RF IV Waveform Measurement and Engineering

- Role in Supporting Non-Linear CAD Design -

Centre for High Frequency Engineering

School of Engineering

Cardiff University

Contact information

Prof. Paul J Tasker – ***tasker@cf.ac.uk***

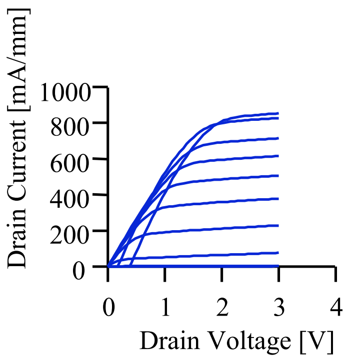
website: www.engin.cf.ac.uk/chfe

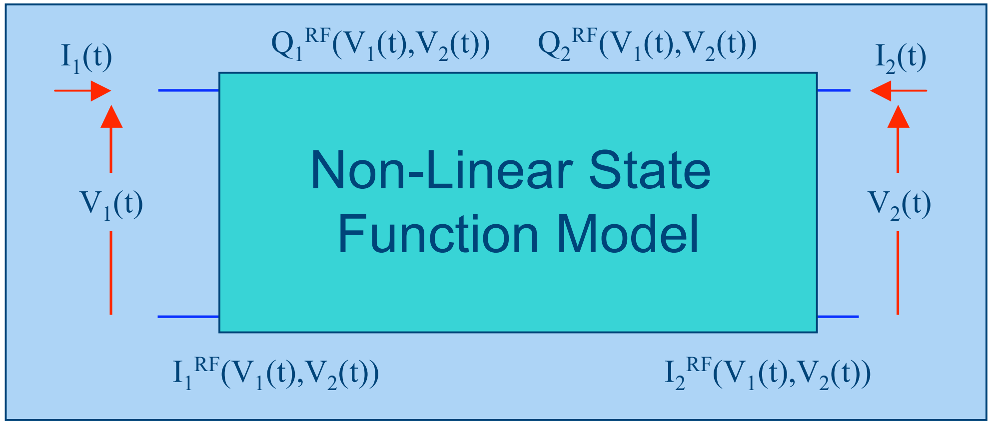
Non-Linear CAD Models:
- state function based formulation

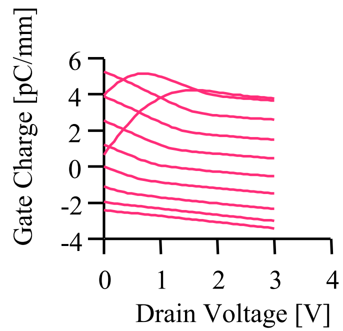
- Time domain formulations
  - Physics Based State function formulation: I & Q
    - Four quasi-static I and Q surface functions
      - Advanced formulations include time delays

$$i_{gs}(t) = I_g\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_g\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$

$$i_{ds}(t) = I_d\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_d\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$







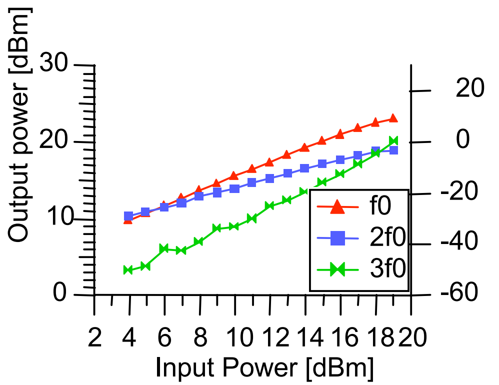
This fundamental formulation is followed by all analytical models and the Root lookup table model

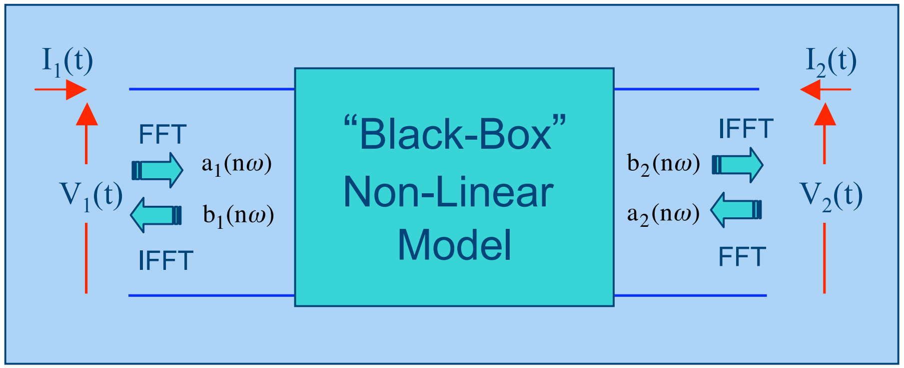
Non-Linear CAD Models:
- behavioral “black box: based formulation

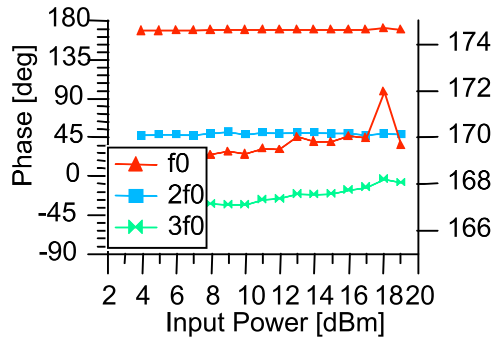
- Frequency or Time domain formulations
  - Behavioral based formulation
    - Many different formulations
      - Analytical or experimental data based

$$i_{ds}(t) = \alpha_0 + \alpha_1 v_{gs}(t-\tau_1) + \alpha_2 v_{gs}(t-\tau_2)^2 + \alpha_3 v_{gs}(t-\tau_3)^3 + ...$$

$$b_2(\omega) = f\big(a_1(\omega), a_1(2.\omega), ..., a_1(n.\omega),, a_2(\omega), a_2(2.\omega), ...a_2(n.\omega)\big)$$







Generally focus on describing a specific behavior

RF I-V Waveform Measurement & Engineering
- role in CAD modelling

- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - I-Q function Extraction
      - *Data Lookup Model Generation*
    - Analytical Model validation and Optimization

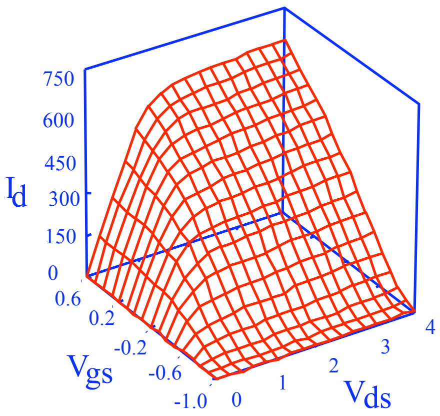
- Behavioural “Black Box” Non-Linear Models
  - Directly Measures Non-Linear Behaviour
    - Directly Import into CAD Tool
      - *Data Lookup behavioural model*
    - Indirectly Import into CAD Tool
      - *Formulated behavioural models (Volterra)*
      - *Emerging non-linear parameter equivalent to linear s-parameters (X-parameters)*

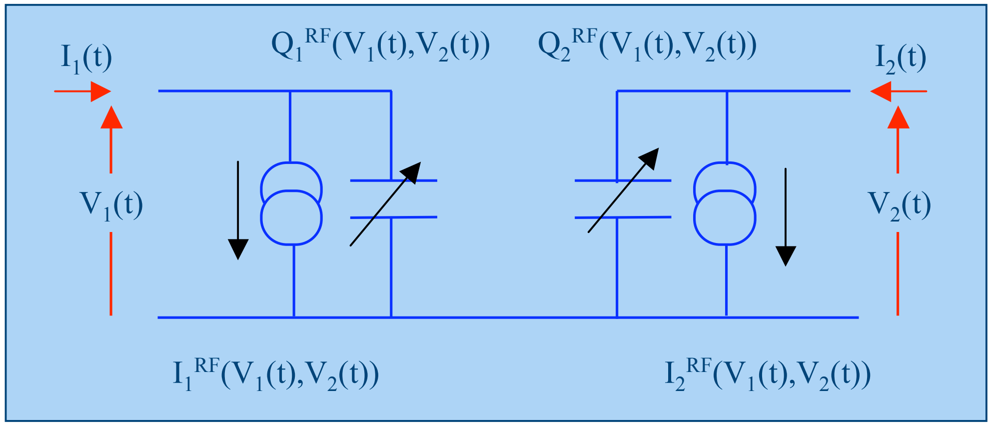
Non-Linear CAD Models:
- state function based formulation

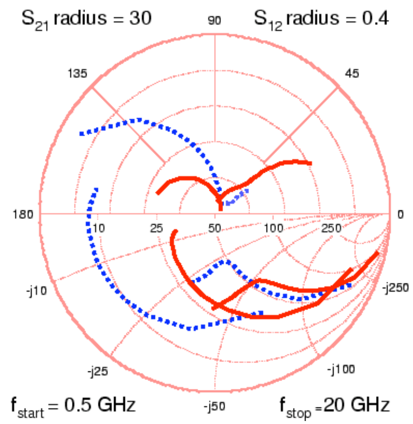
- Requires measurement of the state functions: I & Q
  - DC I-V provides Current State Function
    - Static measurements: trapping and thermal issues
  - S-parameters measure differential of state functions
    - Trapping and thermal issues

$$i_{gs}(t) = \mathrm{I_g}\left(\mathrm{v_{gs}}(t),\mathrm{v_{ds}}(t)\right) + {\partial \mathrm{Q_g}\left(\mathrm{v_{gs}}(t),\mathrm{v_{ds}}(t)\right)} \Big/ {\partial t}$$

$$i_{ds}(t) = \mathrm{I_d}\left(\mathrm{v_{gs}}(t),\mathrm{v_{ds}}(t)\right) + {\partial \mathrm{Q_d}\left(\mathrm{v_{gs}}(t),\mathrm{v_{ds}}(t)\right)} \Big/ {\partial t}$$







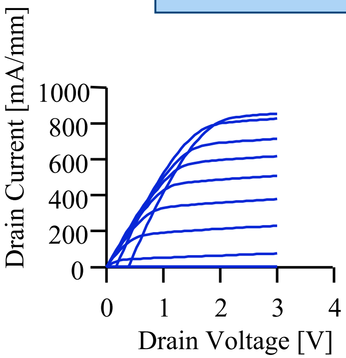
Ideally require direct dynamic measurement of state functions

Non-Linear State Function CAD Models:

- indirect extraction from bias dependent s-parameters

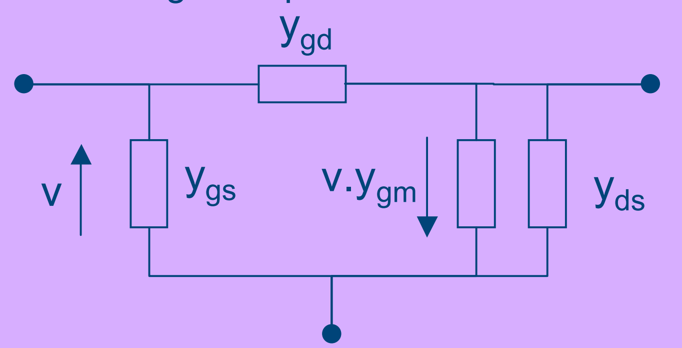
$$i_{gs}(t) = I_g\left(v_{gs}(t),v_{ds}(t)\right) + \frac{\partial Q_g\left(v_{gs}(t),v_{ds}(t)\right)}{\partial t}$$

$$i_{ds}(t) = I_d\left(v_{gs}(t),v_{ds}(t)\right) + \frac{\partial Q_d\left(v_{gs}(t),v_{ds}(t)\right)}{\partial t}$$



Linearize to get s-parameters

Small Signal Equivalent Circuit Model



$$i_{gs} = y_{11}.v_{gs} + y_{12}.v_{ds} \qquad y_{11} = y_{gs} + y_{gd} \qquad y_{12} = -\,y_{gd}$$

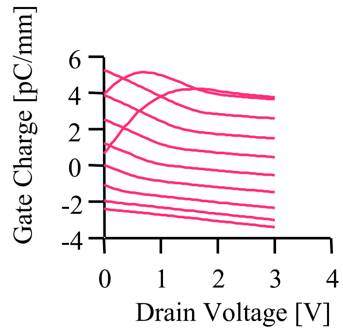
$$i_{ds} = y_{21}.v_{gs} + y_{22}.v_{ds} \qquad y_{21} = y_{gm} - y_{gd} \qquad y_{22} = y_{ds} + y_{gd}$$

Integrate bias dependent linear s-parameters to get non-linear parameters

Non-linear State Functions

$$Q_g = \int \Im(y_{11}).v_{gs} + \int \Im(y_{12}).v_{ds}$$

$$I_d = \int \Re(y_{21}).v_{gs} + \int \Re(y_{22}).v_{ds}$$

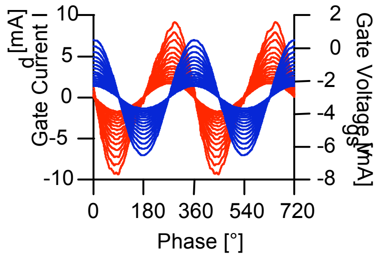


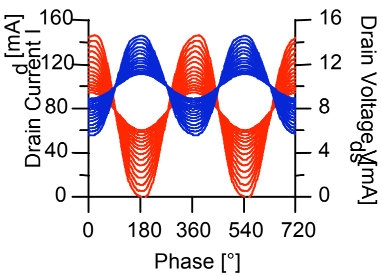
Provides data for Root model or for analytical curve-fitting

