Low Frequency Parasitic Effects in RF Transistors and their Impact on Power Amplifier Performances

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Outline

- Introduction
- Small signal measurement system
- Thermal and traps characterization
- Large signal measurements
- Impact of trapping effects
- Conclusion

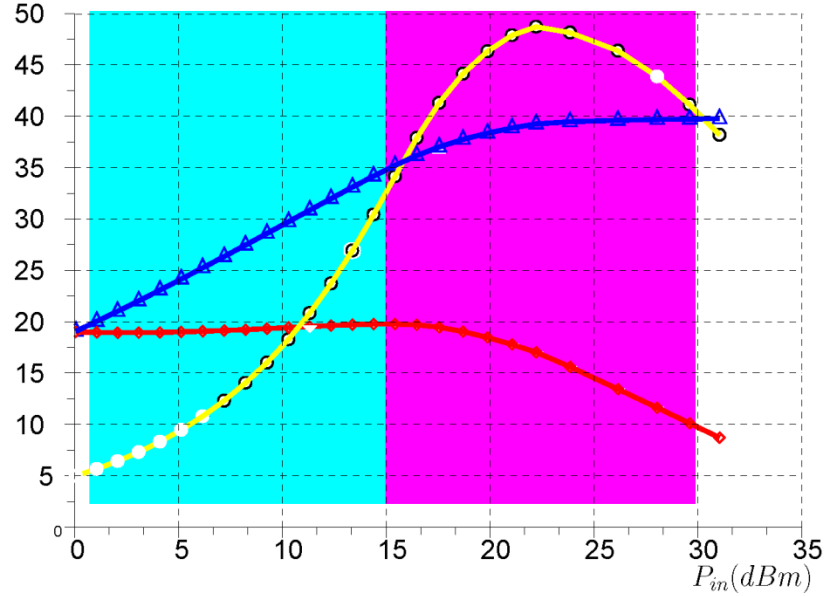
Introduction

- Potential applications of HBTs (GaInP/GaAs, Si/SiGe, InP) and GaAS or AlGaN/GaN HEMTs are numerous
  - For power amplifiers of Radar T/R modules
  - For base stations PA
  - For multi-tone PA in space applications
- All those applications involve complex modulated signals
  - Pulsed, phase/frequency modulated for Radar Systems
  - Highly complex signals (OFDM, X-PSK, …)
- In all these cases the enveloppe of the signals are dynamically varying

Consequences on PA design

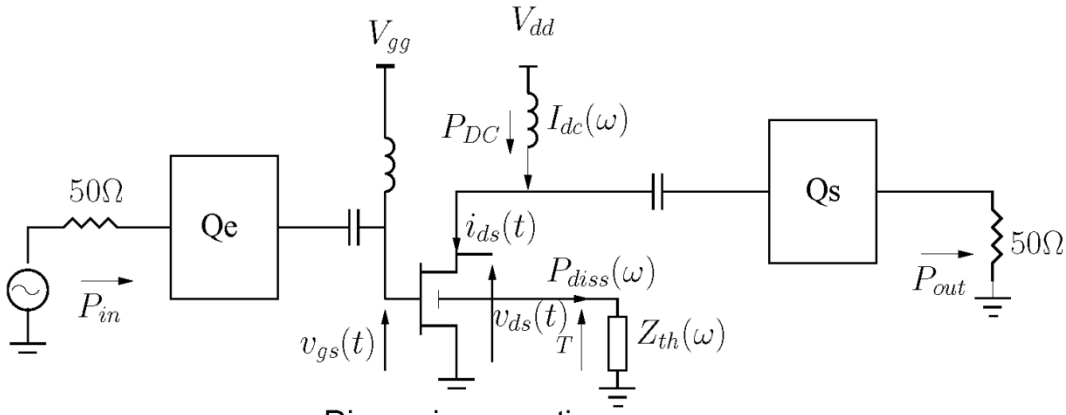
- Designing RF Power Amplifiers still represent a very challenging task
  - Technologies are used at their performance limits
  - Efficiency requires highly nonlinear behavior
  - Linearity is mandatory for Telecomm. Applications
  - Large bandwidth is more and more required in modern systems
  - Sub-system integration of PA is targetted
  - Stability (linear and nonlinear) must be achieved
  - Thermal effects must be managed
  - Low Frequency memory effects mus be understood and managed
- Tools and methods are required for
  - Characterization
  - Modeling
  - Simulation

PA characteristics



Linearity: OK Efficiency: OK

Efficiency: KO Linearity: KO



Dispersion equation

$$i_{ds}(t) = f_{NL}\left(v_{gs}(t), \frac{dv_{gs}(t)}{dt}, v_{ds}(t), \frac{dv_{ds}(t)}{dt}\right)$$

- Linearity and efficiency are conflictual
- Trade-off must be achieved

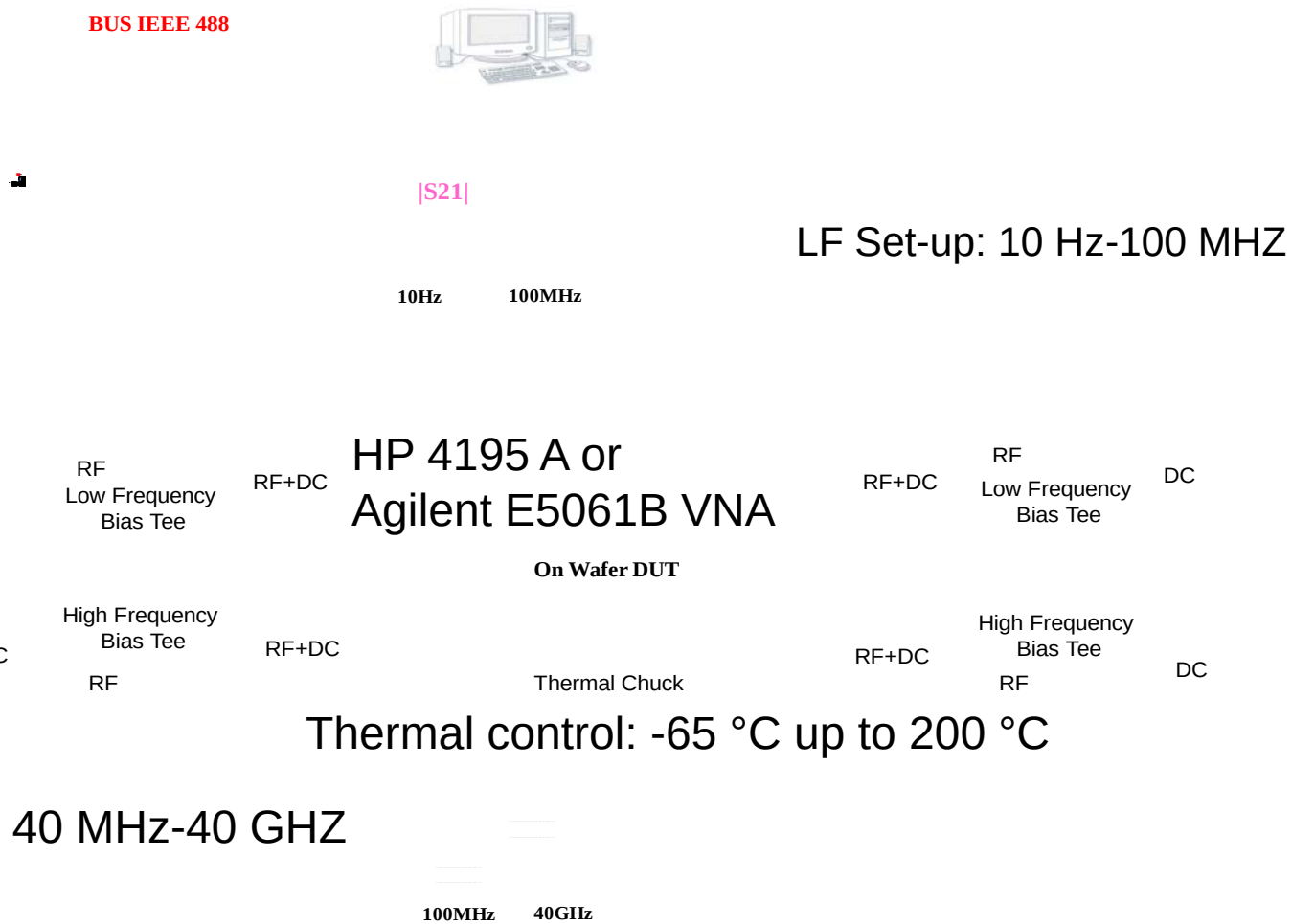
- PA use transistors which are inherently controlled by 3 independent variables.
- The equation of the drain current is dispersive.

Different ways for characterization/modeling

- Parasitic effects still limit the performances of PA
  - **Thermal effects**
  - **Trapping effects**
- Identification through
  - Small-signal characterization
  - I-V (DC and pulse) characterization
  - Large signal characterization (in frequency and time domains)
- All these characteristics should be consistently modeled

Small signal measurements

DC(10Hz)- 40GHz S- parameters measurements



Thermal and traps characterization

HBTs thermal characterization methods

Optical methods

- Infrared thermography
- Raman spectroscopy
- Photo reflectance

Electrical methods

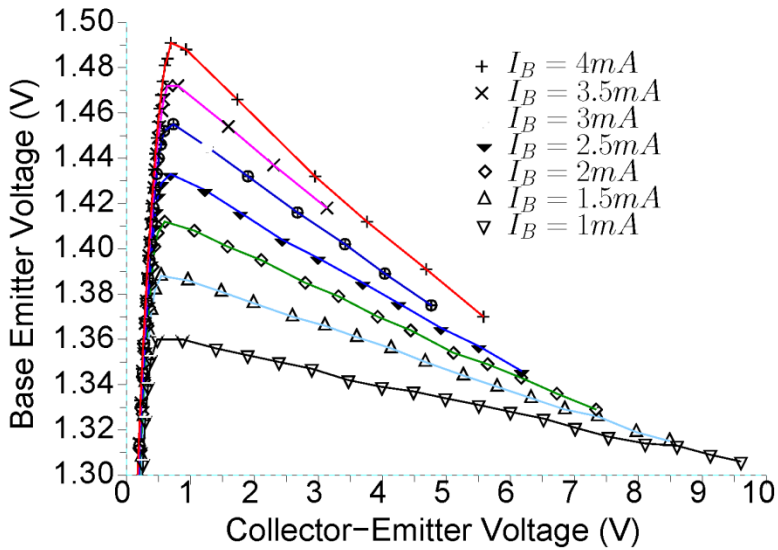
- Input impedance(Xlim)
- current gain(O.Mueller)
- small signal voltage gain (cherepko)

Needs complex equipment and well prepared samples

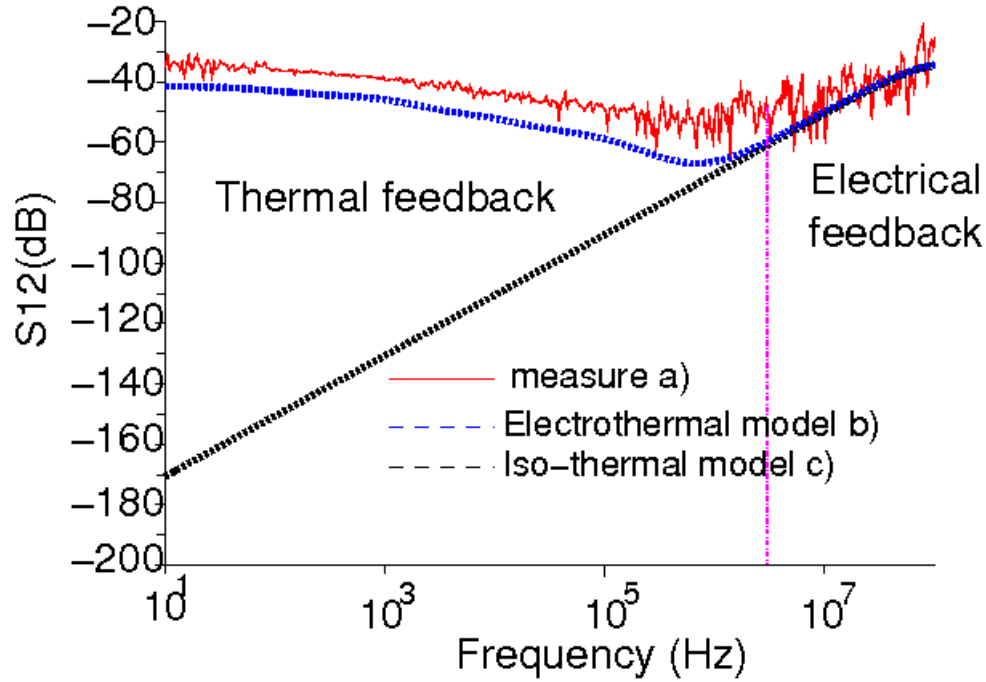
Dependence on the size of the transistor , external loading

Hybrid parameter feedback coefficient h_{12} as the thermometer

Feedback due to temperature for HBTs



GaInP/GaAs HBT DC feedback characteristics at constant Ib



S12 frequency characteristics with and without thermal feedback

- Choice of feedback coefficient as the temperature sensor

Thermal impedance determination

$$\left.\begin{aligned} V_{BE} &= F_1(I_B, V_{CE}, T) \\ I_C &= F_2(I_B, V_{CE}, T) \end{aligned}\right\} \Rightarrow h_{12} = \frac{h_{12ISO} + \varphi \tilde{Z}_{TH} I_{C0} - \gamma \tilde{Z}_{TH} V_{CE0} h_{12ISO} + \varphi h_{22ISO} \tilde{Z}_{TH} V_{CE0}}{1 - \varphi \tilde{Z}_{TH} I_{B0} - \gamma \tilde{Z}_{TH} V_{CE0}}$$

Isothermal hybrid parameters

$$h_{11ISO} = \left.\frac{\partial V_{BE}}{\partial I_B}\right|_{V_{CE},T} \qquad h_{12ISO} = \left.\frac{\partial V_{BE}}{\partial V_{CE}}\right|_{I_B,T} \qquad h_{21ISO} = \left.\frac{\partial I_C}{\partial I_B}\right|_{V_{CE},T} \qquad h_{22ISO} = \left.\frac{\partial I_C}{\partial V_{CE}}\right|_{I_B,T}$$

$$\varphi = \left.\frac{\partial V_{BE}}{\partial T}\right|_{I_B}$$ Base-Emitter voltage thermal coefficient

$$\gamma = \left.\frac{\partial I_C}{\partial T}\right|_{V_{CE}}$$ Collector current thermal coefficient

$$\boxed{Z_{TH}(\omega) = \frac{h_{12} - h_{12ISO}}{\varphi(I_{CO} + h_{12} I_{BO} + h_{22ISO} V_{CEO}) + \gamma V_{CEO}(h_{12} - h_{12ISO})}}$$

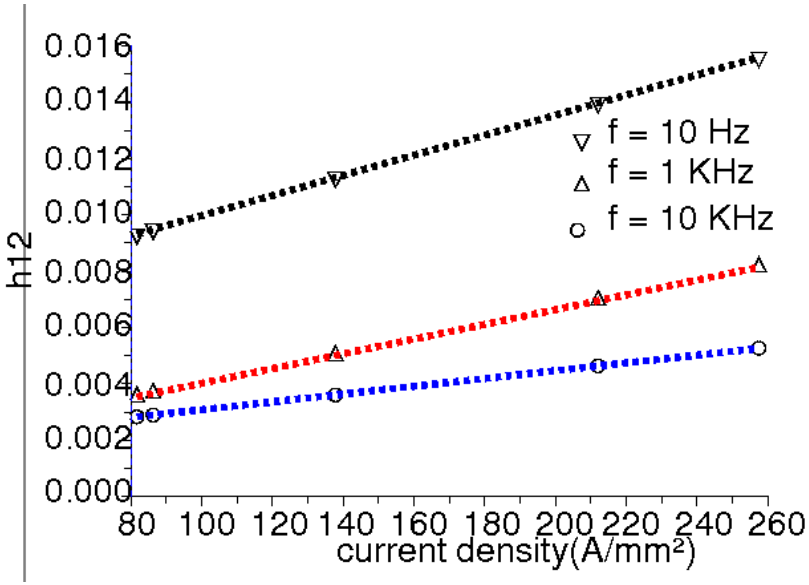
Thermal impedance approximation

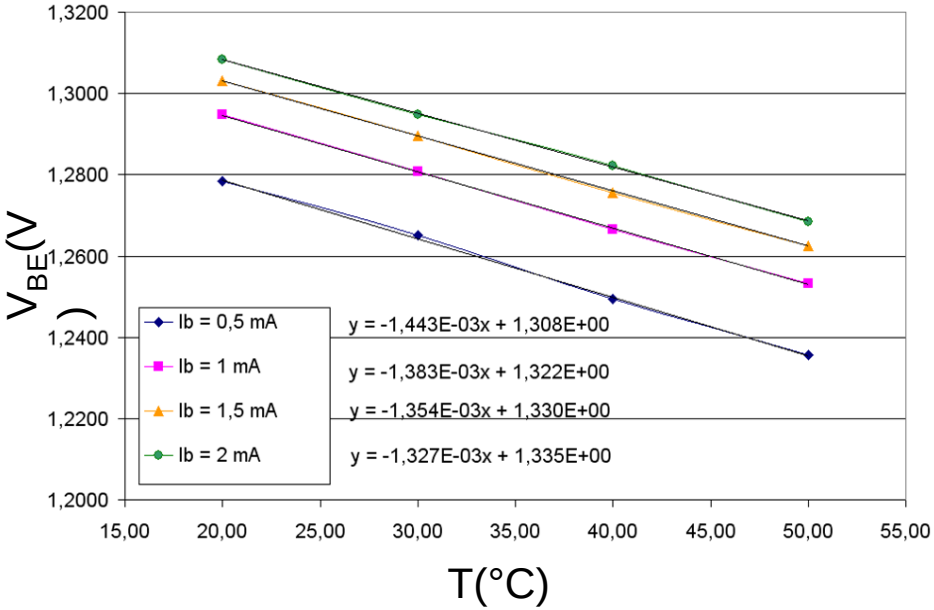
$$\left.\begin{array}{c} h_{12ISO} \cong 0 \\ h_{22ISO} \cong 0 \\ h_{12} I_{BO} << I_{CO} \\ \gamma V_{CEO} h_{22ISO} << \varphi I_{CO} \end{array}\right\} \Rightarrow Z_{TH}(\omega) \approx \frac{h_{12}(\omega)}{\varphi I_{CO}}$$

The feedback coefficient h_{12} is quasi independent of the size of the transistor

$$\left.\begin{array}{l} I_{CO} \cong A_E J_{CO} \\ Z_{TH} \cong z_{TH} / A_E \end{array}\right\} \Rightarrow h_{12}(\omega) \approx \varphi \cdot J_{CO} \cdot z_{TH}(\omega)$$

Measurement process



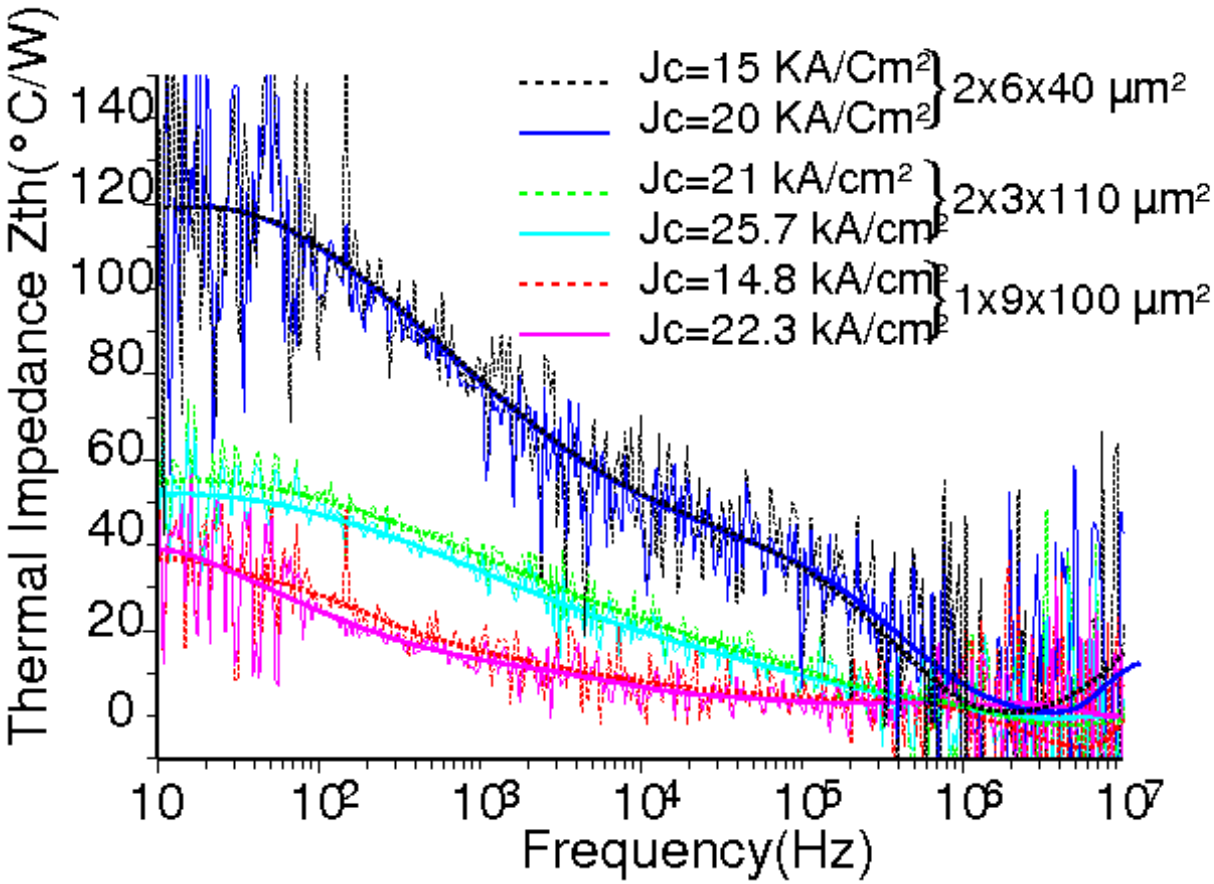


Extraction of the feedback coefficient vs frequency and current density from LF S-parameters measurement

