A Network Analyzer For Active Components

EEEfCom 29 - 30 Juni

ULM

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Version 2

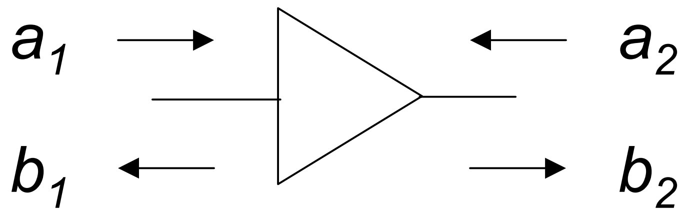
NMDG Engineering
Leading beyond S-parameters

Outline

- Review of S-parameters
- Theory of Large-Signal Network Analysis
- The Large-Signal Network Analyzer
- The Calibration
- Active Component Characterization
  - under CW stimulus
  - under modulation stimulus
  - in non-50 Ohm environment
- Modeling
  - Model verification
  - Measurement-based behavioral model
- Conclusions

Definition of S-parameters

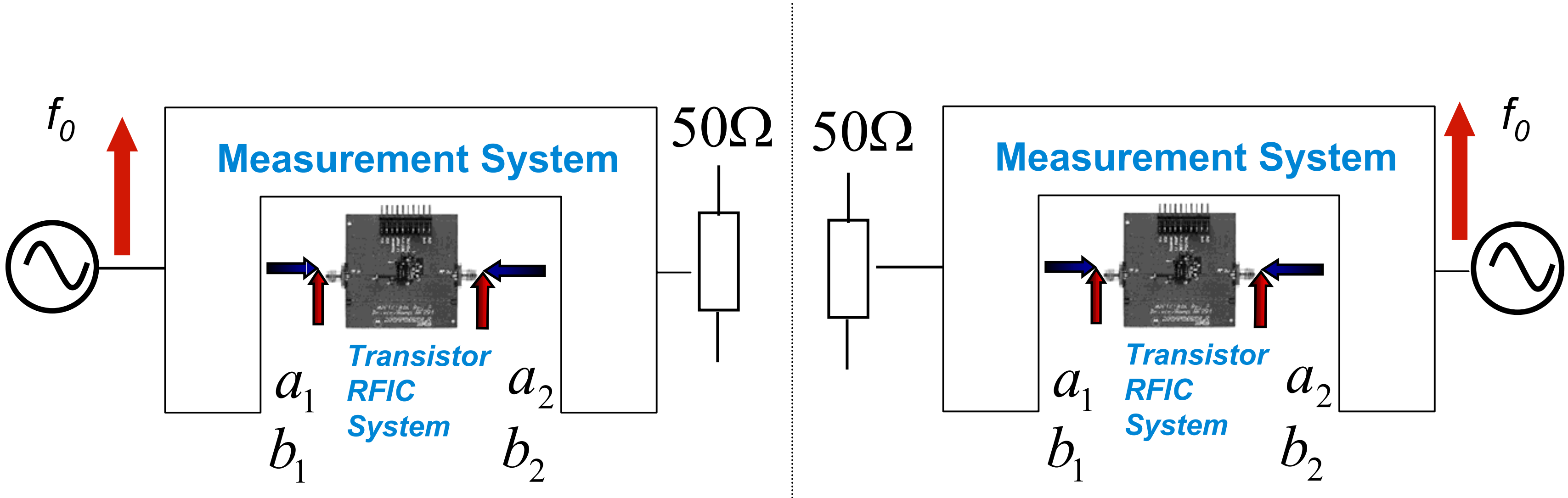
As function of
frequency f_0



$$b_1(f_0) = S_{11}(f_0)\, a_1(f_0) + S_{12}(f_0)\, a_2(f_0)$$
$$b_2(f_0) = S_{21}(f_0)\, a_1(f_0) + S_{22}(f_0)\, a_2(f_0)$$

- S-parameters are a behavioral model
- S-parameters describe completely the linear behavior
- S-parameters cannot be determined properly with one measurement

Measuring S-parameters



Experiment 1 **Superposition** Experiment 2

⇨ $a_{1i}, b_{1i}, a_{2i}, b_{2i}$

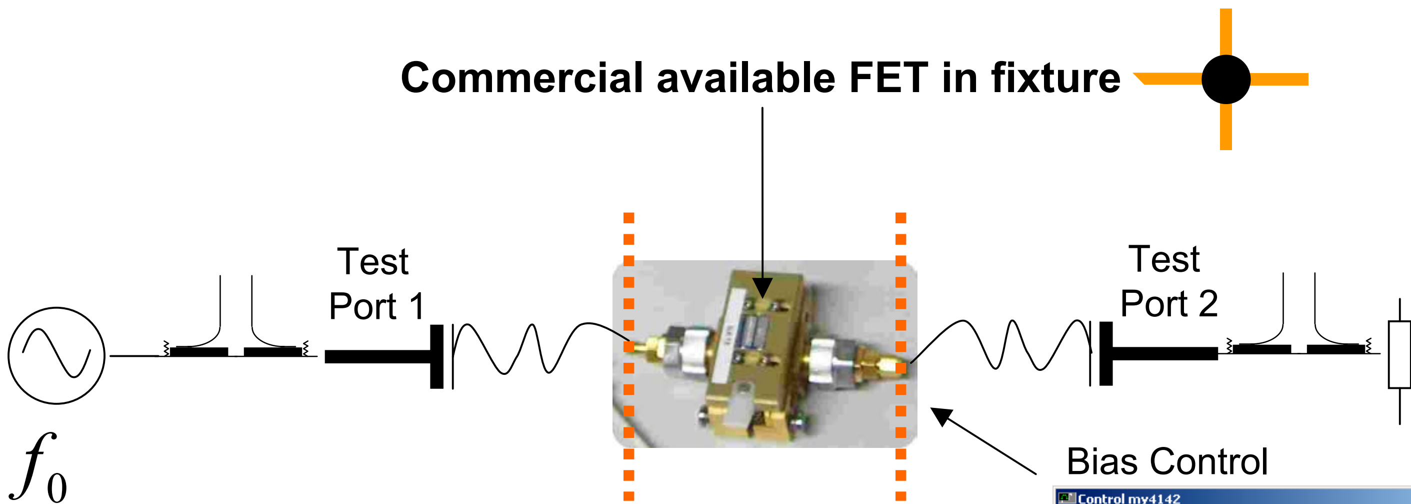
with i representing different experiments ⇨

- **Analysis**

$$b_1 = S_{11} a_1 + S_{12} a_2$$
$$b_2 = S_{21} a_1 + S_{22} a_2$$

f_0

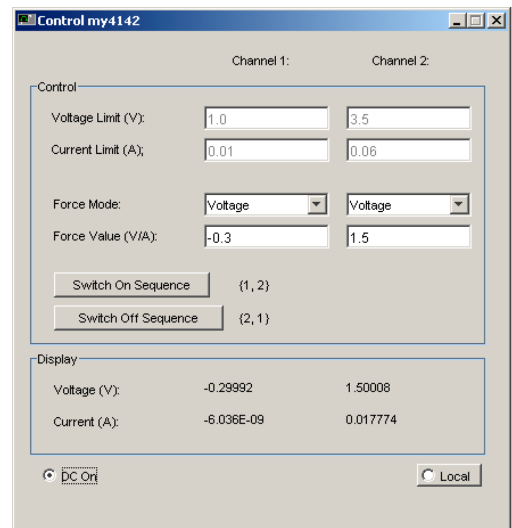
Example: Packaged FET



Calibration

- Short
- Open
- Load
- Thru

f_0: 1GHz - 18 GHz, step = 100 MHz



V_{gs} = -0.3 V V_{ds} = 1.5 V

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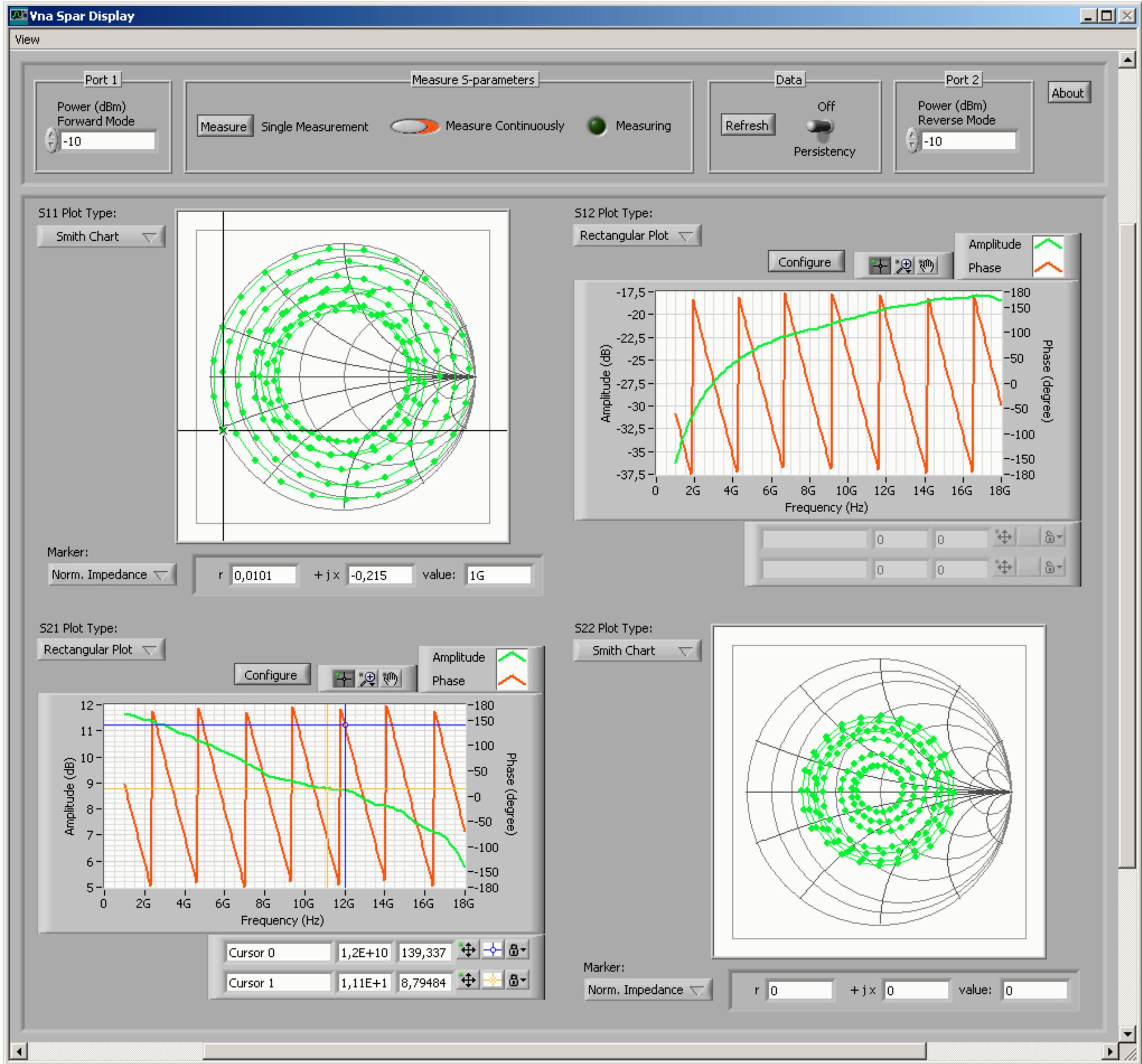
Leading beyond S-parameters

S-parameter Measurement



S_{11}

S_{12}

S_{21}

S_{22}

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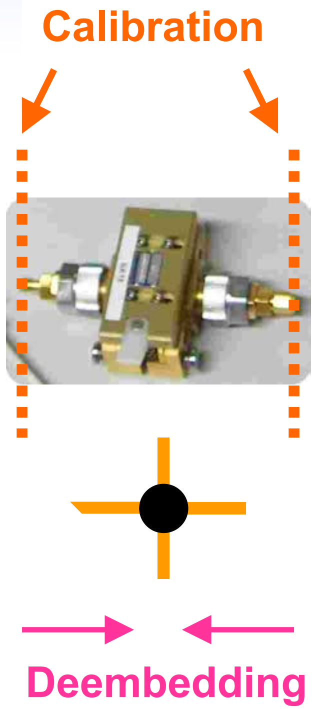
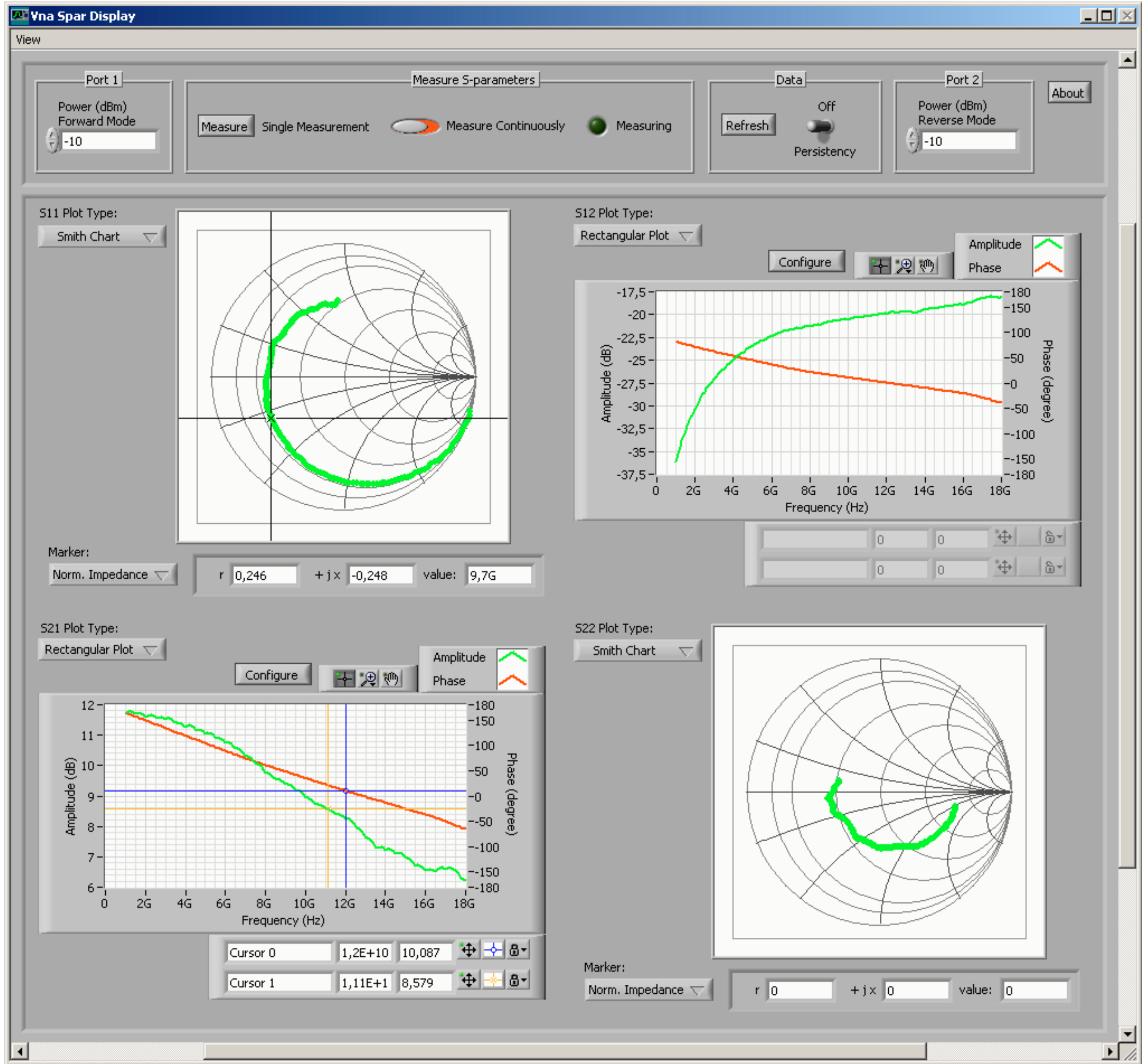
S-parameter Measurement with De-embedding



S_{11}

S_{21}



S_{12}

S_{22}

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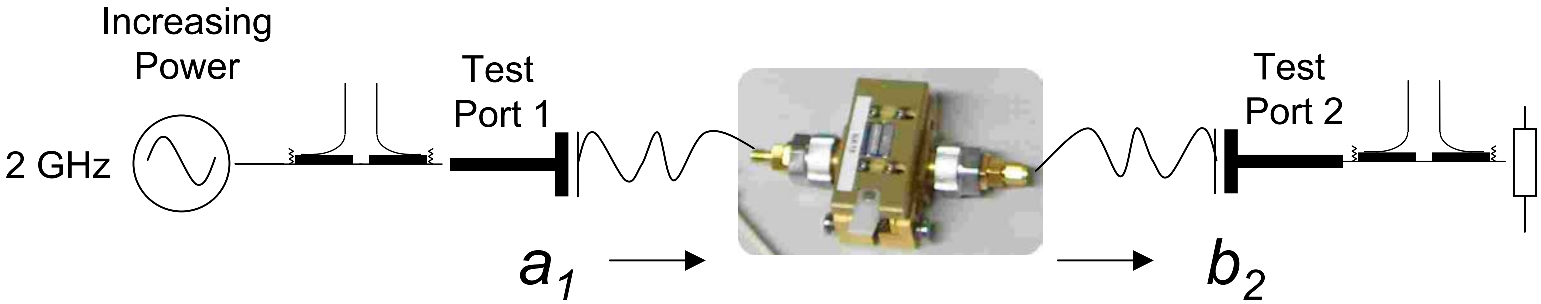
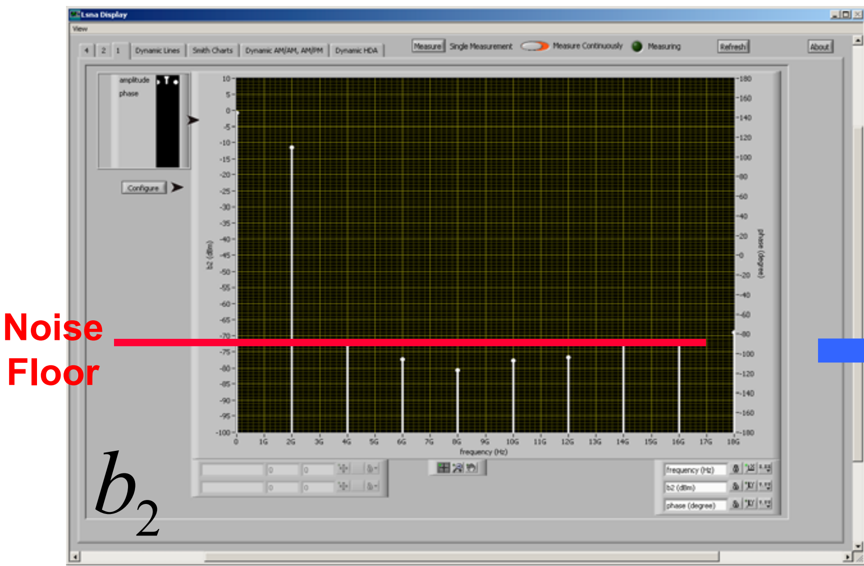
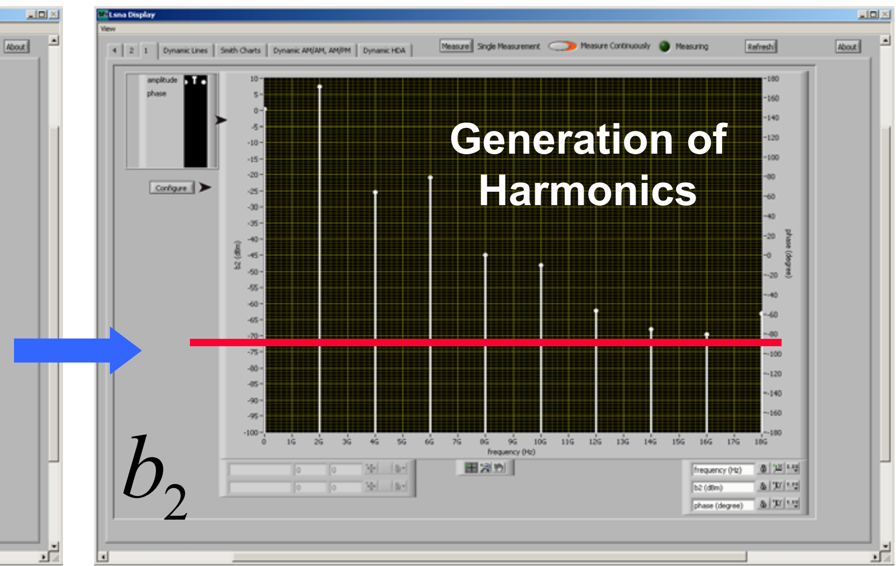
Nonlinear Behavior - Harmonic Generation