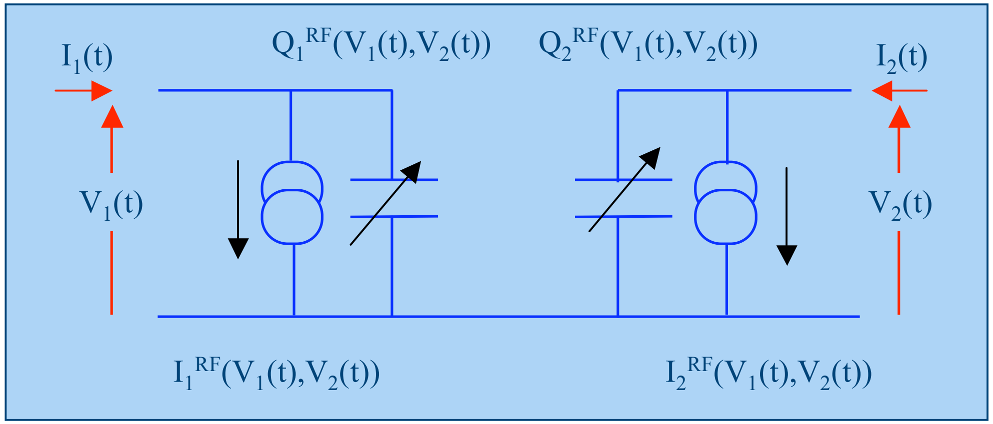
Non-Linear State Function CAD Models:

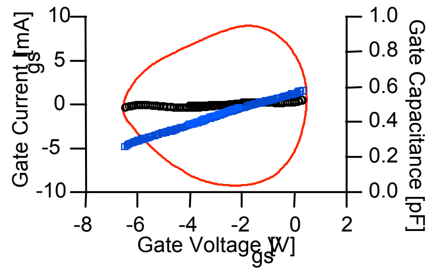
- direct extraction from RF I-V Waveforms

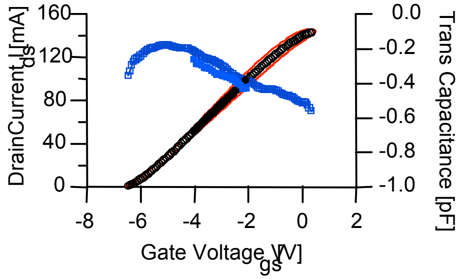
Model uses state functions to describe the arbitrary time dependent terminal current flow resulting from the applied arbitrary time dependent terminal voltages









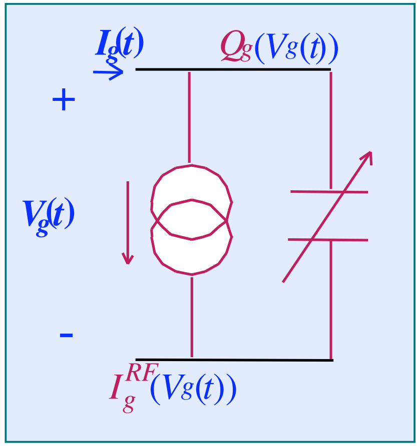


If we have measured the terminal current flow resulting from an applied and measured terminal voltage and we reverse process and determine state functions?

YES: Solutions in both the time and frequency domain.

Non-Linear State Function CAD Models:

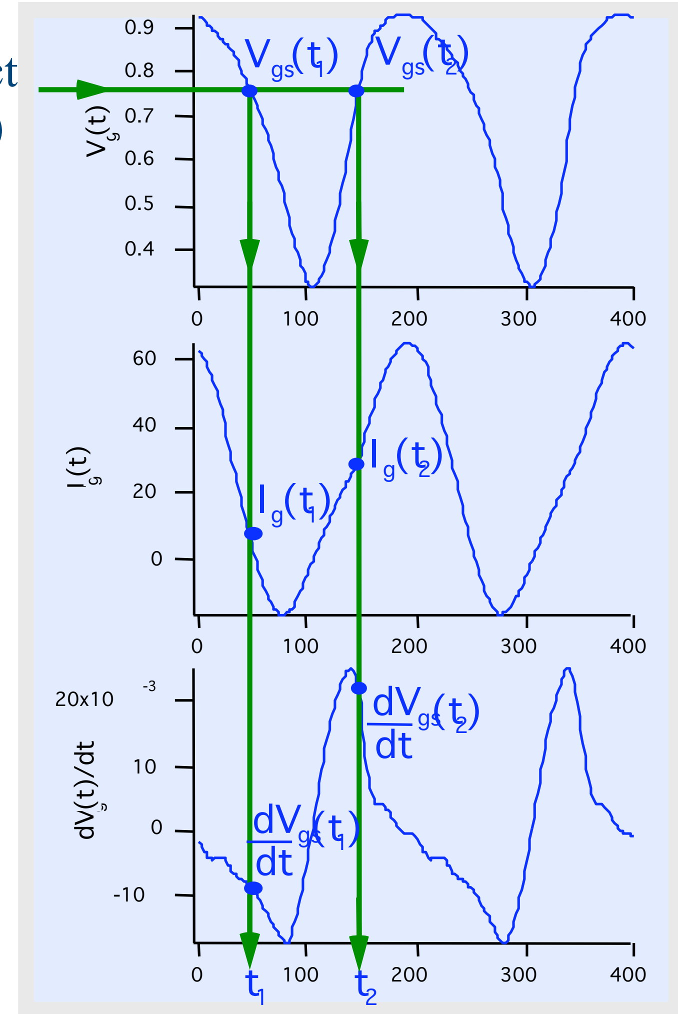
- direct extraction from RF I-V Waveforms



- One-Port Problem
  - Two State functions
  - Depend on one variable

$$i_{gs}(t) = I_g(v_{gs}(t)) + \partial Q_g(v_{gs}(t)) / \partial t$$

Select $V_{gs}(t)$



$$i_{gs}(t_1) = I_g(v_{gs}(t_1)) + C_g . \partial v_{gs} / \partial t (t_1)$$

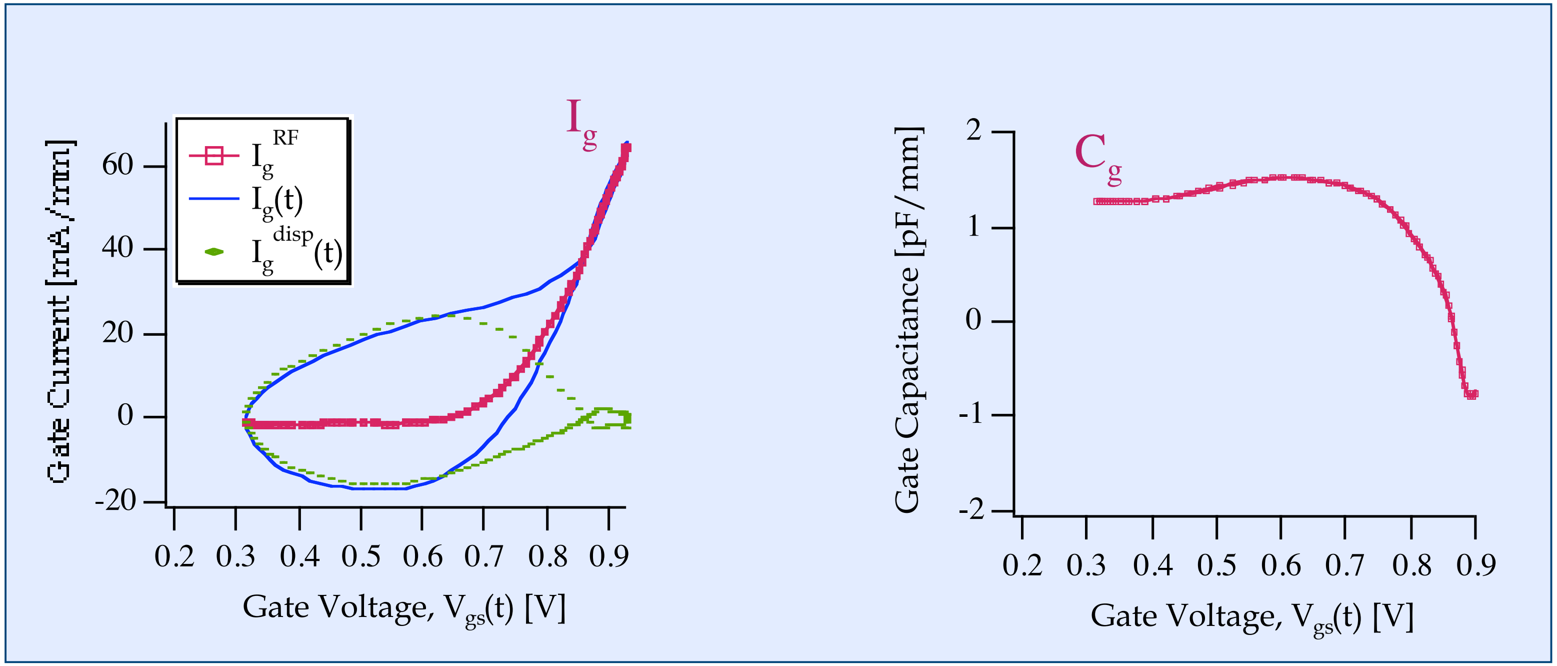
$$i_{gs}(t_2) = I_g(v_{gs}(t_2)) + C_g . \partial v_{gs} / \partial t (t_2)$$

Two equations with two unknowns, so solve for I_g and C_g

Schreurs et al, EuMC 1997

Non-Linear State Function CAD Models:

- direct extraction from RF I-V Waveforms

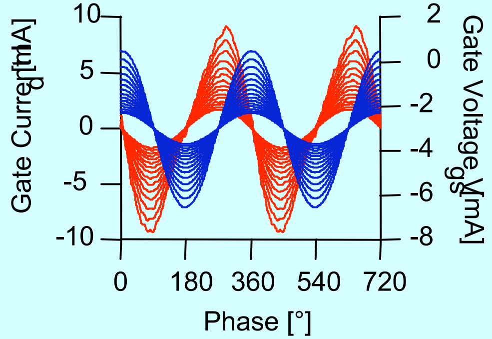


- Extraction of state functions for all measured values of Vgs(t)
- Only one large signal measurement needed
- Model extraction or model validation

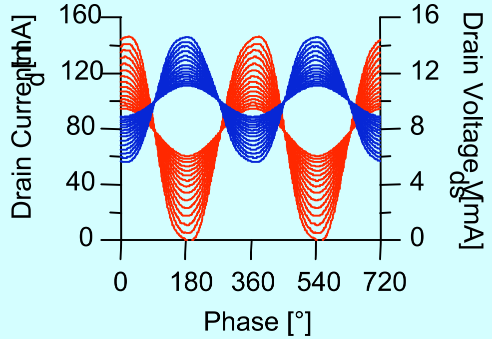
Schreurs et al, EuMC 1997

Non-Linear State Function CAD Models:

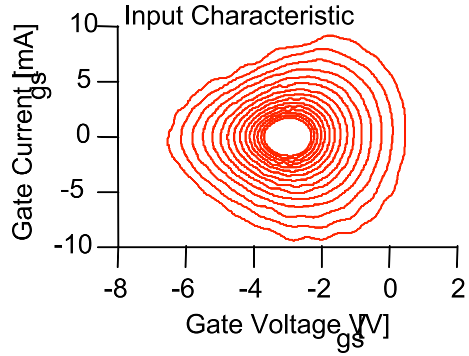
- direct extraction from RF I-V Waveforms



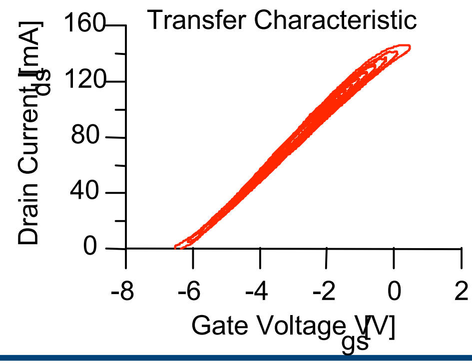
- Waveform Measurement
  Power Sweep @ 1.8 GHz