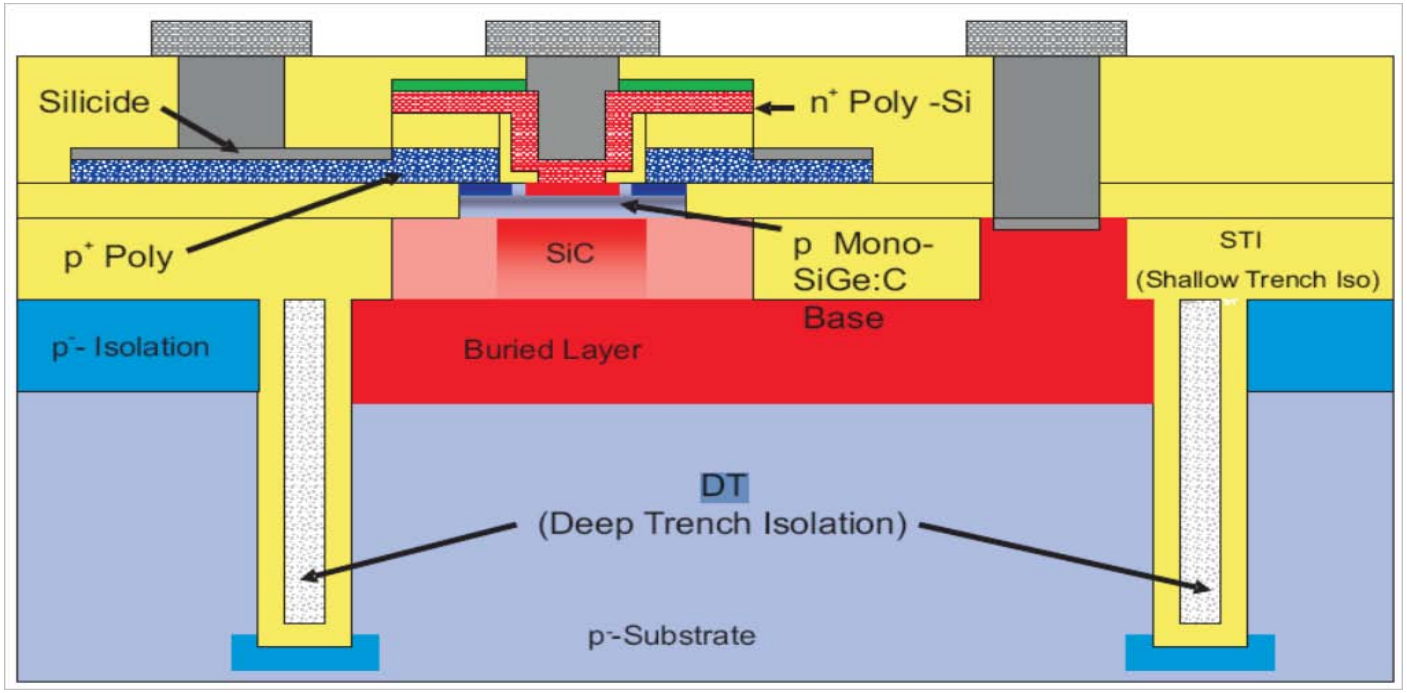
Measurement of the base-emitter temperature coefficient φ

Results for InGaP/GaAs HBTs

- HBT 3x2x2x110 µm² GaInP/GaAs
- HBT 6x2x40 µm² GaInP/GaAs
- HBT 9x2x1x100 µm² GaInP/GaAs



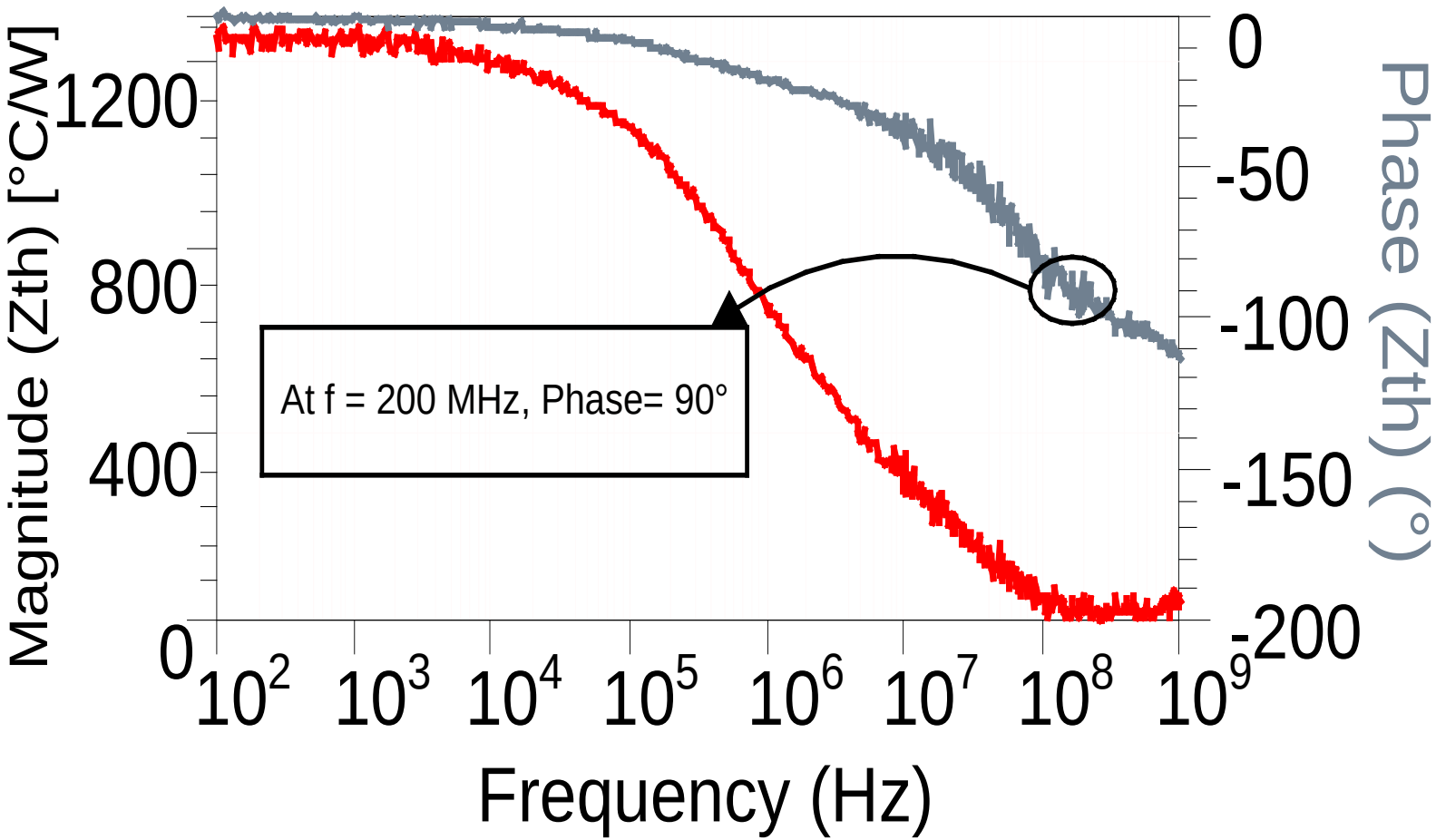
Thermal impedance of SiGe HBTs



transistor SiGe (2x0.35x5.8 µm ²)

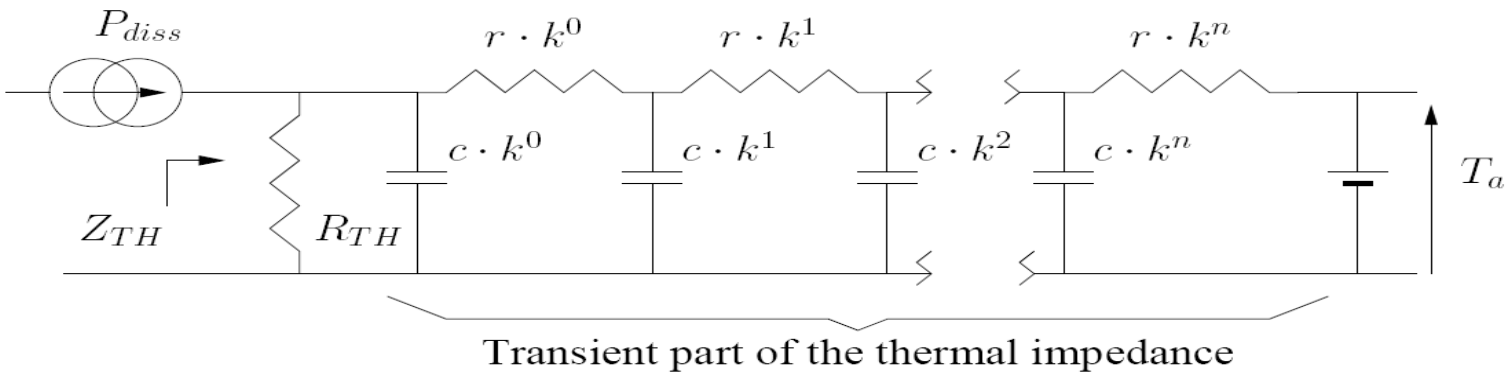
- Infineon technology
- Polysilicon Base and Emitter
- Deep trench isolation
- f_T = 200 GHz and f_{max} = 275 GHz

Frequency variation of Zth for SiGe HBTs

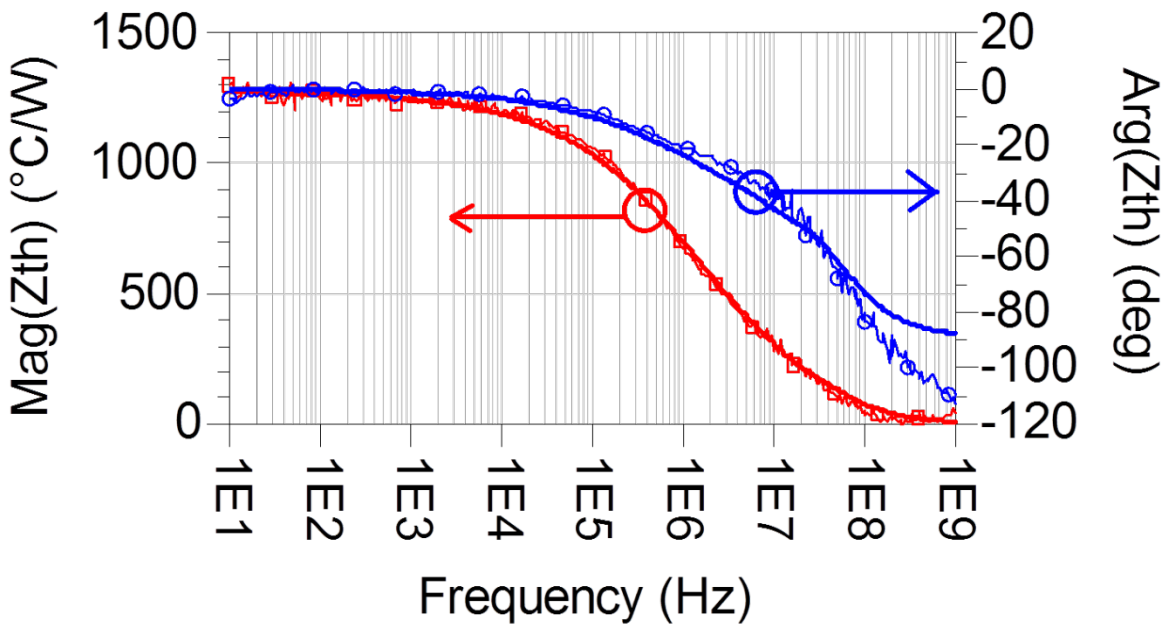


- Thermal dynamic up to 200 MHz → thermal time constants down to several ns can be measured

$Z_{TH}(\omega)$ Model

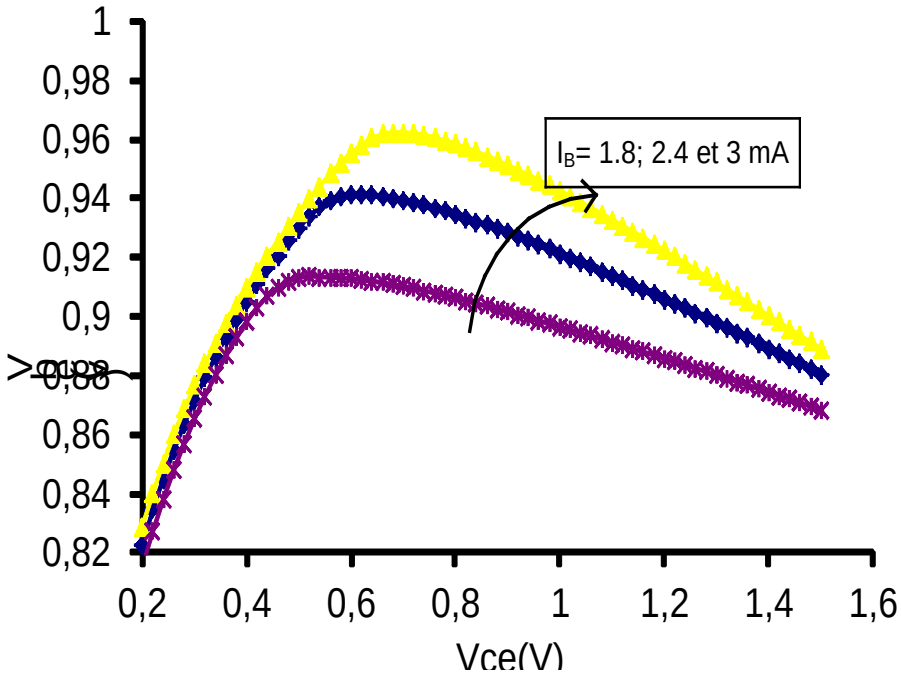


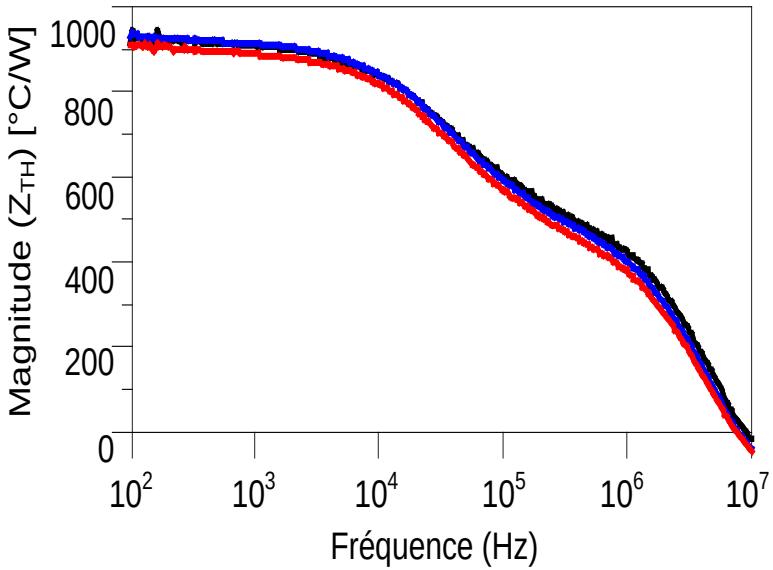
Reduced number of parameters



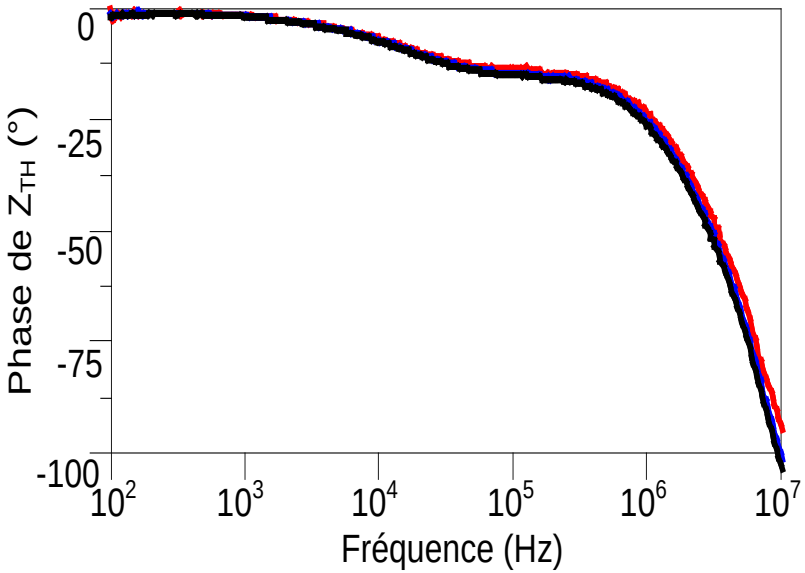
k=2 ; r = 300 °C/W ; c = 19.10^{-12} J/°C ; R_{TH} = 1271 °C/W

Thermal impedance of InP HBTs



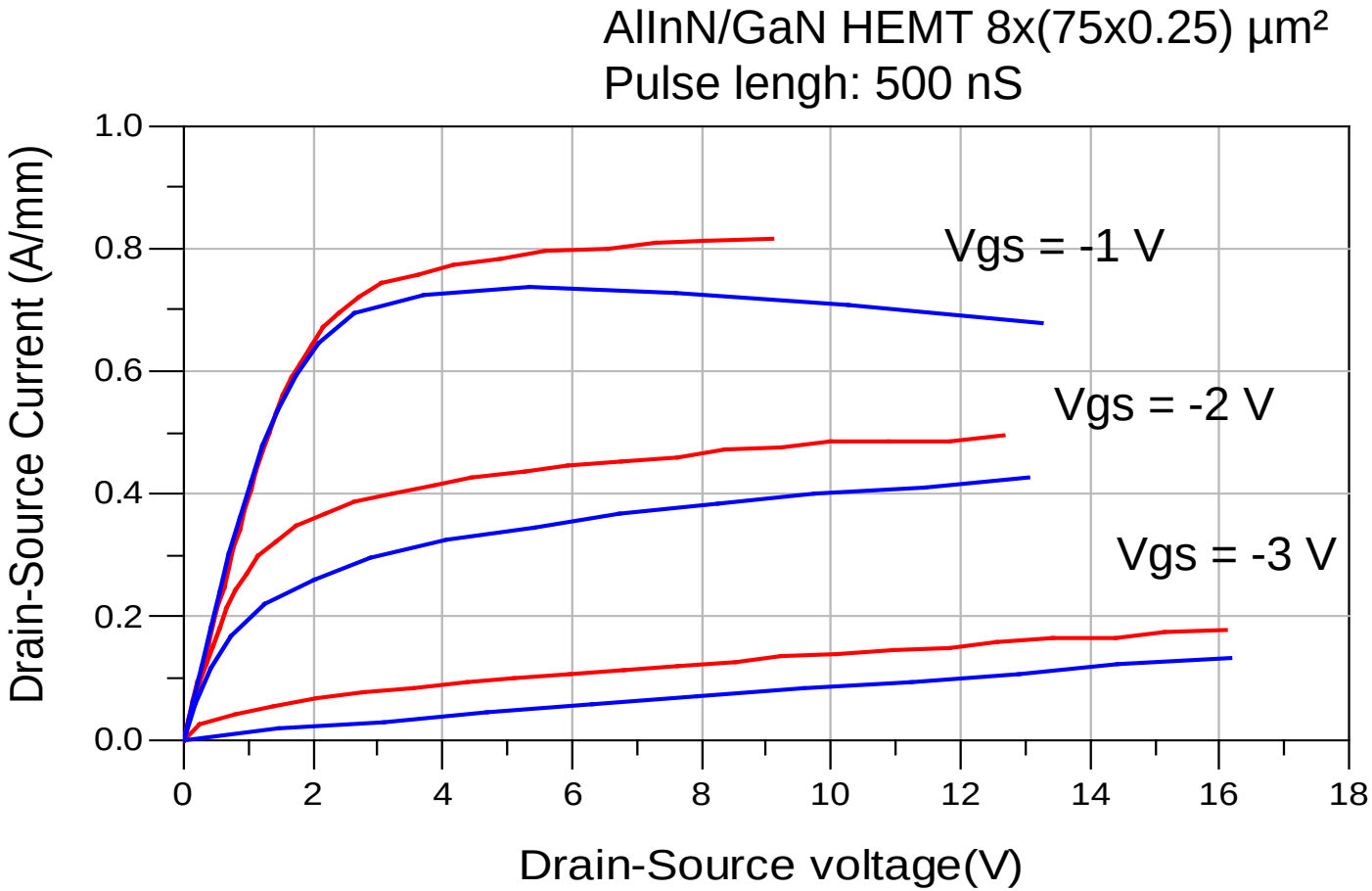


TBH	Emitter area (µm²)	$R_{TH}(h_{12})$
7B3H7	3.7	2500
10B3H7	5.5	1950
3x1M10B3H7	16.4	