$a_1 = -20\ dBm$

$a_1 = 0\ dBm$



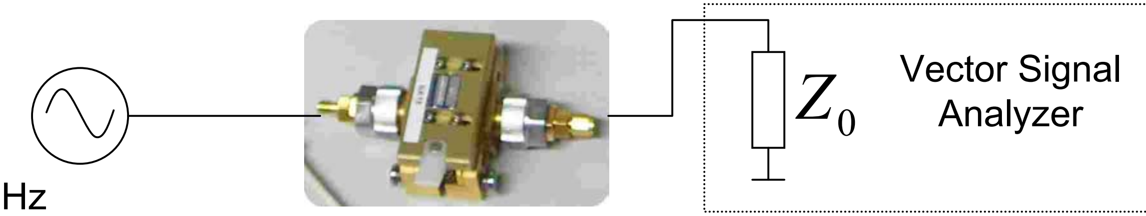


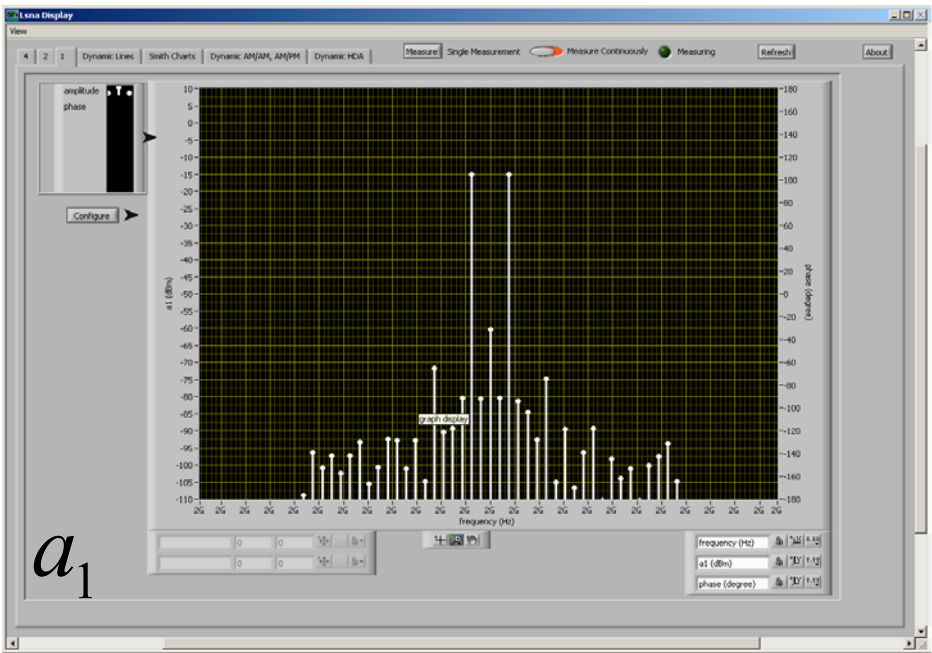
~~Superposition~~

Nonlinear Behavior - Intermodulation Generation

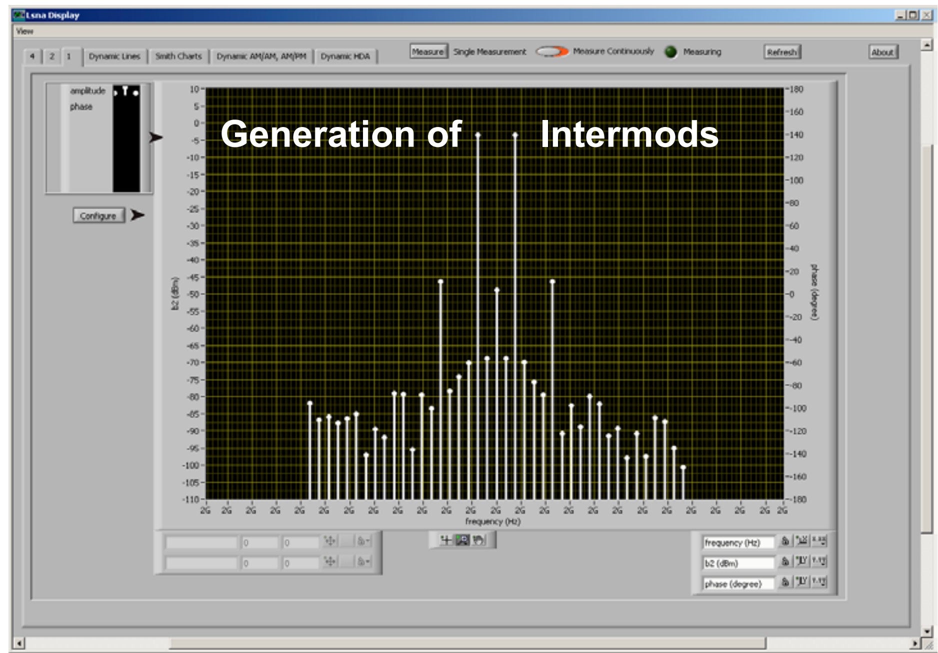
Vector Signal Generator

2-tone, carrier 2 GHz





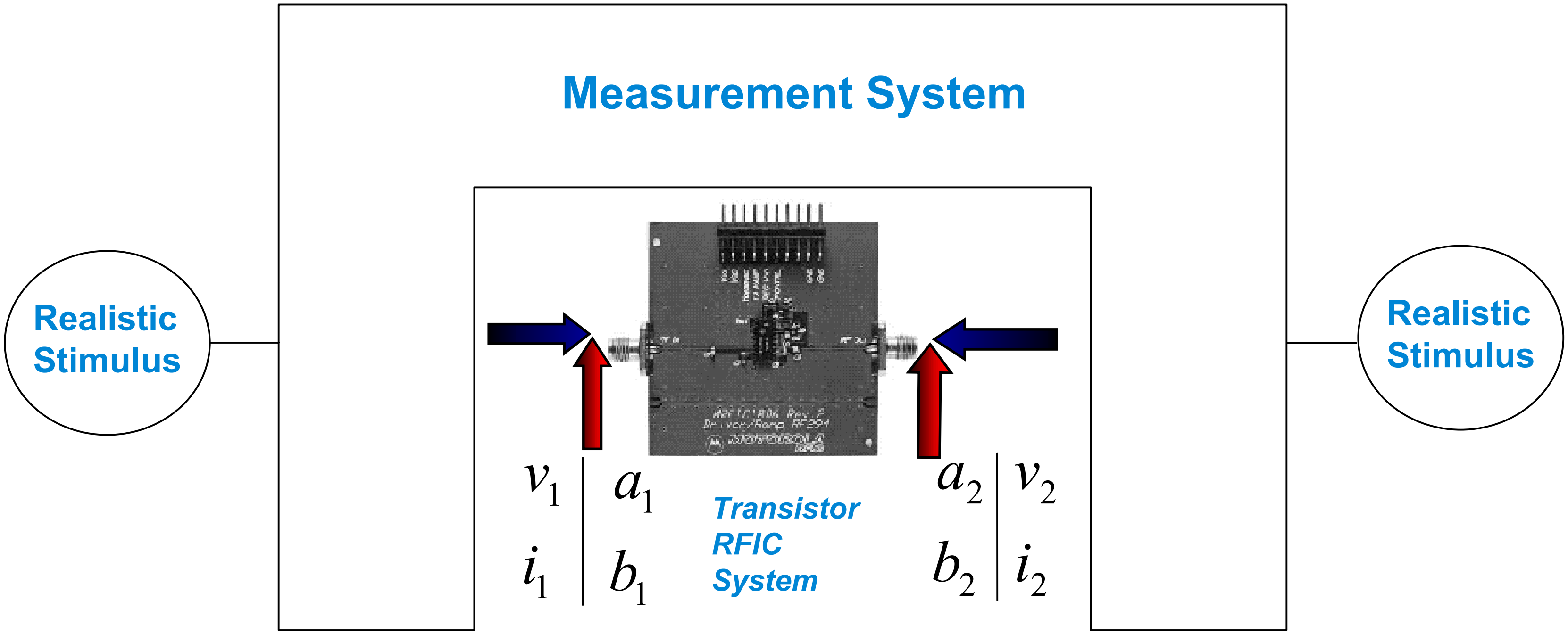
What happens at the input?



Vector Signal Analyzer Display

What is the meaning of this measurement?

Complete Characterization of Active Components

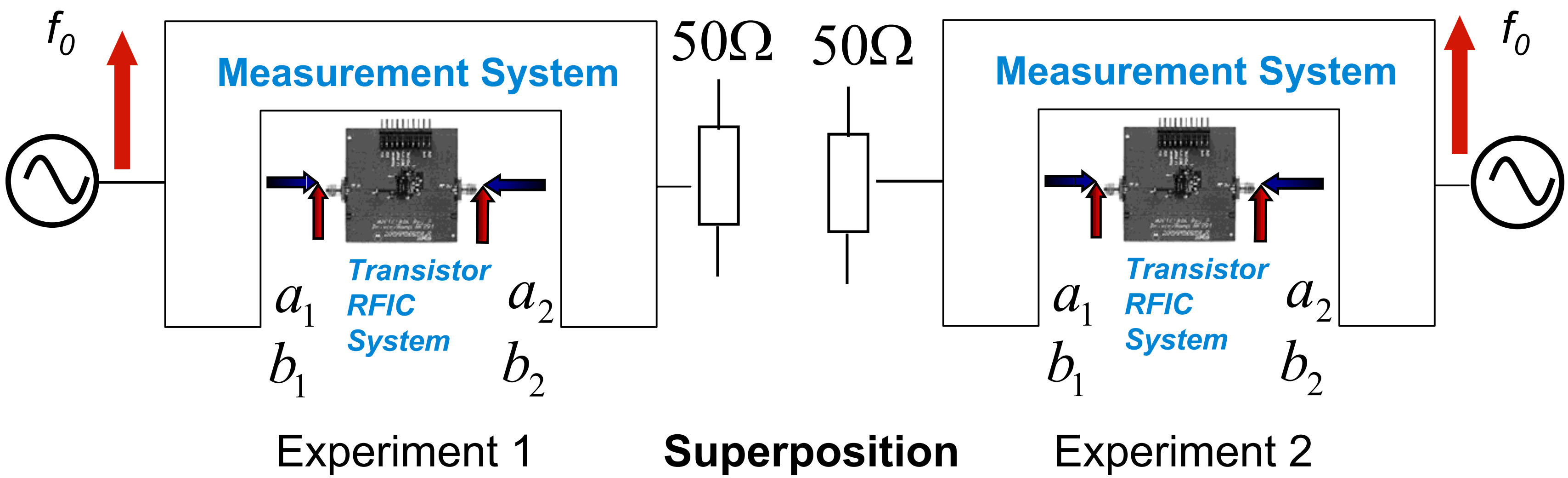


- **Representation Domain**
  - **Frequency (f)**
  - **Time (t)**
  - **Freq - time (envelope)**

- **Physical Quantity Sets**
  - **Travelling Waves (A, B)**
  - **Voltage/Current (V, I)**

Characterization

Small-Signal Network Analysis: S-parameters



⇒ $a_{1i}, b_{1i}, a_{2i}, b_{2i}$

with i representing different experiments ⇒

- **Analysis**

$$b_1 = S_{11} a_1 + S_{12} a_2$$
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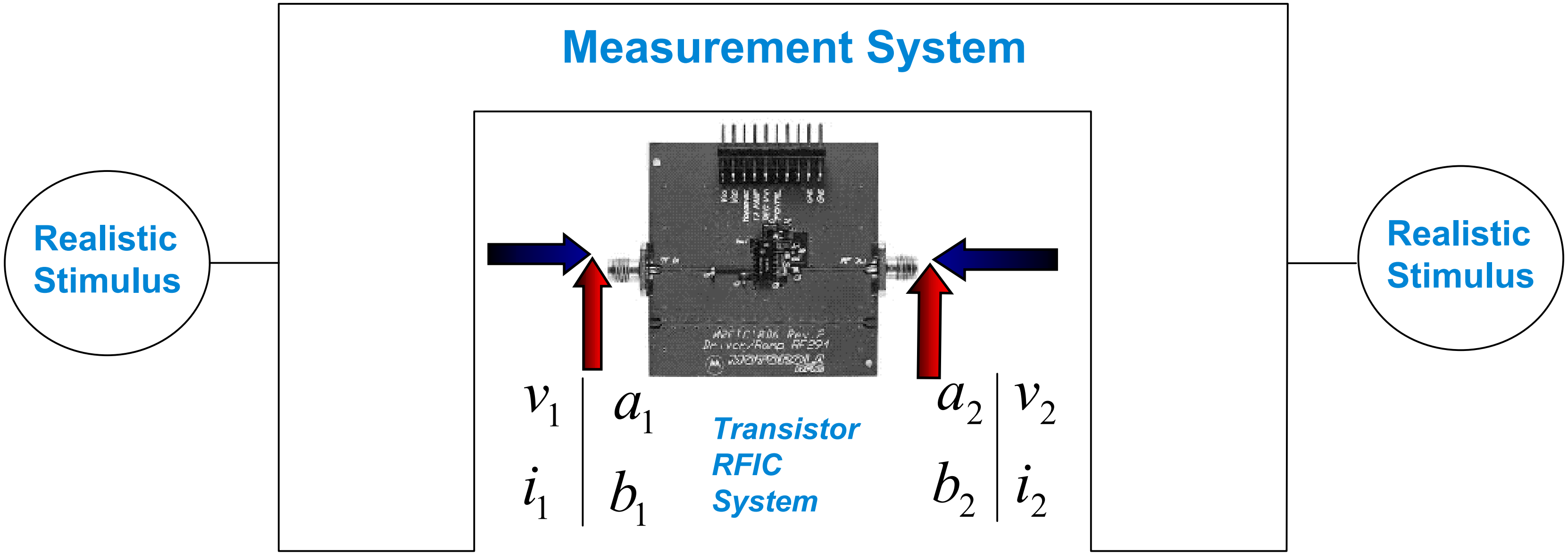
f_0

Large-Signal Network Analysis



Different Experiments

⇨ $a_{1i}, b_{1i}, a_{2i}, b_{2i}$

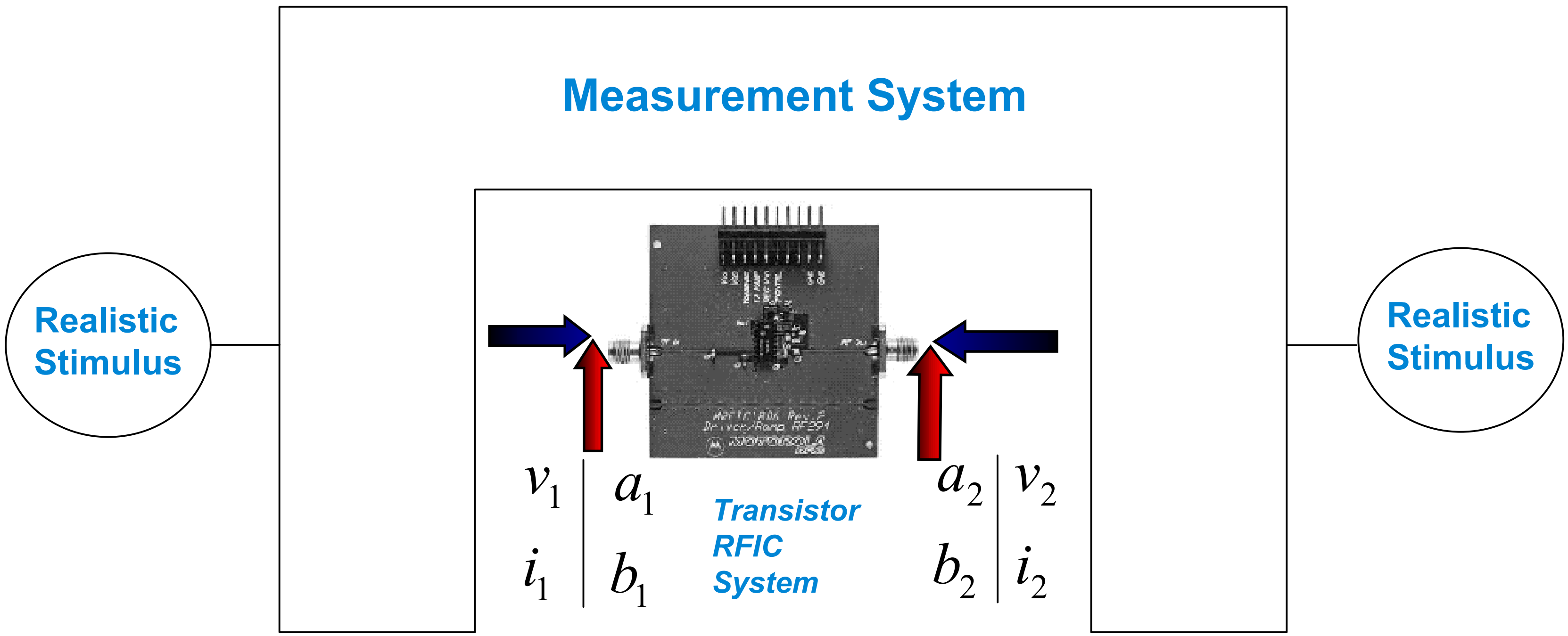
with i representing different experiments ⇨