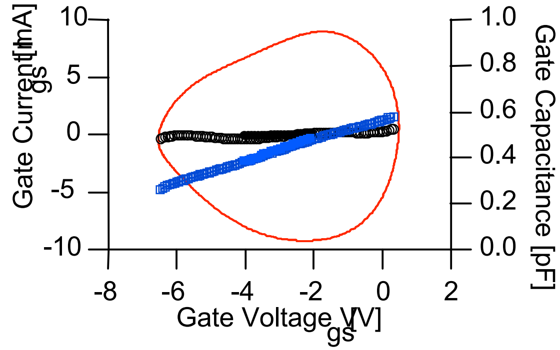


Transistor Behavior

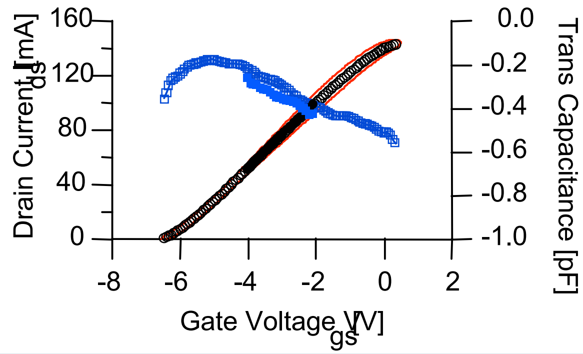


- Performance Understanding
  Reactive Non-Linearity's





- Extraction State Functions I & Q
  Reactive strongly second order



State Functions

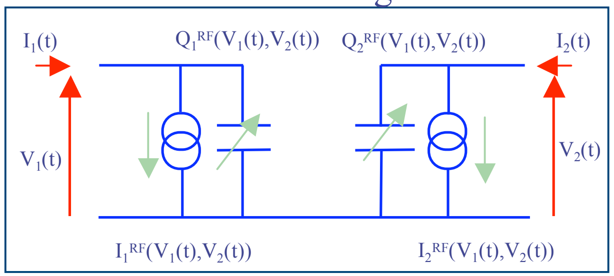
Non-Linear State Function CAD Models:

- direct extraction from RF I-V Waveforms

Stimulate with appropriate engineered waveforms $V_1(t)$ and $V_2(t)$ voltages and perform measurements

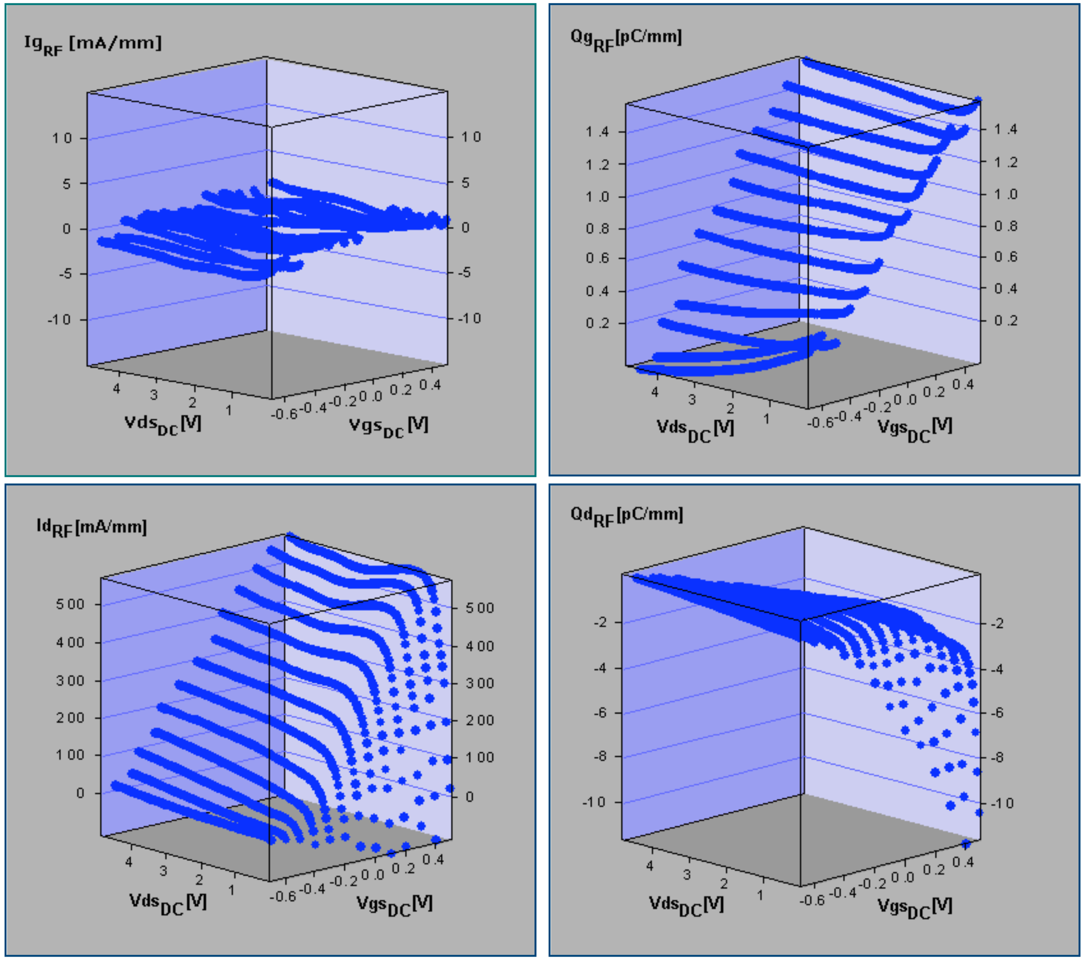
INPUT

Reverse Modelling Process



OUTPUT

Extract I and Q state functions: i.e. their dependence on voltages V_1 and V_2

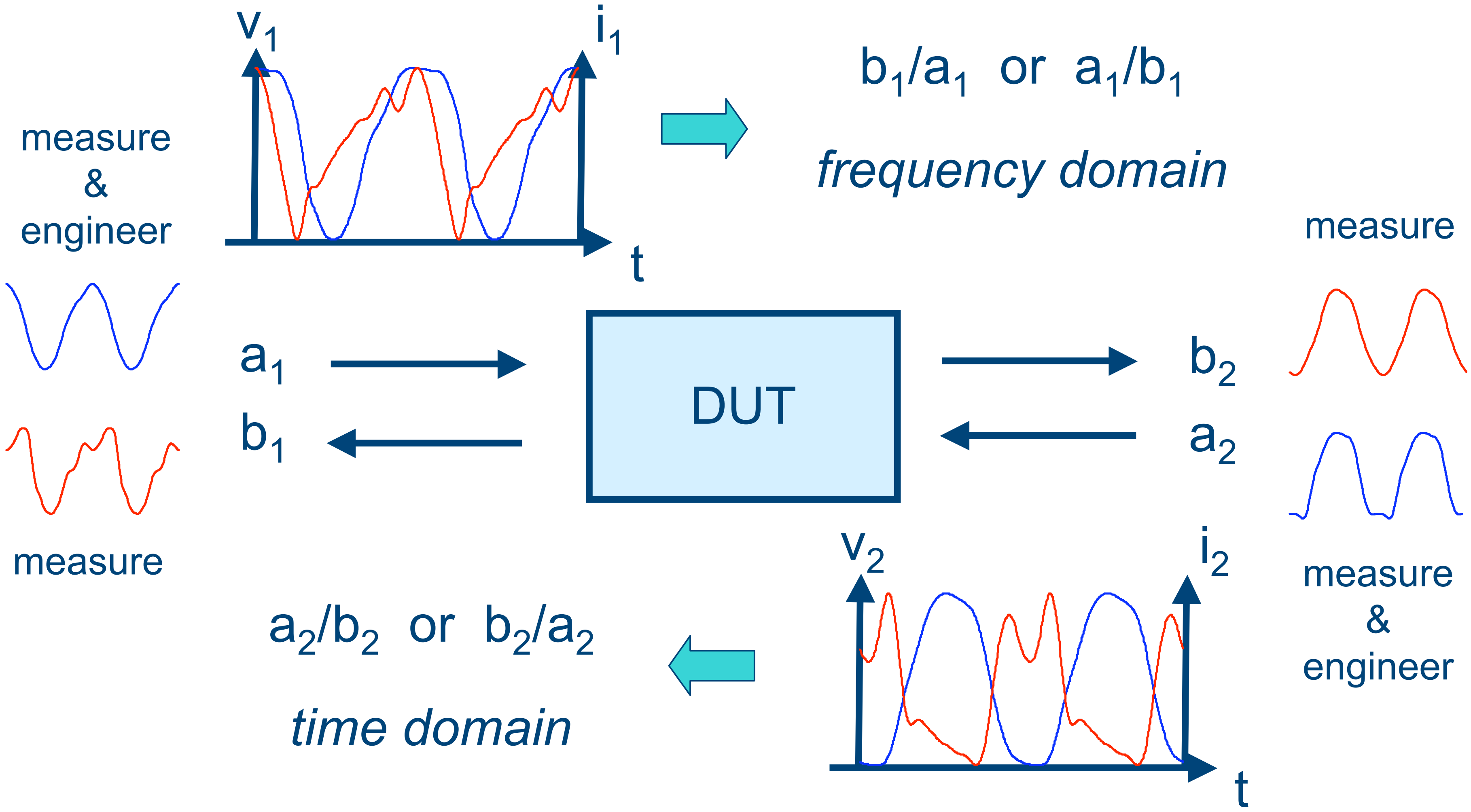


Morgan et al, IMS 2001

- Extracted Fully Dynamic Intrinsic I and Q Surfaces of a pHEMT transistor

Waveform Measurement and Engineering

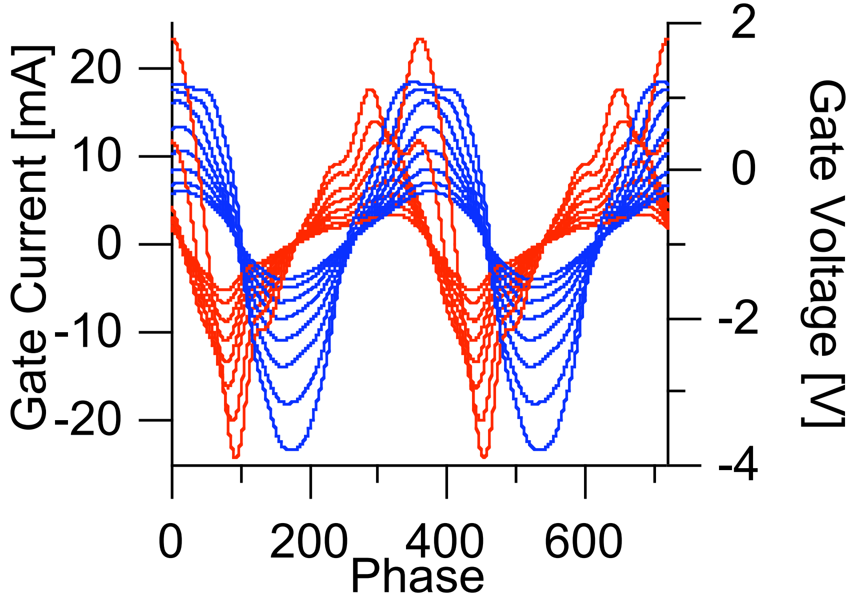
- are we looking at the device or the system?

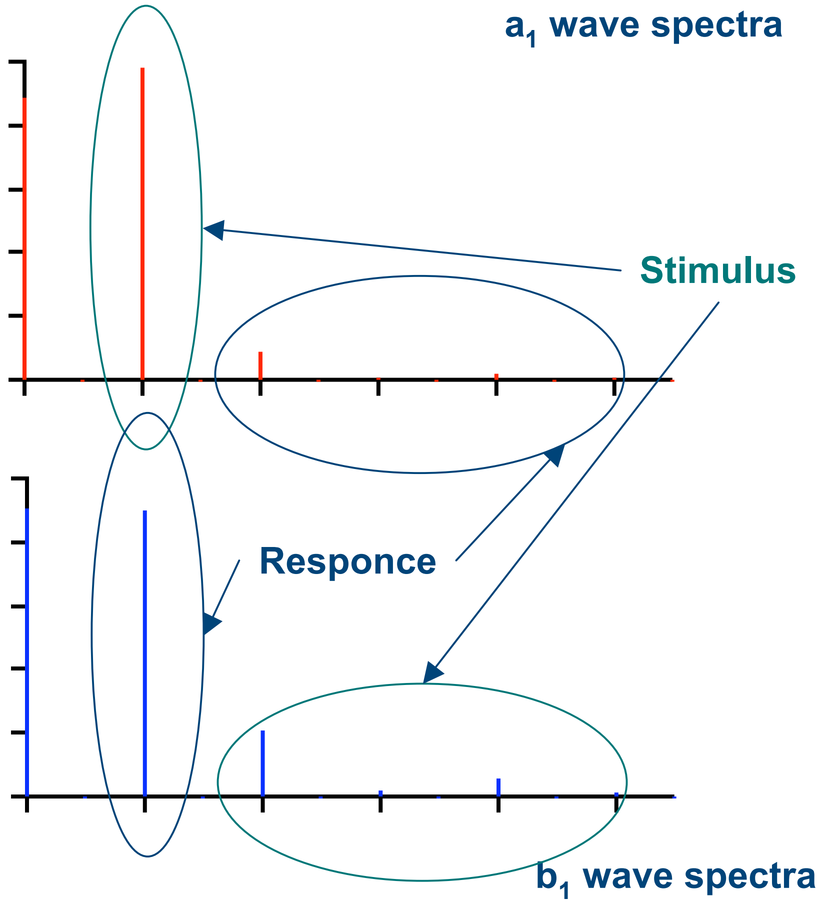


Waveform Measurement and Engineering

- are we looking at the device or the system?