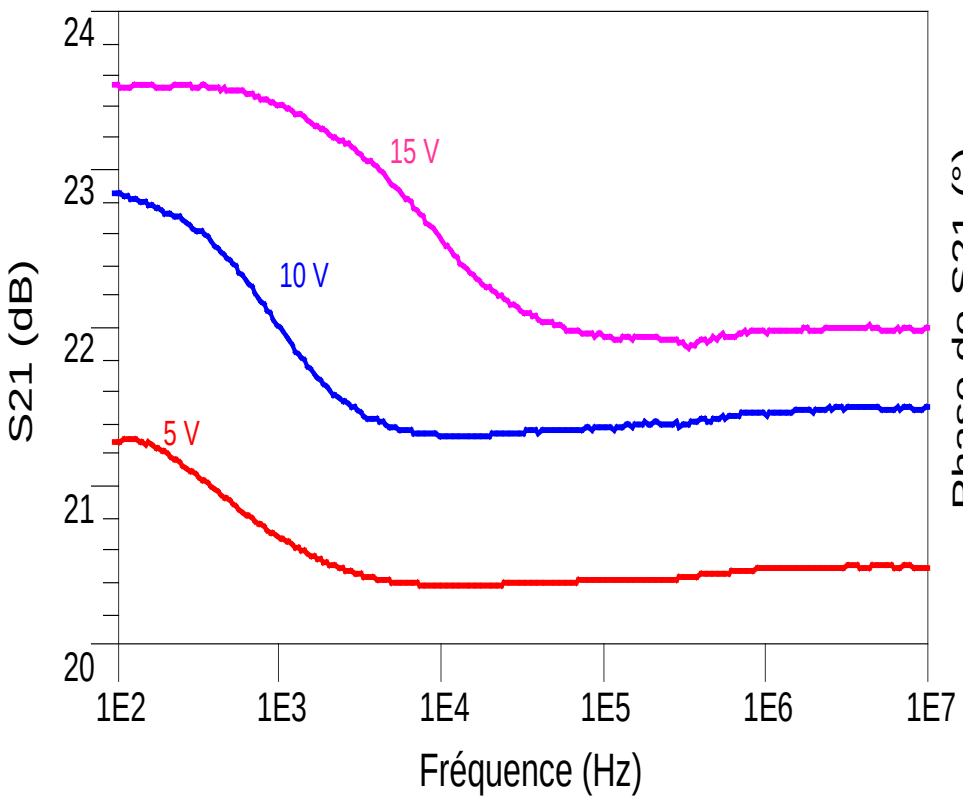
Dispersion due to trapping effects in GaN HEMTs

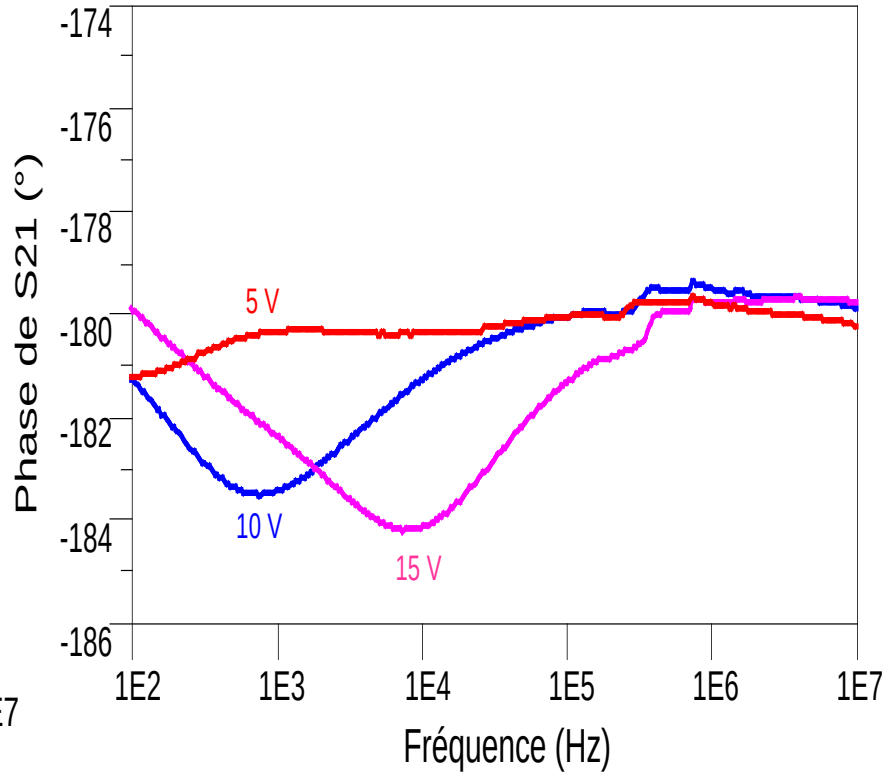
DC and pulsed IV measurement



- Gd_{DC} and Gd_{pulsed} are very different, especially at Vgs = -1V, where the dissipated power is the highest

Low frequency characteristics



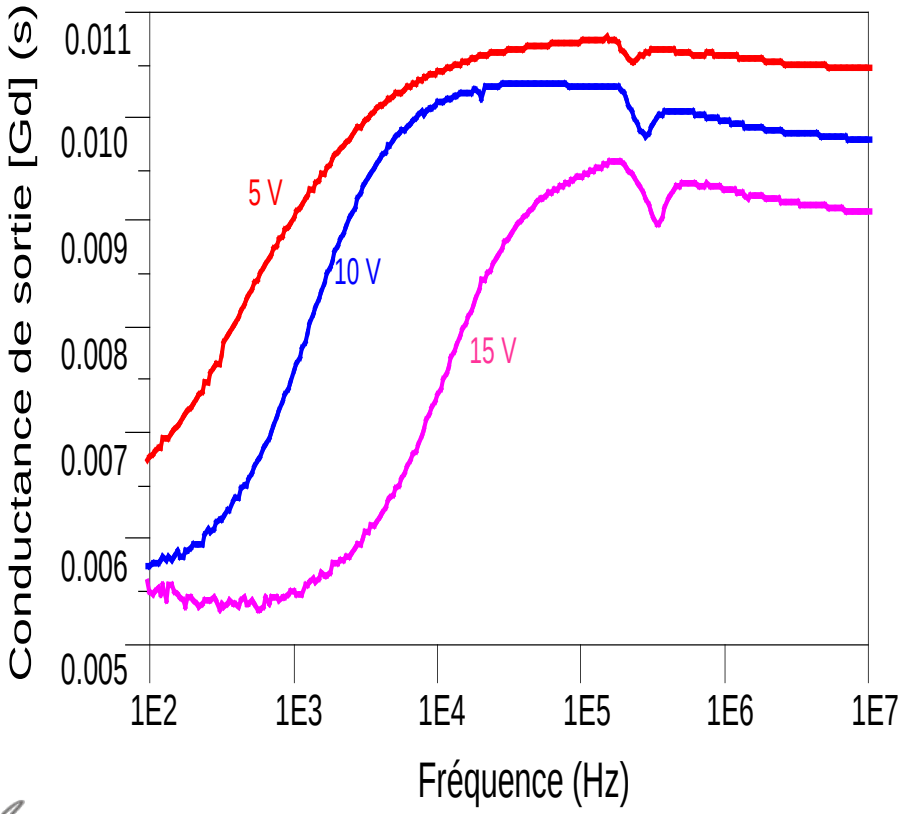


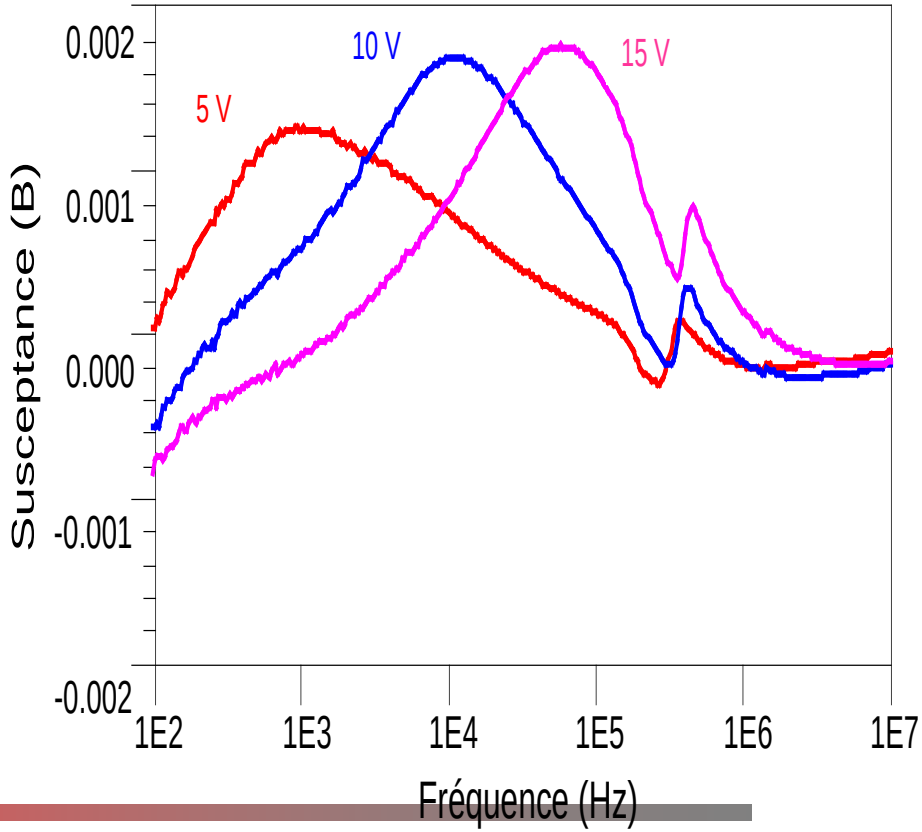
- ✓ transition frequency between DC to RF
- ✓ The variation of this S21 is close to 2dB (due either to traps or to the self-heating)

Influence of bias points in the behavior of Gd

- dissipated power corresponds to a rise of temperature around 15 °C between 5 and 15V (thermal resistance to 18 °C/W by 3D simulation)

