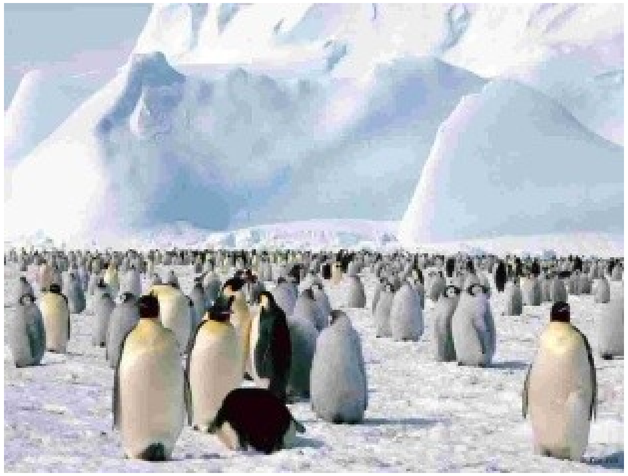
NMDG
LEADING BEYOND S-PARAMETERS

S-functions

“The S-parameters for nonlinear components”

- Measure, Model, Verify, Simulate -



An application in ICE

March 2011

Outline

- Why S-functions? What is the impact?
- S-functions, the “S-parameters” for all nonlinear applications?
- S-functions: Key Benefits
- Theory: from S-parameters to S-functions
- Applicability and Assumptions of S-functions
- Confidence in S-functions
- S-function Extraction and Verification Tool
- Deployment of S-functions in ADS and MWO / VSS
- Strengths and Key Capabilities
- References
- Conclusion

Why S-parameters?

DESIGN

- Complete characterization of a component in linear mode of operation
  - Derive insertion loss, return loss, gain, …
- S-parameters enable system-level interpretation of behavior of the component
  - Low – pass filtering, high reflective, ...
- S-parameters enable design in conjunction with other circuits

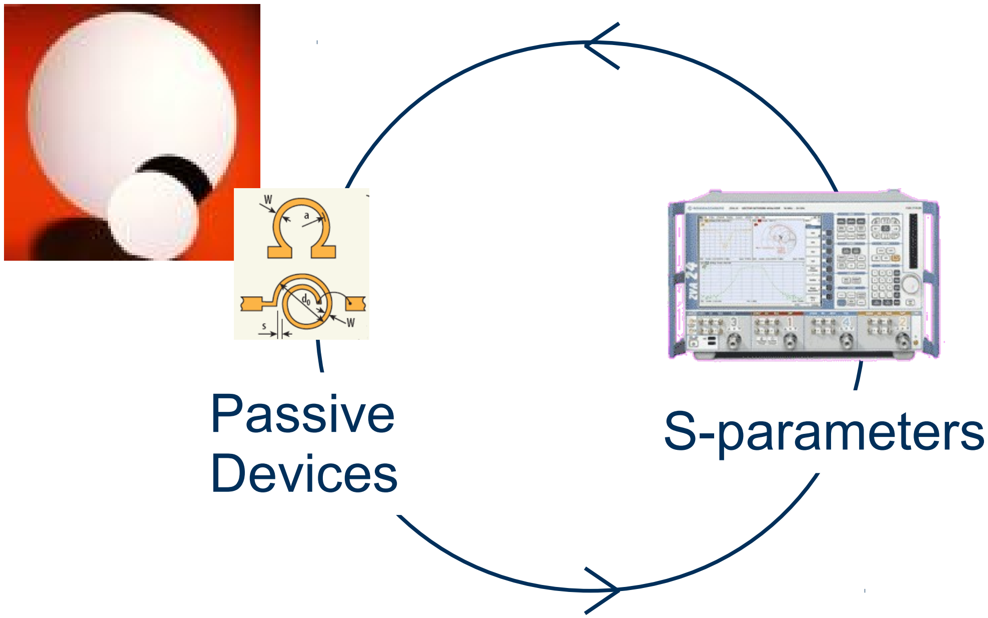
TEST in Manufacturing

- S-parameters can be extracted for the designed circuit
- The S-parameters can be measured for the manufactured circuit and can be compared

S-parameters close the characterization, design and test loop

S-parameter Design- and Test-Cycle for Linear Applications

At the Foundry



Passive Devices

S-parameters

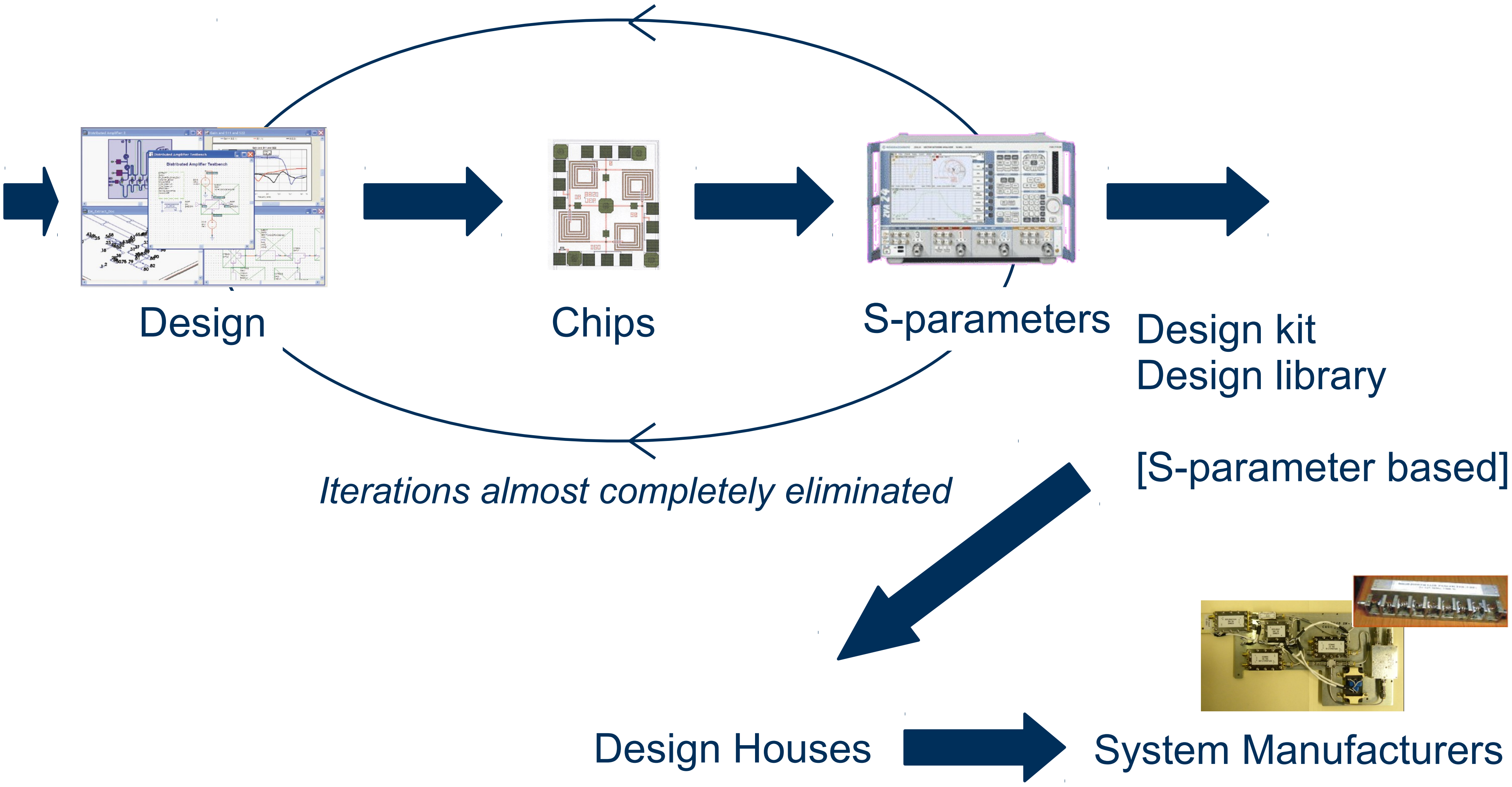
Design kit
Design library

[S-parameter based]

Semiconductor Manufacturer

S-parameter Design- and Test-Cycle for Linear Applications

At the Semiconductor Manufacturer



Design

Chips

S-parameters

Design kit
Design library

[S-parameter based]

Iterations almost completely eliminated

Design Houses

System Manufacturers

Beyond S-parameters???

- **S-parameters**, the behavioural model for “linear” applications

  - Components in linear mode of operation **only**
    - Filters
    - Transistors under small signal of excitation
    - ...

