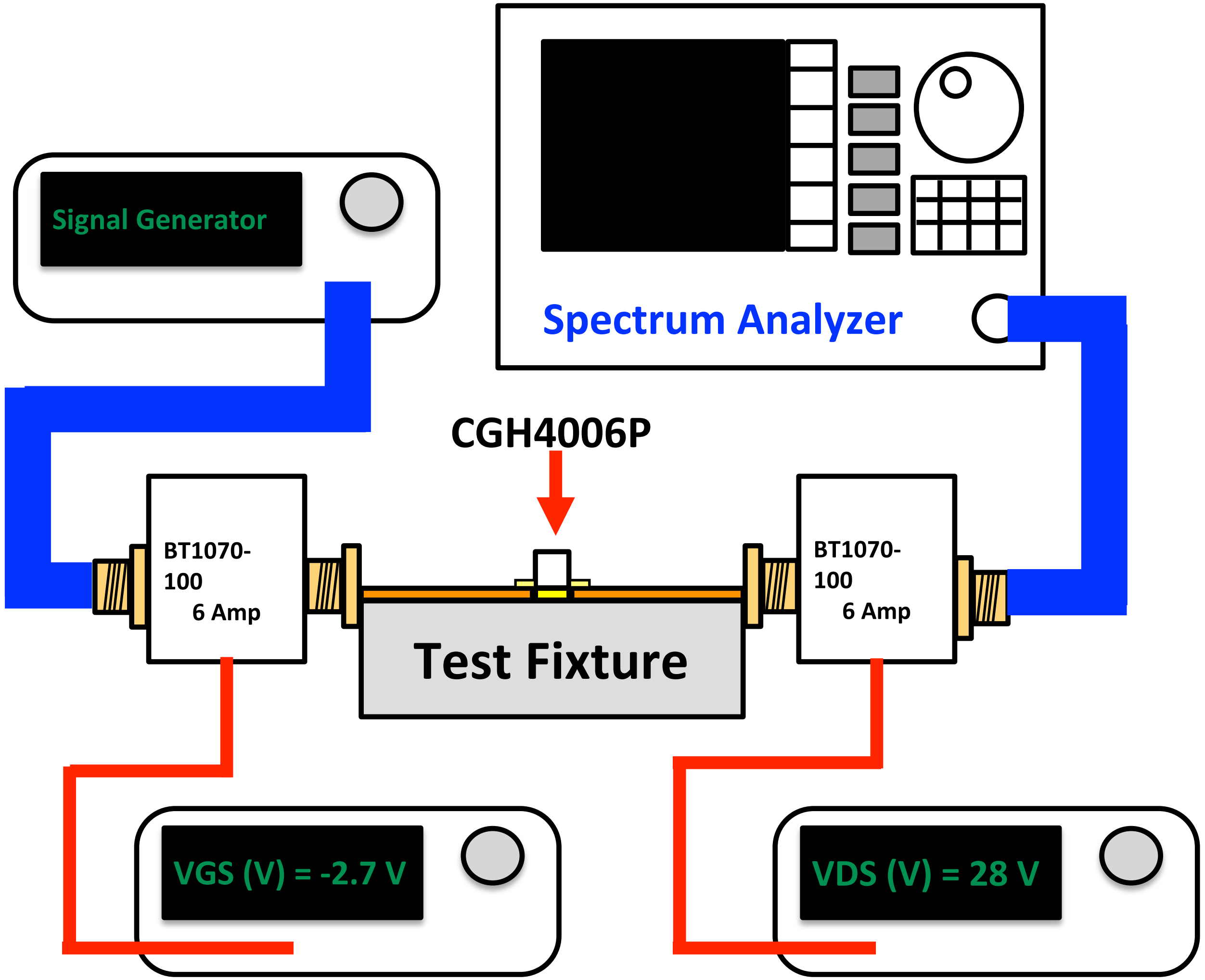


Parametric Oscillations

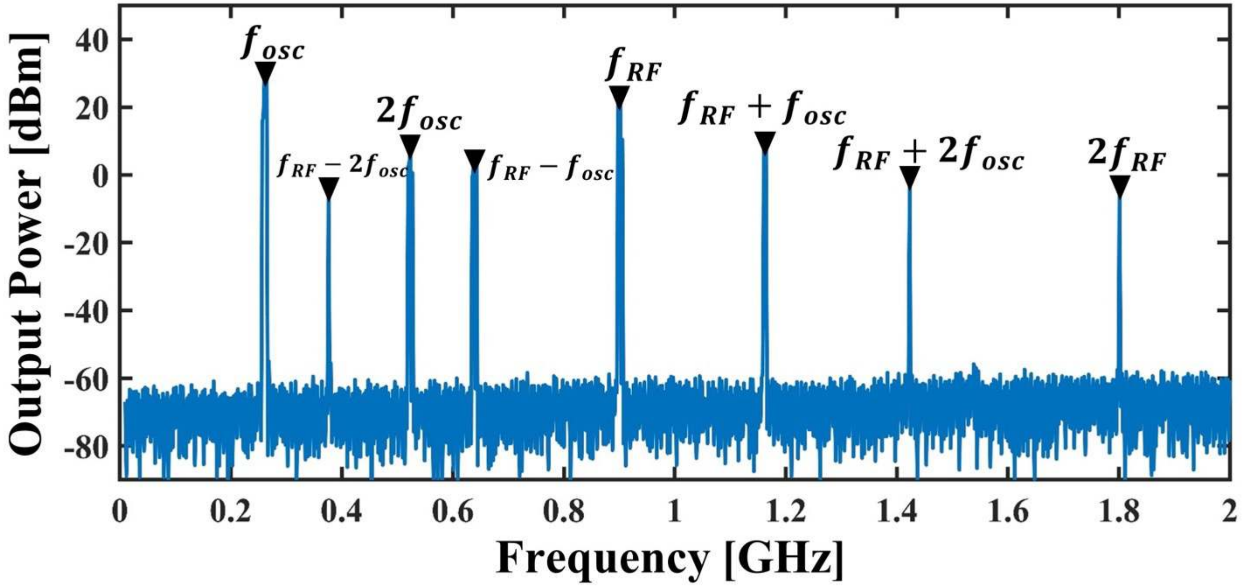


This is an indication that the FET is UNSTABLE

