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Scattering Functions for Nonlinear Behavioral Modeling in the Frequency Domain

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Fundamentals of Nonlinear Behavioral Modeling: Foundations and Applications
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Purpose

- To convince people that

$$\text{Black Box Modeling} \neq \text{Black Magic Modeling}$$

Outline

- Introduction
- Theoretical Concepts
- Applications
- Practical Measurements
- Link to Simulators
- Conclusions

Introduction

- In the late 80’s a need was recognized to “Go beyond S-parameters”
- This implied the development of
  - A mathematical theory to describe certain well defined classes of nonlinear D.U.T. behavior
  - New automated and accurate instrumentation and measurement techniques
- Scattering Functions are one possible solution

Theoretical Concepts

Scattering Functions → Quantities are Waves

for

Nonlinear Behavioral Modeling → Functional Relationship

in the

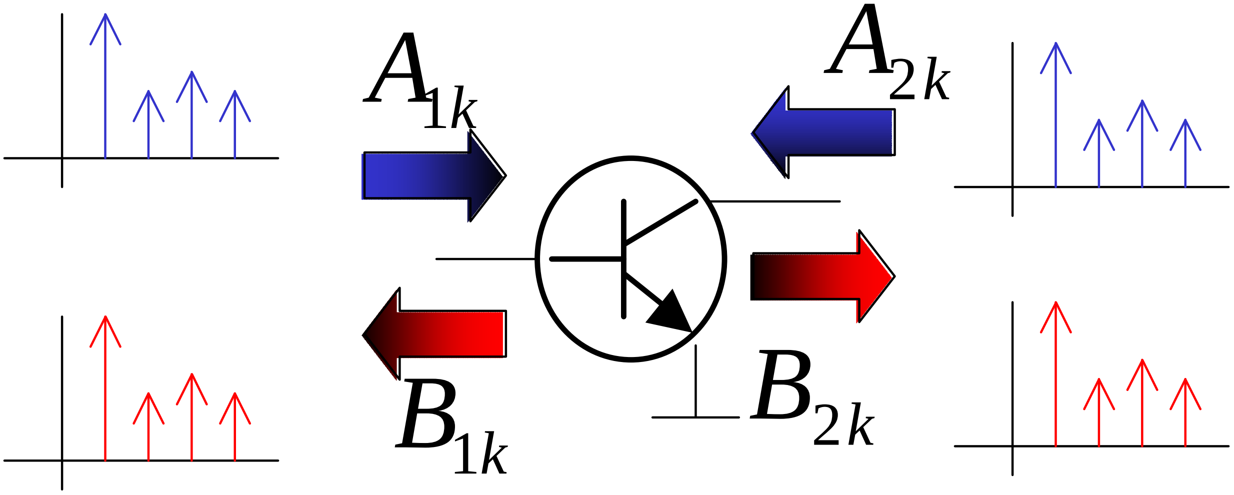
Frequency Domain → Input and Output are Discrete Tone Signals

Quantities are Traveling Voltage Waves

$$\begin{pmatrix} V \\ \\ I \end{pmatrix} \rightarrow \begin{pmatrix} A^{(Z)} \\ \\ B^{(Z)} \end{pmatrix} = \begin{pmatrix} \dfrac{V + ZI}{2} \\ \\ \dfrac{V - ZI}{2} \end{pmatrix}$$

Default value of Z = 50 Ohm (classic S-parameters)

Notation - Graphical Illustration



$$B_{1k} = F_{1k}(A_{11}, A_{12}, ..., A_{21}, A_{22}, ...)$$
$$B_{2k} = F_{2k}(A_{11}, A_{12}, ..., A_{21}, A_{22}, ...)$$

Phase Normalization

- In order to simplify the mathematics we will use "phase normalized" quantities
- This is especially useful since harmonic frequencies are present
- We will use the dominant large-signal A_{11} component as our phase reference (most useful for many applications)