  - Their success is based on its **uniform** approach for **linear** RF and microwave problems both to measure and to simulate

- **What about components in nonlinear mode of operation?**

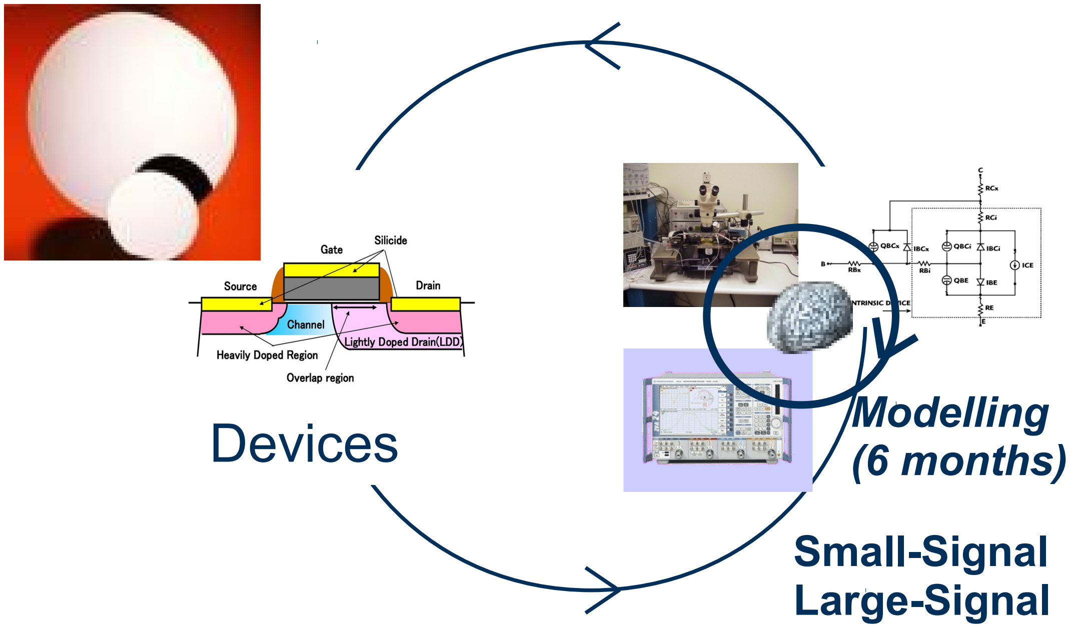
  - No **uniform** approach for nonlinear RF and microwave problems

  - There is a lot of “trial and error” or “measure – tweak”

  - S-parameters are used mainly during device modelling in conjunction with a lot of model expertise to go from small-signal to large-signal

“Trial-Error” Design- and Test-Cycle for “Nonlinear” Applications

At the Foundry



Devices

Modelling (6 months)

Small-Signal
Large-Signal
Load-Pull
Mathematics…

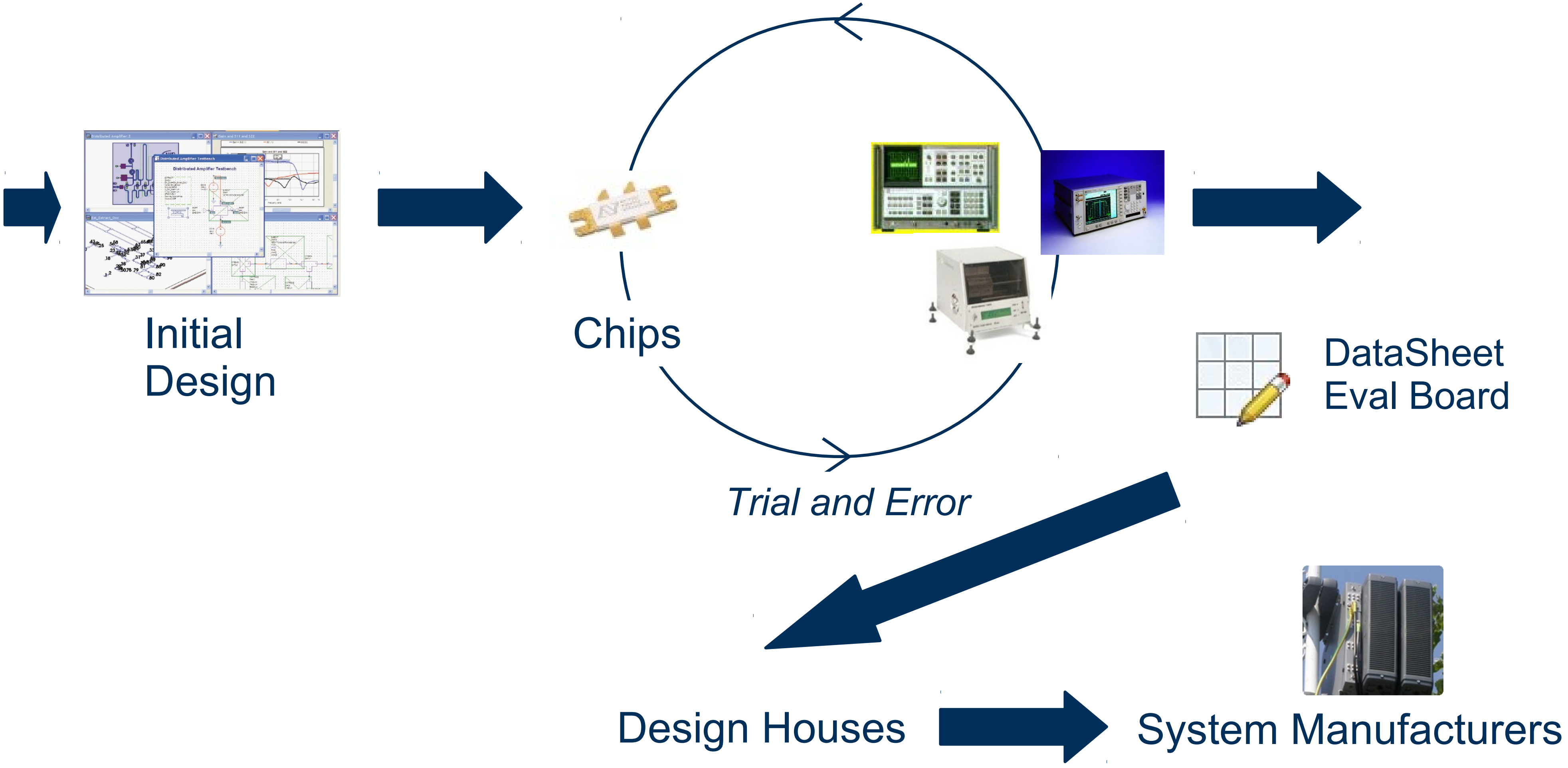
Design kit
Design library

Semiconductor Manufacturer

“Trial-Error” Design- and Test-Cycle for “Nonlinear” Applications

At the Semiconductor Manufacturer

- Models do not meet the needs of application
- To time costly to develop own models
- Wafer fabs cannot worry about specific problems



Initial Design

Chips

Trial and Error

DataSheet
Eval Board

Design Houses

System Manufacturers

The Magic ...

