

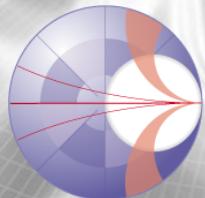
Behavioral models of power RF GaN Transistors

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Agenda

- EPHD description
 - Types of large Signal transistors model
 - Motivation
 - Theory
- EPHD model packaged transistors example
- Benchmarking X-parameter vs EPHD
- Measurement bench & Methodology



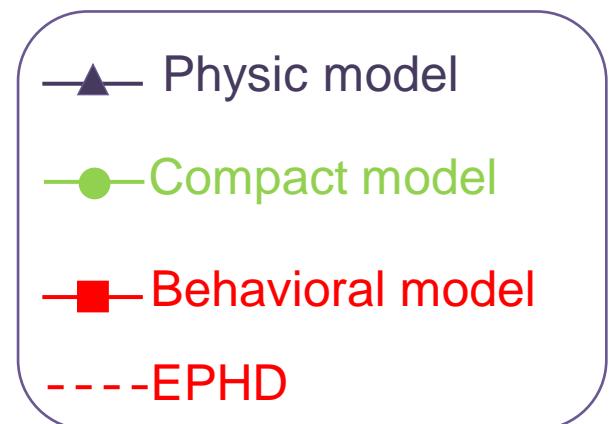
EPHD description

EPHD model packaged transistors

Benchmarking

Measurement Bench & Methodology

Types of Large-Signal Transistor Models



Extrapolation Accuracy

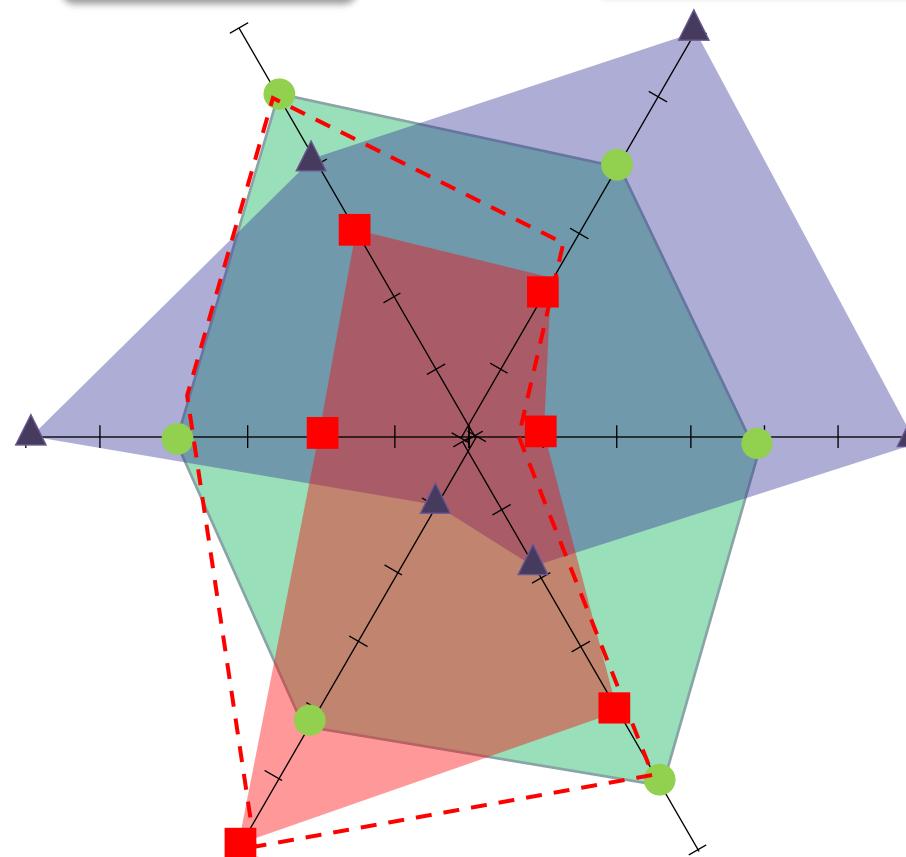
Convergence

Operating Range

Physical Insight

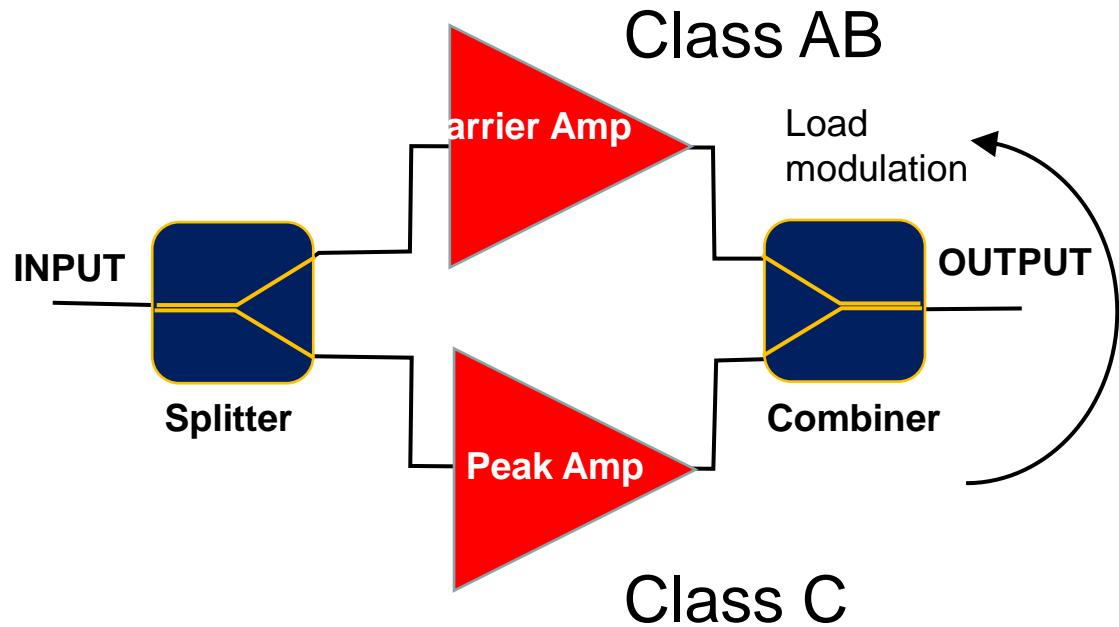
Easy modelling process

Usability for Circuit Design



Motivation

Hybrid Doherty Amplifier Design using a packaged device



Load Pull measurement only ?

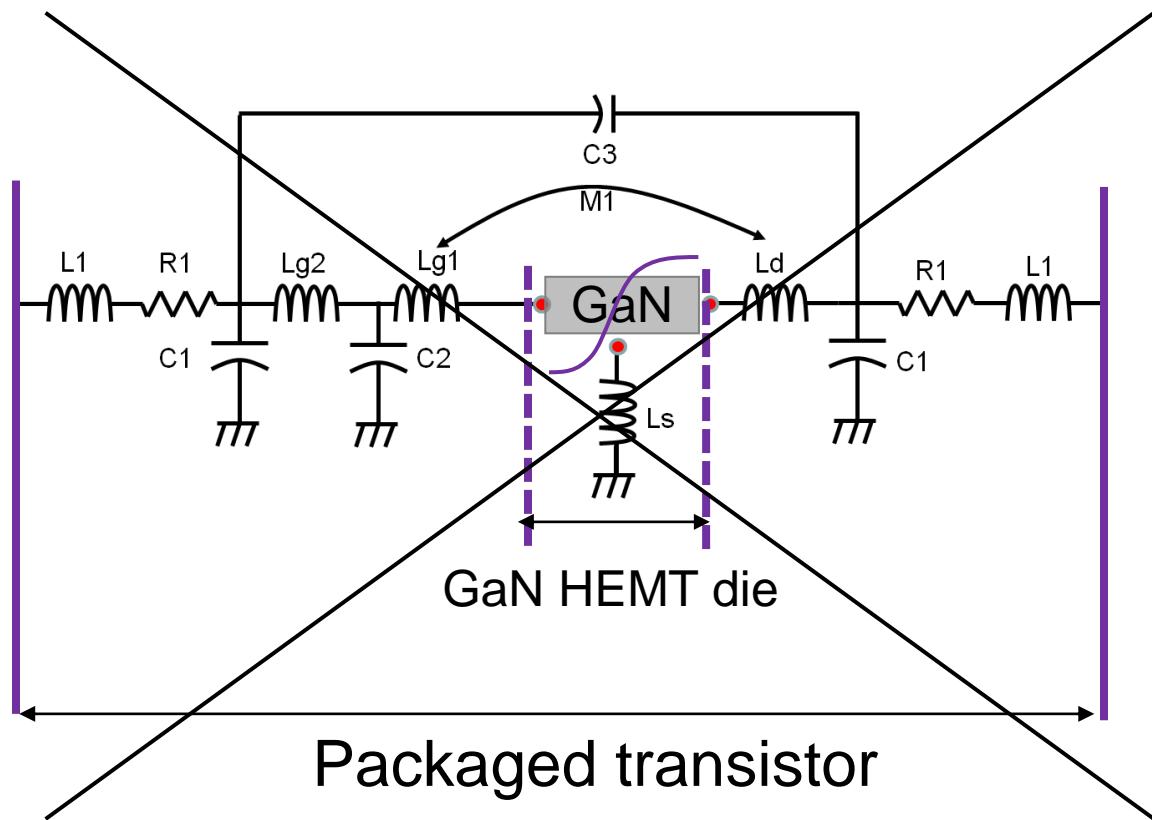
- No : Load Modulation

Transistor model requirement:

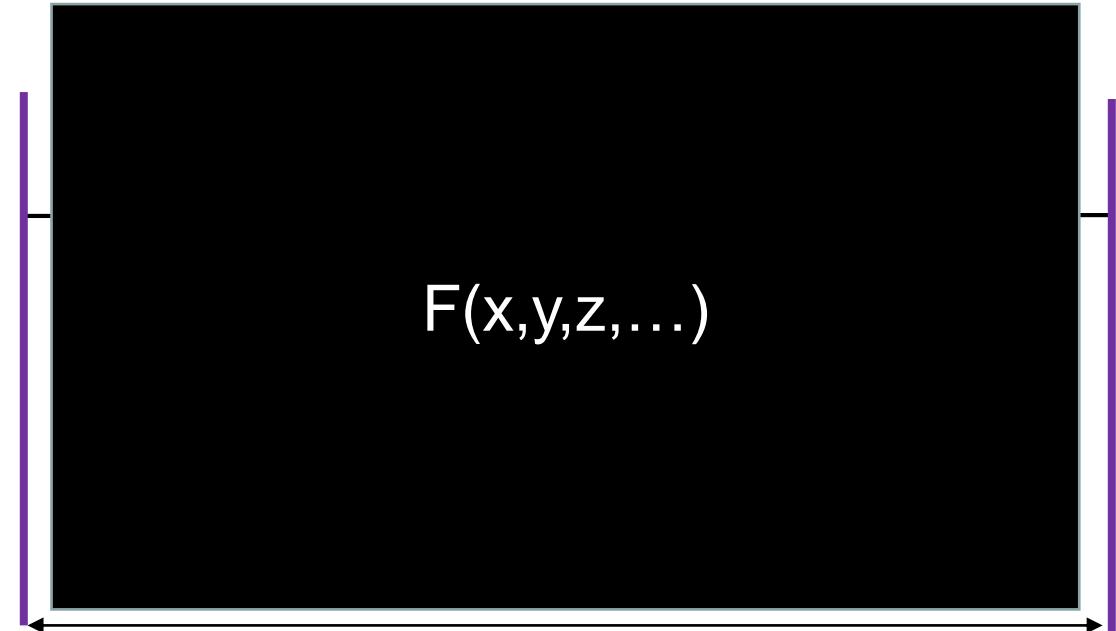
- Accuracy over a wide dynamic range
- Accuracy over different load conditions
- For different class of operating conditions

Compact Model

Black Box Model

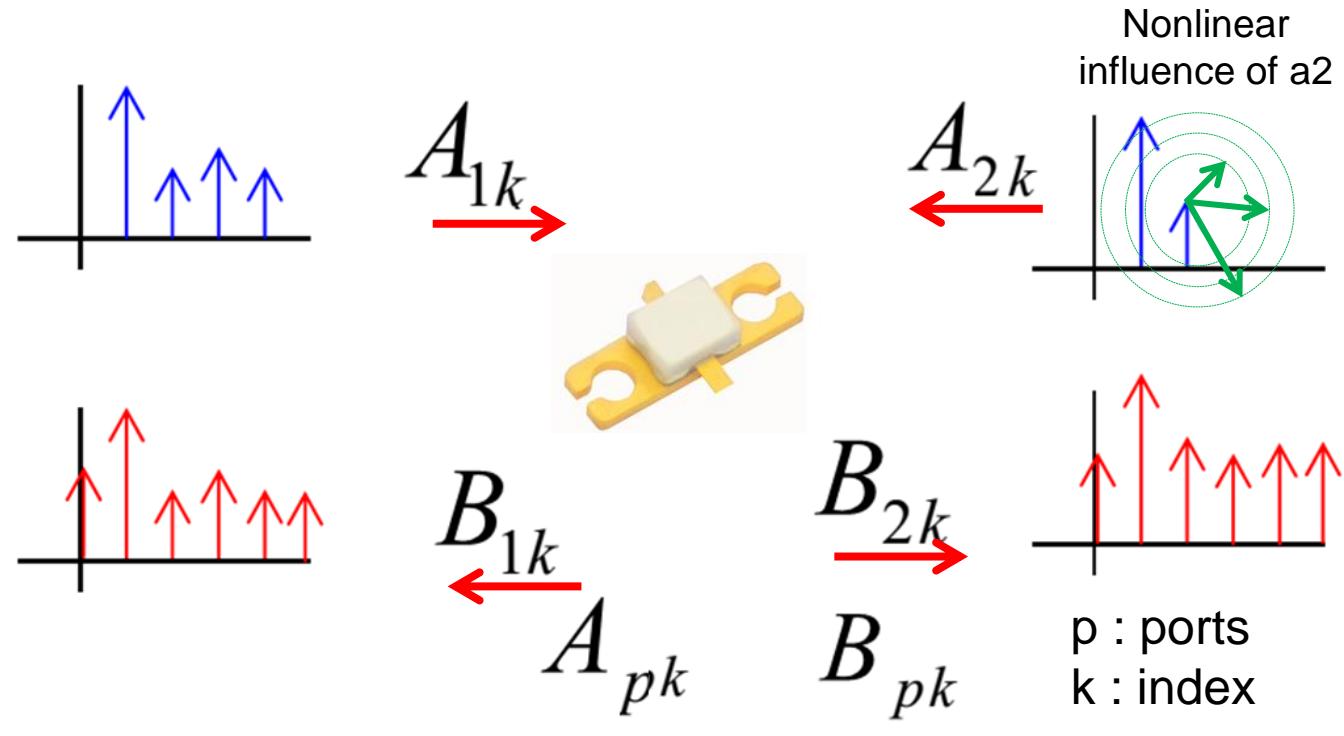


All package elements are finally fitted
by comparison between
measured and simulation



Set of equations

Enhanced Polyharmonic Distortion model



Harmonic superposition 3rd order expansion !

