A new nonlinear HEMT model allowing accurate simulation of very low IM_3 levels for high-frequency highly linear amplifiers design

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Abstract — **Today, confident design of highly linear MMICs is of primary concern for high-frequency applications. Unfortunately, at high frequencies and low output powers, accurate prediction of intermodulation distortions fails with most of the available HEMT models due to nonlinearity extractions based on CW S-parameter measurements at DC bias points or low RF frequency measurements. In this paper, we propose a suitable HEMT model, extracted from pulsed I/V and pulsed S-parameter measurements over a wide frequency range, which allows accurate prediction of intermodulation distortions at both high frequencies and large output power range.**

Index Terms — **Intermodulation distortion, nonlinear model, HEMT, pulsed measurement, high-frequency amplifier.**

I. Introduction

Nowadays, MMIC design has to deal with increasing linearity constraints due to the use of spectrally efficient digital modulations in modern telecommunication systems. Therefore, the efficient design of high-frequency highly linear MMICs requires accurate prediction of intermodulation distortions (IMD), especially of the 3^{rd} order (IM_3), from low output powers up to high output powers (~1dB compression) [1]-[4].

At high output power levels, standard HEMT models often give a good approximation of IM_3 levels which are asymptotically close to each other. However, at low output power levels, discrepancies as high as 20dB can be observed between IM_3 simulation and measurement. Moreover, standard HEMT models fail to predict accurate IM_3 at high frequencies because their nonlinearities and corresponding derivatives are commonly extracted from a set of constant wave (CW) S-parameter measurements at DC bias points, and from harmonic distortion measurements at low RF frequencies.

In this paper, we propose a new modeling approach that relies on accurate pulsed S-parameters and pulsed I/V measurements over a wide frequency range (2-20GHz) and a focused measurement grid. Pulsed measurements enable the whole characterization of devices from a quiescent bias point. This situation corresponds to operating conditions as close as possible to the real world ones [5]. The quiescent point is chosen according to the focused application and defines the thermal and trapping states of the transistor at low output power levels.

From this set of pulsed measurements, all nonlinear differential elements (Gm, Gd, Cgs, Cgd) of the transistor are extracted as a function of the control voltages (Vgs, Vds). The capability of our model to accurately reproduce IM_3 measurements at very low power levels, is based on a coherent extraction of these differential nonlinear elements whose corresponding nonlinearities (Ids, Qgs, Qgd) are fitted by means of specific phenomenological equations. Moreover, the pulsed I/V measurements enable us to determine the cut-off frequency of trapping effects by varying the pulse width without changing the quiescent bias point that keeps constant the thermal state of the device.

At device level, load-pull simulations and measurements of IM_3 data were systematically compared in order to validate the capability of our modeling approach to accurately predict the effect of load impedance.

Finally, simulation and measurement results of a 3-stage 1W Ku-band HPA demonstrate that the proposed model is suitable for the CAD of high-frequency highly linear HPA over a wide output power range up to 1dB compression.

II. New Non Linear HEMT Model

A. Extraction of nonlinear derivatives

Starting from a quiescent bias point Idso (Vgso, Vdso), a small signal model is extracted from pulsed I/V and pulsed S-parameter measurements over a dynamic area (Ids, Vgs, Vds) so that (Vgs=Vgso+dvgo+dvgs and Vds=Vdso+dvdo+dvds) where dvgo, dvdo are the pulsed I/V voltages and dvgs, dvds are the pulsed RF voltages superimposed to the quiescent point. The maximum voltage swings (V_{Gsmin}, V_{GSmax}, V_{DSmin}, V_{Dsmax}) are chosen to define the modeling area as shown in Fig.1 while the minimum values of dvgo and dvdo define the steps of the pulsed measurement grid.

The limits of the extraction area as well as the step size of measurements have to be carefully chosen because of their direct impact on the model accuracy for IM_3 prediction from low to high power levels. On the one hand, the modeling area has to be large enough to account for the global shape of nonlinearities, implicitly of their derivatives, but also for minimizing the effects of systematic measurement errors. On the other hand, the step sizes (dvgo, dvdo) of pulsed measurements have to be small enough to enable the accurate fitting of the local shape of nonlinearities.

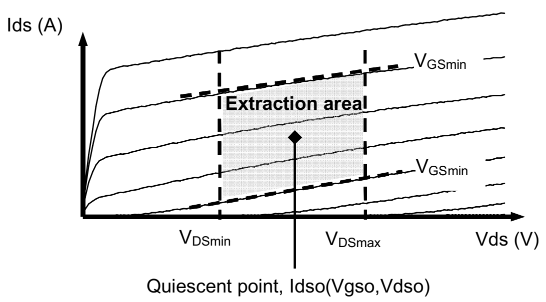
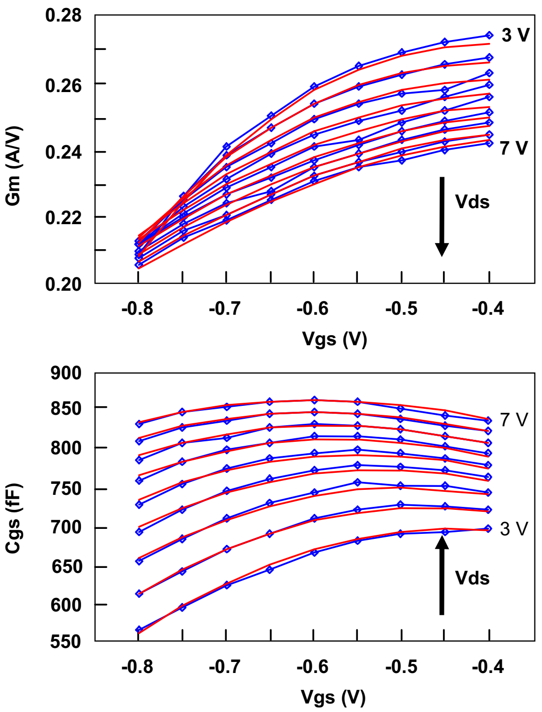


Fig. 1. Extraction area of the HEMT model (pulsed measurement)

As an example, the following figures illustrate the modeling of a 8x75µm GaAs PHEMT at a quiescent bias point of Vgso=-0.6V and Vdso=5V. The device modeling area was fixed to $V_{Dsmin\text{-}to\text{-}max}$ = 3 to 7V and $V_{Gsmin\text{-}to\text{-}max}$ = -0.8 to -0.4V while the minimum steps dvgo and dvdo of the pulsed measurement grid were fixed to 0.05V and 0.5V respectively.

All the nonlinear differential elements extracted from this pulsed measurement grid were then fitted with dedicated phenomenological equations. The validation results (Fig. 2) show very good model agreement over the whole extraction area of the differential elements (Gm, Gd, Cgs, Cgd) as a function of control voltages.



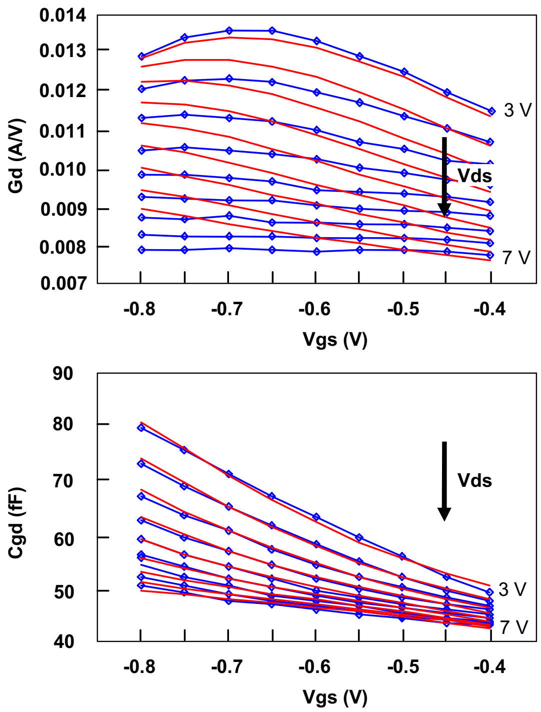


Fig. 2. Measurement-based extracted values (blue diamond) and modeled values (red line) of the differential elements (Gm, Gd, Cgs, Cgd) as a function of Vgs and Vds

From these four differential elements (Gm, Gd, Cgs, Cgd), the three nonlinearities Ids(Vgs,Vds), Qgs(Vgs,Vds) and Qgd(Vgs,Vds) were modeled and implemented in the final model with dedicated equations. The intrinsic part of the nonlinear HEMT model is shown in Fig. 3. A series R-C circuit is placed in parallel to the drain current source in order to model the trapping effects at the given quiescent bias point.