Experimental Results



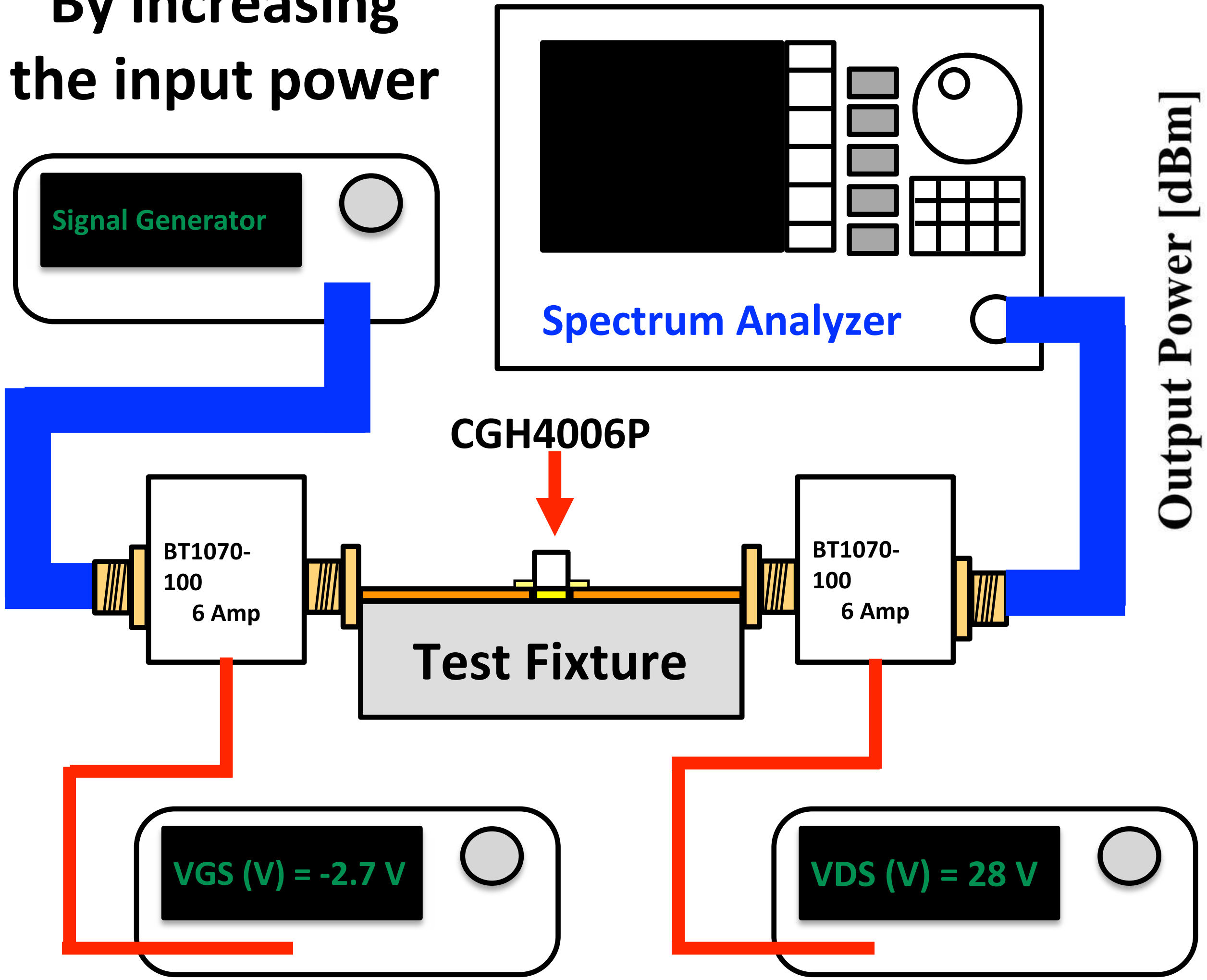
Parametric Oscillations + Intermodulation Distortion