- The model is extended to the third order
- $B_i(t)$ is the Σ of f_0 and harmonic modulated tones
- The main nonlinearities are driven by the incident power wave @ f_0 at the input port

Order 1

Order 2

Order 3

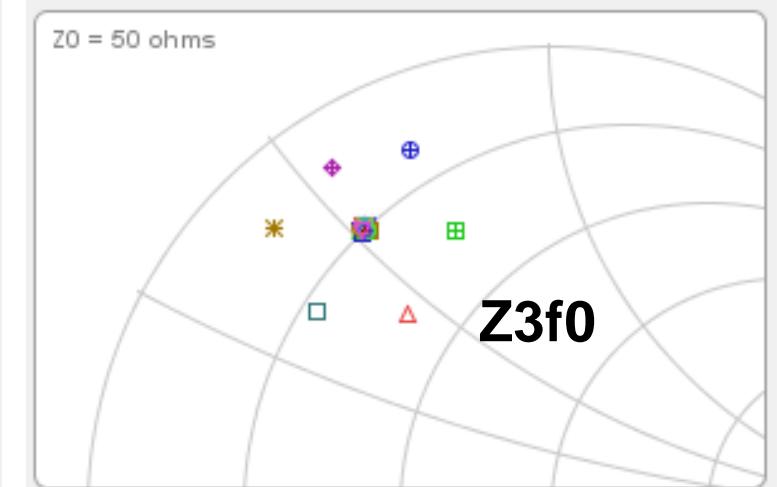
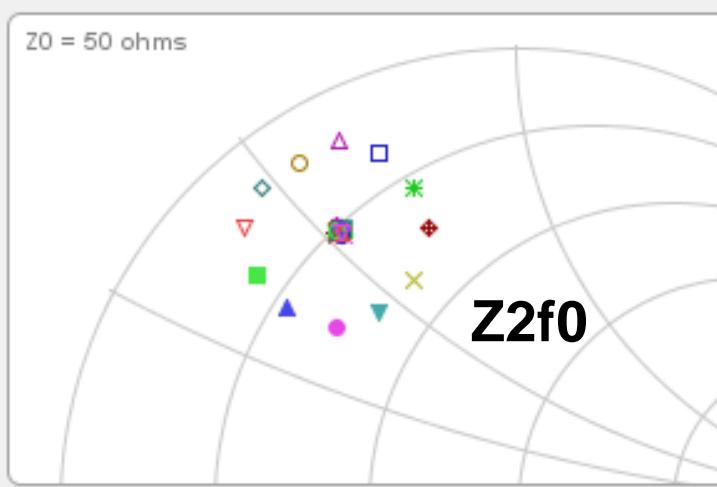
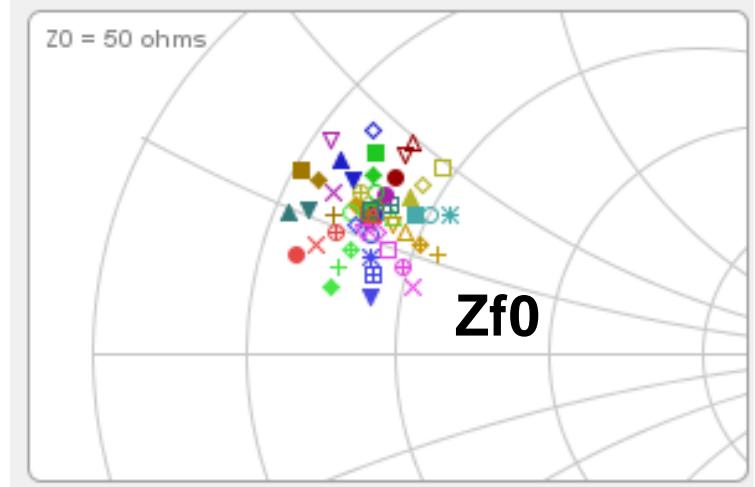
$$\widetilde{b_{ik}(t)} = S_{ik,11,1}(|\widetilde{a_{11}(t)}|)\widetilde{a_{11}(t)} + S_{ik,21,1}(|\widetilde{a_{11}(t)}|)\widetilde{a_{21}(t)} + T_{ik,21,1}(|\widetilde{a_{11}(t)}|)p^{k+1}\widetilde{a_{21}(t)}^*$$

$$+ S_{ik,21,2}(|\widetilde{a_{11}(t)}|)p^{-1}\widetilde{a_{21}(t)}^2 + T_{ik,21,2}(|\widetilde{a_{11}(t)}|)P \widetilde{a_{21}(t)} \widetilde{a_{21}^*(t)} + U_{ik,21,2}(|\widetilde{a_{11}(t)}|)p^3\widetilde{a^{21}(t)}^2$$

$$+ S_{ik,21,3}(|\widetilde{a_{11}(t)}|)p^{-2}\widetilde{a_{21}(t)}^3 + T_{ik,21,3}(|\widetilde{a_{11}(t)}|) \widetilde{a_{21}(t)}^2 \widetilde{a_{21}^*(t)} + U_{ik,21,3}(|\widetilde{a_{11}(t)}|)p^2\widetilde{a_{21}^*(t)} \widetilde{a^{21}(t)}^2 + W_{ik,21,3}(|\widetilde{a_{11}(t)}|)p^4\widetilde{a_{21}(t)}^3$$



Measurement Process for model extraction



For each fundamental frequency, a pattern of load impedances is proposed, as follow :

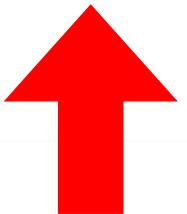
- [49 $Z_{load_{f0}}$] & $[Z_{load_{2f0}} = Z_{ref}]$ & $[Z_{load_{3f0}} = Z_{ref}]$
- $[Z_{load_{f0}} = Z_{ref}]$ & [7 $Z_{load_{2f0}}$] & $[Z_{load_{3f0}} = Z_{ref}]$
- $[Z_{load_{f0}} = Z_{ref}]$ & $[Z_{load_{2f0}} = Z_{ref}]$ & [7 $Z_{load_{3f0}}$]



Behavioural models of power RF GaN Transistors

EPHD

- Higher order of nonlinearity



Measurement extraction speed

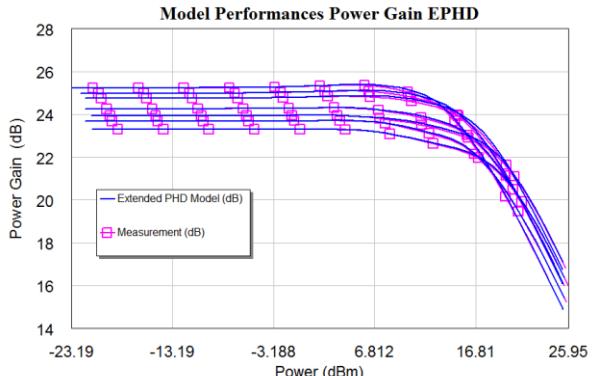
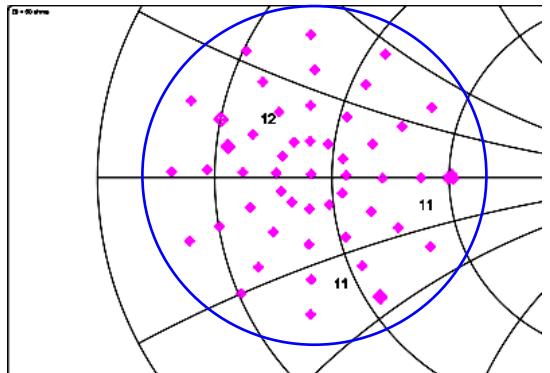
PHD

Measurement can be time consuming

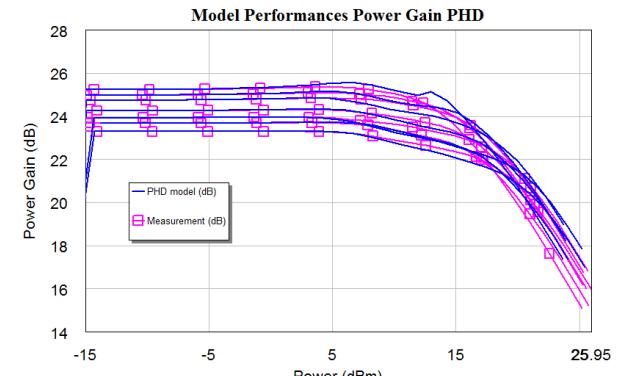
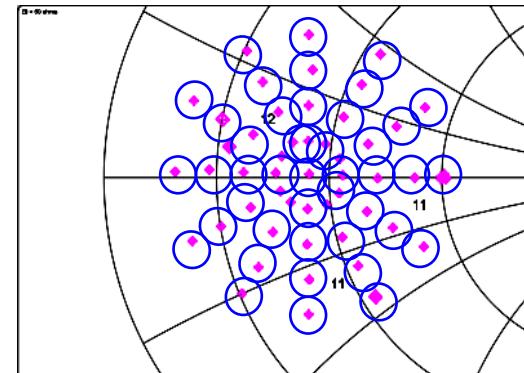
Model Validity

○ Area of Model Validity

- More robust for interpolation and extrapolation



- Interpolation linked to the density of the grid
- Juxtaposition of several models



EPHD description

Benchmarking

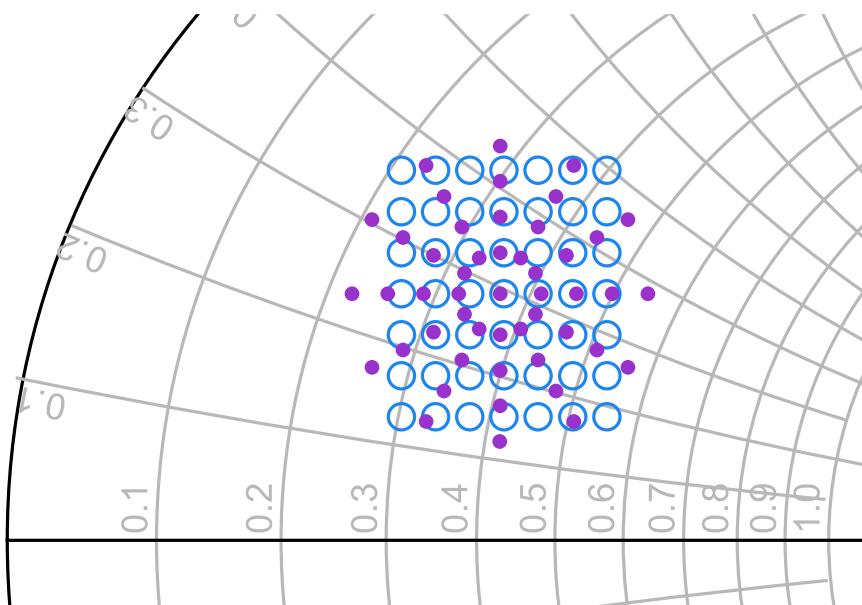
EPHD model packaged transistors

Measurement Bench & Methodology

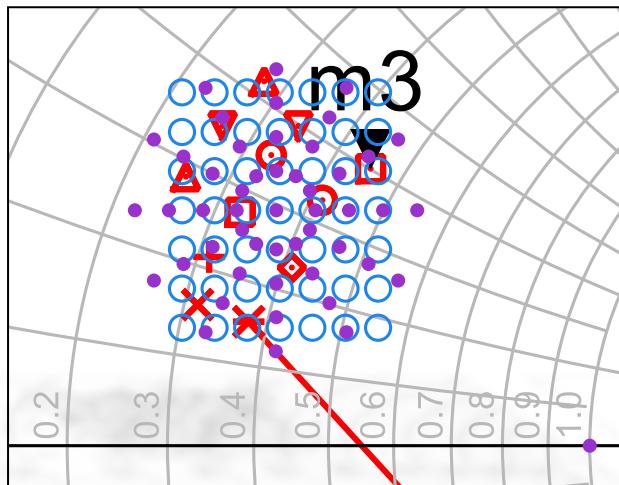


Impedance configuration

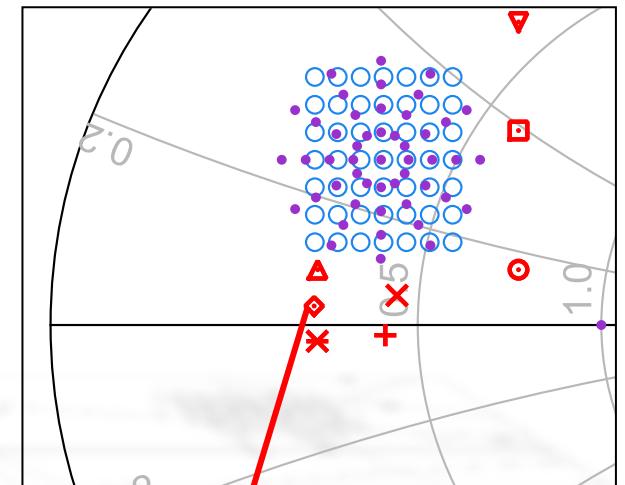
- Reference : Compact Model CREE CGH40
- Model extraction with similar points density(≈ 49 impedances @ f_0)
- Same load impedances @ $2f_0$ & $3f_0$