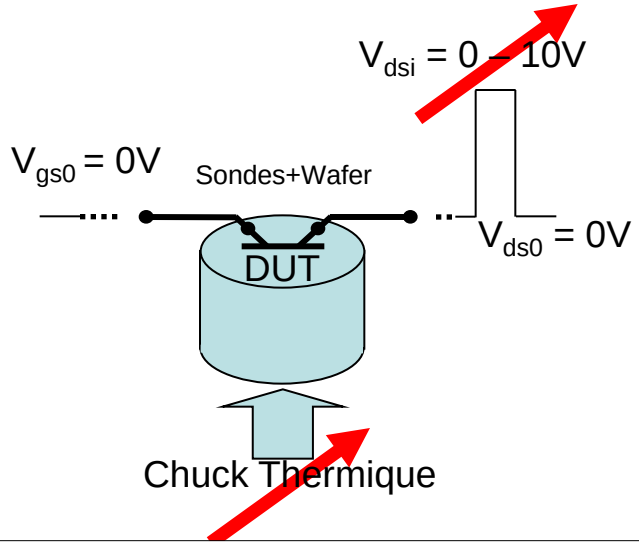
Vds (V)	Ids (mA)
5	28
10	52
15	72

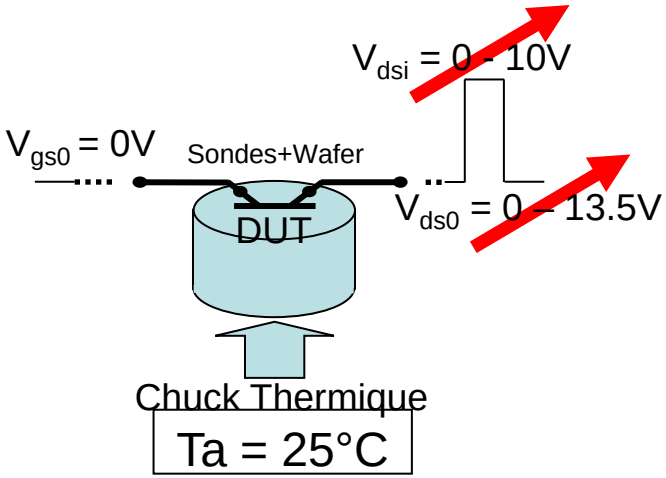


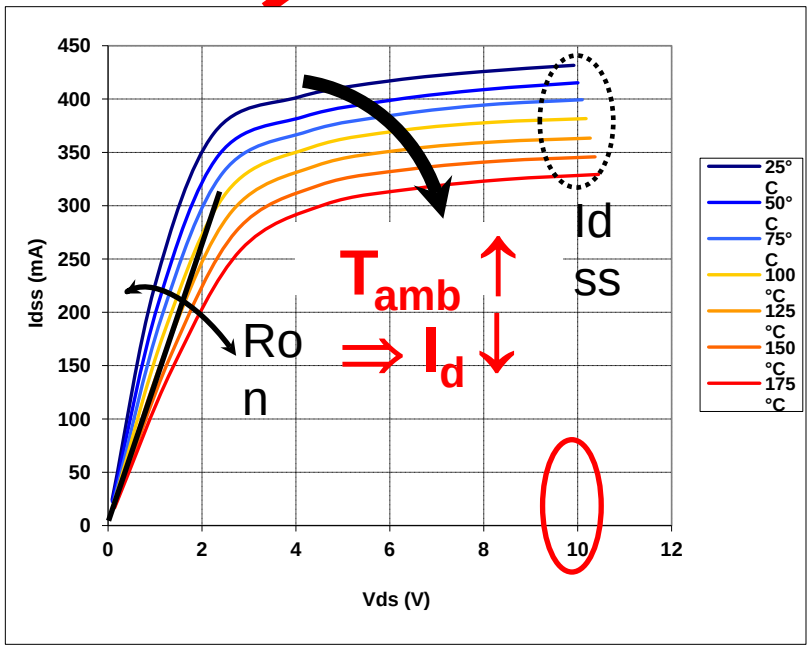


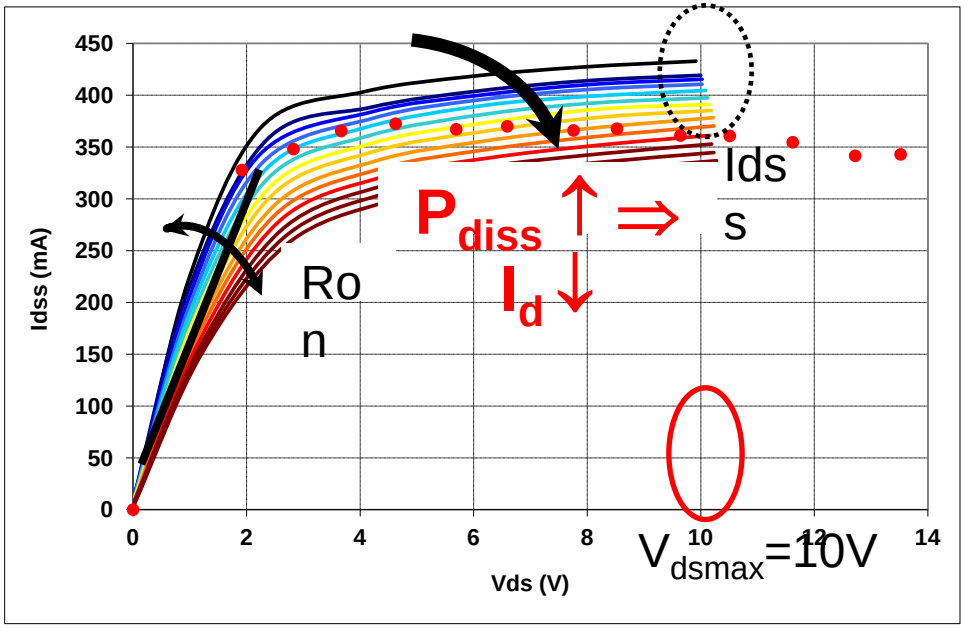
Thermal characterization of GaN HEMTs

Measurement of Ron and Idss at different temperatures and Pdiss

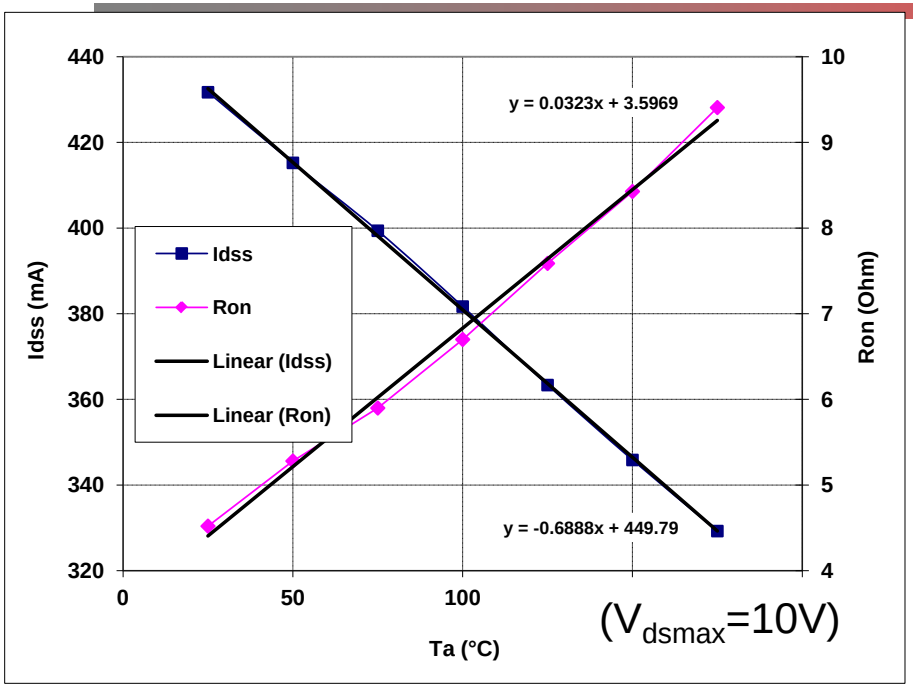


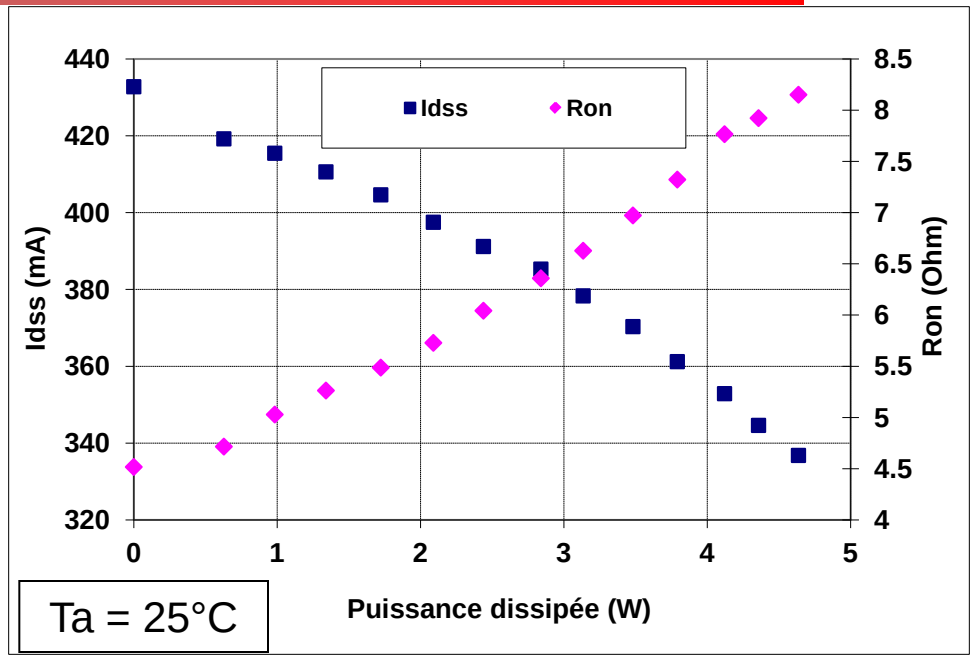






Rth extraction





$$R_{ON}(\Delta T) = R_{ON}(T_0) + \frac{dR_{ON}}{dT} \cdot \Delta T$$

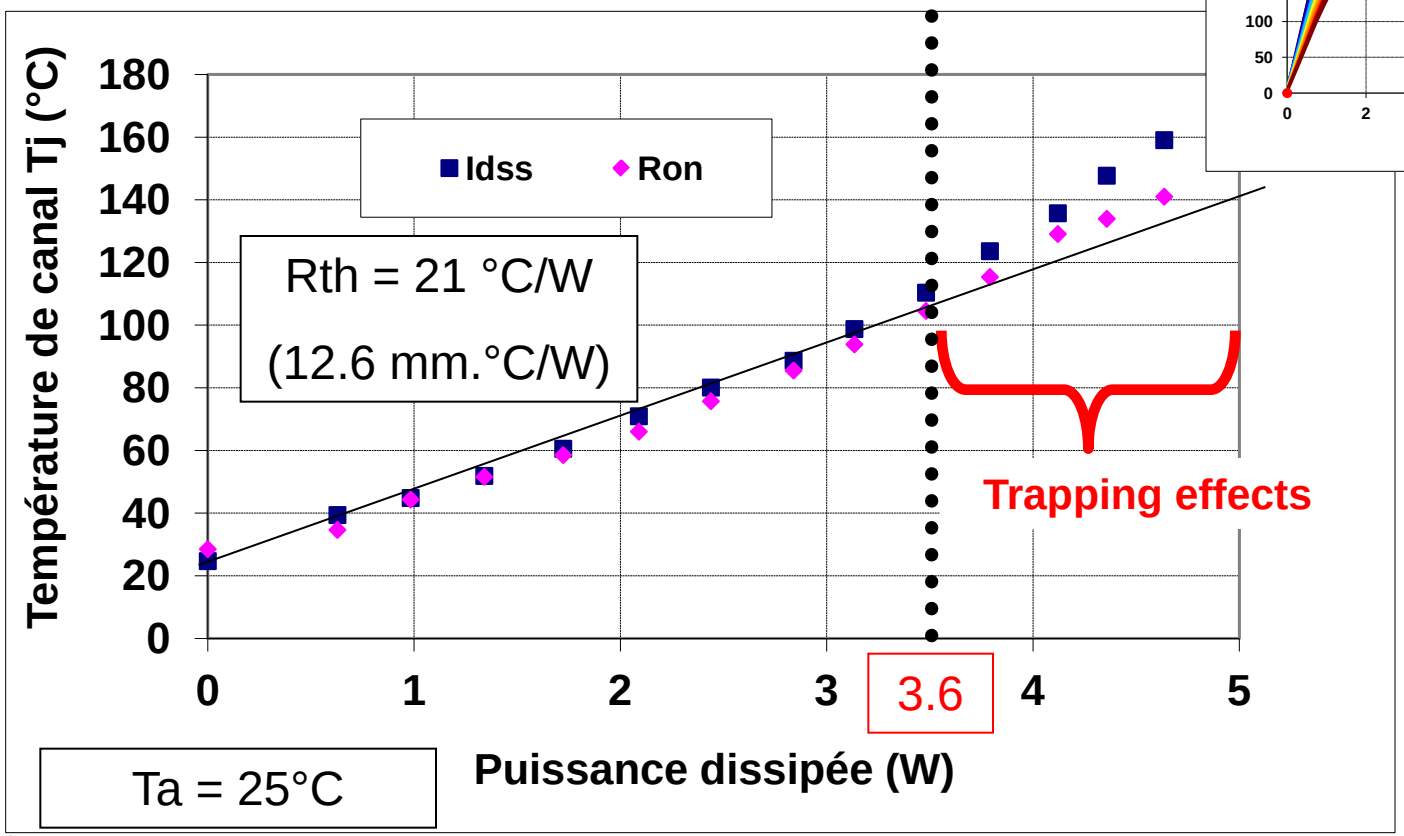
$$R_{ON}(P_{diss}) = R_{ON}(0) + \frac{dR_{ON}}{dP_{diss}} \cdot P_{diss}$$

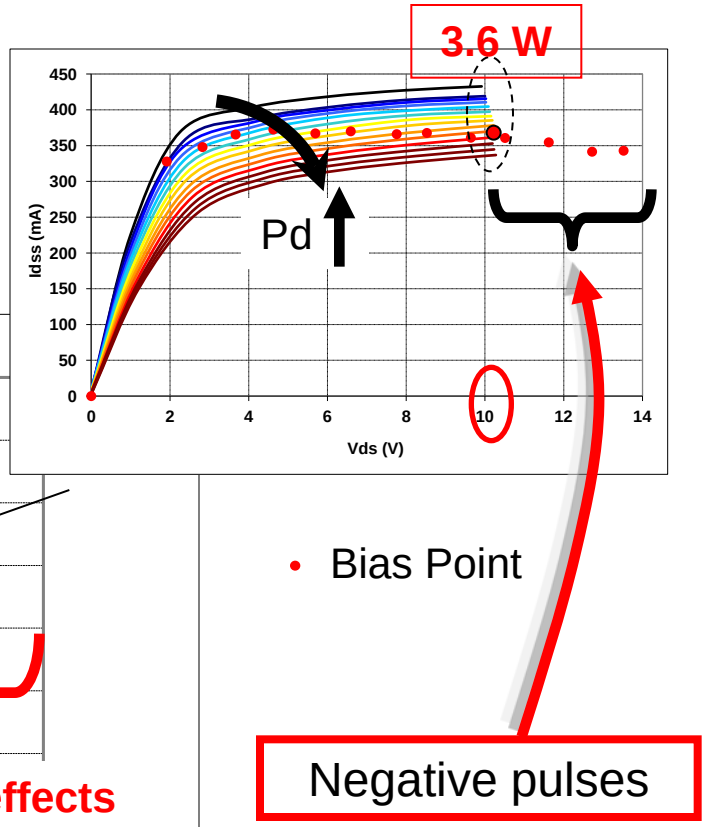
- T_0=25 °C
- $\Delta T = T - T_0$

$$R_{TH} = \frac{\Delta T}{\Delta P_{diss}} = \left(\frac{dR_{ON}}{dP_{diss}}\right) / \left(\frac{dR_{ON}}{dT}\right)$$

DC- Thermal characterization

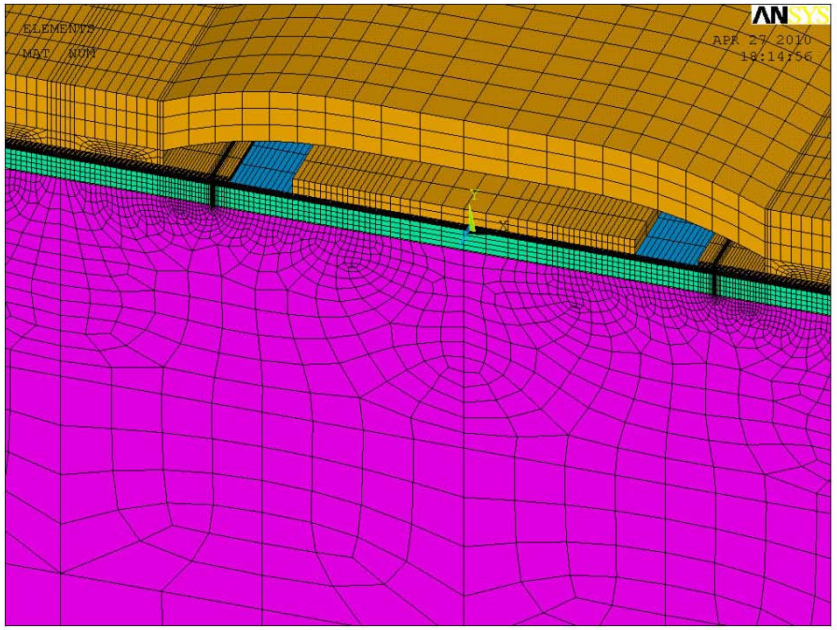
- Rth = 21 °C/W.
- Trapping effects activated above 3.6W





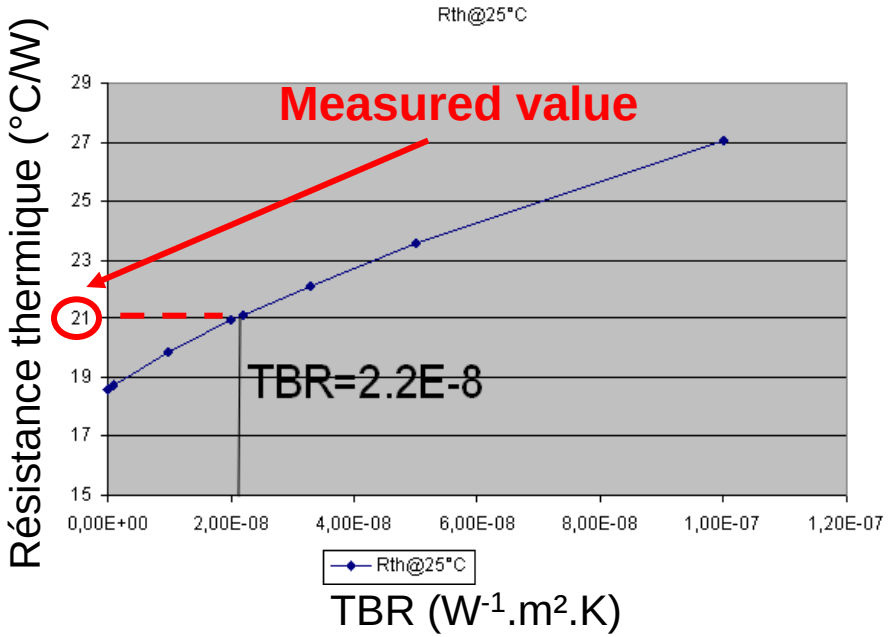
Comparison with 3D simulations

- Thermal Boundary resistance taken into account



(*): A. Sarua and all “Thermal Boundary Resistance Between GaN and Substrate in AlGaN/GaN Electronic Devices”

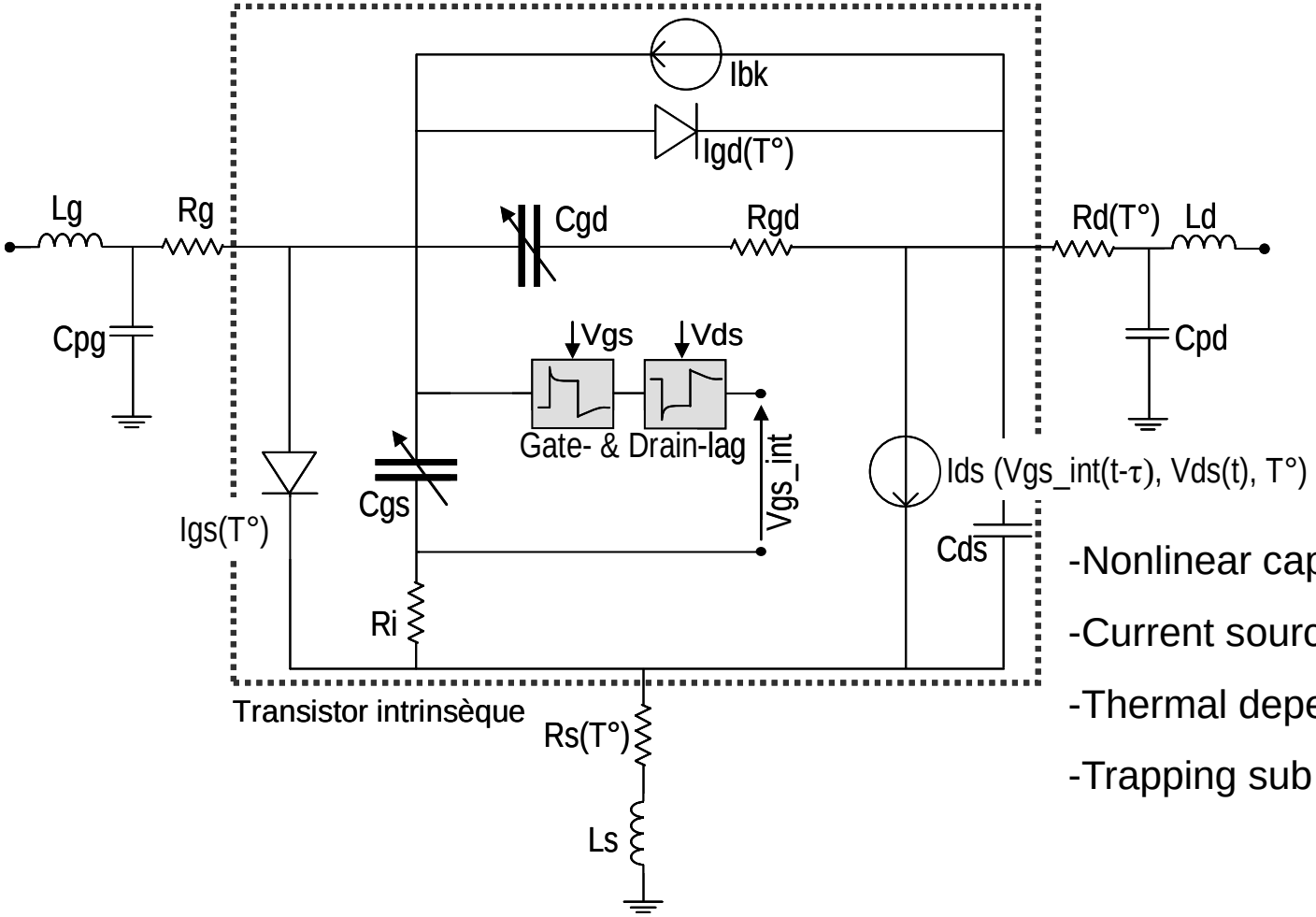
- Rth = 21 °C/W with
- TBR = 2.2E^{-8} m².K/W



- Frequency thermal dispersion still to be characterized through electrical measurements **(interaction of traps and temperature)**

Nonlinear model

Nonlinear electrothermal model with trapping effects



-Nonlinear capacitances

-Current sources

-Thermal dependence

-Trapping sub circuits

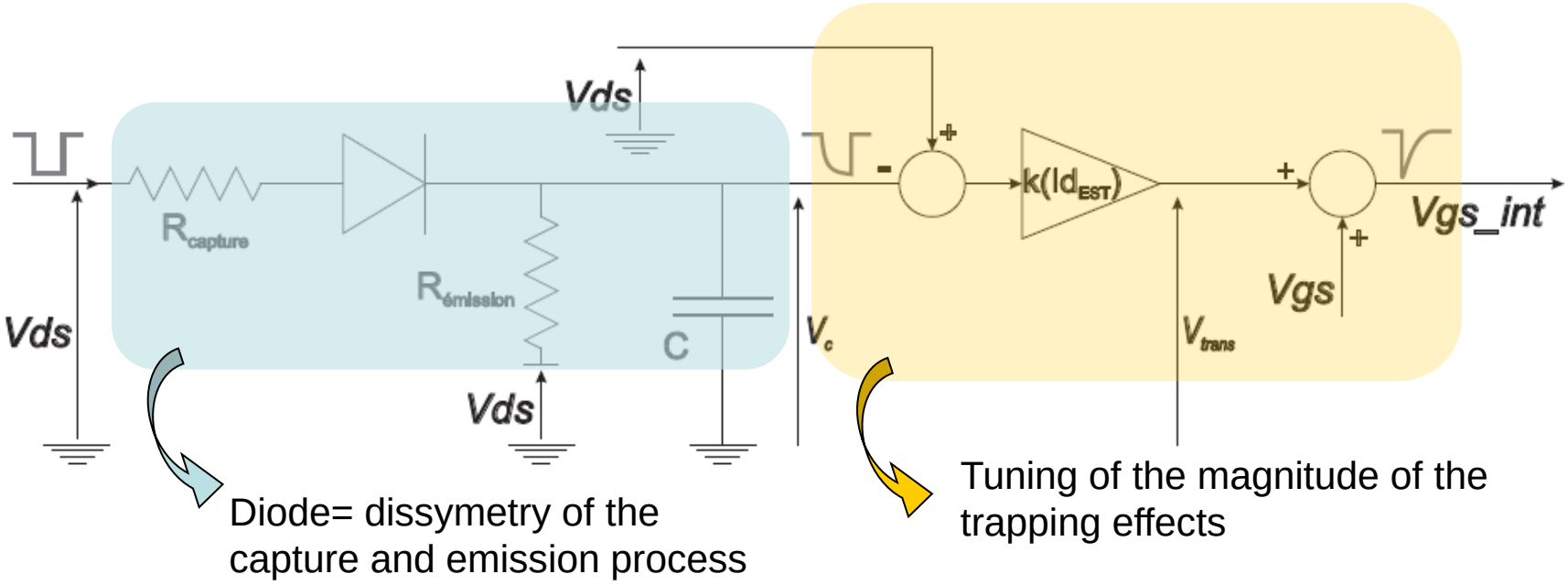
O. Jardel, F. De Groote, T. Reveyrand, J. C. Jacquet, C. Charbonniaud, J. P. Teyssier, D. Floriot, and R. Quere, "An electrothermal model for AlGaN/GaN power HEMTs including trapping effects to improve large-signal simulation results on high VSWR," *IEEE Transactions on Microwave Theory and Techniques,* vol. 55, pp. 2660-2669, Décembre 2007.