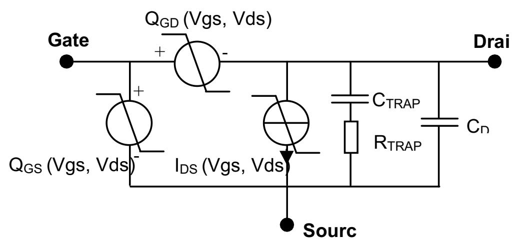


Fig. 3. Intrinsic architecture of the nonlinear HEMT model

B. Modeling of the drain current source

The transconductance Gm(Vgs, Vds) and conductance Gd(Vgs, Vds) are first integrated in order to ensure the consistent modeling of the drain current source [6]. The dedicated equation of Ids was of the following form:

$$Ids(Vgs,Vds) = I_o \cdot FA(Vgs,Vds) \cdot FB(Vds) \cdot FC(Vgs,Vds) \quad (1)$$

with:

$$FA(Vgs,Vds) = 1 + \tanh\left[Alpha \cdot \left(Vds - FX\left(Vgs\right)\right)\right] \quad (2)$$

$$FB(Vds) = \left(1 + A \cdot Vds\right) \cdot \tanh\left[B \cdot Vds\right] \quad (3)$$

$$FC(Vgs,Vds) = 1 + \tanh\left[C \cdot \left(Vgs - FY\left(Vds\right)\right)\right] \quad (4)$$

where (I_o, Alpha, A, B, C) are parameters while FX(Vgs) and FY(Vds) are polynomial expressions.

Using the preceding equation and its derivatives, the final set of its parameters is optimized to simultaneously fit the measured Ids during pulsed I/V measurement and the differential elements (Gm, Gd) extracted from the pulsed (S) measurements. This modeling process ensures the consistency of the drain current model. Finally, the comparison between the simulated Ids current source and the pulsed I/V measurements (Fig. 4) illustrates the good agreement obtained over the whole modeling area.

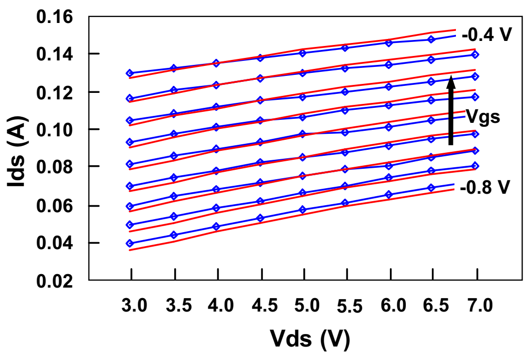


Fig. 4. Modeled current source Ids (blue triangle) versus pulsed I/V measurements (red line) over the modeling area.

C. Charge Modeling

In the same way, the nonlinear charges Qgs and Qgd are respectively coming from the integration of Cgs and Cgd. Different equations can lead to accurate Cgs and Cgd modeling. For instance, equations given in [7] enable accurate charge modeling of our transistor's model.

In order to preserve charge conservation in the circuit, independently of the equations used, the approach proposed by R. Follman [8] has been also implemented.

III. Comparison Between 2-tone Large Signal Simulations and Load-pull Measurements

To check the model accuracy at low power levels, a 2-tone load-pull setup was optimized to enable accurate IM_3 measurements up to 80dBc of carrier to IM_3 ratio (CI_3). The 8x75µm device was characterized at a center frequency of 10.24GHz for two equal amplitude signal components with a frequency difference Δf of 10MHz. The transistor was measured for many load impedances that cover the Smith chart region as shown in Fig. 5.

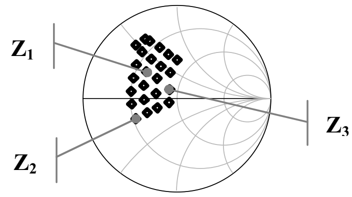


Fig. 5. Smith chart region of 2-tone load-pull measurements

As an example, Fig. 6 shows the comparison between measured and simulated CI_3 as a function of output power for three different loads: Z_1=(21.8+j15.6) Ω ; Z_2=(18-j10) Ω and Z_3=(41.8+j8) Ω.

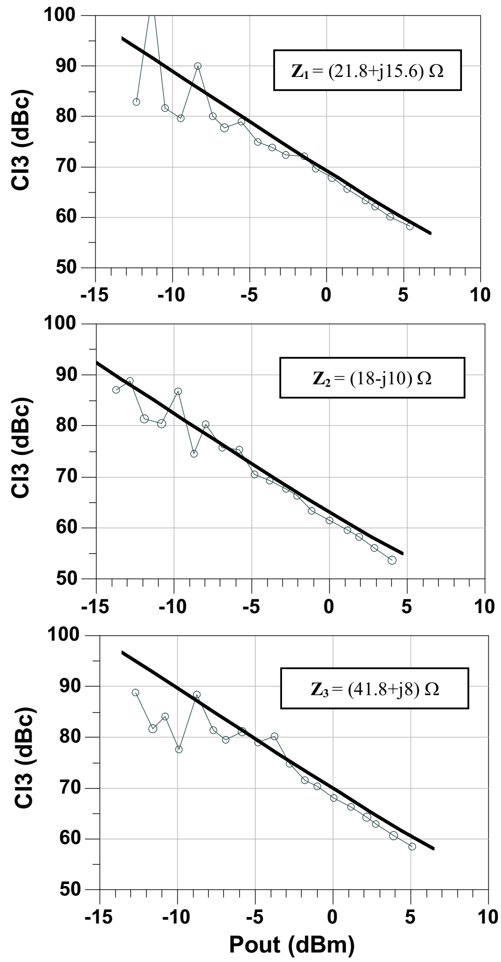


Fig. 6. CI_3 measurements (line+circle) and CI_3 simulations (solid line) versus output power for 3 different loads (Z_1, Z_2 and Z_3)

Fig. 6 illustrates a very accurate prediction of CI_3 for the three output loads with errors less than 2dB over all the considered range of output power. During all the simulation and measurement process of CI_3 load-pull contours, we noted that CI_3 at low power levels was practically independent of the load at Δf frequency and at harmonic frequencies.

IV. Extension of the Modeling Approach up to 1dB Compression Point

The preceding results demonstrate the good agreement obtained with the proposed modeling approach which allows the accurate IM_3 prediction at low output powers. To increase the validity domain of our model, and thus accurately simulate IM_3 and output power near the compression region, the modeling approach was extended to larger voltage swings.

Such an extension of the extraction area was done in order to design a complete 3-stage 1W (saturated) Ku-band HPA integrating 4 PHEMTs (two 8x75µm driving two scaled 8x150µm). The measured CI_3 of the MMIC HPA is shown in Fig. 7 and compared to the simulated CI_3 by using the standard foundry model or the new nonlinear model.

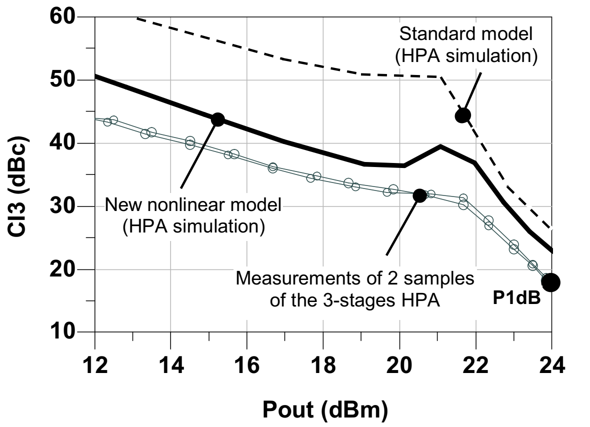


Fig. 7. Measured and simulated CI_3 of the 3-stage HPA versus output power (1 ton) at 14GHz center frequency and Δf of 10MHz.