Interpolation capabilities



Extrapolation capabilities

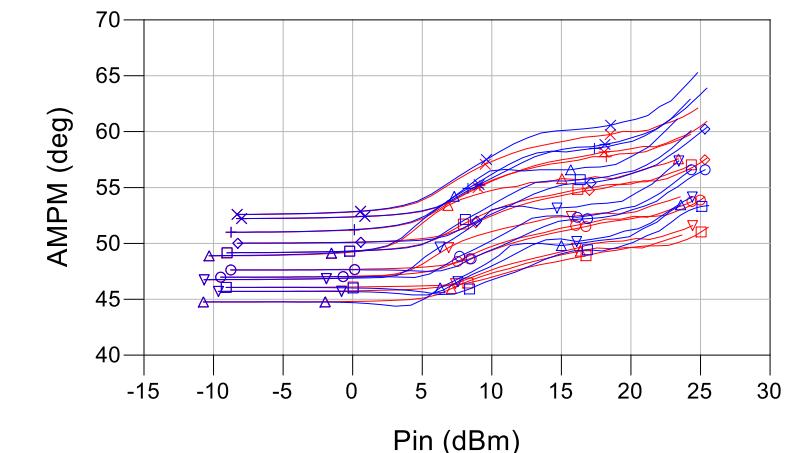
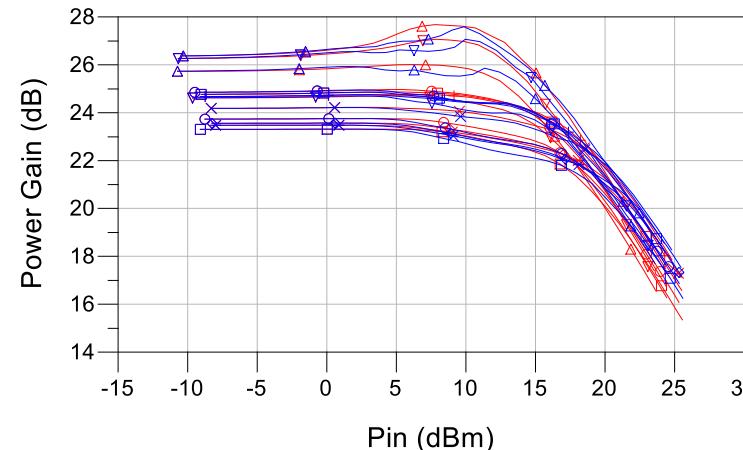
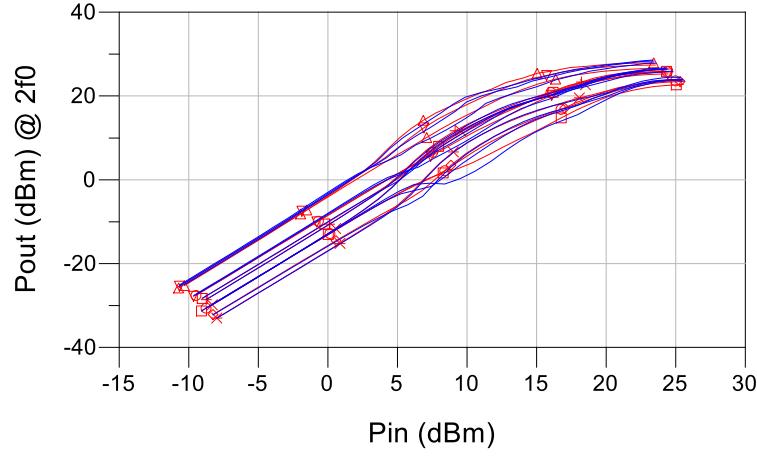
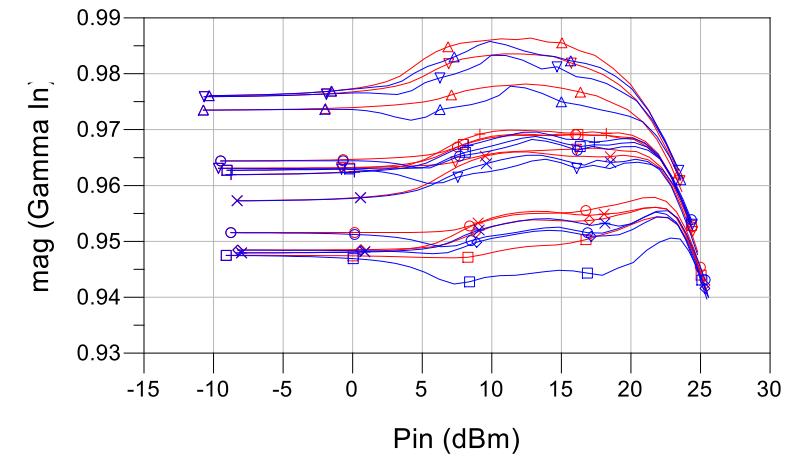
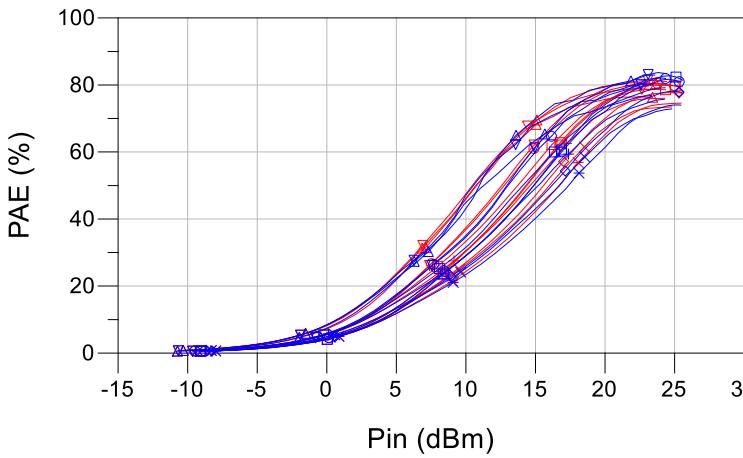
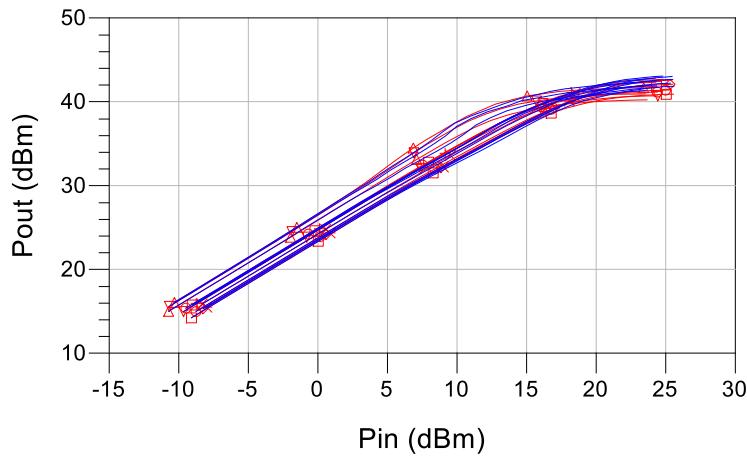


Tests conditions

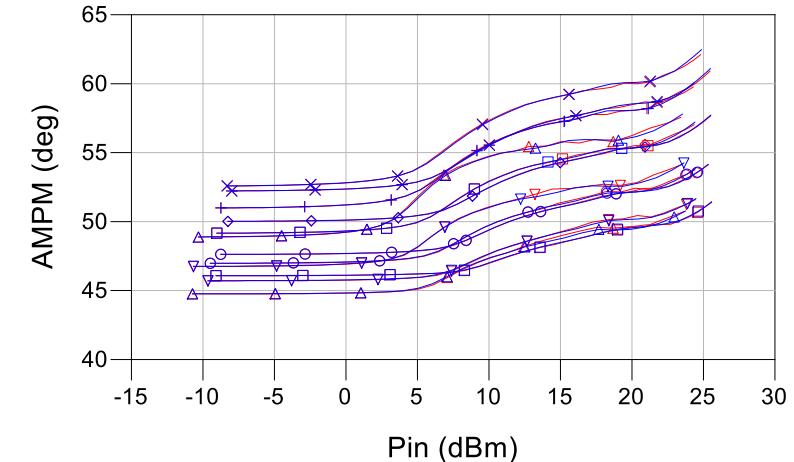
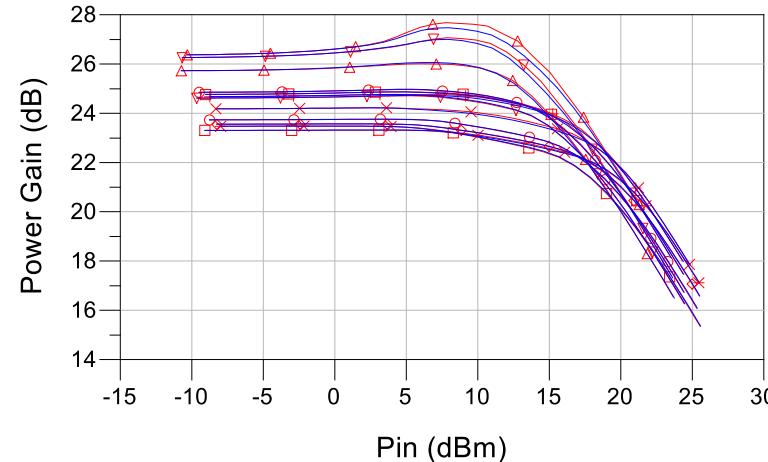
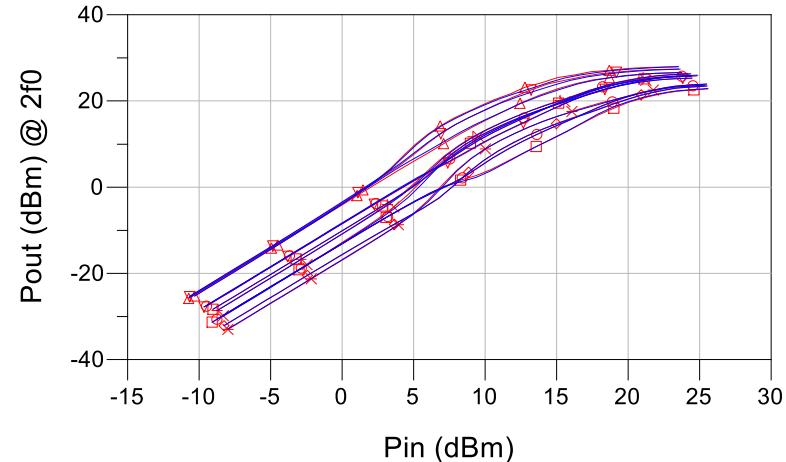
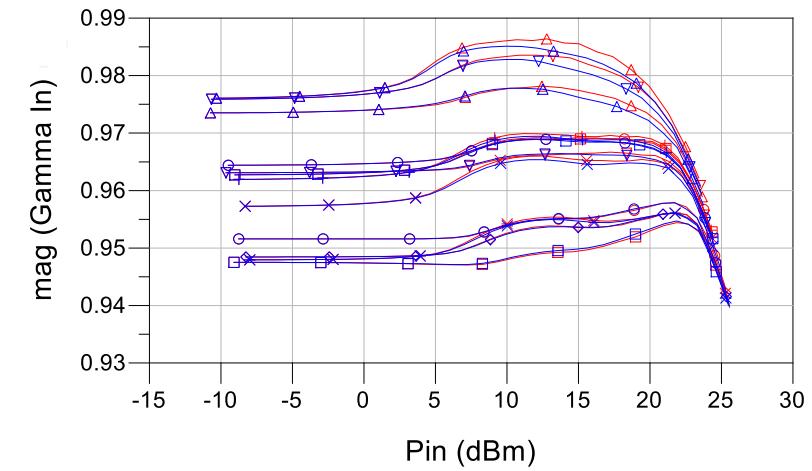
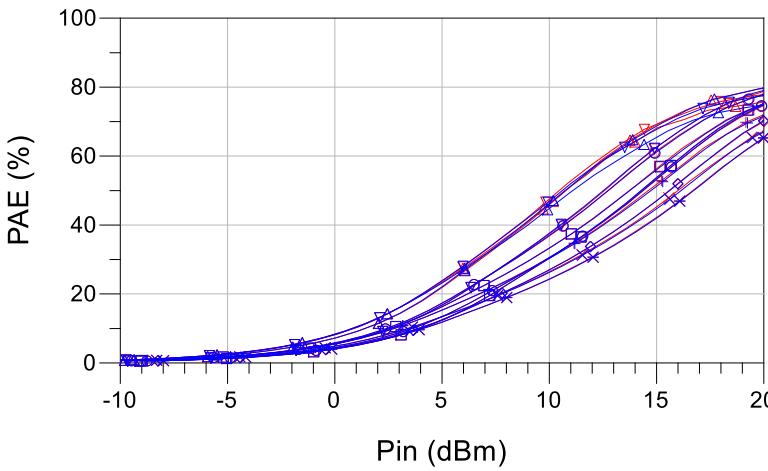
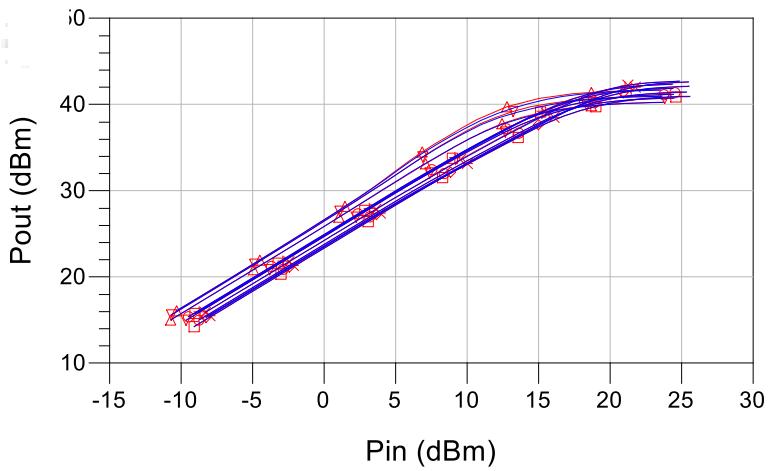
- X-parameters extraction area
- ★ EPHD extraction area