Phase Normalization: Mathematics

- We define a reference phasor: $P = e^{j\varphi(A_{11})}$

- We define phase normalized quantities:

$$A_{mk}^{N} = A_{mk} P^{-k} \qquad B_{mk}^{N} = B_{mk} P^{-k}$$

- Special case: $A_{11}^{N} = \left| A_{11} \right|$

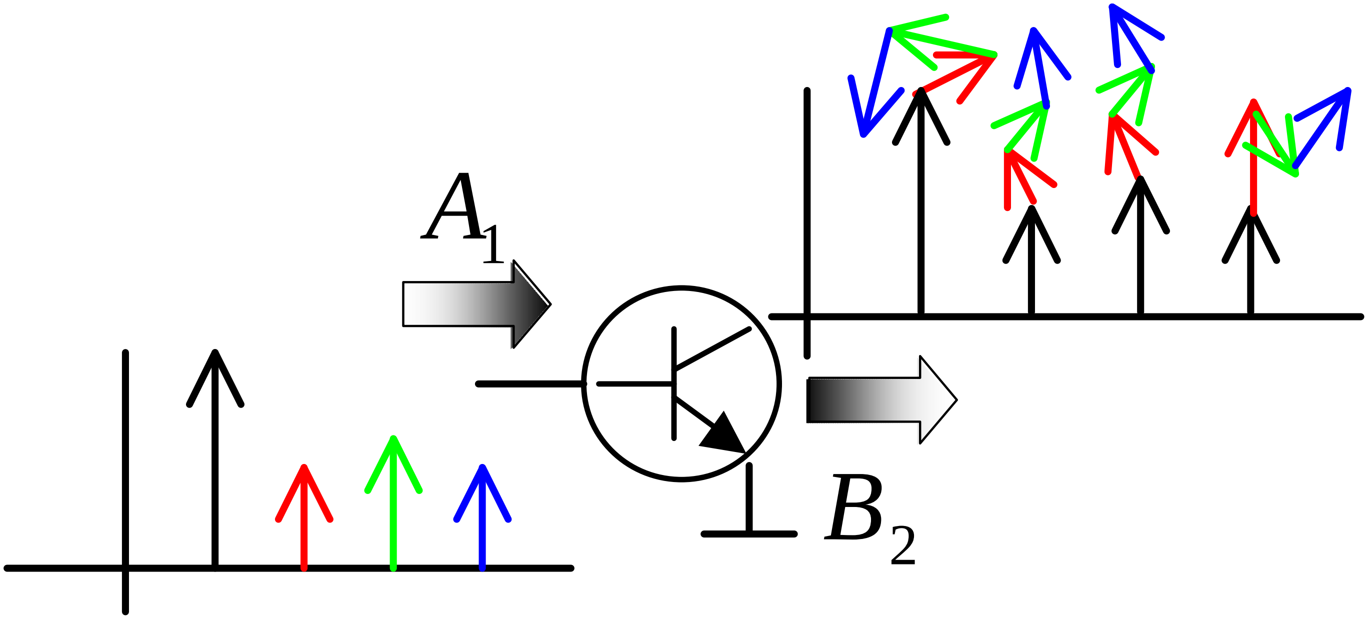
Harmonic Superposition Principle

- In general superposition cannot be used to describe the functional relationship between the spectral components

$$F\left(A + A'\right) \neq F(A) + F(A')$$

- The superposition principe can be used for relatively small components, like e.g. harmonics

Harmonic Superposition: Illustration



Basic Mathematical Equation

$$B_{mk}^{N} = \sum_{nh} S_{mknh}(A_{11}^{N}) A_{nh}^{N} + \sum_{nh} S'_{mknh}(A_{11}^{N}) A_{nh}^{N\,*}$$

- A_{11} assumed to be the only large-signal component
- Superposition assumed to be valid for other A_{nh}
- The notation A* means the complex conjugate of A
- S and S' are called the scattering functions
- Note that $S'_{mk11} = 0$

Applications: Compression and AM-PM conversion

- Only considering B_{21} and A_{11} results in

$$B_{21}^{N} = S_{2111}(A_{11}^{N})A_{11}^{N}$$

- This can be rewritten as

$$S_{2111}(|A_{11}|) = \frac{B_{21}}{A_{11}}$$

- $S_{2111}(|A_{11}|)$ represents the compression and AM-PM conversion characteristic