Topology of the trapping effects model

- Trapping effects modify the gate command (back gating)

➔ transients on Vgs Transients of the drain current

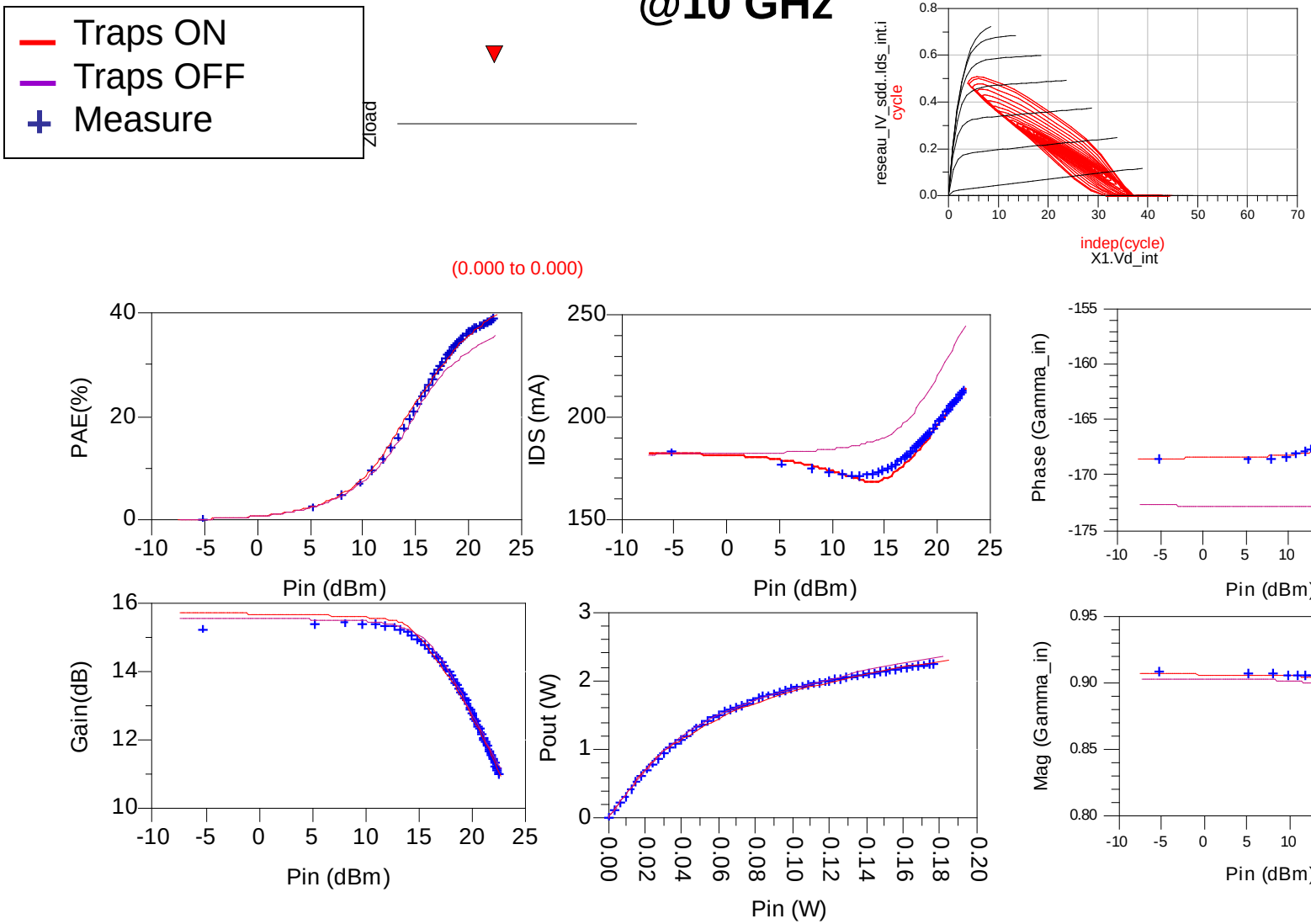
- Charge of the capacitance= Ionized traps
- Charge through Rcapture, Emission through Remission



Fundamental assumption : dissymetry of the capture and emission process

Large signal impact of traps in CW

8x75 µm AlGaN/GaN HEMT in Class AB, Vds=25 V , DC Bias , RF CW, @10 GHz



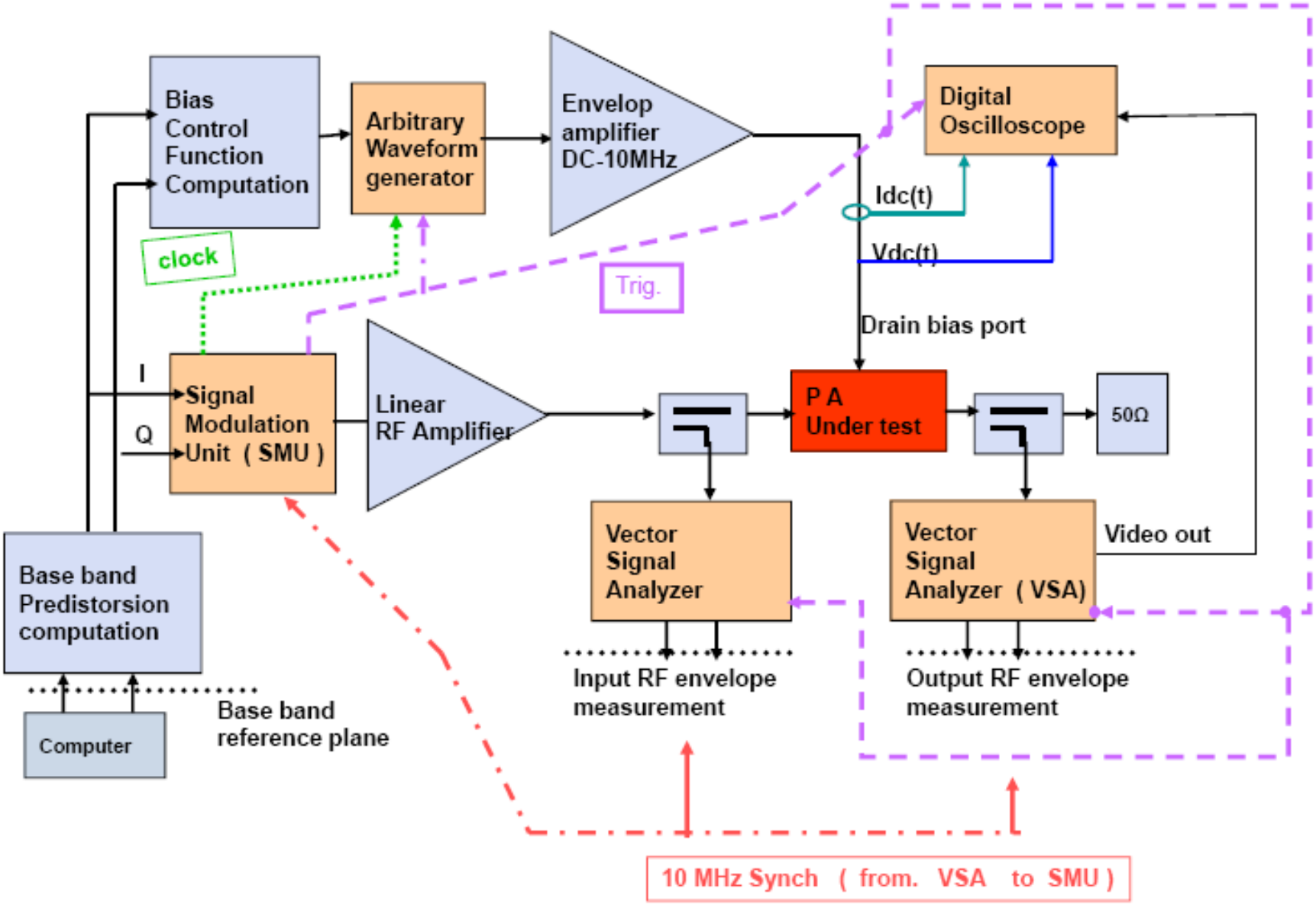
Dynamic large signal RF effects

Questions:

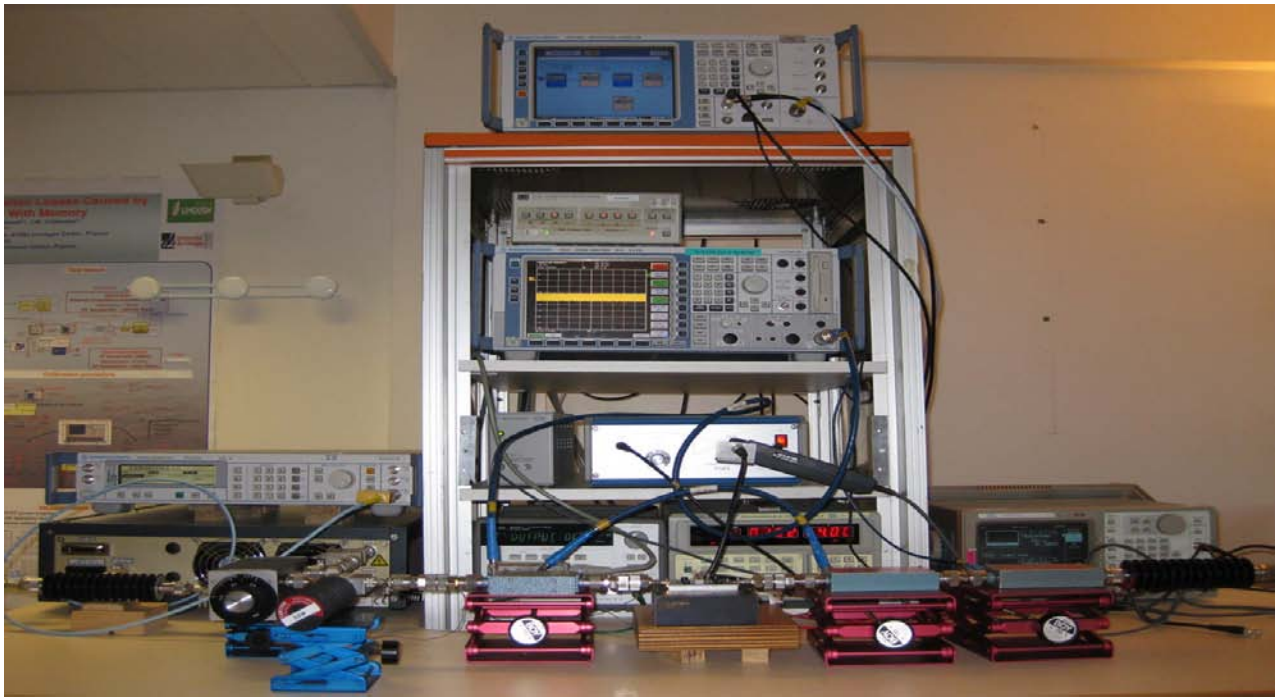
- What is the impact of an enveloppe dynamically varying signal ?
- How to characterize this impact ?

- Two kinds of measurements have been performed through the use of dedicated test benches
  - **Time domain enveloppe characterization**
    - test set specialized for the optimization of Envelope Tracking PA
    - allows a simultaneaous control and measurement of input/output characteristics and gate/drain voltages and currents
  - **Time domain (TD) pulsed Large Signal Network Analyzer (LSNA)**
    - Allows TD multiharmonic Load Pull measurements in various pulse configurations

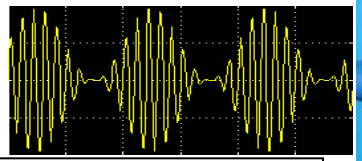
Time Domain Enveloppe Test Bench

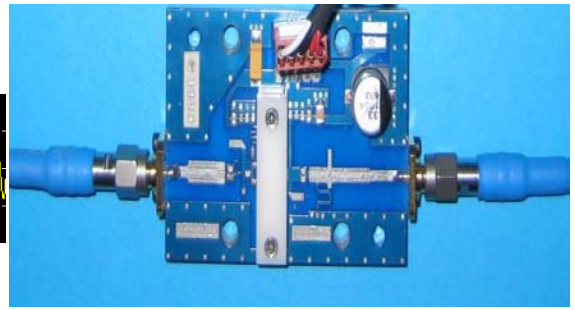


GaN PA demoboard 10W - 3.6 Ghz from CREE

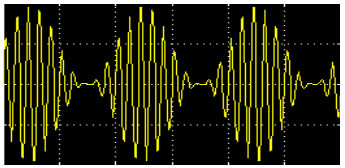


RF input signal

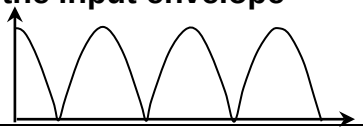




RF output signal



Magnitude of the the input envelope

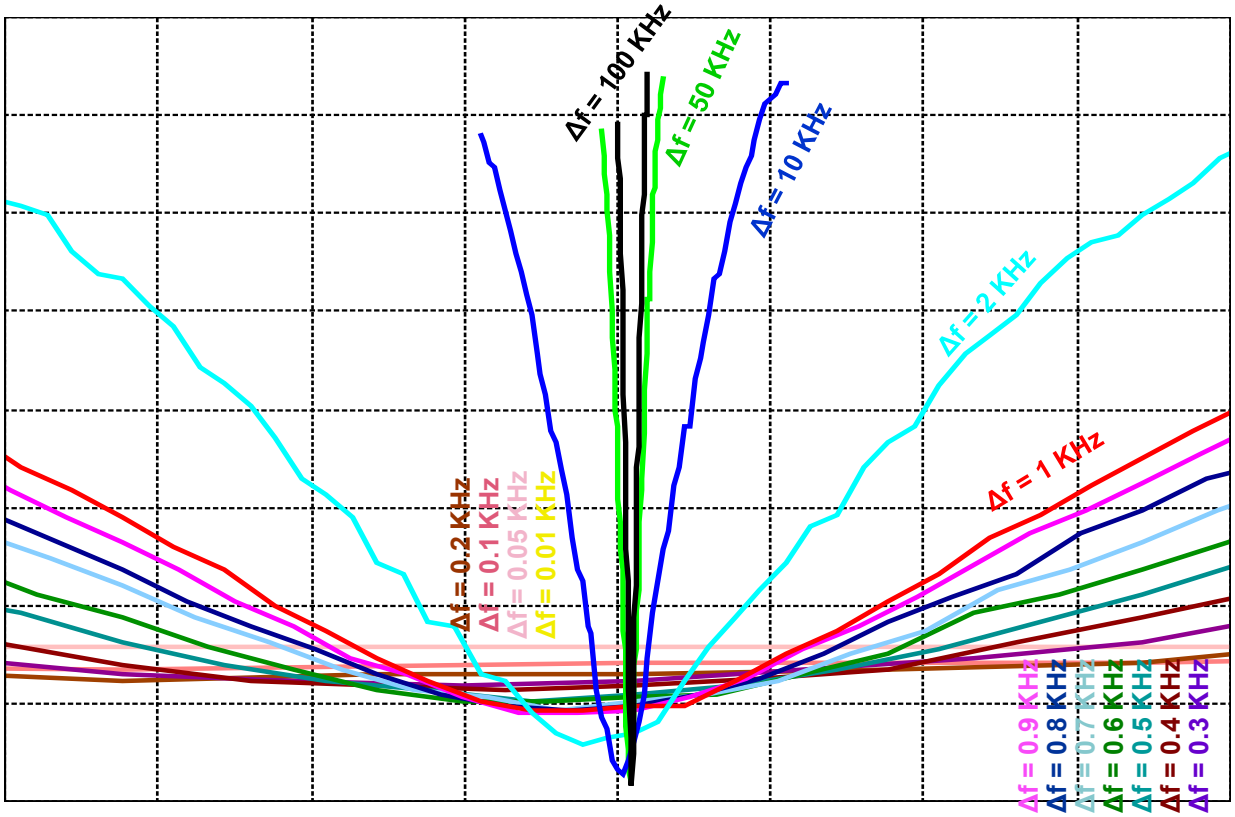


Demoboard GaN CREE 10W , 3.6Ghz
Vdso=28V , Idso =200mA

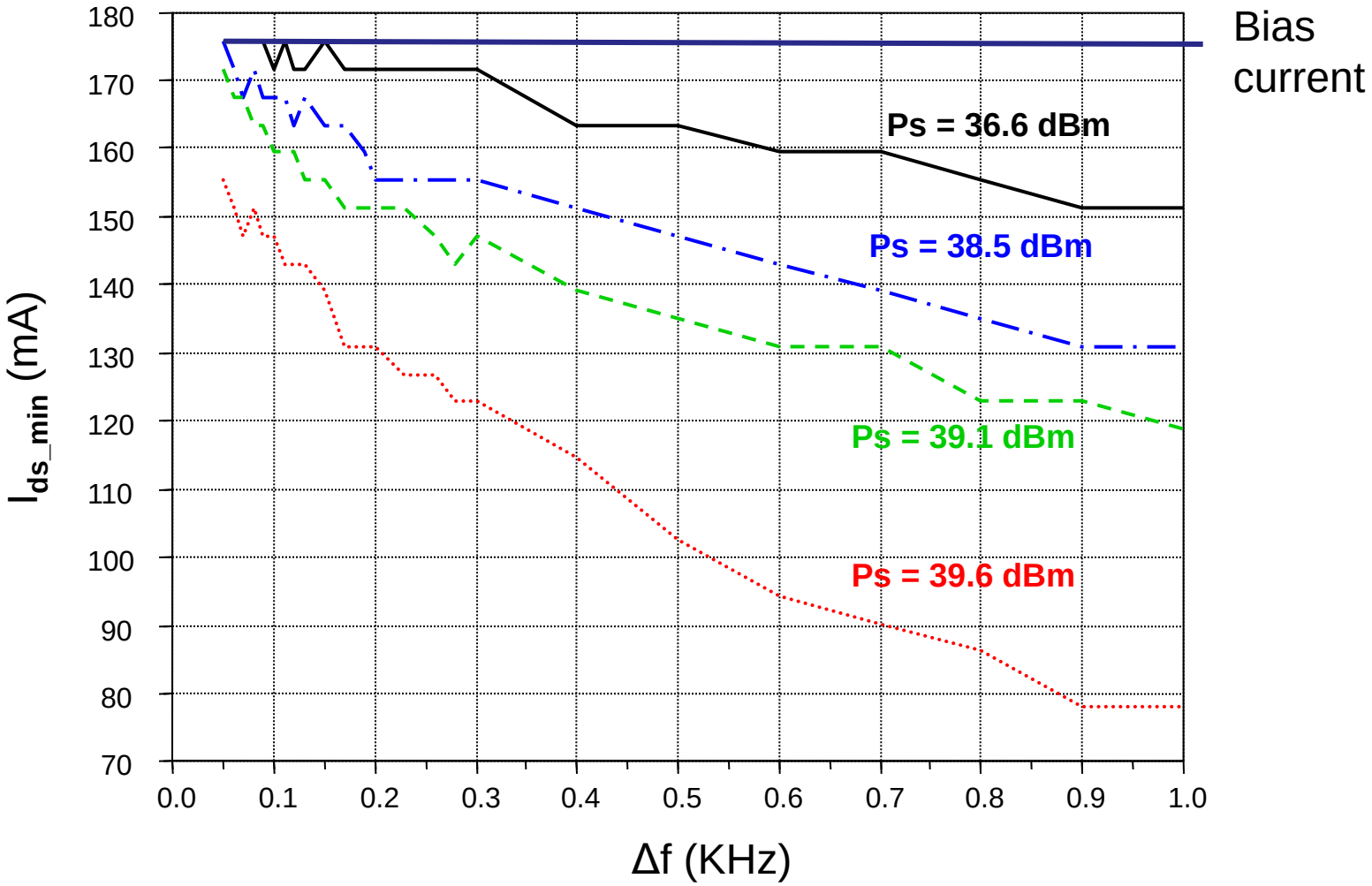
Magnitude of the the output envelope

Results: Measurement of the Average Drain Current

- At very low modulation frequencies when the input power is zero the average drain current recovers the bias value
- this is no longer the case when the modulation frequency increases

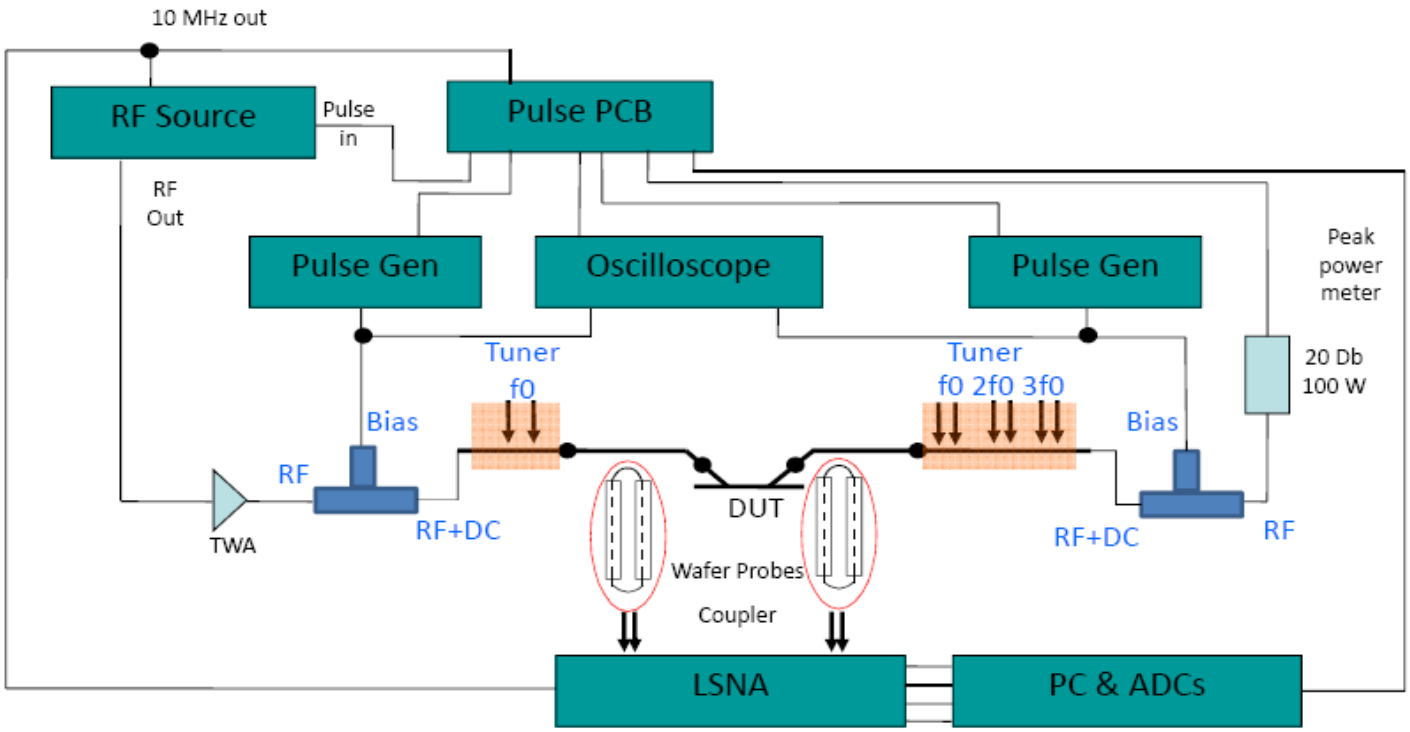


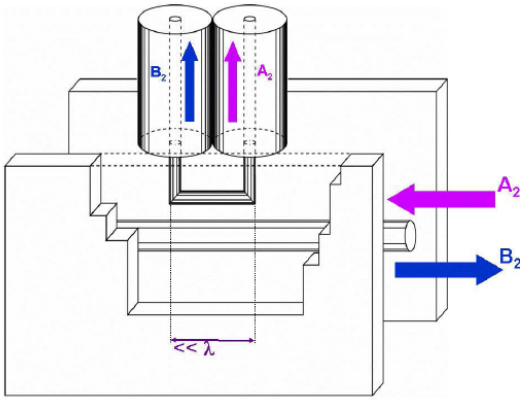
Minimum current value vs output power and frequency