Class AB model : X-parameters

Interpolation

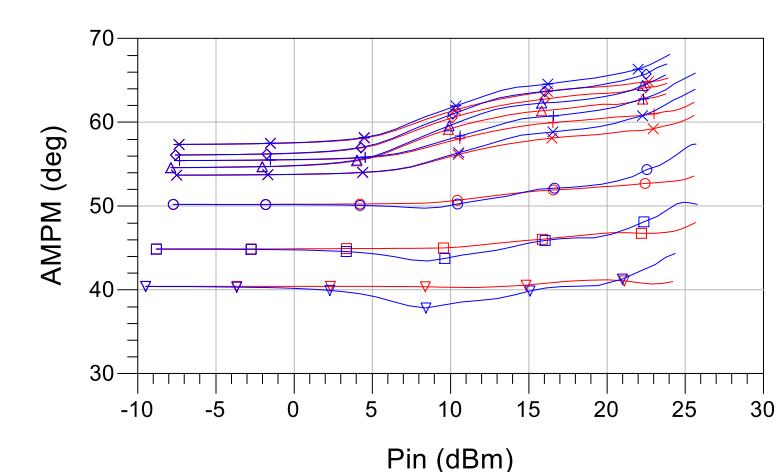
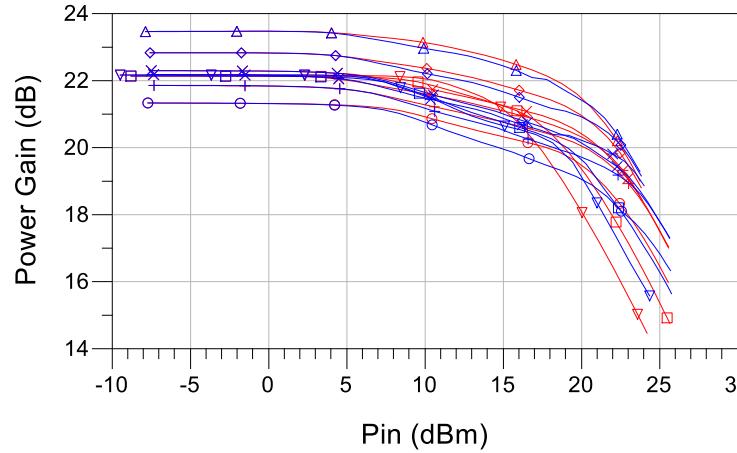
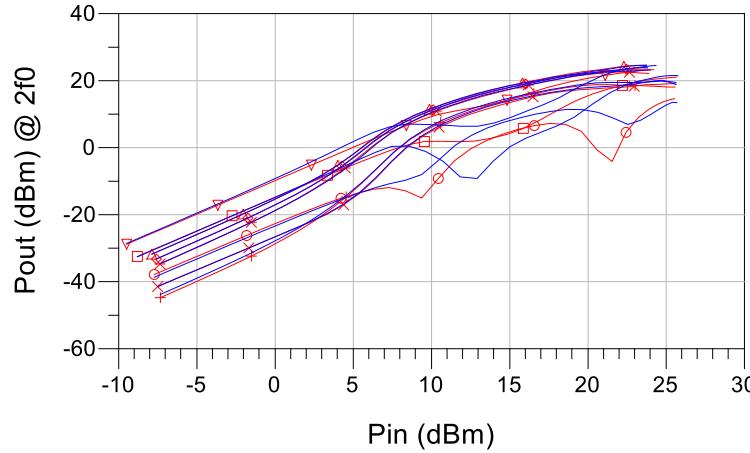
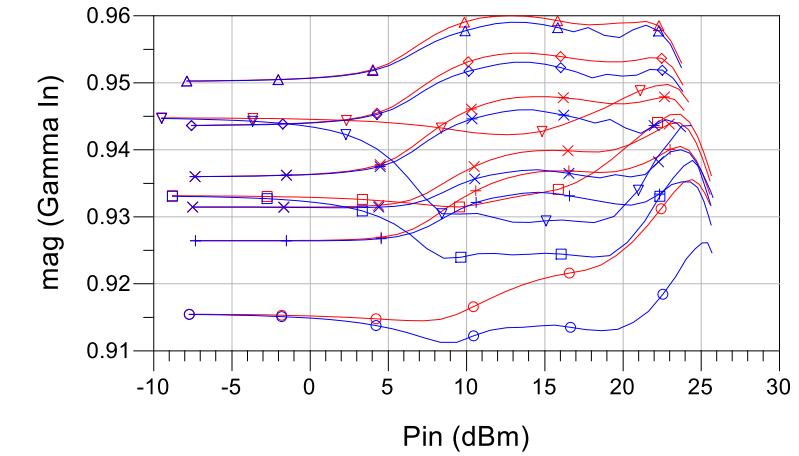
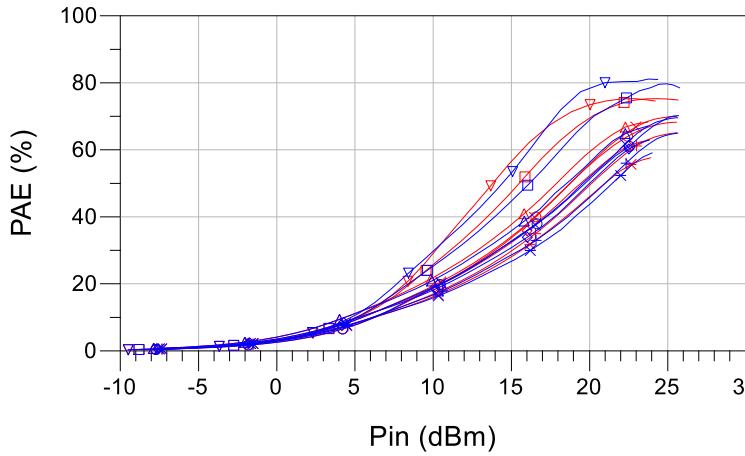
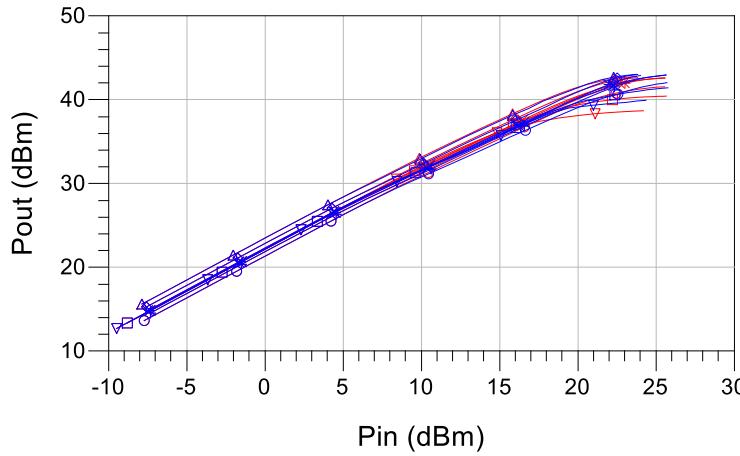


Class AB model : EPHD Interpolation

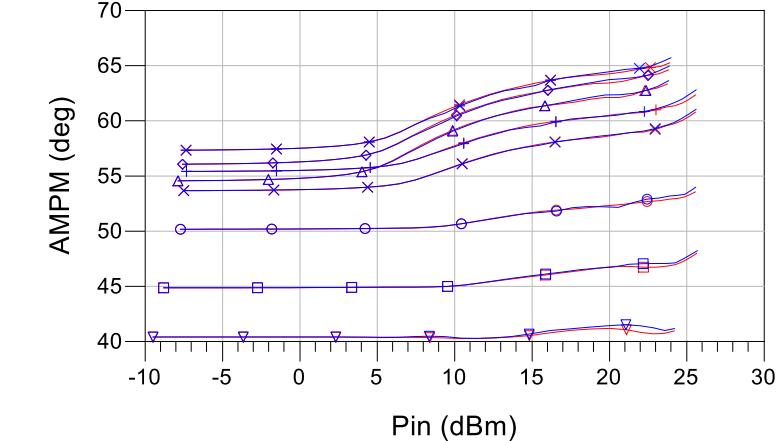
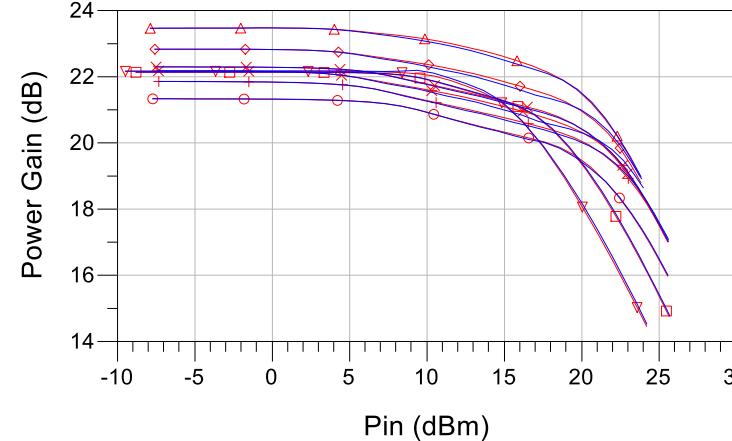
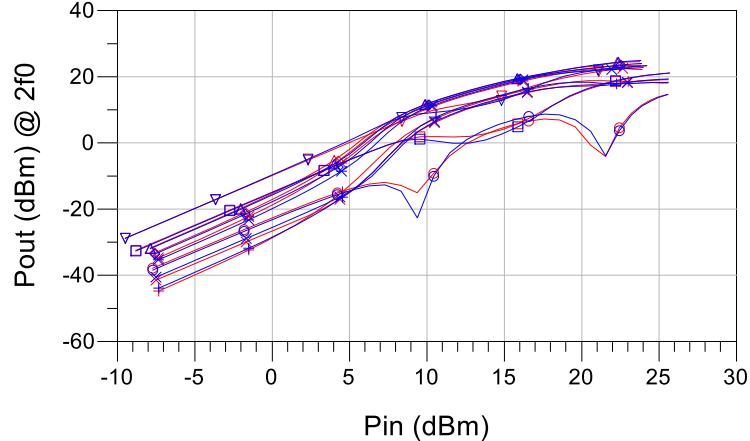
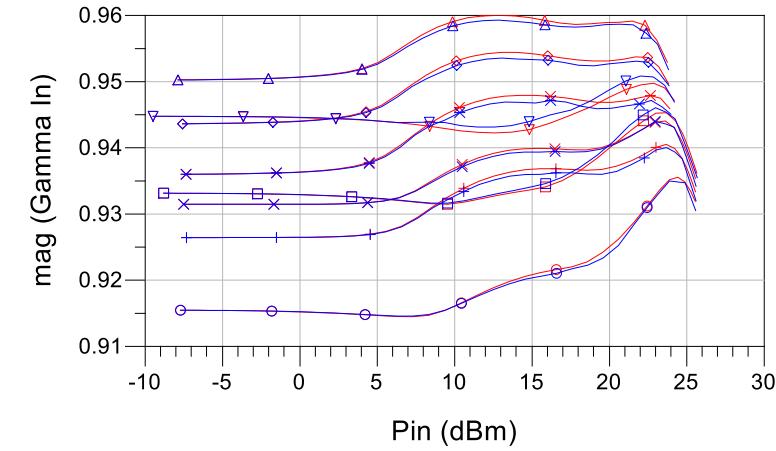
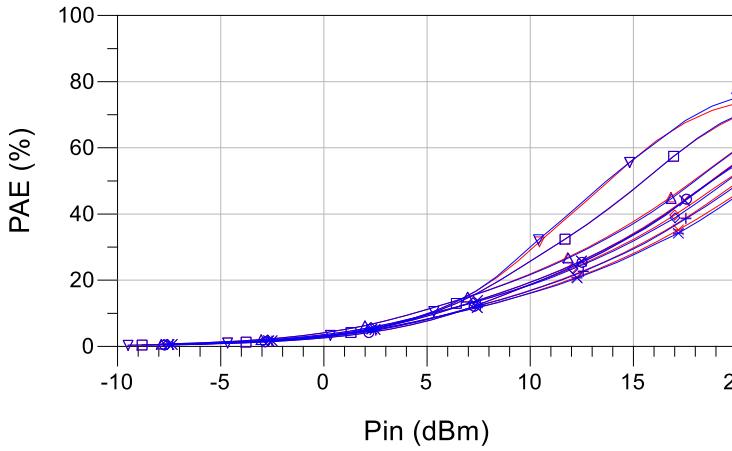
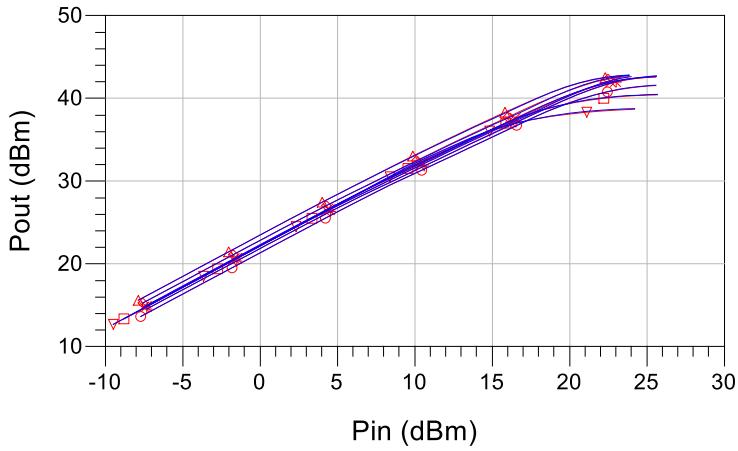