Large-Signal Input Match

- Only considering B_{11} and A_{11} results in

$$B_{11}^{N} = S_{1111}(A_{11}^{N})A_{11}^{N}$$

- This can be rewritten as

$$S_{1111}(|A_{11}|) = \frac{B_{11}}{A_{11}}$$

- $S_{1111}(|A_{11}|)$ represents the large-signal input reflection coefficient

Hot S_{22}

- Considering B_{21}, A_{21} and A_{11} results in

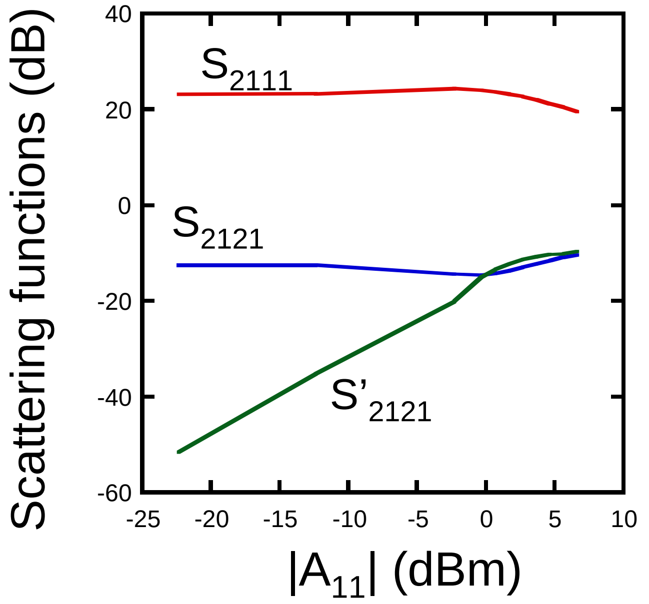
$$B_{21}^{N} = S_{2111}(A_{11}^{N})A_{11}^{N} + S_{2121}(A_{11}^{N})A_{21}^{N} + S'_{2121}(A_{11}^{N})A_{21}^{N^{*}}$$

- Multiplying both sides with P results in

$$B_{21} = S_{2111}(|A_{11}|)A_{11} + S_{2121}(|A_{11}|)A_{21} + S'_{2121}(|A_{11}^{N}|)P^{2}A_{21}^{*}$$

- The combinaton of S_{2121} and S'_{2121} are a scientifically sound format for "Hot S_{22}"

Measurement Example



- Note that the amplitude of S'_{2121} becomes arbitrary small for $|A_{11}|$ going to zero

Harmonic Distortion Analysis

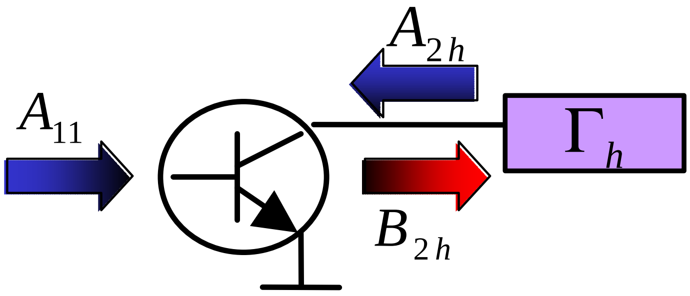
- Only considering A_{11} and B_{2k} one can calculate the harmonic distortion as a function of $|A_{11}|$