- "Forward and Reverse Looking" Measurements
  - separation in the frequency domain
    - fundamental
      - Input Impedance $S_{11}(b_1/a_1)$
    - harmonics
      - source Impedance (a_1/b_1)

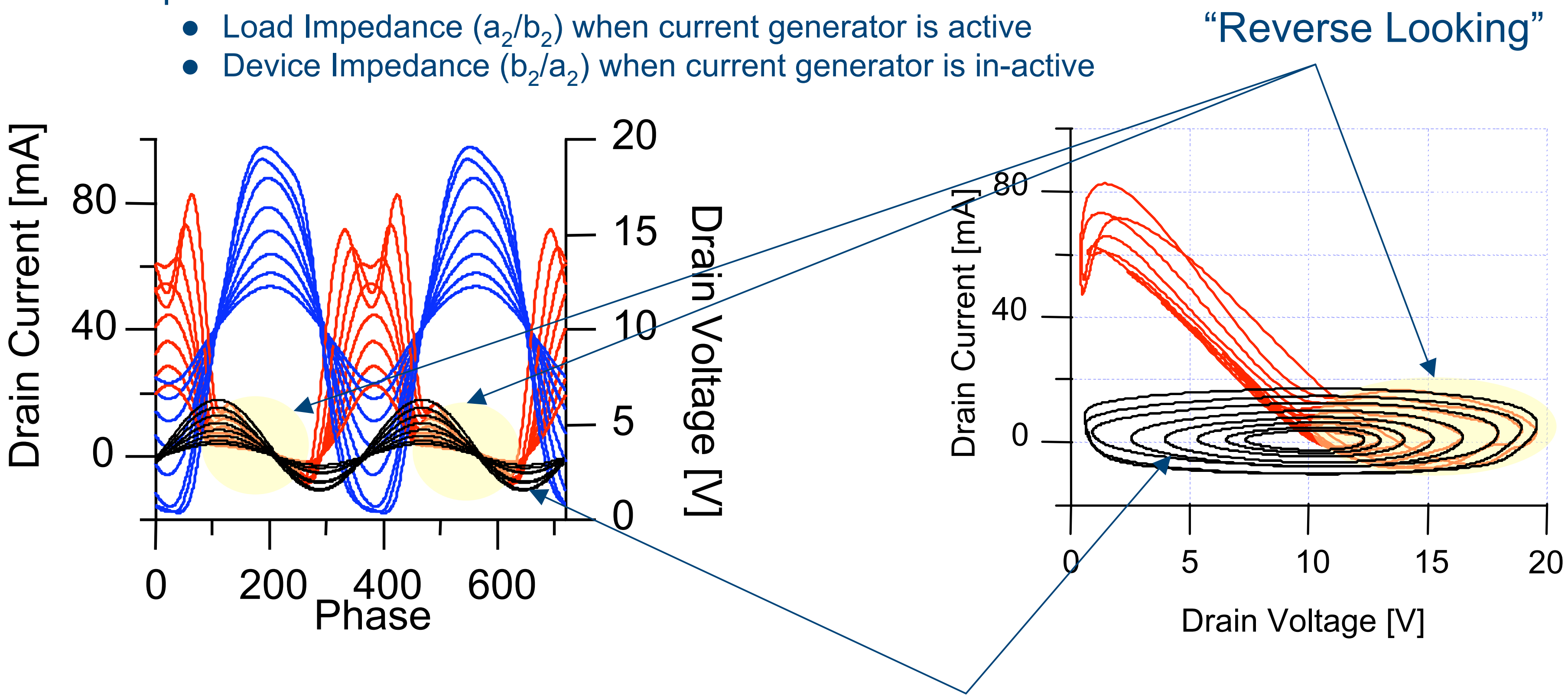




Waveform Measurement and Engineering

- are we looking at the device or the system?

- "Forward and Reverse Looking" Measurements
  - separation in the time domain
    - Load Impedance (a_2/b_2) when current generator is active
    - Device Impedance (b_2/a_2) when current generator is in-active



Extract Output Capacitance C_{ds} = 0.4 pF/mm

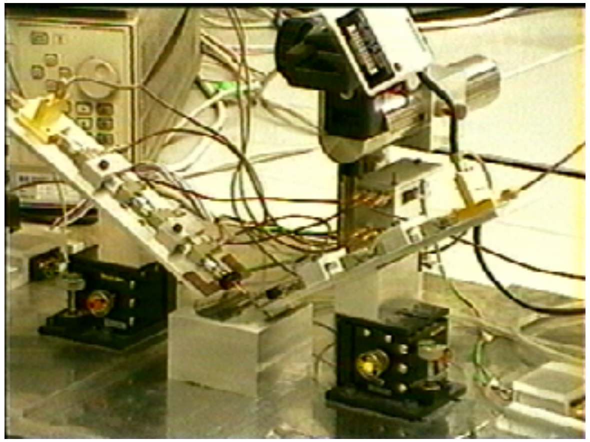
RF I-V Waveform Measurement & Engineering

- role in CAD modelling

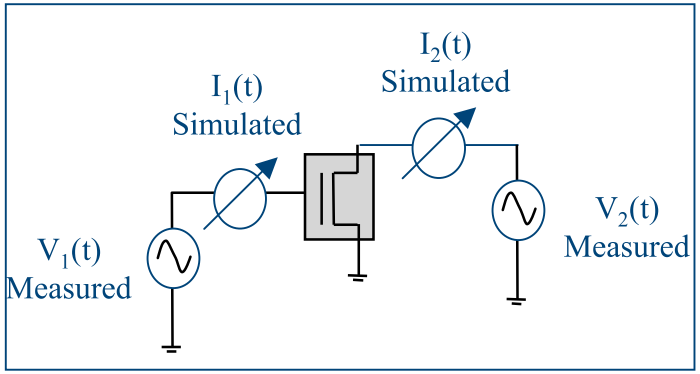
- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - I-Q function Extraction
      - *Data Lookup Model Generation*
    - Analytical Model validation and Optimization

Transistor RF I-V Waveforms
– *Verification of non-linear CAD models*

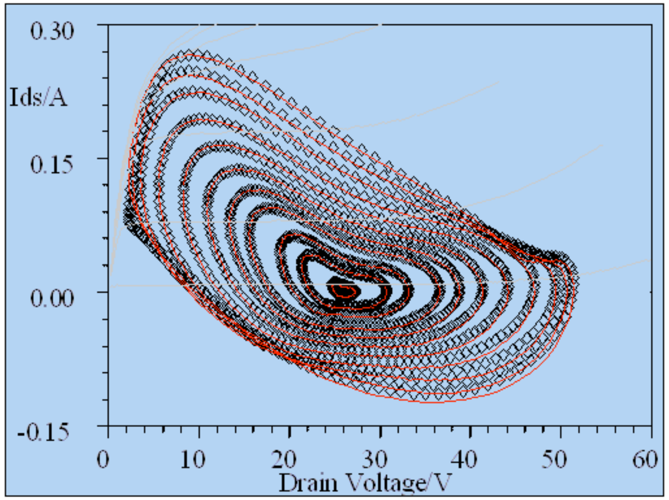
- Control mode of excitation
  - Similar to circuit operation
  - Maximize coverage of output I-V space, state variable space.



Measure: $V_1(t)$, $V_2(t)$ and $I_1(t)$, $I_2(t)$



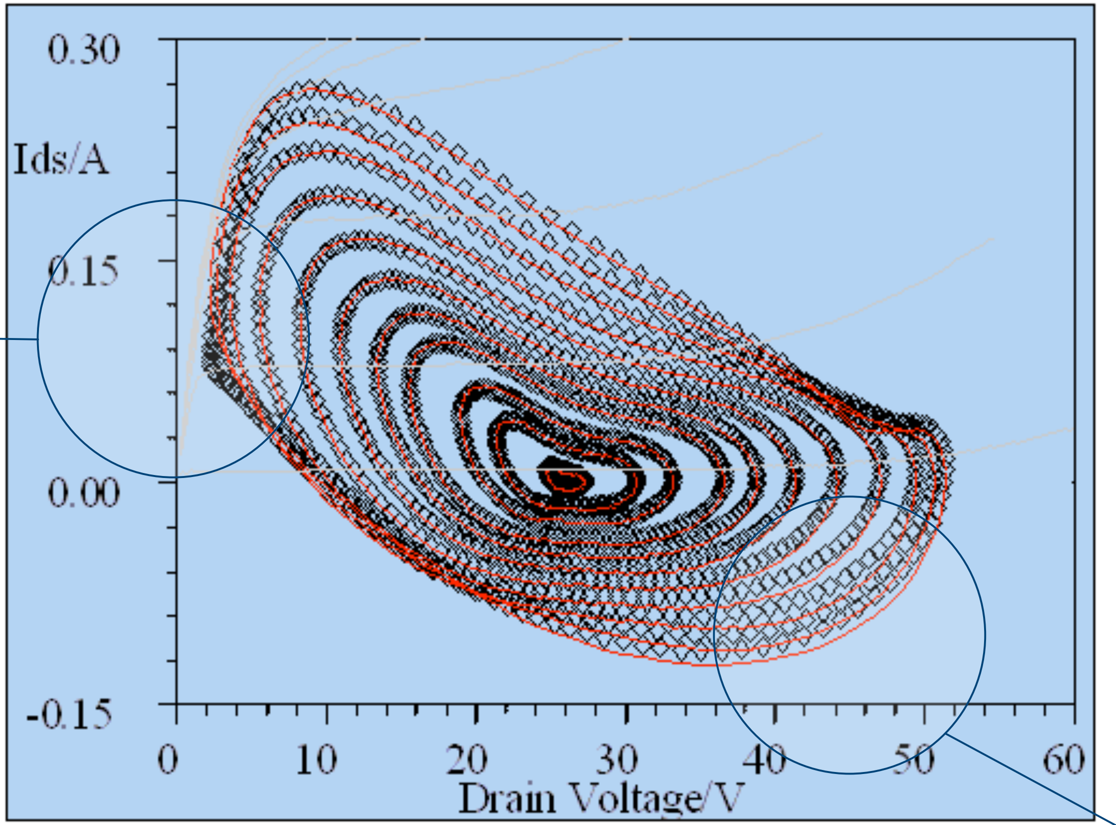
Import Measured $V_1(t)$ and $V_2(t)$ into the simulator



Compare Simulated $I_1(t)$, $I_2(t)$ with Measured $I_1(t)$, $I_2(t)$

Transistor RF I-V Waveforms
– Verification/Optimization of non-linear CAD models

Provides insight to why and where the model is failing to accurately predict non-linear behavior



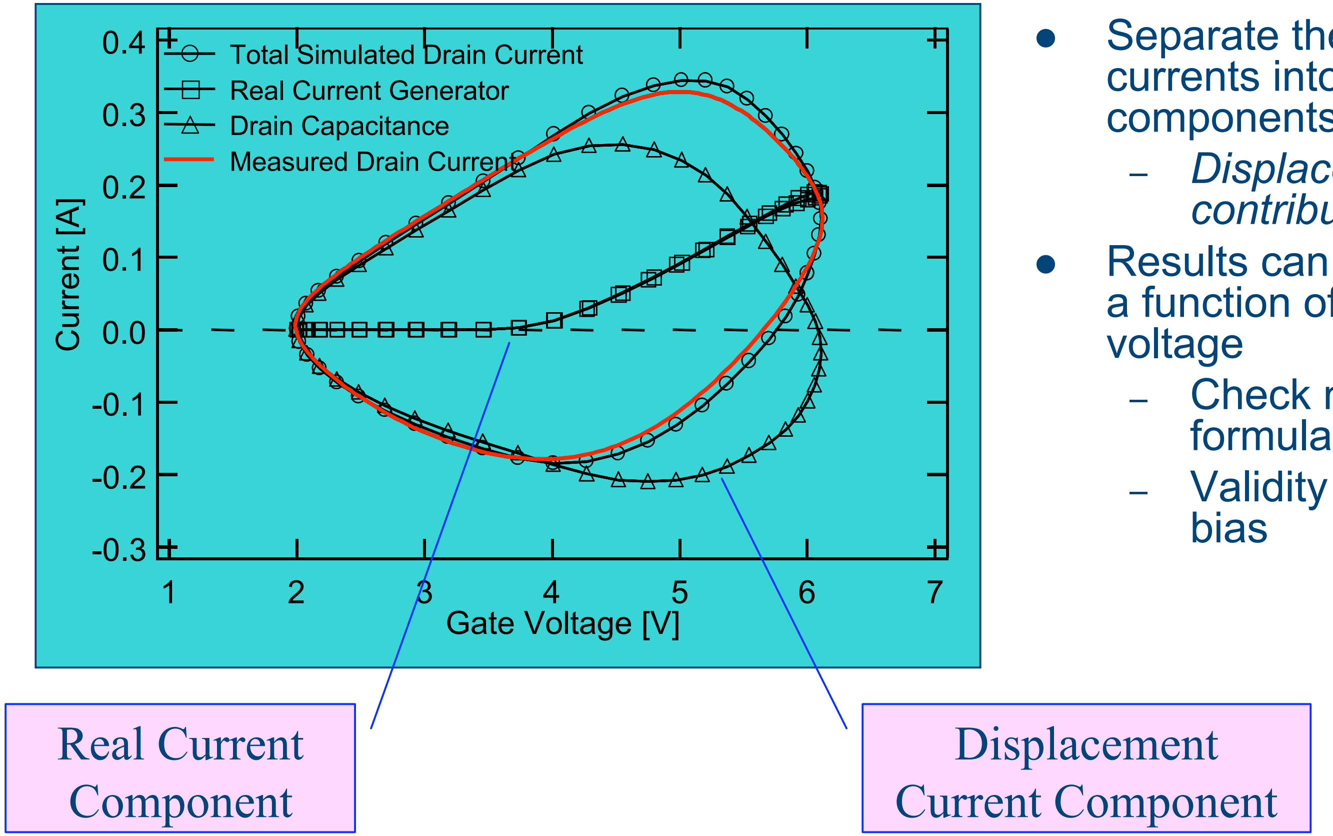
Some divergence near knee

Some divergence at pinch-off

More robust and useful than what is typically done: simply comparing simulated and measured Power performance

Transistor RF I-V Waveforms

– Verification/Optimization of non-linear CAD models



- Separate the measured currents into their individual components
  - *Displacement and real contributions*
- Results can be presented as a function of input or output voltage
  - Check model formulations
  - Validity as a function of bias

- Result, in this case, show that the LDMOS model used is not accurately modelling the variation of output capacitance as a function of gate bias.