Class AB model : X-parameters

Extrapolation



Class AB model : EPHD Extrapolation





Benchmarking Conclusion

- EPHD ensure more accurate interpolations in areas where the gain & current curvatures have sharp variations
- EPHD predictions are more accurate in load extrapolation conditions due to the higher order of nonlinearity description.
- For low input impedance areas, or negative input impedances, X-parameters formalism does not allow to run a proper model extraction
- Both models allow good simulation convergence
- Extraction time for X-parameters is higher than the extraction time for EPHD (measurements)
- Accurate to simulate harmonic behavior

EPHD description

Benchmarking

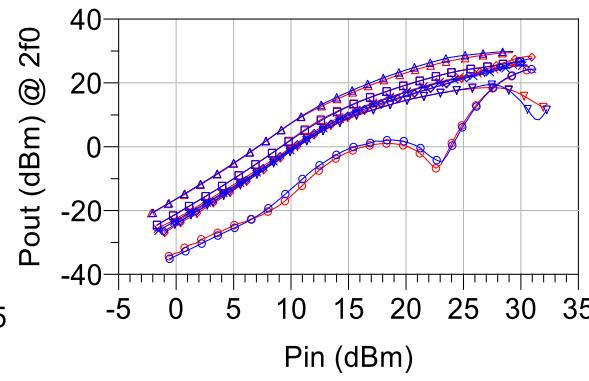
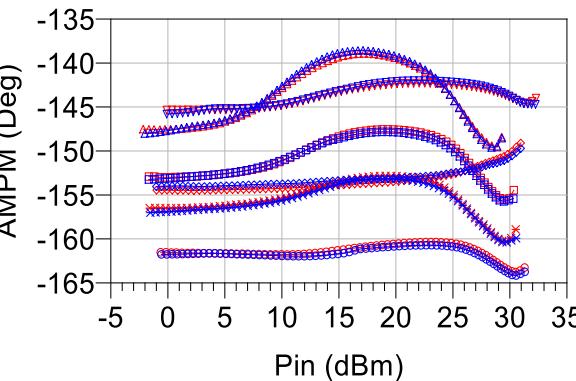
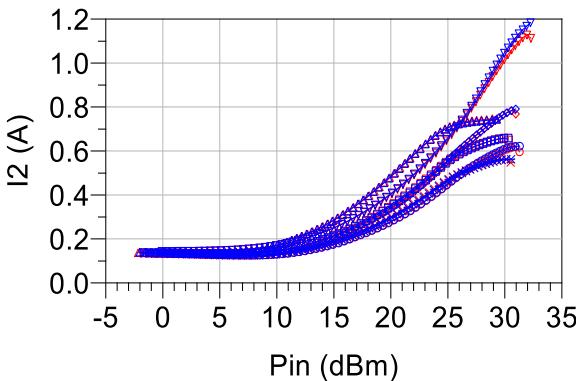
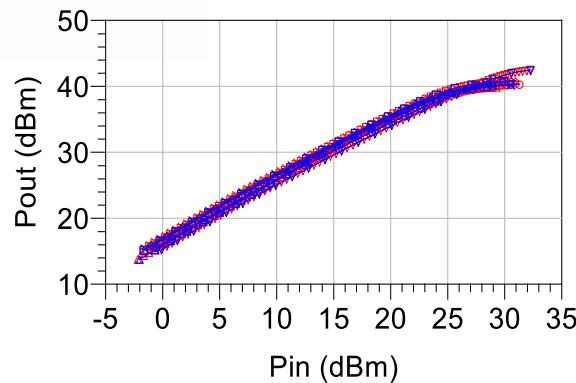
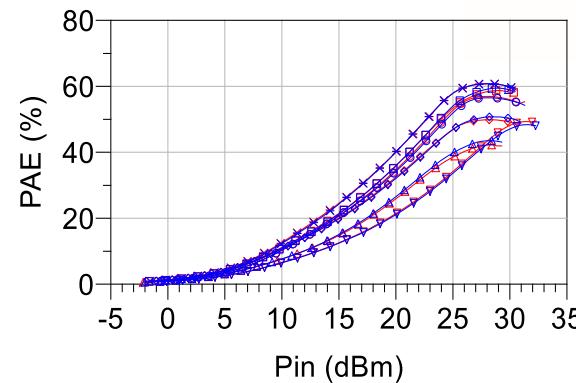
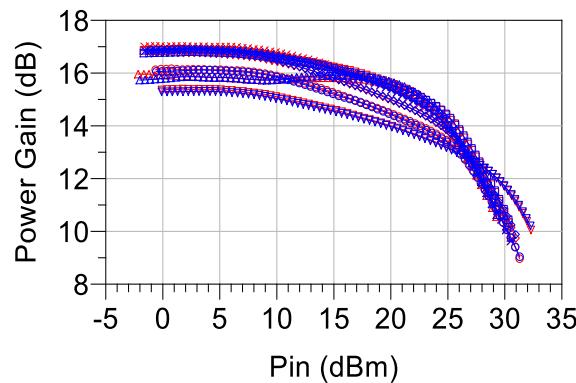
EPHD model packaged transistors

Measurement Bench & Methodology

EPHD: Model vs Measurement

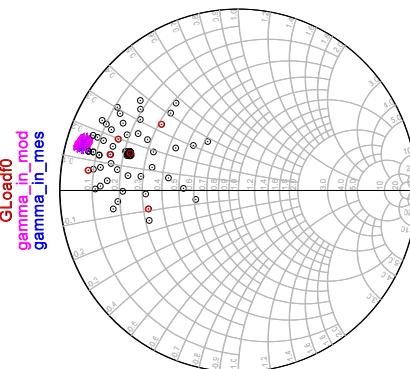
- Class AB model @ 3,7GHz

→ EPHD
 → Measurement



The model is able to reproduce the measurements which have been used for the model extraction

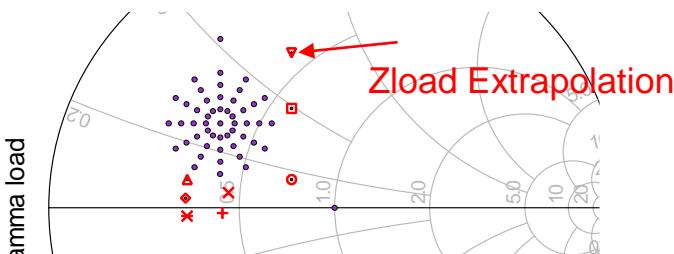
Class AB



EPHD: Model vs Measurement

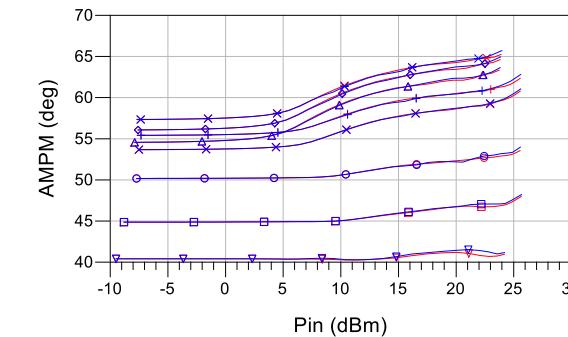
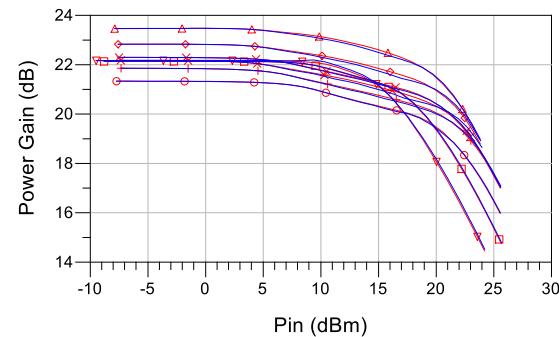
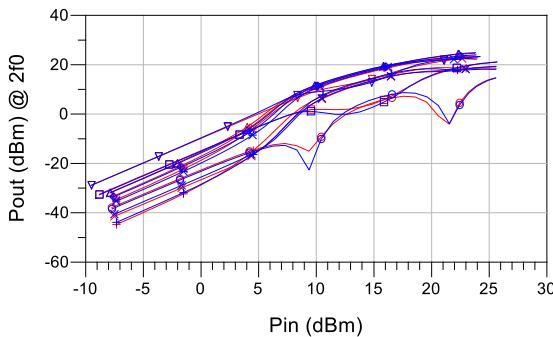
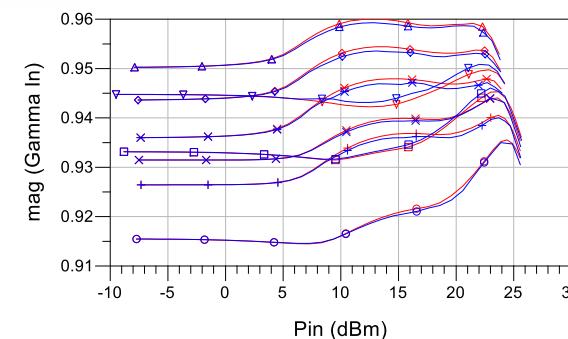
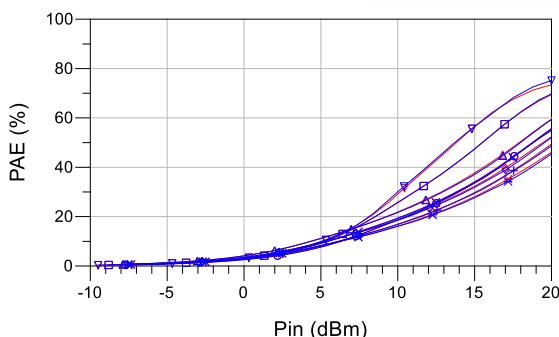
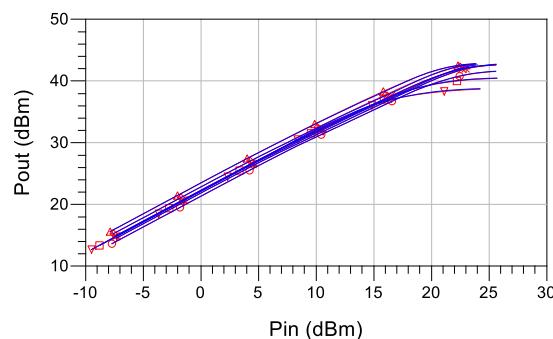
- Class AB model @ 3,7GHz

→ EPHD
→ Measurement



The model is able to reproduce the measurements which have **NOT** been used for the model extraction