- **Analysis**

$$f(v_1, v_2, i_1, i_2, t \mid f) = 0$$

$$g(v_1, v_2, i_1, i_2, t \mid f) = 0$$

Large-Signal Network Analysis in a nutshell



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Characterization

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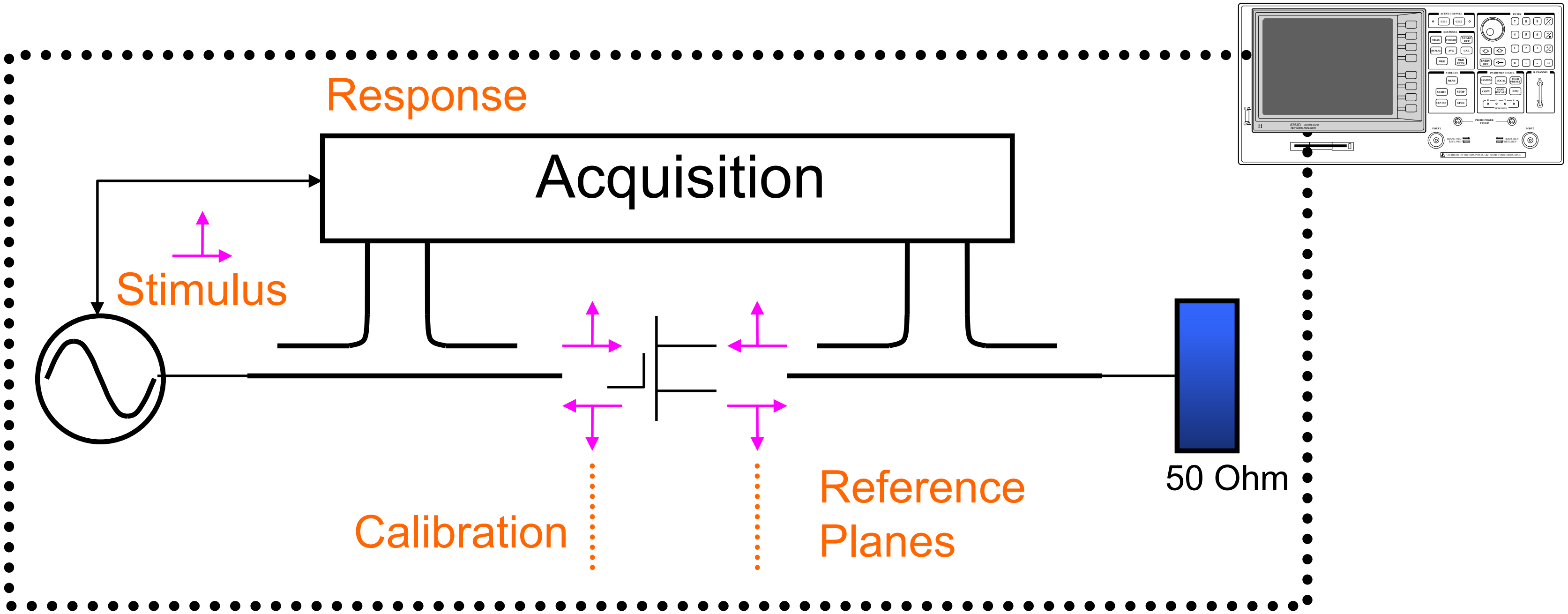
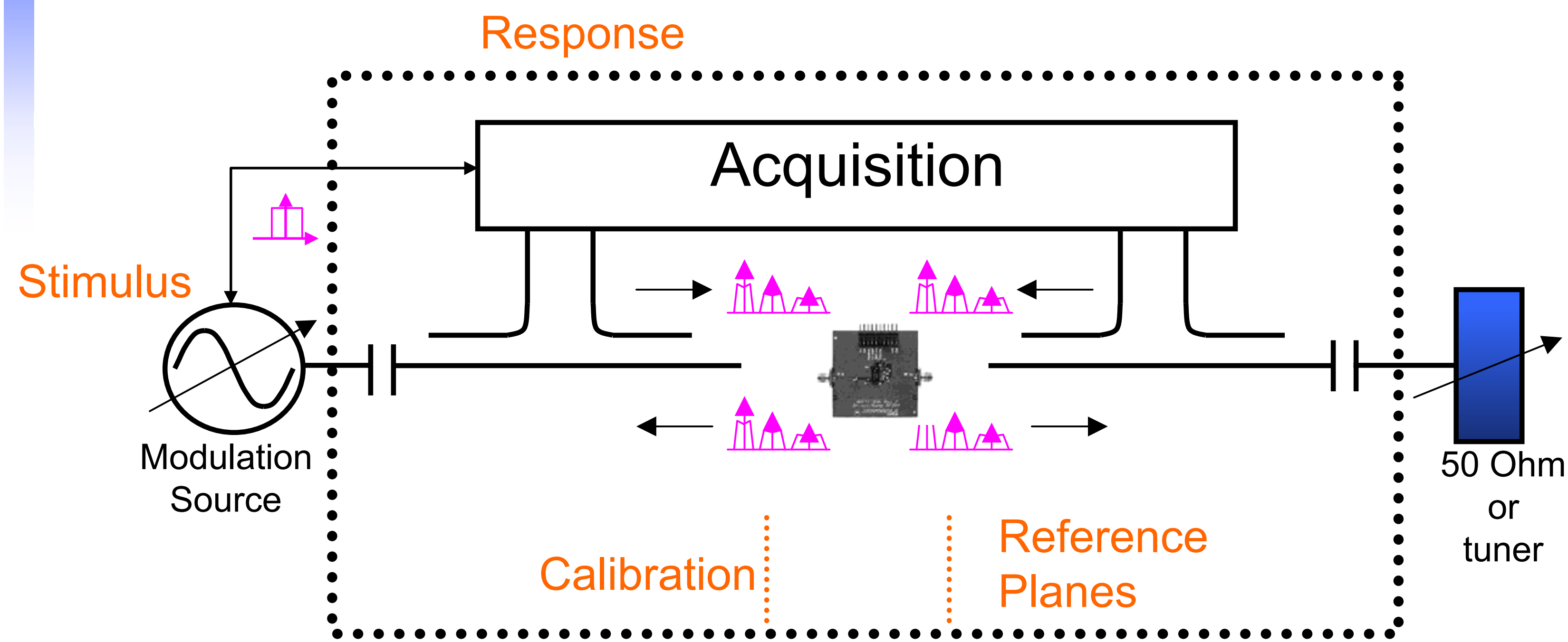
Vector Network Analyzer



S-parameters

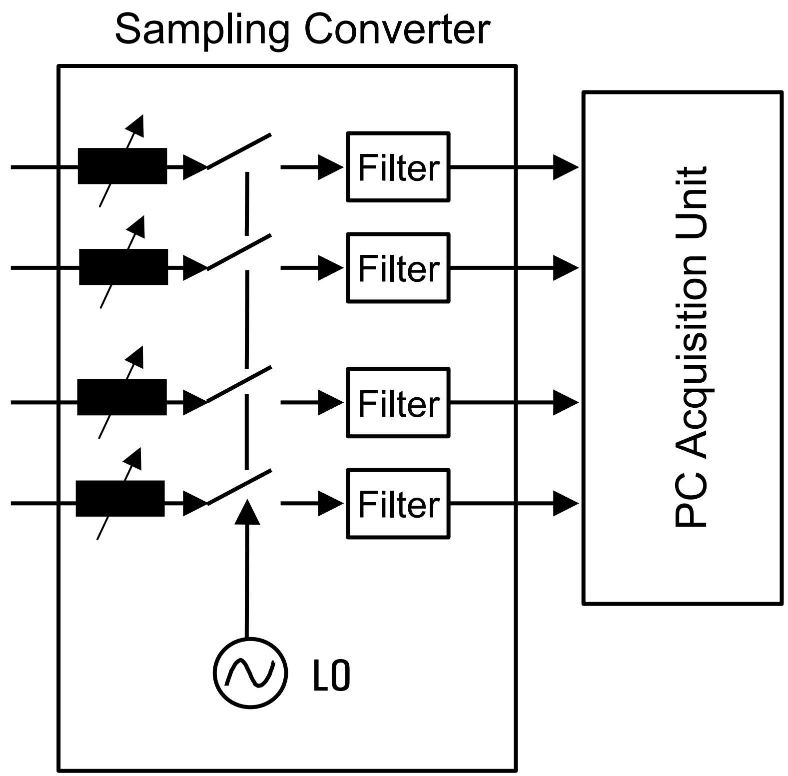
Analysis

Large-Signal Network Analyzer



Complete Spectrum
Waveforms
Harmonics and Periodic Modulation

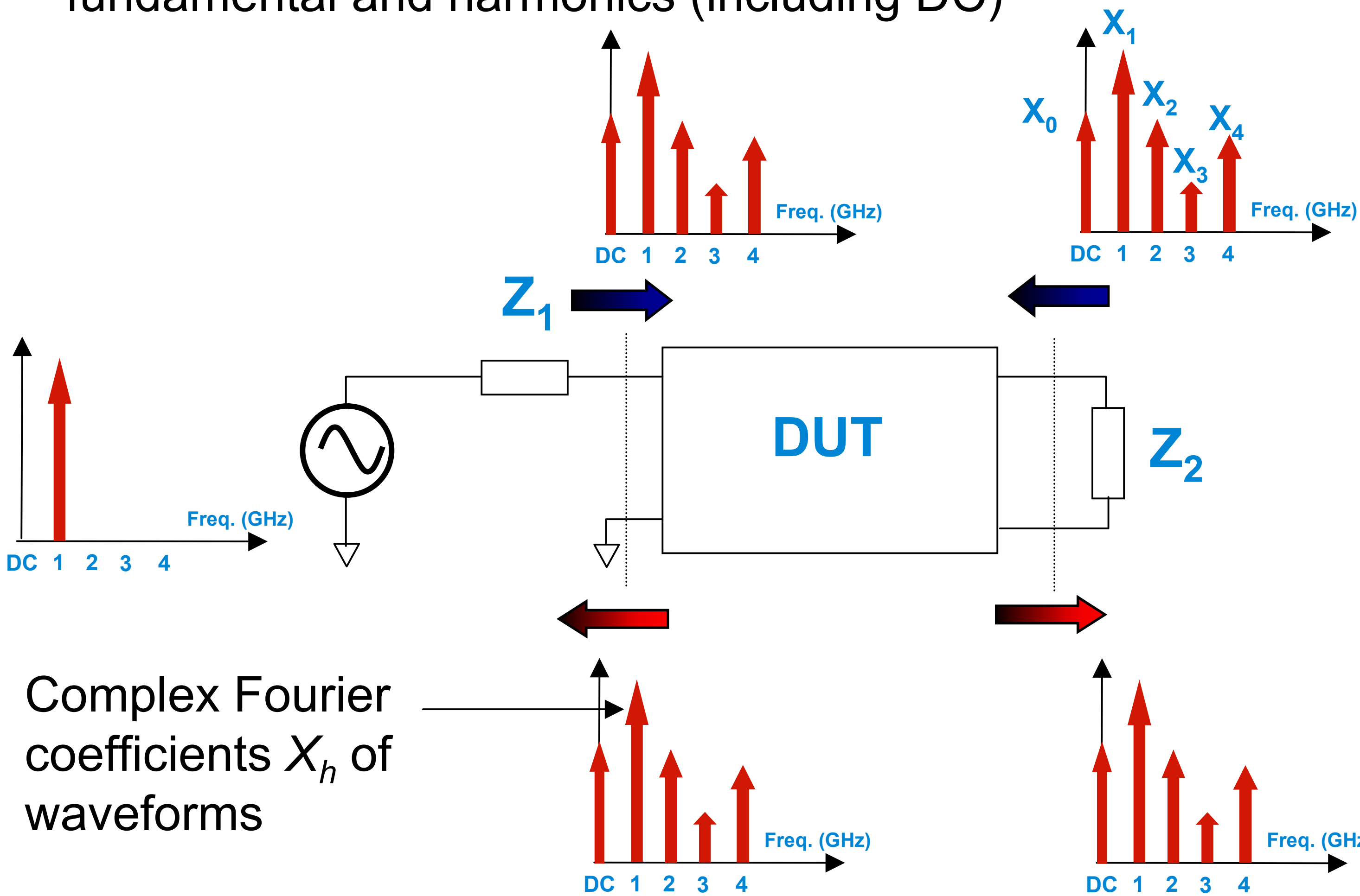
Acquisition in LSNA



Capturing broadband HF signals (harmonics and modulation) using low-frequency data - acquisition requires samplers

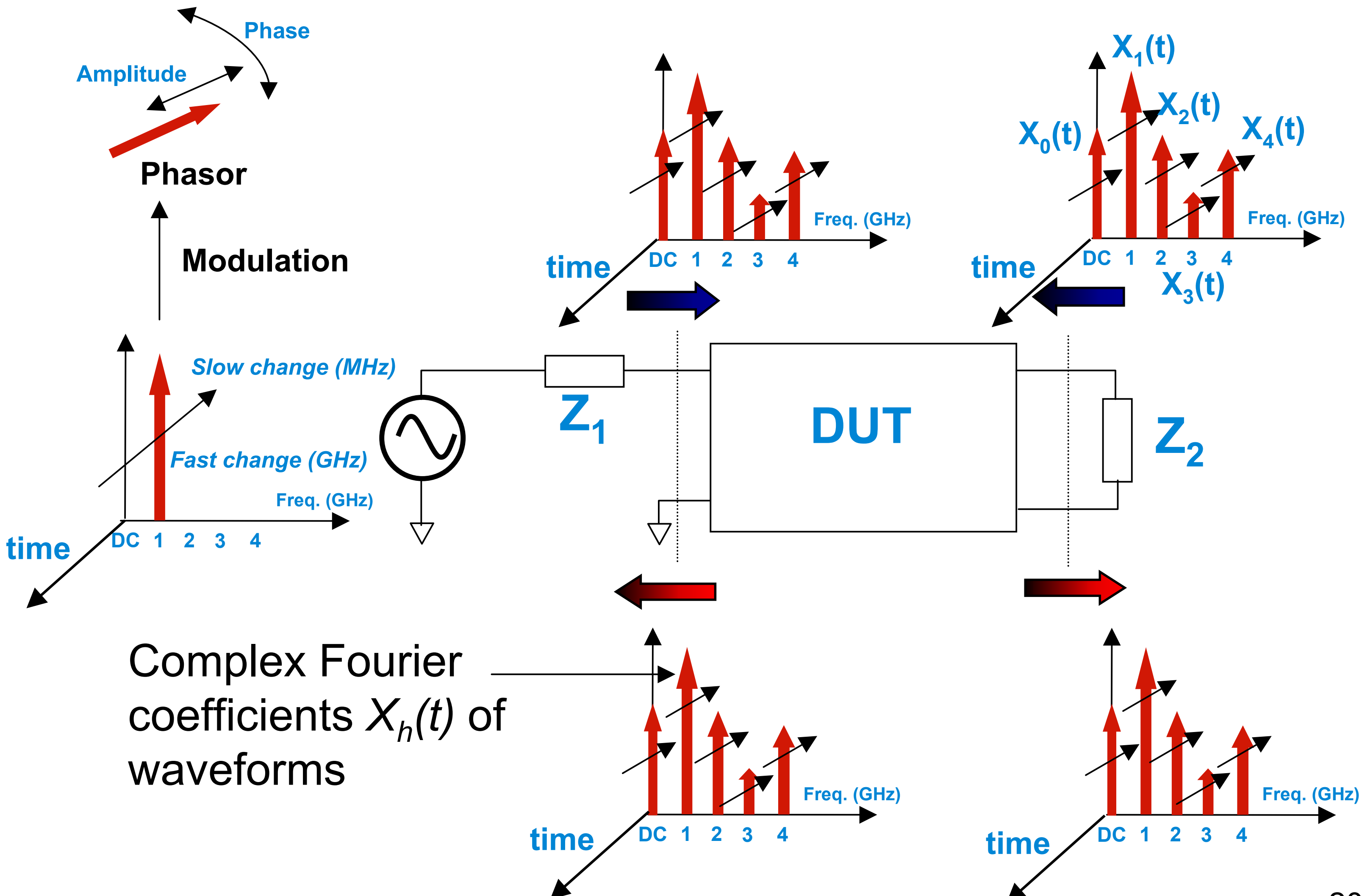
Representation Domain: Continuos Wave Signal

All voltages and currents or waves are represented by a fundamental and harmonics (including DC)



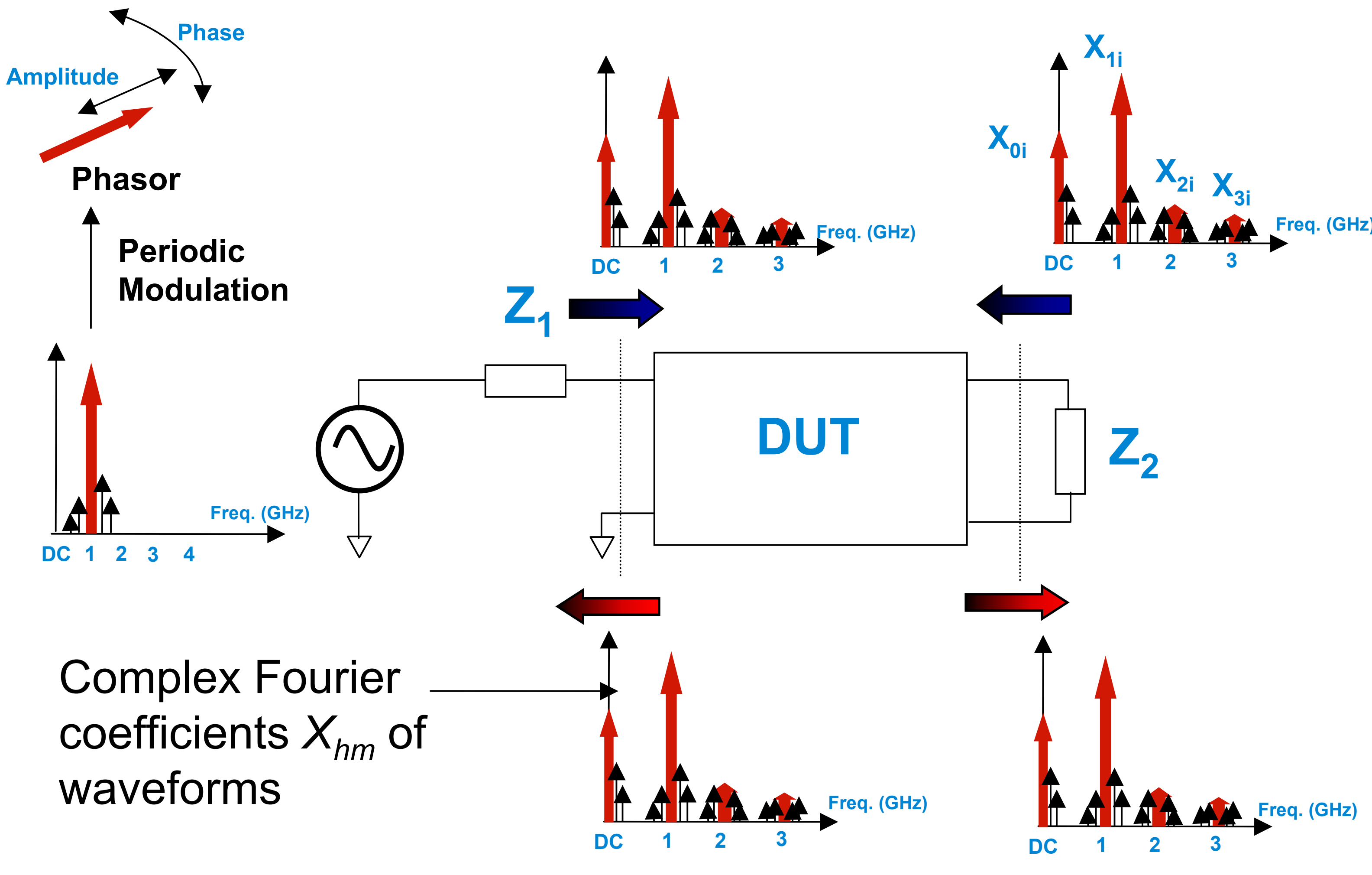
Complex Fourier coefficients X_h of waveforms