RF I-V Waveform Measurement & Engineering
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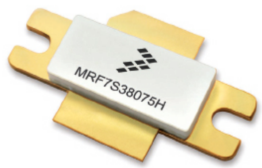
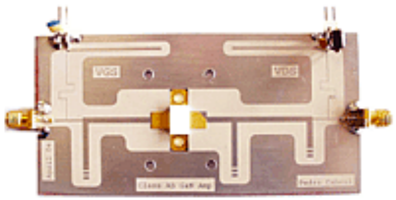
Review Linear Design Situation

- back to basics: s-parameters behavioral models

DUT

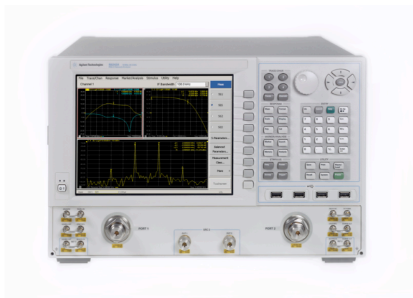


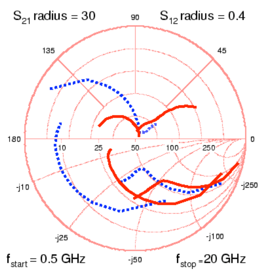
Amplifier



Gain, Bandwidth, Stability, Matching

Vector Network Analyzer



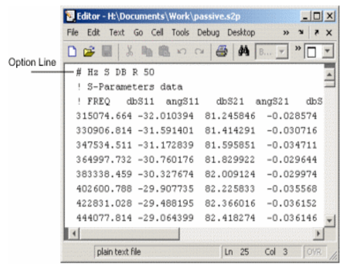


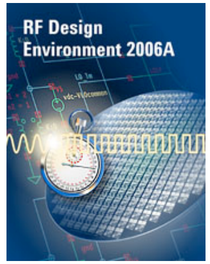
"datasets"

modeling

Characterization and CAD Design Enabling Tool

- *utilize measured s-parameter data tables in RF CAD Tools*





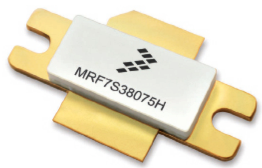
Can simply transform s-parameter to any arbitrary impedance environment

Can also measure say S_{21} and S_{11} as function on input drive to get a very basic non-linear behavioral model

Consider Non-Linear Design Situation

- large signals: waveform based behavioral models

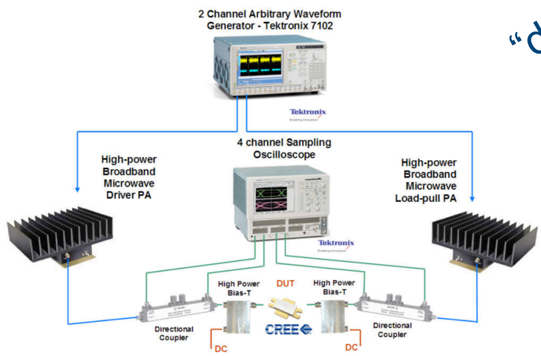
DUT

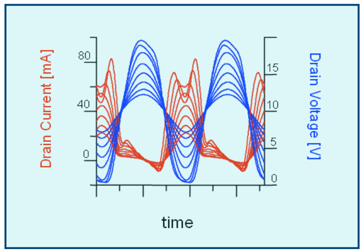


Amplifier

Power, Efficiency, Linearity

Waveform Measurement and Engineering



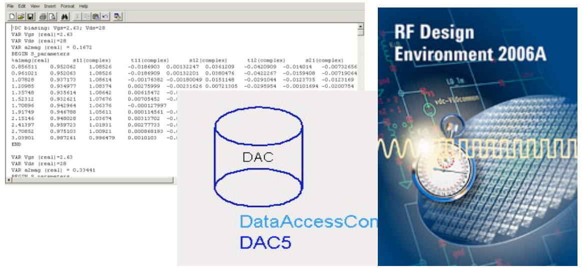


Characterization and CAD Design Enabling Tool

"datasets"

modeling

- *utilize measured waveform data tables in RF CAD Tools*



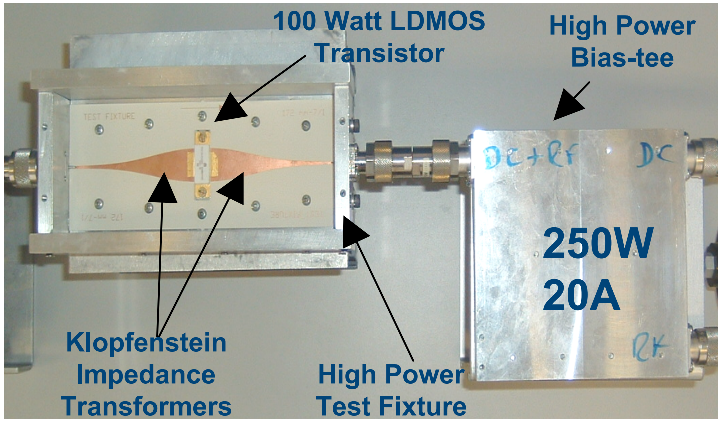
Cannot simply transform waveforms to any arbitrary impedance environment

Can measure as a function of input and/or output fundamental and harmonic load impedances: *CAD interpolation and extrapolation*

CAD Enabled Waveform Engineering

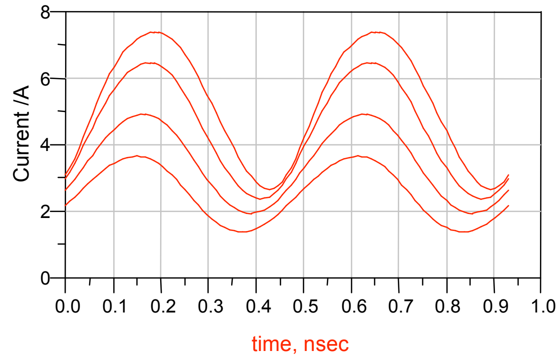
- Direct Waveform Look-up (DWLU) Data Model

Measure Waveforms



Sweep:

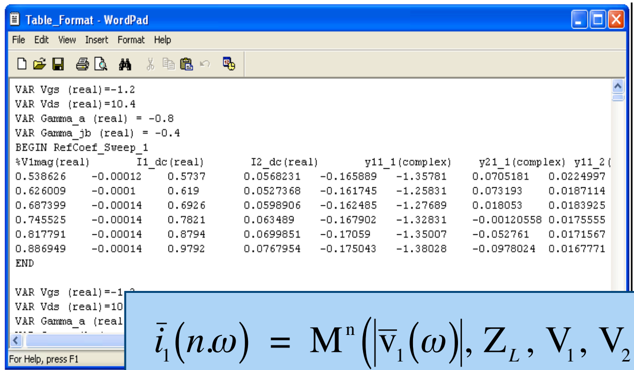
P_{in}, Γ_{LOAD}, Bias



Formulate in frequency domain

FFT

Populate multi-dimensional datasets



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Table_Format - WordPad
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VAR Vds (real)=10.4
VAR Gamma_a (real) = -0.8
VAR Gamma_jb (real) = -0.4
BEGIN RefCoef_Sweep_1
%V1mag(real)       I1_dc(real)        I2_dc(real)        y11_1(complex)     y21_1(complex)  y11_2(
0.538626   -0.00012   0.5737     0.0568231   -0.165889   -1.35781   0.0705181    0.0224997
0.626009   -0.0001    0.619      0.0527368   -0.161745   -1.25831   0.073193     0.0187114
0.687399   -0.00014   0.6926     0.0598906   -0.162485   -1.27689   0.018053     0.0183925
0.745525   -0.00014   0.7821     0.063489    -0.167902   -1.32831   -0.00120558  0.0175555
0.817791   -0.00014   0.8794     0.0699851   -0.17059    -1.35007   -0.052761    0.0171567
0.886949   -0.00014   0.9792     0.0767954   -0.175043   -1.38028   -0.0978024   0.0167771
END