As demonstrated in Fig. 7, simulation of the 3-stage MMIC HPA gives an accurate prediction of CI_3 levels as a function of output power, making the proposed model suitable for accurate IM_3 simulation up to 1dB compression. It can be noticed that IMD 'sweet spots' are also simulated with an excellent agreement.

At low and medium powers, around 15dB discrepancy is observed on CI_3 level between the standard model and the new nonlinear model. Finally, CI_3 predictions are asymptotically almost the same at the highest power levels for both models.

V. Conclusion

A new nonlinear HEMT model dedicated to the accurate simulation of low IM_3 level at high frequencies is proposed. The modeling technique is based on accurate pulsed measurements and the use of dedicated equations to ensure the consistency between the nonlinearities and their derivatives. This modeling approach was applied to a 8x75 GaAs PHEMT device and validated by systematic comparisons of IM_3 simulations and 2-tone load-pull measurements for different output loads have demonstrated excellent agreements.

The proposed model was then extended to IM_3 prediction at higher output powers near the compression region. Such an extension was validated through the comparison of simulated and measured CI_3 of a 3-stage 1W (saturated) MMIC HPA at 14GHz demonstrating a very good agreement on CI_3 over a wide range of output power.

This makes the proposed HEMT model suitable for the CAD of high-frequency highly linear amplifiers. First, simulations of low-level CI_3 load-pull contours are used to optimize the output load at fundamental frequencies whereas simulations around the 1dB compression point are used to optimize the output loads at Δf and at harmonic frequencies.

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Outline

- *Motivation*
- *Principles of accurate prediction of IMD_3 levels*
- *Application : HPA simulation*
- *Conclusion*

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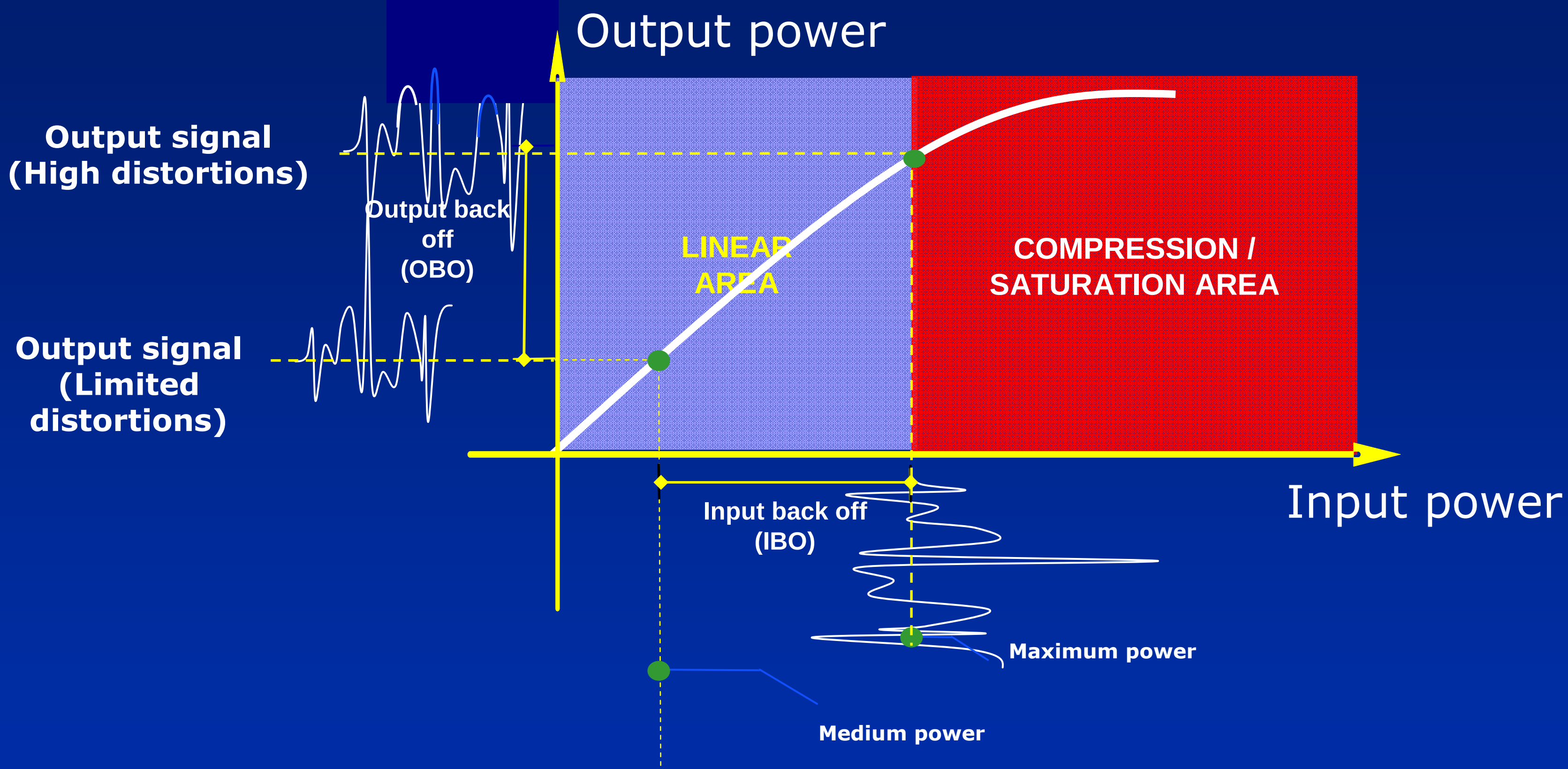
Modern telecommunication systems

- ***High Power Amplifier (HPA)***
  - « Key » component for telecommunication systems
    - Limits the overall linearity of transmission systems
    - Consumes major part of the available DC power
- ***Trade-off between Ps / Gp / PAE / IMD_3***
  - Application field
  - Nature of the signal to be amplified
- ***Telecommunication applications***
  - Complex digital modulations
    - Powerful trade off : data rate / spectral efficiency
    - Needs amplification of non-constant envelope signals

HPA operating point



- **Consequences of output back off operation :**
  - ↗ linearity performances
  - ↘ power added efficiency
  - ↘ output power

CRITICAL TRADE OFF

Third order intermodulation prediction

- **« Standard » transistor models**
  - Allow « correct » IMD_3 prediction in saturated operation
  - Give erroneous IMD_3 prediction for both low output power levels and high frequency operation
- **Accurate IMD3 prediction model needs**
  - Pulsed measurement characterization
  - Local and global accurate fitting of device non-linearity

CURRENT TRANSISTOR MODEL INEFFICIENT

to allow accurate IMD_3 optimization in critical HPA designs at low output power levels and at high frequency