$$B_{21} = S_{2111}(|A_{11}|)A_{11}$$

$$B_{22} = S_{2211}(|A_{11}|)A_{11}P$$

$$B_{23} = S_{2311}(|A_{11}|)A_{11}P^2$$

Harmonic Loadpull Behavior

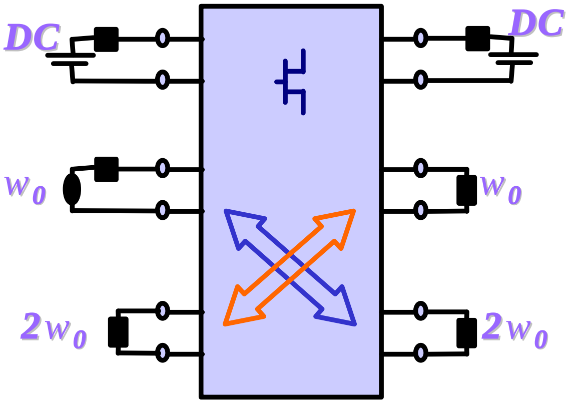


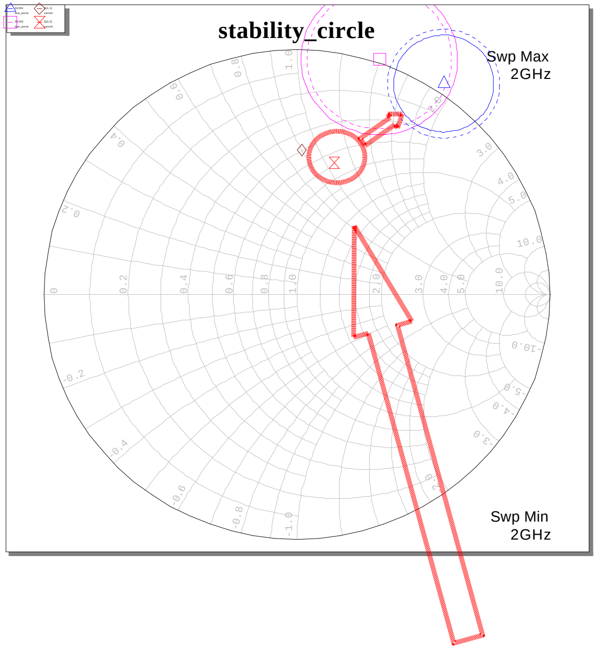
$$B_{2k}^N = \sum_h S_{2k2h}(A_{11}^N)A_{2h}^N + \sum_h S'_{2k2h}(A_{11}^N){A_{2h}^N}^*$$

$$A_{2h}^N = \Gamma_h B_{2h}^N$$

- Solve the set of equations (linear in the real and imaginary parts of A_{2h} and B_{2h})

New Stability Circles for Multiplier Design





Stability is not ensured

Research performed by
Prof. Giorgio Leuzzi
(Universita dell'Aquila, Italy)

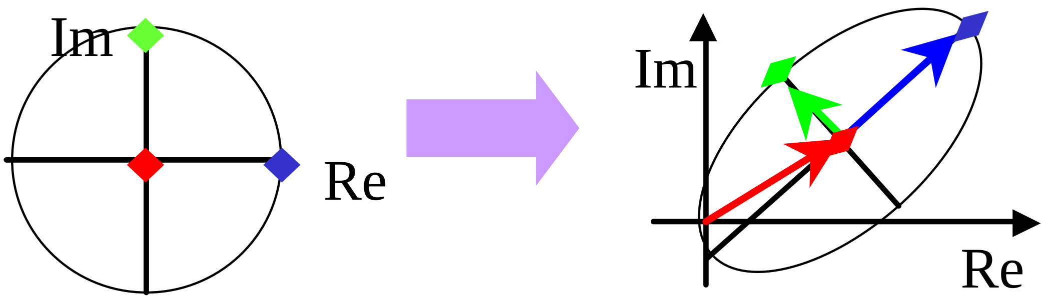
Practical Measurement: Experiment Design Concept