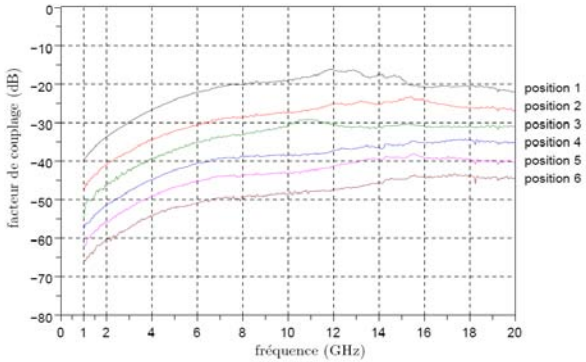


- The minimum value decreases when the frequency and the output power increase

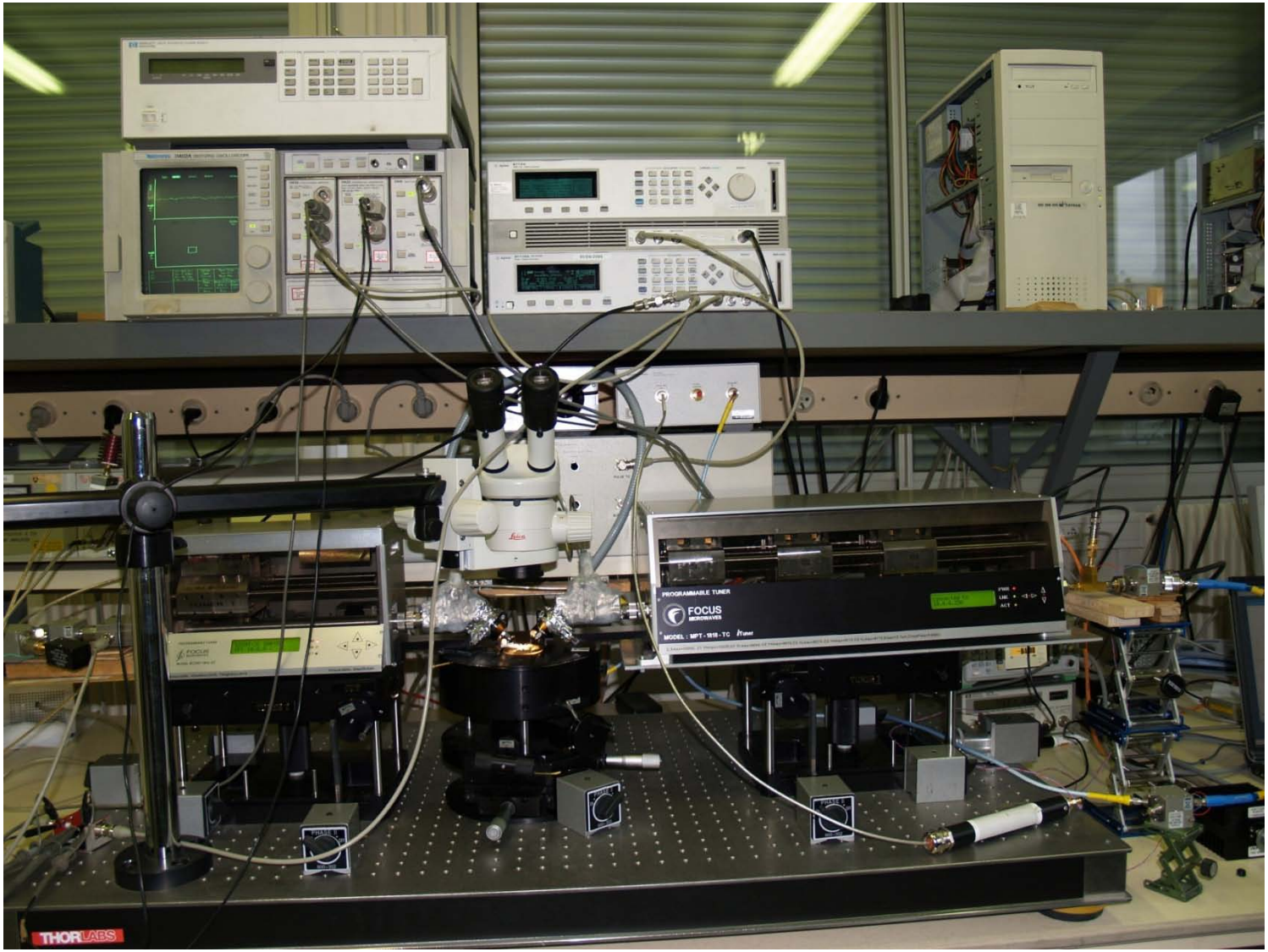
Pulsed LSNA-organisation



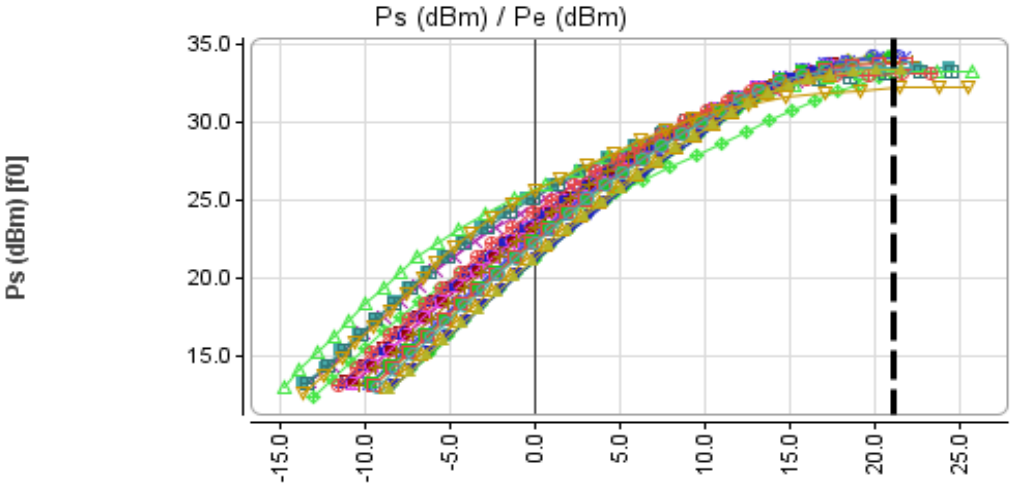


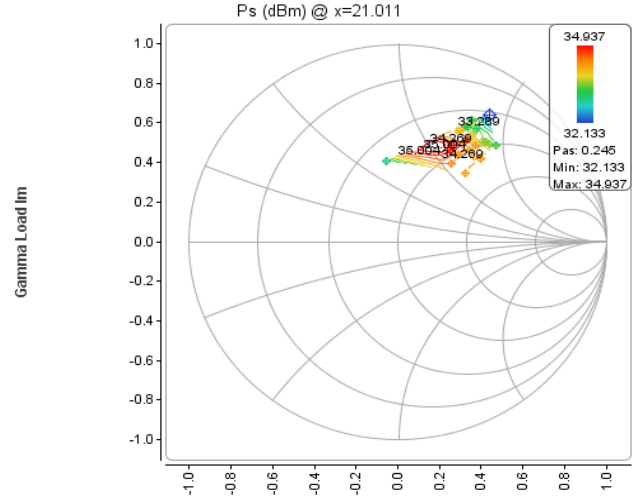


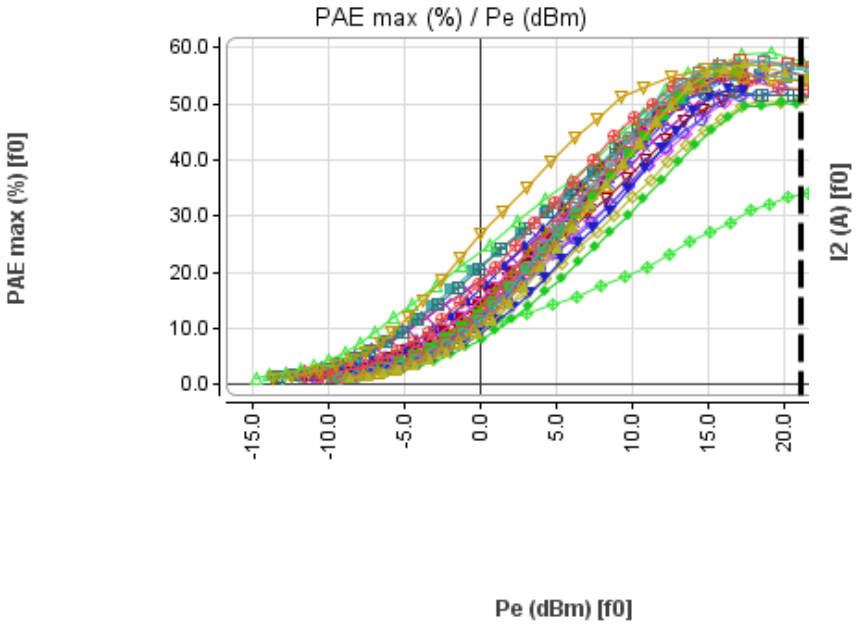
Pulsed LSNA- The set-up

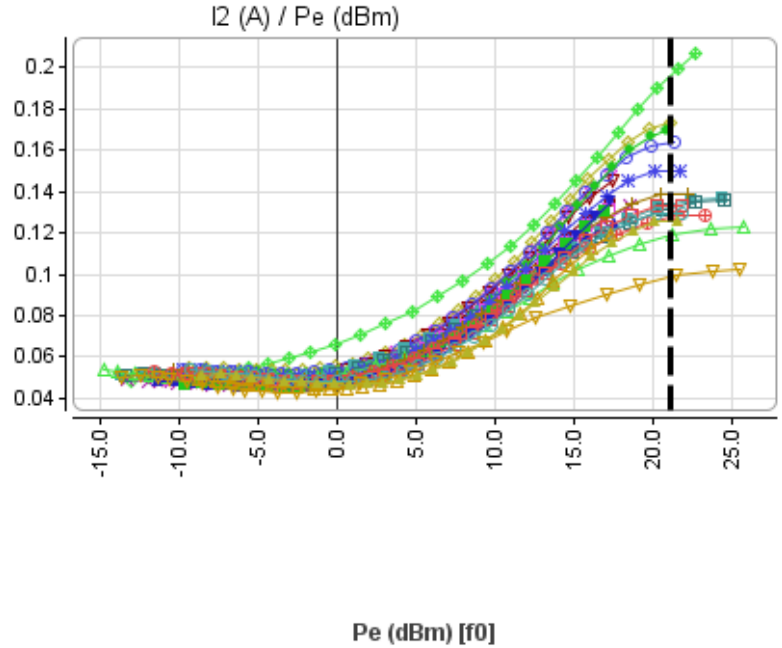


Transistor HEMT AlGaN/Gan 8x75 µm @ 6GHz



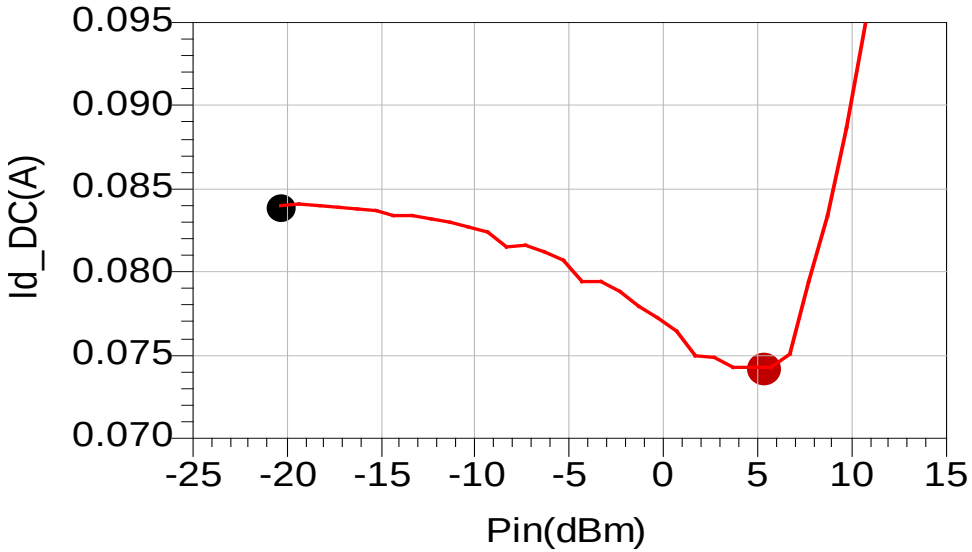


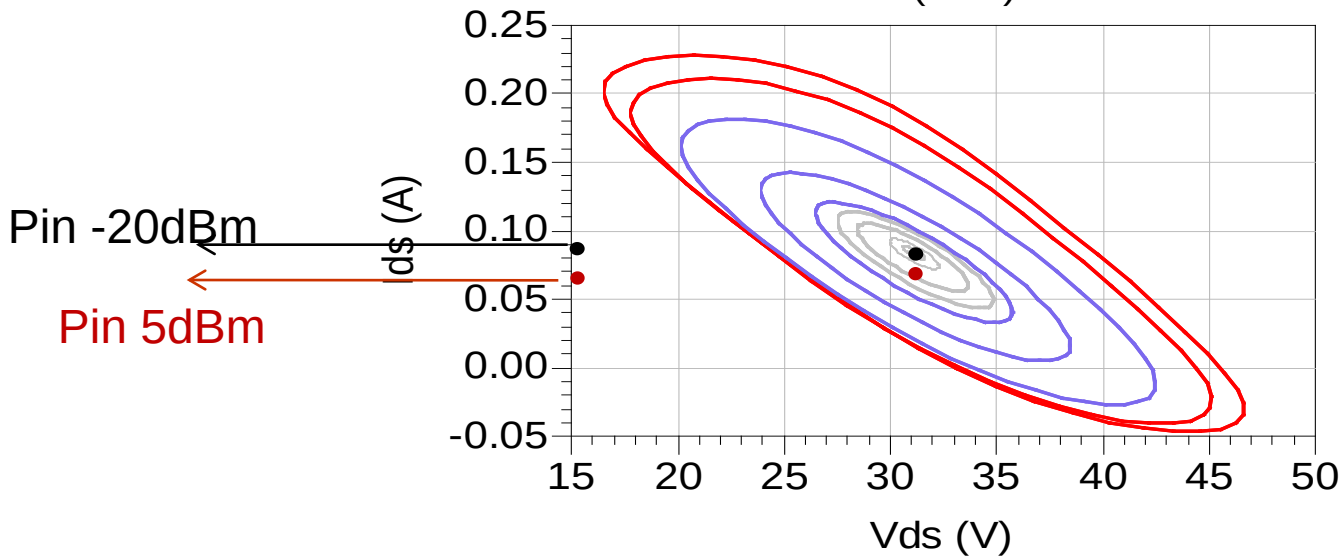




Average drain current a key figure

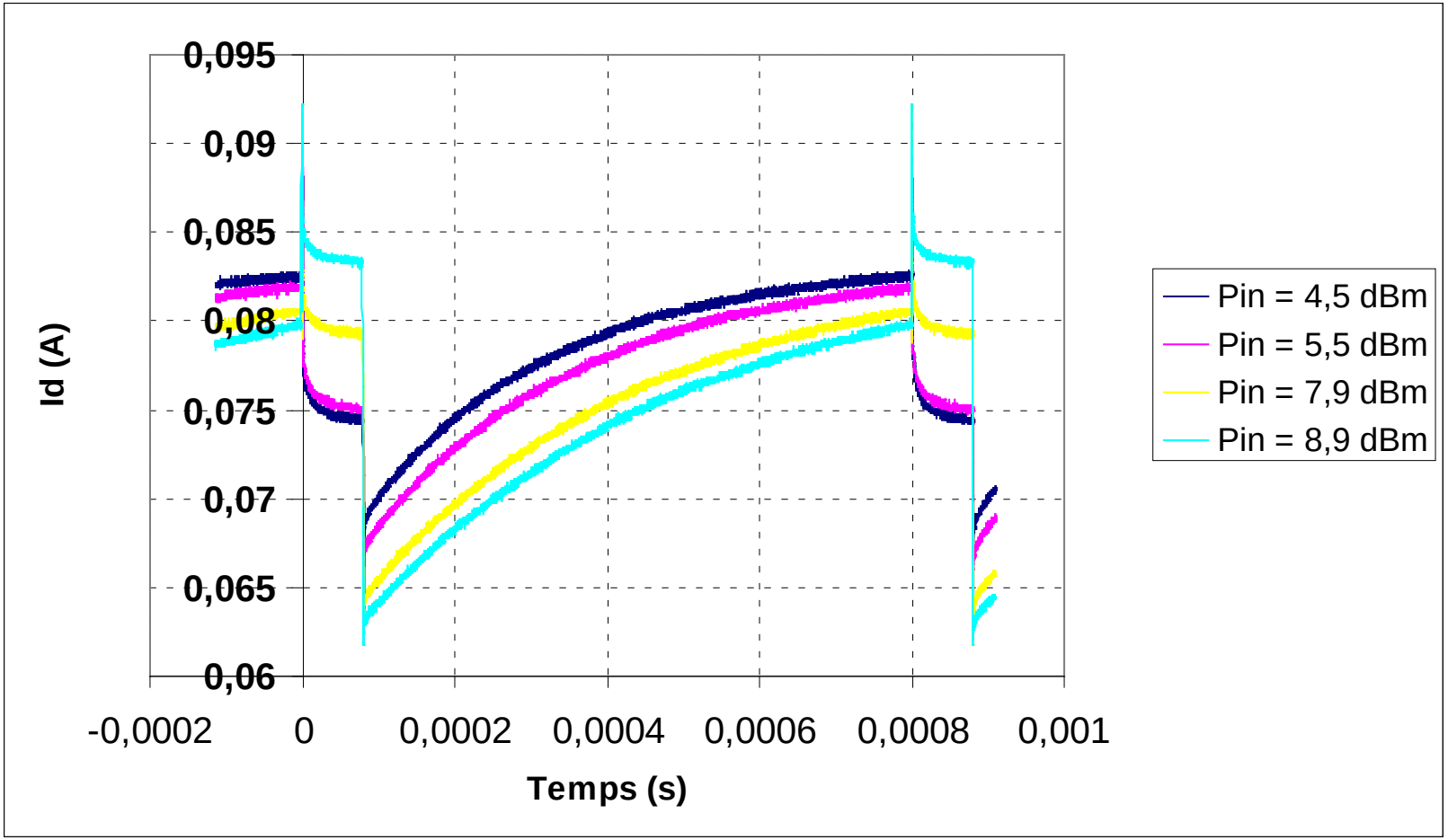
- Load pull @ 6 GHz (pulsed)
- Drain Voltage 30V (DC)
- Drain current 84 mA
- Zload (@fo)= $0.467*e^{j34.47°}$
- Zload(@2fo) = 50 Ohms