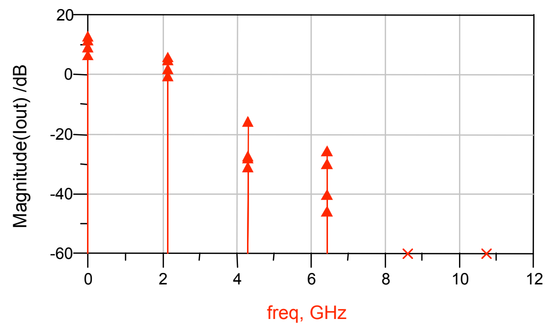
VAR Vgs (real)=-1
VAR Vds (real)=10
VAR Gamma_a (real
For Help, press F1
```

$$\bar{i}_1(n.\omega) = M^n\left(\left|\bar{v}_1(\omega)\right|, Z_L, V_1, V_2\right).\bar{v}_1(\omega)^n$$

$$\bar{i}_2(n.\omega) = N^n\left(\left|\bar{v}_1(\omega)\right|, Z_L, V_1, V_2\right).\bar{v}_1(\omega)^n$$

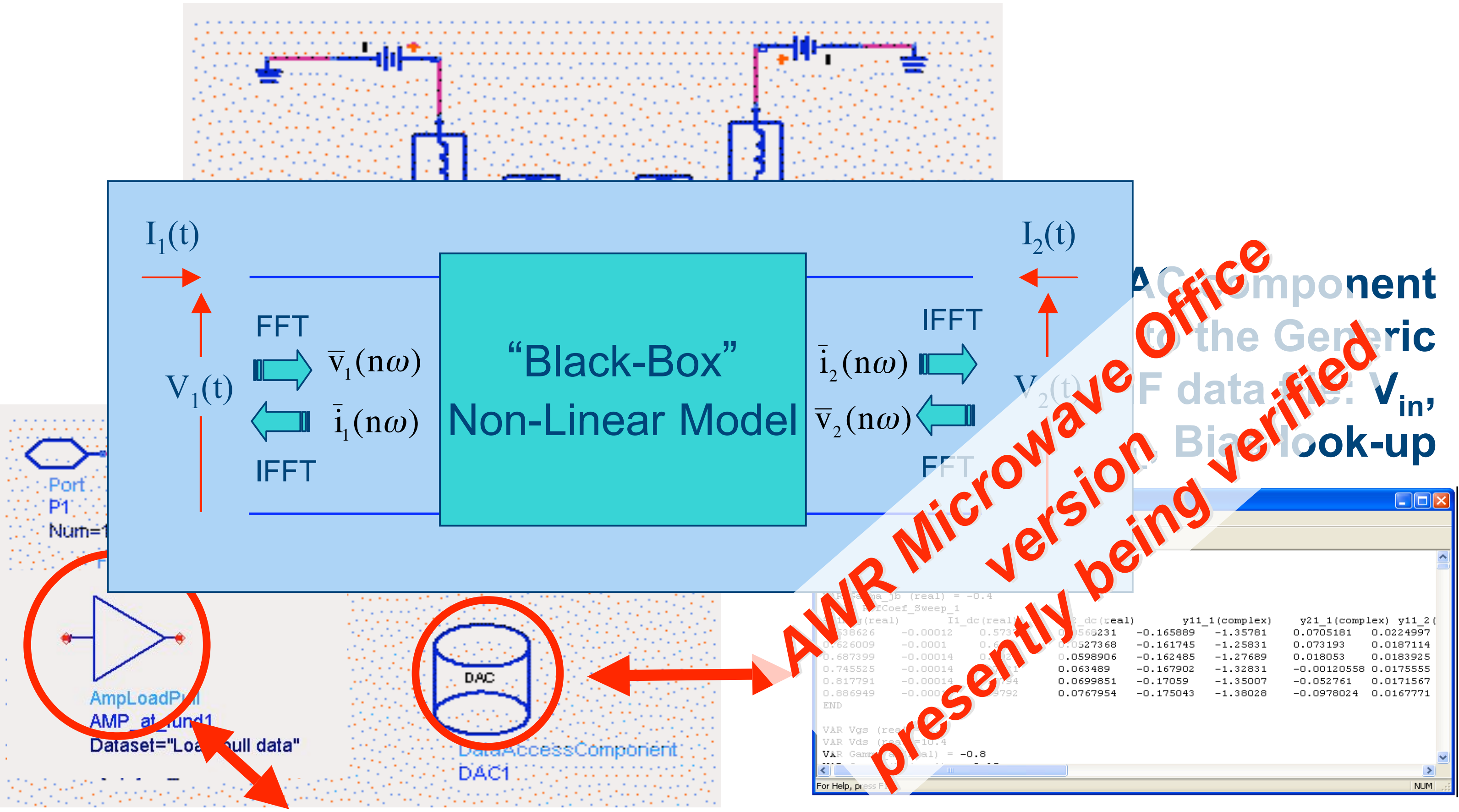
Phase Ref

Scale



CAD Enabled Waveform Engineering
- DWLU Data Model Implementation

Data Import Unit constructed in *Agilent ADS using FDD & DAC*

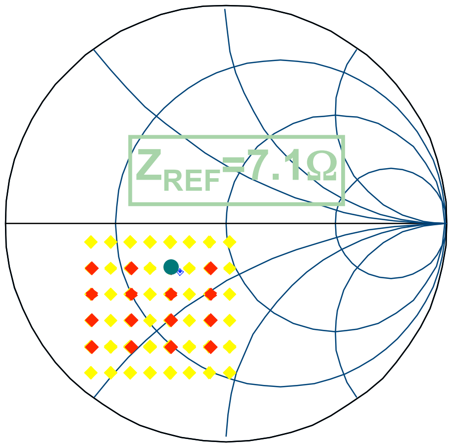


Requires Z_L determination

CAD Enabled Waveform Engineering

- DWLU Data Model Utilization

100W
LDMOS

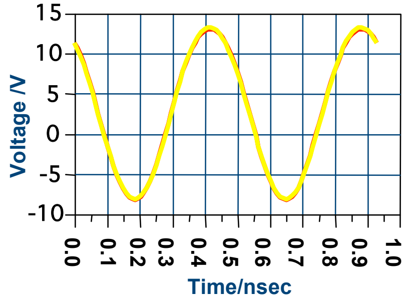


Simulate on Data Look-up Grid

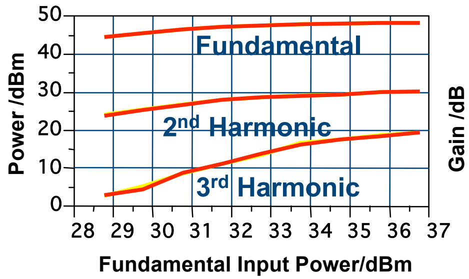
----- Measured

----- Simulated

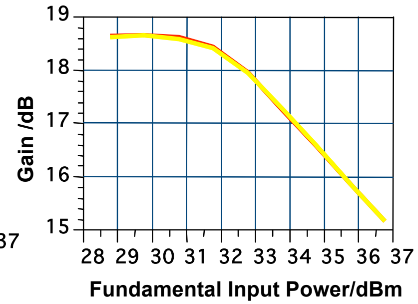
I/P Voltage Waveform



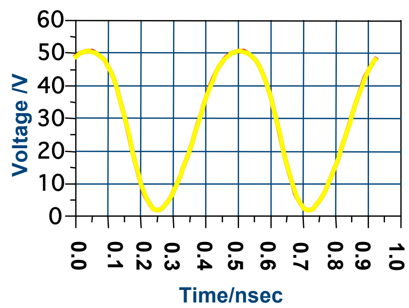
Output Power vs Pin



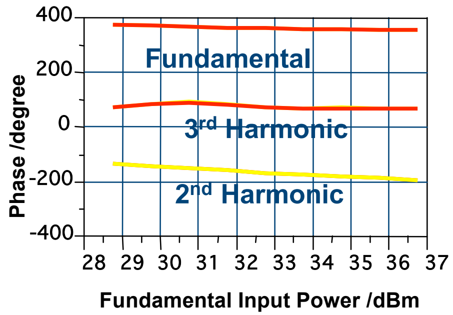
Gain vs Pin



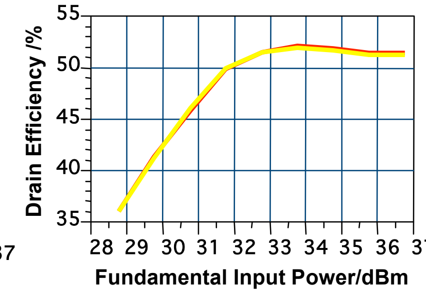
O/P Voltage Waveform



Output Phase vs Pin



Efficiency vs Pin

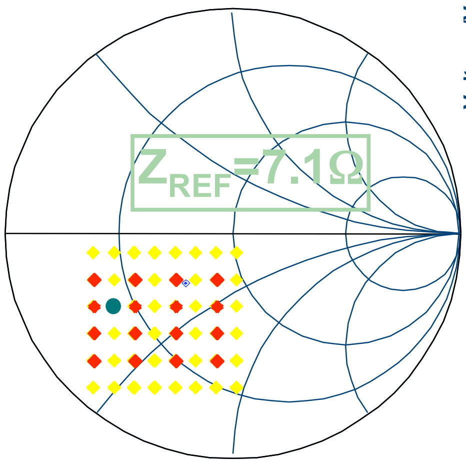


DWLU Accurately regenerates RF waveforms

CAD Enabled Waveform Engineering

- DWLU Data Model Utilization

100W
LDMOS

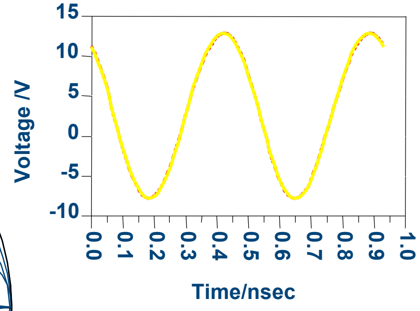


Simulate off Data Look-up Grid

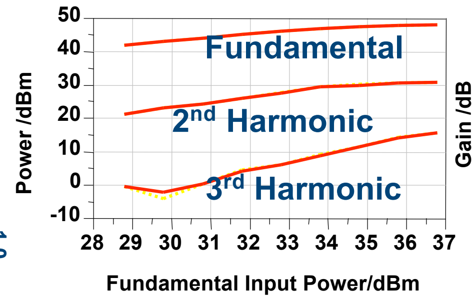
----- Measured

----- Simulated

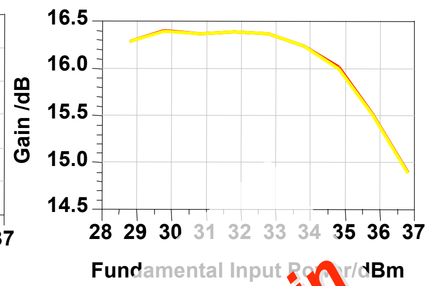
I/P Voltage Waveform



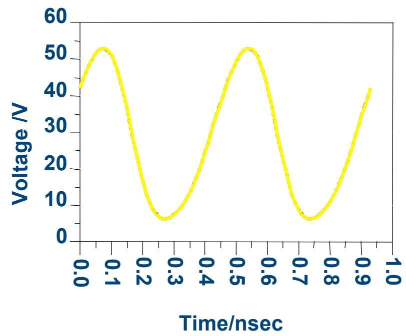
Output Power vs Pin



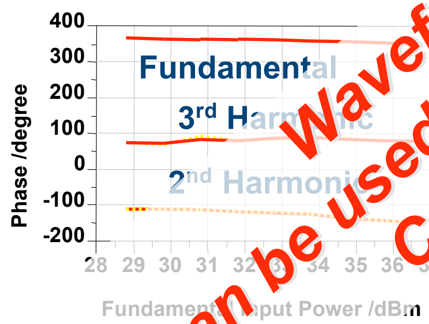
Gain vs Pin



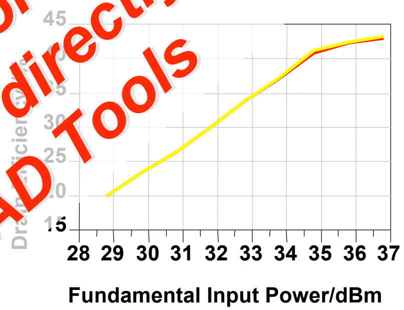
O/P Voltage Waveform



Output Phase vs Pin



Efficiency vs Pin



Waveforms can be used directly within CAD Tools

DWLU Accurately interpolates RF waveforms

CAD Based Waveform Engineering

- Parameter Based Data Models: Formulation Concepts

- Non-linear Data look-up
  - Direct looks up measured waveform data
    - Stored in the frequency domain

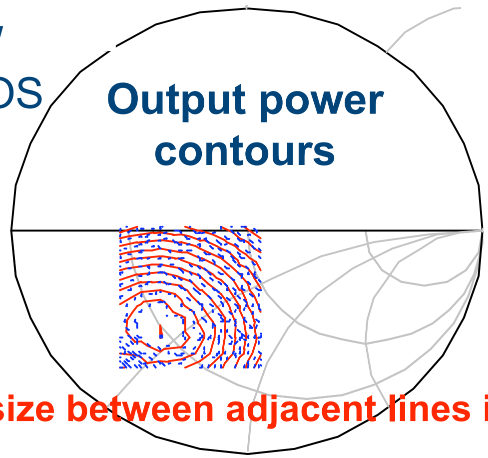
- Non-linear Data Formulation: Parameter look-up
  - Transform waveform data into "circuit parameters"
    - Equivalent functionality to linear data formulation: s-parameters
      - Circuit analysis and design formulation
      - Travelling wave a-b rather than I-V formulations
    - Agilent Solution: X-parameters
      - Natural extension of linear s-parameters data-set to non-linear data-set
    - Cardiff Formulations
      - Natural extension of X-parameters. Cardiff "Mixing" Formulation for load-pull contours: contains higher order mixing terms

CAD Based Waveform Engineering

- Formulated Based Data Lookup Models FDLU

$$b_k = \sum_{m=0}^{\frac{n-1}{2}} C_{k,m}\left(\frac{Q}{P}\right)^m a_1 + \sum_{m=0}^{\frac{n-1}{2}} U_{k,m}\left(\frac{P}{Q}\right)^m a_2 \qquad Q=\mathrm{phase}(a_1),\; P=\mathrm{phase}(a_2)$$

100W LDMOS



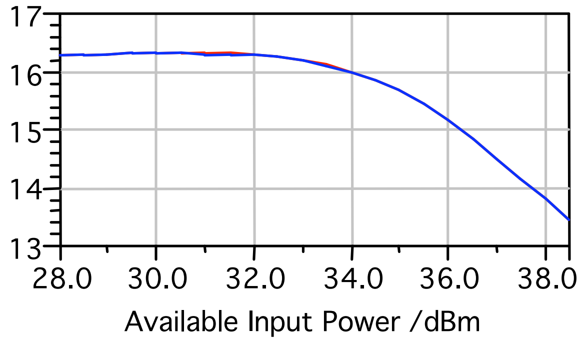
Step size between adjacent lines is 0.2dB

$C_{k,m,} = f(|a_1(f_o)|, |a_2(f_o)|)$ & $U_{k,m,} = f(|a_1(f_o)|, |a_2(f_o)|)$

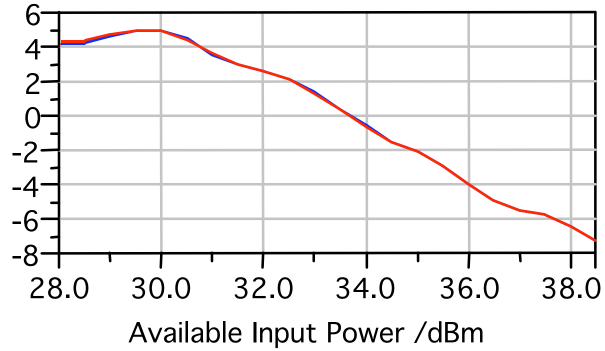
Good simulation accuracy can be kept for quite a large area on Smith Chart

Fast and robust simulation implementation

Gain



AM to PM

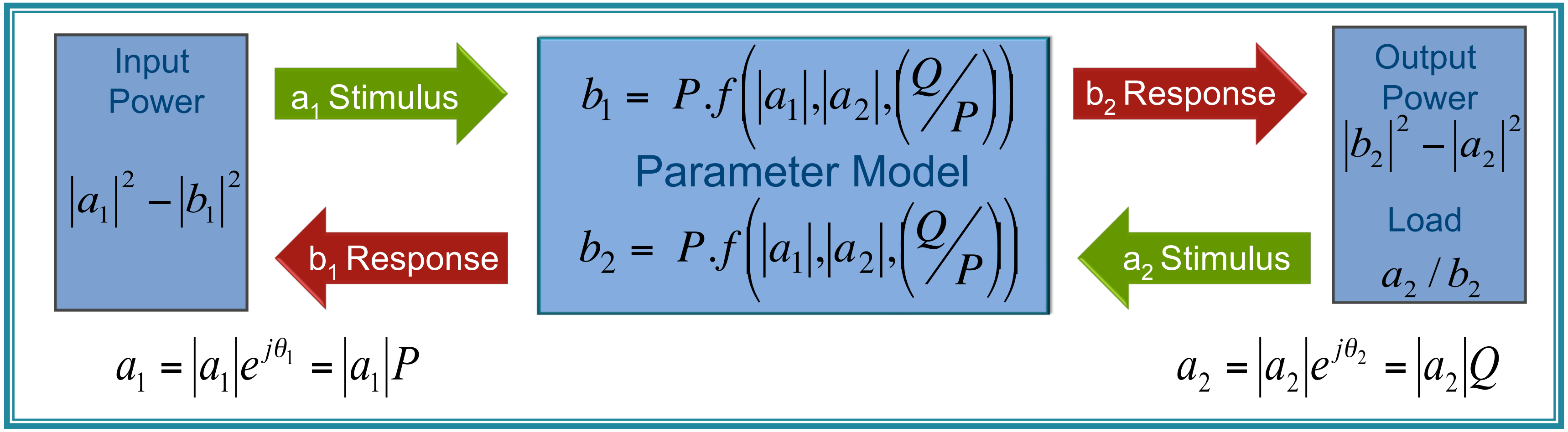


Good accuracy for different drive power levels

CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- "Circuit" Formulation Requirement: *remove direct reference to load*
  - Component dependency: $f(|a_1|,|a_2|,(Q/P))$



Linear System uses s-parameters: 1st order system

Constant Parameters

$$b_1 = \left\{ S_{11} \cdot |a_1| \cdot P + S_{12} \cdot |a_2| \cdot Q \right\}$$

$$b_2 = \left\{ S_{21} \cdot |a_1| \cdot P + S_{22} \cdot |a_2| \cdot Q \right\}$$

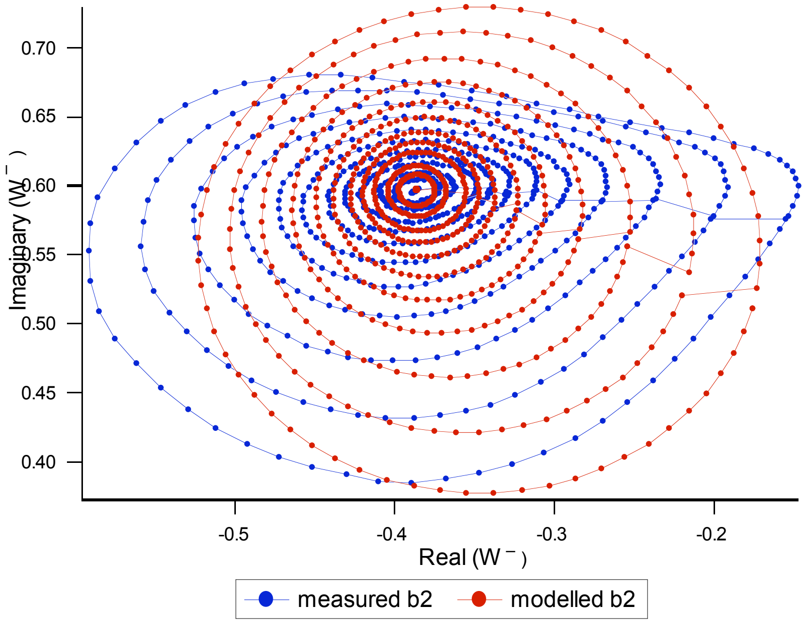
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Use of s-parameters in non-linear design: "Hot" S-parameters
  - Wrong functionality:
    - model circular function
    - measurement elliptical functionality