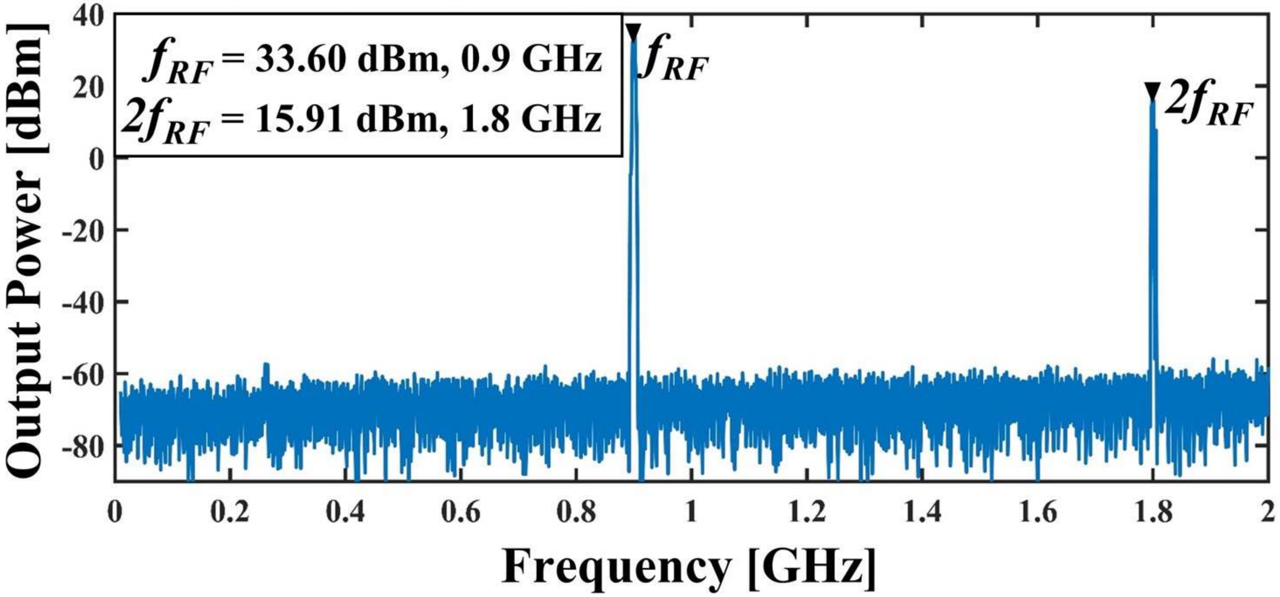
A very BAD IDEA to use the FET as an amplifier

Experimental Results

By increasing the input power



…and as predicted in **SIMULATION**



The parametric oscillations have been disappearing. It seems the FET is STABLE

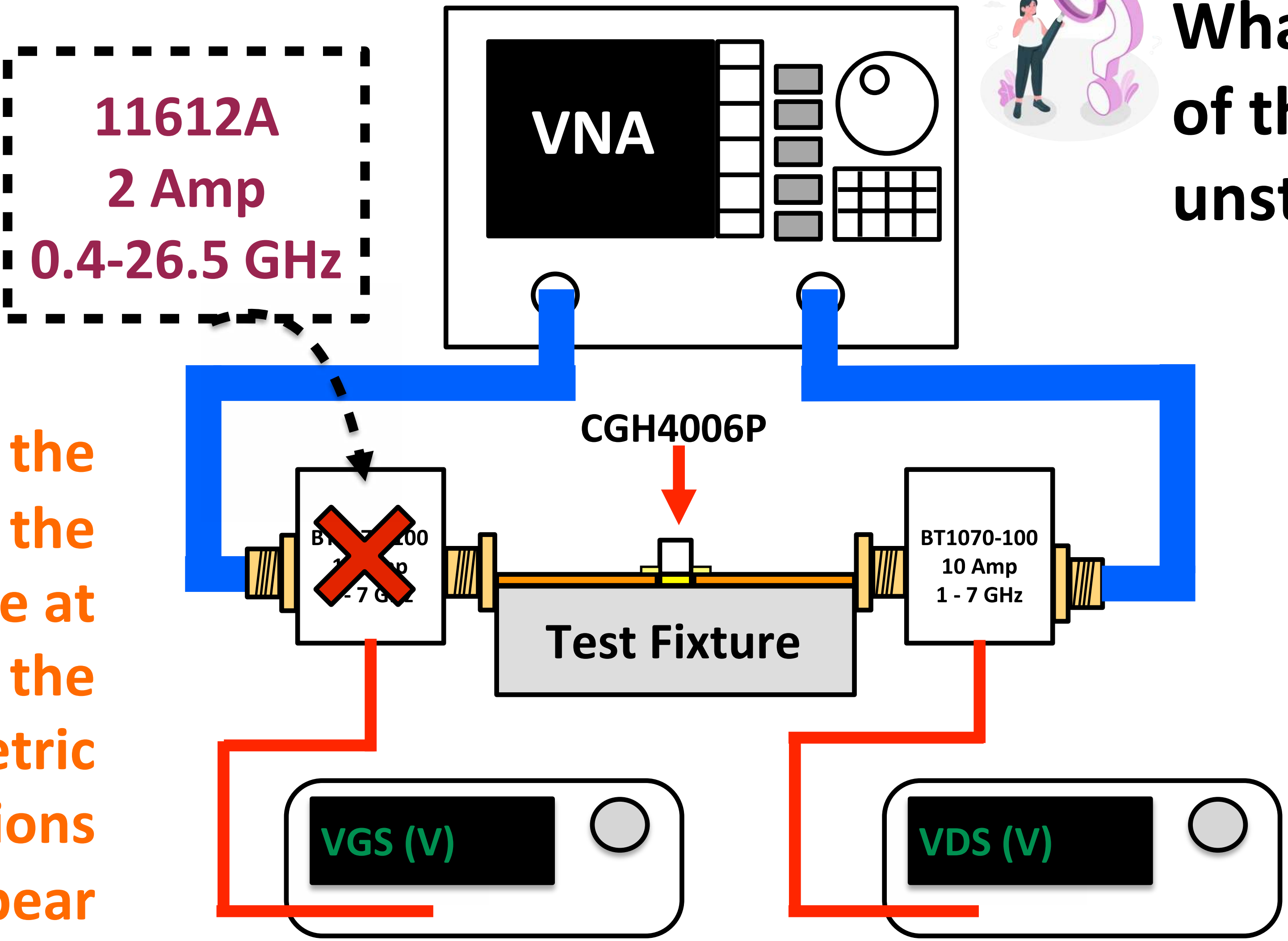
Experimental Results

This experiment suggests:

- **When the gain is compressed, the FET is stable.**
- **The main problem of stability lies in the case of low input power.**

Thus, the classical stability analysis using stability circles could help to understand the instability problem of the FET at the characterization moment

Experimental Results



What is the likely cause of the FET being unstable?