- Simple example: S_{2111}, S_{2121} and S'_{2121}

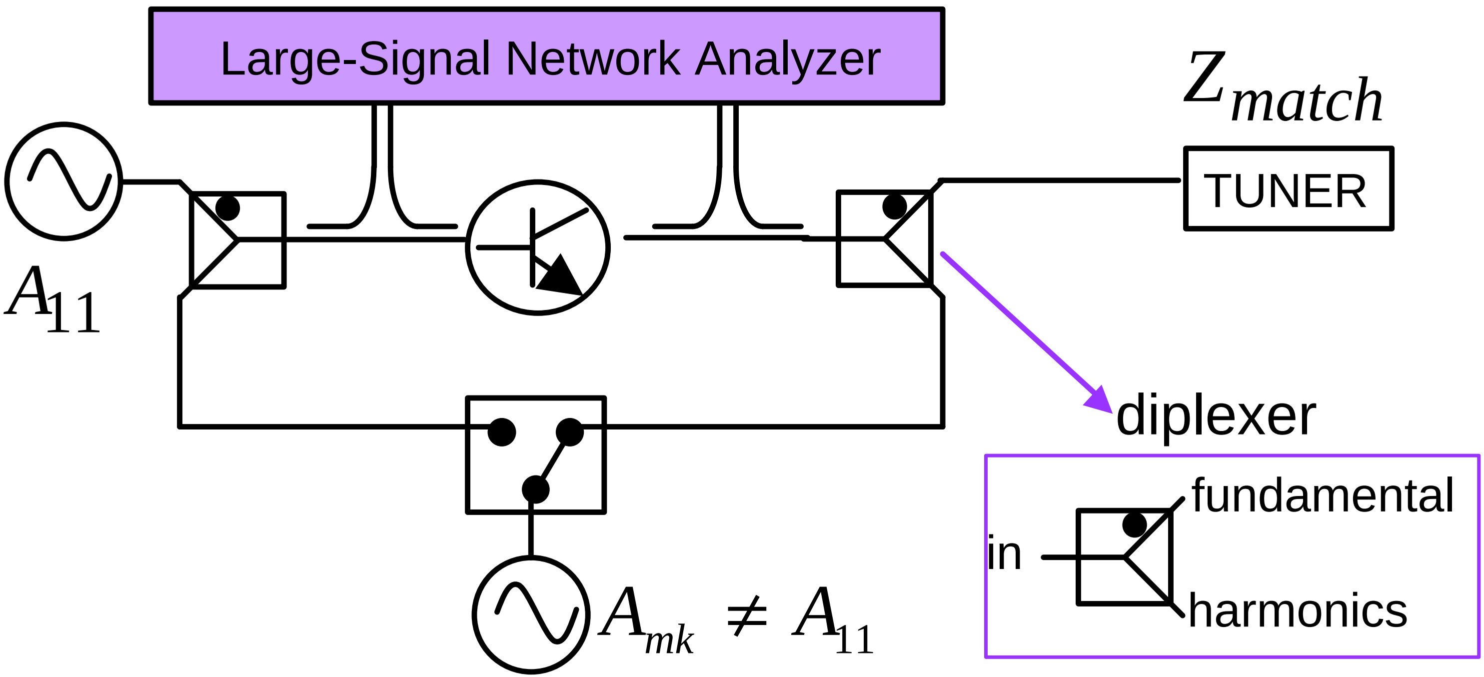
$$B_{21}^{N} = S_{2111}(A_{11}^{N})A_{11}^{N} + S_{2121}(A_{11}^{N})A_{21}^{N} + S'_{2121}(A_{11}^{N})A_{21}^{N^{*}}$$