$$b_1 = P.\left\{S_{11} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^0 + S_{12} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^1\right\}$$

$$b_2 = P.\left\{S_{21} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^0 + S_{22} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^1\right\}$$



Parameter dependency: $S_{m,n}(|a_1|,|a_2|)$

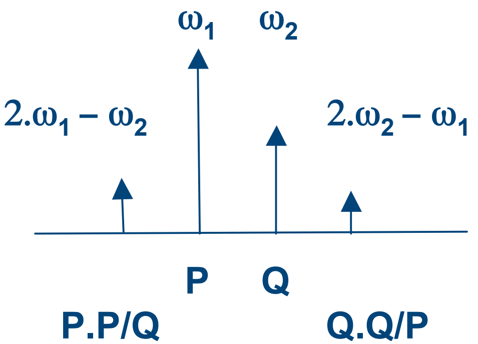
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Non-Linear System: *include mixing components*
  - Weakly Non-Linear System: 3rd order: relates to S&T Parameters (X-parameters)

$$b_1 = \left\{ X^T_{12} \cdot |a_2| \cdot P^2 / Q + X^S_{11} \cdot |a_1| \cdot P + X^S_{12} \cdot |a_2| \cdot Q + \cancel{X^T_{11} \cdot |a_1|} \cdot Q^2 / P \right\}$$

$$b_2 = \left\{ X^T_{22} \cdot |a_2| \cdot P^2 / Q + X^S_{21} \cdot |a_1| \cdot P + X^S_{22} \cdot |a_2| \cdot Q + \cancel{X^T_{21} \cdot |a_1|} \cdot Q^2 / P \right\}$$



Allow $\omega_1 = \omega_2$

For small perturbation reduces to three parameters: X-parameters

$$b_1 = P.\left\{ X^T_{12} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^{-1} + X^S_{11} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^{0} + X^S_{12} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^{1} + X^T_{11} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^{2} \right\}$$

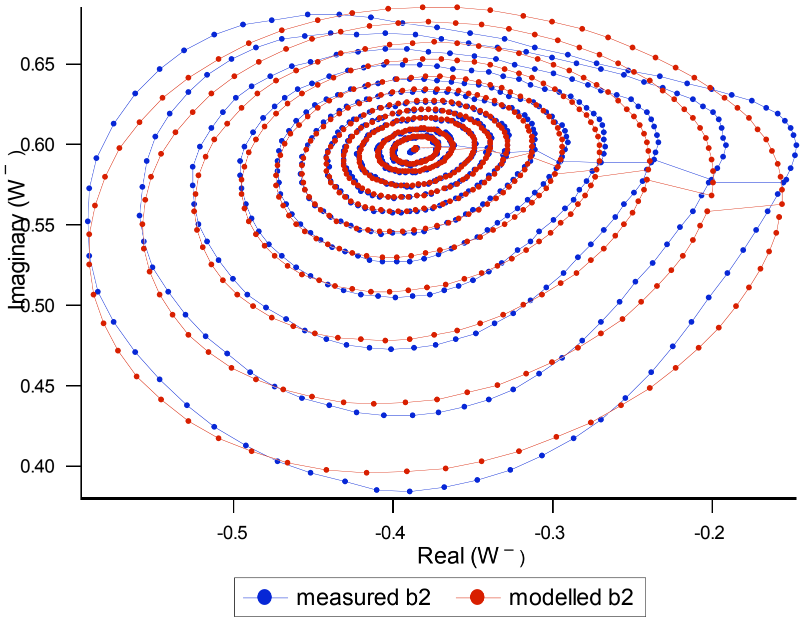
$$b_2 = P.\left\{ X^T_{22} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^{-1} + X^S_{21} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^{0} + X^S_{22} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^{1} + X^T_{21} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^{2} \right\}$$

Parameter dependency: $X_{m,n}(|a_1|)$

CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- 3rd Order Mixing Model: S&T-parameters (X-parameters)
  - Significantly improved functionality:
    - model is now an elliptical function
    - measurement elliptical functionality
  - Next Step
    - Compute local X-parameters
      - function of load
    - Allow for full amplitudes dependence
    - Increase order of mixing



$$b_1 = P.\left\{X_{12}^{T}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X_{11}^{S}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X_{12}^{S}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X_{11}^{T}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2}\right\}$$

$$b_2 = P.\left\{X_{22}^{T}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X_{21}^{S}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X_{22}^{S}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X_{21}^{T}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2}\right\}$$

Parameter dependency: $X_{m,n}(|a_1|,|a_2|)$

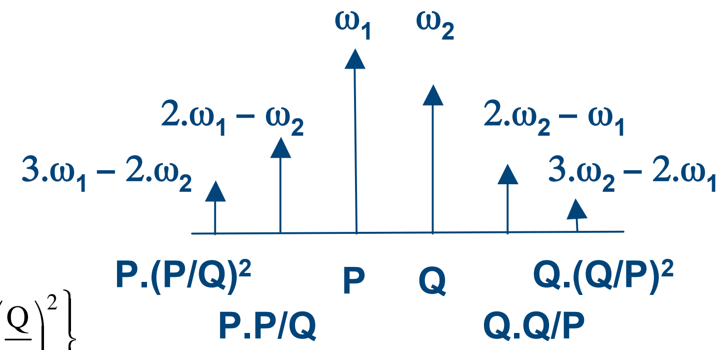
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Non-Linear System: *include mixing components*
  - Strongly Non-Linear System: n^th order: relates to C&U Parameters (R-parameters)

$$b_1 = P.\left\{S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1\right\}$$

$$b_2 = P.\left\{S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1\right\}$$



Allow $\omega_1 = \omega_2$

$$b_1 = P.\left\{X^T_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + X^S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + X^T_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2\right\}$$

$$b_2 = P.\left\{X^T_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + X^S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + X^T_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2\right\}$$

$$b_1 = P.\left\{R_{1,-2}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-2} + R_{1,-1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + R_{1,0}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + R_{1,1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + R_{1,2}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2 + R_{1,3}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^3\right\}$$