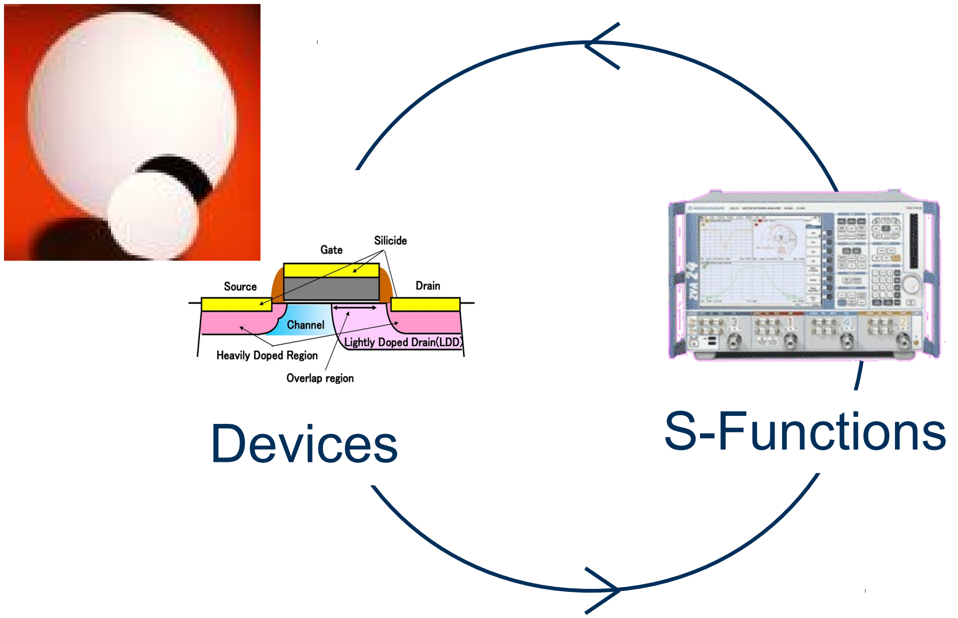
S-Parameters

S-

S-functions

The S-function Design- and Test-Cycle for Active Devices

At the Foundry



Devices

S-Functions

Design kit
Design library

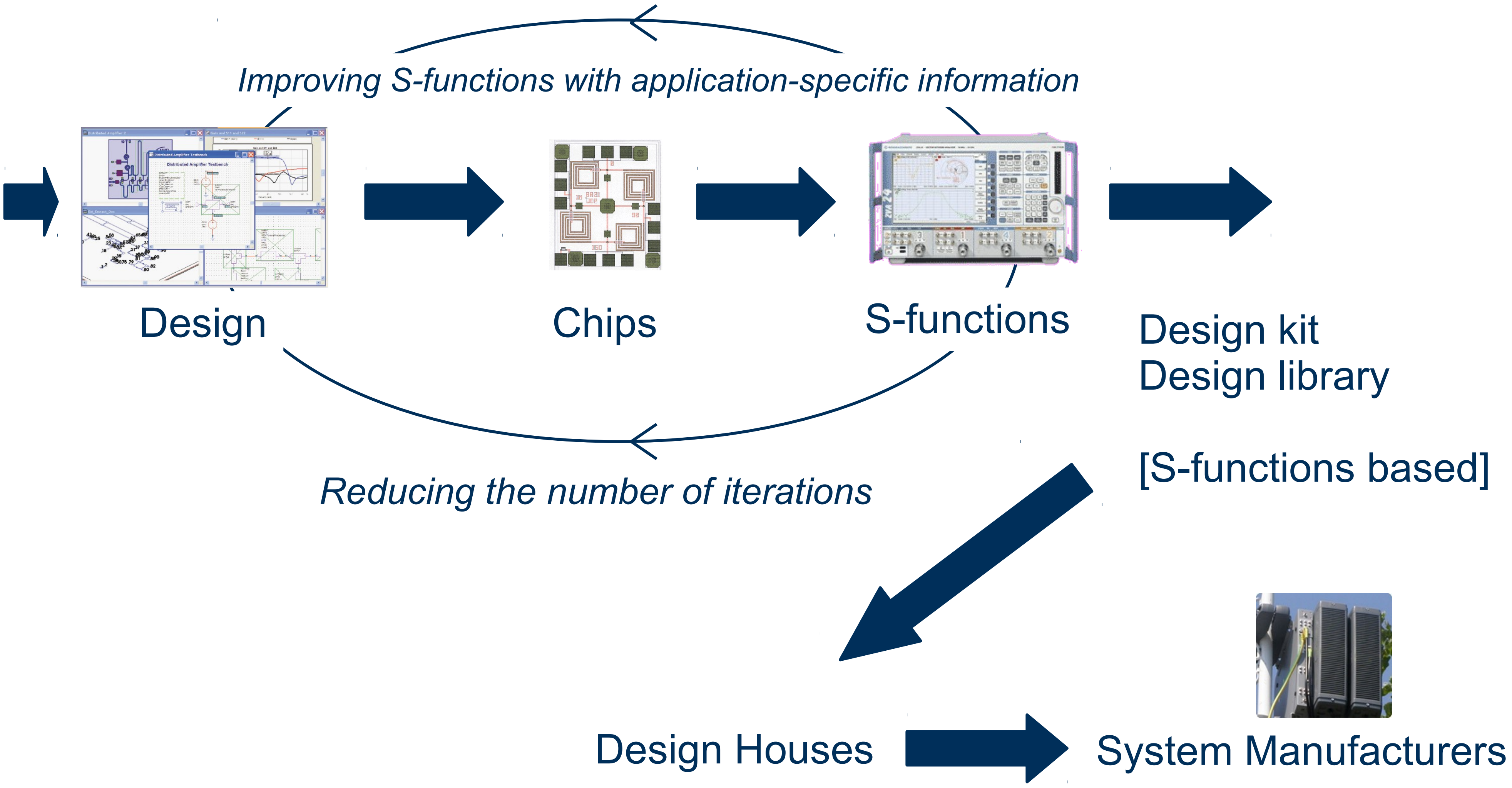
[S-functions based (*)]

Semiconductor Manufacturer

(*) S-functions for different applications

The S-function Design- and Test-Cycle for Active Devices

At the Semiconductor Manufacturer



Improving S-functions with application-specific information

Design

Chips

S-functions

Design kit
Design library

[S-functions based]

Reducing the number of iterations

Design Houses

System Manufacturers

Why S-functions? Adopting the S-parameter paradigm

DESIGN

- "Complete" characterization of a component in nonlinear mode of operation for specific applications under a relevant set of conditions
  - Derive "insertion loss", "return loss", "gain", "mismatch", conversion coefficients

- S-functions enable system-level interpretation of behaviour of the component
  - Power- dependent Low – pass filtering, power conversions, …
  - Ideal for dividers, multipliers and mixers

- S-functions enable design in conjunction with other circuits
  - When the signals are limited to the relevant set of conditions

TEST in Manufacturing

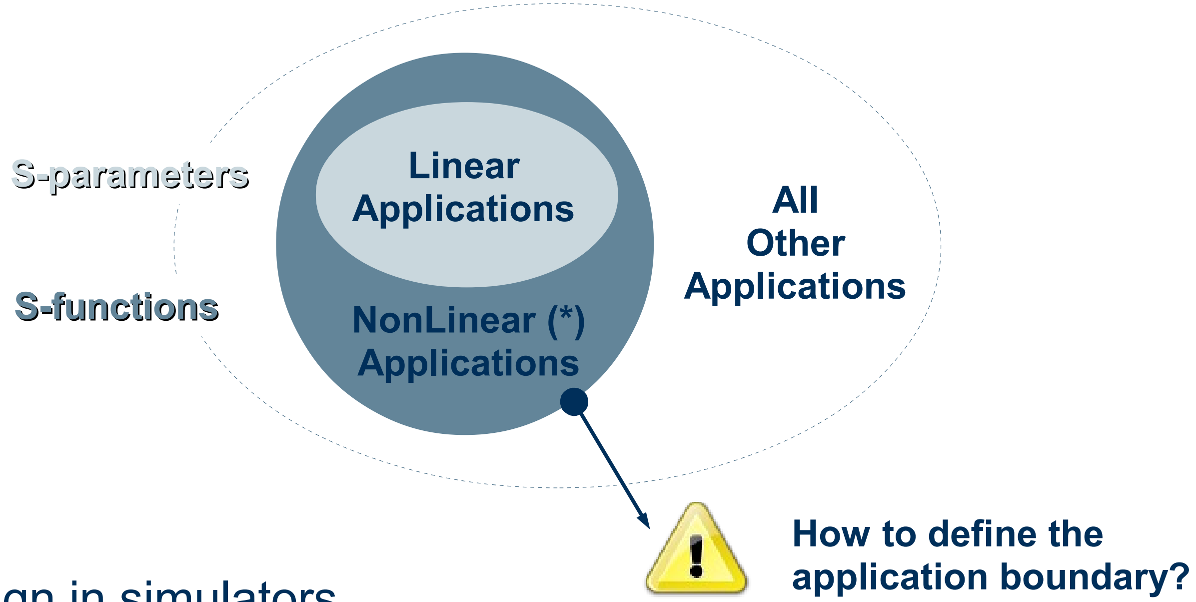
- S-functions can be extracted for the designed circuit

- The S-functions can be measured for the manufactured circuit and can be compared

S-functions close the characterization, design and test loop

S-Functions, the “S-parameters” for nonlinear applications?

- **S-Functions**, the behavioural model for nonlinear applications
  - Deal with a subset of nonlinear RF and microwave phenomena in a **uniform way** as a natural extension of S-parameters
  - Will not solve “all” nonlinear problems
  - Can be “measured”
  - Can be used for design in simulators
  - Can be used for test to compare with realizations in simulator



How to define the application boundary?

(*): Nonlinear behaviour determined by a small number (e.g. 2) of tones

S-Functions – Key Benefits

S-Functions are for nonlinear applications ...

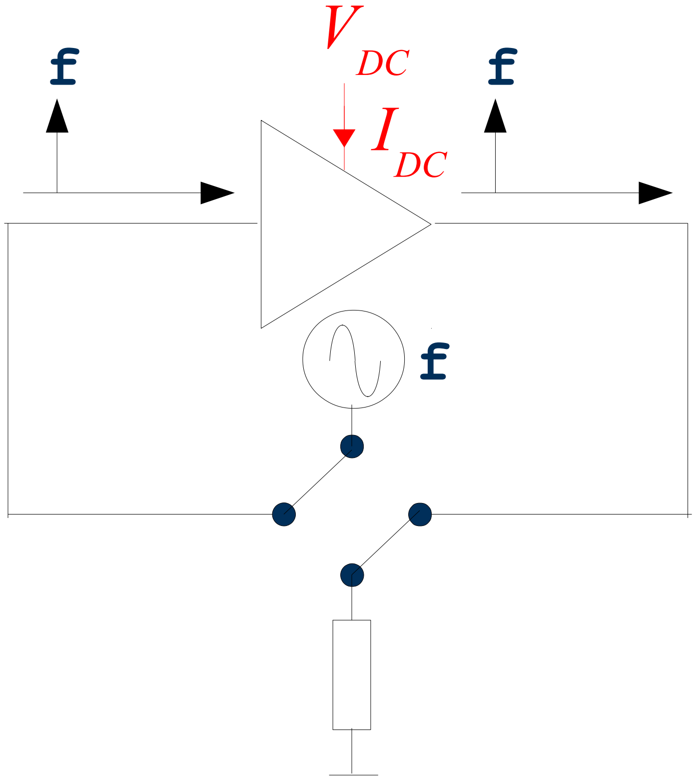
... what S-parameters are for linear applications