Representation Domain: Amplitude and Phase Modulation of Continuos Wave Signal



Complex Fourier coefficients $X_h(t)$ of waveforms

Representation Domain: Periodic Modulated Signals



With proper processing the class of signal is extendable to any type of multi-tone signal

Practical Limitations of LSNA

- Large-Signal Network analysis will be performed using periodic stimuli
  - one - tone and harmonics
  - periodic modulation and harmonics
  - other types of multi - tones are possible
- The devices under test maintain periodicity in their response

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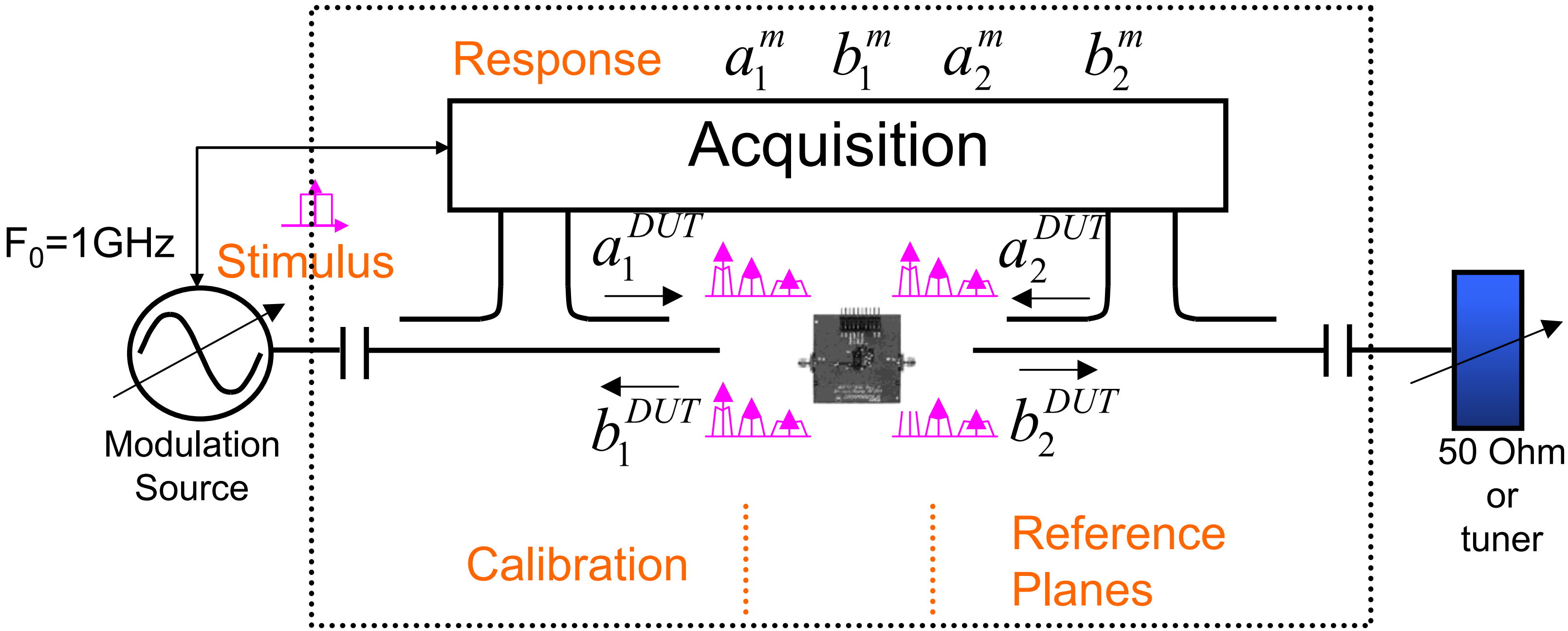
NMDG Engineering
Leading beyond S-parameters

LSNA Calibration



$$\begin{bmatrix} a_1^{DUT} \\ b_1^{DUT} \\ a_2^{DUT} \\ b_2^{DUT} \end{bmatrix} \xleftrightarrow[\text{Relationship}]{\text{Linear}} \begin{bmatrix} a_1^{m} \\ b_1^{m} \\ a_2^{m} \\ b_2^{m} \end{bmatrix} \Rightarrow$$

Actual waves at DUT

Measured waves

- Regular VNA Calibration
- Power Calibration (power meter)
- Phase Calibration (pulse gen)

Measurement Traceability

Relative Cal

Phase Cal

Power Cal

Agilent
Nose-to-Nose
Standard (*)

EOS

(NIST)

(demonstrated already with NIST)

National Standards

(*) Licensed to Maury and NMDG

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Available Large-Signal Network Analyzers

MT4463A - 20 GHz

MT4463B - 50 GHz

Active HF Component Characterization Requirements

DC IV Characterization

Adding
… DC Capability

MT4463A/B

Small-Signal

Large-Signal

Accurate

Complete

Modulation Characterization

Adding
… Modulation Capability

Active Tuning

Adding
… Pre-match Tuner
… Second Source

Under different Impedance Conditions

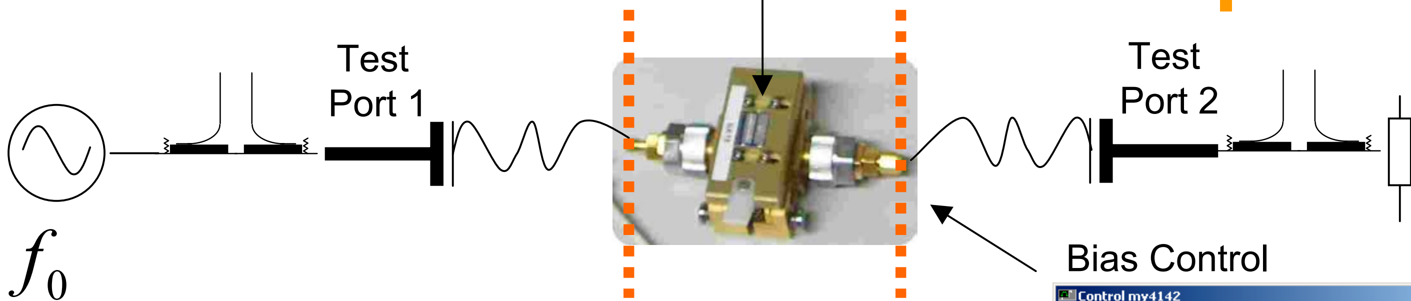
Passive Tuning

Adding
… Tuners

Example: Packaged FET

One connection
Complete Characterization

Commercial available FET in fixture



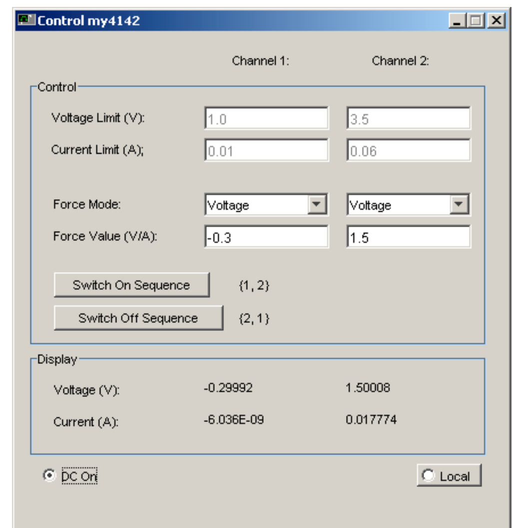
f_0

Frequency Grid: f_0 = 2GHz, 9 harmonics
Resolution BW: 1000 Hz

Absolute Calibration using SOLT

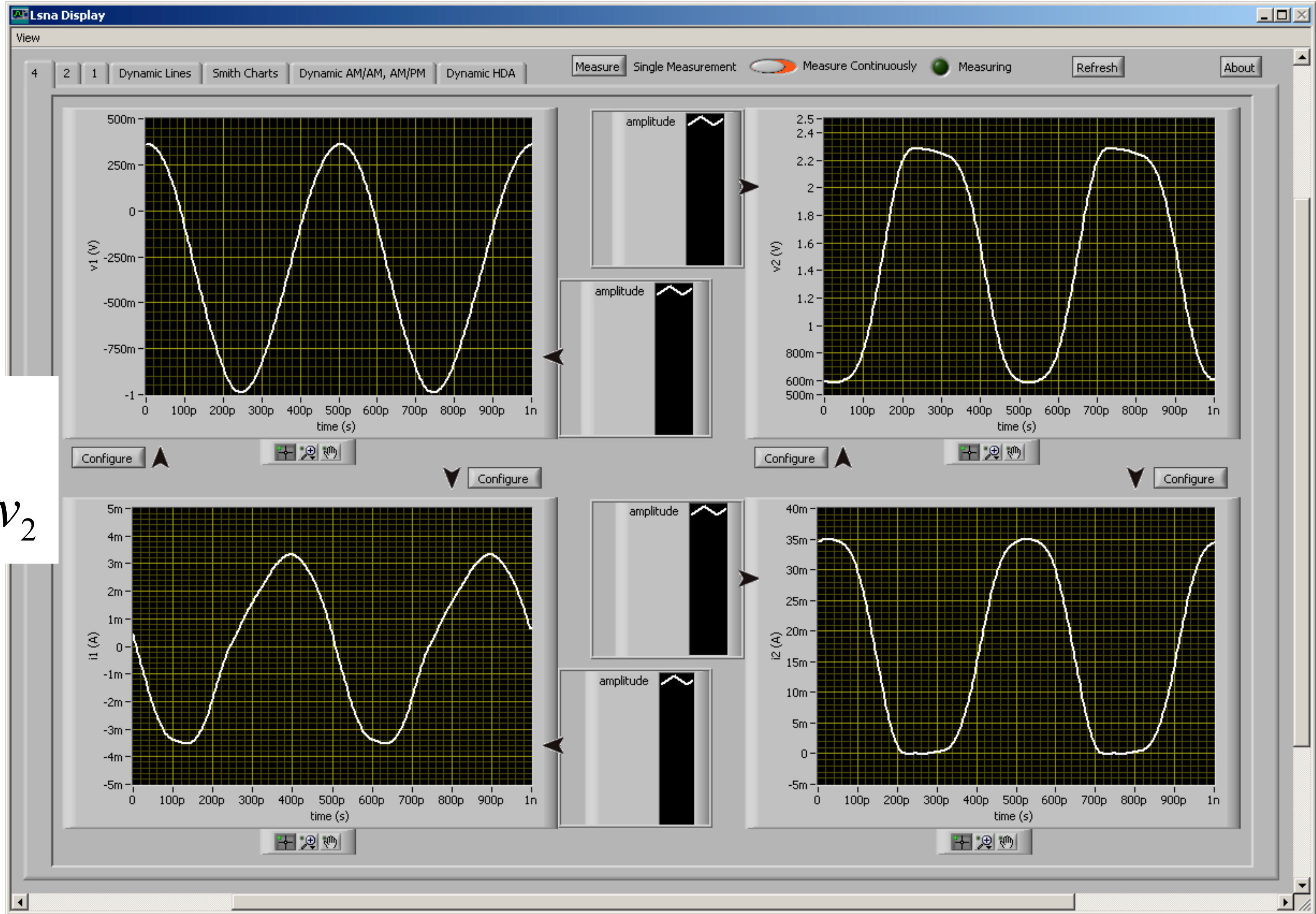
Deembedding

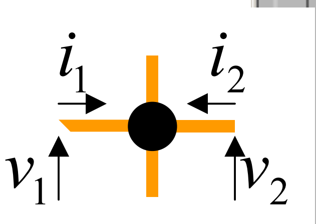
Bias Control



V_{gs} = -0.3 V V_{ds} = 1.5 V

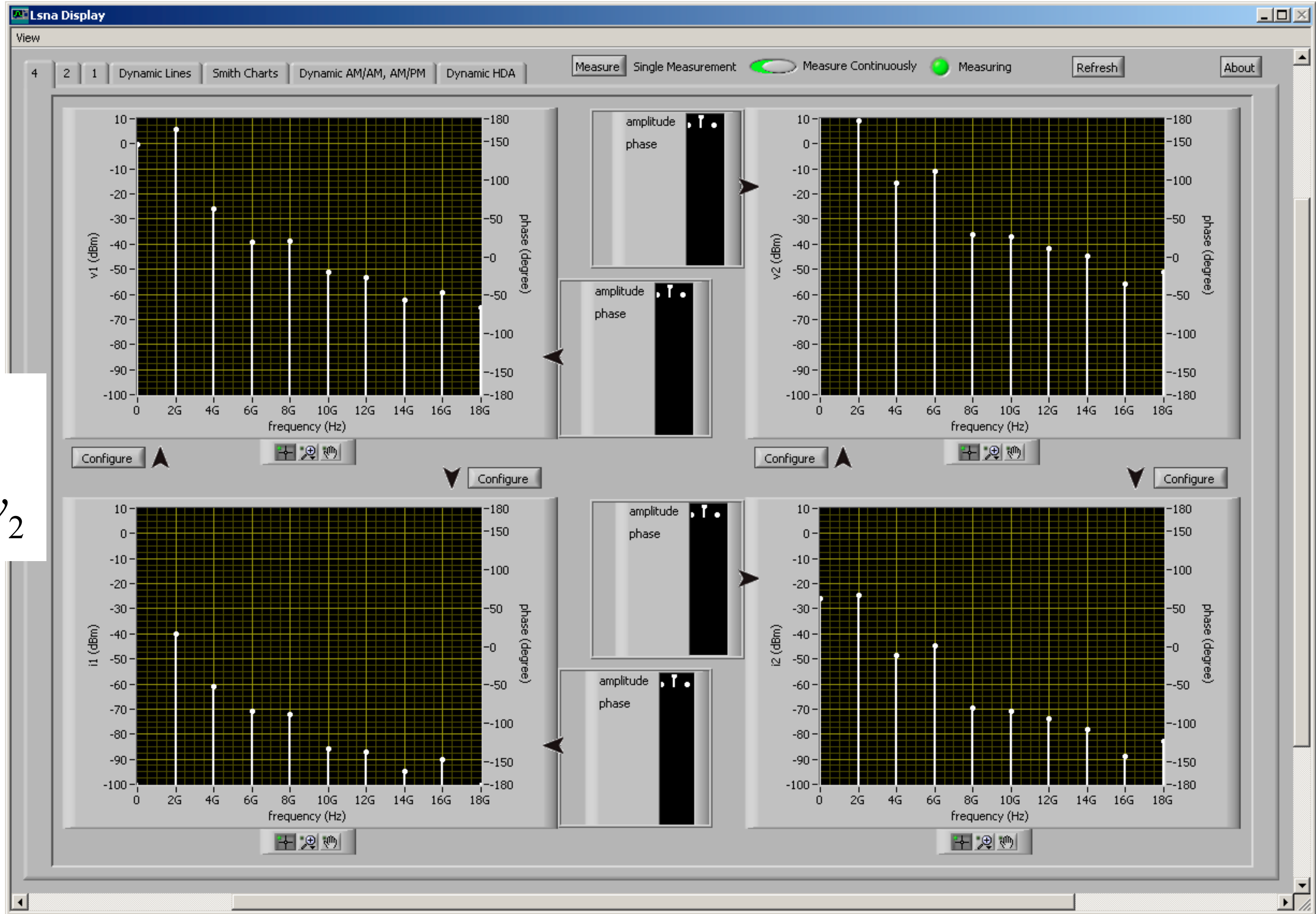
Large-Signal Measurements - CW - Voltage/Current

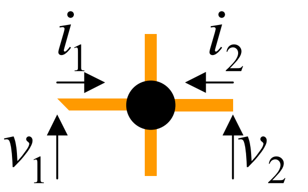




Time domain

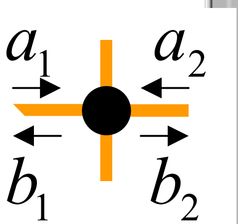
Large-Signal Measurements - CW - Voltage/Current