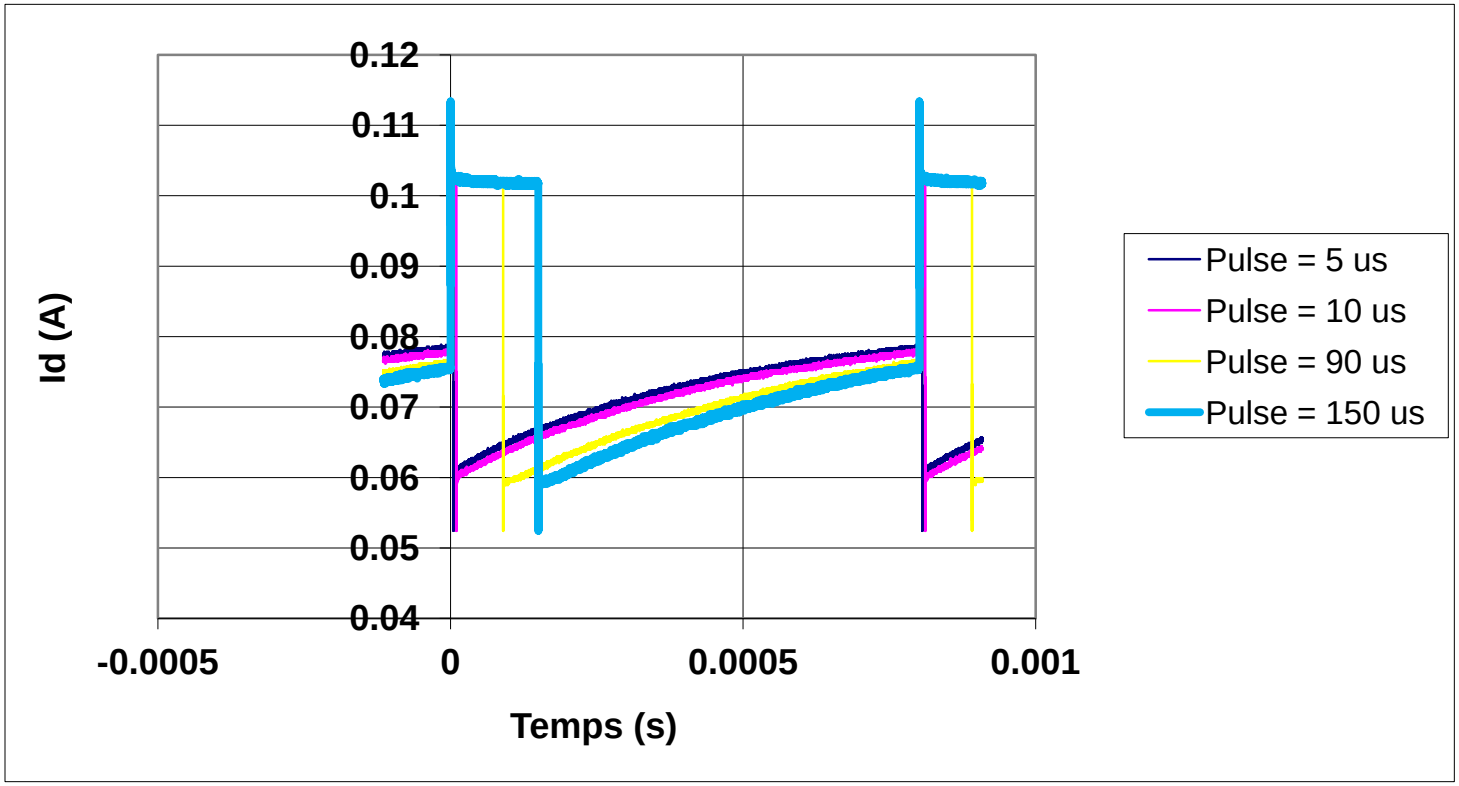
Profile of the average drain current vs input power

- DC Bias Drain Voltage 30V & Drain current 84 mA
- Pulse duration: 80µs ; pulse period 800µs



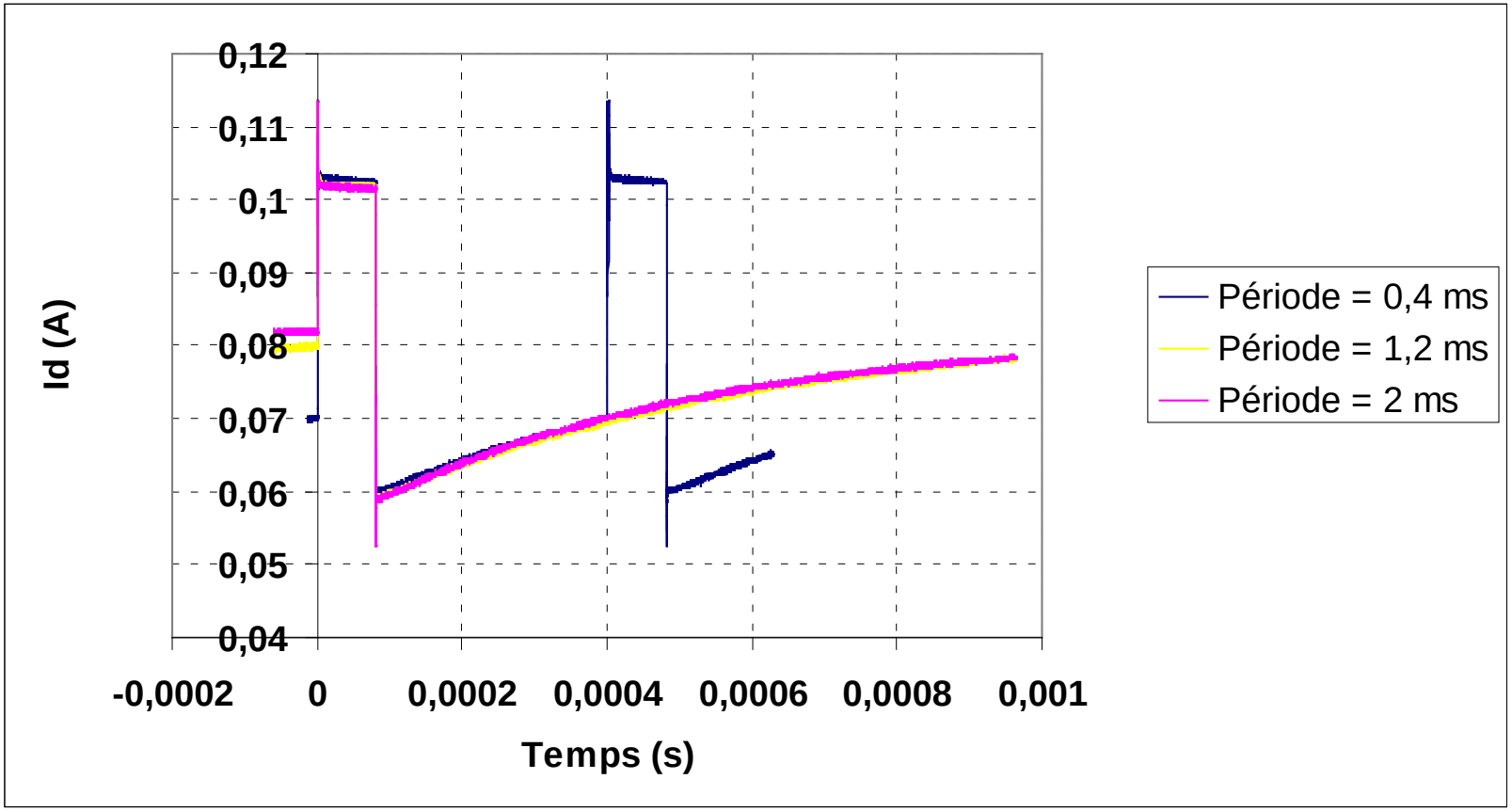
Profile of the average drain current vs pulse duration

• The key point is that the minimum value of the drain current does not depend on the value of the duty cycle.



Profile of the average drain current vs pulse period

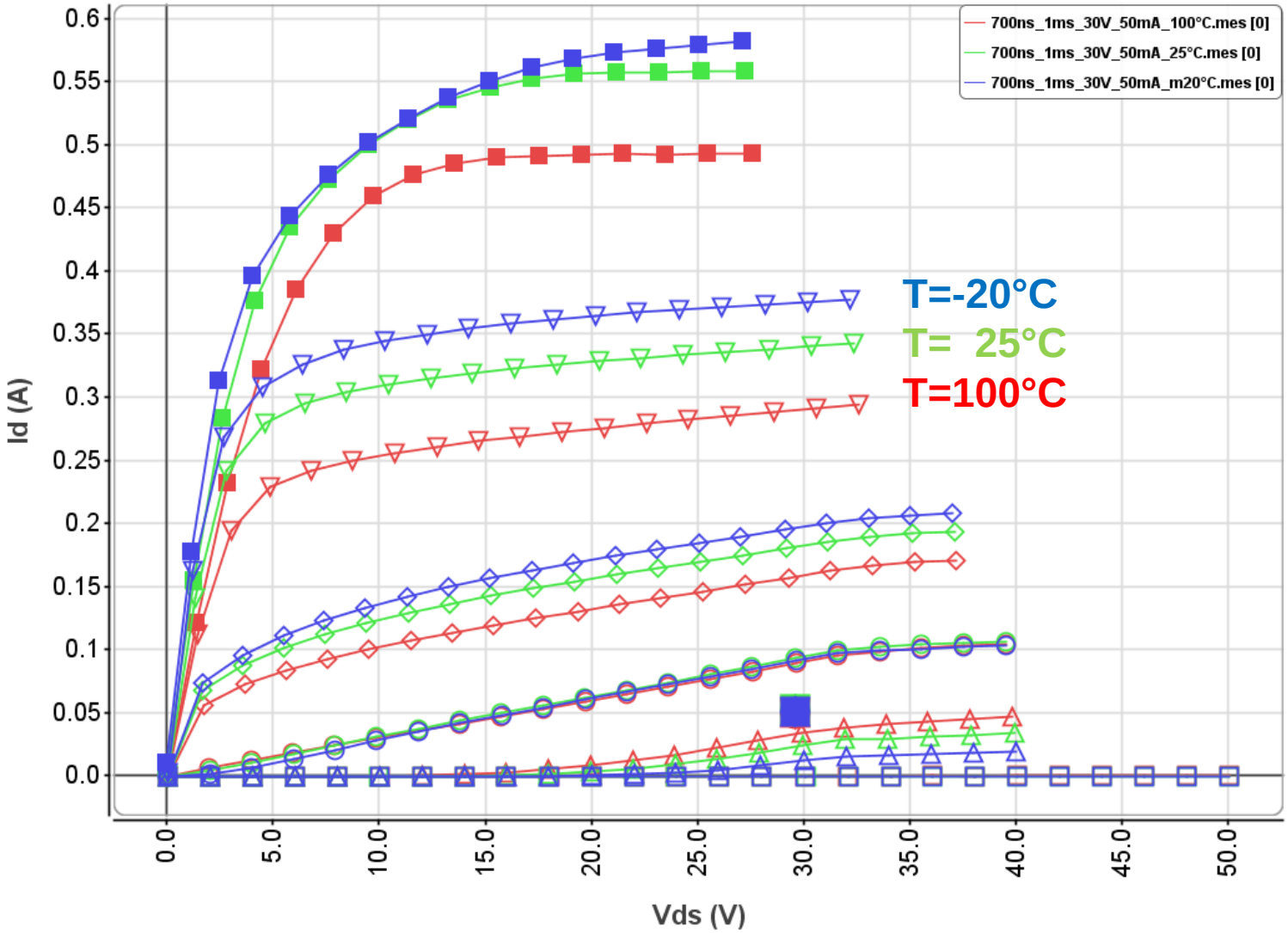
- pulse duration 80µs
- input power Pin = 10.9 dBm



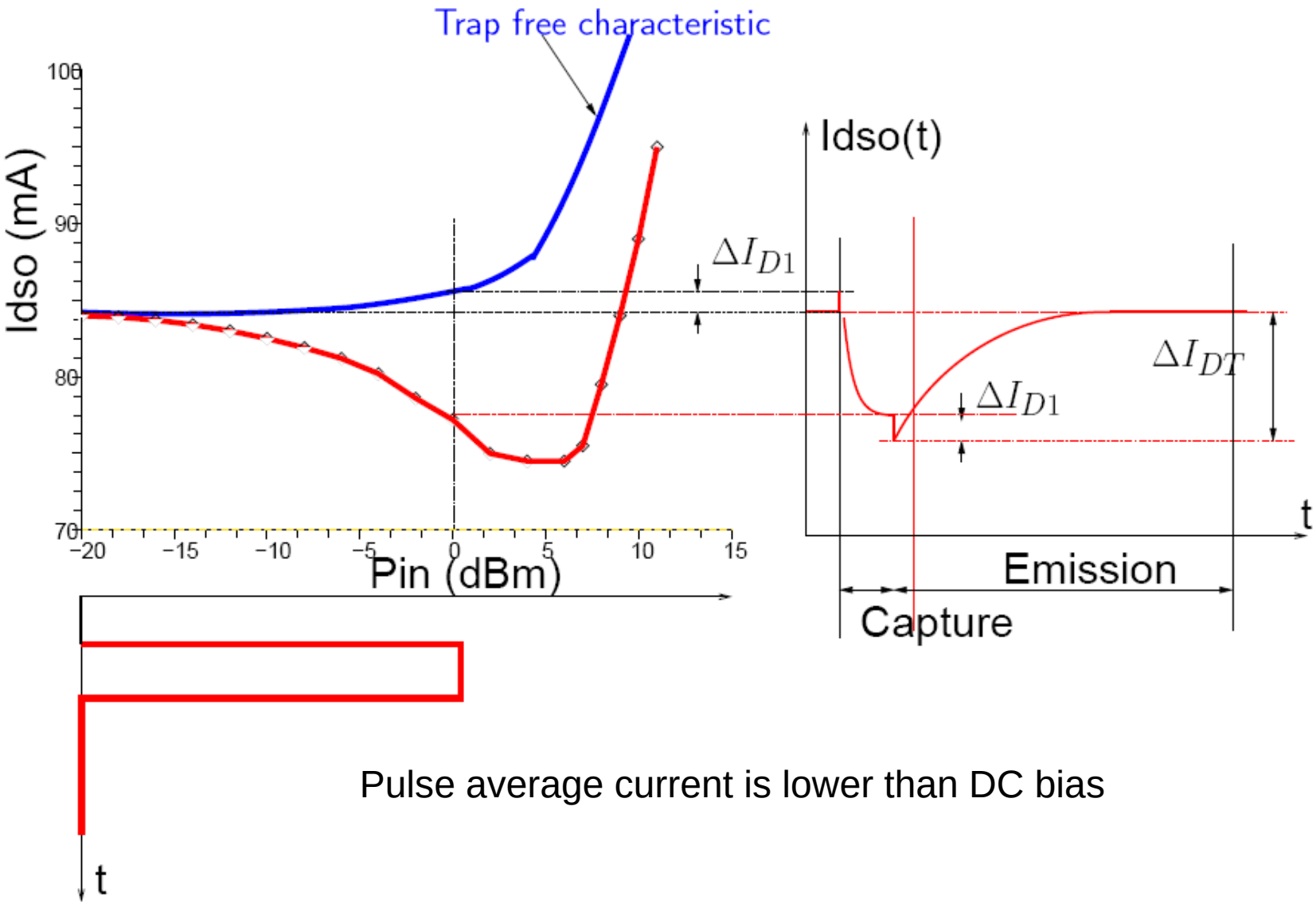
Interpretation

- What is the main reason of these behaviors ?
  - o Self heating effects ?
  - o Trapping effects ?
- Self heating effects are indeed present in the transistors but cannot explain the observed behavior.
  - o In pulsed conditions when the pulse duration increases the minimum current should decrease as the temperature rises. This is not the case
  - o The transistor are biased at relatively low currents where temperature effects do not severely impact the current level. Even a large temperature increase could not lead to such a large current variation.
  - o Complete 3D thermal simulations of the 4x75µm device have confirmed that the temperature plays a minor role in the shape of the average current
- **Trapping effects are likely to be the main responsibles.**

Thermal characteristics of the 8x75µm AlGaN/GaN HEMT

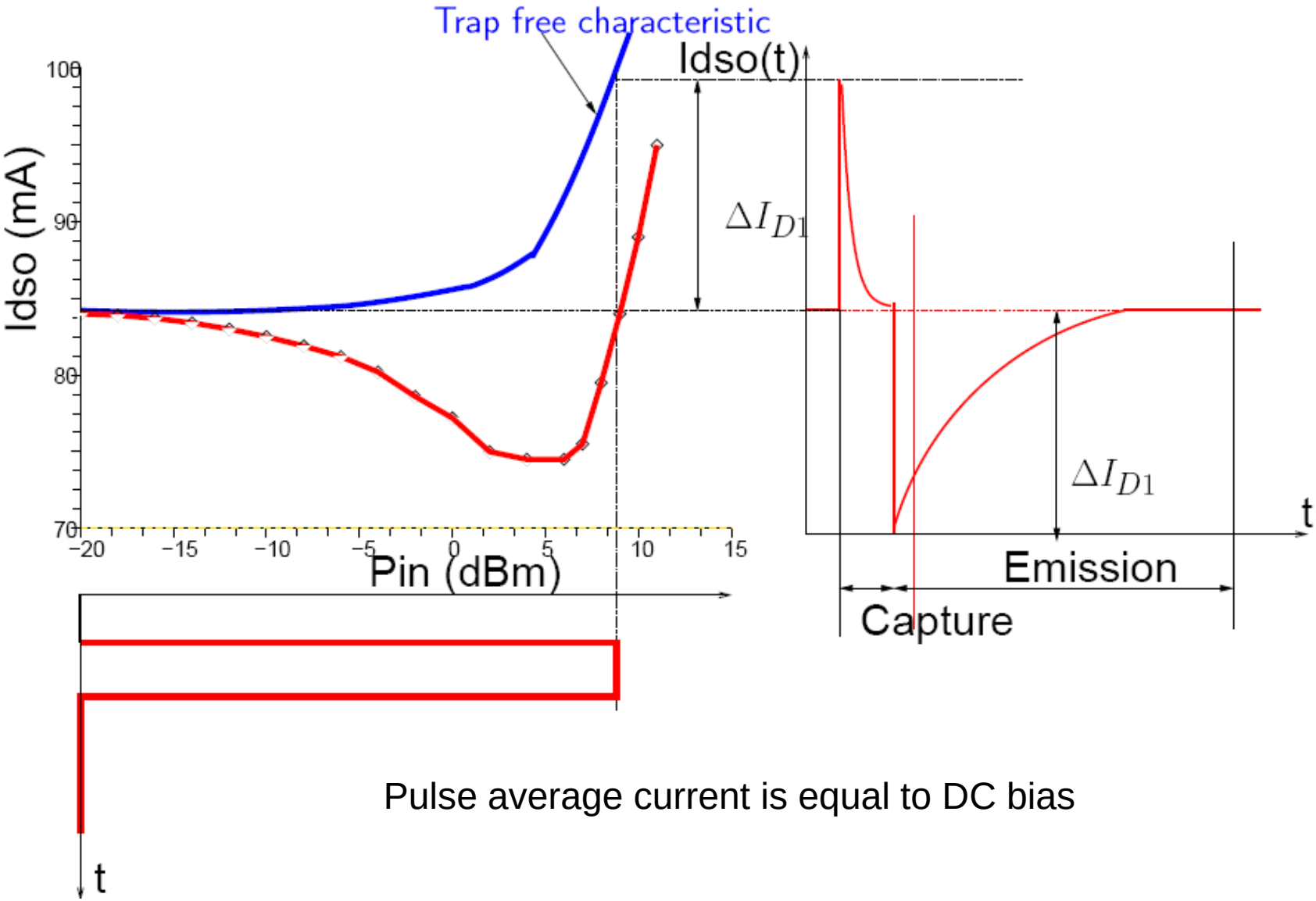


Pulse profile explanation (Pin=0dBm)