- **Simplify the use of HF components and circuits**
  - Complement limited data sheets with more complete system-level models
  - Complement evaluation boards, enabling upfront more realistic simulations
- **Improve and speed up the design and test process**
  - Adequate replacement when classic models fail
  - Simulate with a behavioural model, optimized for your design problem
  - Same Look and Feel as S-parameters: measure, model, <u>verify</u> and simulate
  - Verify the realized circuit with S-functions against the simulation during test
- **Shorter time to market for component manufacturers and buyers**

From S-parameters to S-functions

S-parameters measured at fixed DC bias point

→ $S(f)$



Keep signal small to stay in a linear mode of operation

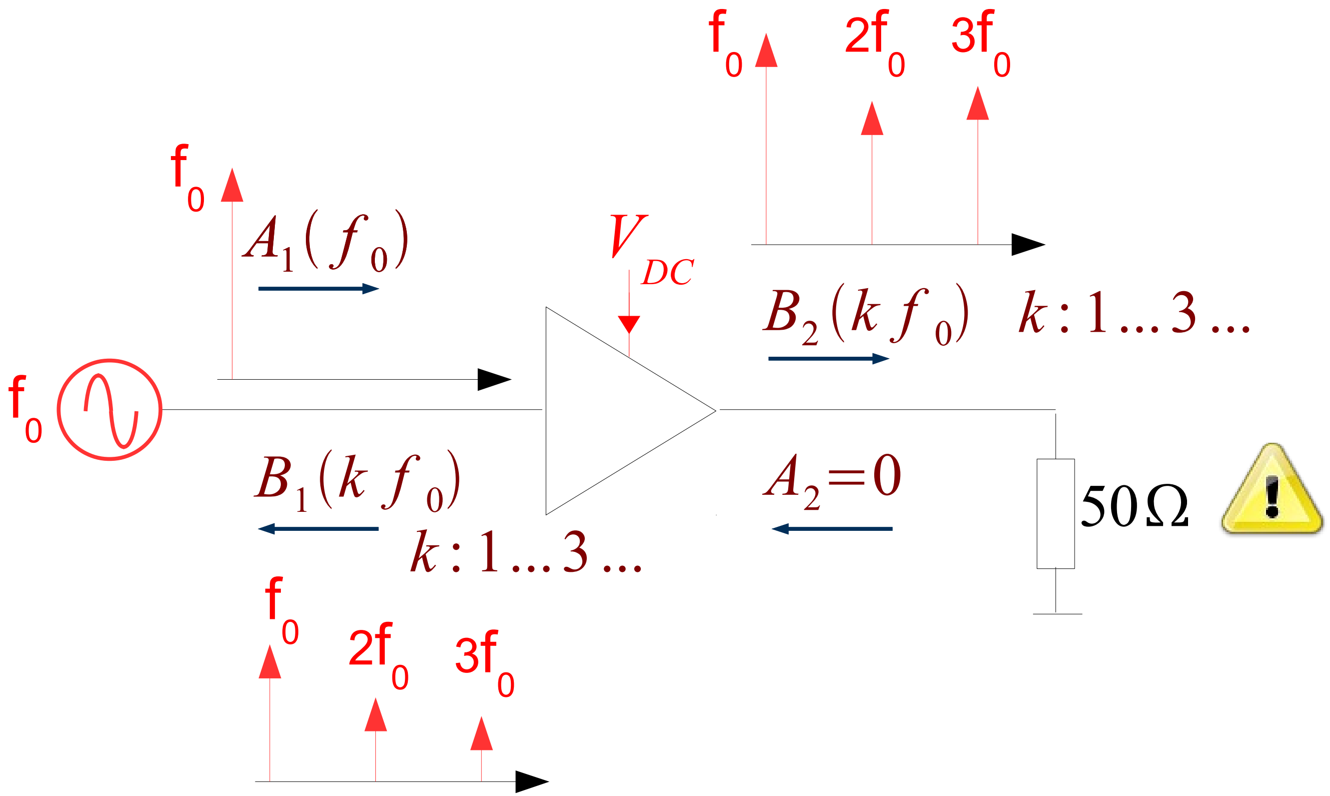
S-parameters measured at different DC bias points

Linear → $S(V_{DC}; f)$

Nonlinear → $I_{DC}(V_{DC})$

Remark: for the sake of intuitive explanation, mathematics is not 100% correct

From S-parameters to S-functions

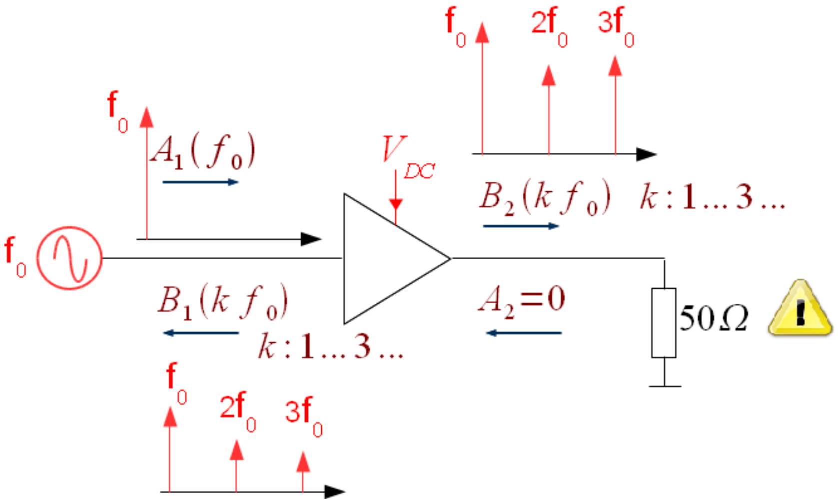


Simple model and “easy” to measure

Nonlinear ➡ $B_m(n f_0)=F_{mn}(V_{DC}, f_0, |a_1(f_0)|)$

Nonlinear ➡ $I_{DC}=H(V_{DC}, f_0, |a_1(f_0)|)$

From S-parameters to S-functions



Simple model and “easy” to measure

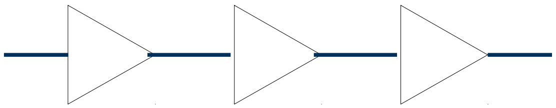
$$B_m(n\,f_0)=F_{mn}(V_{DC},f_0,|a_1(f_0)|)$$

$$I_{DC}=H(V_{DC},f_0,|a_1(f_0)|)$$

- AM-AM
- AM-PM
- Harmonic Distortion

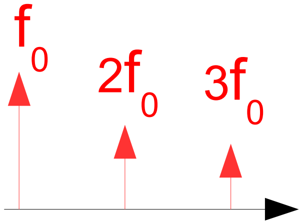
But not useful in the real world

- S-functions should be able to predict cascades



Input contains harmonics !!

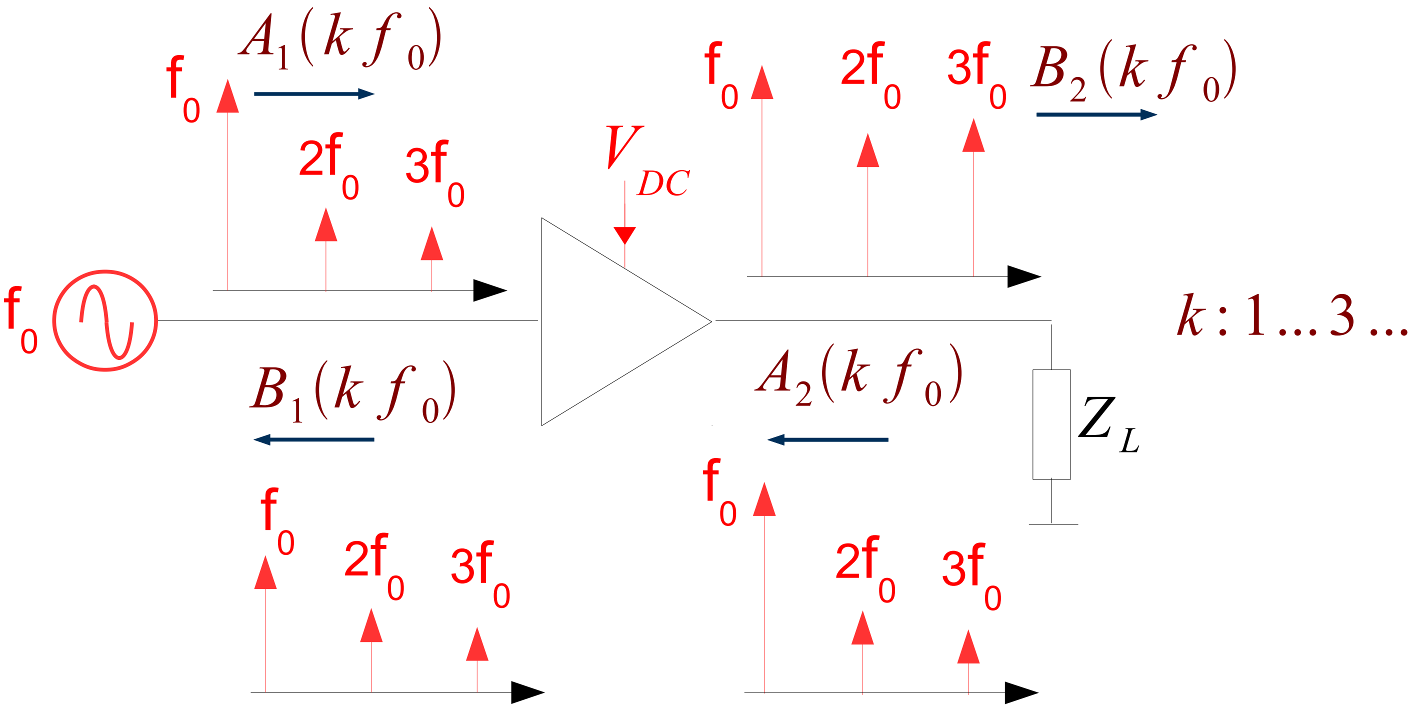
- “Easy” to measure .... not in reality
  - Harmonic distortion of source
  - Imperfect match at input and output