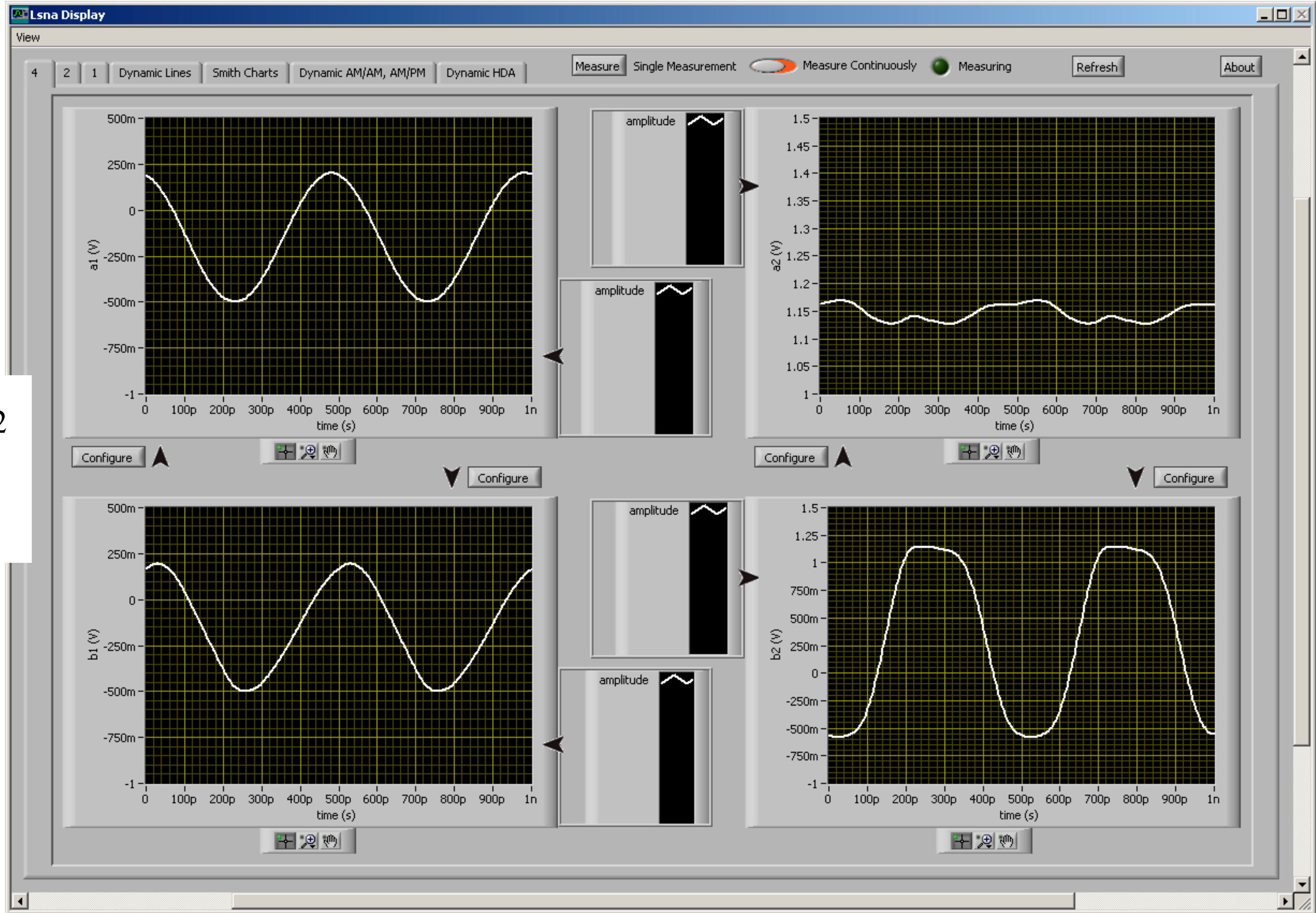




Frequency domain

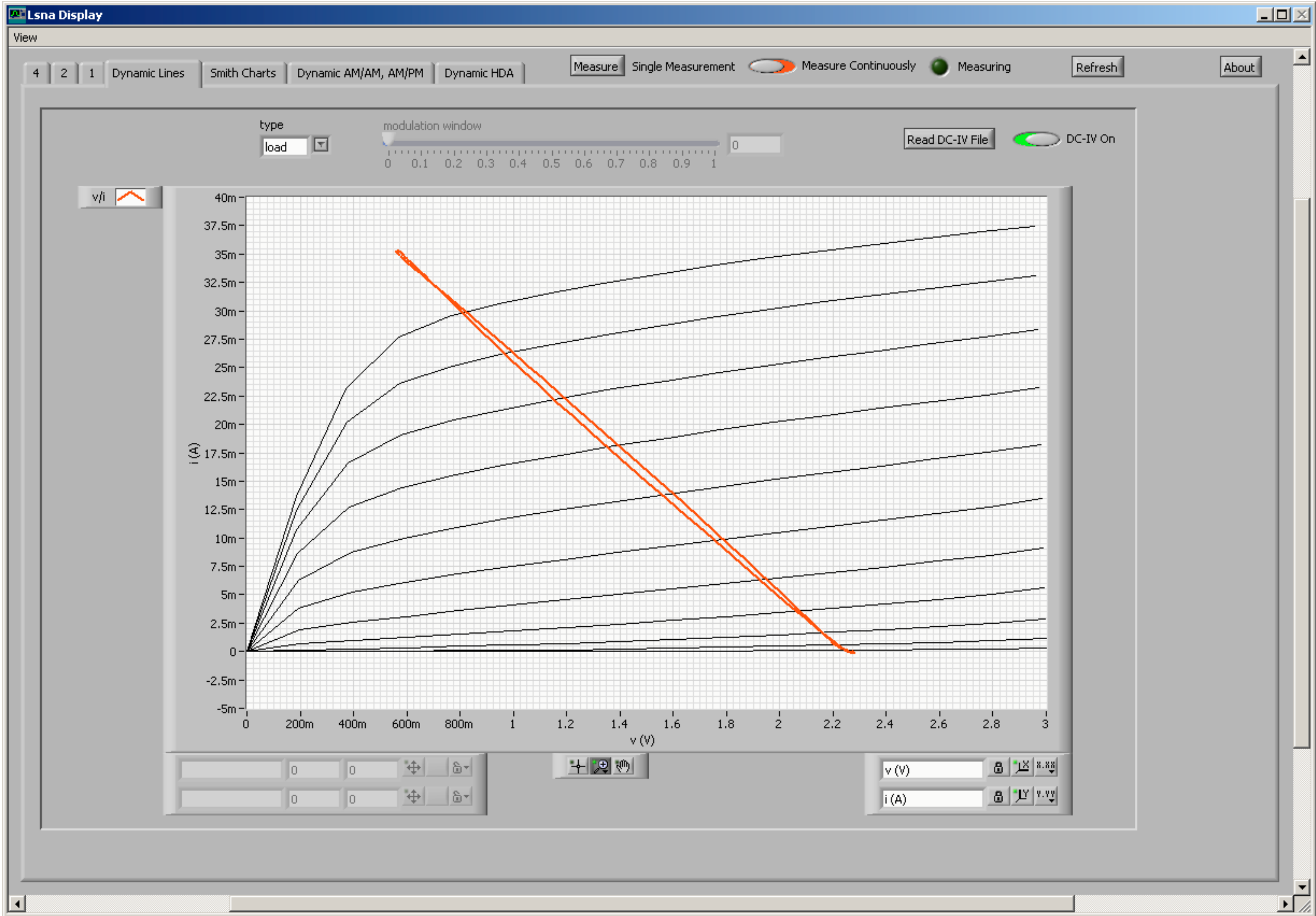
Large-Signal Measurements - CW - Voltage Waves





Time domain

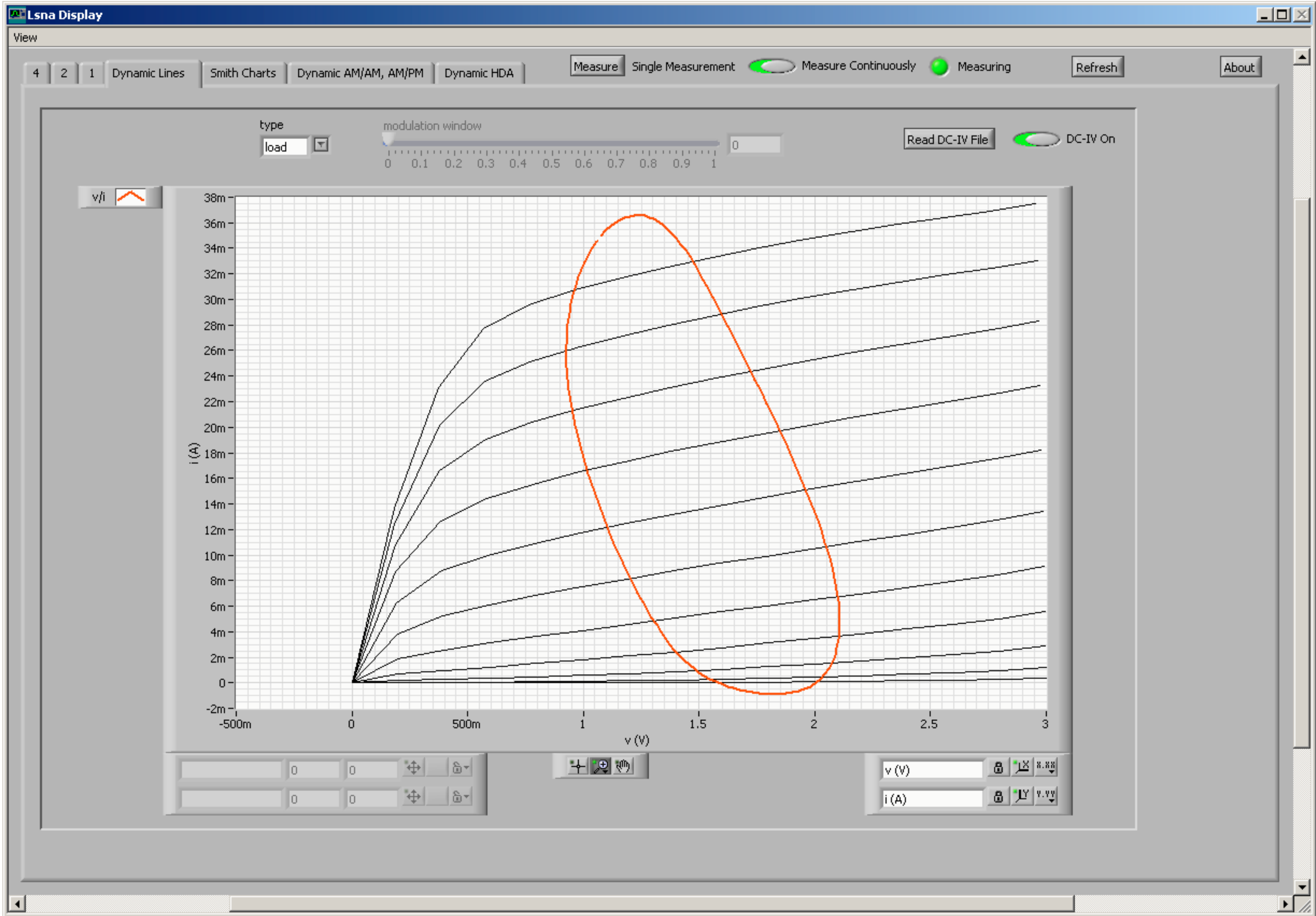
DC-IV curve and RF Load Line (1)



Large-signal - 50 Ohm Termination

DC-IV curve and RF Load Line (2)

Open Termination



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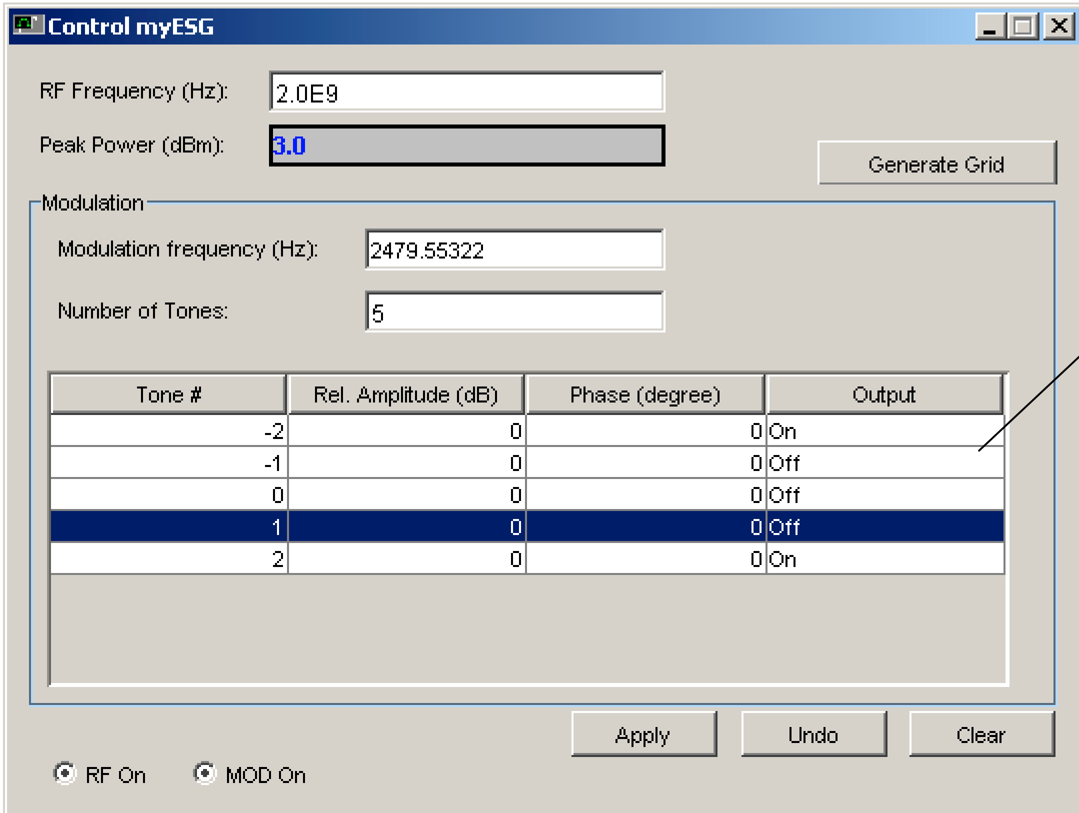
Periodic Modulation - Multi-tone generation