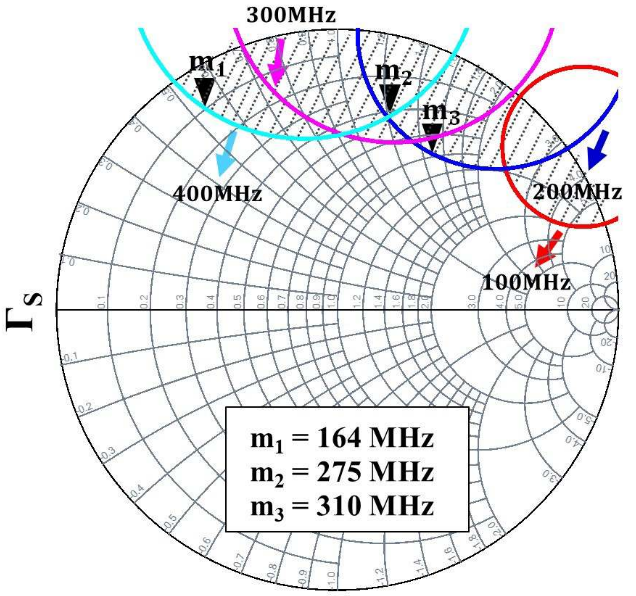
Probably the Bias-Tees

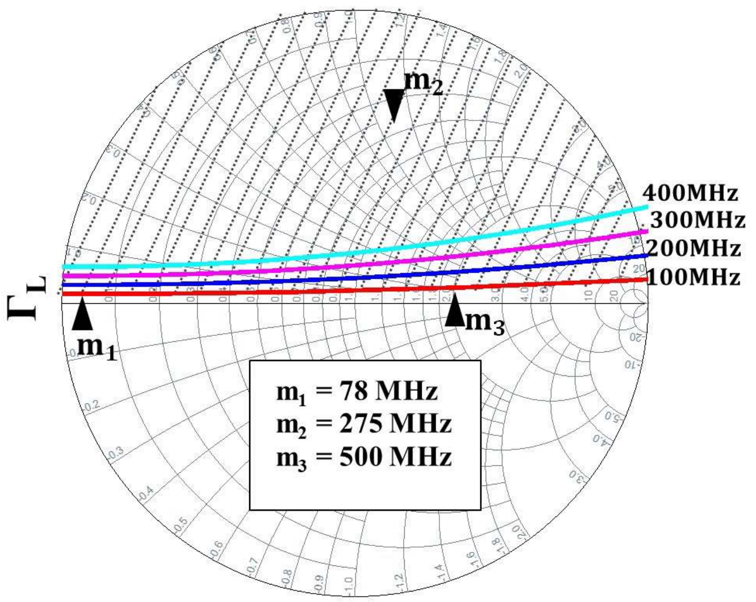
This change corroborates that the bias tees are responsible for the instability

After the change of the bias-tee at the gate, the parametric oscillations disappear

Experimental Results

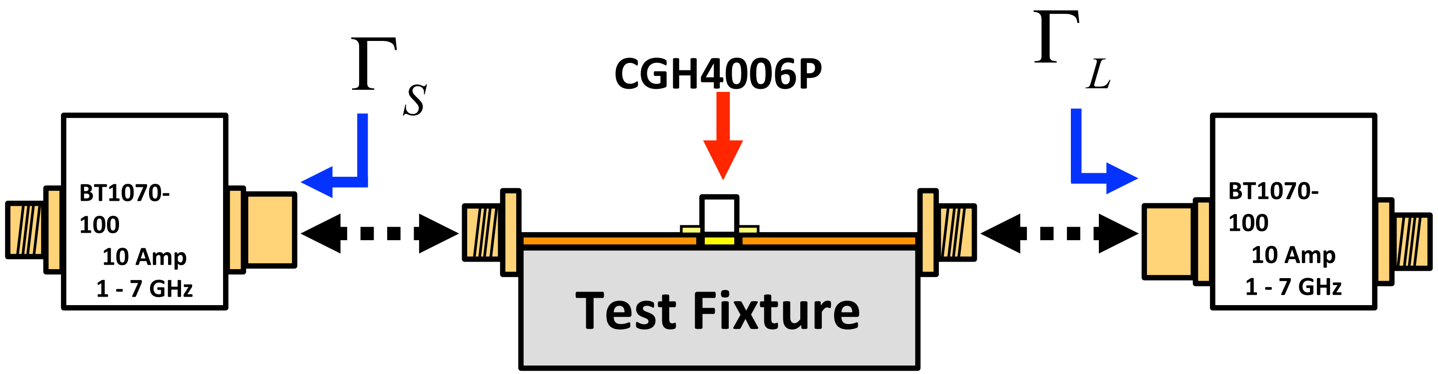
A first approach to verify the effect of the Bias-Tee is computing the input and output stability circle of the FET with the model of the vendor