$A_1(k\,f_0)$

$A_2(l\,f_0)$

From S-parameters to S-functions



$$B_m(n f_0) = F_{mn}(V_{DC}, f_0, |a_1(f_0)|)$$

$$I_{DC} = H(V_{DC}, f_0, |a_1(f_0)|)$$

"Simple" model extension ⇓

$$B_m(n f_0) = F_{mn}(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of } (a_i(j f_0)))$$

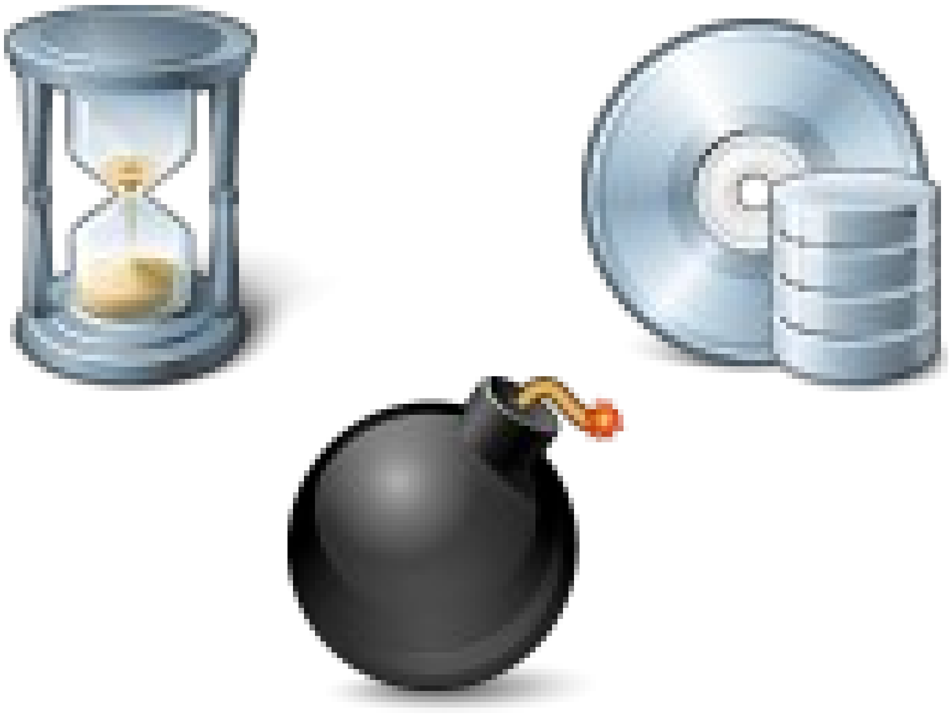
$$I_{DC} = H(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of } (a_i(j f_0)))$$

From S-parameters to S-functions

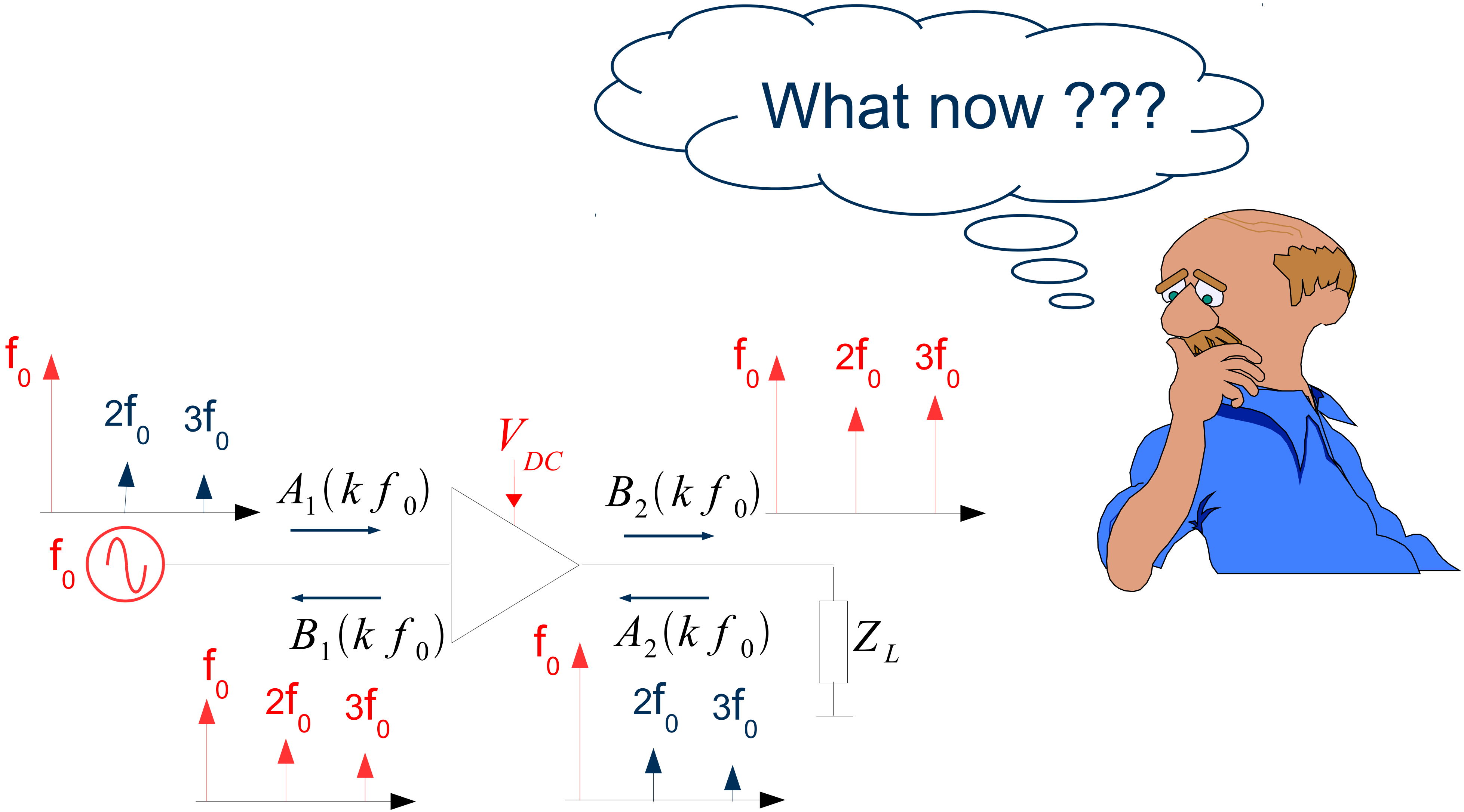
$$B_m(n f_0)=F_{mn}(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of}\,(a_i(j f_0)))$$

$$I_{DC}=H(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of}\,(a_i(j f_0)))$$

