Transistor and Amplifier Modeling Methods for Microwave Design

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UNIVERSITY OF SOUTH FLORIDA

PRECISION MEASUREMENTS AND MODELS YOU TRUST

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- Dr. David Snider, Univ. South Florida
- Ray Pengelly and Simon Wood, Cree, Inc.
- Dr. Steve Maas, Non-linear Technologies, Inc.
- Dr. Peter Aaen, Freescale
- Dr. Yusuke Tajima, Auriga Measurement Systems

Overview

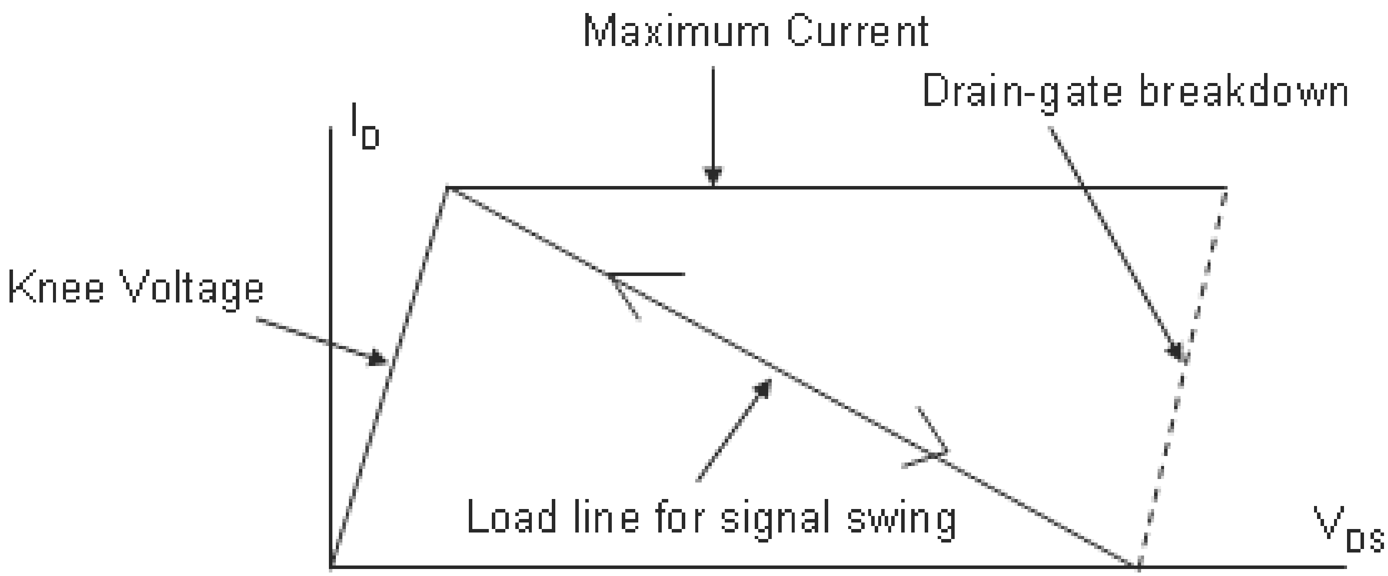
- Nonlinear Modeling
- Thermal and Trap Issues
- MESFET and PHEMT Modeling
- MOSFET Modeling
- HBT Modeling
- Behavioral Modeling of Amplifiers
- References

Motivation/Need for Non-Linear Models for PA Design

- The demand of accurate models
  - Accurate models can predict precisely the performances of RF circuit designs – yet challenges remain!
  - PA Design has become more complex in terms of competing multi-dimensional requirements of BW, efficiency, linearity and power performance.
- Electro-thermal effects often a critical issue for accurate HPA modeling
- Requirement of Isothermal measurements
  - Self-heating effects held constant
  - Some applications (GSM, radar) required pulsed operation.
- Advance model testing
  - Wireless systems use various digital modulation signals.
  - Are currently available models adequate for emerging requirements?

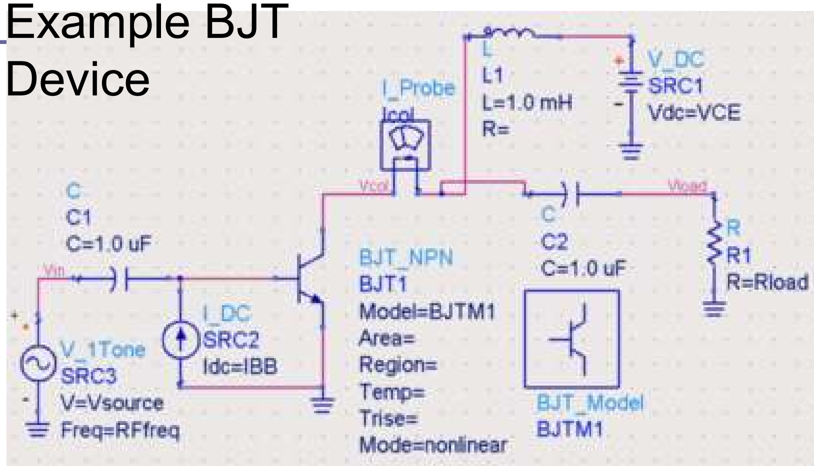
Nonlinear Modeling

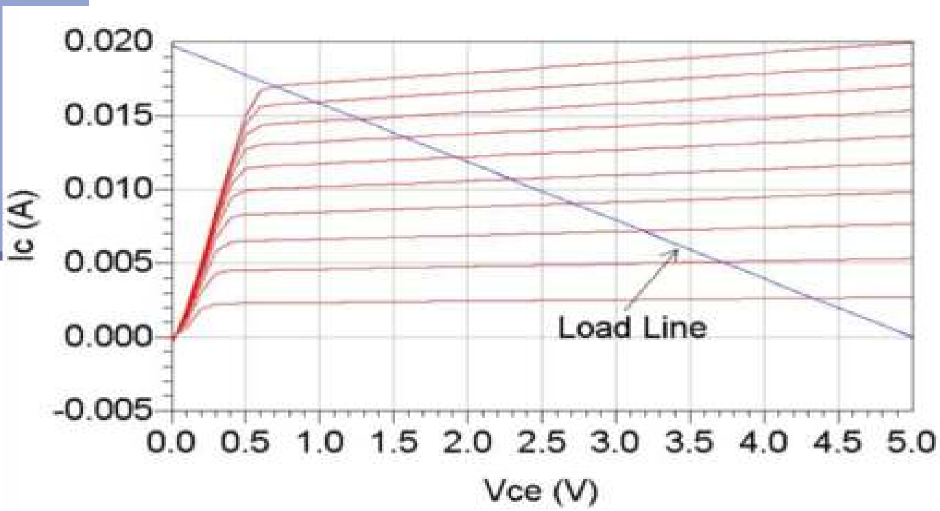
- Device behavior is different under large-signal conditions than for small-signal conditions.

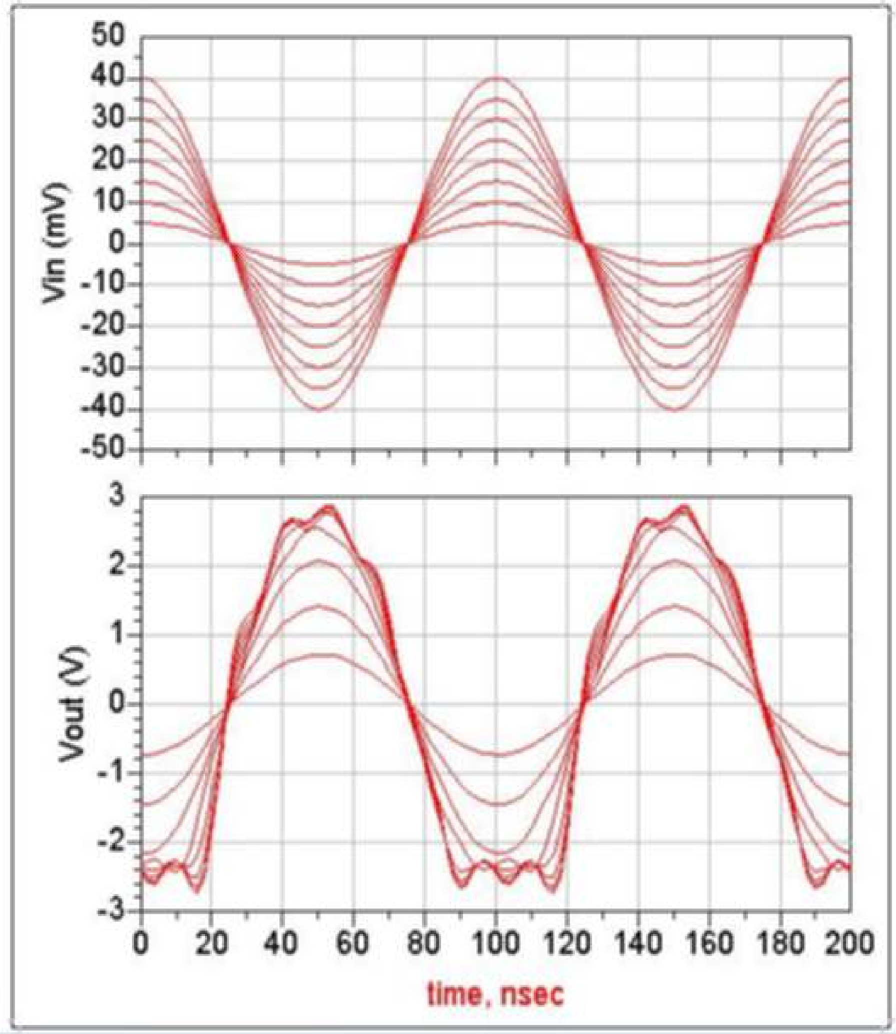


Source of PA Nonlinearities

Example BJT Device







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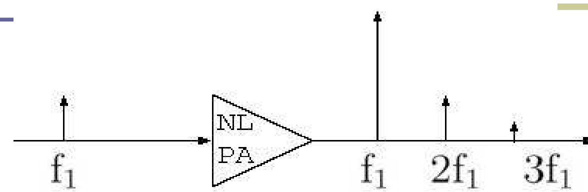
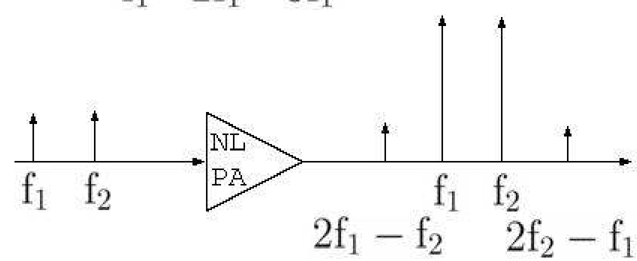
Basic Nonlinearities of PAs