- Perform 3 independent experiments

Input A_{21} Output B_{21}



Typical Measurement Setup



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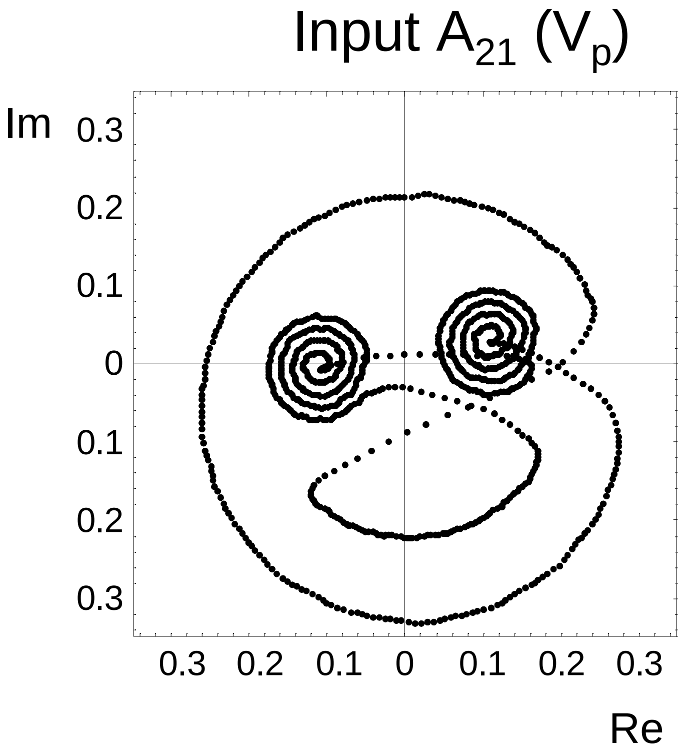
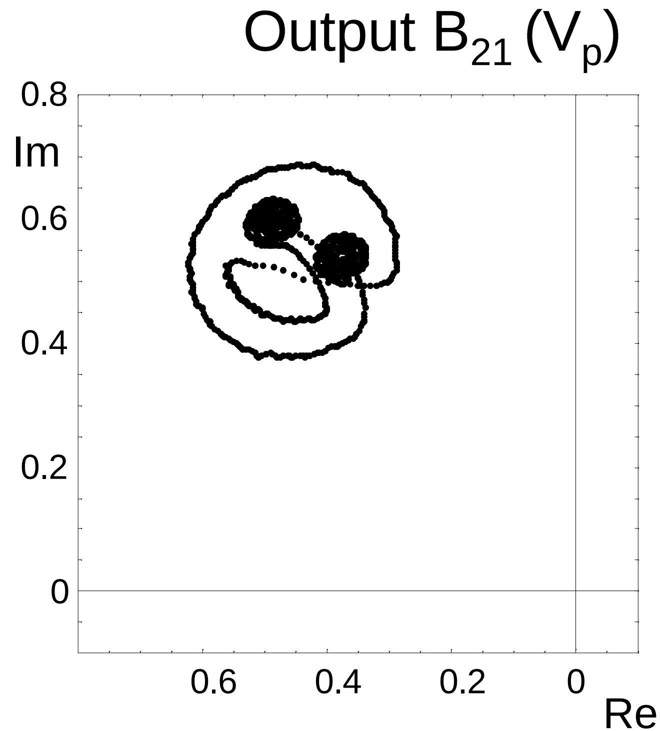
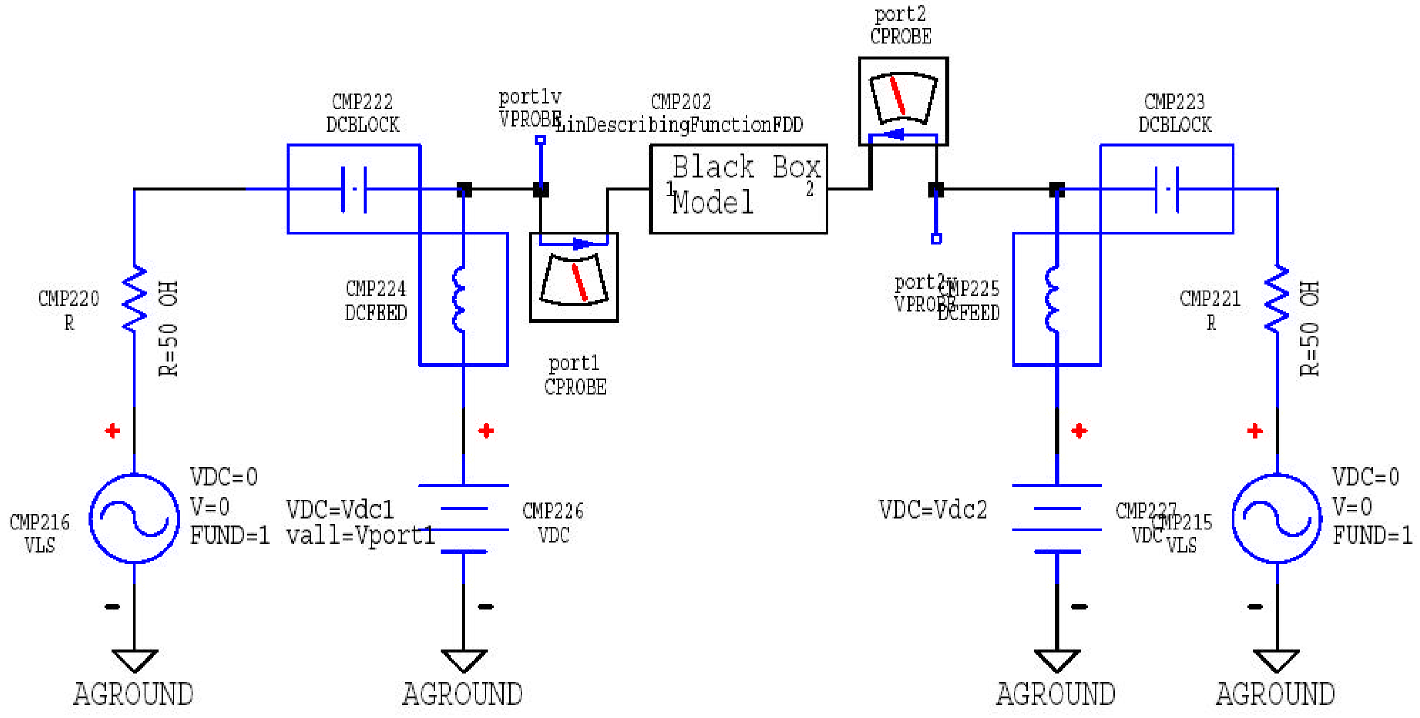
Measurement Example