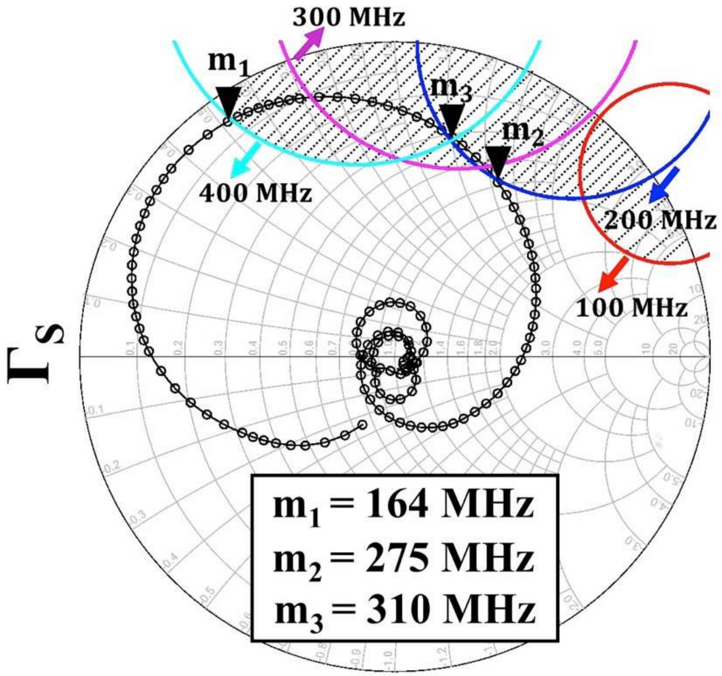


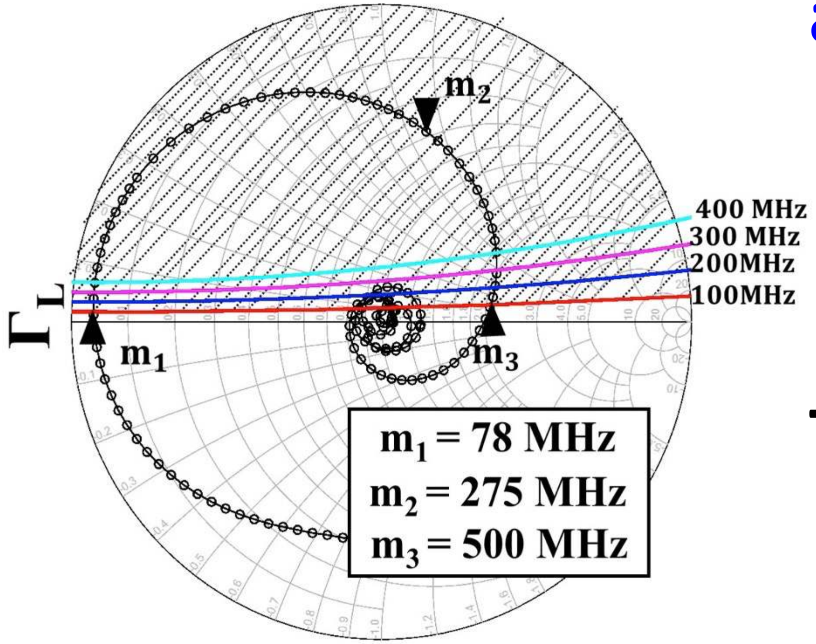


A simulation at low-frequency of the stability circles shows the possible region of Γ can cause the instability of the GaN FET

Experimental Results





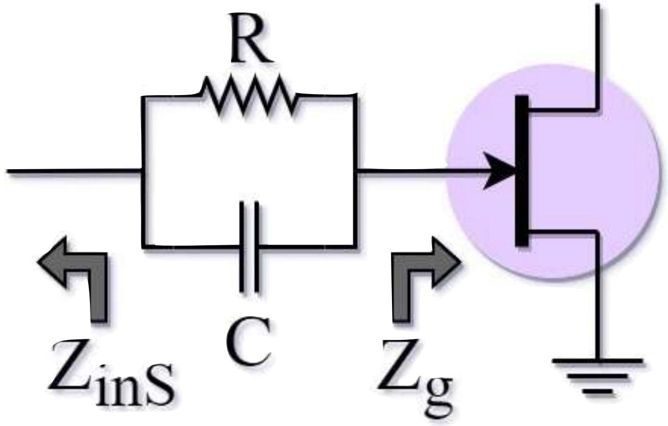


Comparing the frequency range at which Γ_S y Γ_L are inside the instability area simultaneously reveals that at 164 – 275 MHz, the FET is potentially unstable

This information is suitable for designing a stability circuit

Experimental Results

In the literature, a parallel R-C network in series with the gate of the GaN FET is widely used, but without an explanation of how to determine the value of R or C



This R-C network works as a high-pass filter, where the cut-off frequency (*f_c*) is determined as:

$$f_c = \frac{\kappa}{2\pi C\alpha} \pm \frac{\sqrt{R\kappa - \alpha\left[\left(R+\rho\right)^2 + \kappa^2 - 8\,\mathrm{Re}\left(Z_{inS}Z_g\right)\right]}}{2\pi RC\alpha} \qquad (4)$$

Where:

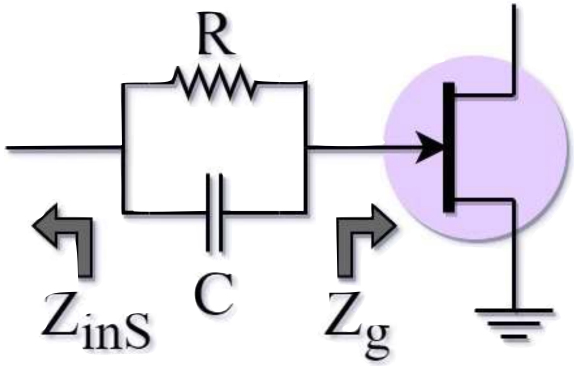
$$\kappa = \mathrm{Im}\left(Z_{inS} + Z_g\right) \qquad (5)$$