- Frequency generation

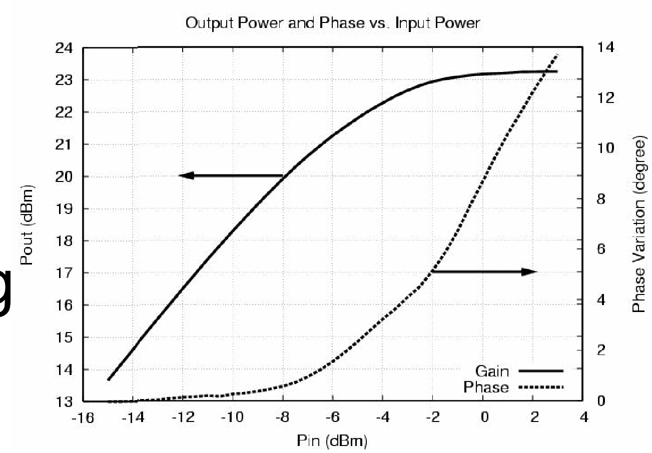


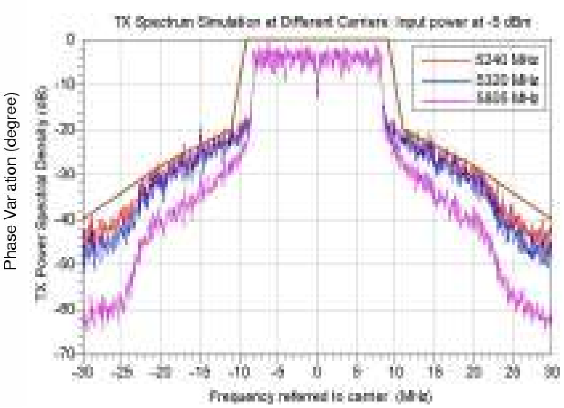
$$m\omega_1 \pm n\omega_2.$$

- Intermodulation

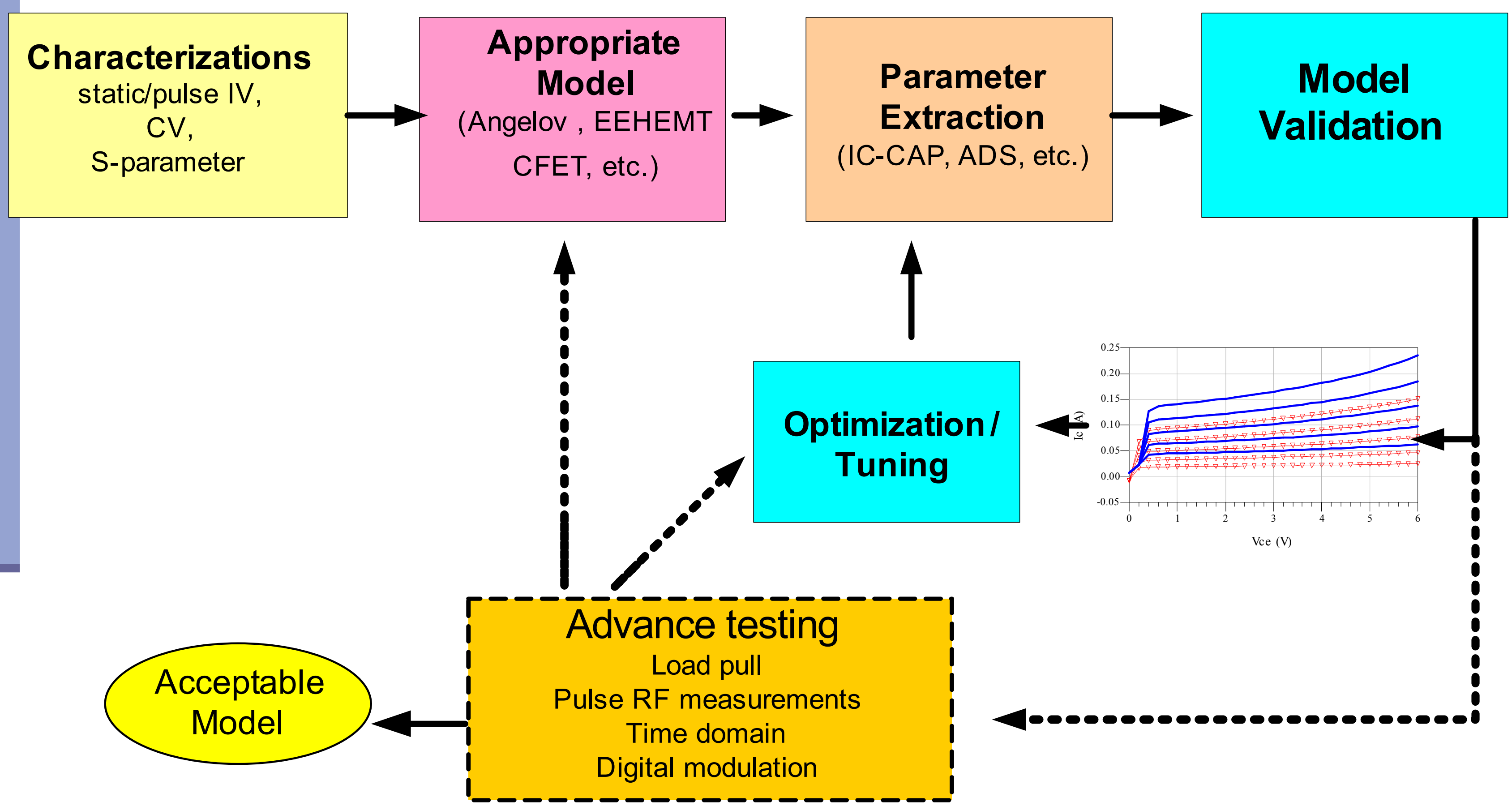


- AM-AM and AM-PM conversion
- Spectral spreading

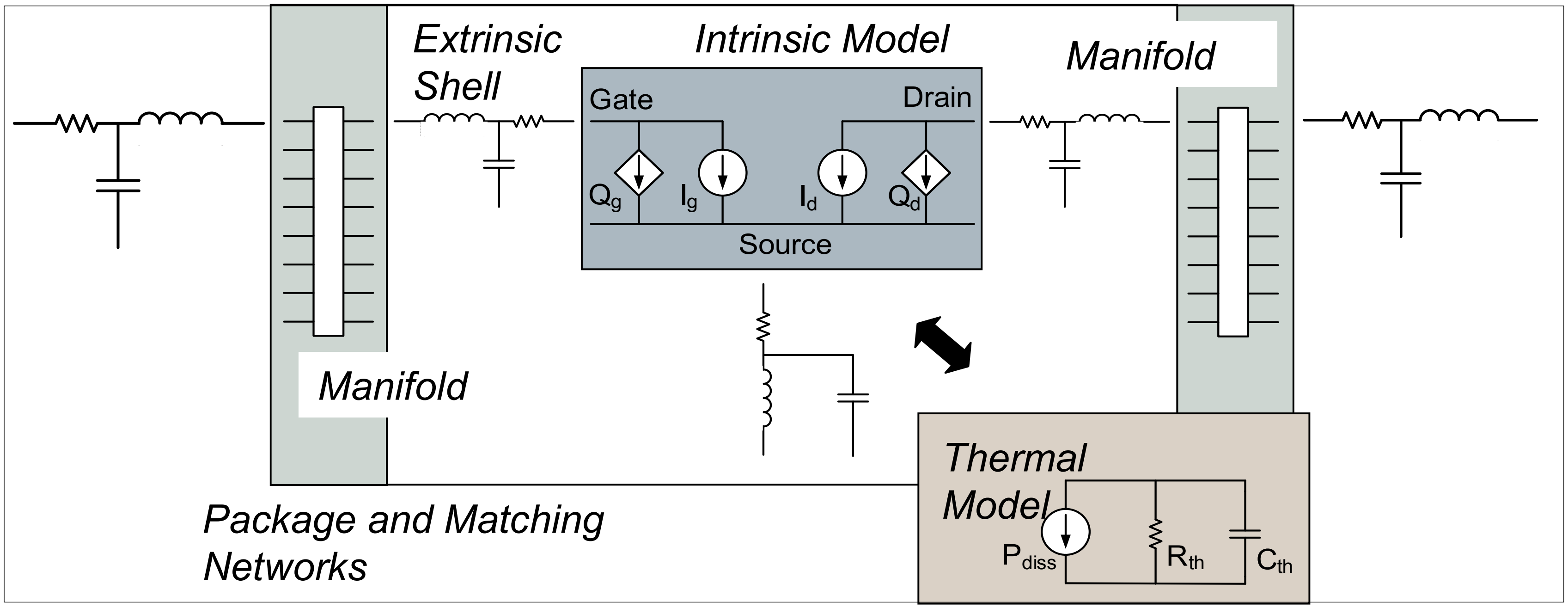




NL Transistor Modeling Process



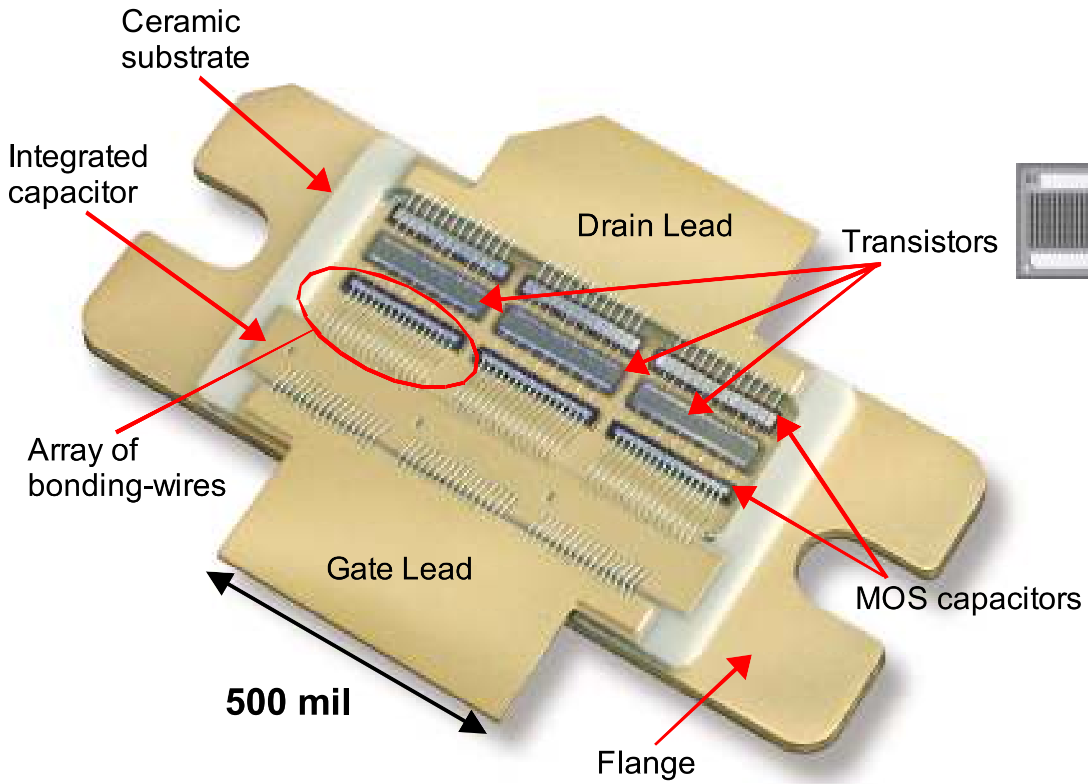
Schematic Representation of Power FET

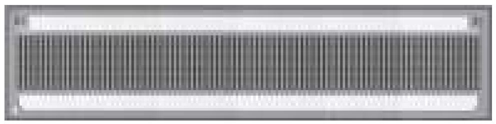


- Accurate simulation and measurements are required.
- Shell representation of packaged entire transistor.

Used with permission from Peter Aaen of Freescale

Inside an RF Power Transistor





- This packaged transistor operates at 2.1 GHz and is capable of producing 170 W (CW) output power.

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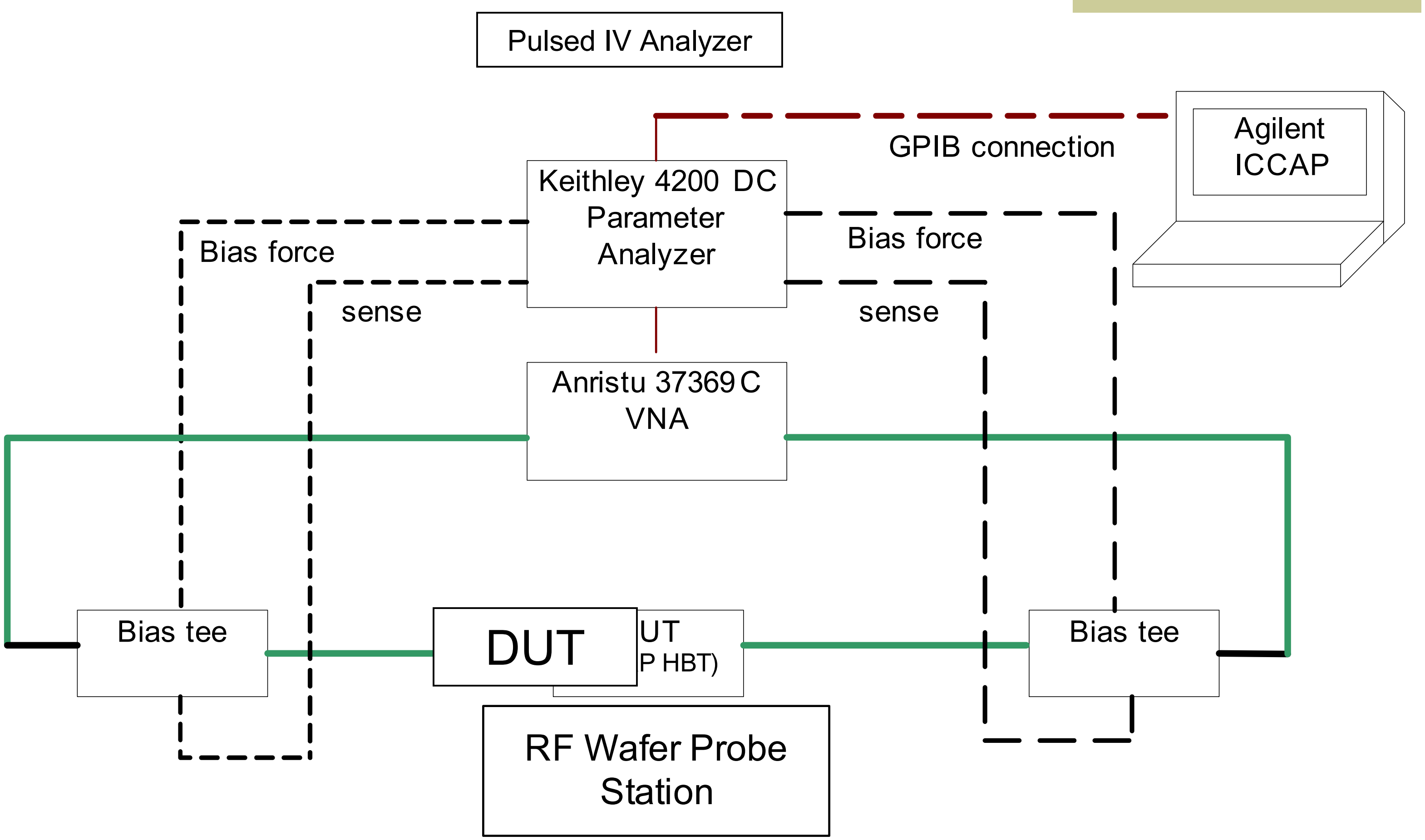
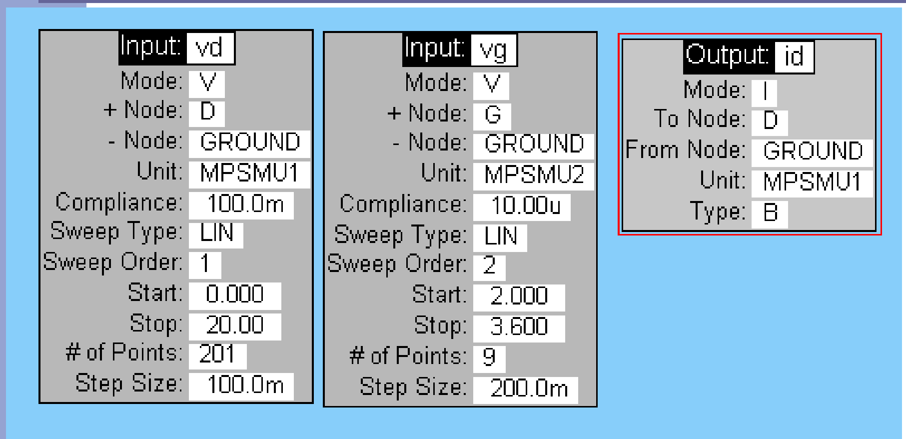
freescale™ semiconductor

Test Configuration for NL Transistor Model Development

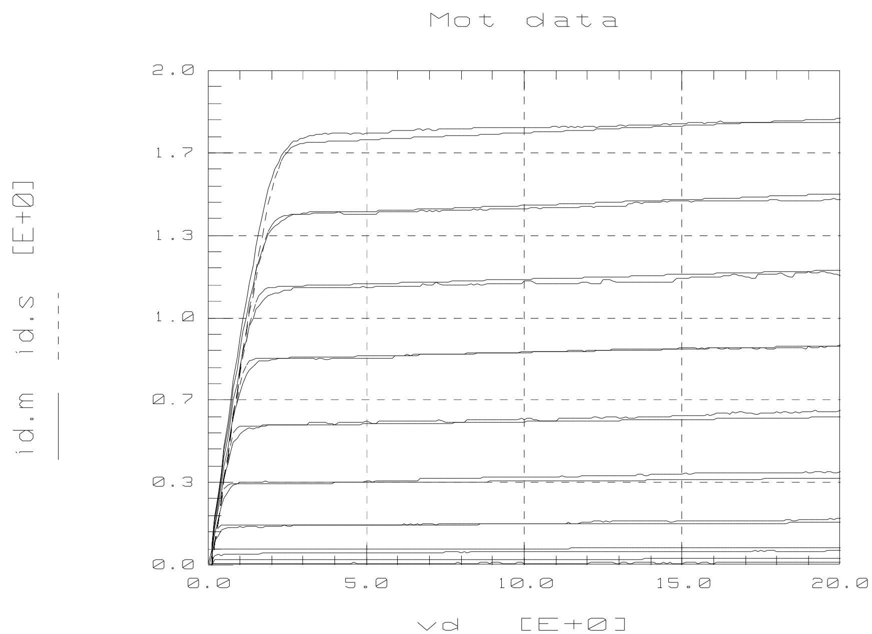


Extraction of I_D Equation



IC-CAP Setup

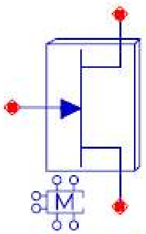
Measured (Solid Lines) and Simulated (Dashed Lines) IV Data:



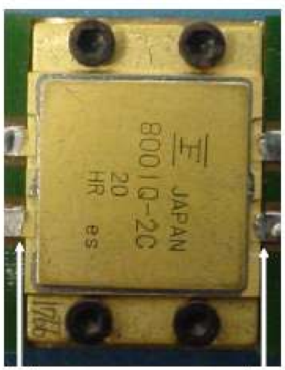
The quality of the IV extraction plays a large part in determining the path of the large-signal swing in the IV plane as well as gain and output conductance.