Outline

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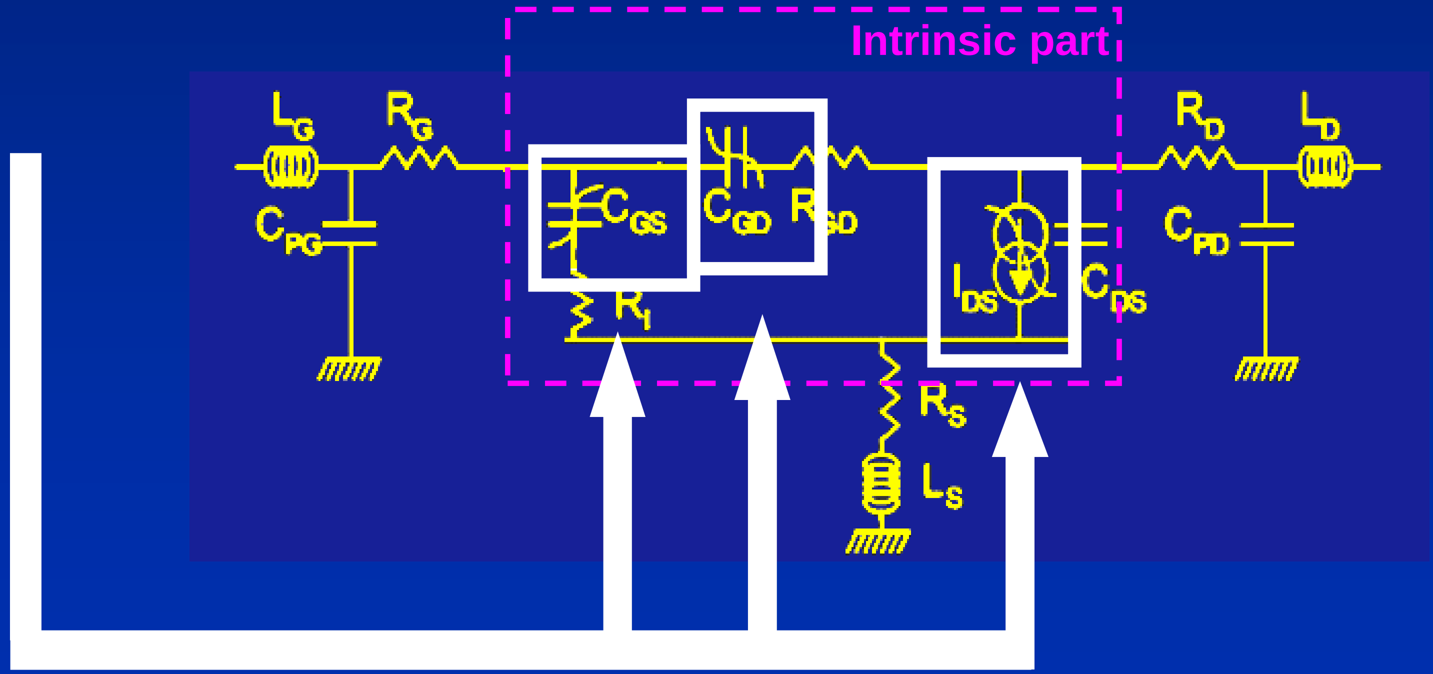
Field effect transistor topology

- Well-known « Pi » architecture
- 3 main nonlinear elements
  - – Ids, Cgs, Cgd

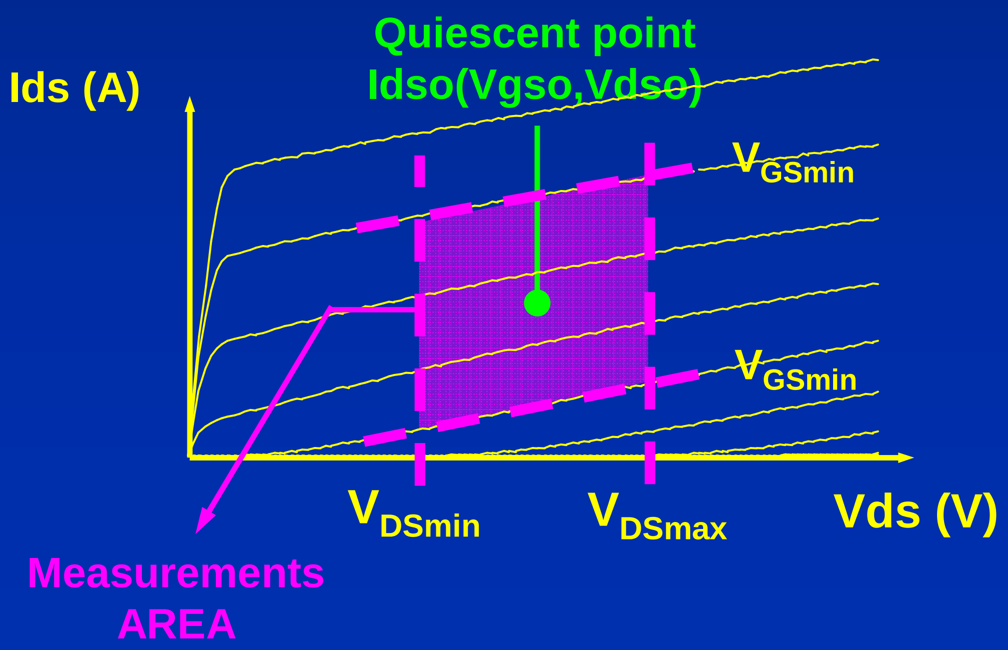


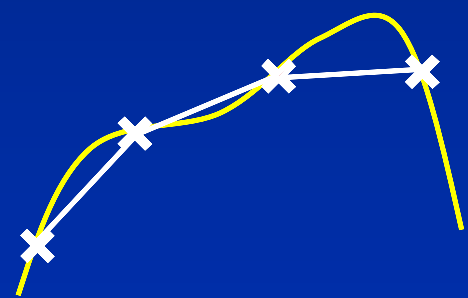
Pulsed I/V + pulsed [S] measurements

- **Measurements as close as possible to the device operating conditions**
  – Quasi-constant thermal state
  – “Limited” traps effects
- **Direct deembedding of all NLDE**
  – Current source IDS
    - Gm and Gd, partial IDS derivatives
  – Non-linear capacitances Cgs and Cgd
- **Large frequency bandwidth characterization**
  – 2 to 40GHz

Accurate nonlinear modeling principles

- **Trade off** : Equations complexity / measurements fit
- **Window, step measurements <u>must</u> account for**
  - **global** non-linearity shapes
  - **local** non-linearity shapes