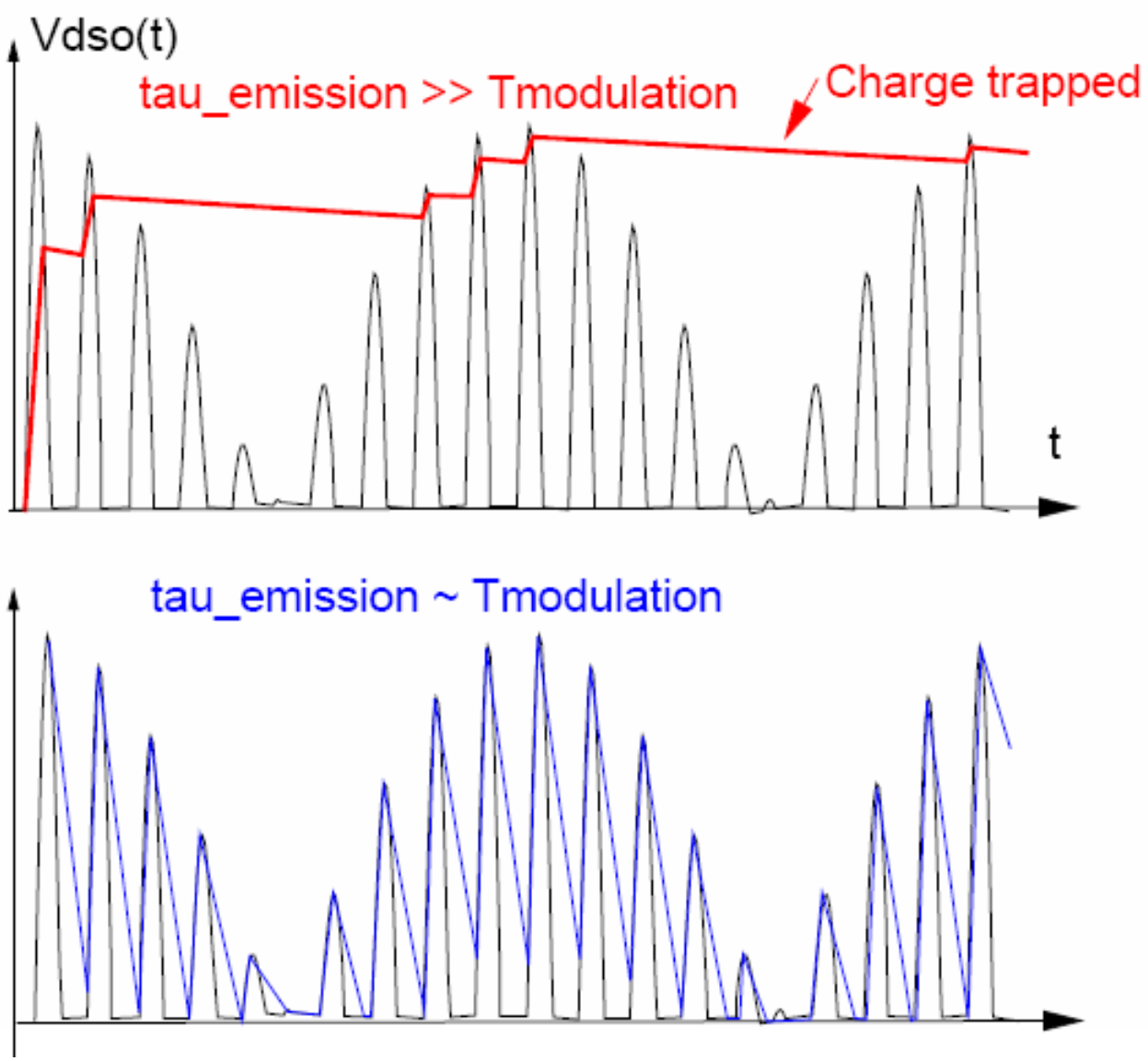
Pulse average current is lower than DC bias

Pulse profile explanation (Pin=8.5 dBm)

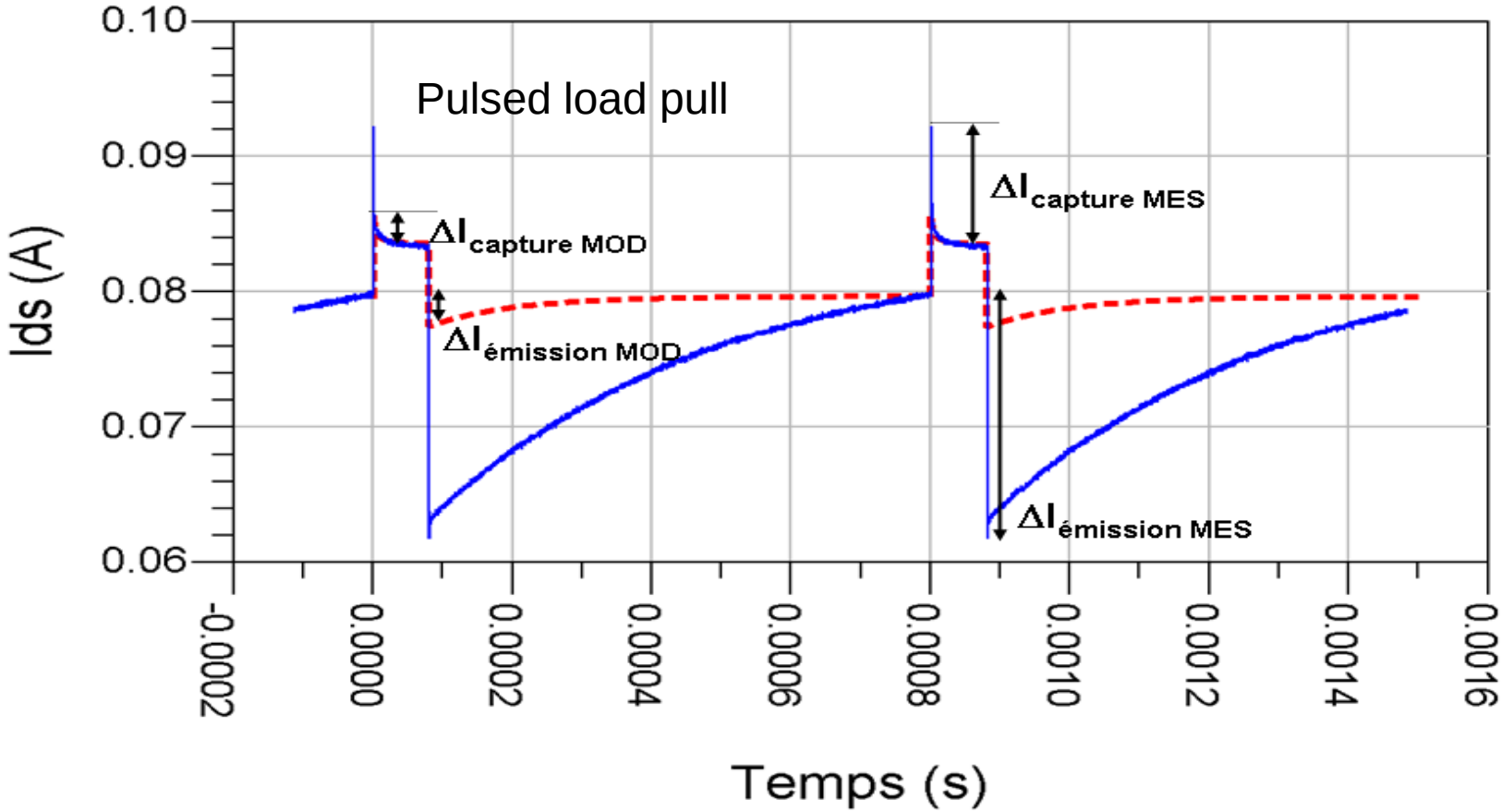


Pulse average current is equal to DC bias

Current profile for the two-tone modulation

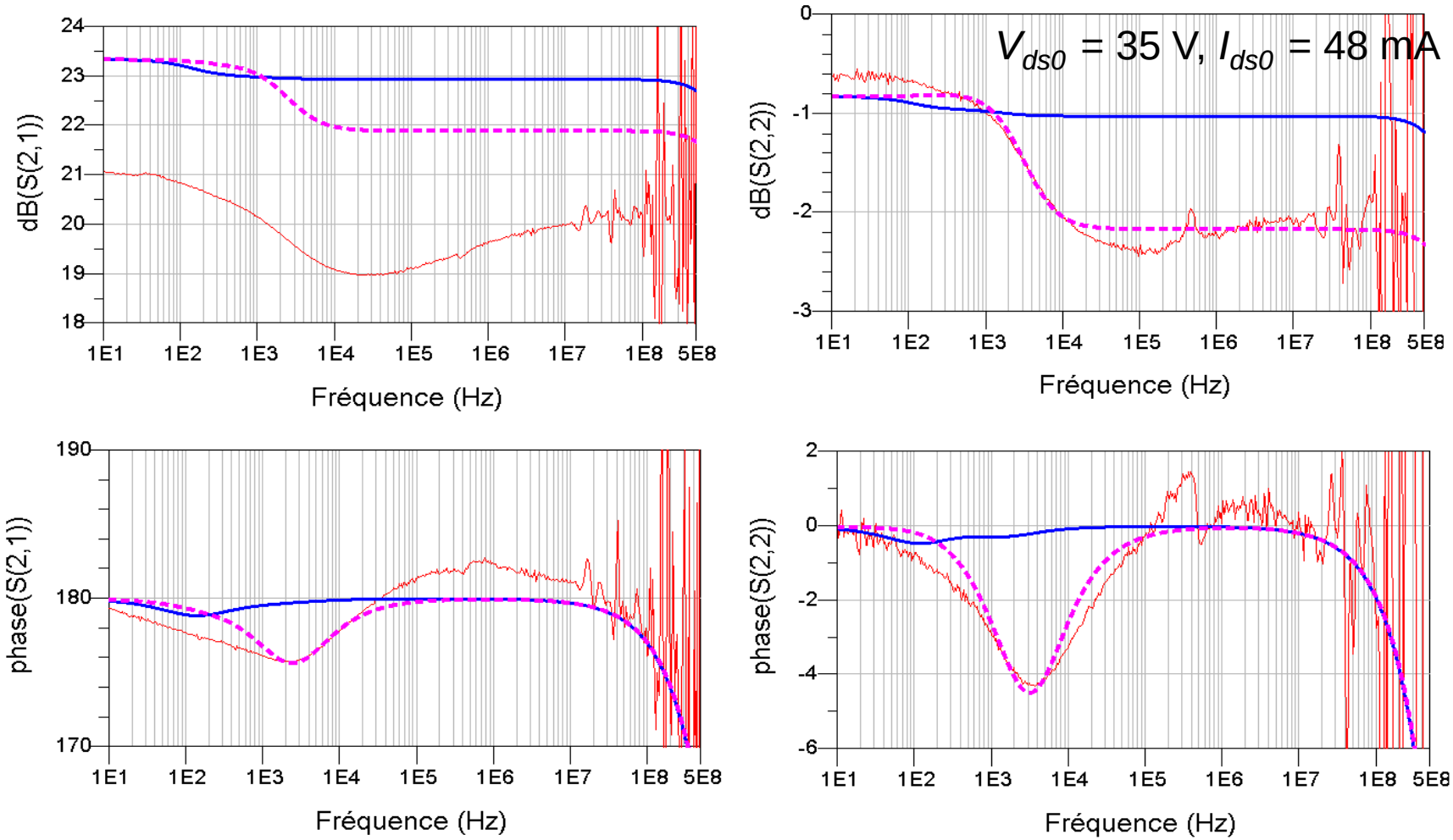


Discussion



- Qualitative behavior OK but quantitative Not OK
- In order to get a good fit we have to increase the trapping effect

LF Dispersion aspect



- When trapping effects are increased good accuracy with LF characteristics
- **But RF output power and PAE are not well described**

Conclusions

- Trapping effects have a significant impact on the dynamics of RF modulated signals.

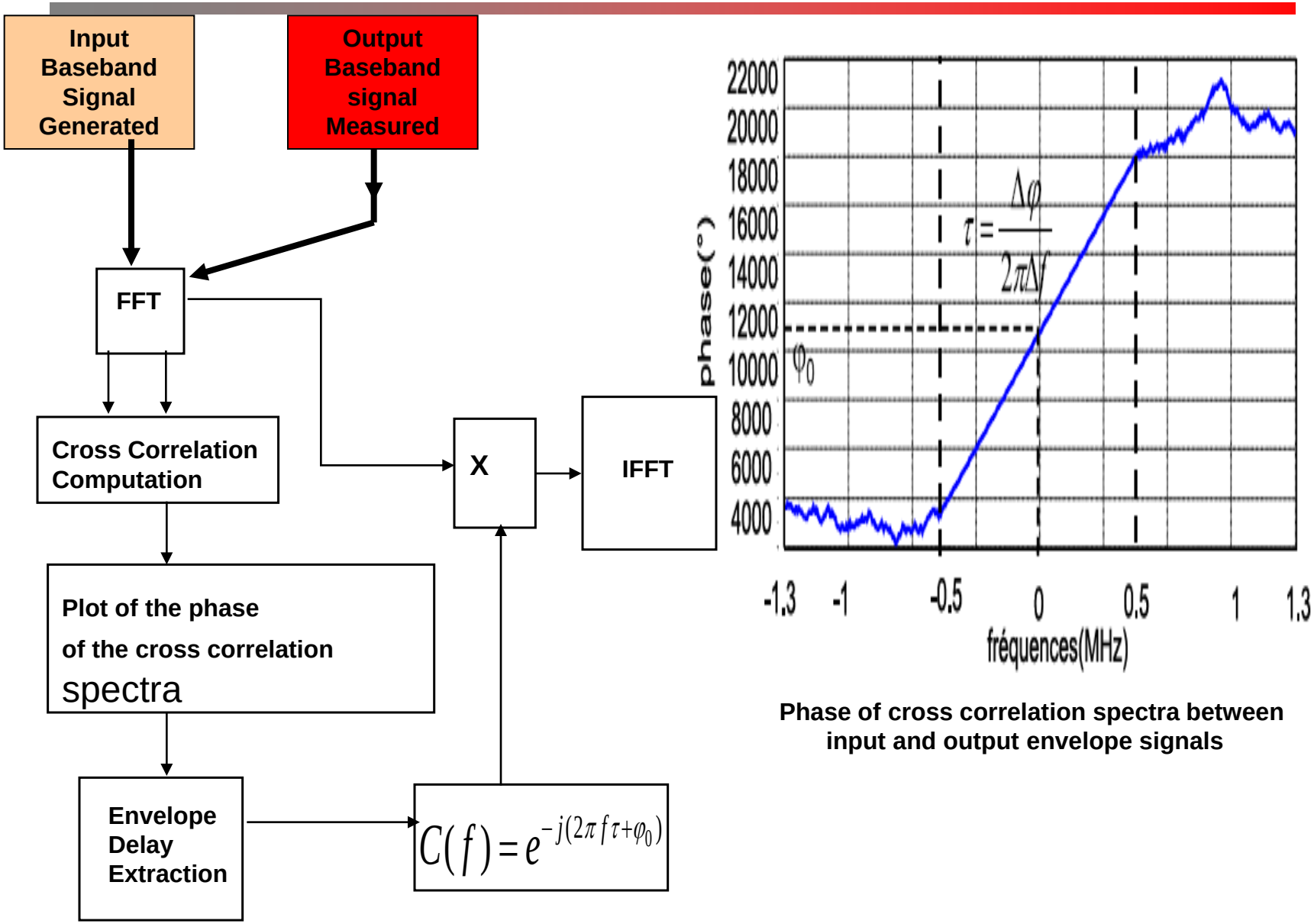
- They lead to complex nonlinear memory effects that have to be taken into account for system design

- The model proposed by Jardel & Al exhibits good qualitative behavior but further investigation must be performed to accurately fit the quantitative values.

    o nonlinear behavior of the trapping process

    o separation of thermal and trapping effects

Time alignement procedure (input-output)



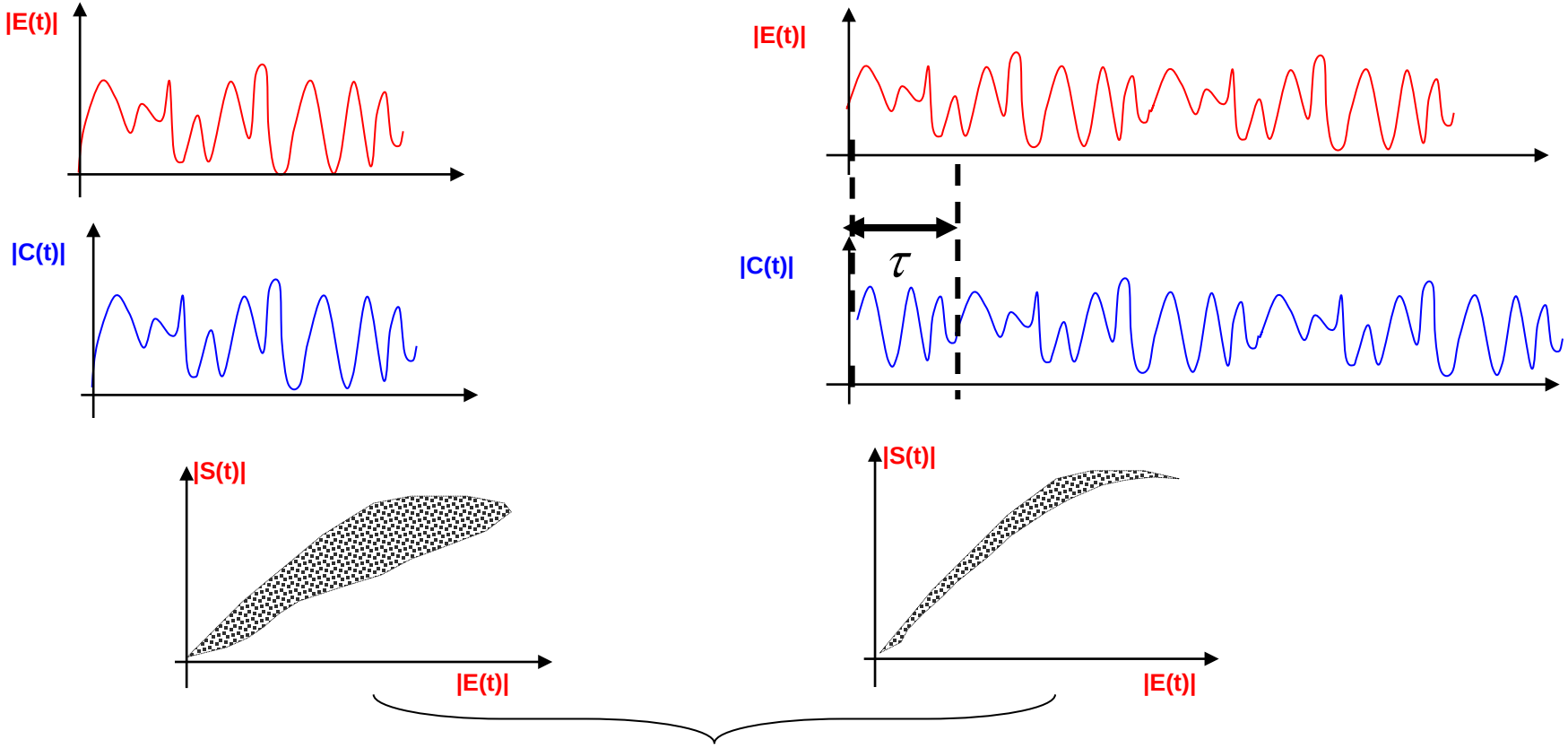
Phase of cross correlation spectra between input and output envelope signals

Time alignement procedure (envelope-drain bias)

|E(t)| is the magnitude of the input envelope signal

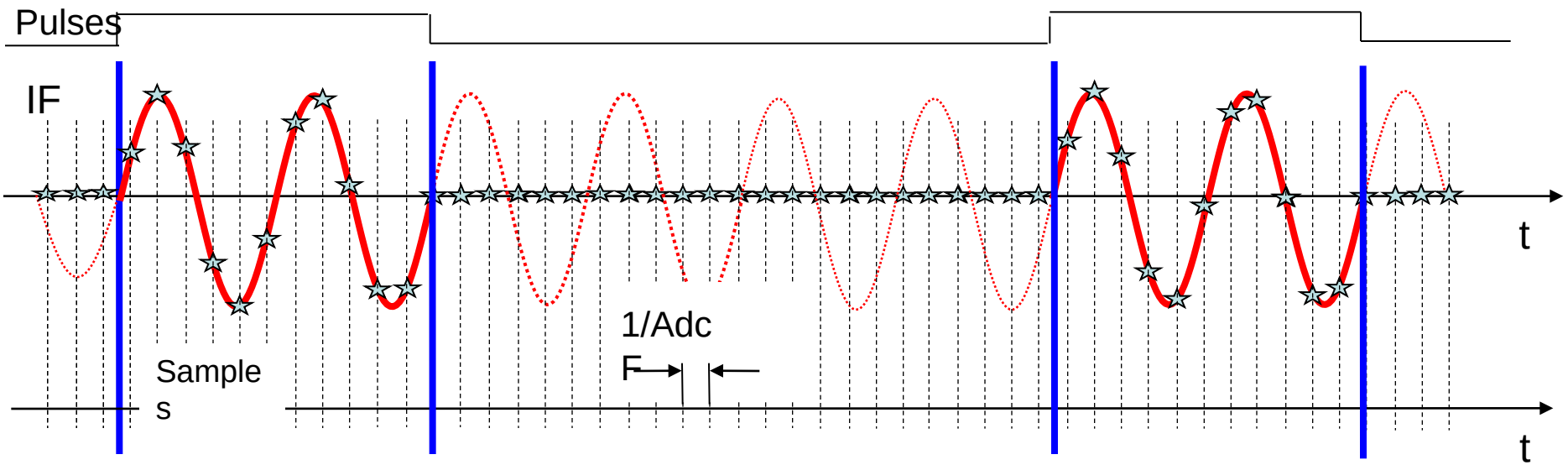
|C(t)| is the drain bias signal

|S(t)| is the magnitude of the output envelope signal



τ is tuned to minimize the hysteresis of the **|S(t)| versus |E(t)| characteristic**

Stroboscopic approach of pulsed RF receiver



Sampling and quantization of IF signal

All samples of IF signal are not to be considered : interesting data are only during the pulses. 2 ways :

- Adcs always running with large memory, and sorting of memory arrays ;
- Adcs with trigger and burst capabilities.