80 W MESFET

Model Representation

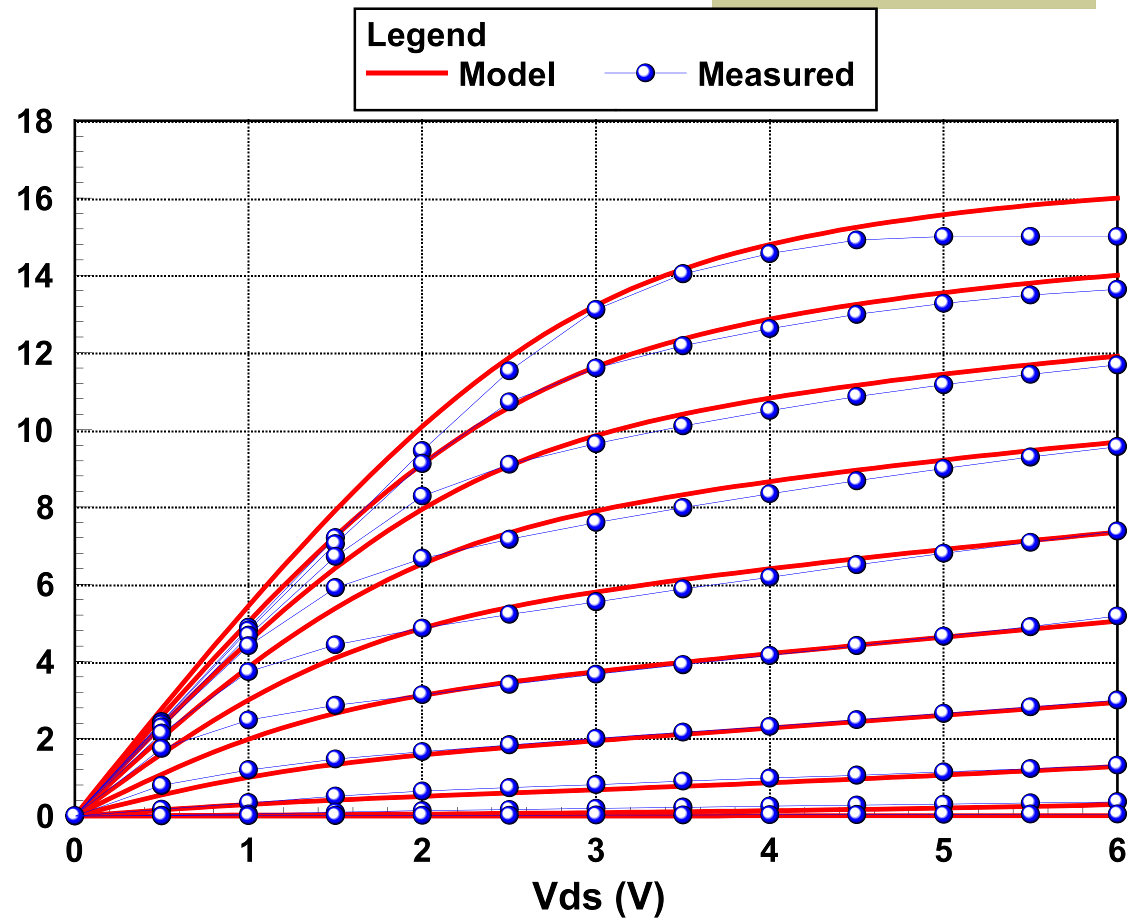


Test Layout

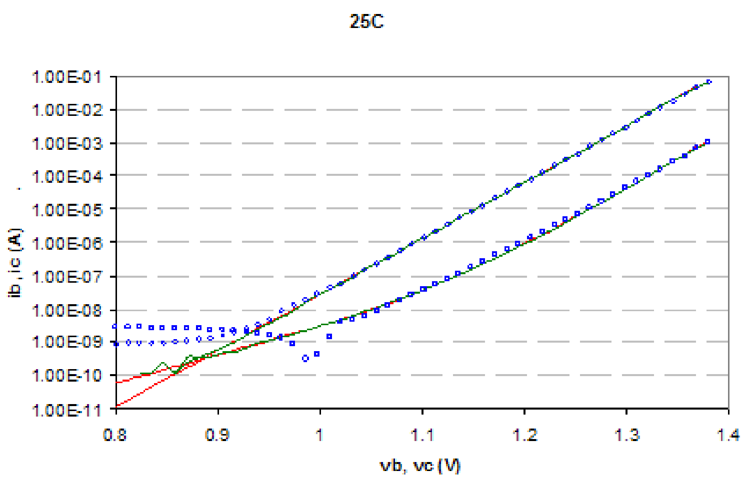


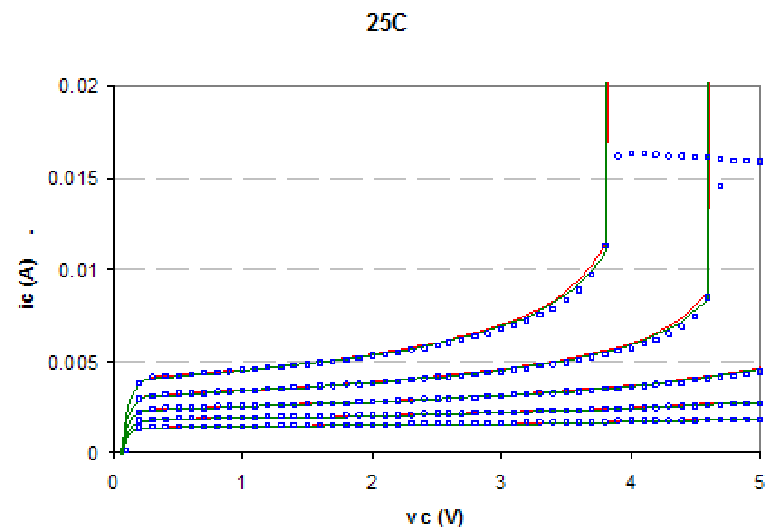
Reference planes

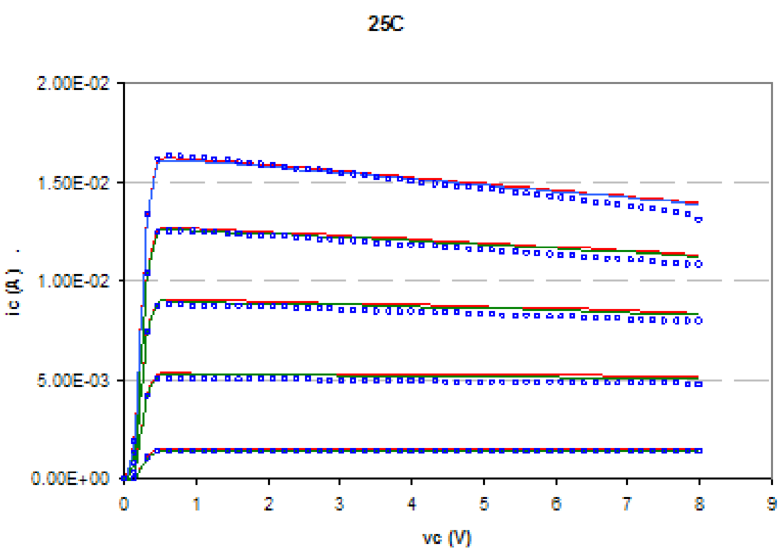
Dimensions in mils

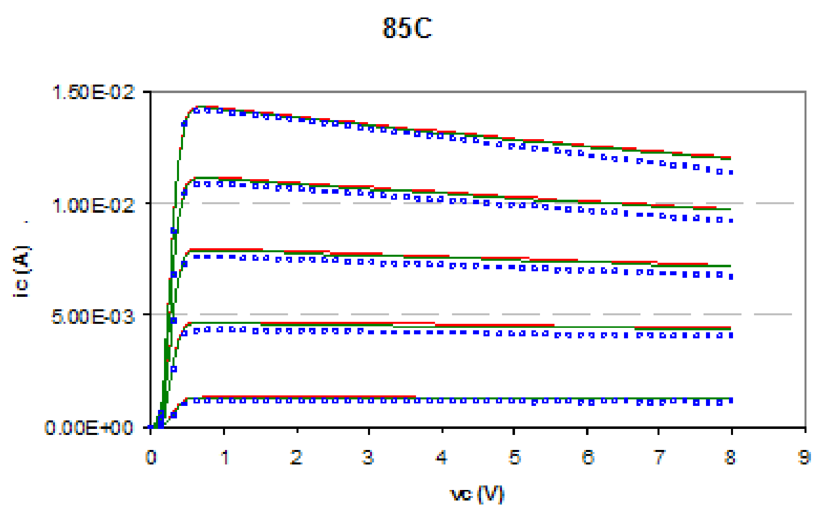


Mextram Model for InGaP HBT





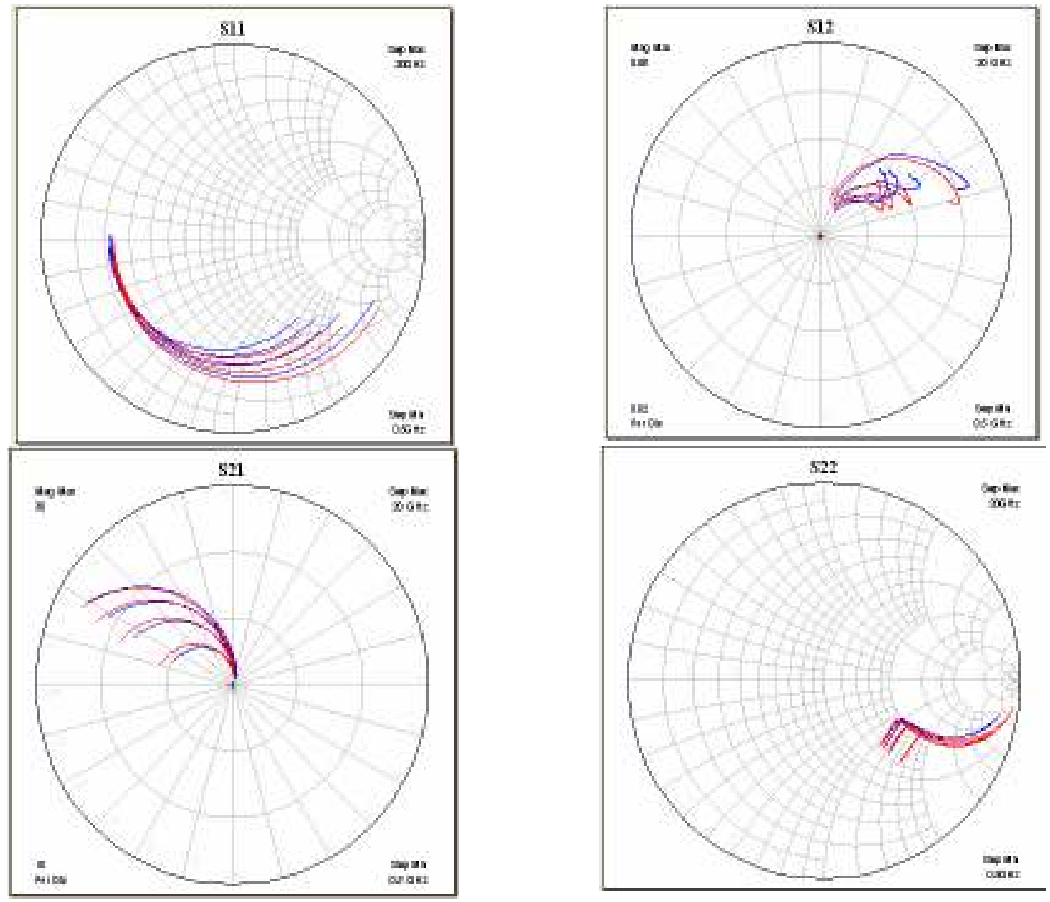




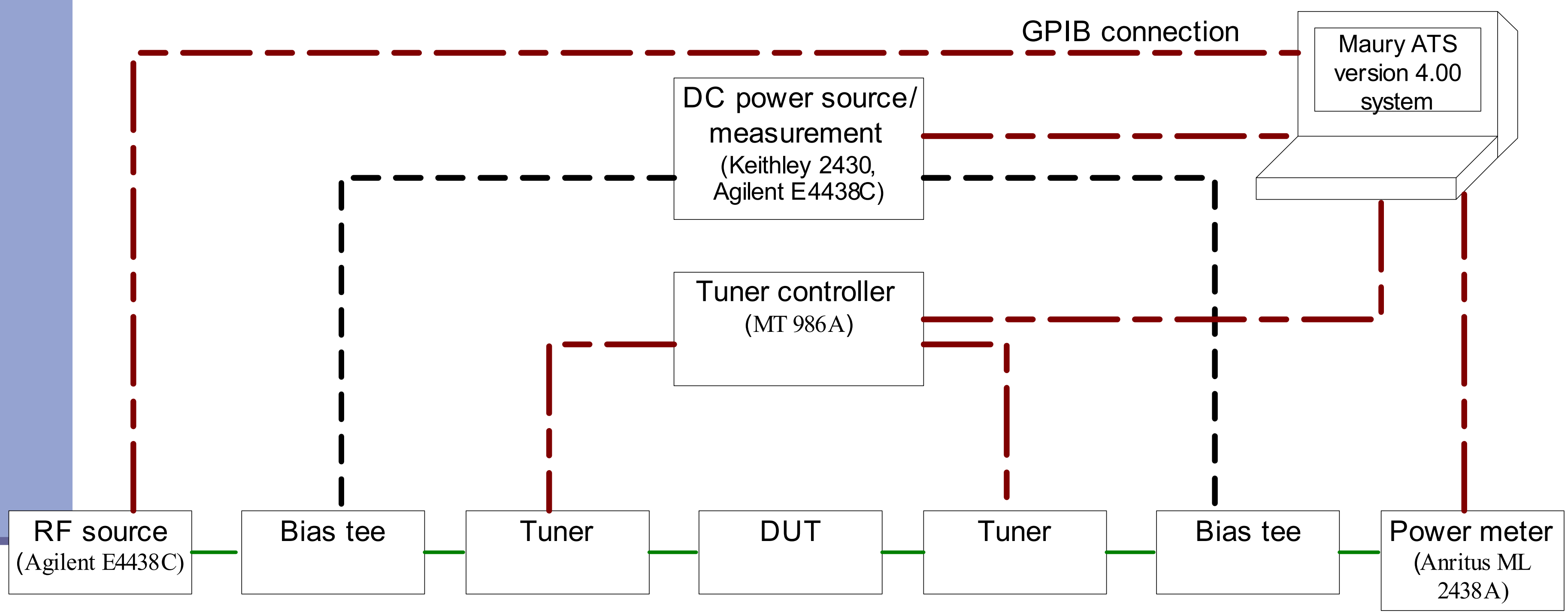
Mextram Model for InGaP HBT

Measured (blue) and Modeled (red) S-parameters

ib= 50~200uA in a step of 50uA and vce= 3V. The frequency range is from 0.5 to 20 GHz with the ambient temperature 25°C.



Test Configuration for NL Transistor Model Validation

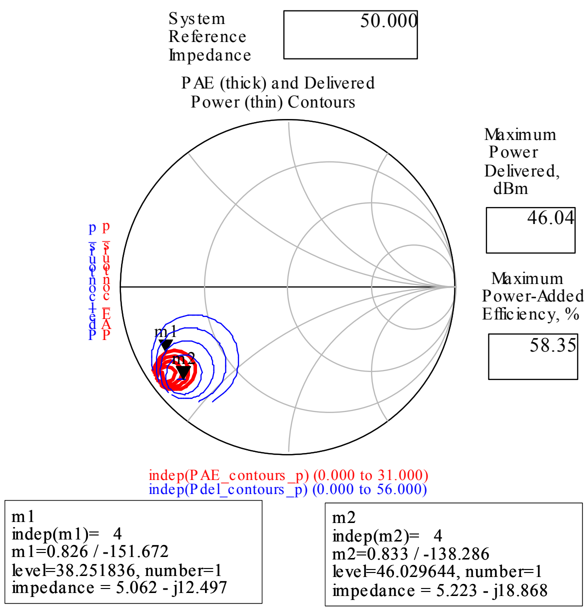


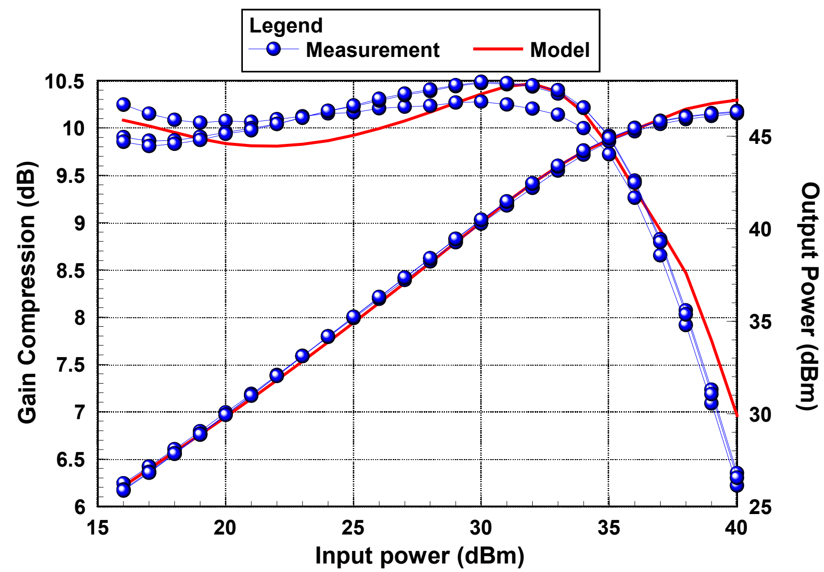
Note: Can also be performed under pulsed RF conditions with minor modifications to setup.

80 W MESFET

1850 MHz loadpull results (Source = 13.5-j25.0 Ohms)

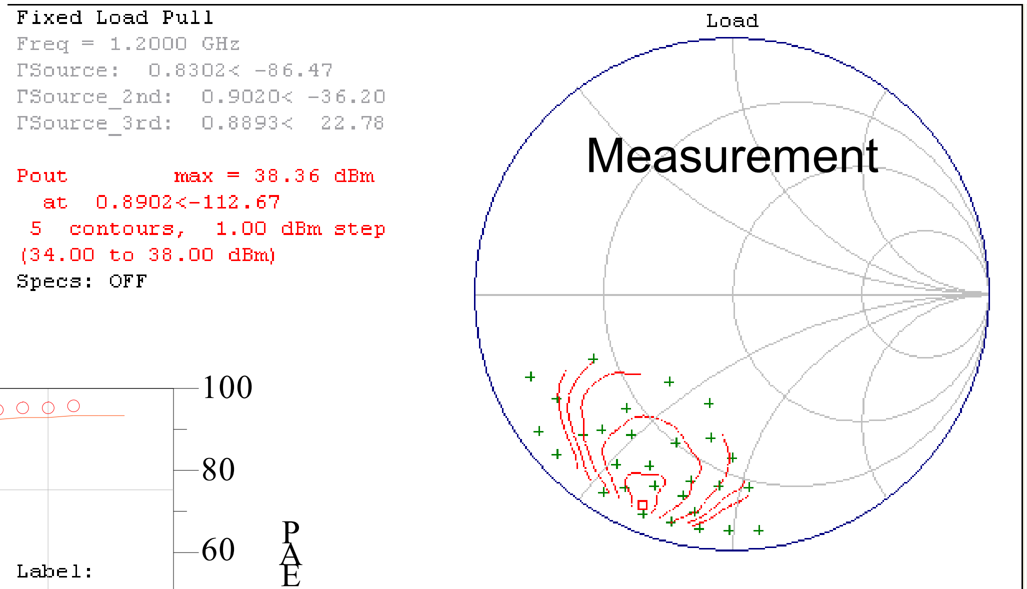
	Pout	Load	Load
Device 1	45.92	6.6-j18	4.78-j16.2
Device 2	45.86	6.86-j17.91	4.78-j16.86
Model	46.08	5.23-j18.04	5.06-j12.5

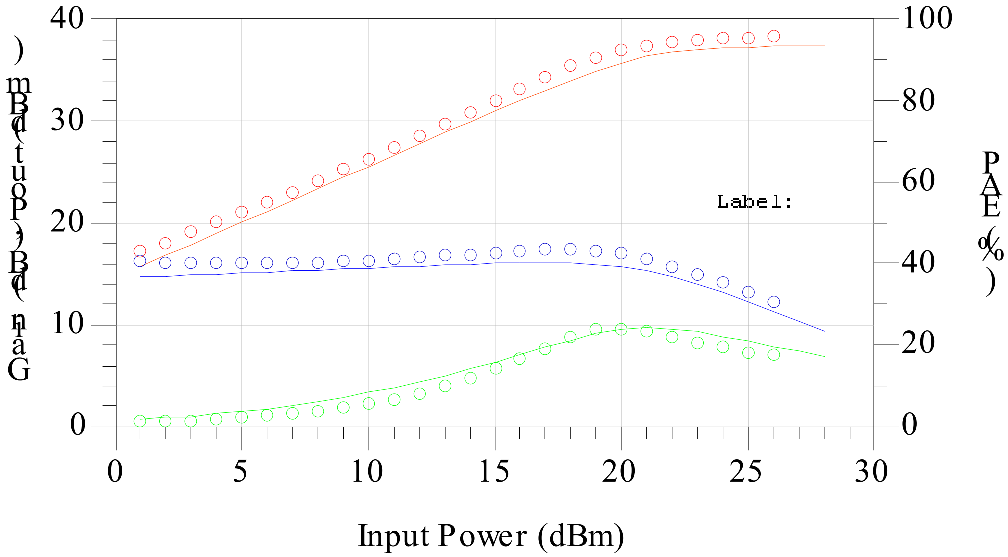




Pulsed Load-Pull – HVVI Device

"MET" Model Developed by Modelithics

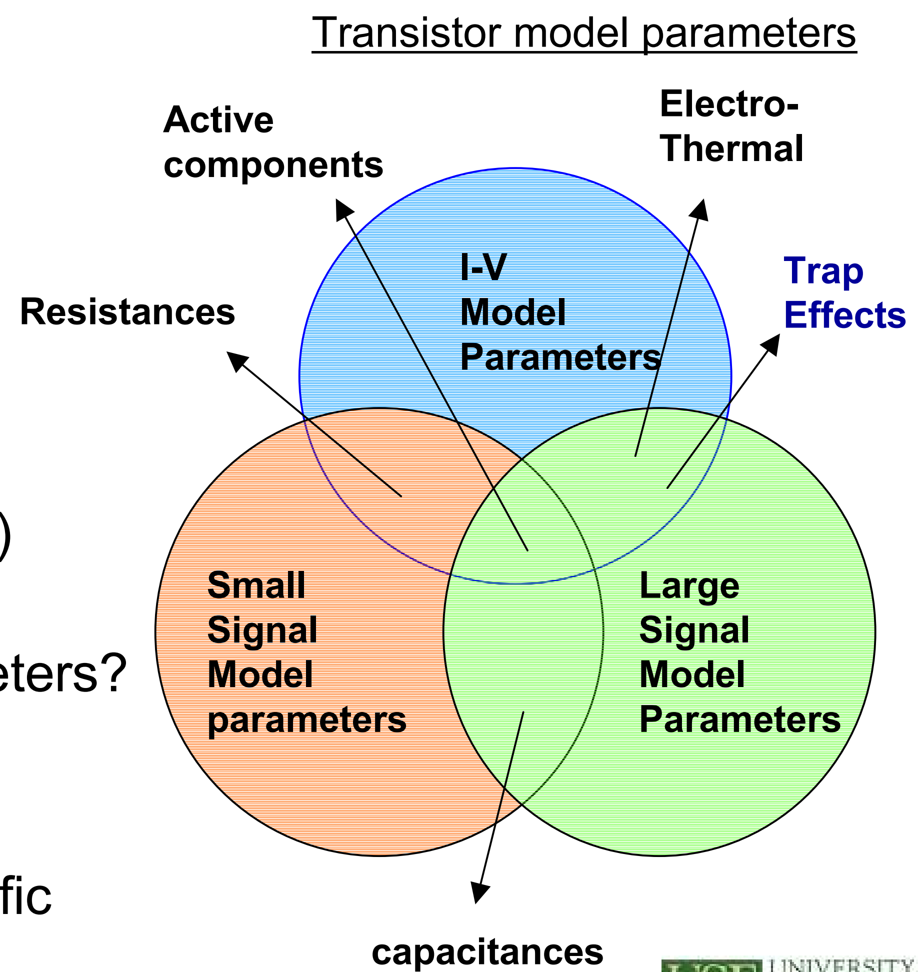




Pin = 23dBm, Freq = 1200 MHz, Vds = 28 V, Vgs = 1.65 V. ΓS= 0.83 < -98 . In measurement pulse width = 200us, pulse separation = 2ms.

What are the main considerations for non-linear Non-linear transistor models?

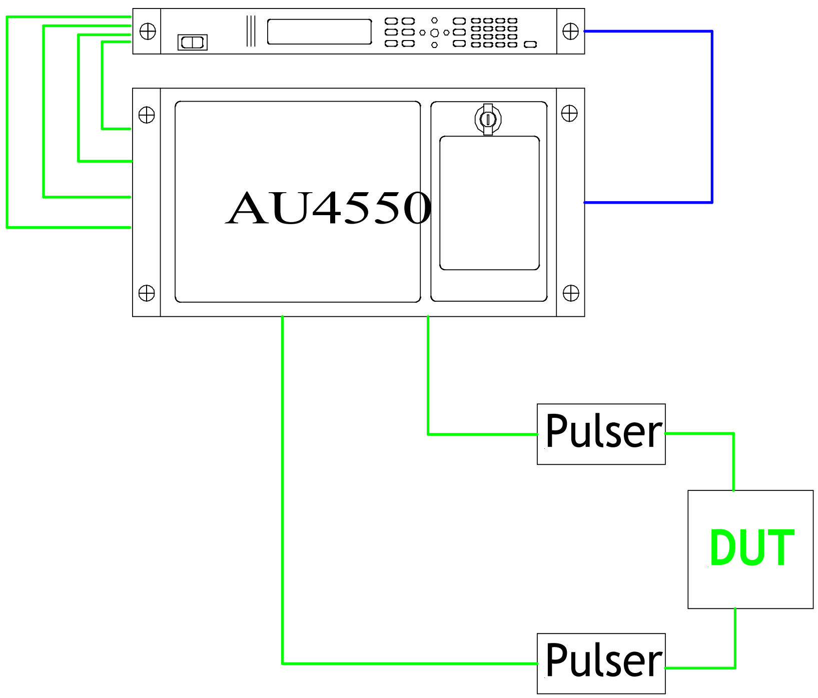
- **Overall measurement accuracy**
  - Correct calibration
  - Repeatability
  - De-embedding model
  - RFIV vs. DCIV
- **Suitability of model**
  - equation set (model template) limitations/intent
  - physically meaningful parameters?
- **Model testing/validations**
  - Conventional - general
  - Advanced – application specific



Pulsed IV Measurement

- Measurements are performed during brief (~0.2 μs) excursions from a quiescent bias.
- The pulses are usually separated by at least 1 ms.
- Thermal and trap conditions during the measurement are those of the quiescent bias, as in high-frequency operation.