$$\rho = \mathrm{Re}\left(Z_{inS} + Z_g\right) \qquad (6)$$

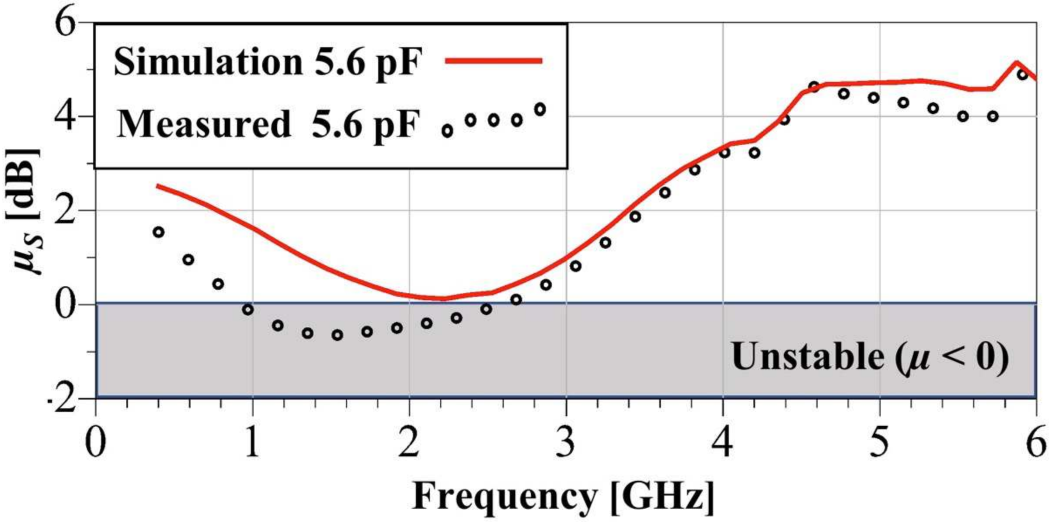
$$\alpha = \kappa^2 + \rho^2 - 8\,\mathrm{Re}\left(Z_{inS}Z_g\right) \qquad (7)$$

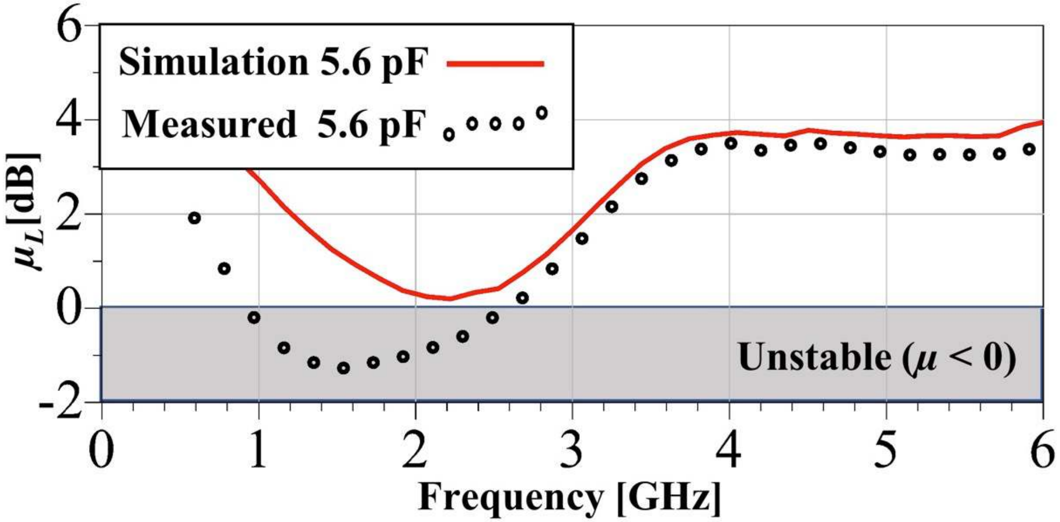
Experimental Results

Thus, assuming a f_c = 0.4 GHz, R = 100 Ω, Z_{inS} = 50 Ω, and Z_g is the input impedance of the FET obtained with S-parameters



C = 5.6 [pF]