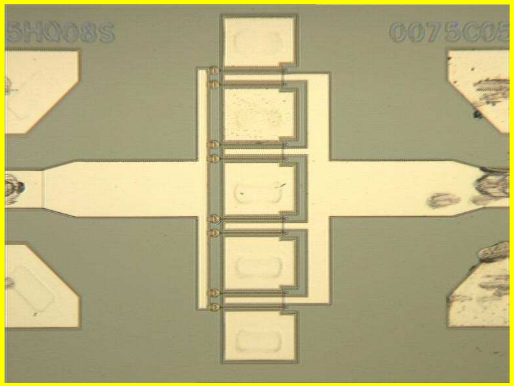




Problem of inappropriate step size measurements choice

Example of device characterization

- **Transistor under test**

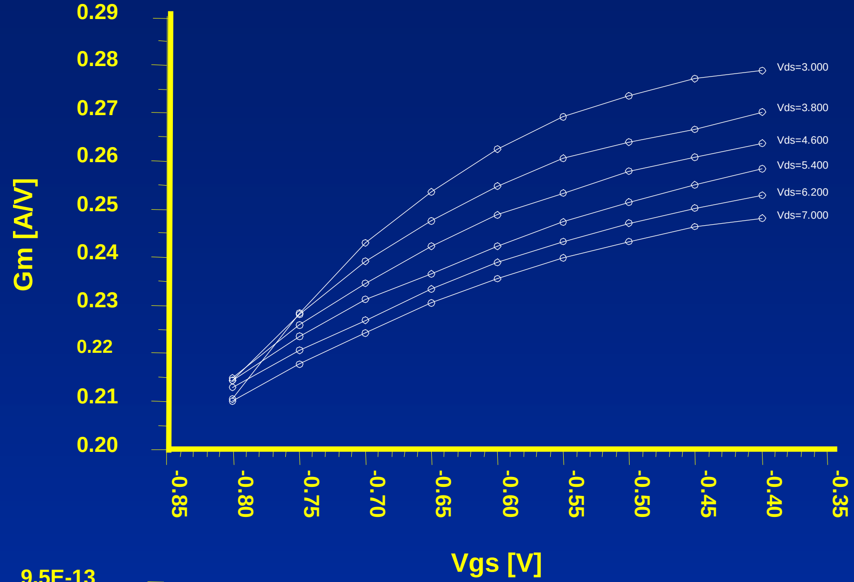


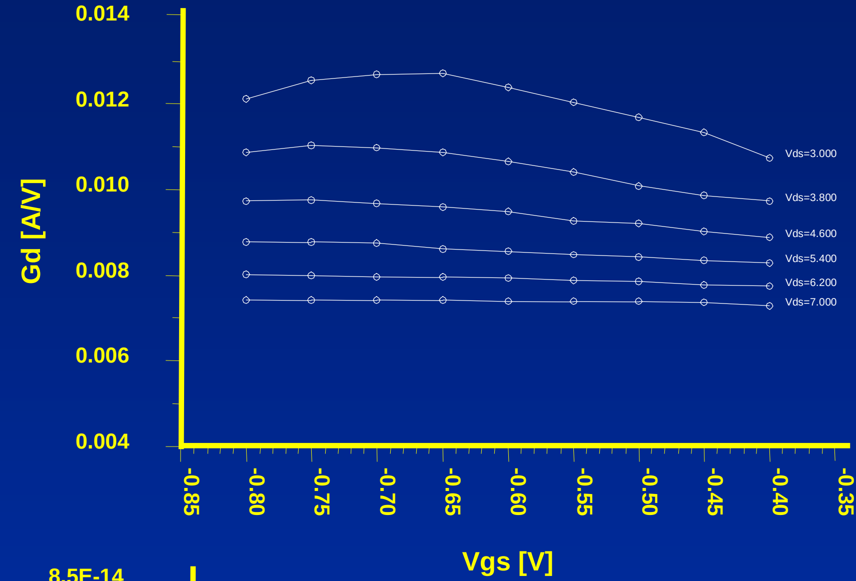
Technology	pHEMT 0.15µm
Size (µm)	8x75
Vdso (V)	5
Idso (mA)	100

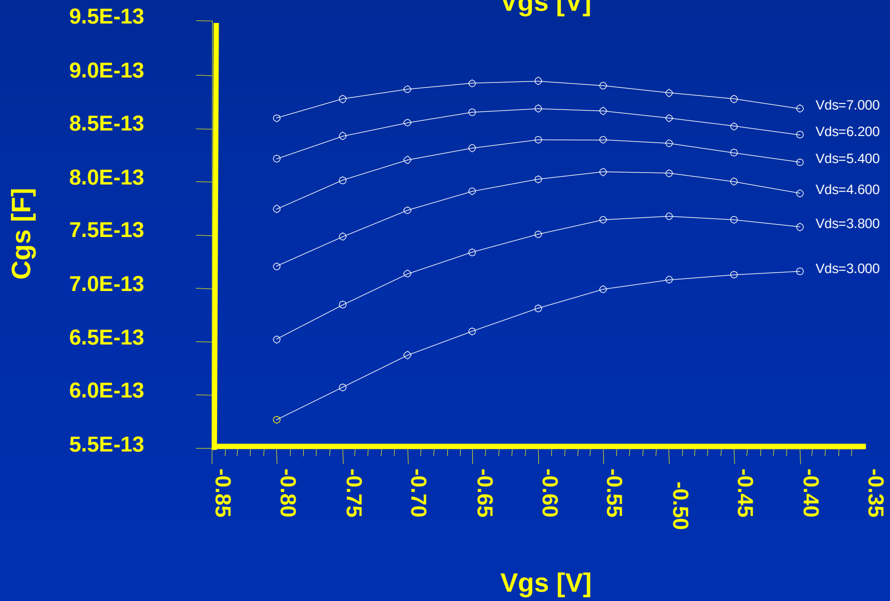
- **Measurement area**

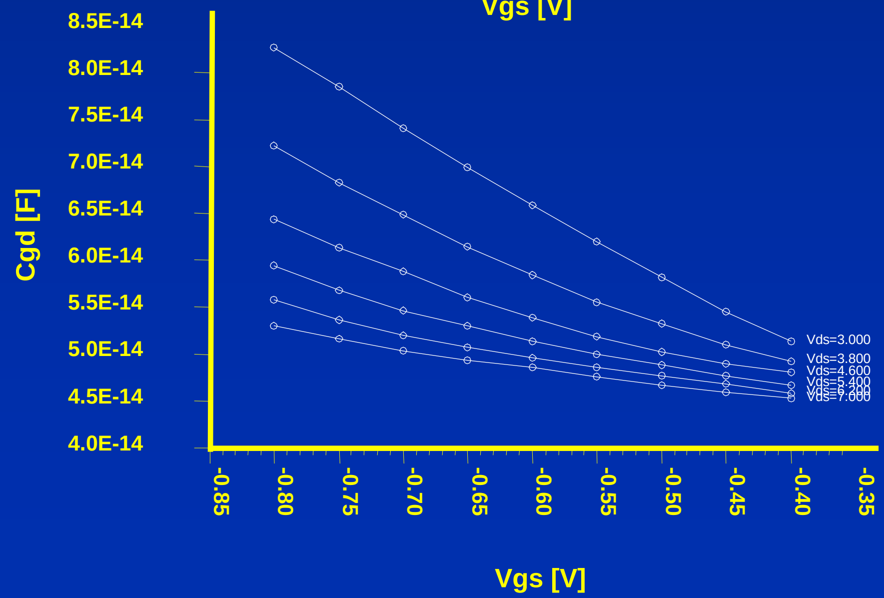
$Vds_{min/max}$ (V)	Vdso ± 2V
Vds step (V)	0.2
$Vgs_{min/max}$ (V)	Vgso ± 0.2V
Vgs step (V)	0.05

Results of NLDE extraction









Phenomenological fitting functions

- **<u>Consistent</u> current source modeling**
  - **Ids(Vgs,Vds) function**

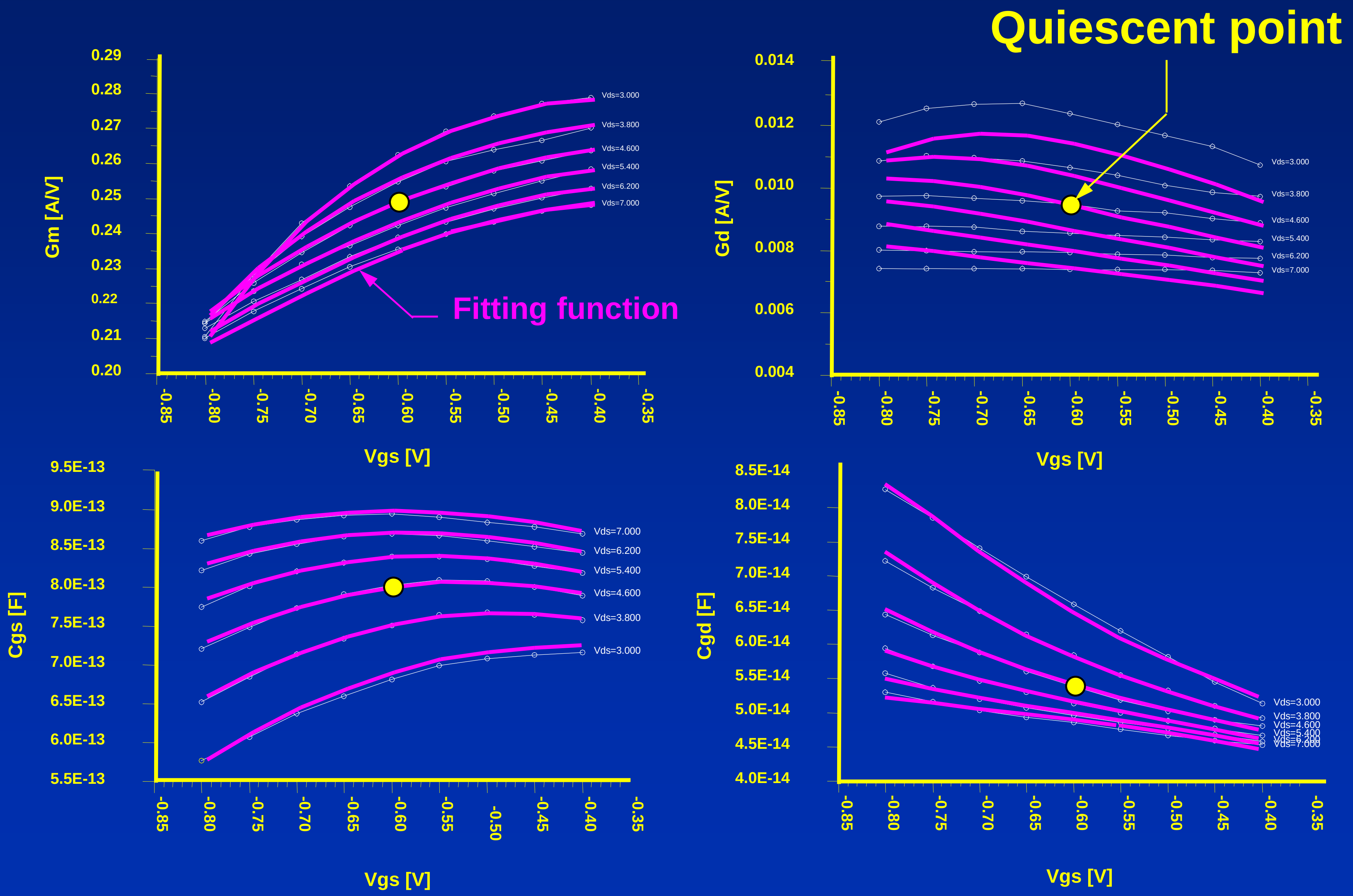
$$IDS(Vgs,Vds) = IDS_0 \cdot \left(1 + \tanh\left[Alpha_1 \cdot \left(Vds - FX_1(Vgs)\right)\right]\right) \cdot \left(1 + \tanh\left[C_1 \cdot \left(Vgs - FY_1(Vds)\right)\right]\right) \cdot \left(1 + A_1 \cdot Vds\right) \cdot \tanh\left[B_1 \cdot Vds\right]$$