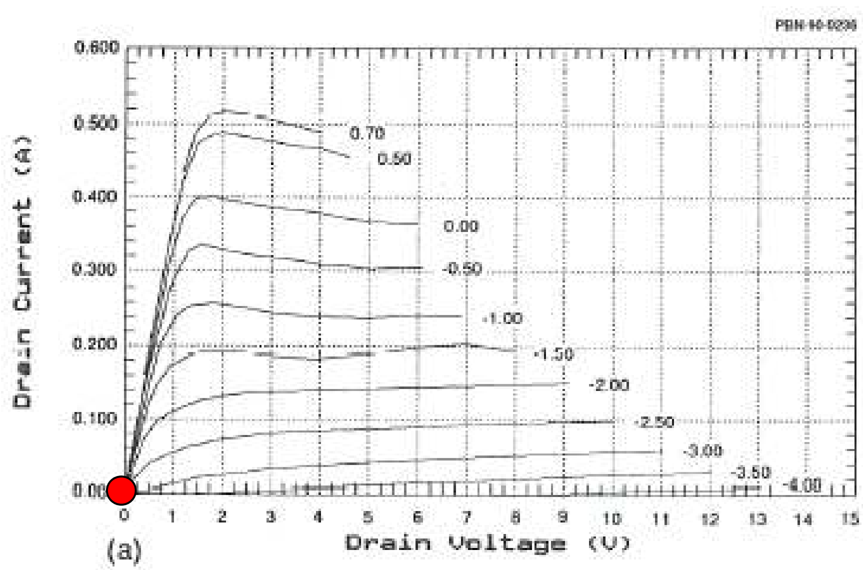
Pulsed IV system AU4550



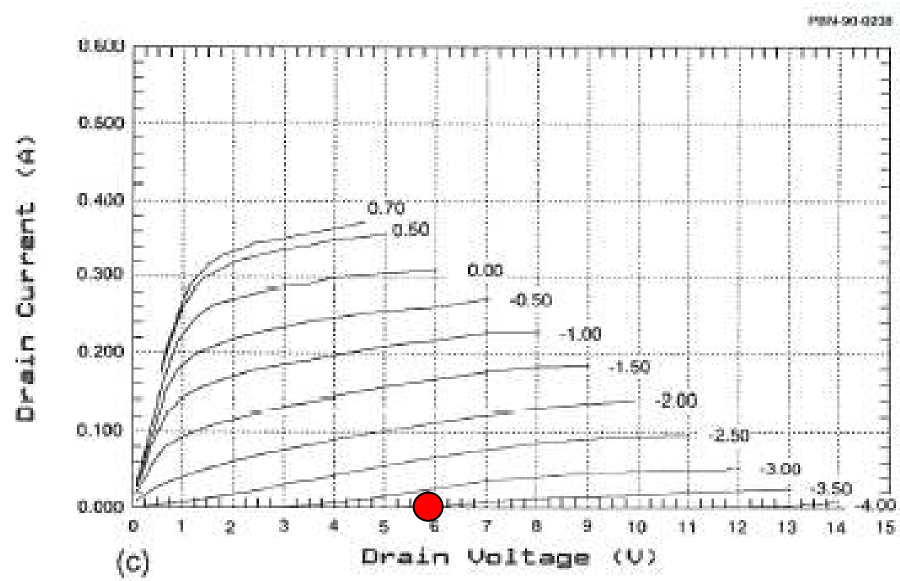
From Yusuke Tajima, used with permission.

Why Pulsed IV?

1. Thermal   2 Field induced traps



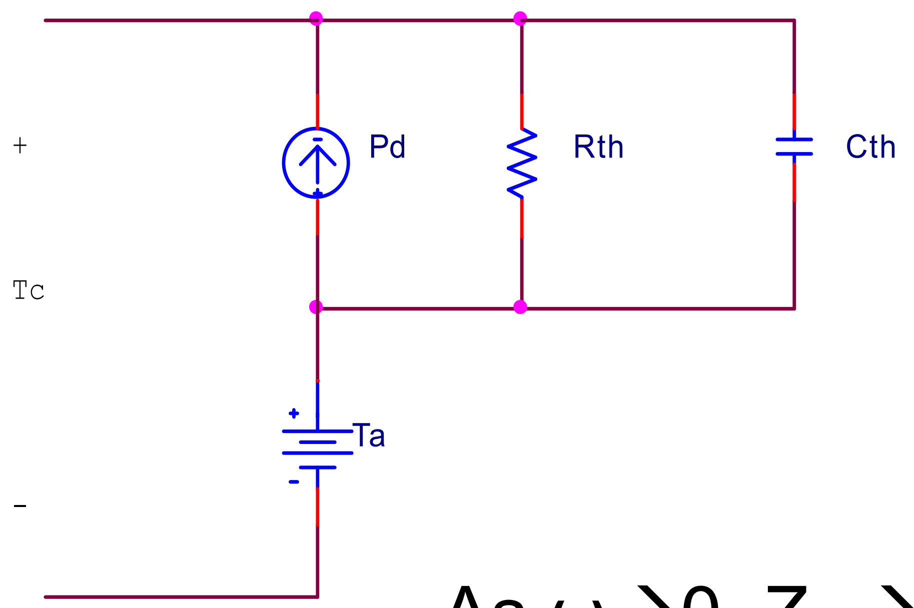
Quiescent condition 0Vd, 0Vg



Quiescent condition 6Vd,-4Vg

Pulsed IV data of a pHEMT at different quiescent conditions

Electrothermal "Circuit"



$$T_C = Z_{th} P_D + T_A$$

$$Z_{th} = R_{th} // \left(\frac{1}{j\omega C_{th}} \right)$$

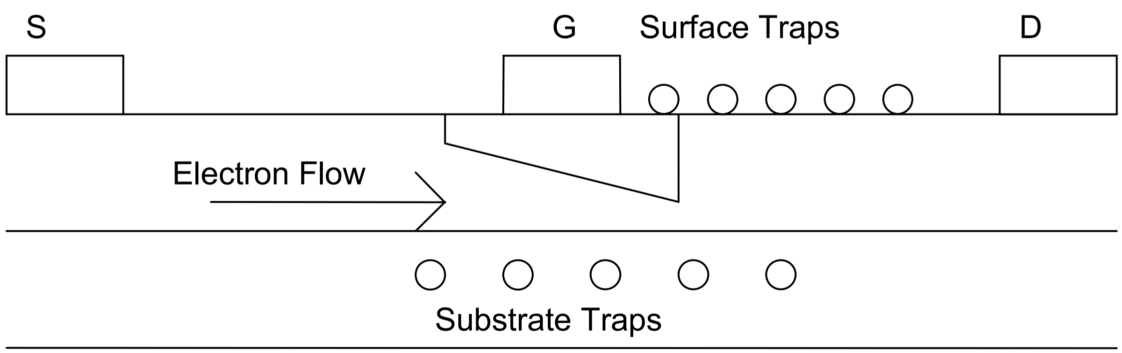
$$C_{th} = \frac{\tau_{th}}{R_{th}}$$

As $\omega \rightarrow 0$, $Z_{th} \rightarrow R_{th}$

As $\omega \rightarrow$ large, $Z_{th} \rightarrow 0$

Trapping Effects

- Trapping Effects in MESFETs*:
  - Substrate Traps
  - Surface Traps
- Electron Capture → Fast Process
- Electron Emission → Slow Process



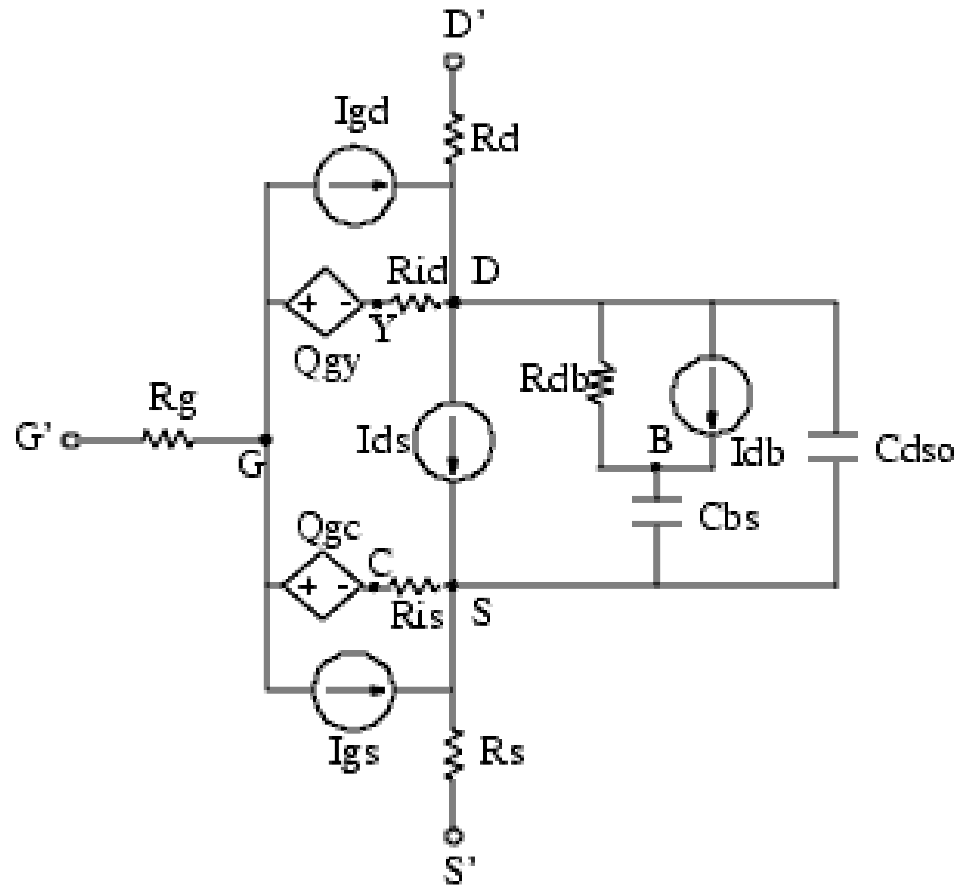
*C. Charbonninud, S. DeMeyer, R. Quere, J. Teyssier, 2003 Gallium Arsenide Applications Symposium, October 6-10, 2003, Munich.

A Subset of Available FET Model (Templates)

FET models	Number of parameters	Bias dependent capacitance/ Electro-Thermal effect	Original Device Context
JFET [1]	27	No/No	GaAs FET
Curtice3 [2]	59	Yes/No	GaAs FET
CFET [3]	48	Yes/Yes	HEMT
EE HEMT1 [4]	71	Yes/No	HEMT
Angelov [5]	80	Yes/Yes	HEMT/MESFET
CMC (Curtice/Modelithics/Cree) [6]	55	Yes/Yes	LD MOSFET
MET (Motorola Electro-Thermal) [7]	62	Yes/Yes	LD MOSFET
MOS Level 1/2/3 [1]	40/48/47	Yes/Yes	MOSFET
BSIM3 (v3.24) [8]	148	Yes/Yes	MOSFET
BSIMSOI3 [9]	191	Yes/Yes	SOI MOSFET

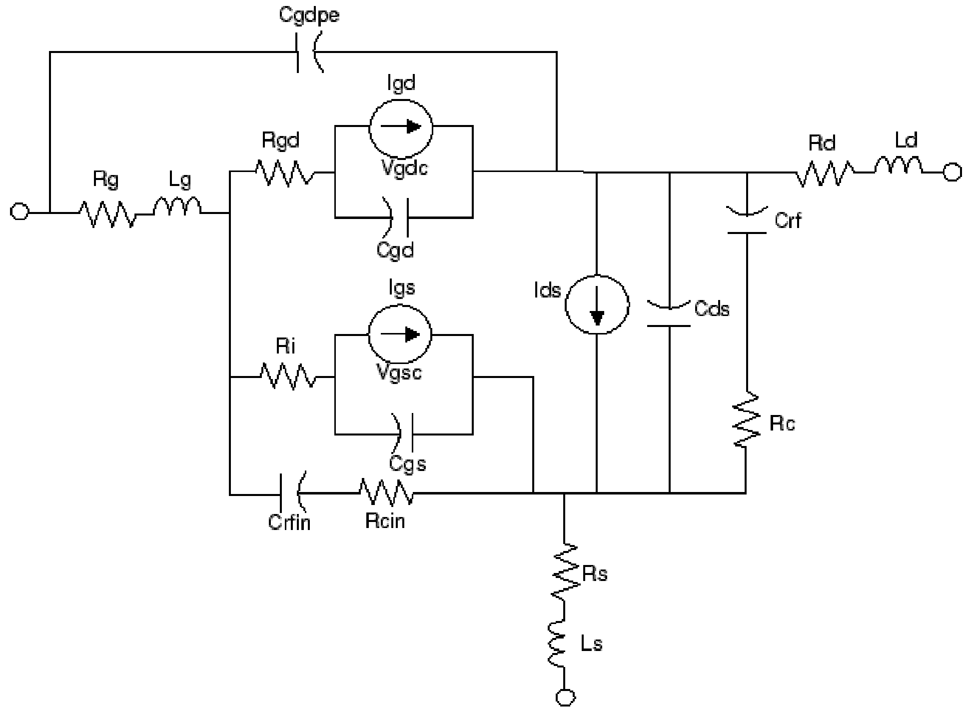
EEHEMT Large Signal FET Model

- DC and AC behavior separated → simpler extraction
- Temperature effects modeled through equations – not electro-thermal circuit.



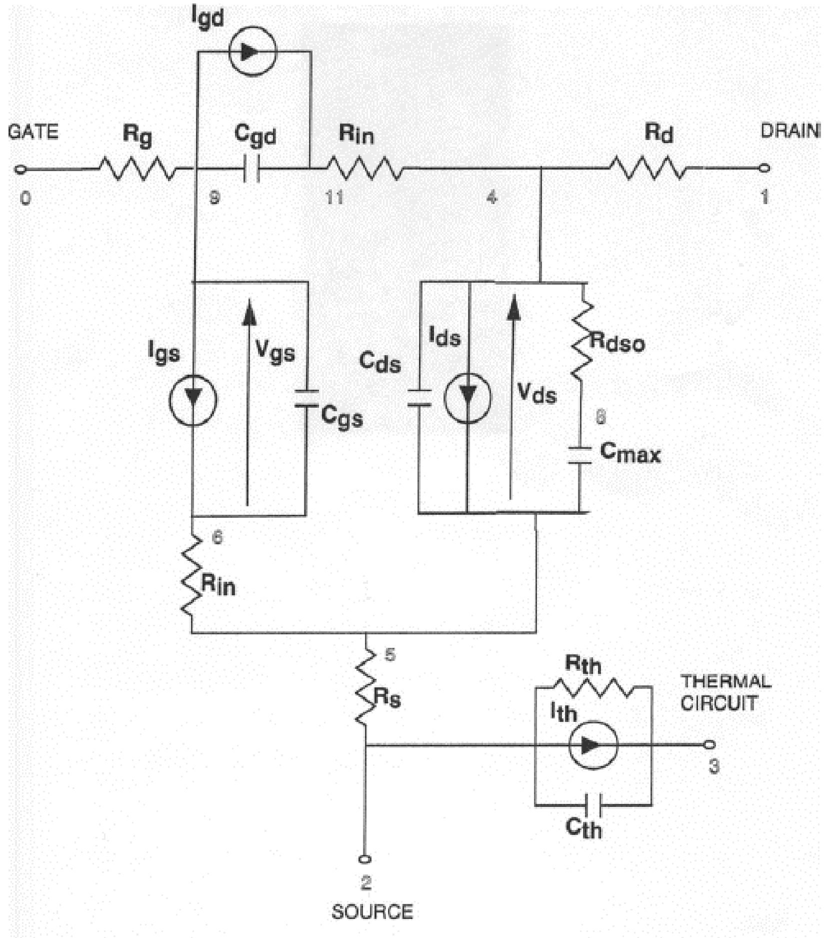
Angelov Large-Signal FET Model

- Traditional single-pole electrothermal subcircuit (not shown) accounts for heating effects
- Available in most simulators also in Verilog A



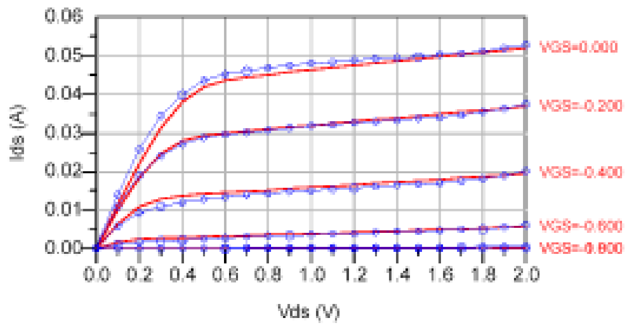
CFET Model Topology

- Developed by Dr. Walter Curtice and used by Modelithics.
- Designed for GaAs/GaN MESFETs and HEMTs.