$$b_2 = P.\left\{R_{2,-2}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-2} + R_{2,-1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + R_{2,0}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + R_{2,1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + R_{2,2}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2 + R_{2,3}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^3\right\}$$

CAD based Waveform Engineering

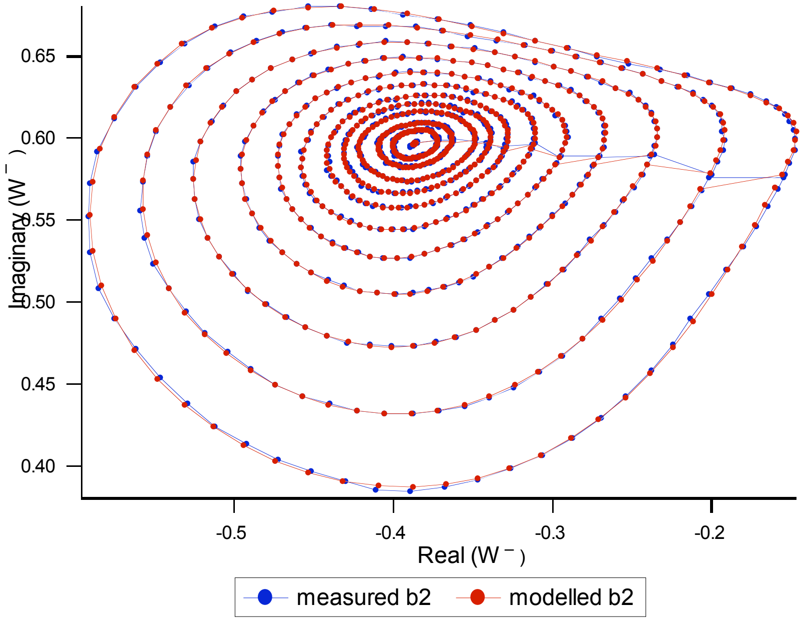
- Parameter Based Data Models: Cardiff Formulation

- Modelling with Extracted Fundamental $R_{m,n}$ components: $g(|a_1|,|a_2|)$
  - Accurate reproduction of measured b_2 contours (load-pull contours) with 7^{th} order (Q/P) phase model
  - Avoids any implicit load based lookup

$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P.\sum_{n=-(N-1/2)}^{n=(N+1/2)} \left\{ R_{m,n} \left(\frac{Q}{P}\right)^n \right\}$$

Parameter dependency: $R_{m,n}(|a_1|, |a_2|)$

7^{th} order model: R-parameters



Collapse large data lookup to small (6*12 or 8x12) $R_{m,n}$ parameter lookup

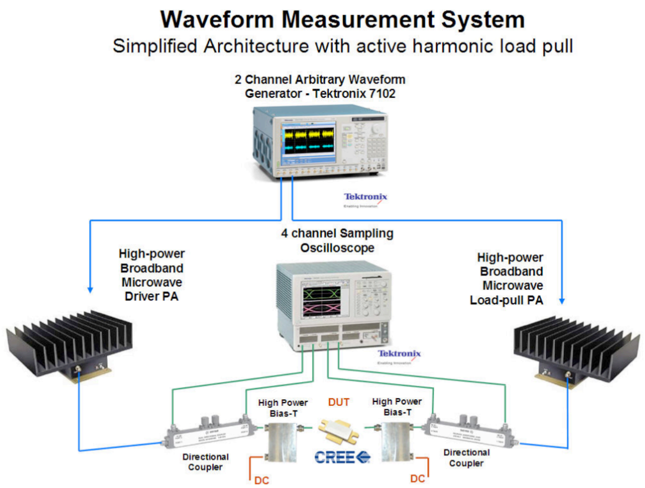
CAD based Waveform Engineering

- Parameter Based Data Models: Cardiff Formulation

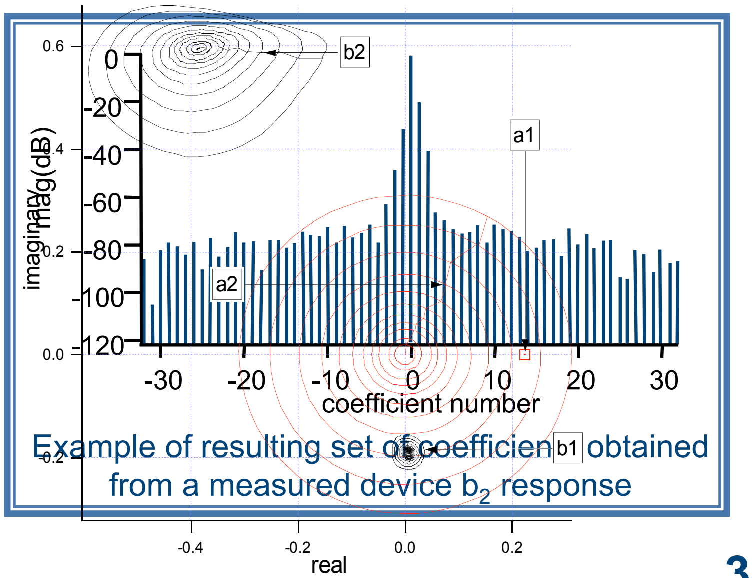
- Cardiff "Circuit" Parameter Formulation
  - Generalized to n^{th} order in terms of the relative phase component (Q/P)

$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P.\sum_{n=-(N/2-1)}^{n=(N/2)}\left\{R_{m,n}\left(\frac{Q}{P}\right)^n\right\} \text{ where } R_{m,n} = g(|a_1|,|a_2|)$$

  - Determination of parameters $R_{m,n}$ requires measurements at constant $|a_1|$ and $|a_2|$ while sweeping relative phase component (Q/P), normalized to optimum load: easy to achieve with active load-pull



Extract model coefficients

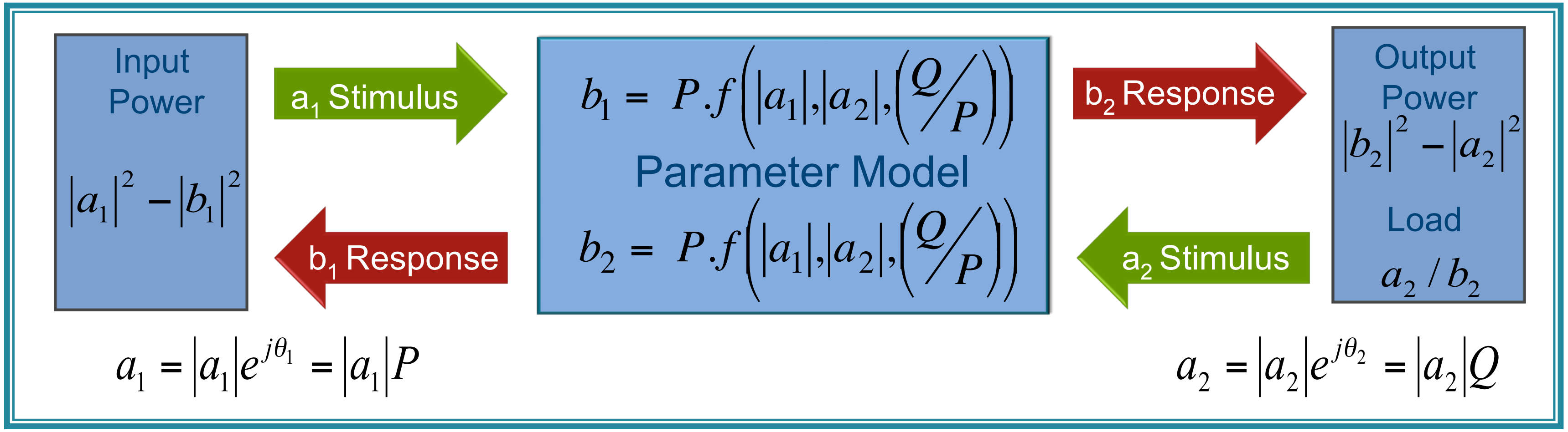


Example of resulting set of coefficients obtained from a measured device b_2 response

CAD based Waveform Engineering

- Parameter Based Data Models: Cardiff Formulation

- "Circuit" Formulation that is an extension of linear s-parameters
  - *remove direct reference to load*
  - Formulation dependency: $f(|a_1|,|a_2|,(Q/P))$
    - Function dependency: $f(|a_1|,|a_2|)$



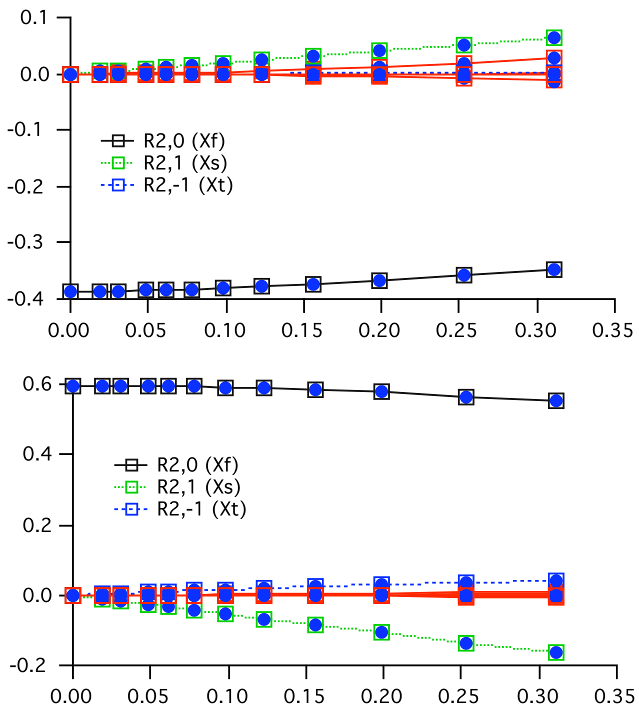
$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P. \sum_{n=-\left(N/2-1\right)}^{n=\left(N/2\right)} \left\{ R_{m,n} \left(\frac{Q}{P}\right)^n \right\}$$

Parameter dependency: $R_{m,n}(|a_1|,|a_2|)$

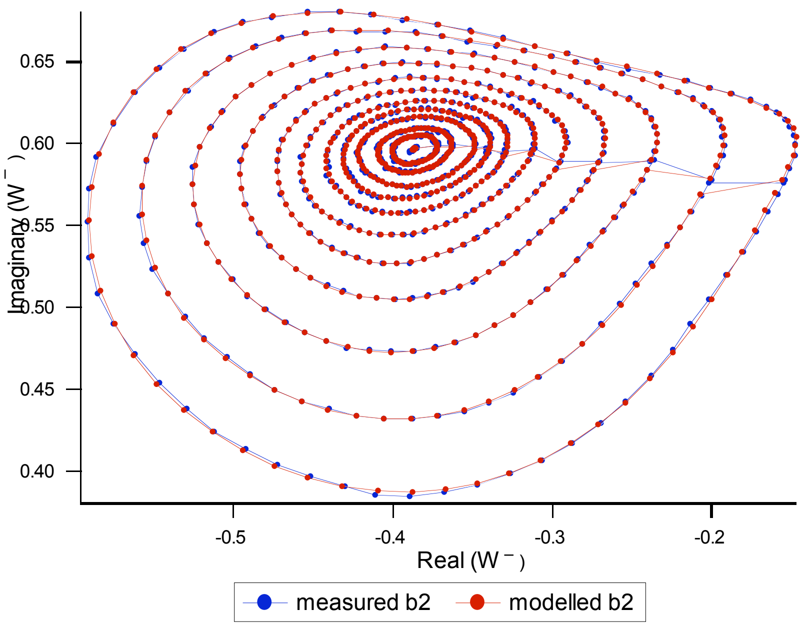
CAD based Waveform Engineering

- Parameter Based Data Models: Cardiff Formulation

- Magnitude Function Fitting to Extracted Fundamental $R_{m,n}$ components: $g(|a_1|,|a_2|)$
  - $R_{m,n} = \alpha_0 + \alpha_1.|a_2| + \alpha_2.|a_2|^2 + \alpha_3.|a_2|^3 + \alpha_4.|a_2|^4 + \alpha_5.|a_2|^5 + \alpha_6.|a_2|^6 + \alpha_7.|a_2|^7$
  - Only 20 relevant coefficients
    - Accurate reproduction of measured b_2 contours (load-pull contours) with 7th order model



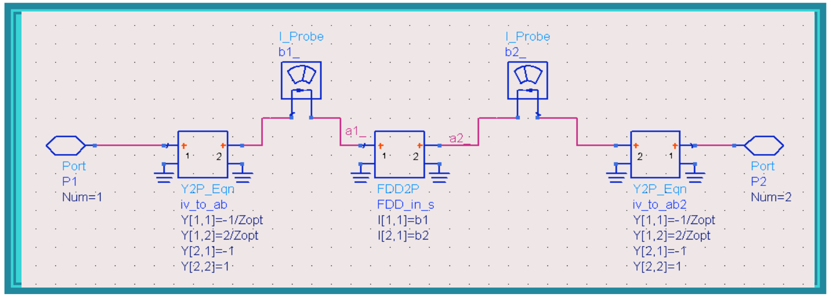
7th order model: R-parameters



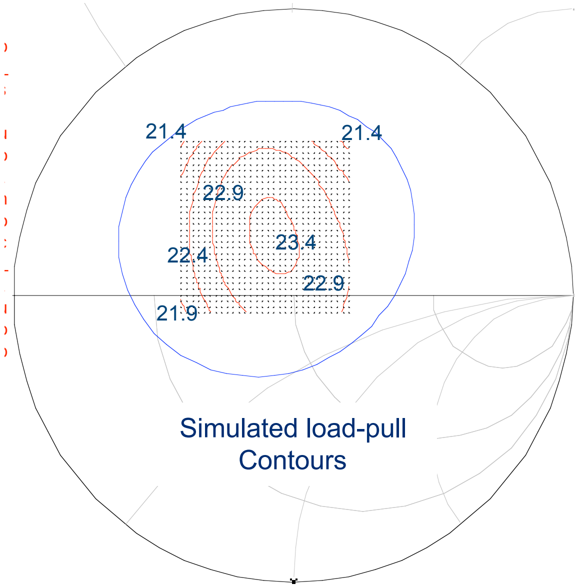
CAD based Waveform Engineering

- Parameter Based Data Models: CAD Implementation

Schematic of ADS Simulation



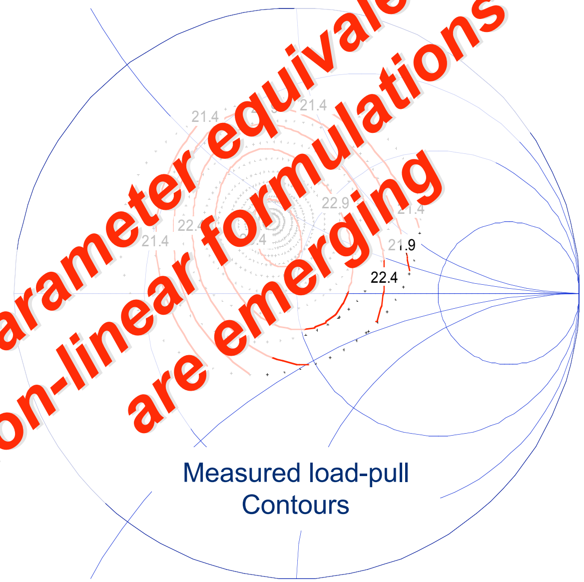
The model can be directly imported into CAD software, after processing the measurement data.



Simulated load-pull Contours (Left)

Load-pull Power Contours

Measured load-pull Contours (Right)



S-parameter equivalent non-linear formulations are emerging

RF I-V Waveform Measurement & Engineering
- role in CAD modelling

- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - Analytical Model validation and optimization
    - I-Q function Extraction
      - *Data Lookup Model Generation*

- Behavioral "Black Box" Non-Linear Models
  - Directly Measures Non-Linear Behaviour
    - Directly Import into CAD Tool
      - *Data Lookup behavioural model*
    - Indirectly Import into CAD Tool
      - *Formulated behavioural models (Volterra)*
      - *Emerging non-linear parameter equivalent to linear s-parameters (X-parameters)*