  - **Gm and Gd functions**
    - **Derived from Ids(Vgs,Vds) function**
    - **<u>Same parameter set</u> for Ids, Gm, Gd**

- **2D nonlinear capacitance modeling : Cgs, Cgd**

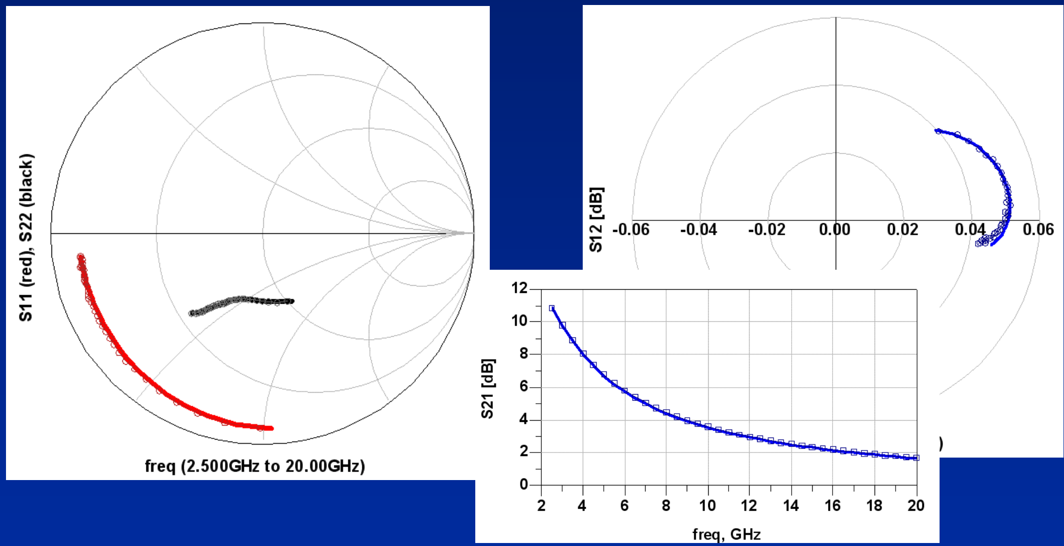
$$CG_X(Vgs,Vds) = CG_{X0} \cdot \left(1 + \tanh\left[Alpha_X \cdot \left(Vds - FX_X(Vgs)\right)\right]\right) \cdot \left(1 + \tanh\left[C_X \cdot \left(Vgs - FY_X(Vds)\right)\right]\right) \cdot \left(1 + A_X \cdot Vds\right) \cdot \tanh\left[B_X \cdot Vds\right]$$

NLDE fitting results

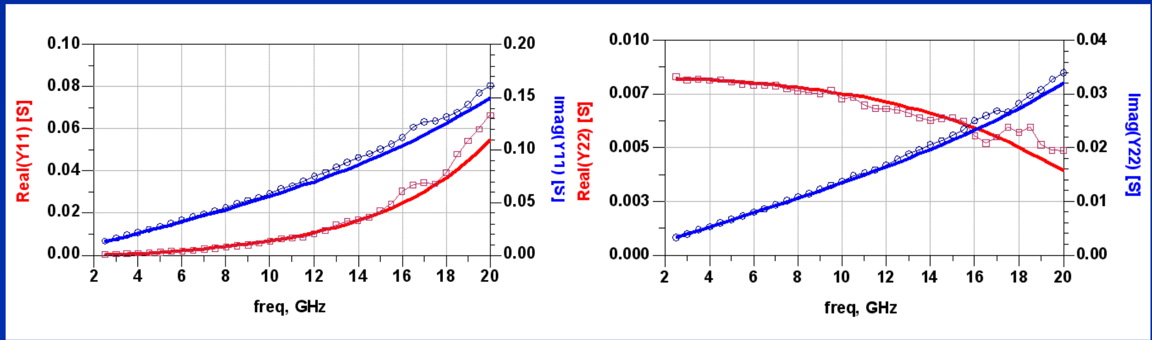


S + Y parameters at quiescent point

S parameters



Y parameters



2 tones load-pull measurements

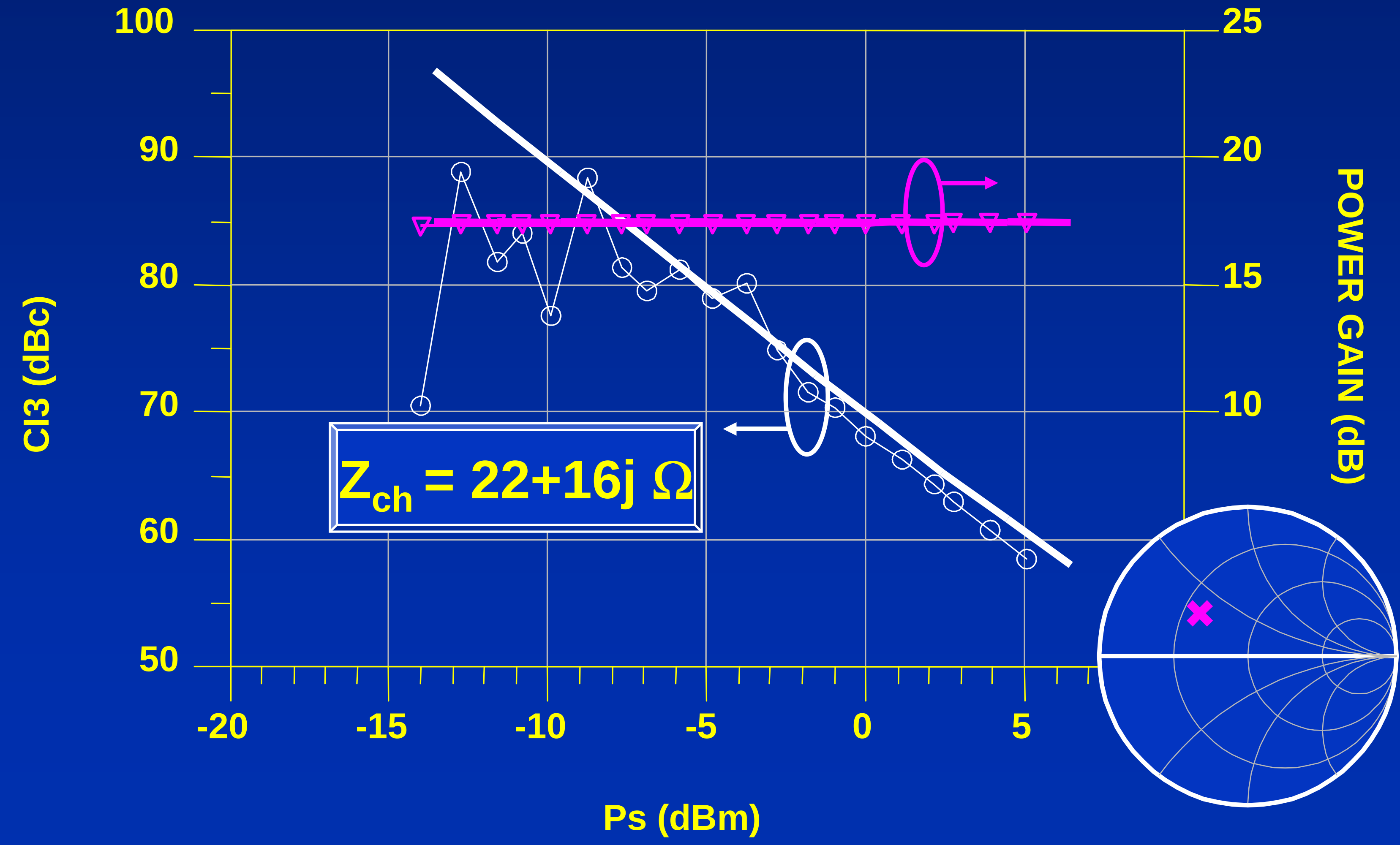
- **Xlim institute test bench**
  - Center frequency, f_c : 10 GHz
  - Frequency difference, dF : 10 MHz