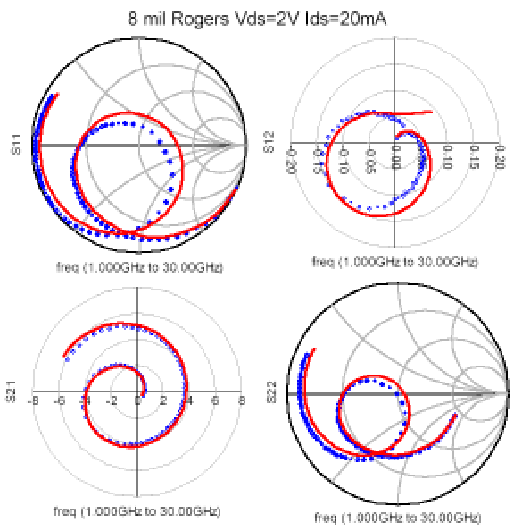


Non-Linear (EEHEMT) Model for NE 3210 S01

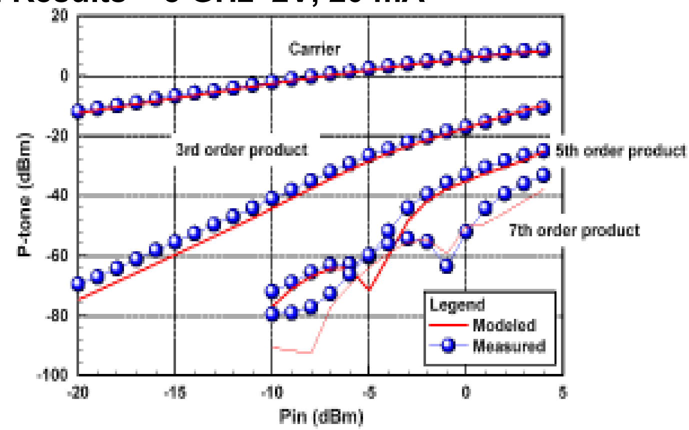
IV Fit



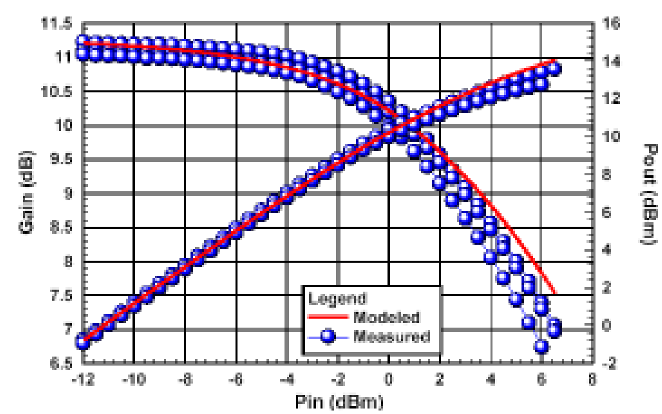
S-Parameter Fits
2V, 20 mA



2-Tone IM Results – 8 GHz 2V, 20 mA



Power Compression – 8 GHz 2V, 20 mA



MOSFET Modeling

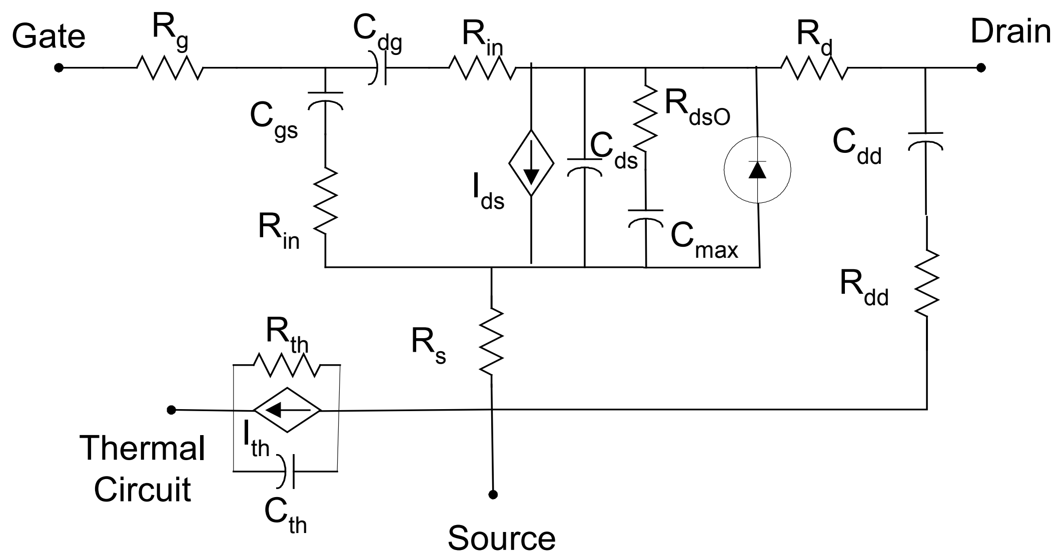
- Motorola's Electro-Thermal (MET) Model
- Curtice-Modelithics-Cree (CMC) Model
- Both of these models possess traditional electrothermal subcircuits.
- Used for Si LDMOSFET, VDMOSFET devices

  → No traps

  → Electrothermal subcircuit and temperature dependence extraction are much simpler!

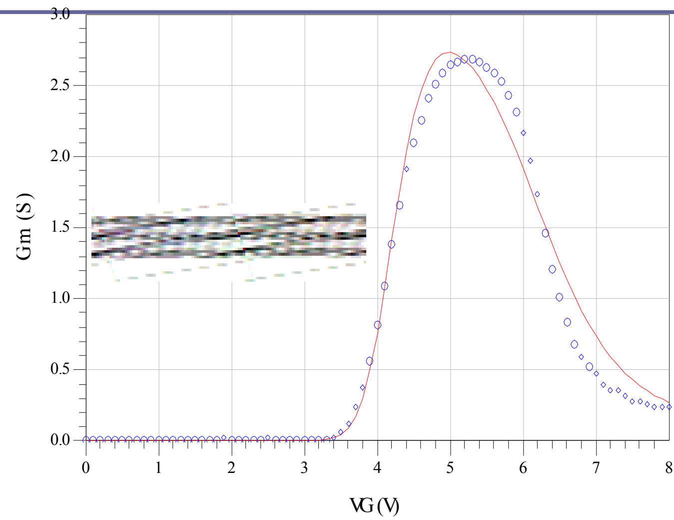
Curtice-Modelithics-Cree Topology

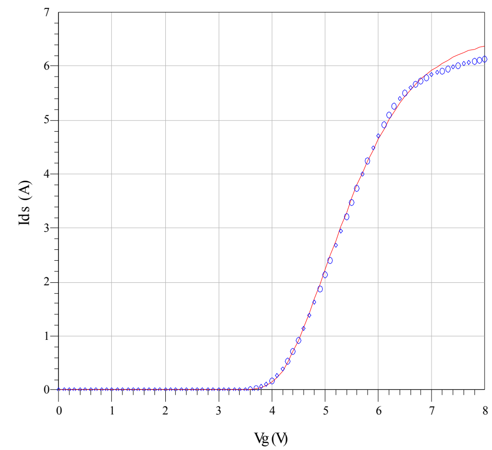
- The Curtice-Modelithics-Cree (CMC) model is a proprietary electro-thermal LDMOS model
- Four region (4R) current model based on work of Fager et.al. (see IEEE Trans. MTT, Dec. 2002)
- The model provides accurate predictions of power, efficiency and distortion performance over a wide range of devices sizes.

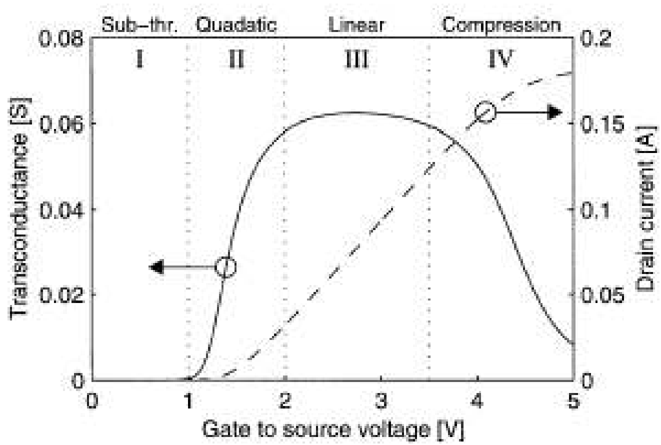


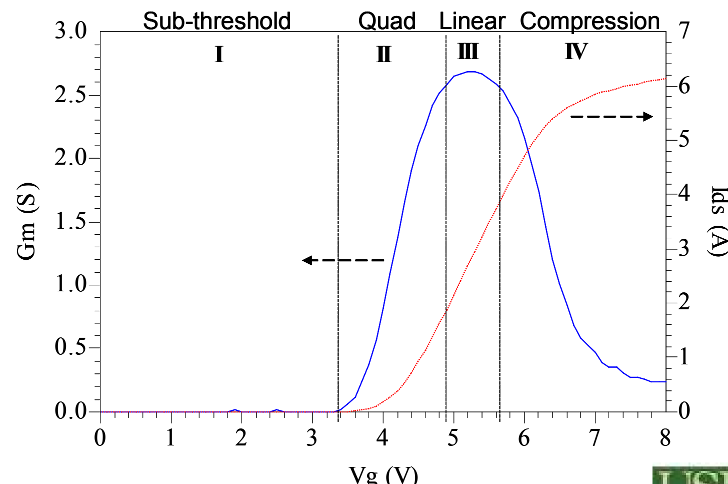
See W. Curtice, L. Dunleavy, W. Clausen, and R. Pengelly, ,High Frequency Electronics Magazine, pp18-25, Oct.. 2004.

30 W LDMOS Device Modeling



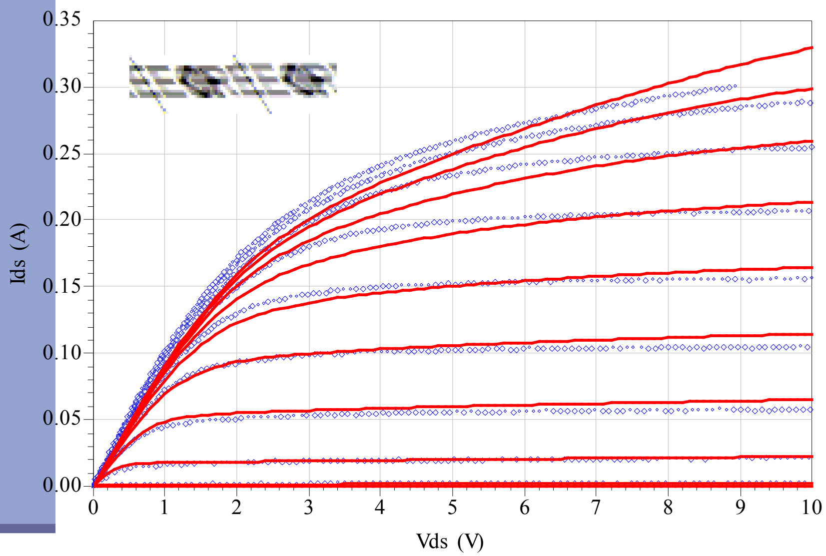


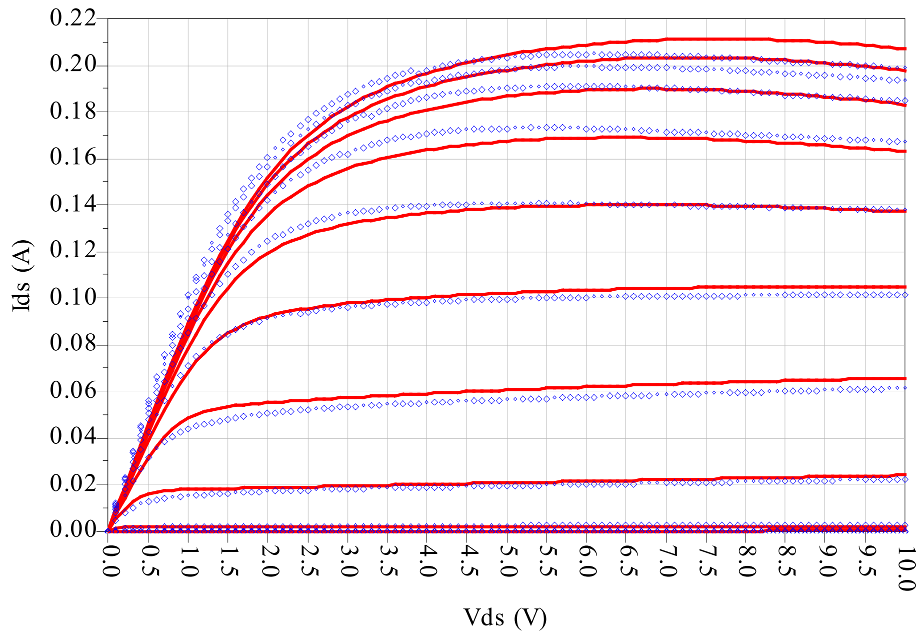




LDMOS Model Fit to Pulsed IV Data

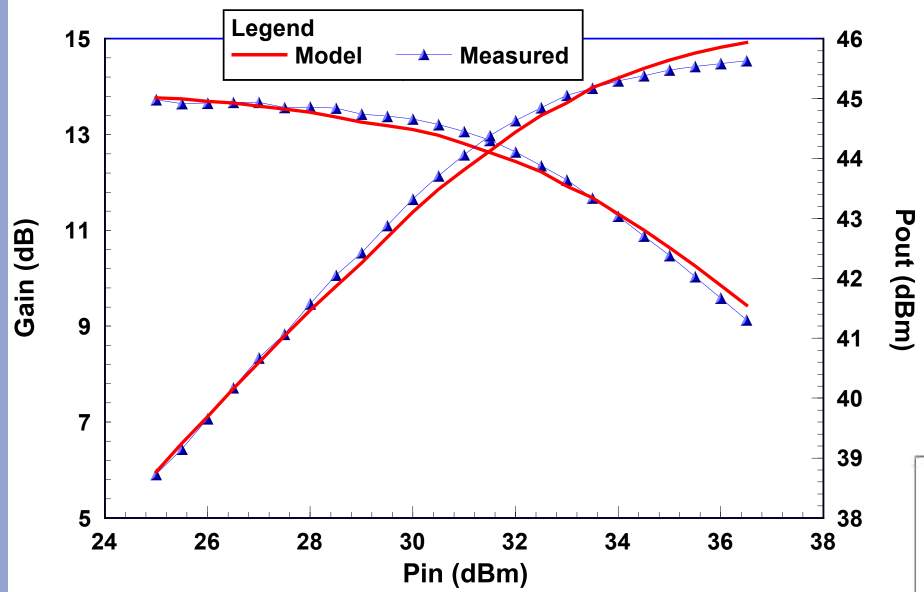
CMC Model for 1 W: solid lines, model pulsed IV data: dashed lines