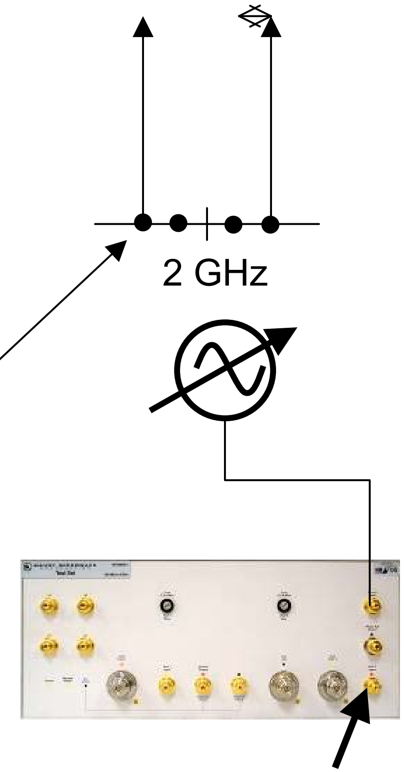
Carrier

Modulation

Tones



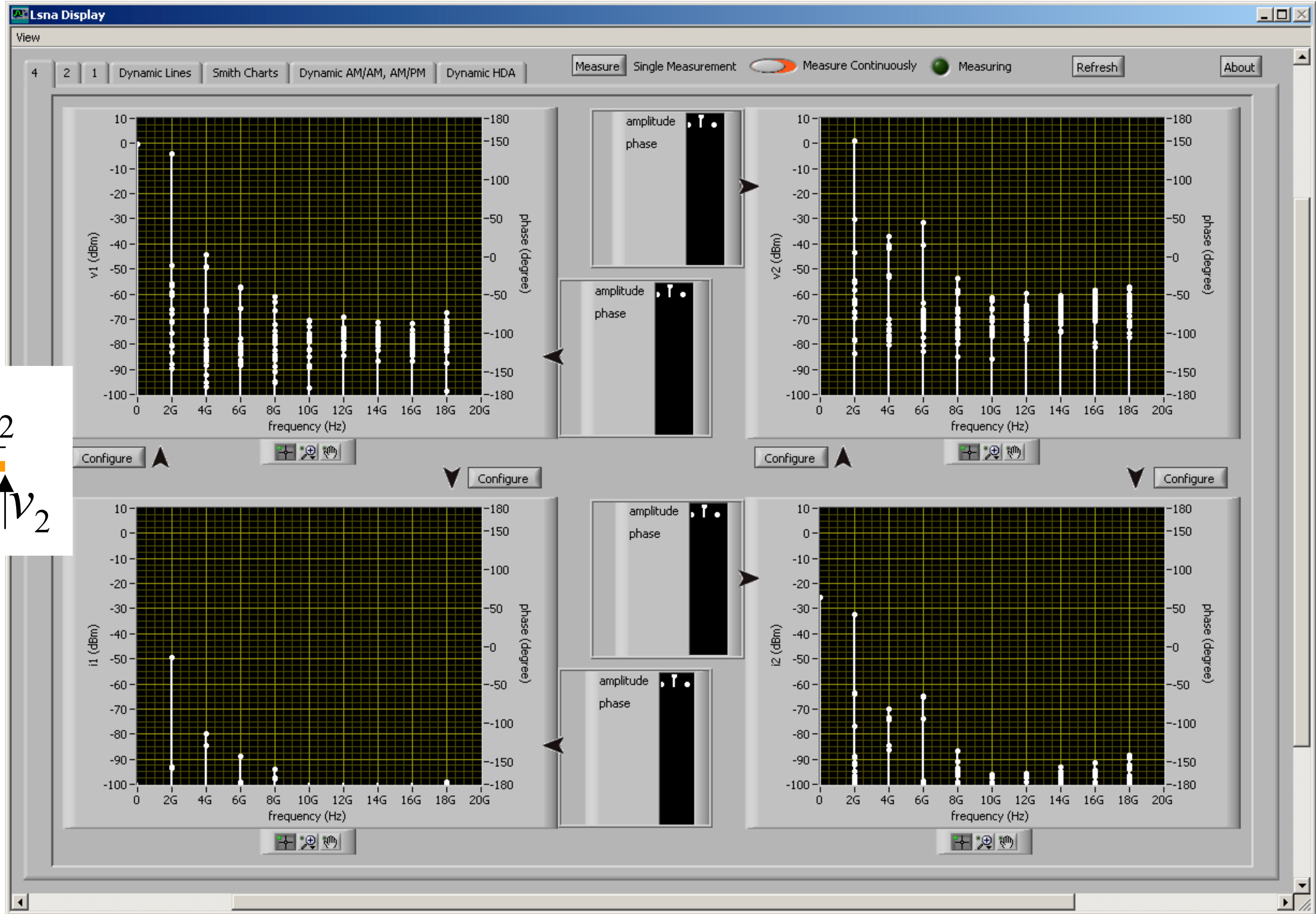
$\Delta f = 2480.0\ Hz$

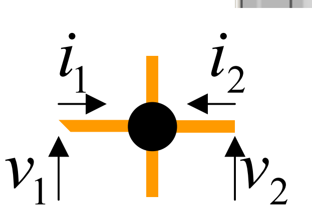


50 Ohm Termination

Generation of Multi-tone

Large-Signal Measurements - Modulation - Voltage/Current

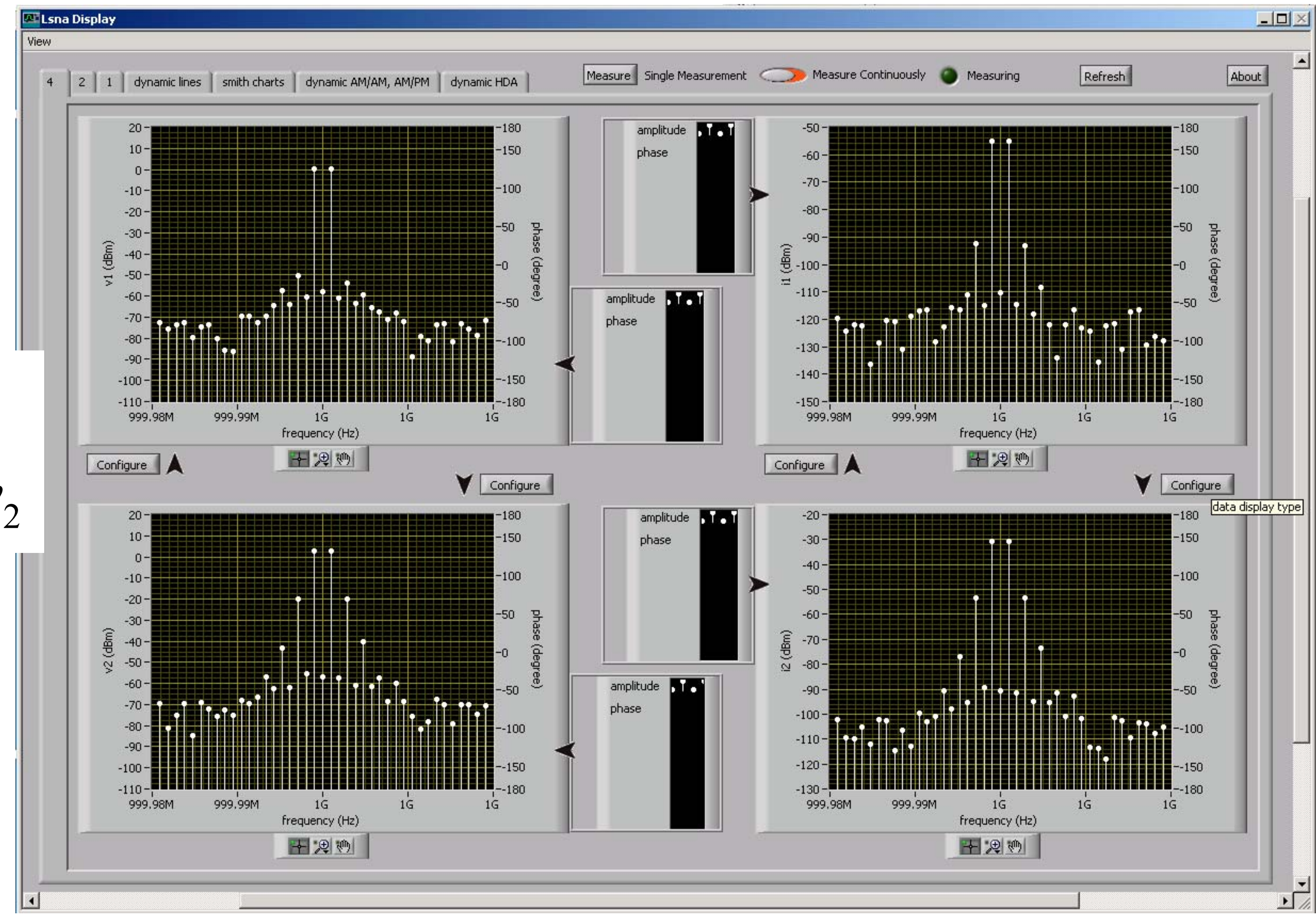


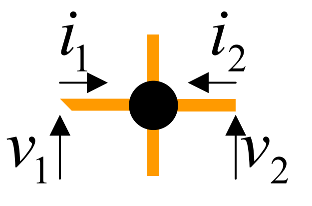


Frequency domain

Large-Signal Measurements - Modulation - Voltage/Current

Zoom into one of the spectral components (fundamental frequency)





Frequency domain

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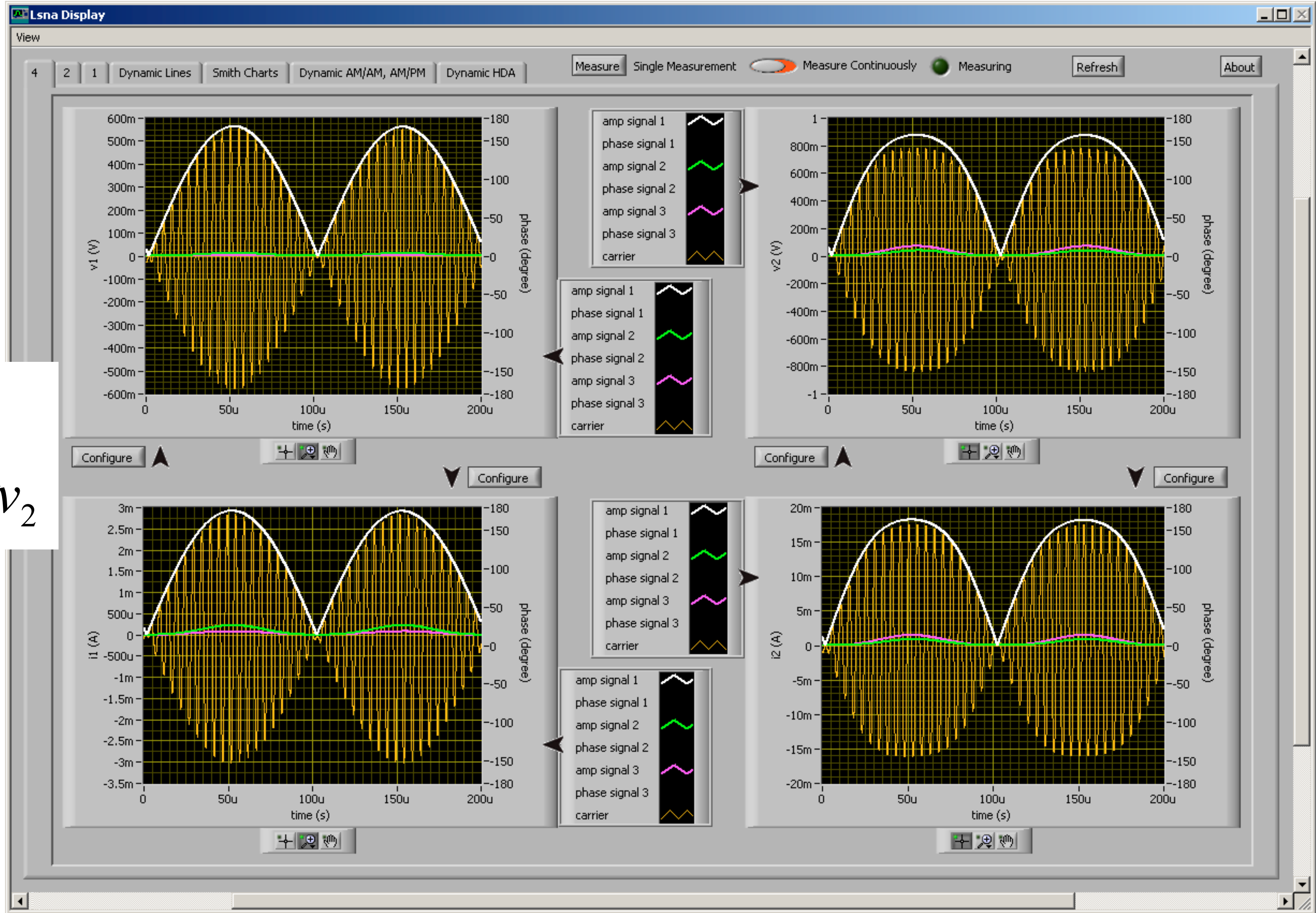
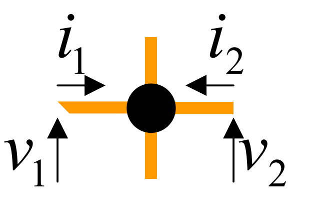
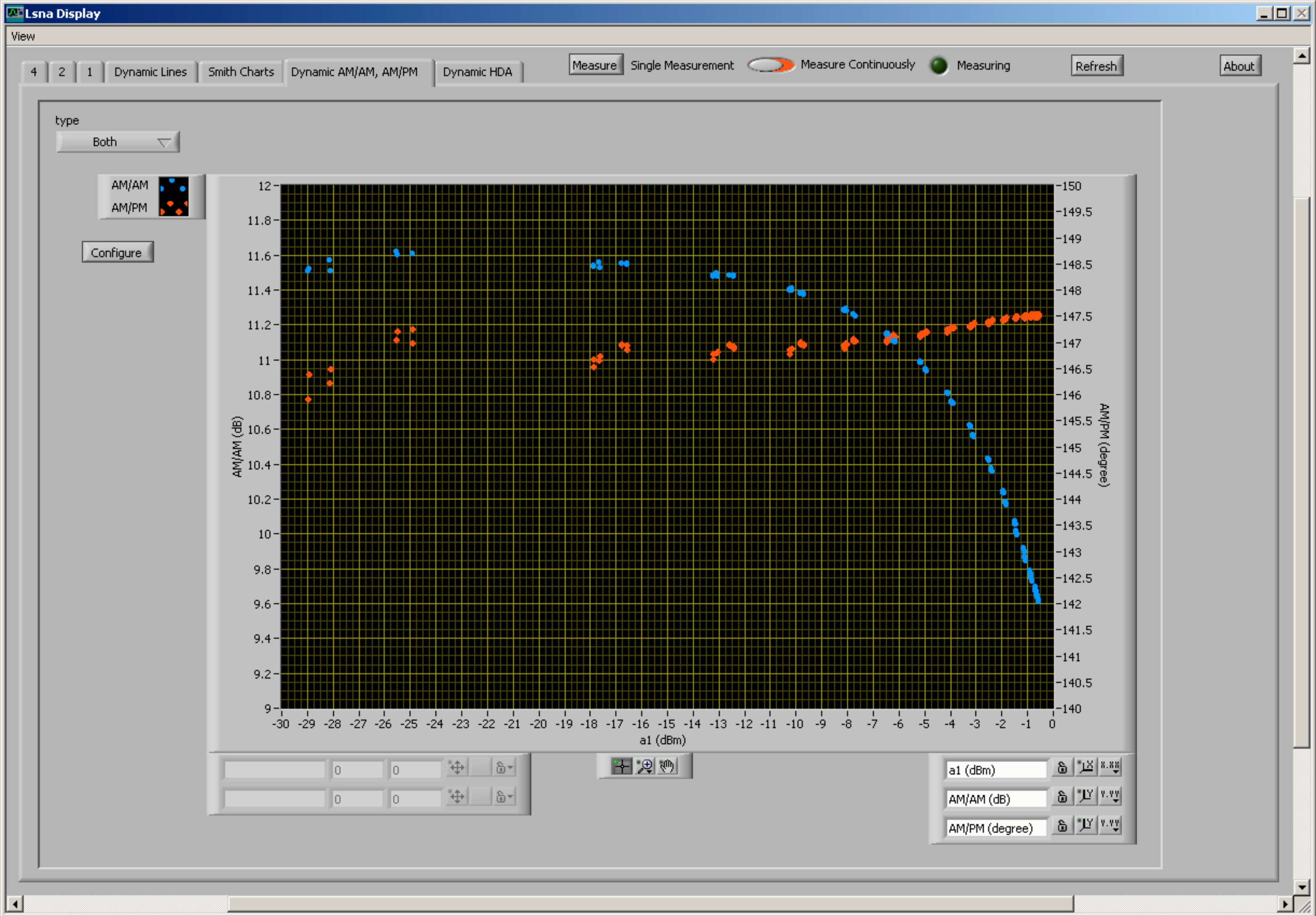




Frequency - Time domain

Dynamic AM/AM and AM/PM (two-tone 10kHz spacing)



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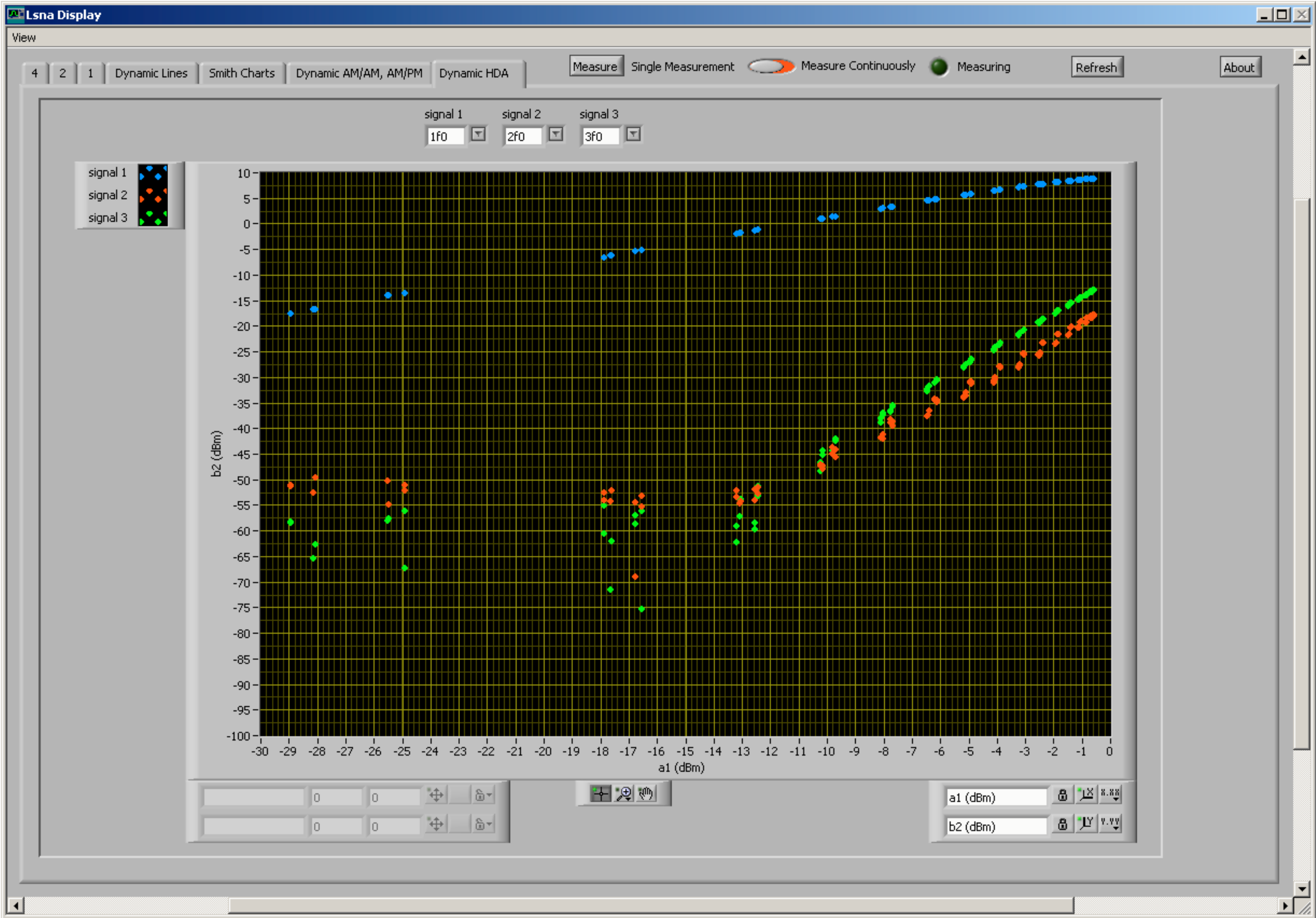
Dynamic HDA (two-tone 10kHz spacing)



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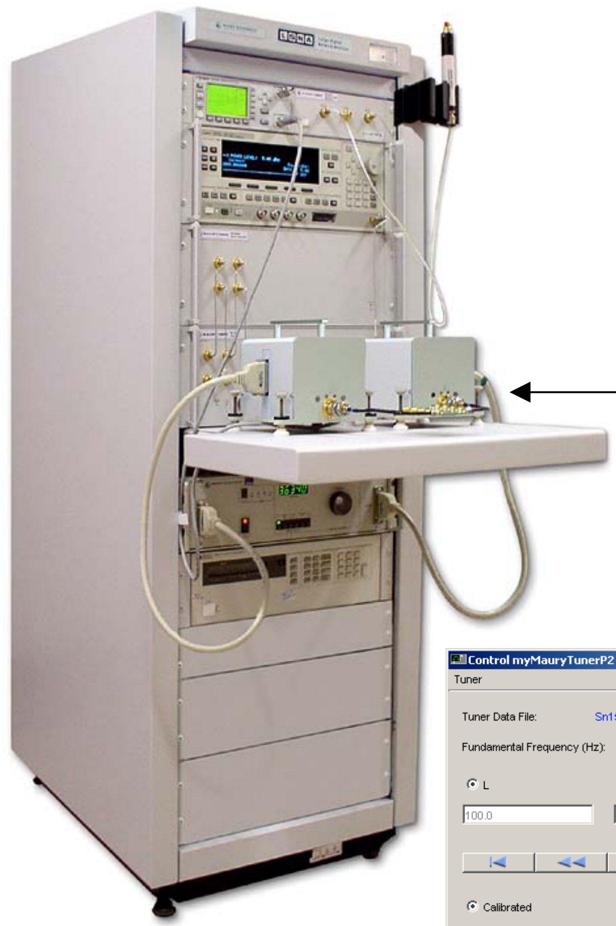
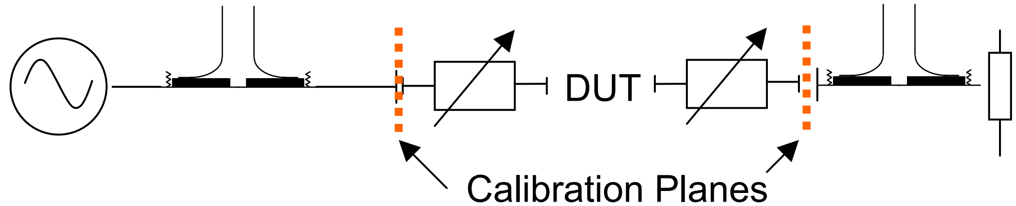
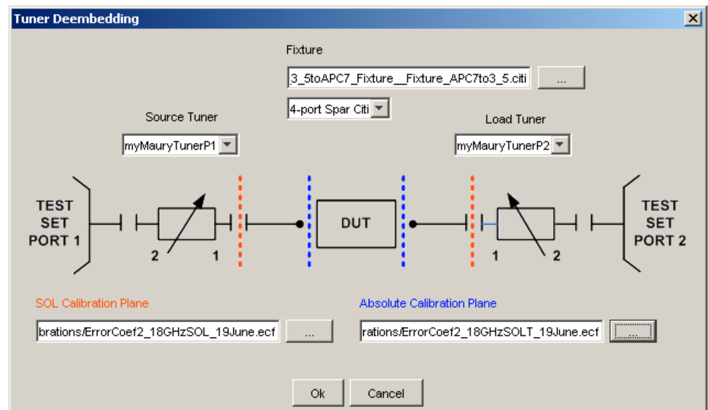
Component Characterization with Passive Tuners