  - 2 tones test bench tuned for very low intermodulation distortions measurements

IM_3 prediction accuracy

- **2 tones LP Measurements VS. Simulations**

(fc = 10GHz, df = 10MHz)



IM_3 prediction accuracy

- 2 tones LP Measurements VS. Simulations

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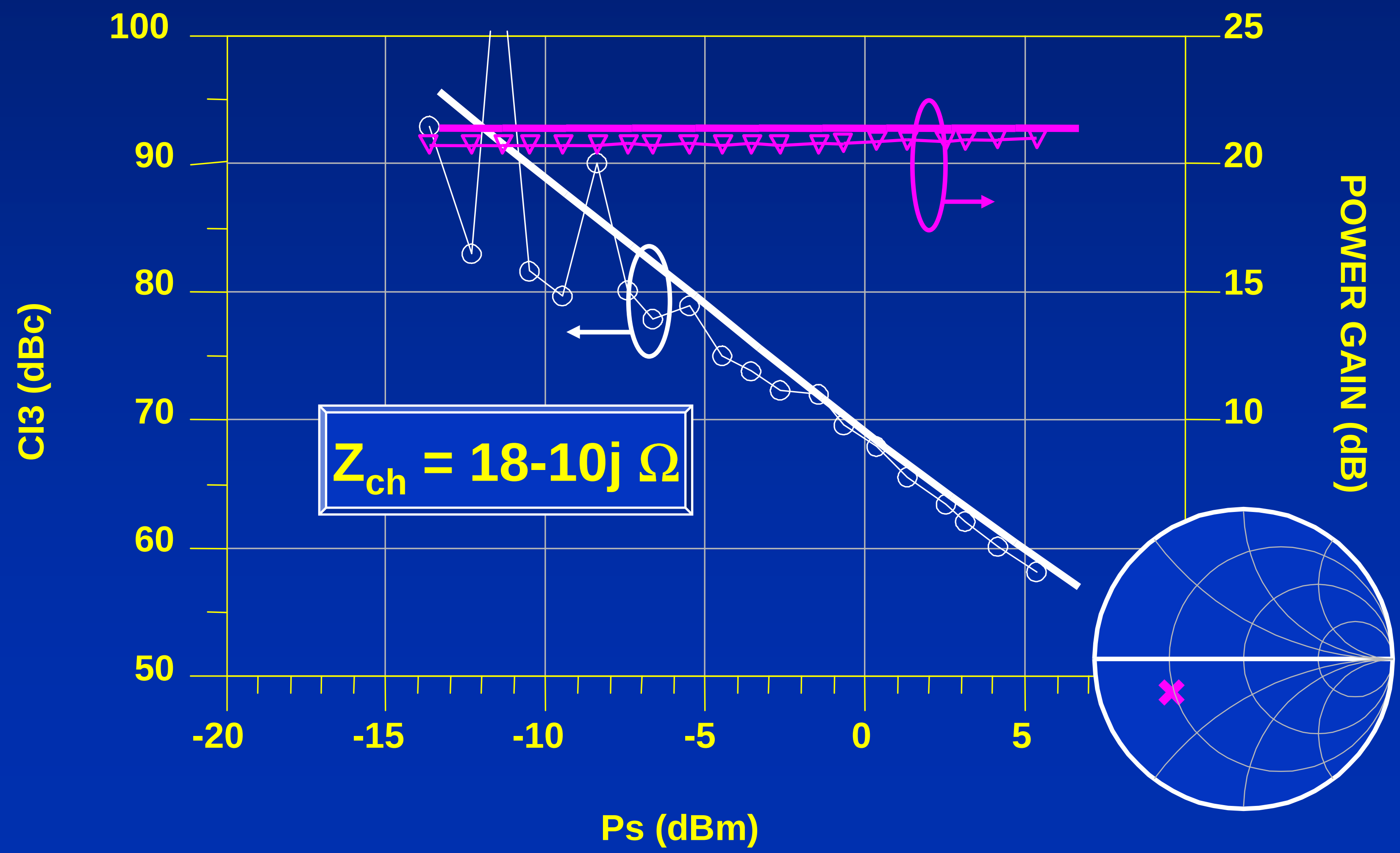

IM_3 prediction accuracy

- **2 tones LP Measurements VS. Simulations**

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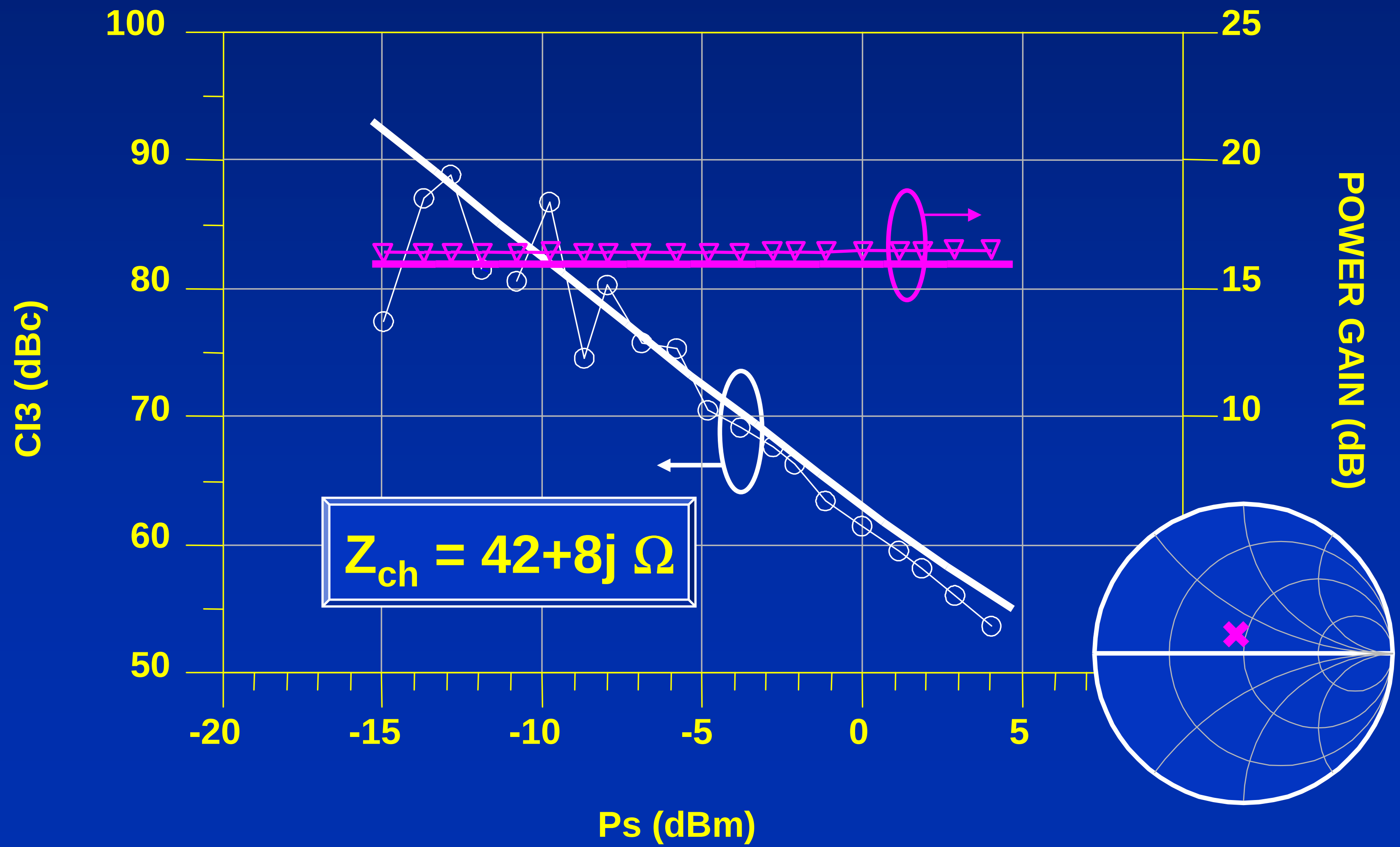