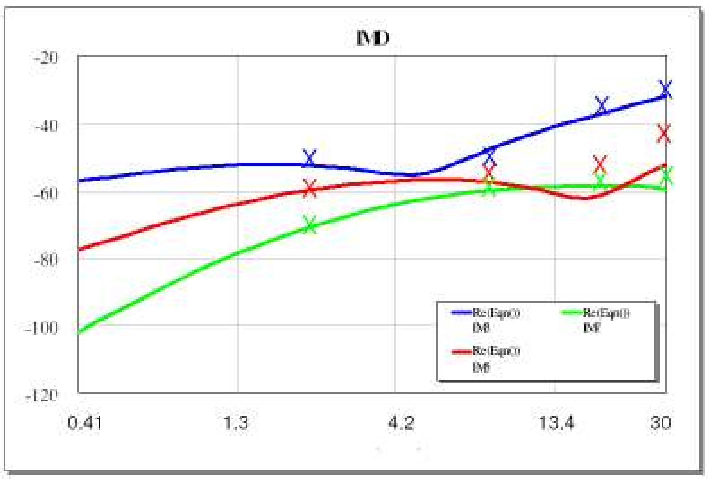




Setting Thermal Resistance to 0 or Rth value Removes and adds Self-Heating

30 Watt LDMOS Power FET

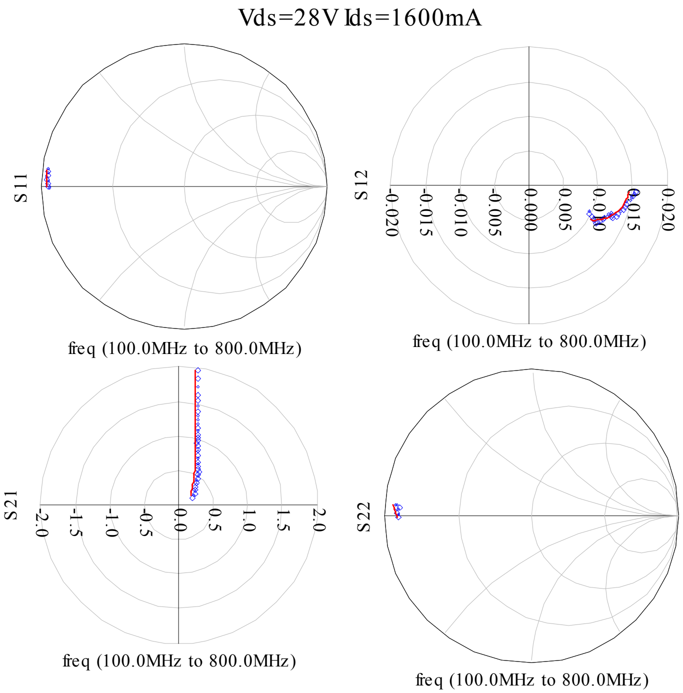


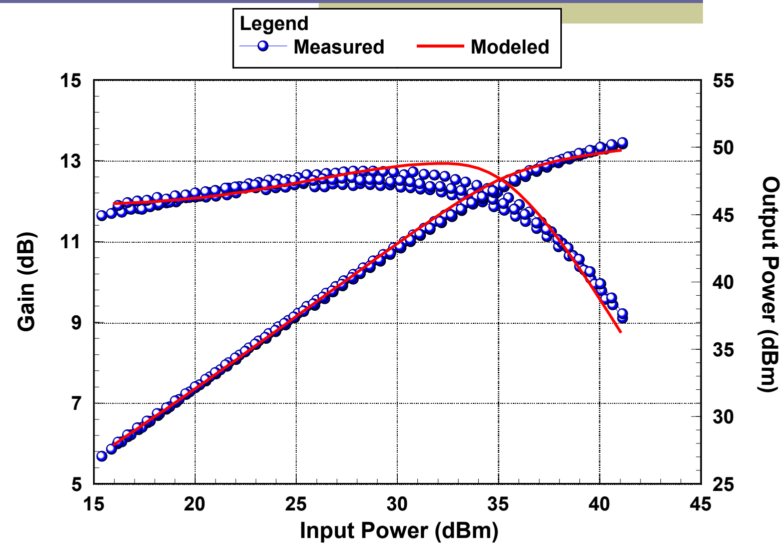


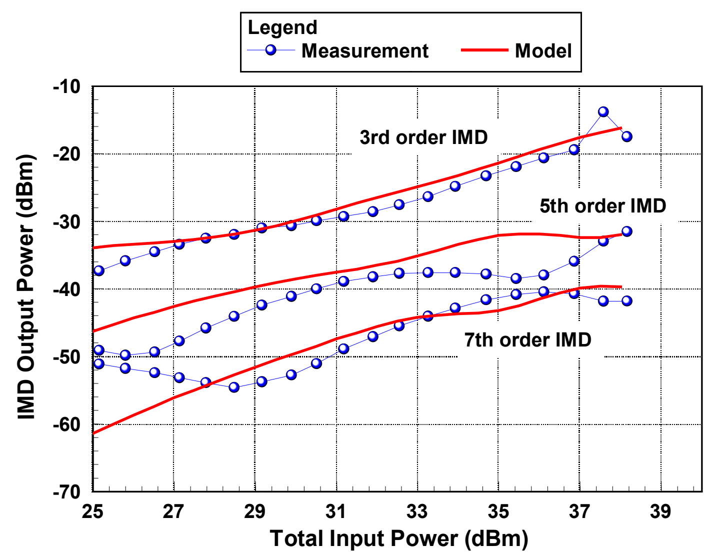
Blue is IM3
Red is IM5
Green is IM7

Crosses are Cree data sheet values

150W Phillips Power Transistor – Curtice-Modelithics-Cree (CMC) Model



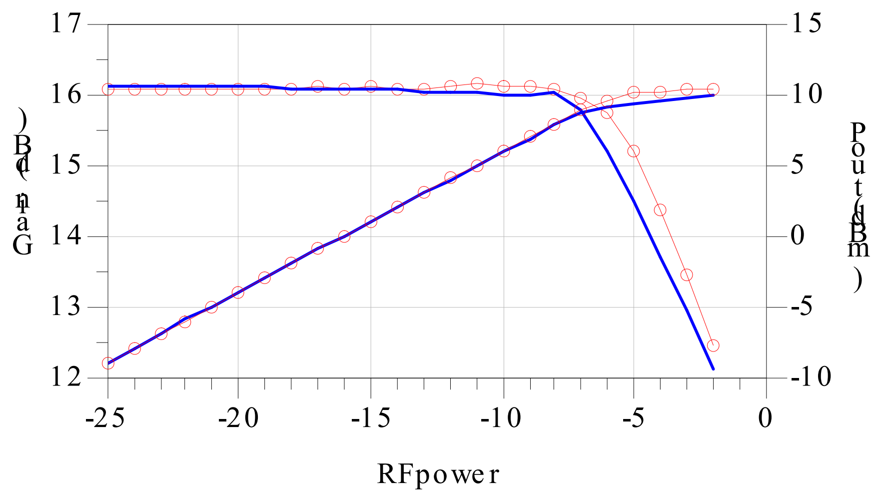


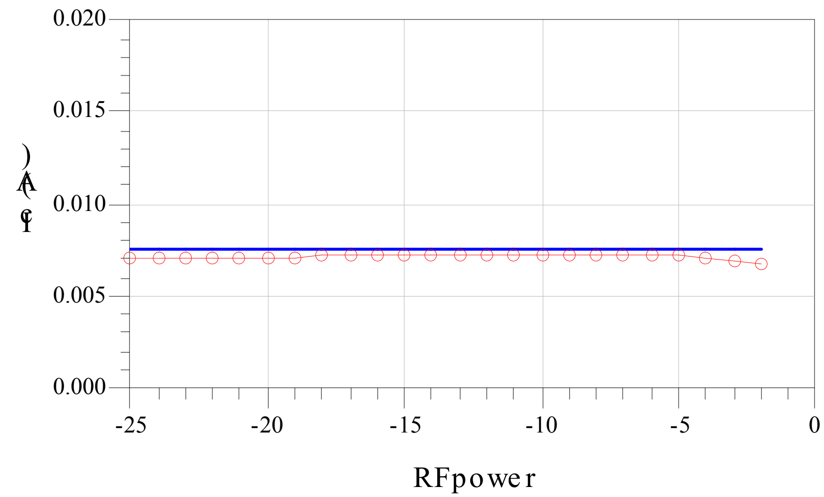


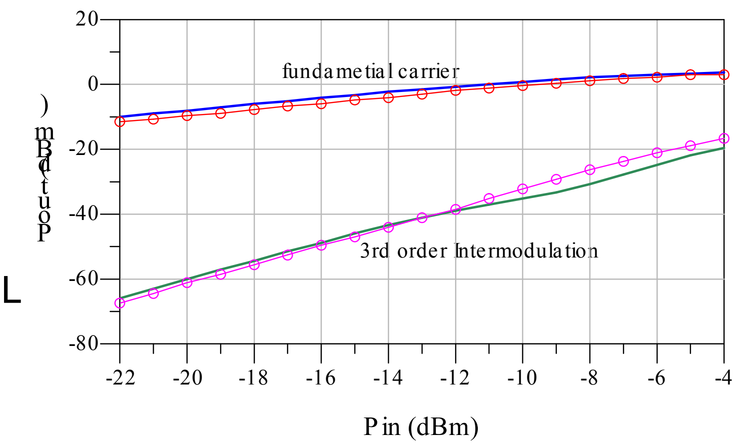
Available HBT Model (Templates)

BJT models	Number of parameters	substrate effect / self heating	Original Device Context
GP (1970)	24	No/No	Si BJT
VBIC (1985)	102	Yes/Yes	SiGe BJT
Mextram (1987)	81 (version 504)	Yes/Yes	SiGe HBT
HICUM (1995)	114	Yes/Yes	GaAs HBT
Agilent (2003)	124	Yes/Yes	InP/GaAs HBT
FBH (2005)	80	No/Yes	GaAs HBT
Curtice (2004)	58	No/Yes	GaAs HBT

Mextram Model for 3x20x2 InGaP HBT





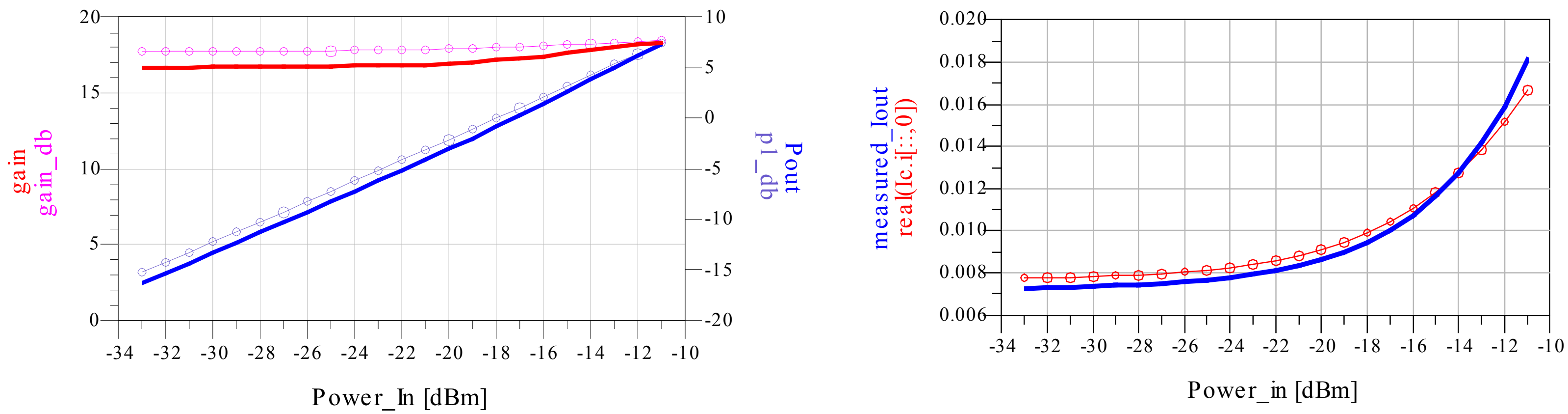


5.5 GHz power sweep results at vc= 3V and ib= 100uA.
Source reflection coefficient Gms= .06522<148.97 (mag<deg); L
Load reflection coefficient Gml= .07354<36.24 (mag<deg).

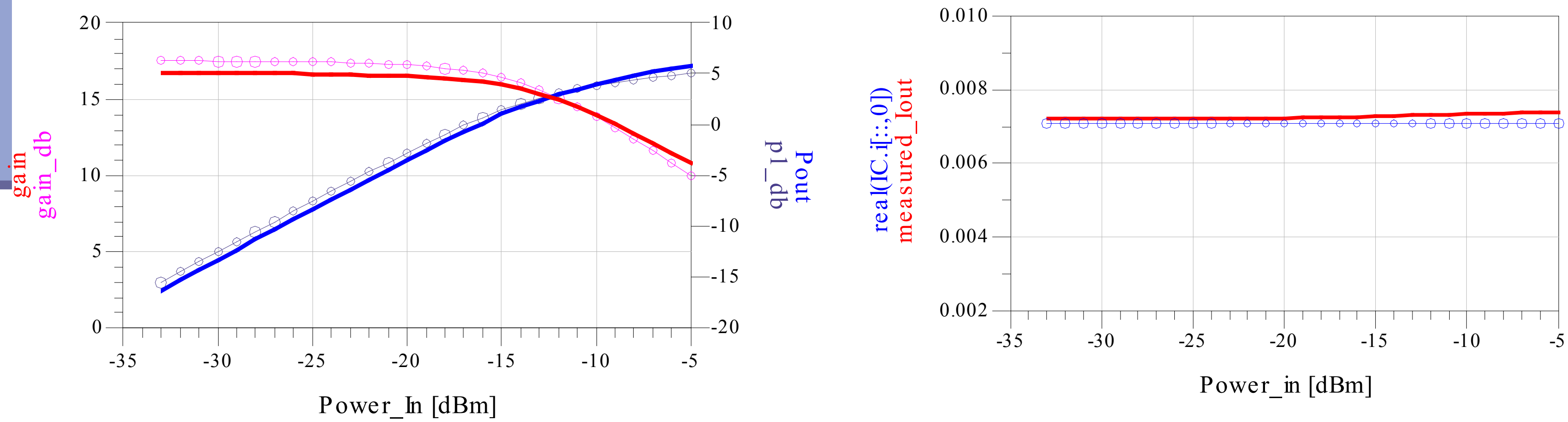
- Constant Base Current vs. Constant Base Voltage -

(See B. Lee, L. Dunleavy „” *High Frequency Electronics*, May 2007.)

-o- line: Mextram 504 model and solid line: measurements



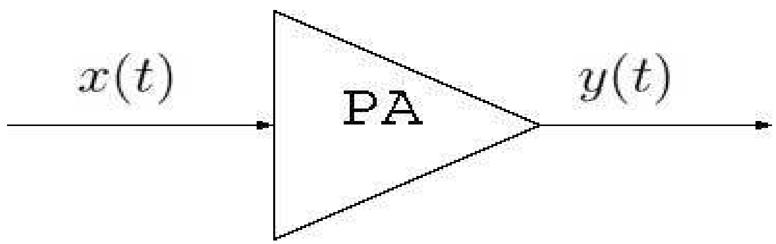
(a) The case of constant base voltage (Vb=1.33V)



(b) The case of constant base current (Ib=89.4uA)

Behavioral Models

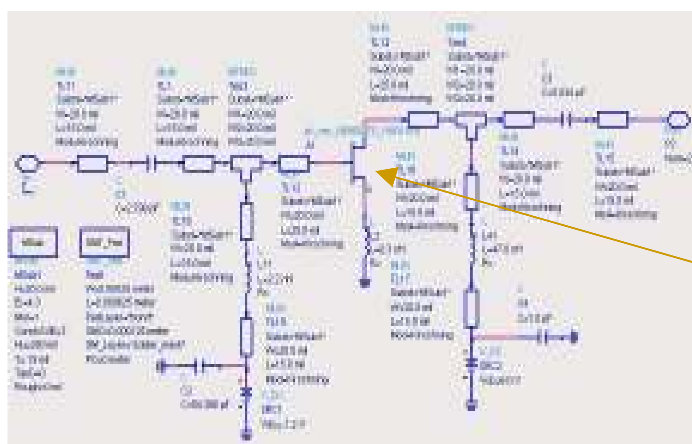
- Empirical models (behavioral models, black-box models)
  - Requires no knowledge about the internals of the PA
  - Based on the observation of the input-output signal relationships
  - Its simulation performance heavily depends on the dataset used for the extraction of the model
  - It fits well to the given datasets and requires small simulation time;
  - However it may suffer when trying to extrapolate the PA performance or fit to different datasets (by that means different PA topologies)



$$y(t) = k_1 x(t) + k_2 x(t)^2 + k_3 x(t)^3$$

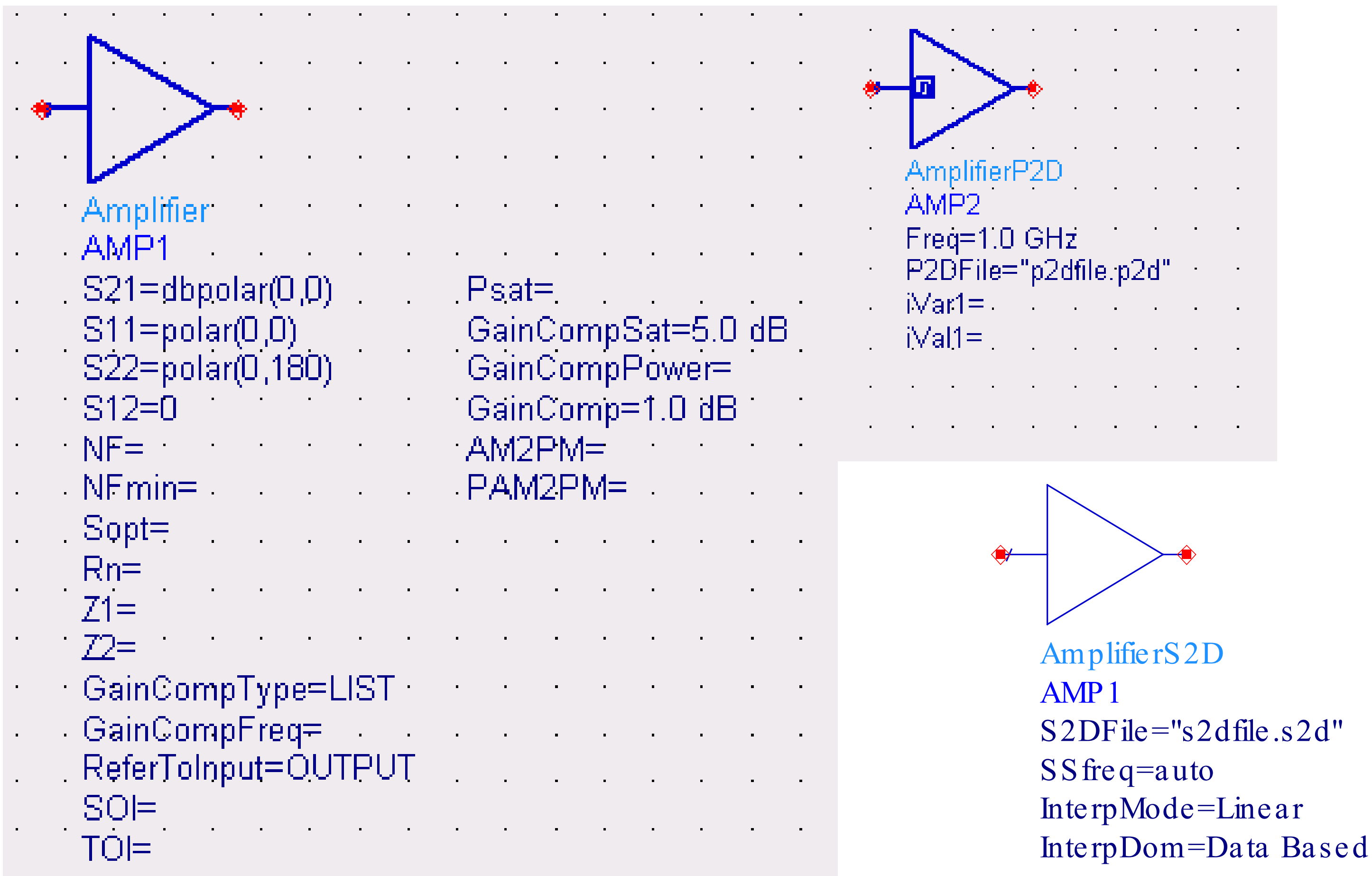
PA Modeling Techniques

- Circuit Level Models (Physical Models)
  - Based on the knowledge of the amplifiers' circuit structure
  - Require accurate active device models and other components
  - The simulation results can be accurate, however, time-consuming

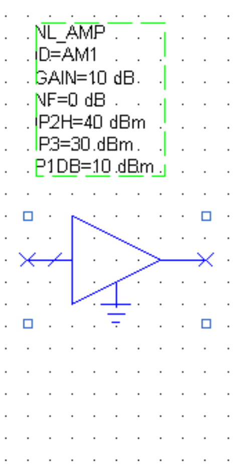


Accurate
NL device model
needed

"Built-in" ADS Amplifier Models



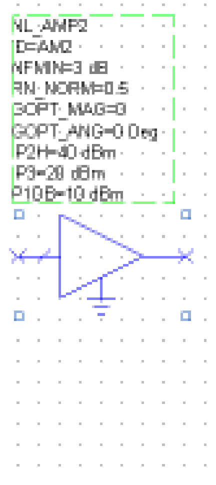
"Built-in" AWR Models



Element Options: NL_AMP - Nonlinear amplifier system model (Closed Form) Properties

Parameters | Statistics | Display | Symbol | Layout | Model Options | Vector

Name	Value	Unit	Tune	Opt	Limit	Lower	Upper	Description
ID	AM1							Element ID
GAIN	10	dB	☐	☐	☐	0	0	Mid-band transducer gain
NF	0	dB	☐	☐	☐	0	0	Noise Figure
IP2H	40	dBm	☐	☐	☐	30	30	Mid-band output IP2 (harmonic)
IP3	30	dBm	☐	☐	☐	30	30	Mid-band output IP3
P1DB	10	dBm	☐	☐	☐	30	30	Output 1-dB compression point
S11...	0		☐	☐	☐	0	0	Input reflection coefficient magnitude
S11...	0	Deg	☐	☐	☐	0	0	Input reflection coefficient phase angle
S22...	0		☐	☐	☐	0	0	Output reflection coefficient magnitude
S22...	0	Deg	☐	☐	☐	0	0	Output reflection coefficient phase angle
Z0	50		☐	☐	☐	0	0	Port impedance
TDLY	0	ns	☐	☐	☐	0	0	Group delay



Element Options: NL_AMP2 - Advanced system model for a small-signal amplifier Properties

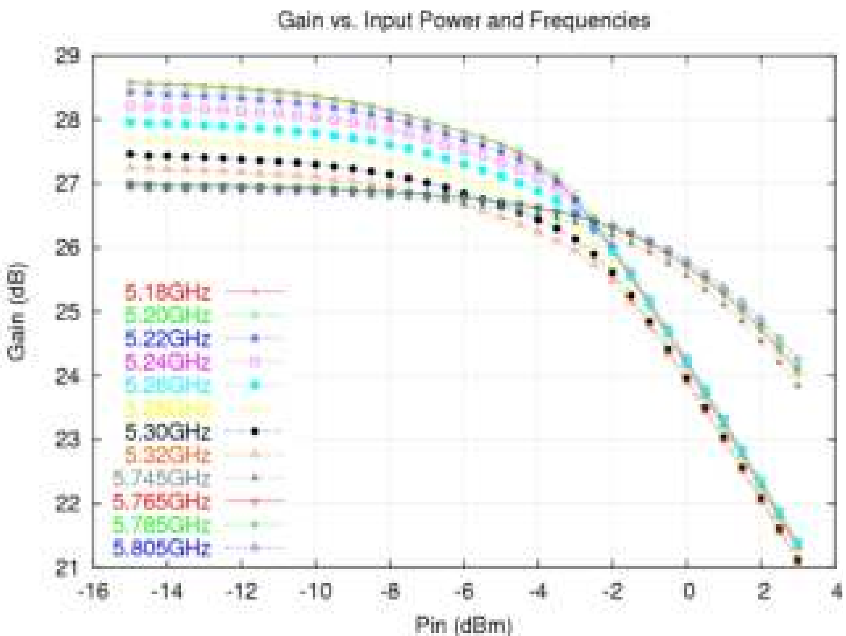
Parameters | Statistics | Display | Symbol | Layout | Model Options | Vector