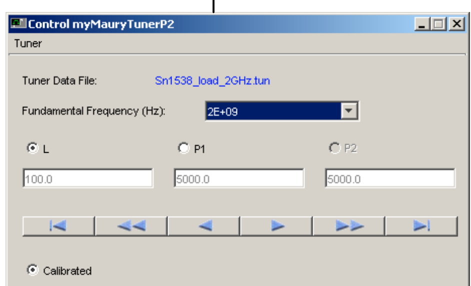




Error-coefficients depend on tuner position



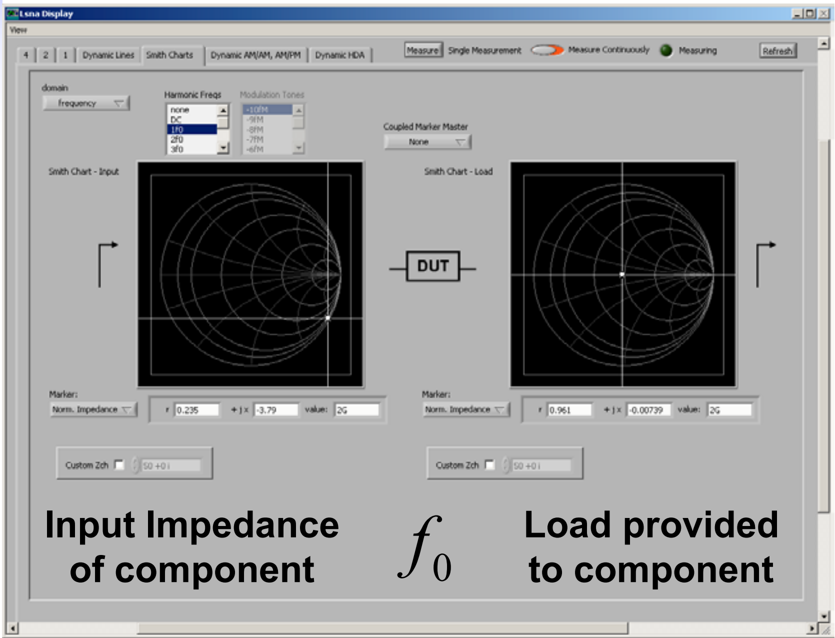
Tuner De-embedding



Tuner Control + Automatic Correction
(Probe(s) and carriage)

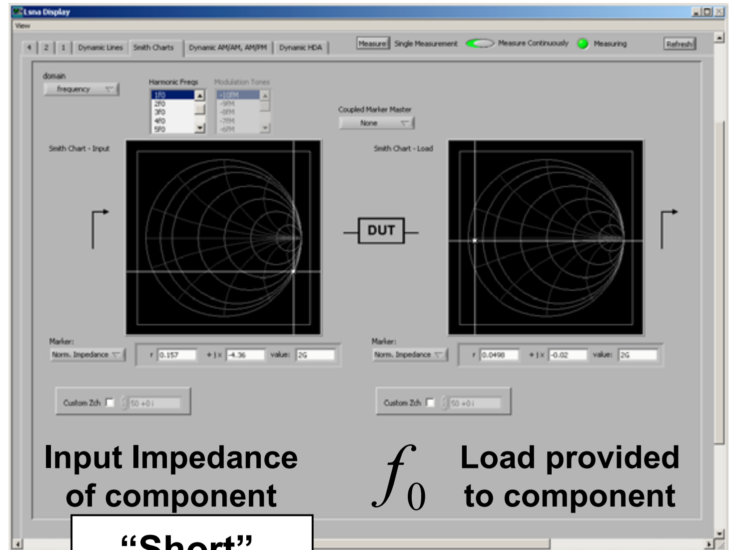
NMDG Engineering
Leading beyond S-parameters

Input and Load Impedance under CW

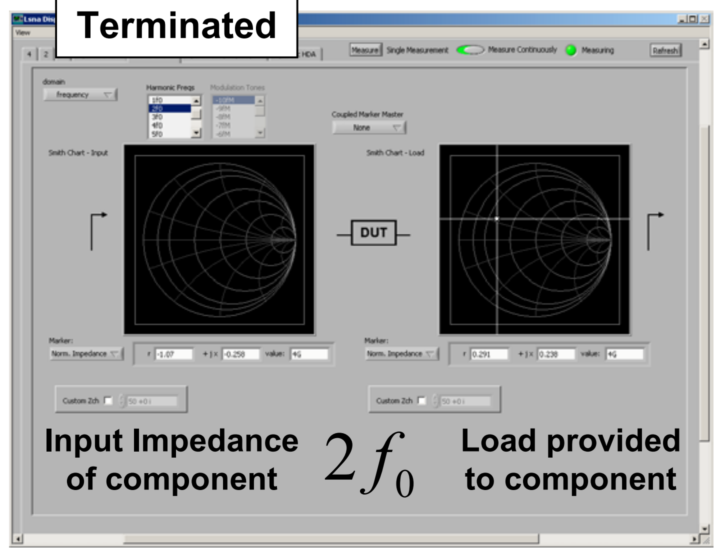


50 Ohm Terminated

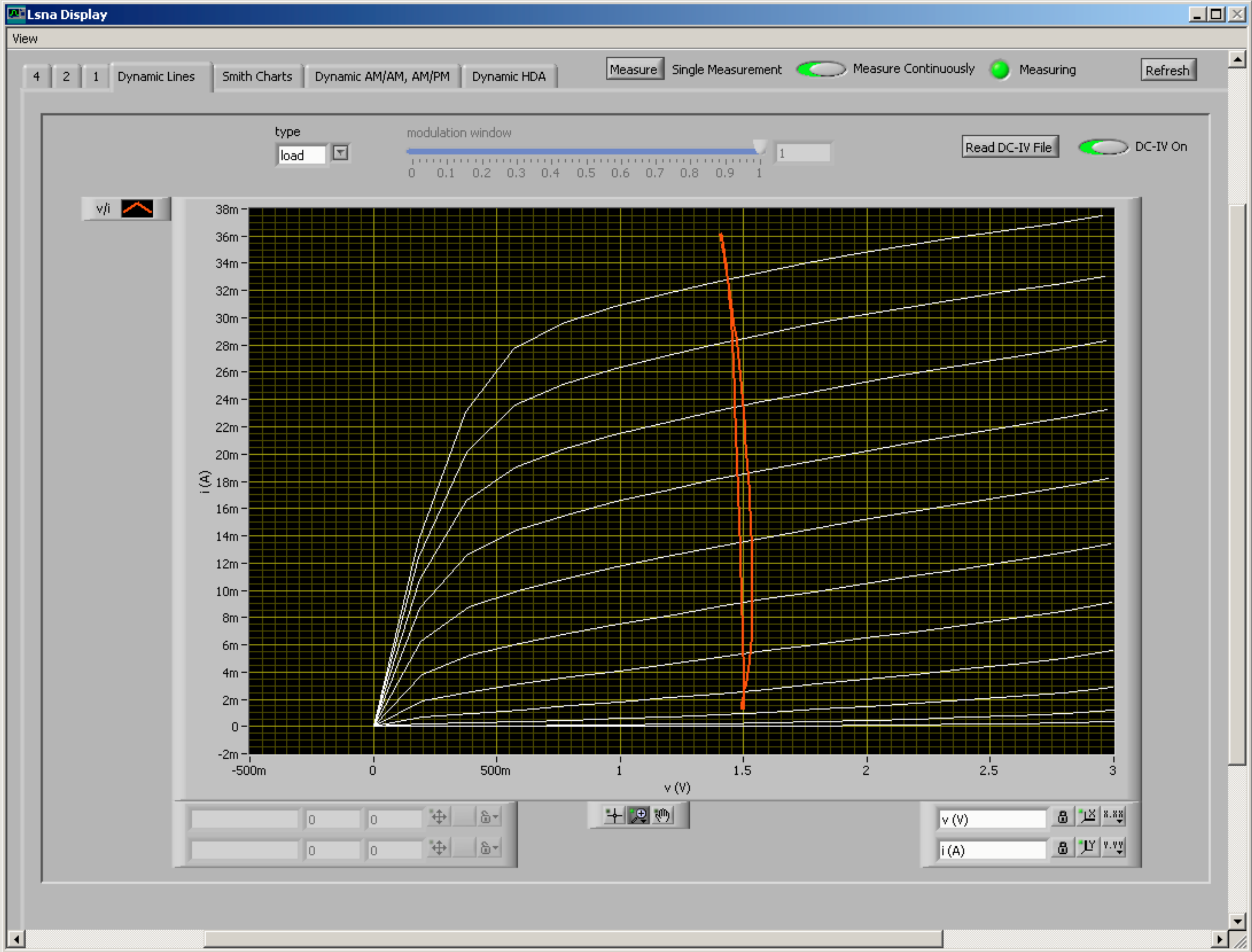
"Tuning"



"Short" Terminated

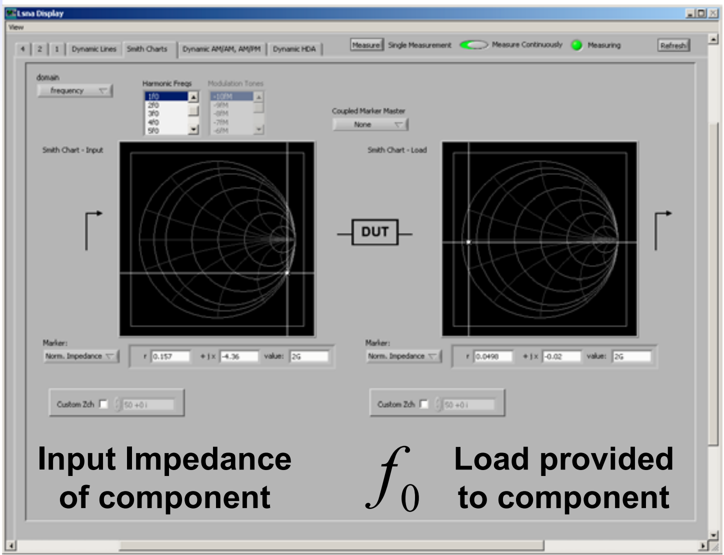


DC-IV curve and RF Load Line with "Short"



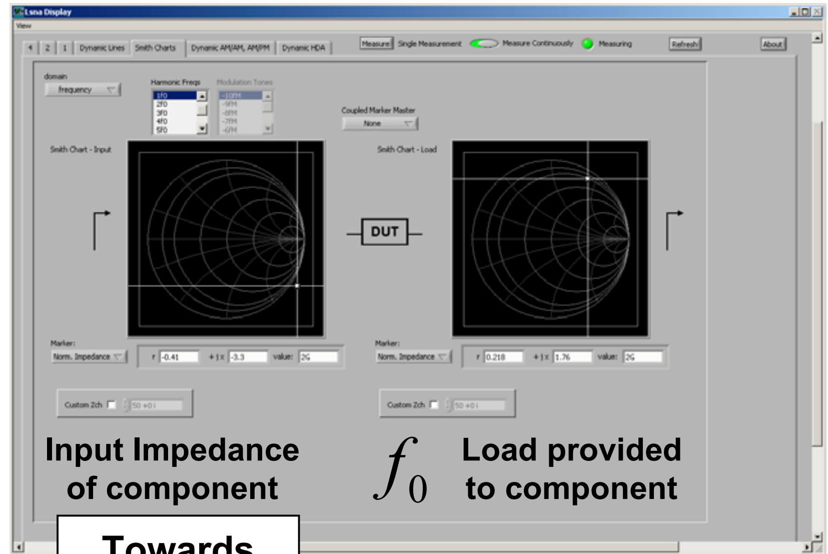
"Short" Terminated

Input and Load Impedance under CW

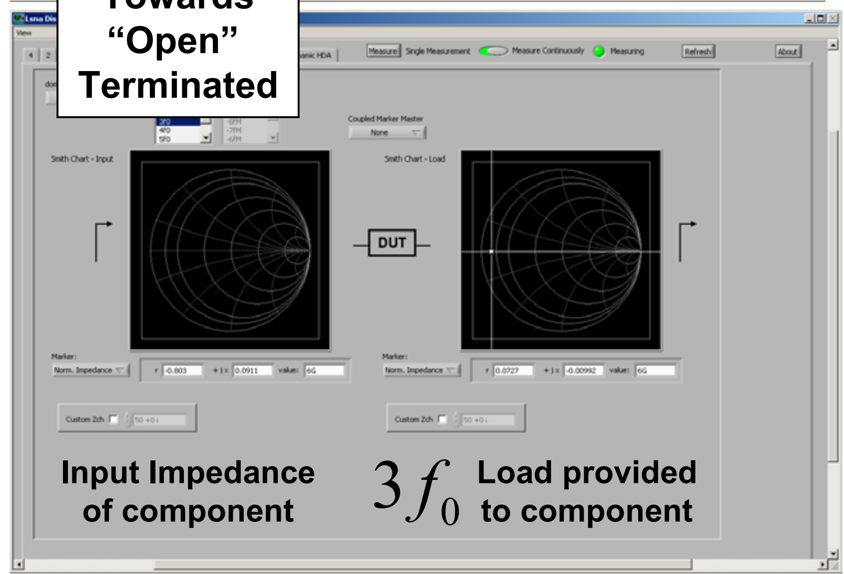


"Short" Terminated

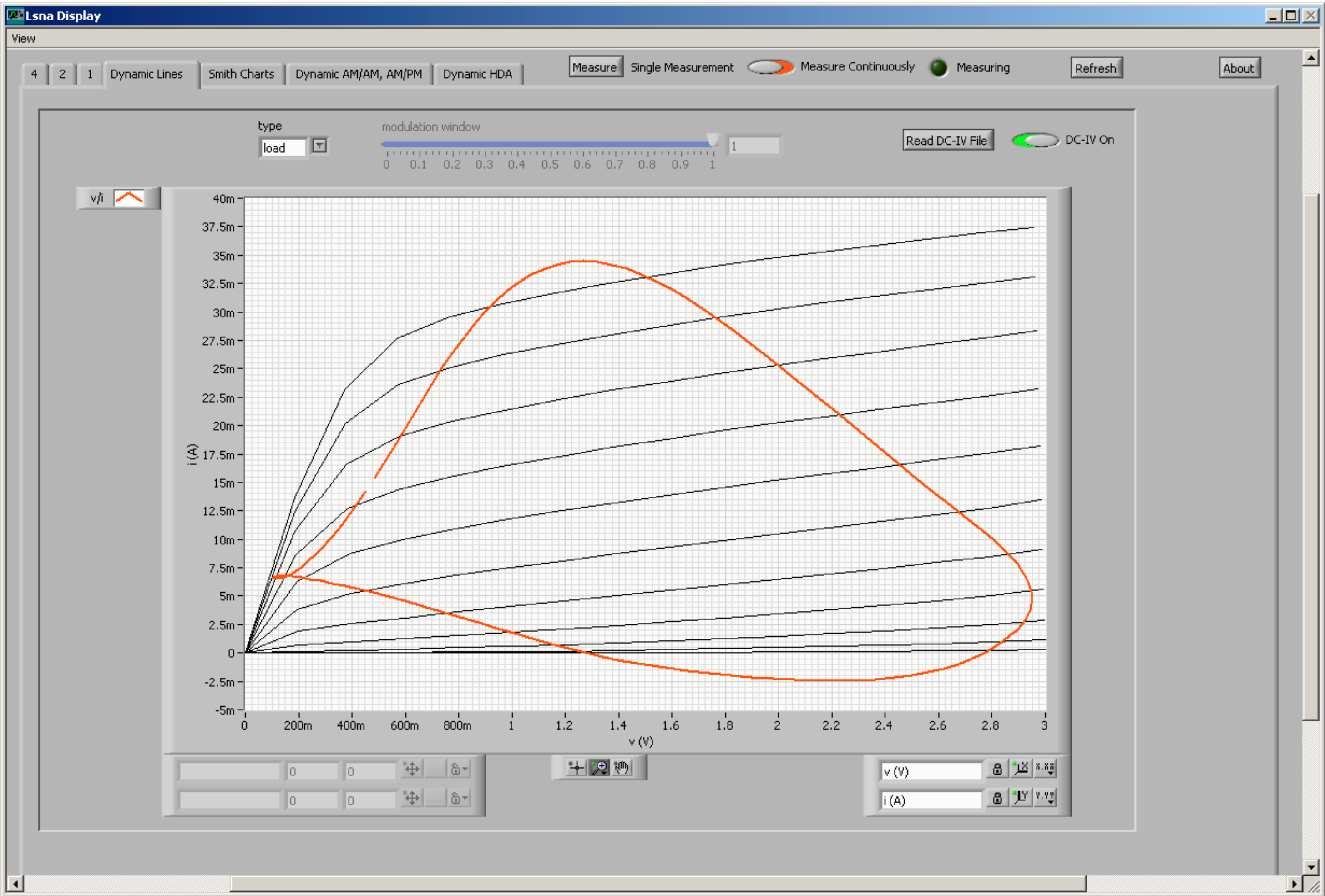
"Tuning"



Towards "Open" Terminated



DC-IV curve and RF Load Line with "Towards Open"

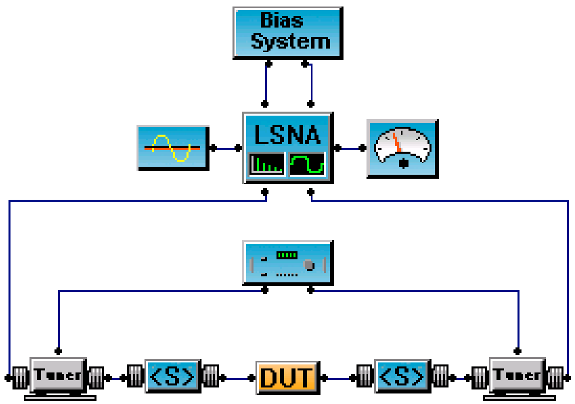


"Towards Open" Terminated

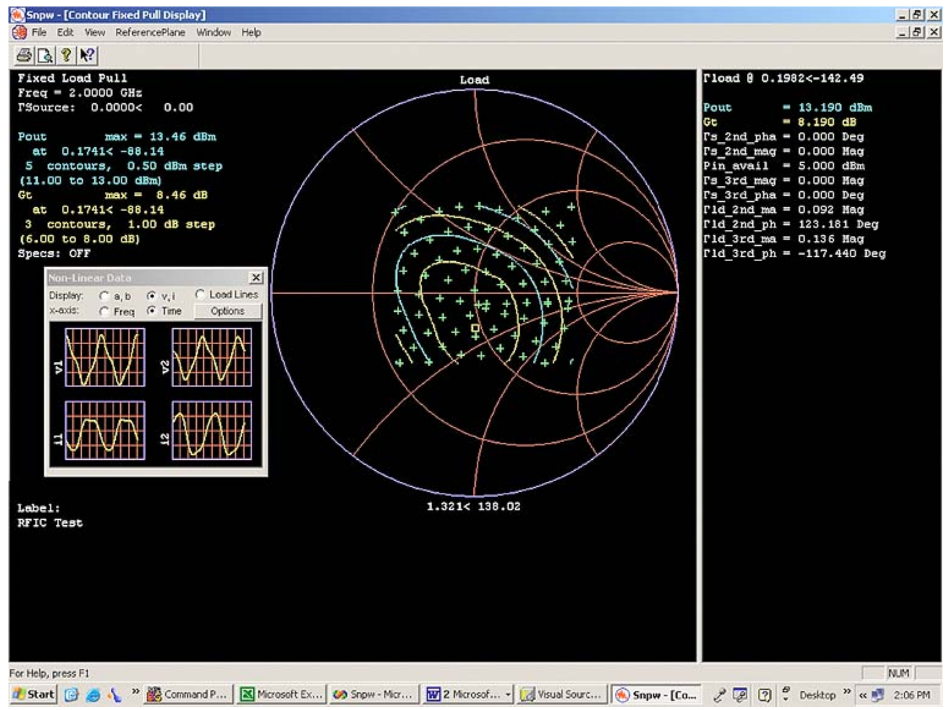
NMDG Engineering
Leading beyond S-parameters