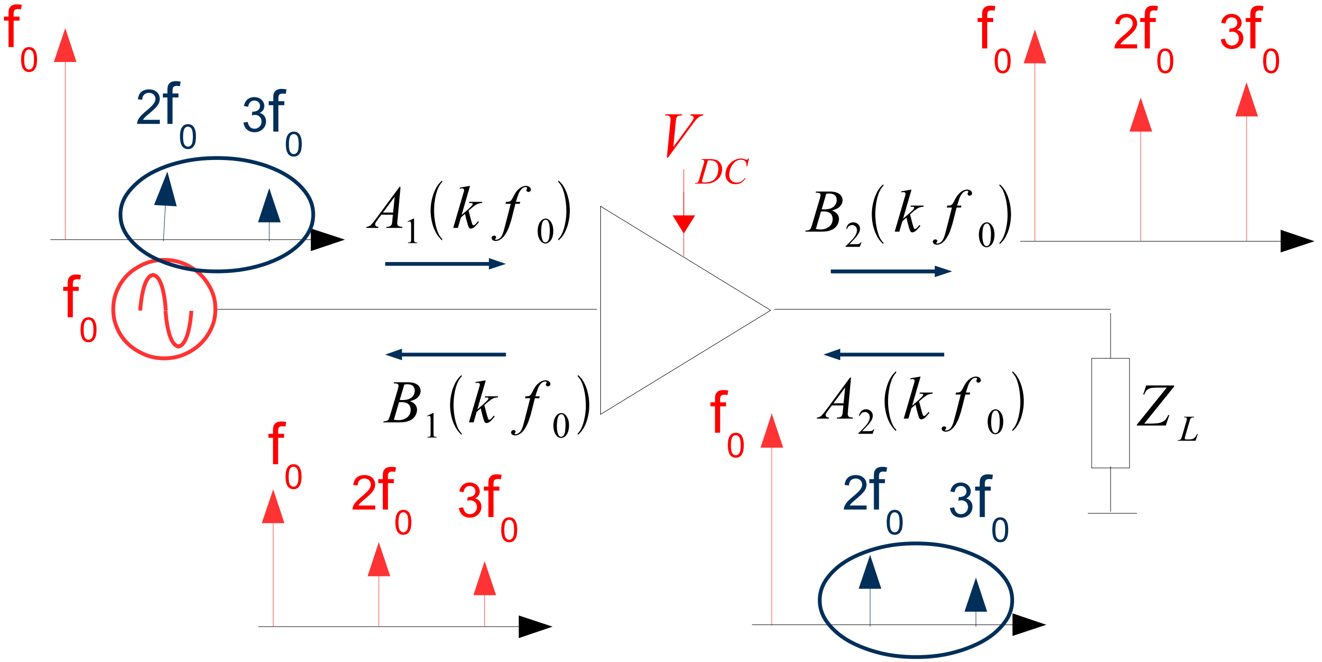
⚠ Huge number of combinations with sweeps in amplitude and phase



From S-parameters to S-functions



From S-parameters to S-functions

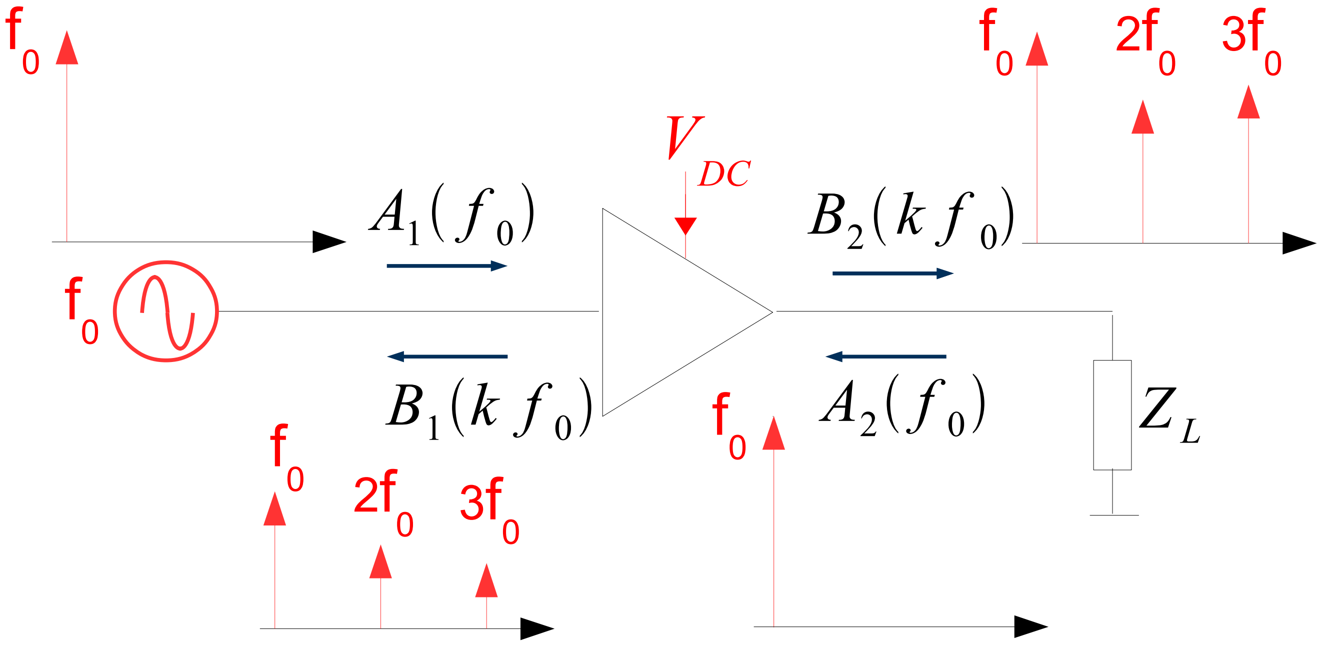


In many cases : $A_1(k f_0), A_2(k f_0)$ with $k > 1$ SMALL

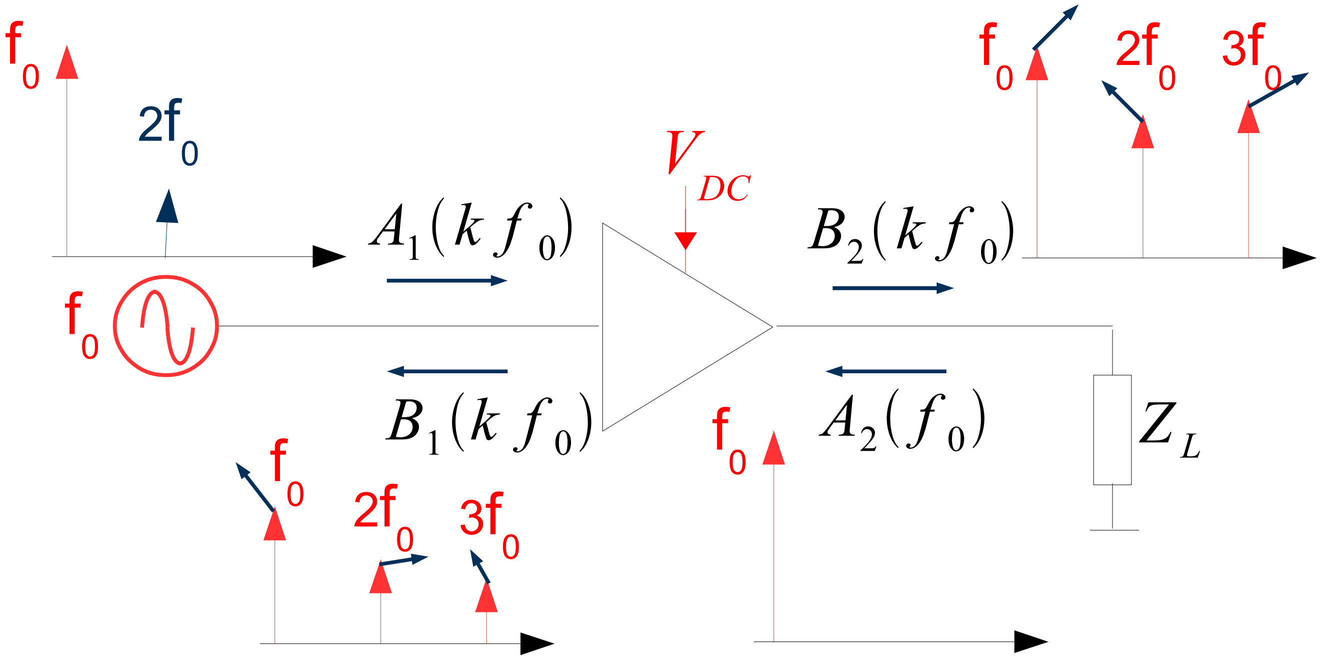
⇨ Linearize equations in $A_1(k f_0), A_2(k f_0)$ with $k > 1$