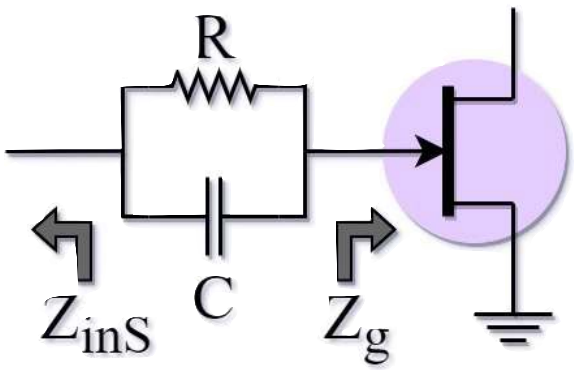


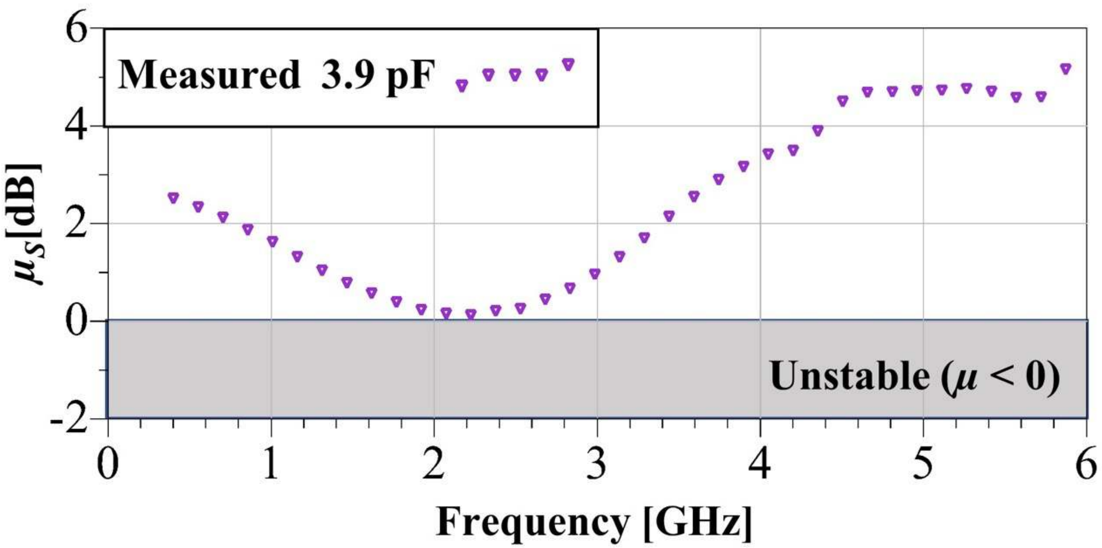


Simulations do not agree with the measurements, and it seems that it is unstable

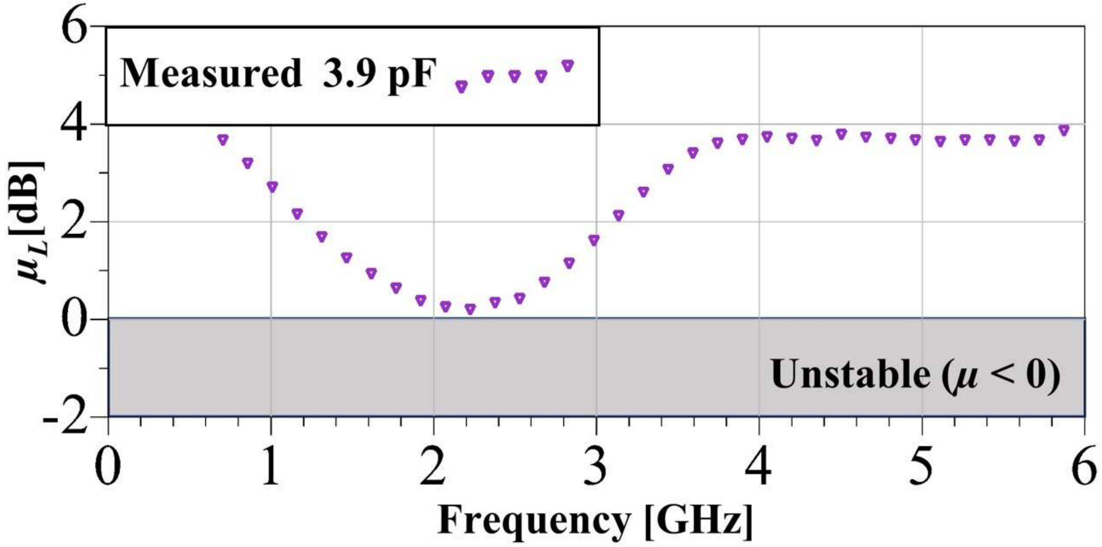
Experimental Results

Tuning the value of C, shows that





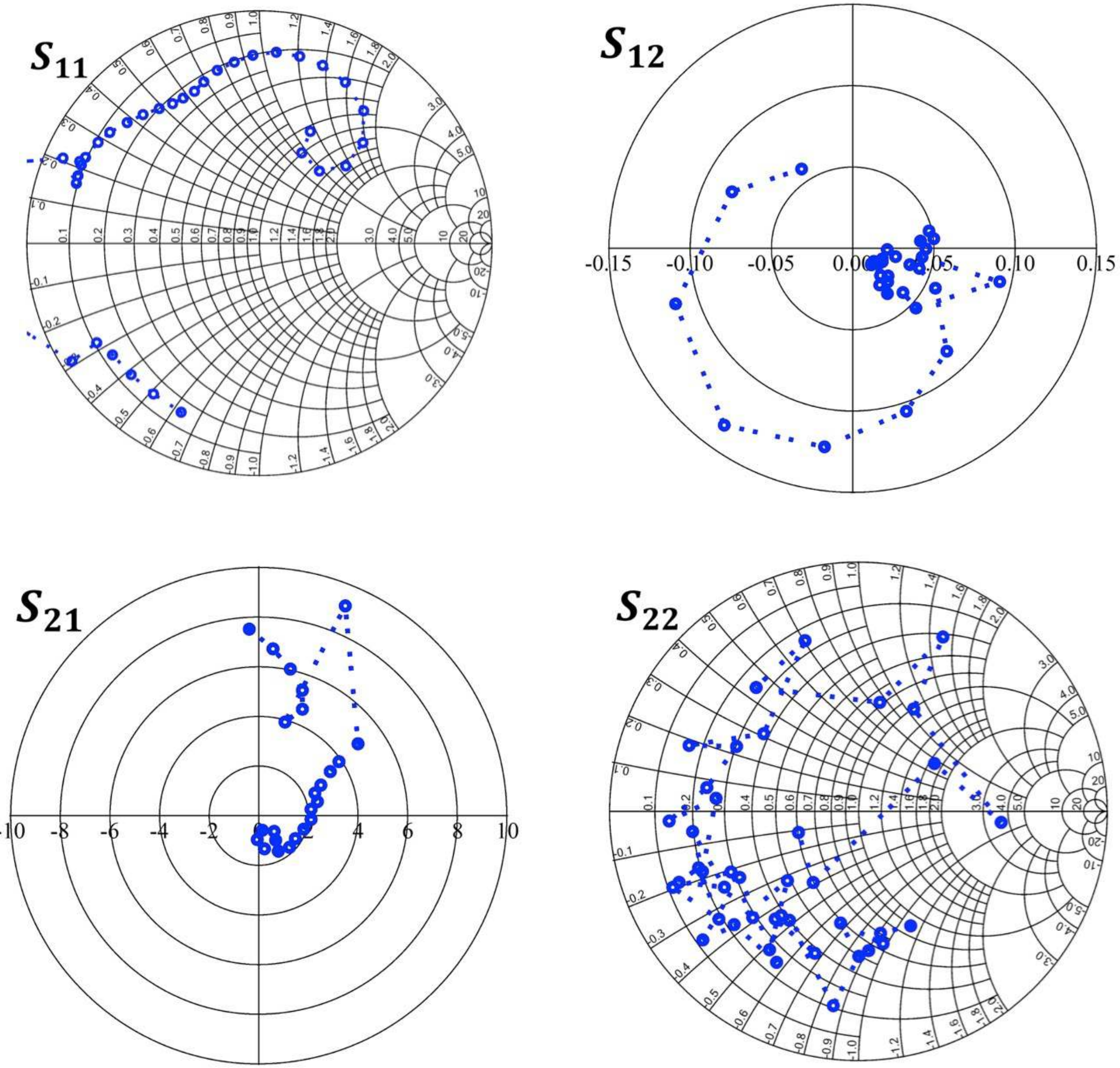
C = 3.9 [pF]