Class AB

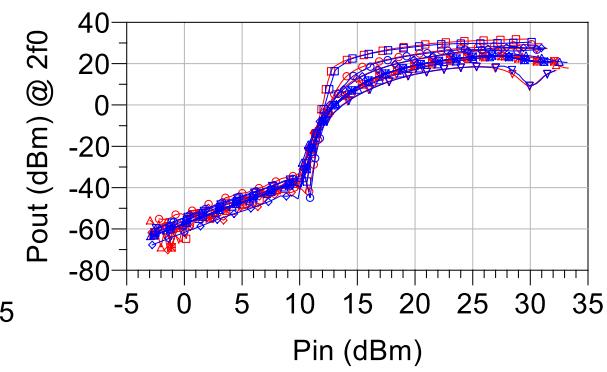
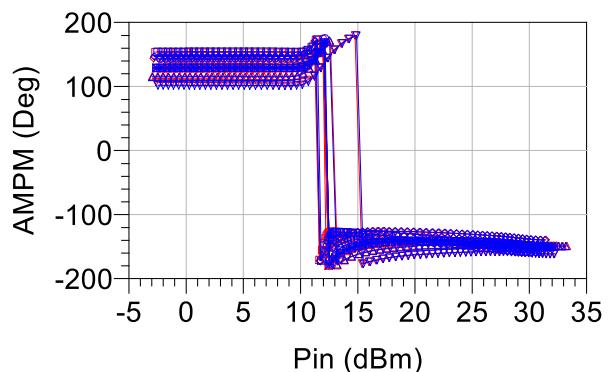
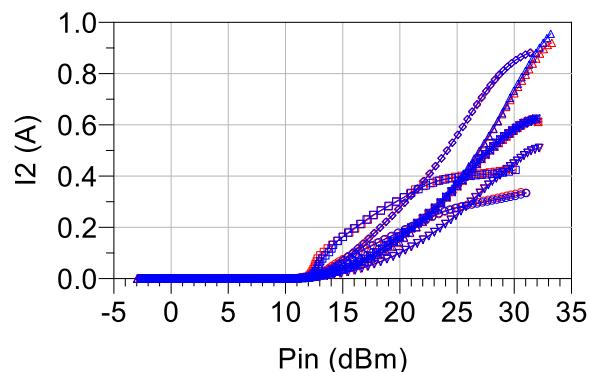
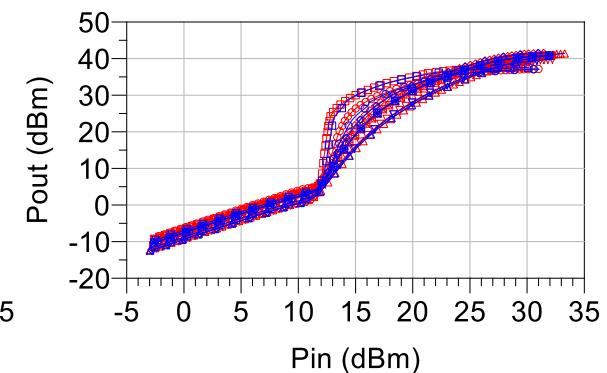
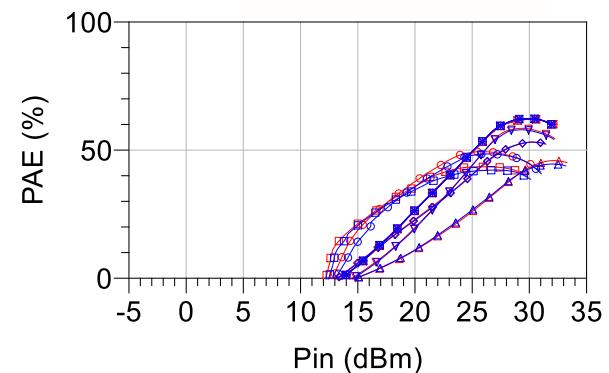
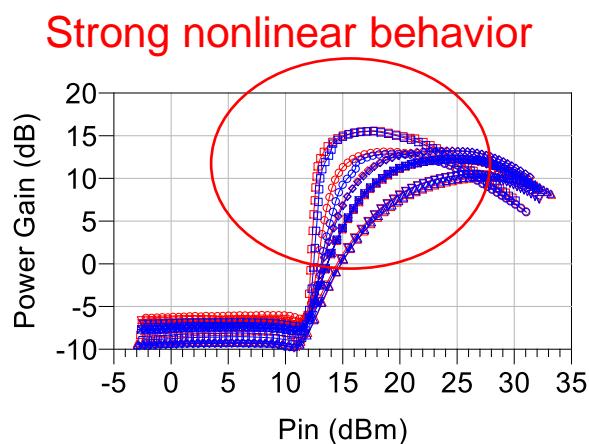


EPHD: Model vs Measurement

- Class C model @ 3.7GHz

→ EPHD

→ Measurement



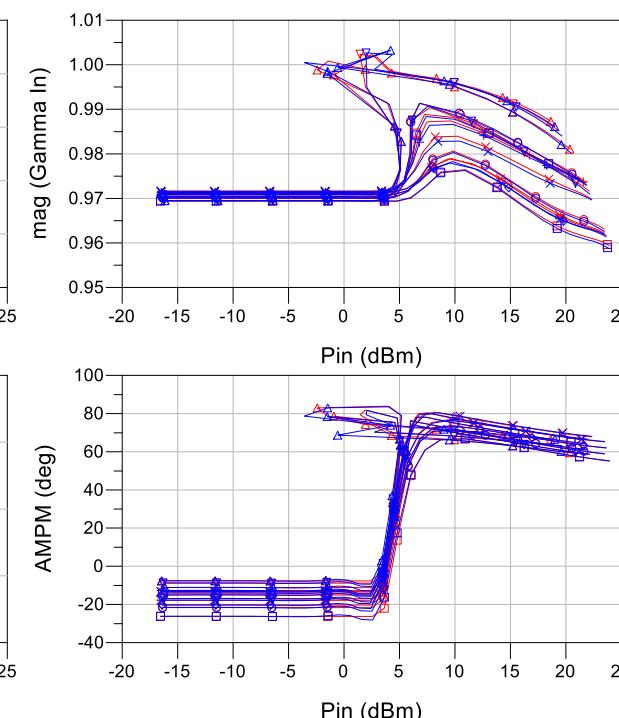
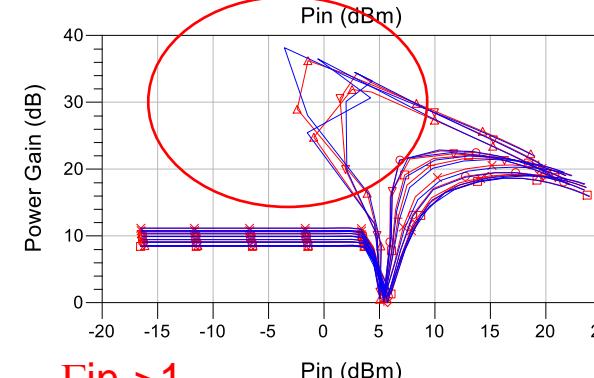
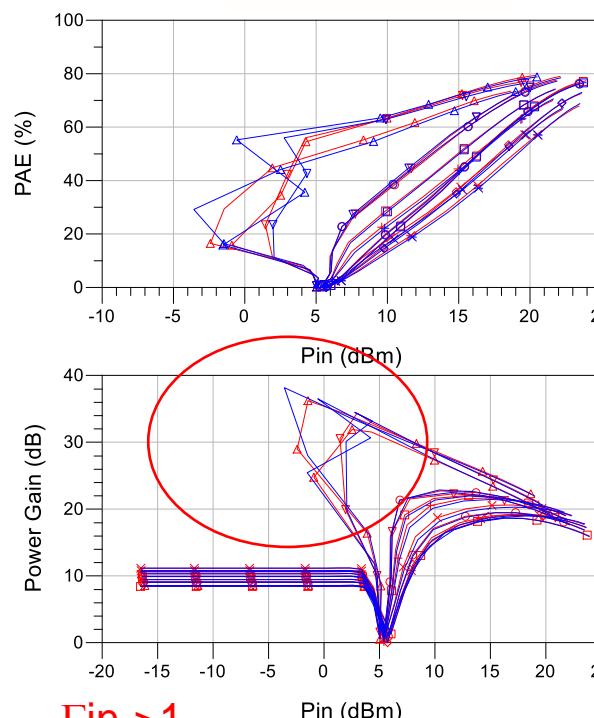
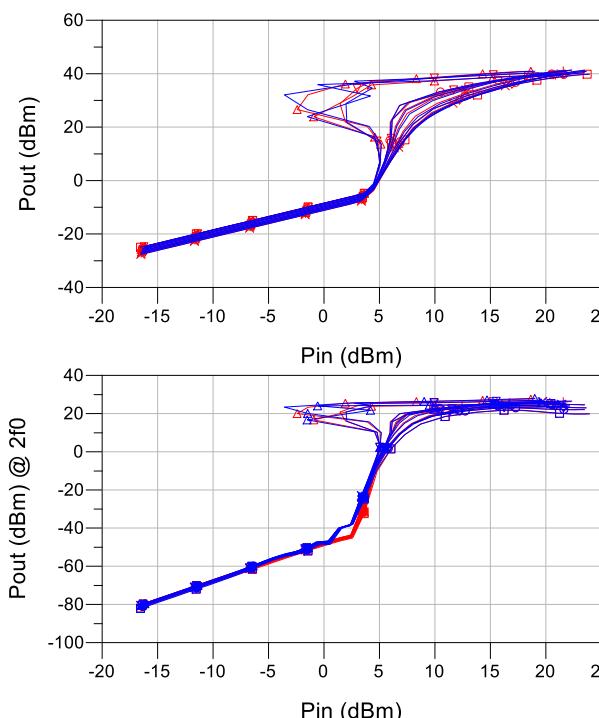
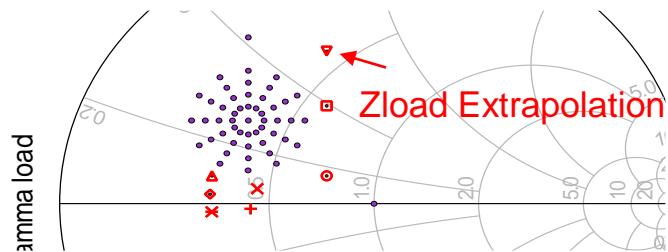
The model is able to reproduce the measurements which have been used for the model extraction

Class C -> see Power Gain curve shape

EPHD: Model vs Measurement

- Class C model @ 3,7GHz

→ EPHD
→ Measurement



The model is able to reproduce the measurements which have **NOT** been used for the model extraction