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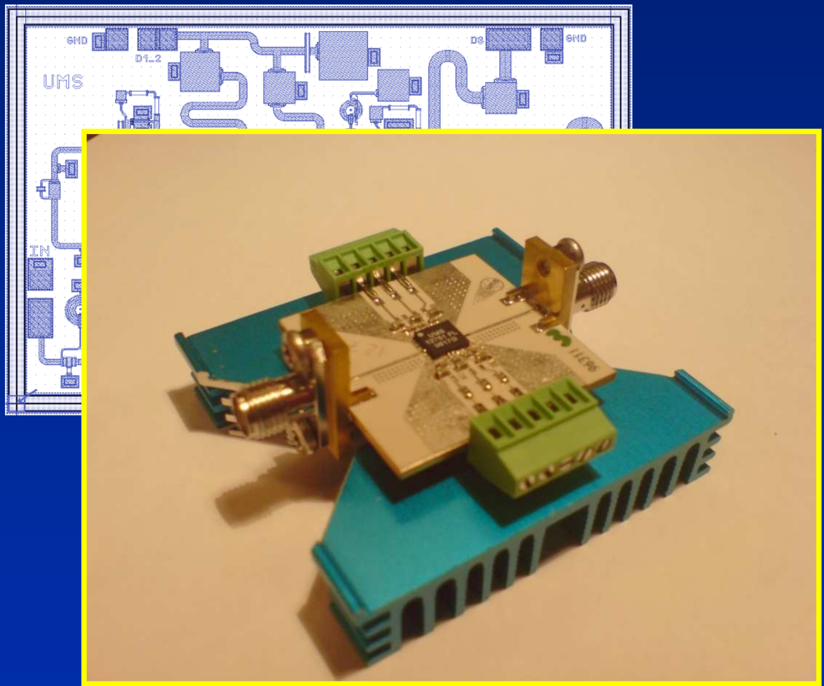
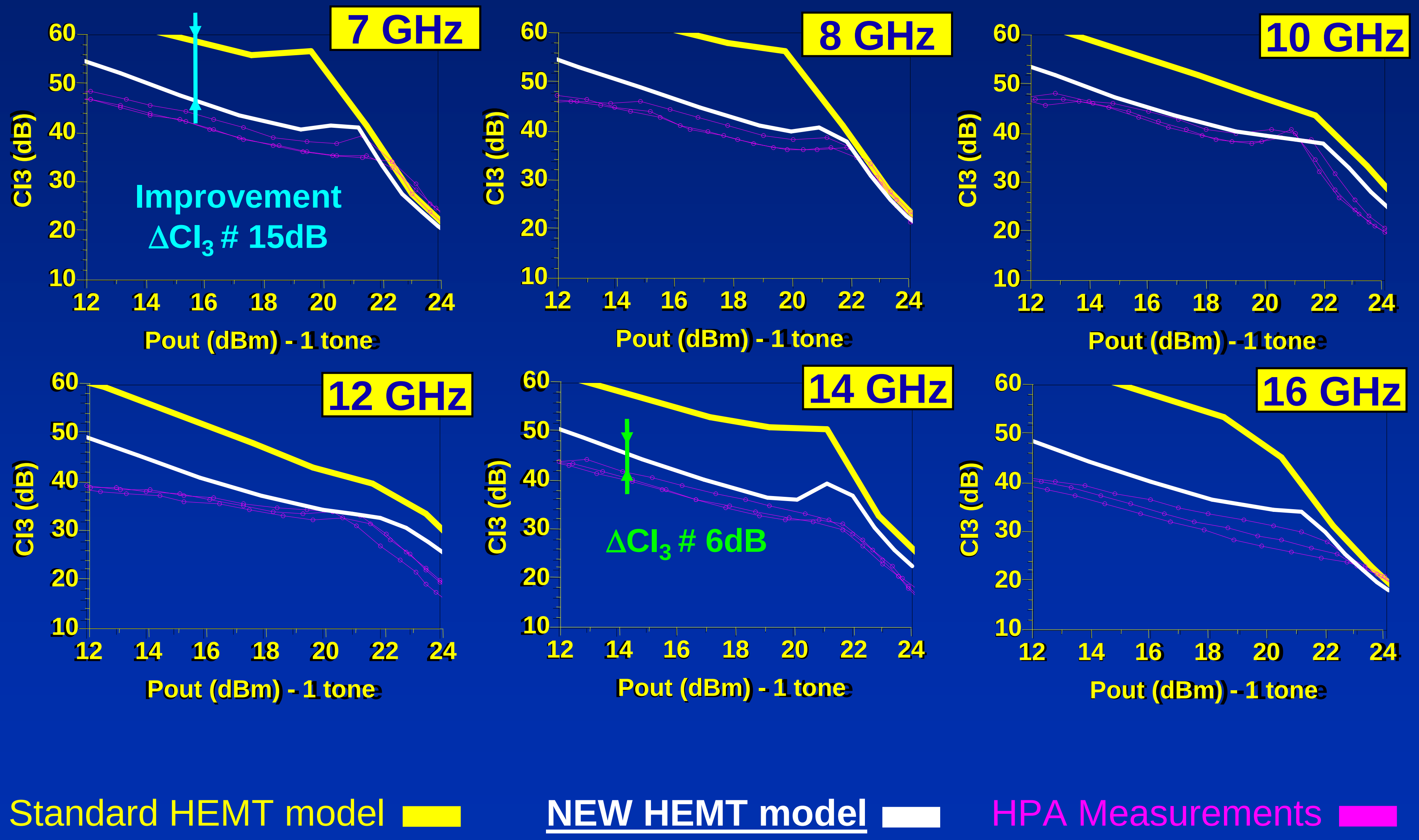
3 stages ***high power amplifier*** ***(7-16 GHz)***



Performances

Symbol	Typ	Units
Fop	7-16	GHz
Gp	21	dB
P1dB	29	dBm
Ids	700	mA
IP3	37	dBm

HPA : Measurements vs. Simulations



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Conclusion

- **Accurate IMD_3 modeling method has been developped**
- **Method based on :**
  - Accurate device characterization (pulsed IV + pulsed [S])
    - As close as possible to the device operating conditions
  - Development of dedicated phenomenological functions
    - Accurate fitting of both **local** and **global** shapes of each non-linear differential element
- **Modeling method validation : HPA design**
  - Accurate CI_3 prediction in a **3 stages** HPA (7-16GHz)

THANK YOU