Name	Value	Unit	Tune	Opt	Limit	Lower	Upper	Description
ID	AM2							Element ID
NFMIN	3	dB	☐	☐	☐	0	0	Minimum noise figure (dB)
RN_NORM	0.5		☐	☐	☐	0	0	Noise resistance (normalized to Z0)
GOPT_MAG	0		☐	☐	☐	0	0	Source reflection coefficient for optimum NF, magnitude
GOPT_ANG	0	Deg	☐	☐	☐	0	0	Source reflection coefficient for optimum NF, phase
IP2H	40	dBm	☐	☐	☐	30	30	Mid-band output IP2 (harmonic)
IP3	20	dBm	☐	☐	☐	30	30	Mid-band output IP3
P1DB	10	dBm	☐	☐	☐	30	30	Output 1-dB compression point
S11MAG	0		☐	☐	☐	0	0	Input reflection coefficient magnitude
S11ANG	0	Deg	☐	☐	☐	0	0	Input reflection coefficient phase angle
S22MAG	0		☐	☐	☐	0	0	Output reflection coefficient magnitude
S22ANG	0	Deg	☐	☐	☐	0	0	Output reflection coefficient phase angle
S21MAG	3.1623		☐	☐	☐	0	0	S21 magnitude
S21ANG	179...	Deg	☐	☐	☐	0	0	S21 phase angle
S12MAG	0		☐	☐	☐	0	0	S12 magnitude
S12ANG	0	Deg	☐	☐	☐	0	0	S12 phase angle
Z0	50		☐	☐	☐	0	0	Port reference (normalizing) impedance

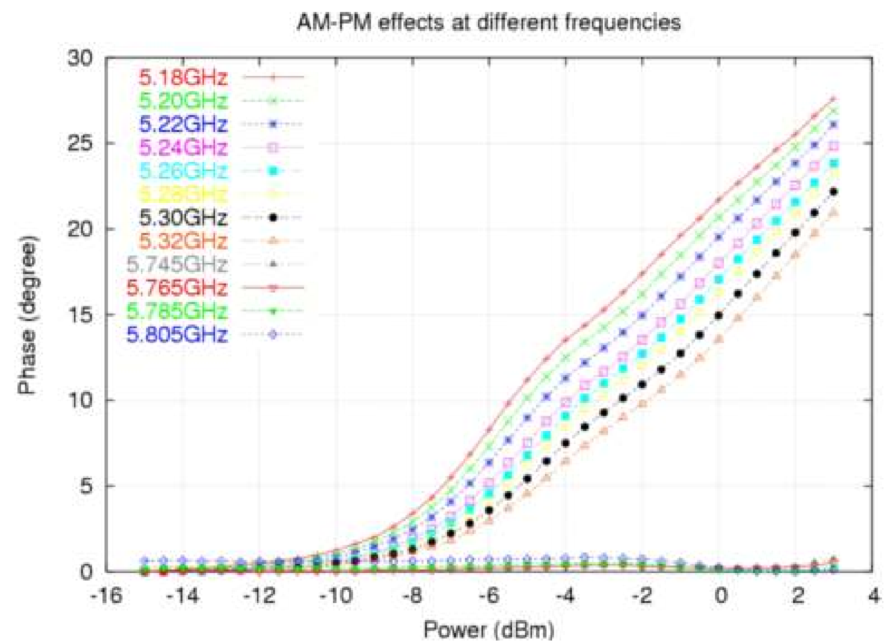
Capabilities of Built-in Models

- S-parameter, NPar
- Gain compression
- Phase compression
- TOI, etc
- Can use multiple dimensional datasets, including nonlinear gain compression information vs bias, temperature, frequency, etc
- Can simulate in envelope domain for outputs such as ACPR/Spectral spreading

Frequency-related Memory Effects



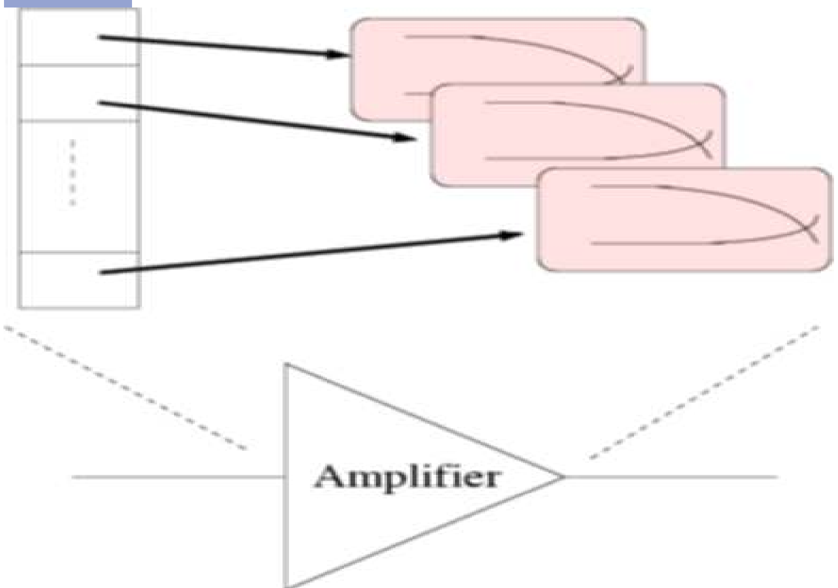
Measured results for
Murata XM5060 PA sample

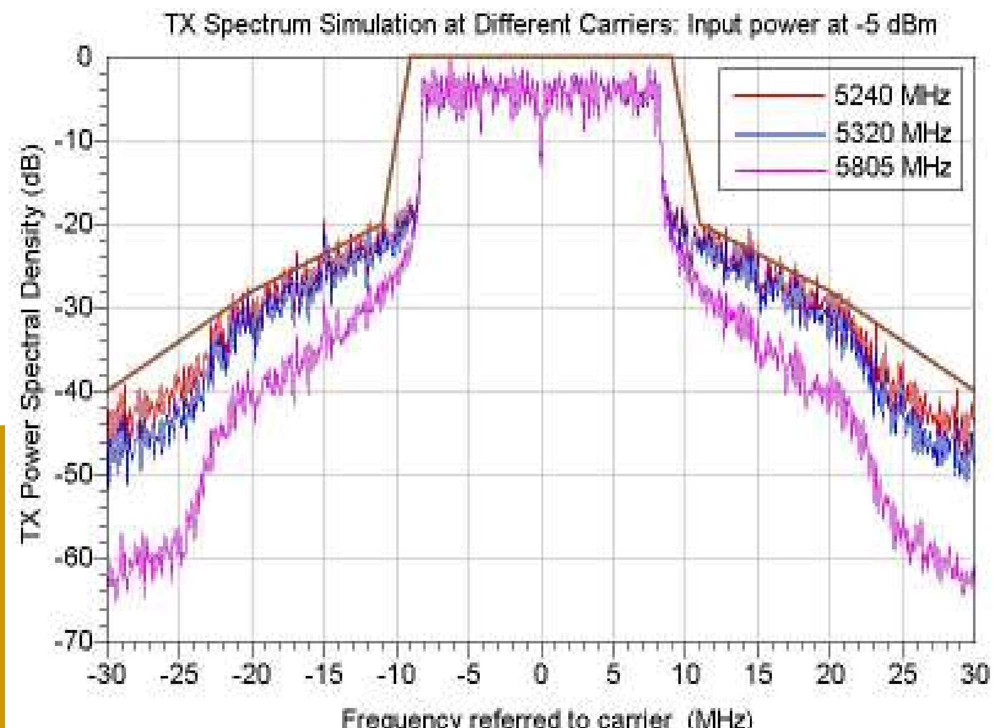


Carrier frequency related AM-AM and AM-PM variation

Example Approach for Frequency-related Nonlinear Effects – ADS Amplifier Model

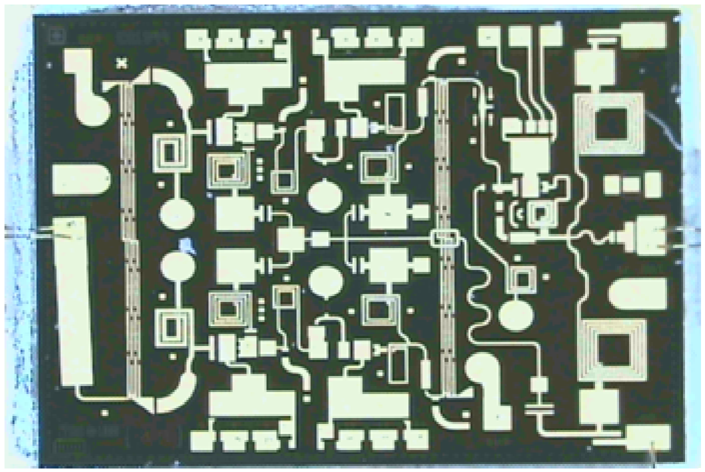
Simple file driven model constructed based on the measured datasets at different frequencies.

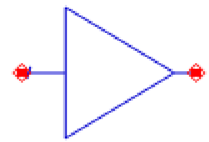




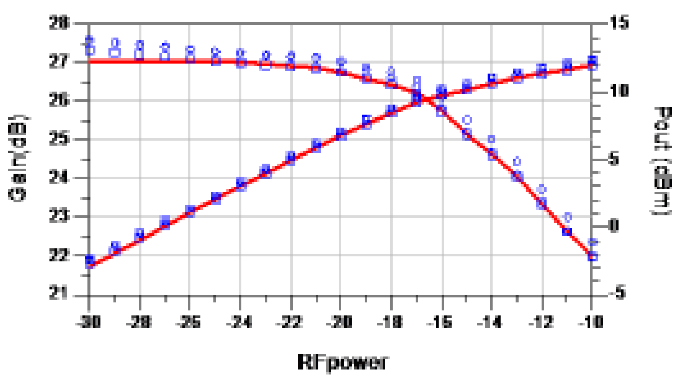
Simulated output spectrum shows the correlation between the spectral regrowth and the PA performance at different frequencies.

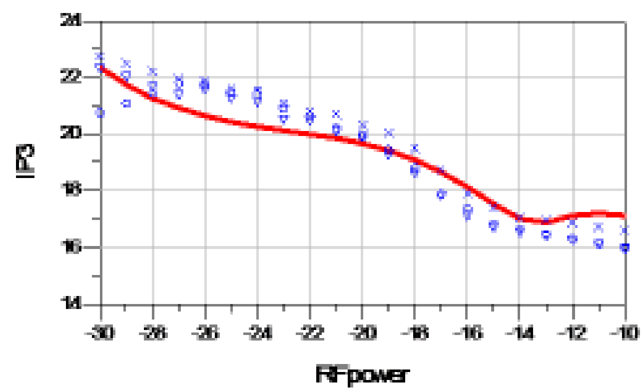
Combined P2d/S2D Model





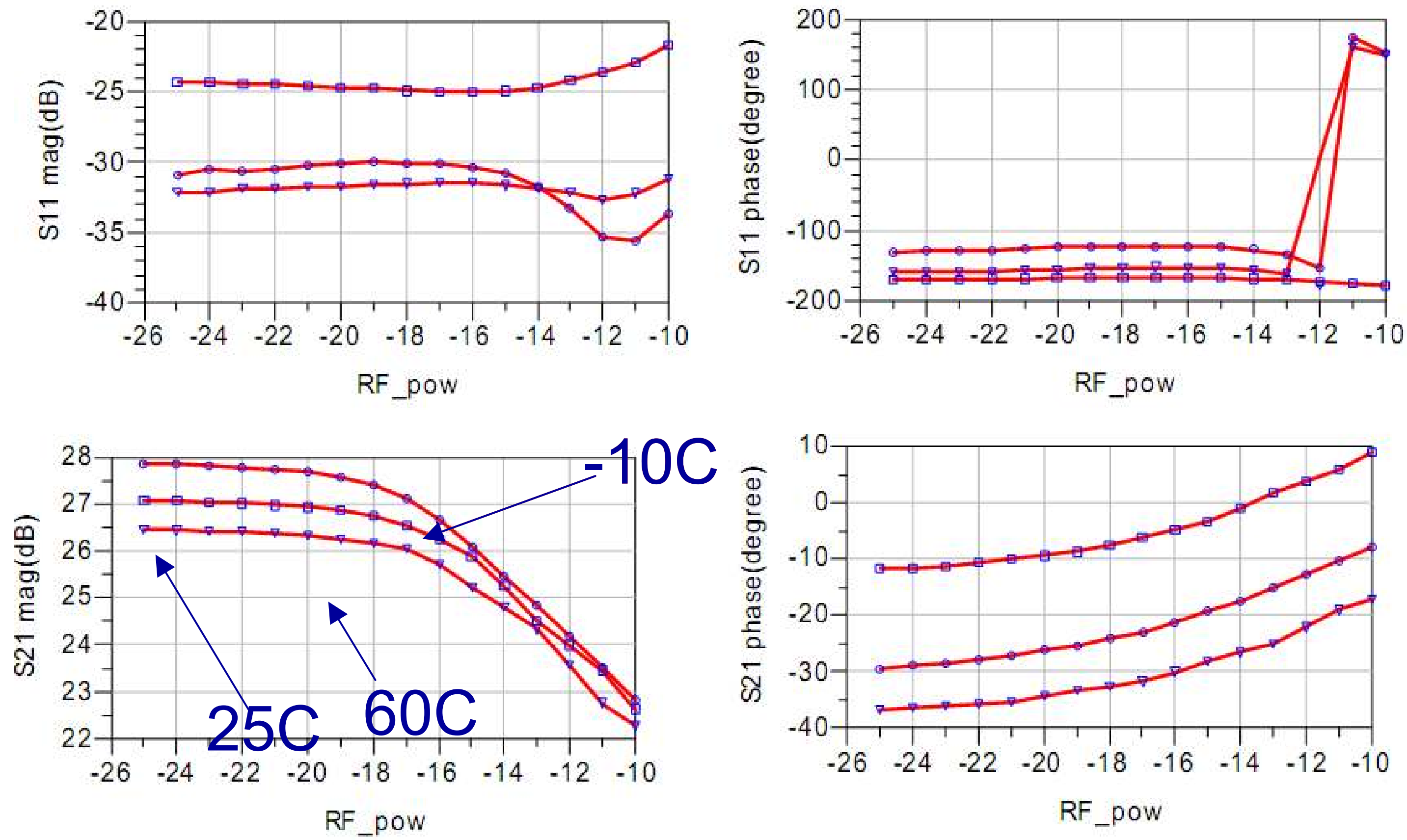
AMP_TRI_TGA8399-SCC
AMP_TGA8399_SCC_1
RFfreq=2 GHz
CEFreqSpacing=1 MHz
Bias=5
temp=25
sim_mode=0
BWRemove=0





P2D/S2D MMIC example (cont)

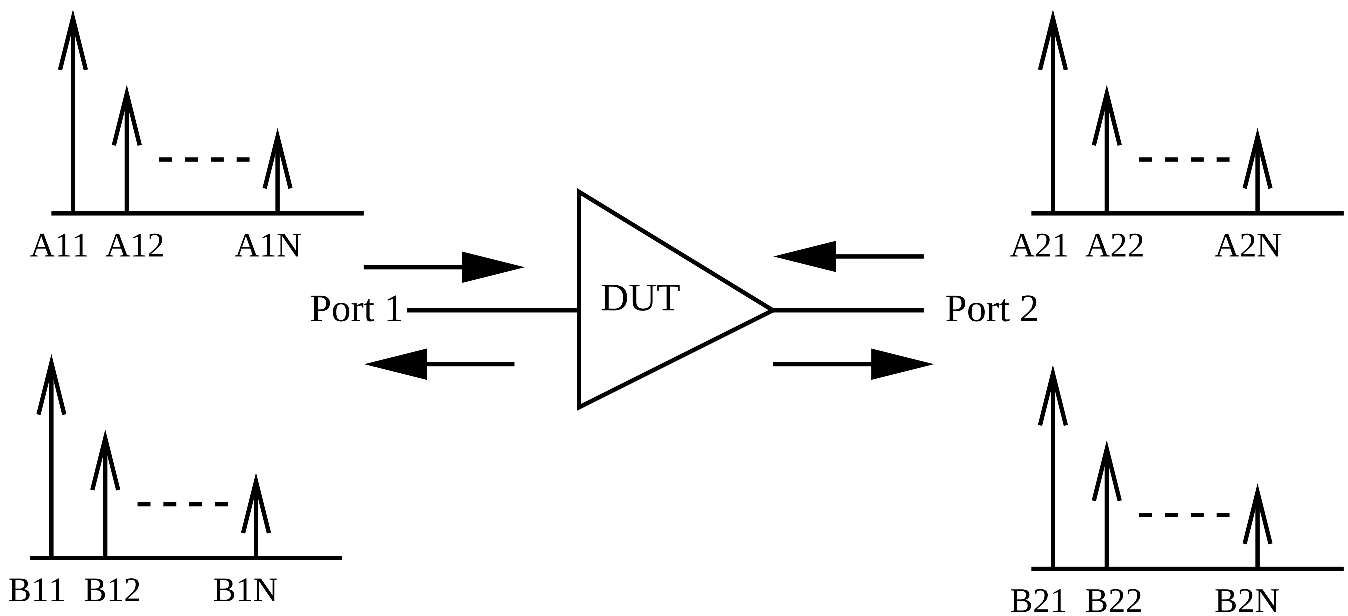
Triquint TGA8399B MMIC amplifier, bias of 5V, frequency at 11.25 GHz



Comparison of the measured and simulated Power. Blue is measurement; Red is model result.
Circle for –10C, square for 25C and triangle for 60C.

Large Signal Scattering Function Theory

- Designed to overcome the limitation of the small-signal S-parameter
- Take into account the fundamental tones as well as the harmonics
- The S-parameters become amplitude-dependent



Poly-Harmonic Distortion (PHD) Behavioral Model (Root et. al.)

- Recent application of the large-signal scattering function theory includes the "PHD Model" which targets the broad-band amplifiers
- It combines the A11-dependent S and T functions to characterize the B_{pk} at different port "p" and harmonic index "k"
- It is implemented in ADS using FDD component and DACs

$$B_{pk}(|A_{11}|, f) = \sum_{q} \sum_{l=1,\dots,M} S_{pq,kl}(|A_{11}|, f) \cdot P^{k-l} \cdot A_{ql} + \sum_{q} \sum_{l=1,\dots,M} T_{pq,kl}(|A_{11}|, f) \cdot P^{k+l} \cdot A_{ql}^{*} \tag{1}$$

$$T_{p1,k1} = 0. \tag{2}$$

- *D.E. Root, J. Verspecht, D. Sharrit, J. Wood, A. Cognata, "Broad-band poly-harmonic distortion (PHD) behavioral models from fast automated simulations and large-sinagl vectorial network measurements", IEEE Trans. Microw. Theory Tech., vol. 53, no. 11, pp. 3656–3664, Nov. 2005.*

Simplified Large-signal model (J. Liu et. al.)