From S-parameters to S-functions

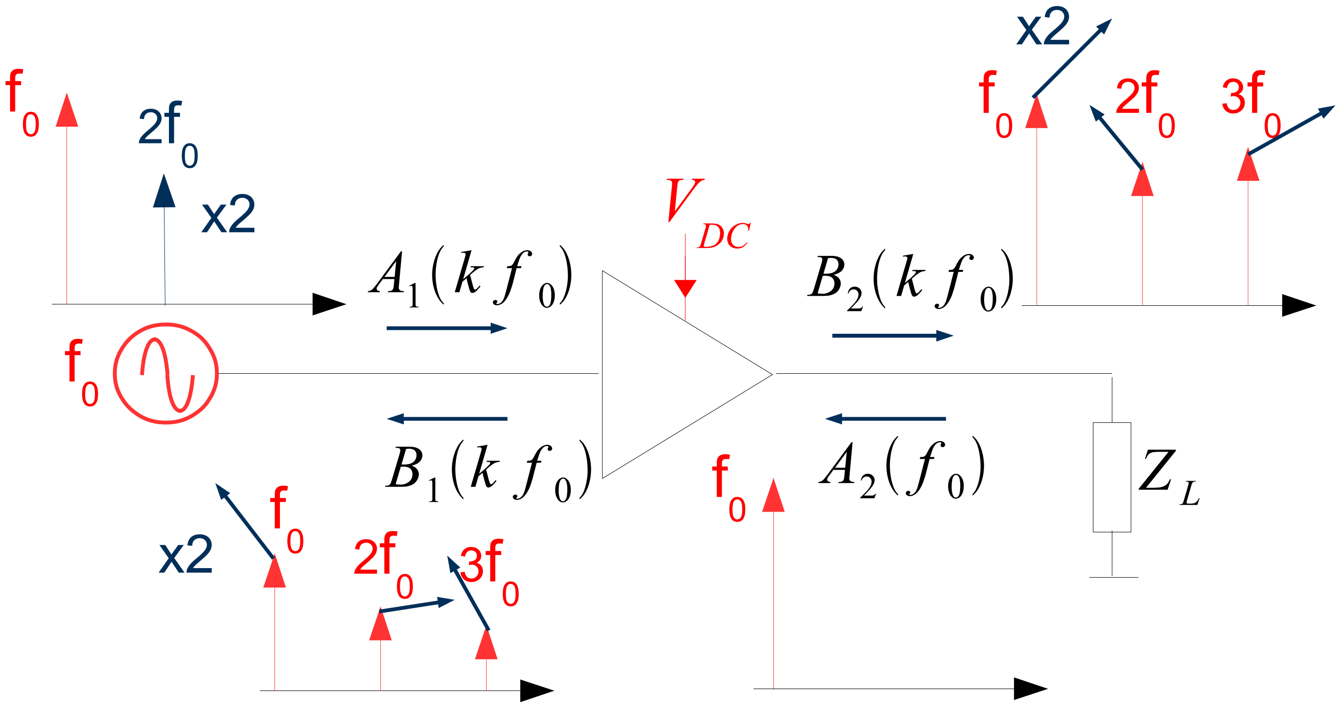
The intuitive approach



From S-parameters to S-functions



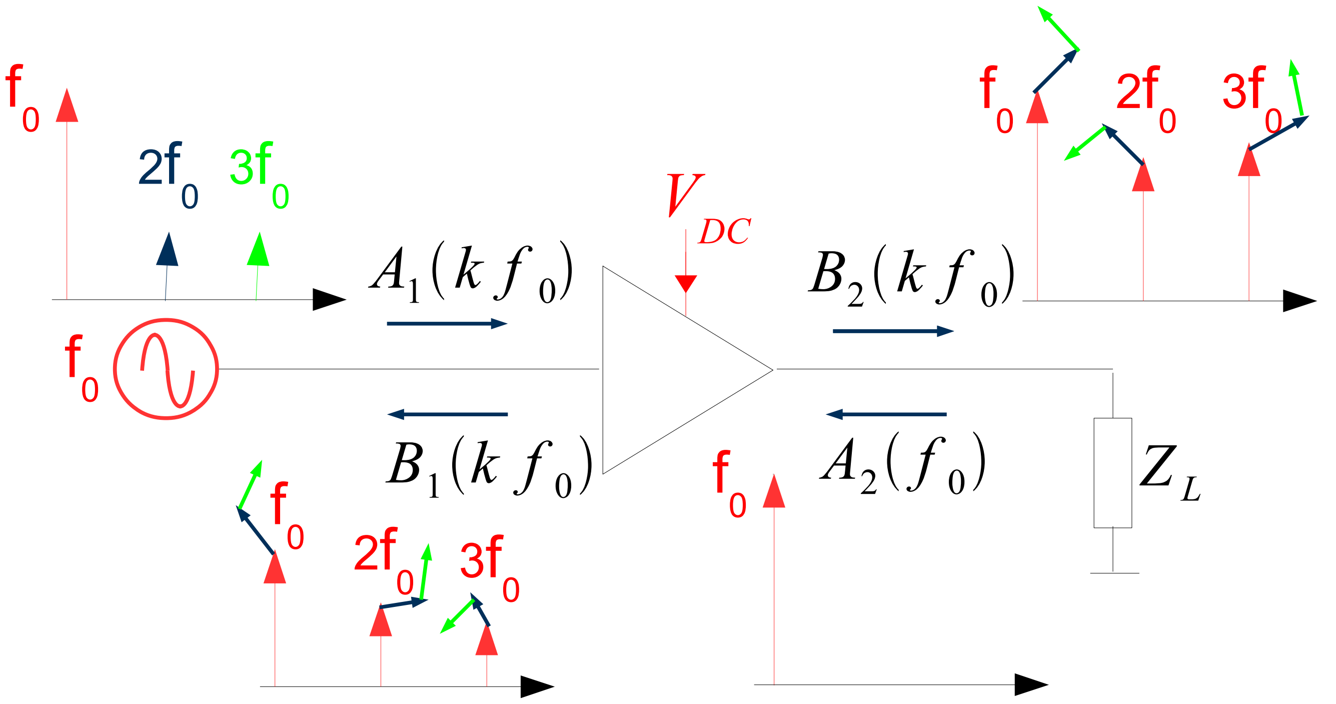
From S-parameters to S-functions



LINEAR

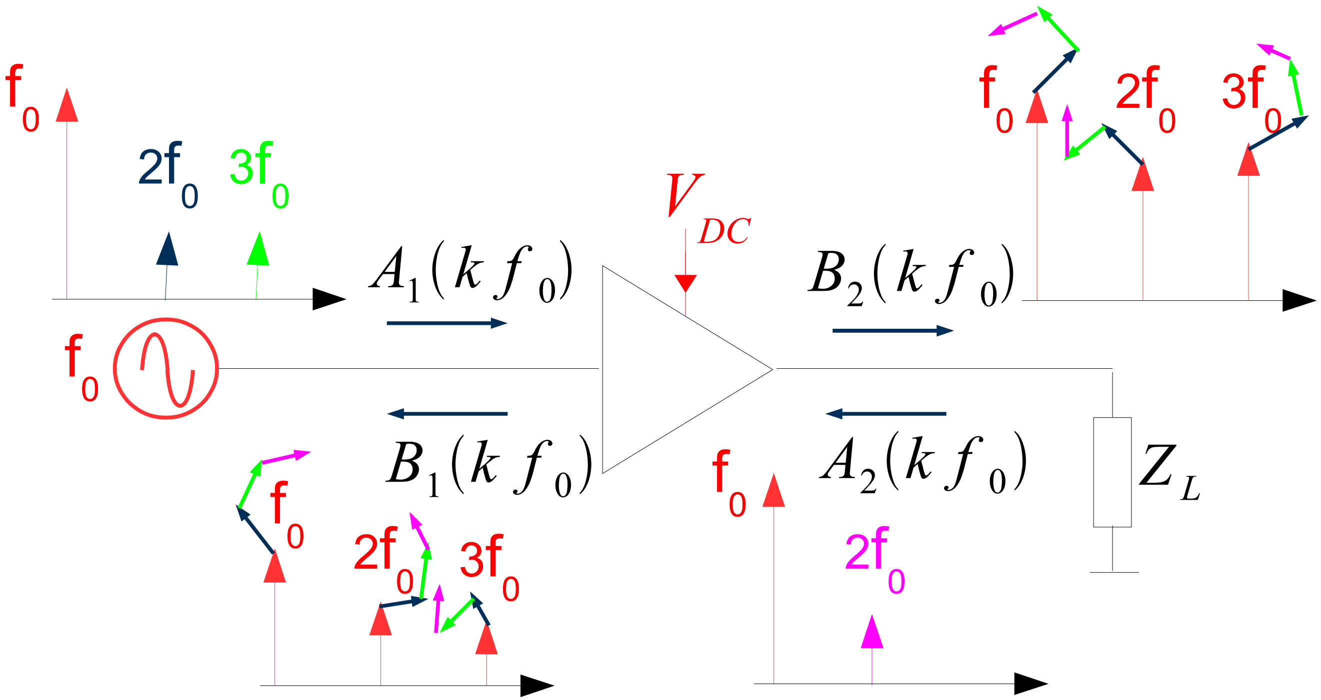
But with frequency conversion, like a mixer