Link to Harmonic Balance Simulators

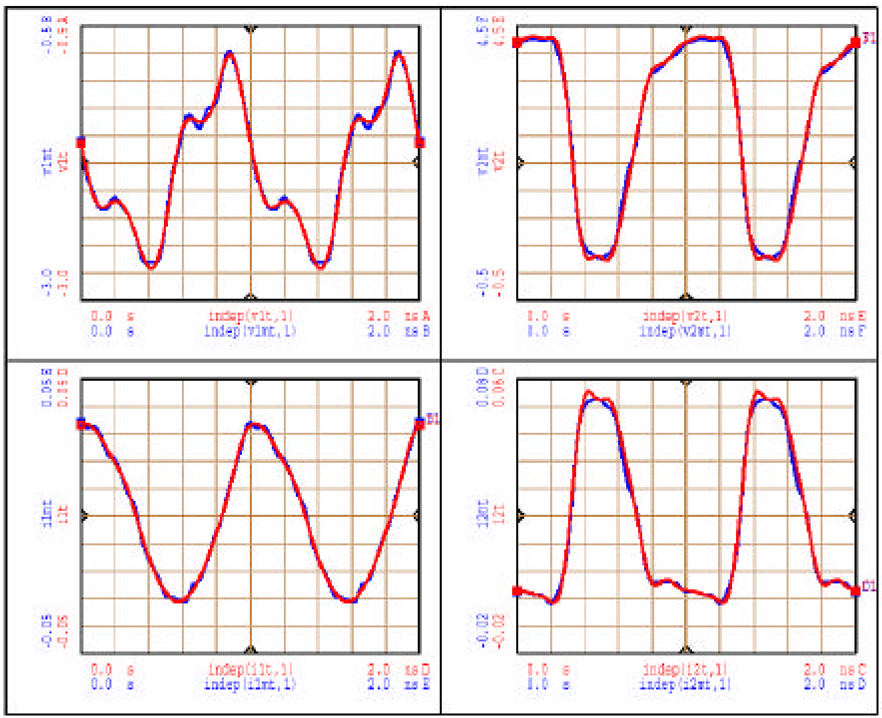


Simulated Model versus Measurements

Powertransistor Waveforms

Gate Voltage

Drain Voltage



Gate Current

Drain Current

Conclusions

- scattering functions are a Black Box modeling approach without Black Magic
- They can accurately describe many classic concepts like e.g. AM-PM, compression, harmonic distortion, Hot S_{22}, loadpull,…
- They can automatically be measured using a Large-Signal Network Analyzer
- They are compatible with harmonic balance simulators