Utilize the large-signal scattering function theory and consider the fundamental tone only, we can get a simplified model equation shown below:

$$B_2 = S_{21}A_1 + S_{22}A_2 + T_{22}A_2^*$$

$$= S_{21}A_{11} + S_{22}B_2\Gamma_L + T_{22}(B_2\Gamma_L)^*$$

$$S_{21} = C_1 + jC_2$$

$$S_{22} = C_3 + jC_4$$

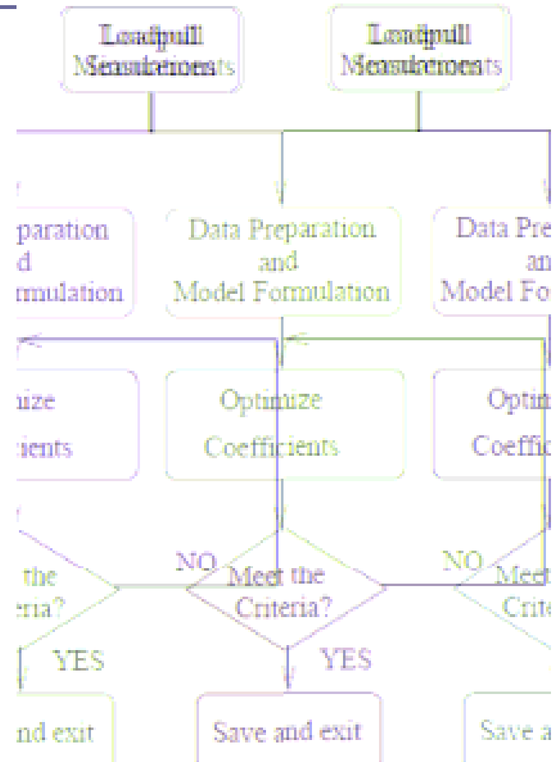
$$T_{22} = C_5 + jC_6$$

The Cn (n=1 to 6) are the model coefficients and should be derived from optimizations

Can be implemented in ADS using FDD component

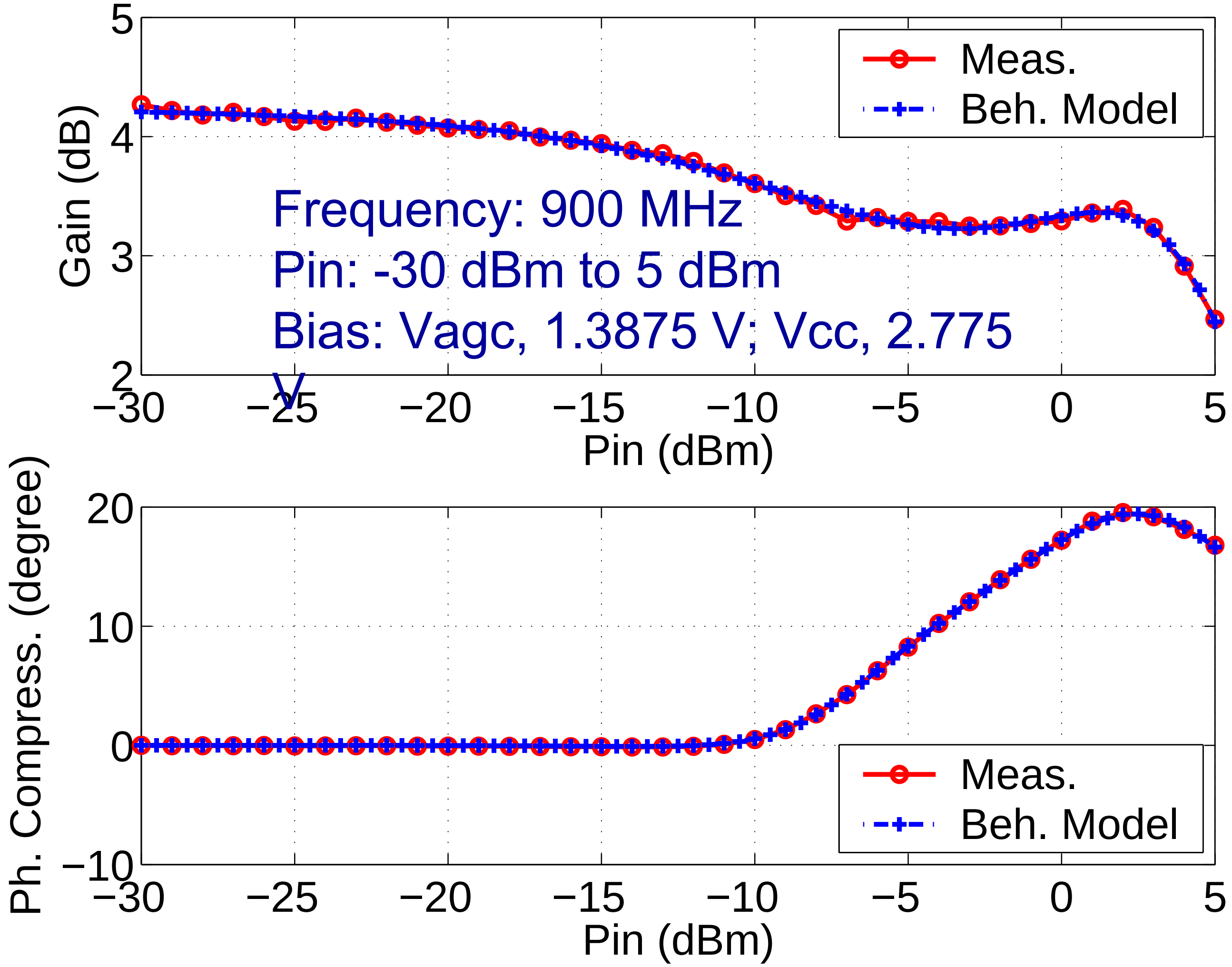
Derivation of the model

- The advantage of this model is that it depends on readily available load-pull and VNA instruments and more available measurement processes
- Measurements required to derive this model
  - Small signal S-parameters
  - AM-AM loadpull measurement,
  - AM-PM loadpull measurement



J. Liu, L.P. Dunleavy and H. Arslan, "Large Signal Behavioral Modeling of Nonlinear Amplifiers Based on Loadpull AM-AM and AM-PM Measurements", IEEE Trans. Microw. Theory Tech., vol. 54, no. 8, pp. 3191–3196, Aug. 2006.

Gain and phase compression at 50 ohm (MAX2373 RFIC LNA)



Modelithics

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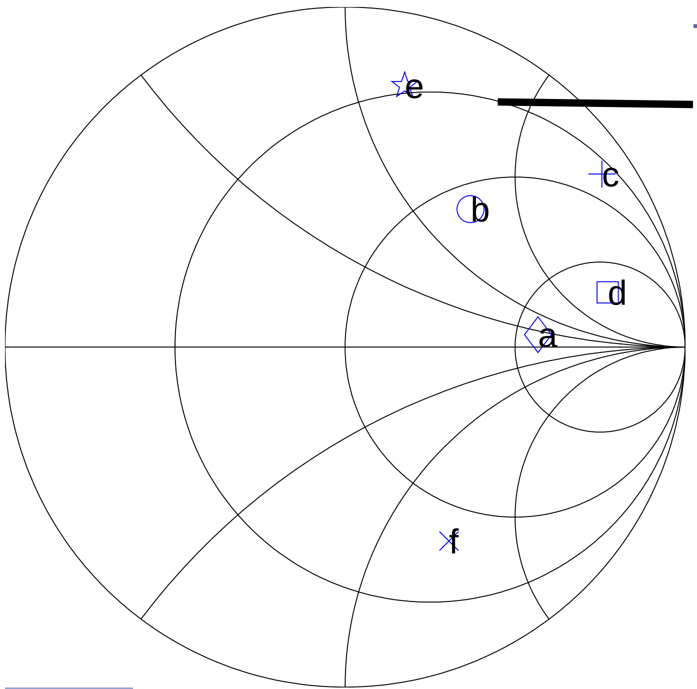
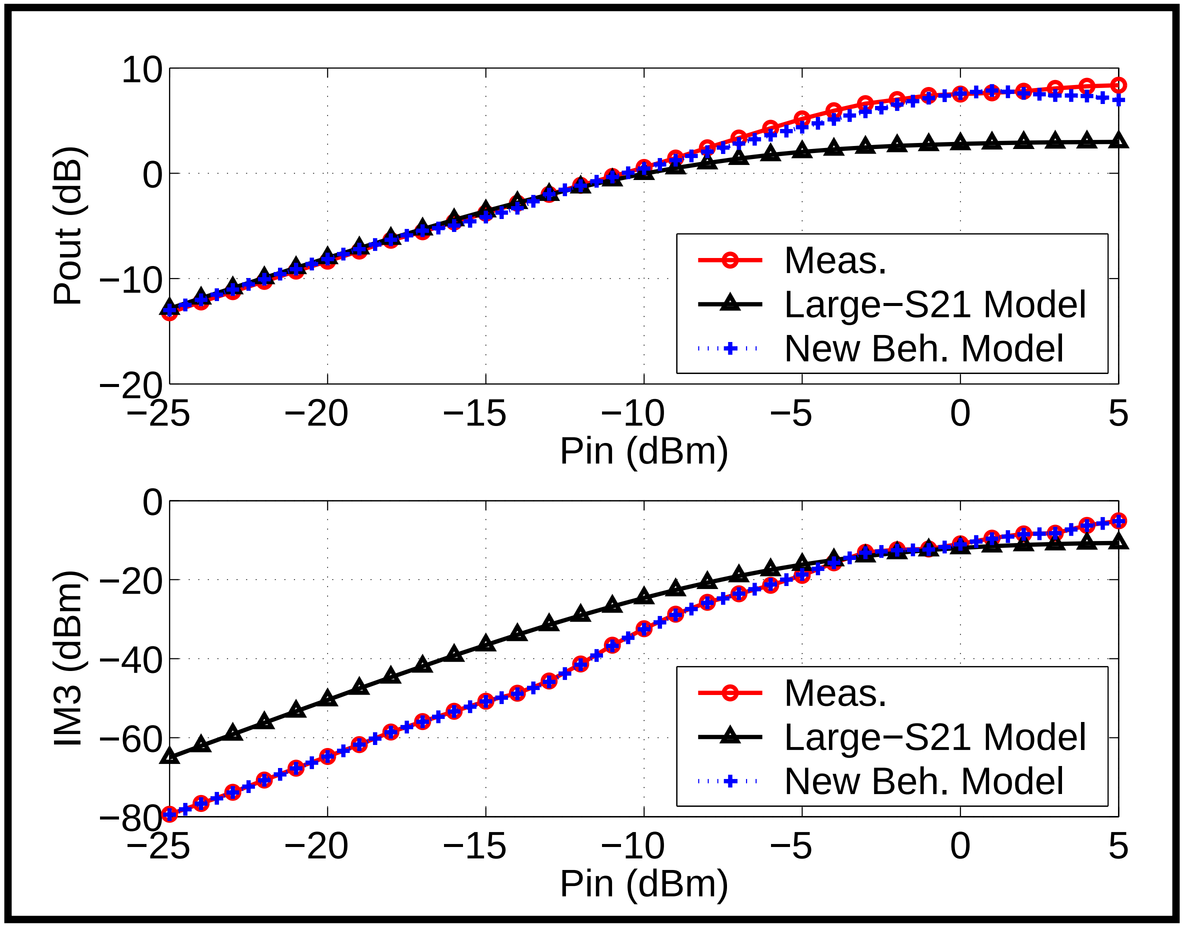
Simulated Fund. tone and IM3 at load b





Note: the “Large S21 model” neglects the last conjugate term.

Volterra Modeling for System Simulation

- Volterra methods are based on the idea that a nonlinear transfer characteristic can be expressed as a *functional series*.

$$w(t) = \int_{-\infty}^{\infty} h_1(\tau) s(t-\tau_1) d\tau_1$$

$$+ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) s(t-\tau_1) s(t-\tau_2) d\tau_1 d\tau_2$$

$$+ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_3(\tau_1, \tau_2, \tau_3) s(t-\tau_1) s(t-\tau_2) s(t-\tau_3) d\tau_1 d\tau_2 d\tau_3 + \ldots$$

- The h_n are *nth order Volterra kernels*. w(t) is the response and s(t) is the excitation.
- The expression can be viewed as an n-dimensional convolution integral.

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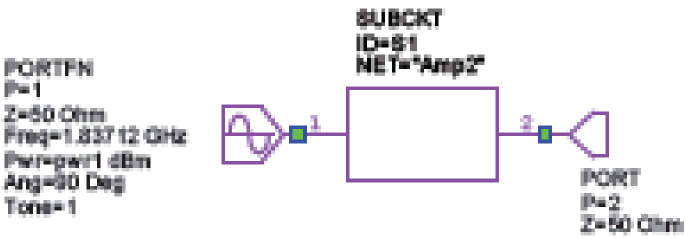
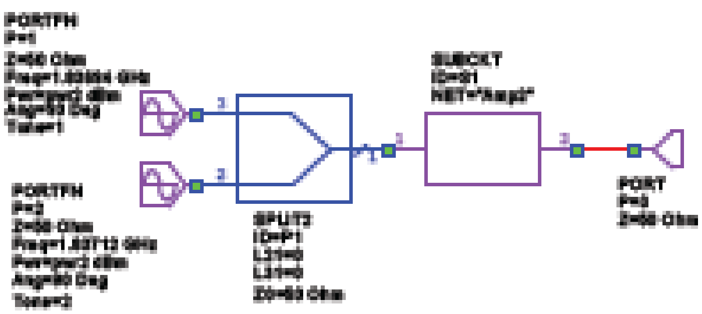
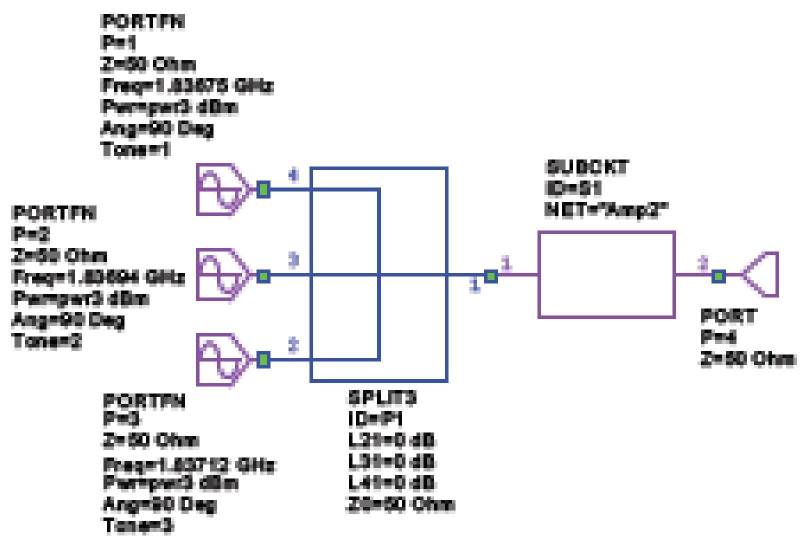
Volterra Model Extraction

The model is extracted from one, two, and three-tone HB analyses of the circuit.







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VSS Simulation: Class AB Cellular PA

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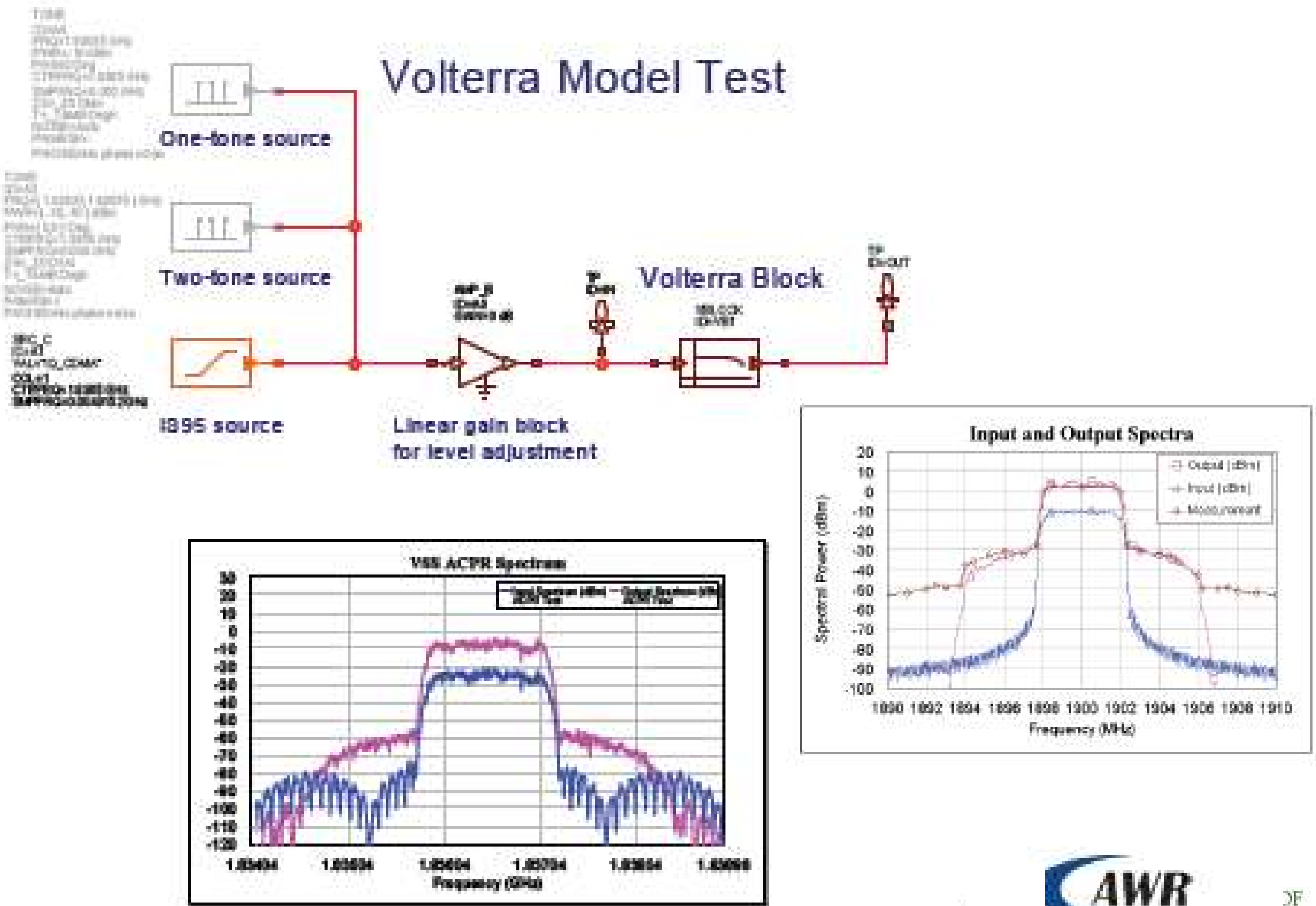

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Summary

- Non-linear device measurement/modeling requires…
  - Careful attention to measurement setup/accuracy
  - Pulsed multi-temperature testing
  - High current/high power instrumentation and components
  - Advanced non-linear instrumentation (e.g. load-pull)
- Large signal modeling requires
  - Advanced models (templates) and extraction techniques.
  - Focused expertise that can pull together the varied aspects of IV, S-parameter and non-linear test results into an effective modeling extraction and validation.
  - A measurement/modeling team is best!

Summary (cont'd)

- A Good Behavorial Model…
  - Needs be created based on measurement datasets through instruments available to the modelers.
  - Good News! More advanced non-linear test instruments/software are becoming available.
  - Model should be easy to use and no more complex than necessary.
  - Powerful enough to present multiple dimensional datasets for designers to inspect the amplifier's performance in a system view
  - (Ideally) Model should be supported in popular CAE software packages.

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