Integration with Load-Pull Software

LSNA Power Block Diagram



The waveforms contain all aspects of the component behavior



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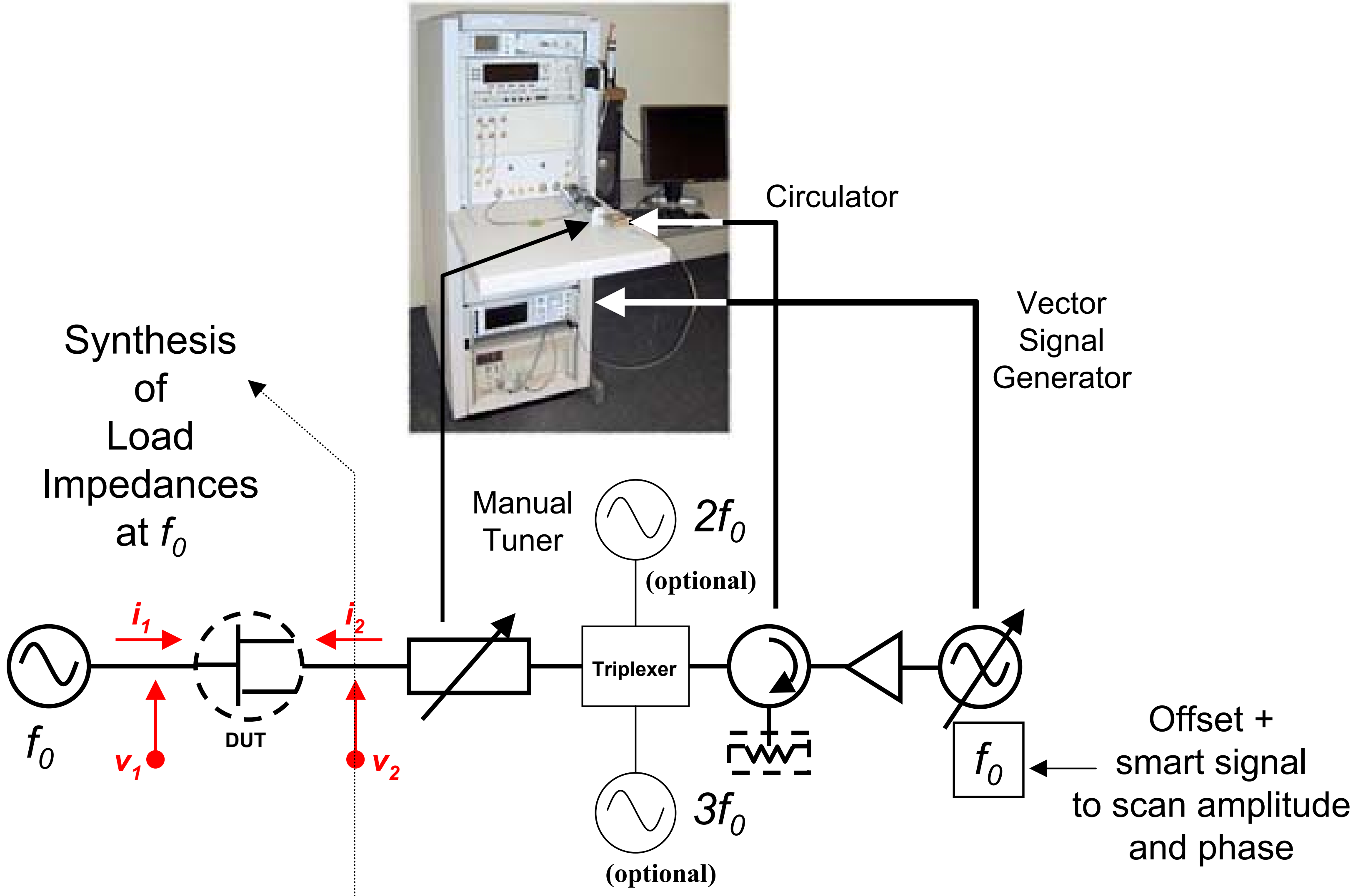
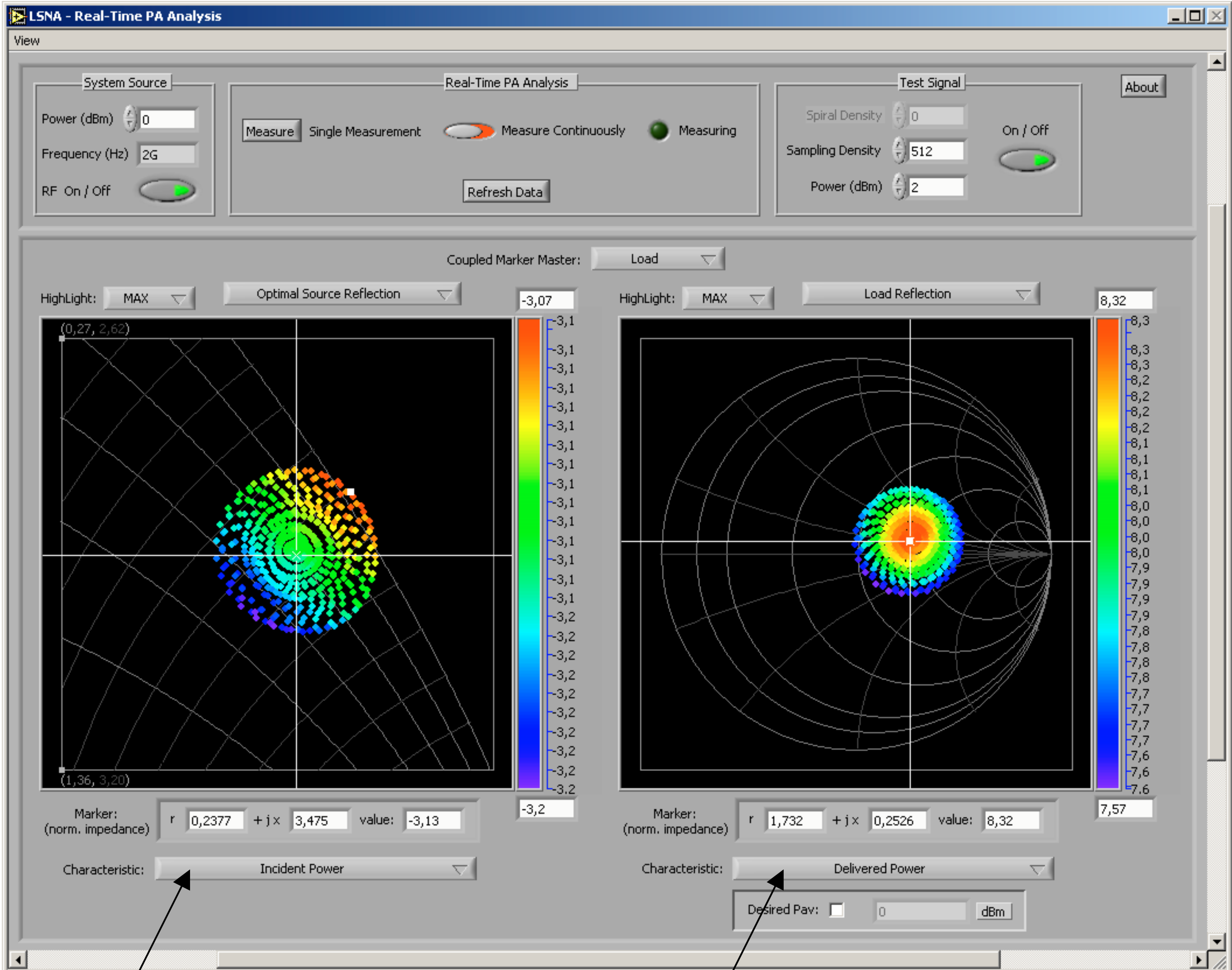
Real-Time Component Characterization - Setup



Real-Time Component Characterization



Corresponding Input Impedances

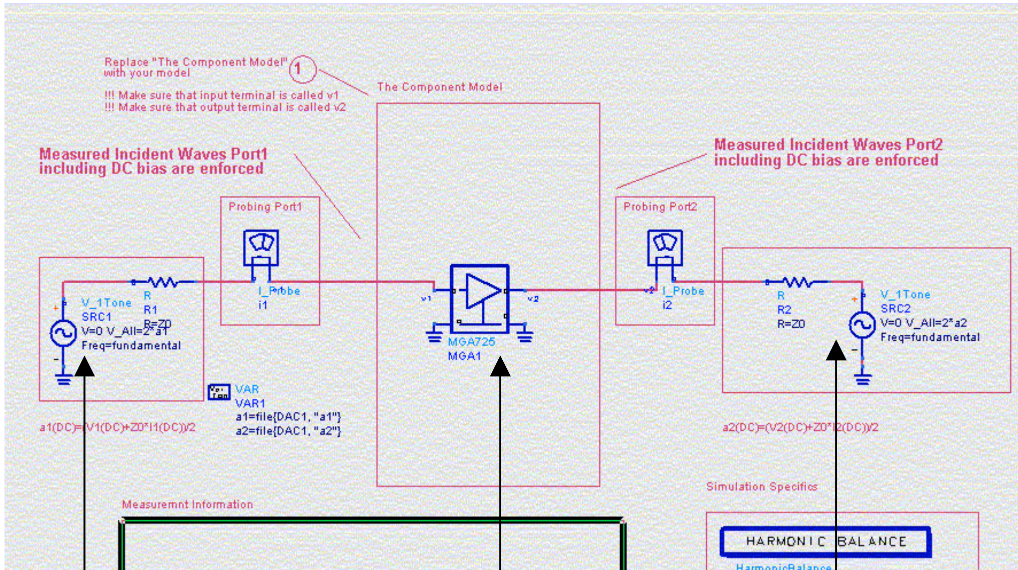
Component Characteristic, like

Incident Power **Delivered Power**

Outline

- Review of S-parameters
- Theory of Large-Signal Network Analysis
- The Large-Signal Network Analyzer
- The Calibration
- Active Component Characterization
  - under CW stimulus
  - under modulation stimulus
  - in non-50 Ohm environment
- Modeling
  - Model verification
  - Measurement-based behavioral model
- Conclusions

Transistor Model Verification in ADS



Measured a_1, including fundamendal and harmonics

Model to Certify

Measured a_2, including fundamendal and harmonics

- The model is brought into **the same state** as the real component
- The simulated response should be equal to the measured response for a good model
- The comparison is done at **the essential data**, common to both: Voltage and Currents

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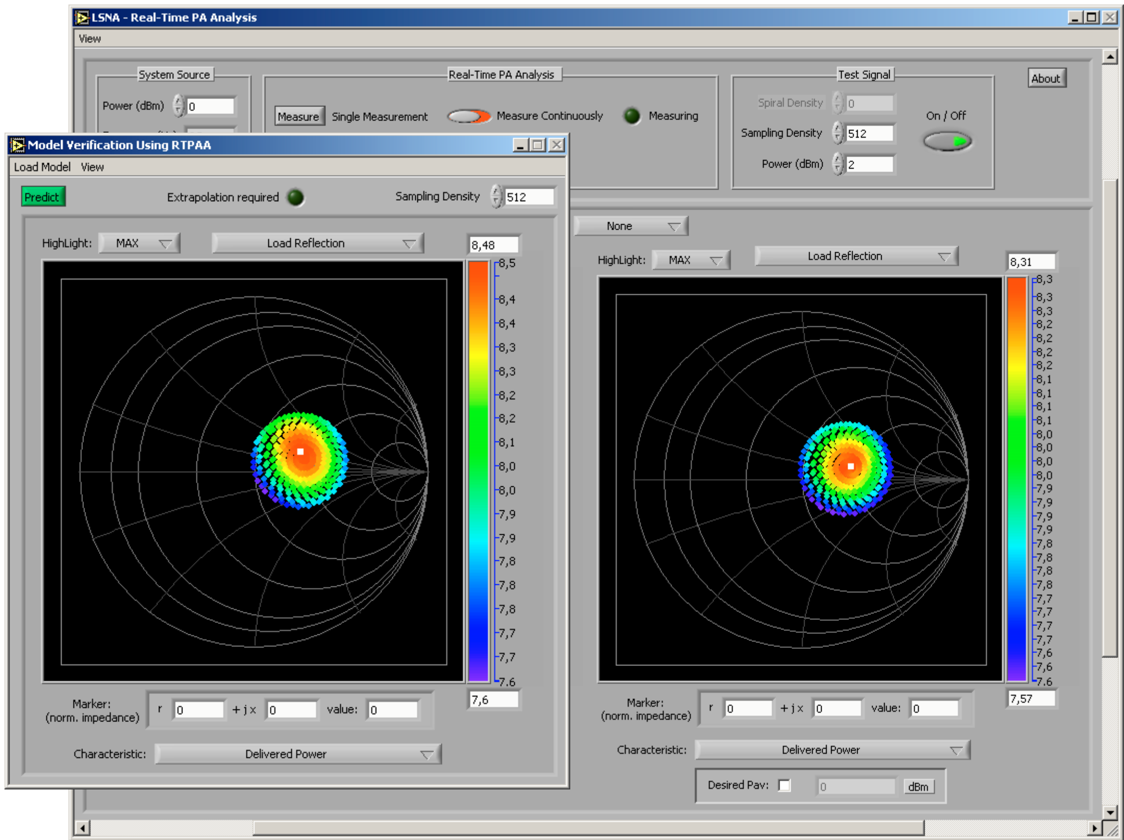
Measurement-based Behavioral Modeling

$$b_1(f_0) = f\left(a_1(f_0), a_2(f_0)\right)$$
$$b_2(f_0) = g\left(a_1(f_0), a_2(f_0)\right)$$

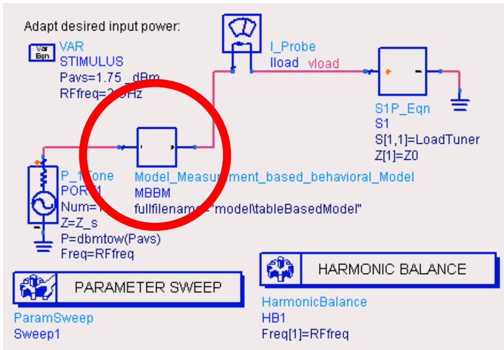
Valid for
- Range of a1
- Closed area on Smith Chart at output

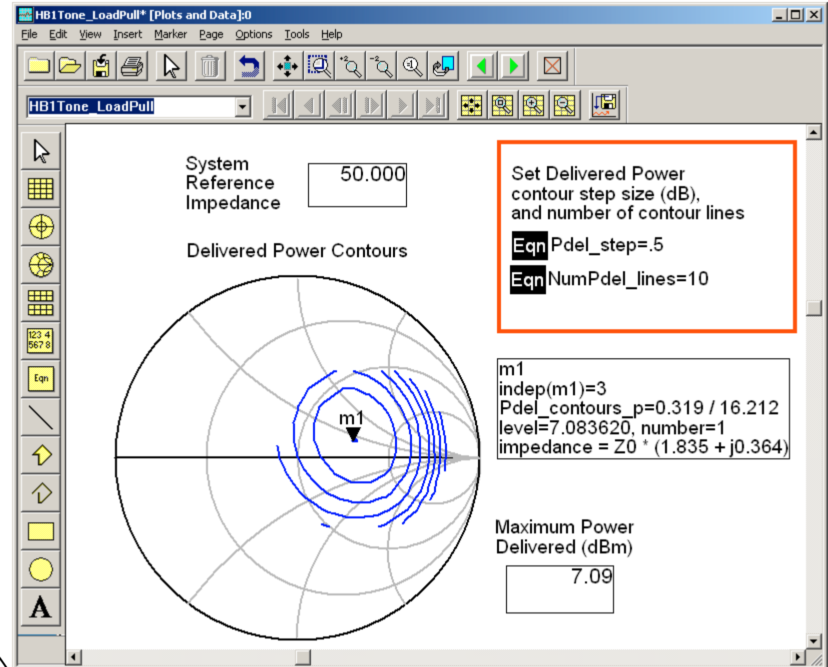
Model Prediction



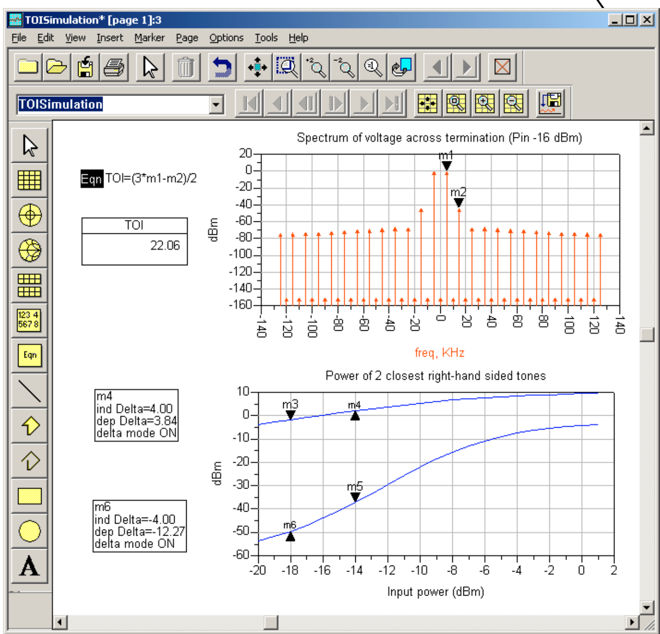
Measurement

Measurement-based Behavioral Model in ADS





Load-pull Simulation with P_{in} = - 5 dBm



… and more …

Third-Order Intercept Point

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Conclusion

- A Network Analyzer for active component characterization has been presented
- It measures the essential information (voltage and currents at component ports) to characterize the nonlinear behavior
  - accurately and completely
  - in a unified way from transistor to system
  - under realistic conditions
- The Network Analyzer is ideal to study the behavior from small-signal to large-signal with one connection using simple and complex signals
- The Network Analyzer is ideal to certify models
- The Network Analyzer is ideal to create behavioral models

Technical information NMDG Engineering Leading beyond S-parameters **http://www.nmdg.be/**

Sales information bsw TestSystems & Consulting AG **http://www.bsw-ag.de/**