Class C → see Power Gain curve shape

EPHD: Frequency Interpolation Capabilities

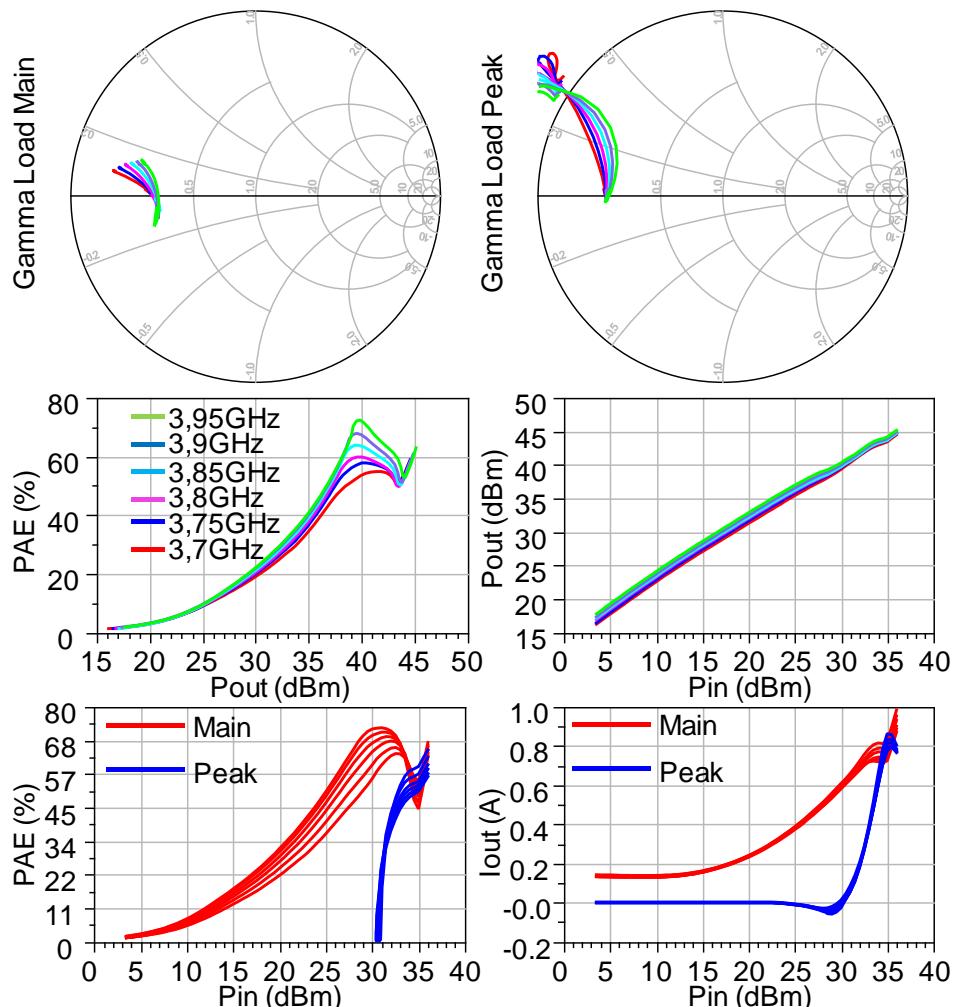
- EPHD extraction for 3,7 & 3,95 GHz

EPHD extraction area
including Z_{Opt_PAE} and Z_{Opt_Pout}

Frequency interpolation
capabilities

Convergence

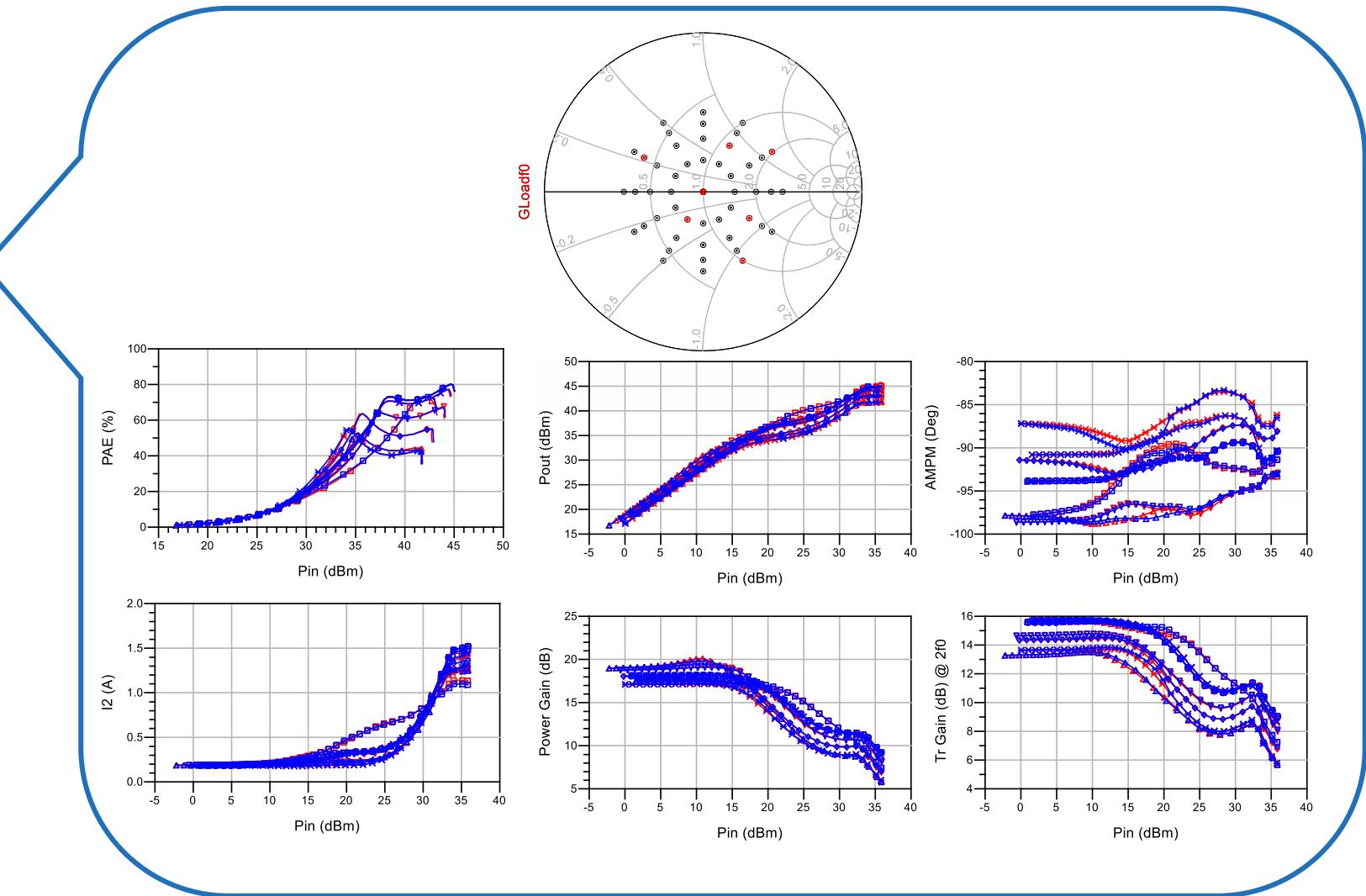
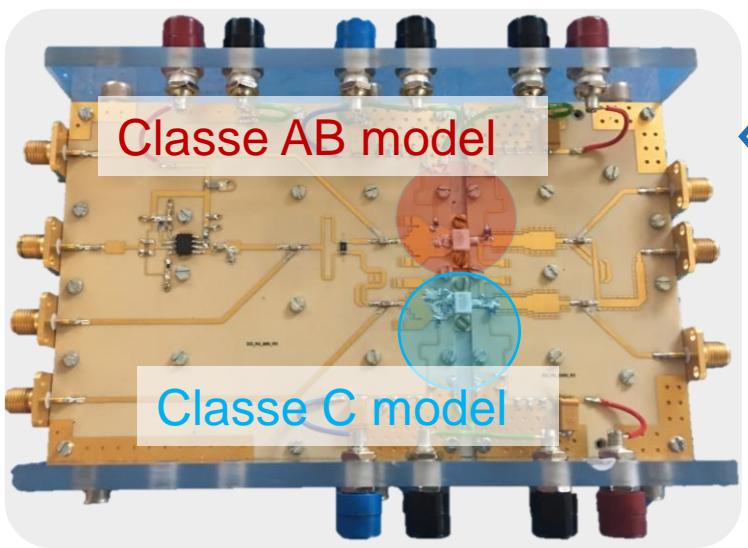
Dynamic variation of the load impedance





EPHD: Circuit Realization

- Doherty PA realization in band [3,7 - 3,95 GHz]



Benchmarking Conclusion

- Strong model robustness for simulations in both AB and C Class (with strong NL behavior regarding the gain curve shape)
- Strong model robustness for dynamic load modulation (extrapolated impedance have been verified)
- Accurate to simulate harmonic behavior
- Ability of the EPHD to predict the overall Design performances without any convergence issues even for extrapolated loading conditions.
- Proof of concept has been made on a real test case
- EPHD model extraction is a software module part of the IVCAD catalogue (already sold as a turnkey solution)
- The EPHD is a promising candidate for the design and realization of power amplifiers of future telecommunication systems due to its robustness and reliability.



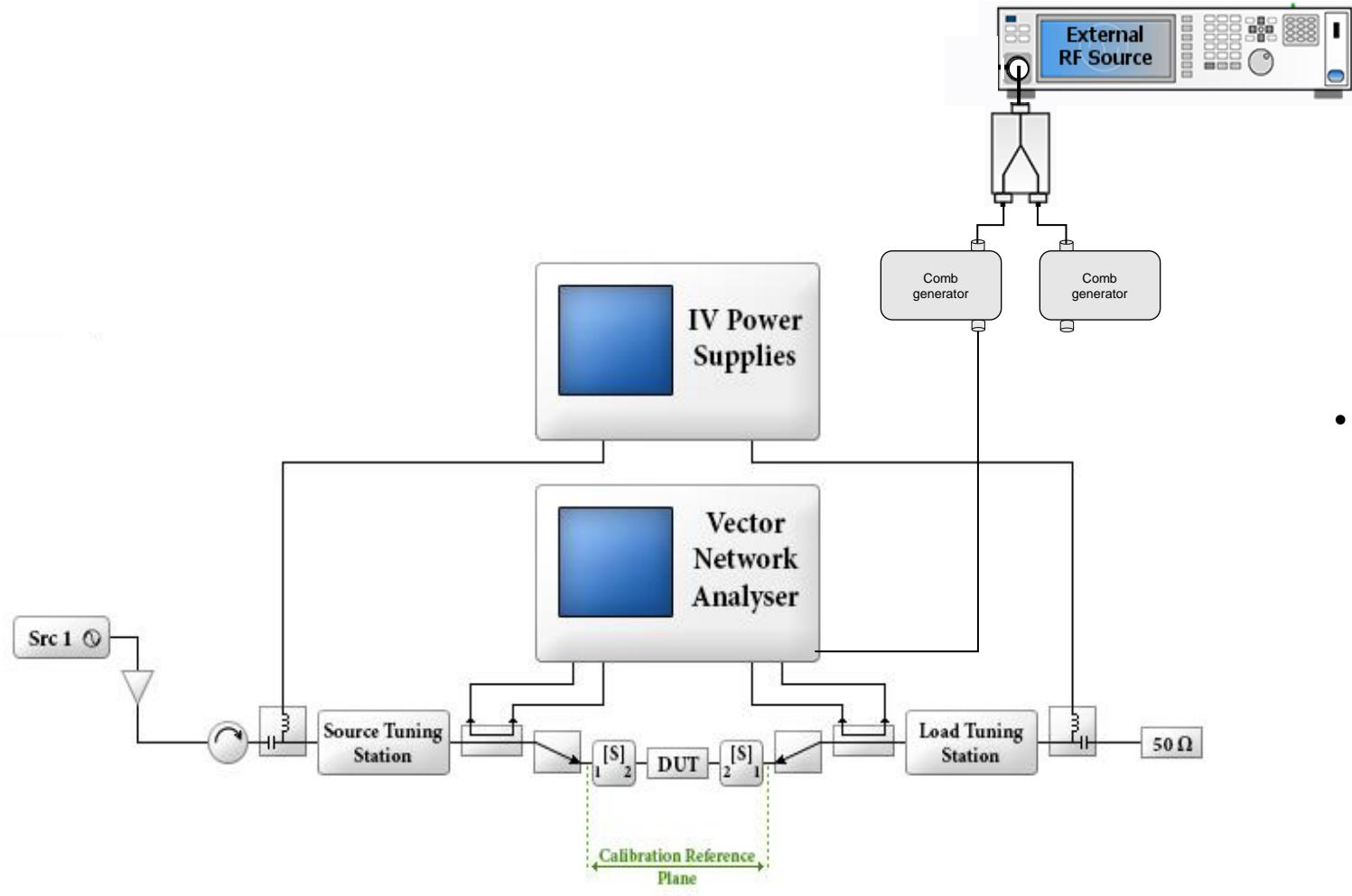
EPHD description

EPHD model packaged transistors

Benchmarking

Measurement Bench & Methodology

Measurement bench



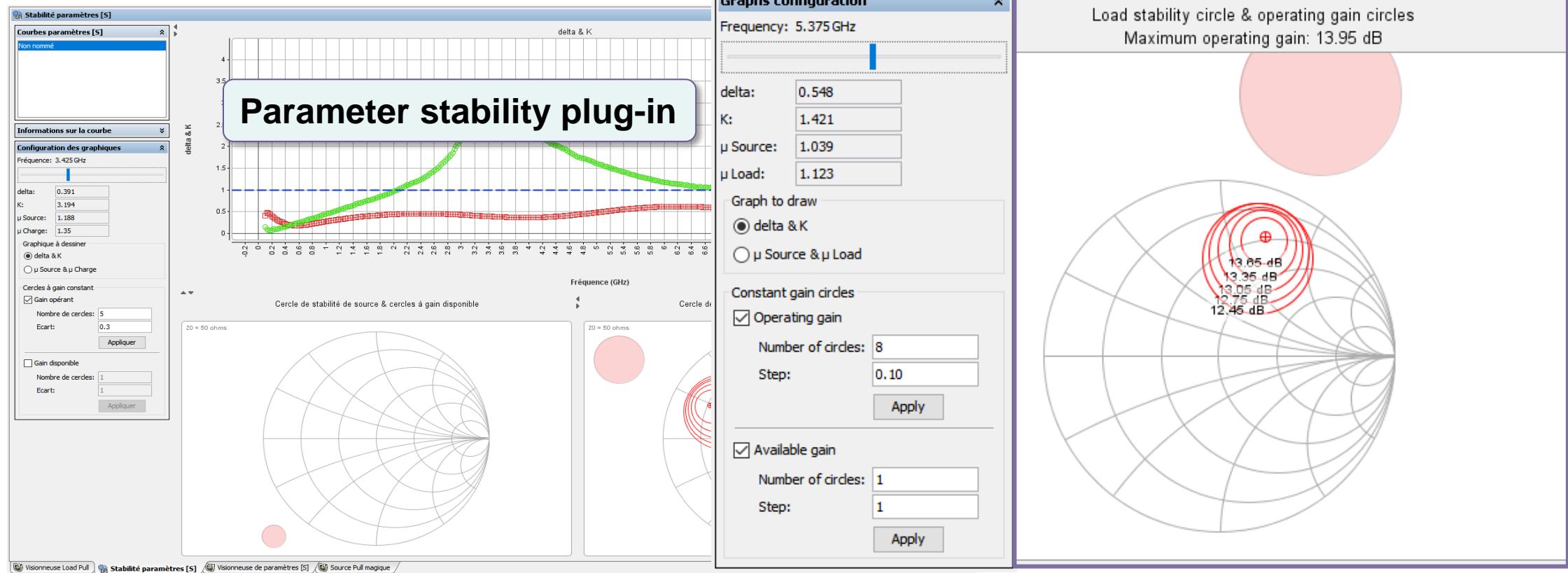
- **Hardware :**
 - Vector Network Analyzer
 - Power Meter
 - Instrumentation driver
 - Circulator
 - Couplers
 - Fundamental & Harmonic tuner (passive, hybrid or active)
 - Comb generator (+ External RF Source)
 - Power Supply (DUT Bias)

- **Software :**
 - IVCAD
 - Vector Receiver Load Pull (MT930C)
 - Time domain waveform LSA (MT930GA)
 - EPHD model extraction (MT930R1)
 - Basic Visualisation (MT930B1)
 - Advanced Visualization (MT930B2)
 - Measurement Toolbox (MT930P)
 - Active Load Pull (MT930H) optional

Extraction methodology (1)