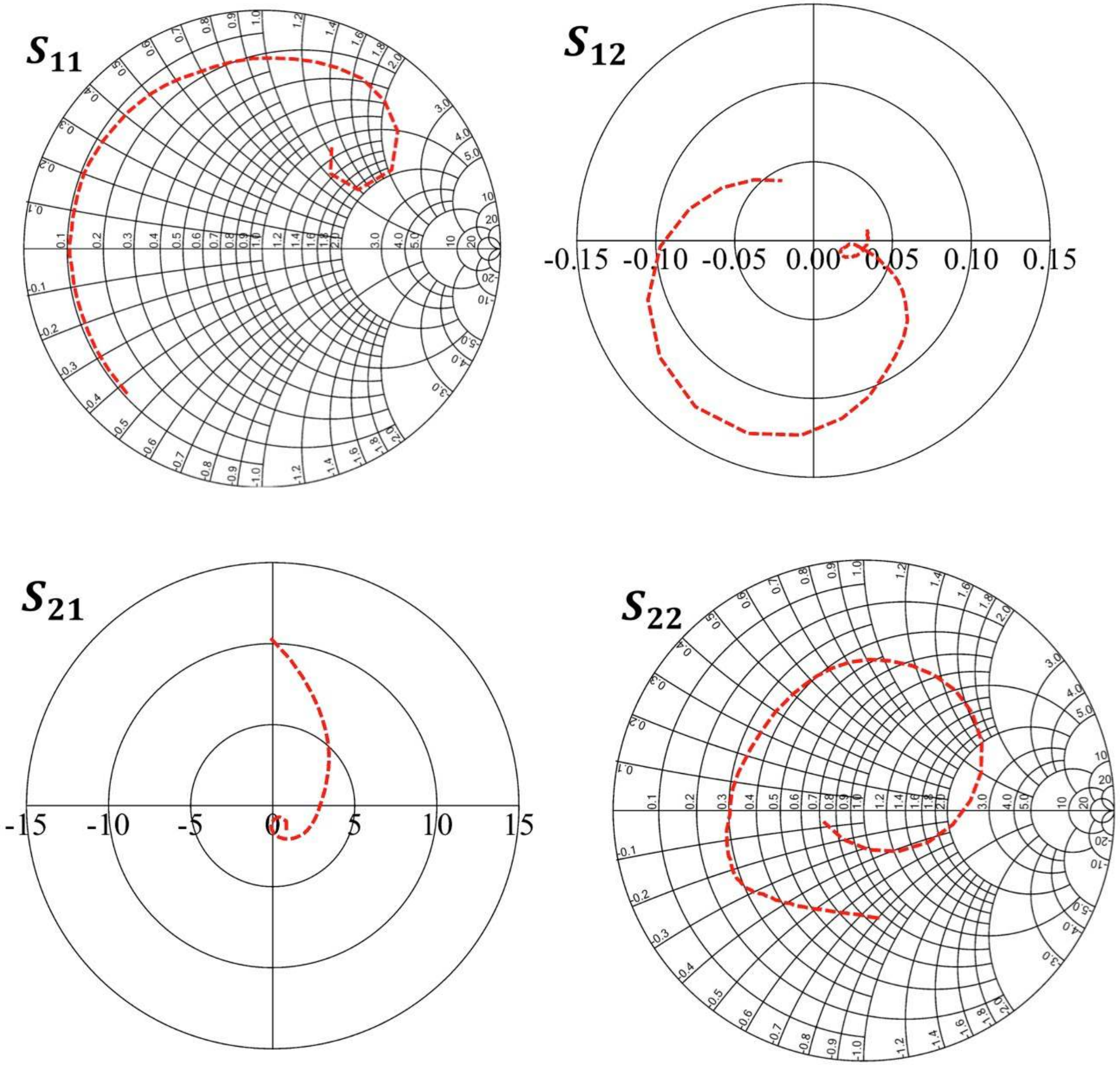
Now the measurements show that the FET is STABLE

Experimental Results

w/o Stabilized



Stable



Outline

Conclusion

- During the characterization of the FET, the bias tees could be the source that caused the instability.
- Incorporating the X-Parameters in the μ factor allows for analyzing the effect of the input power on the stability of the FET.
- The simulation and experimental results corroborated that compressing the gain can stabilize an unstable FET.
- Since the FET under high gain compression level condition is stable, the small-signal stability analysis methods become more relevant.
- Although the results demonstrated that the FET is stable under high-gain compression, it is more recommendable to use a high-pass filter at the gate of FET with cut-off frequency higher than the possible parametric oscillations to stabilize the transistor.