1 → First step : location of optimum Gain on linear condition

→ S parameter data or measurement – IVCAD ideal matching [S22*]



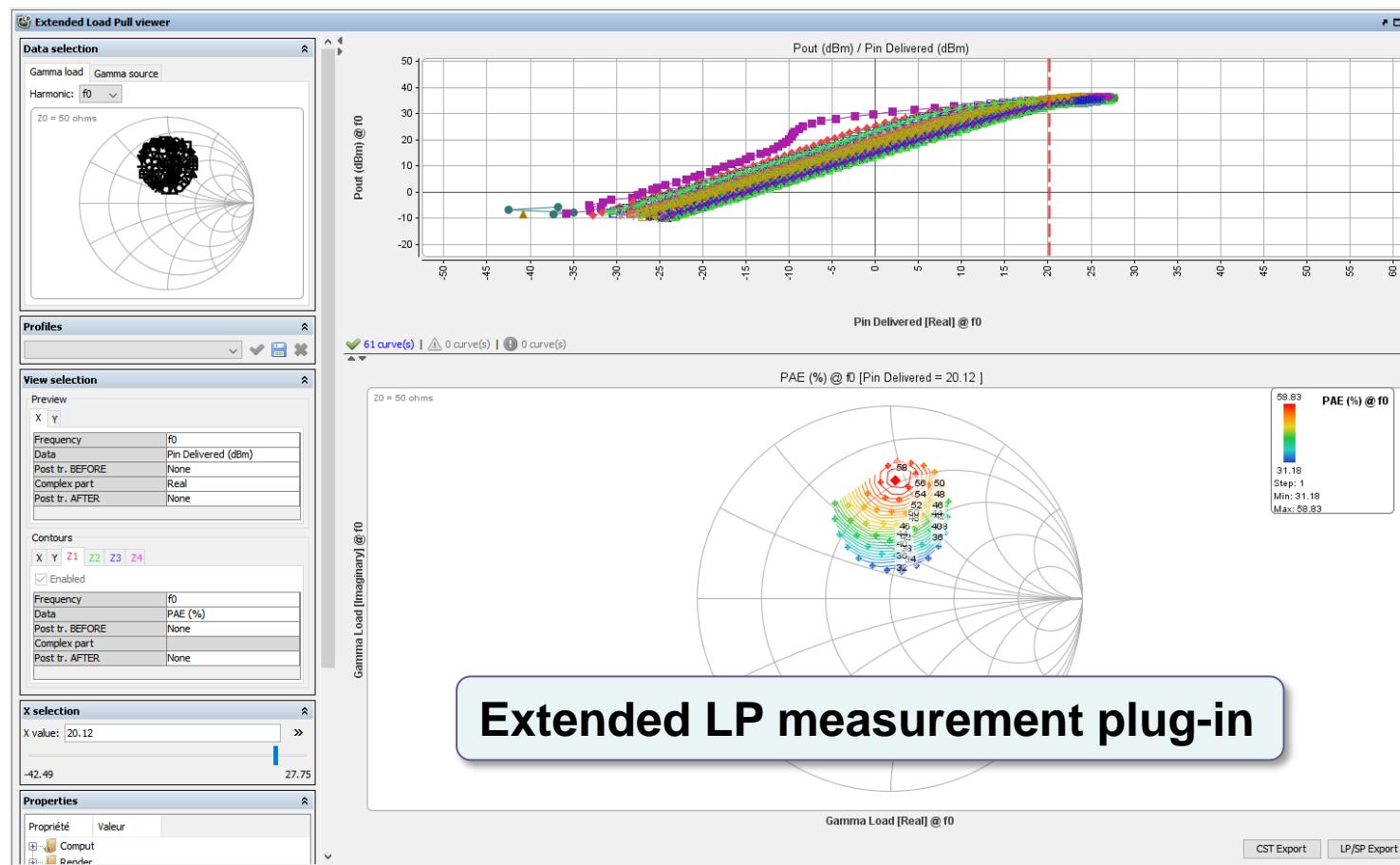
Extraction Methodology (2)

2

Second step : Search of PAE/ Pout optimum @ f₀



PS/IS with pattern f₀ definition with High resolution (~60 curves)

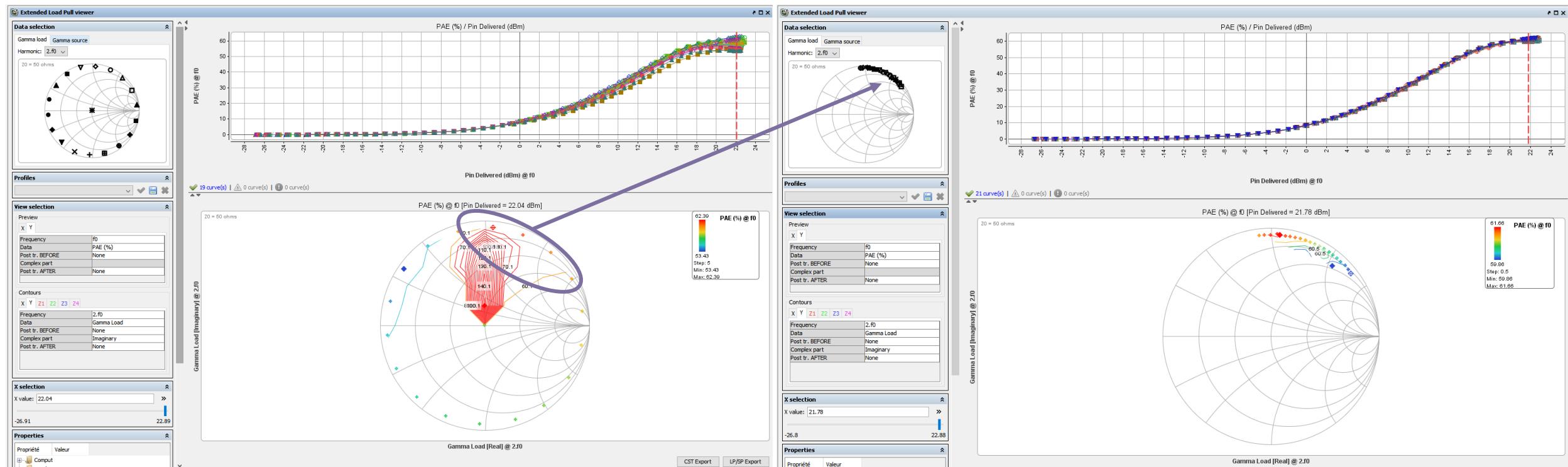


Extraction Methodology (3)

3

Third step : harmonic influence (nf_0 , $n>1$) [mf₀ with m<n on Opt PAE]

Example : pattern 2f₀ definition with High gamma settings (~20 curves)

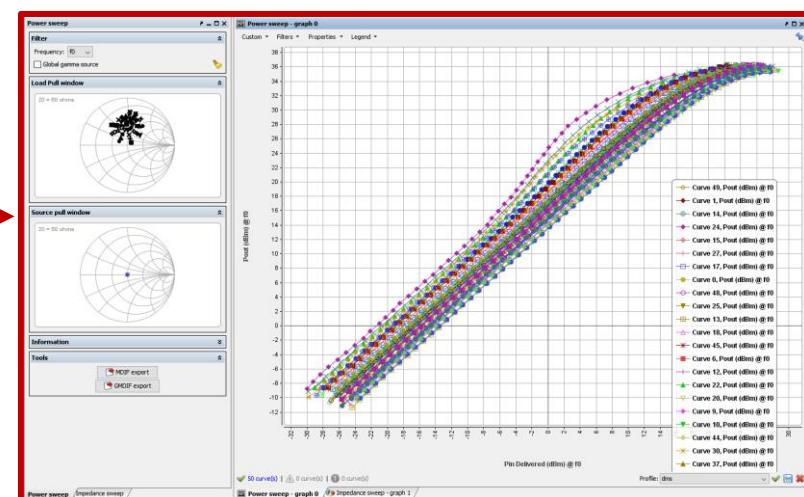
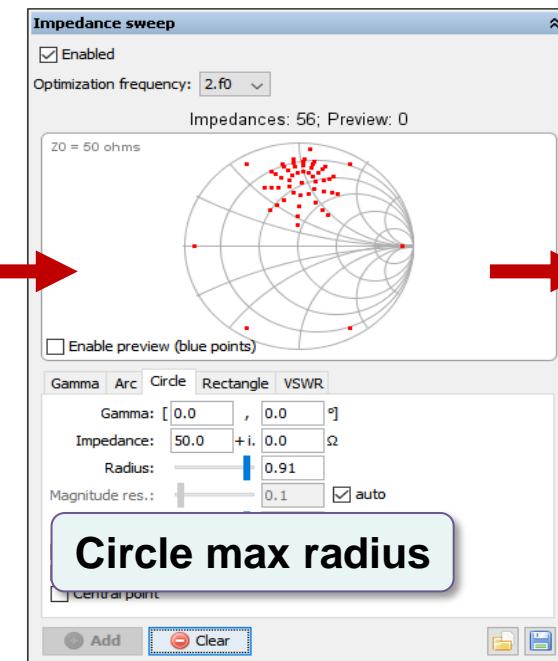
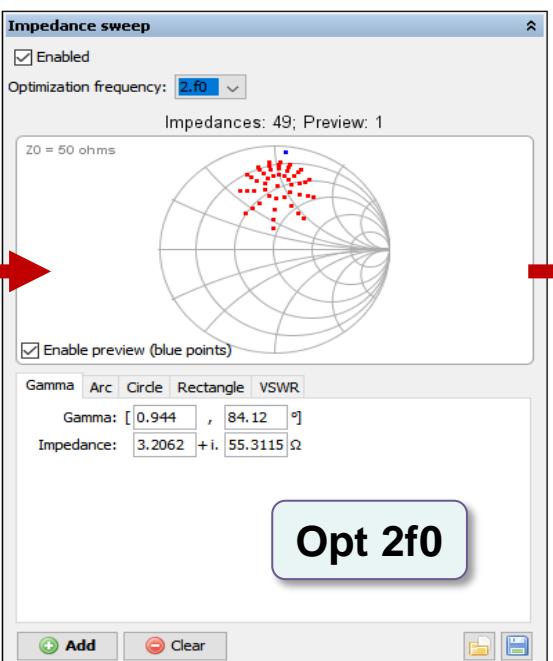
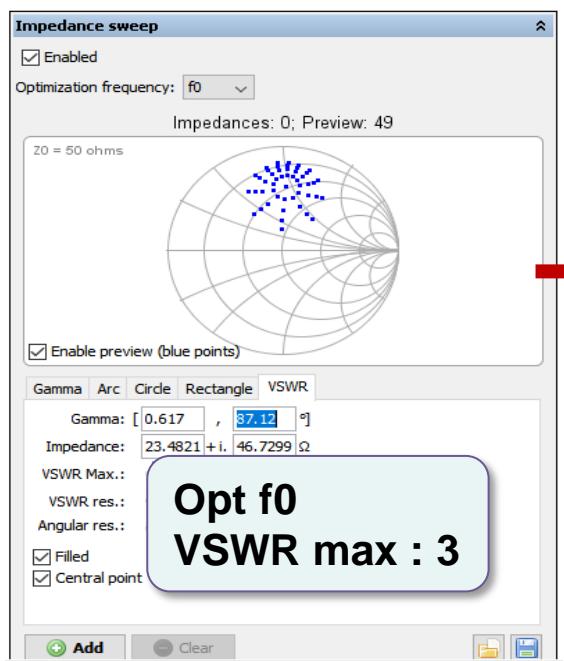


Extraction Methodology (4)

4

Fourth step : pattern definition for EPHD extraction]

Setup & Measurement plug-in – LP Measurement – Power Sweep



EPHD Using IVCAD : Sweep plan Measurement

Sweep plan script

The screenshot shows the IVCAD software interface for sweep plan measurement. On the left, the 'Sweep plan' tree view is highlighted with a red oval. It lists various actions such as 'Change measurement configuration', 'DUT ON', 'Output DUT biasing', 'Input DUT biasing', '1 loop', 'Loop/Group (nestable)', 'Wait', 'Message', 'DUT power state', 'DUT biasing', 'DUT biasing optimization', 'Change wafer', 'Change prober temperature', 'Move prober', 'Move tuner', 'DUT biasing sweep (nestable)', 'Temperature sweep (nestable)', 'Wafer plan (nestable)', 'Probe plan (nestable)', 'Impedance sweep (nestable)', 'Frequency sweep (nestable)', 'Power sweep (nestable)', and 'Script (nestable)'. A specific section under 'DUT biasing' is highlighted with a blue oval and contains three nested loops for impedance sweeps at f_0 , $2f_0$, and $3f_0$.

DUT bias

Impedance sweep @ f_0 (49)

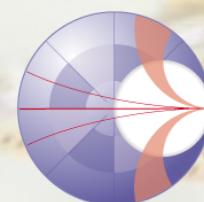
Impedance sweep @ $2f_0$ (7)

Impedance sweep @ $3f_0$ (7)

Other loops for other frequencies

Settings of sweep plan actions

The right panel displays the 'Settings of selected action' dialog. It shows the 'Orientation' set to 'Load', 'Location' set to 'Target', 'Harmonic' set to ' f_0 ', and 'Show calibration area at' set to 'GHz'. There is also a checkbox for 'Override measurement configuration if possible (only for target location, and same orientation/harmonic)'. Below this is a preview window showing a Smith chart with red data points. At the bottom, there are buttons for 'Add', 'Clear', 'Apply', and 'Restore'.



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