From S-parameters to S-functions

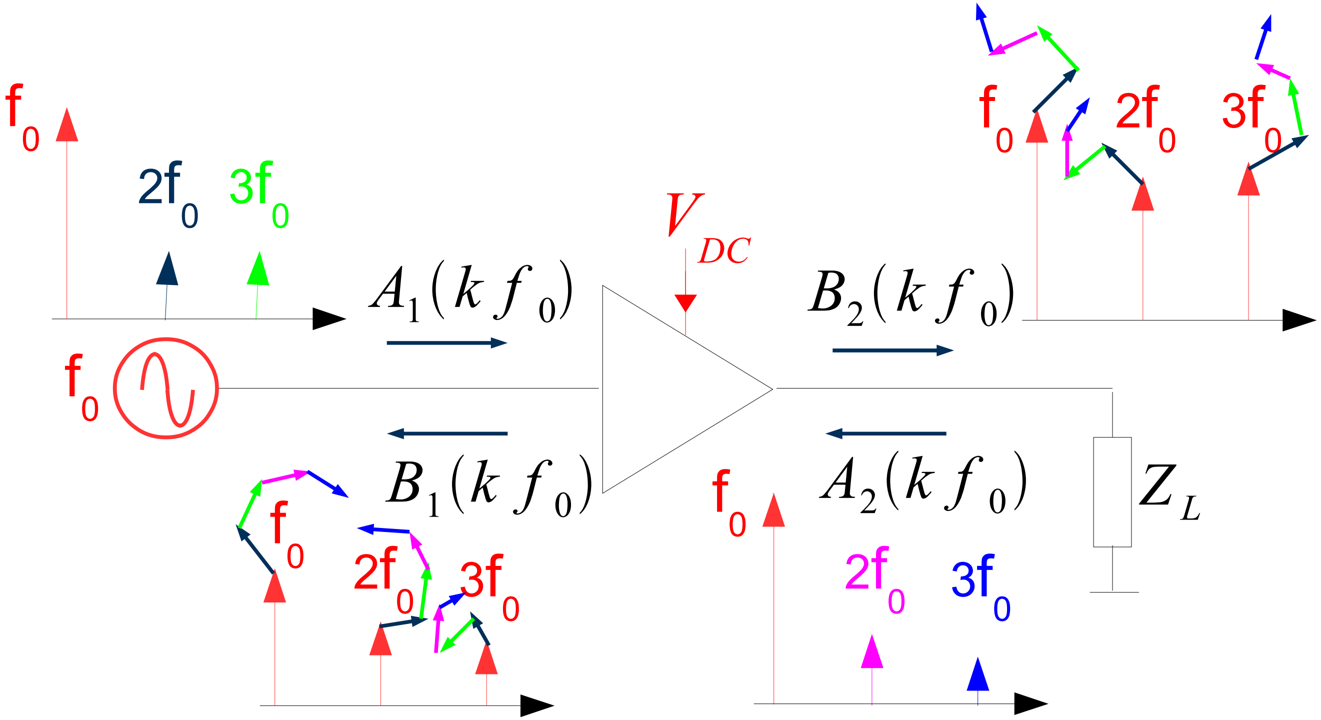


LINEAR Superposition

From S-parameters to S-functions



From S-parameters to S-functions



From S-parameters to S-functions

The Mathematical Approach

$$B_m(n f_0) = F_{mn}(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of } (a_i(j f_0)))$$

$$I_{DC} = H(V_{DC}, f_0, |a_i(j f_0)|, \text{all phase comb of } (a_i(j f_0)))$$

Linearization

The S-functions

$$I_{DC} = Sf_{0001}(V_{DC}, A_{11}, A_{21}) + Sf_{00ij}(V_{DC}, A_{11}, A_{21})\boxed{A_{ij}} + Sfc_{00ij}(V_{DC}, A_{11}, A_{21})\boxed{A_{ij}^*}$$

$$B_{mn} = Sf_{mn01}(V_{DC}, A_{11}, A_{21}) + Sf_{mnij}(V_{DC}, A_{11}, A_{21})\boxed{A_{ij}} + Sfc_{mnij}(V_{DC}, A_{11}, A_{21})\boxed{A_{ij}^*}$$

“LSOP”

“Tickle tone”

Sf_{mnij}
m: output port
n: frequency at output port m
i: input port
j: frequency at input port i

with $j > 1$

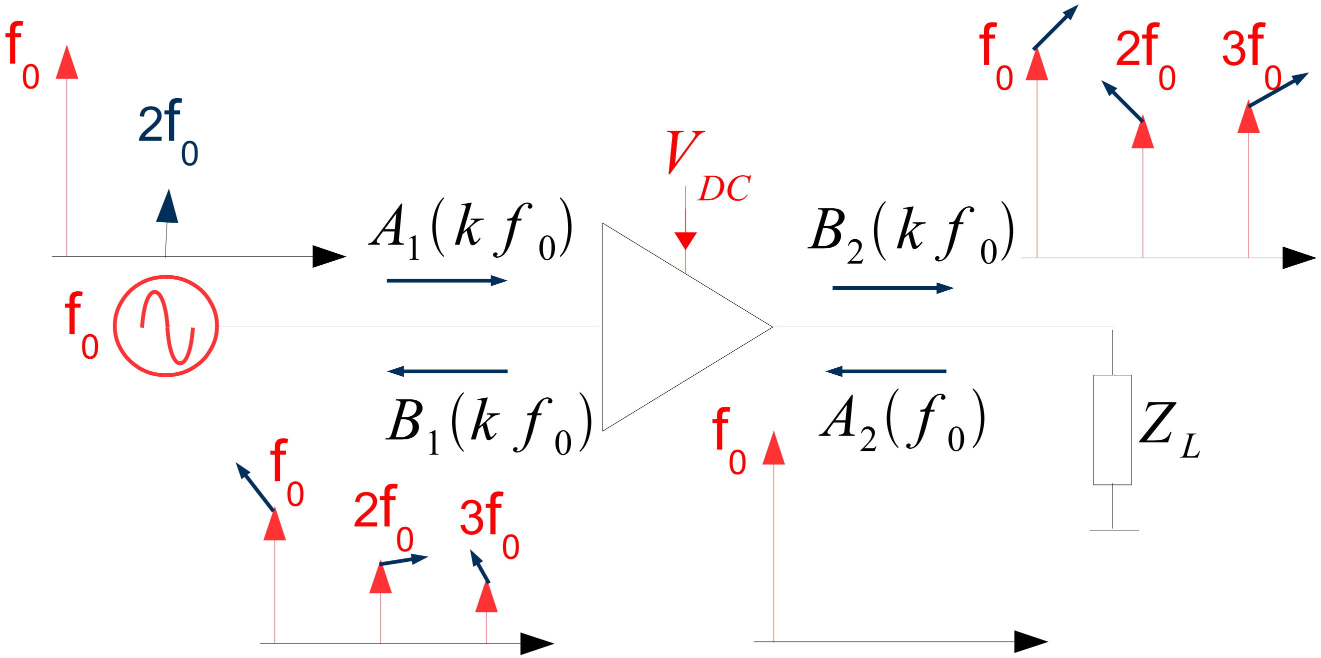
with $B_{mn} \equiv B_m(n f_0)$

with $A_{ij} \equiv A_i(j f_0)$

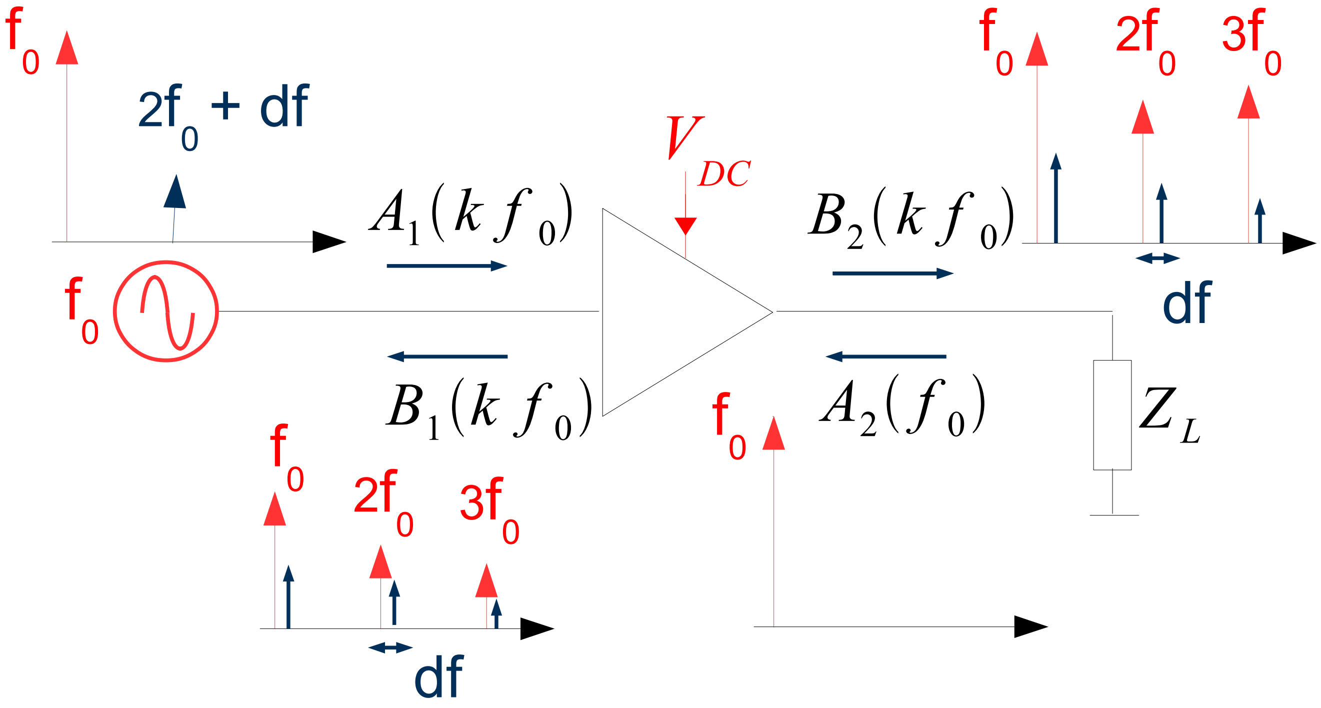
LSOP: large-signal operating point

⚠ Sweep in strongly reduced LSOP

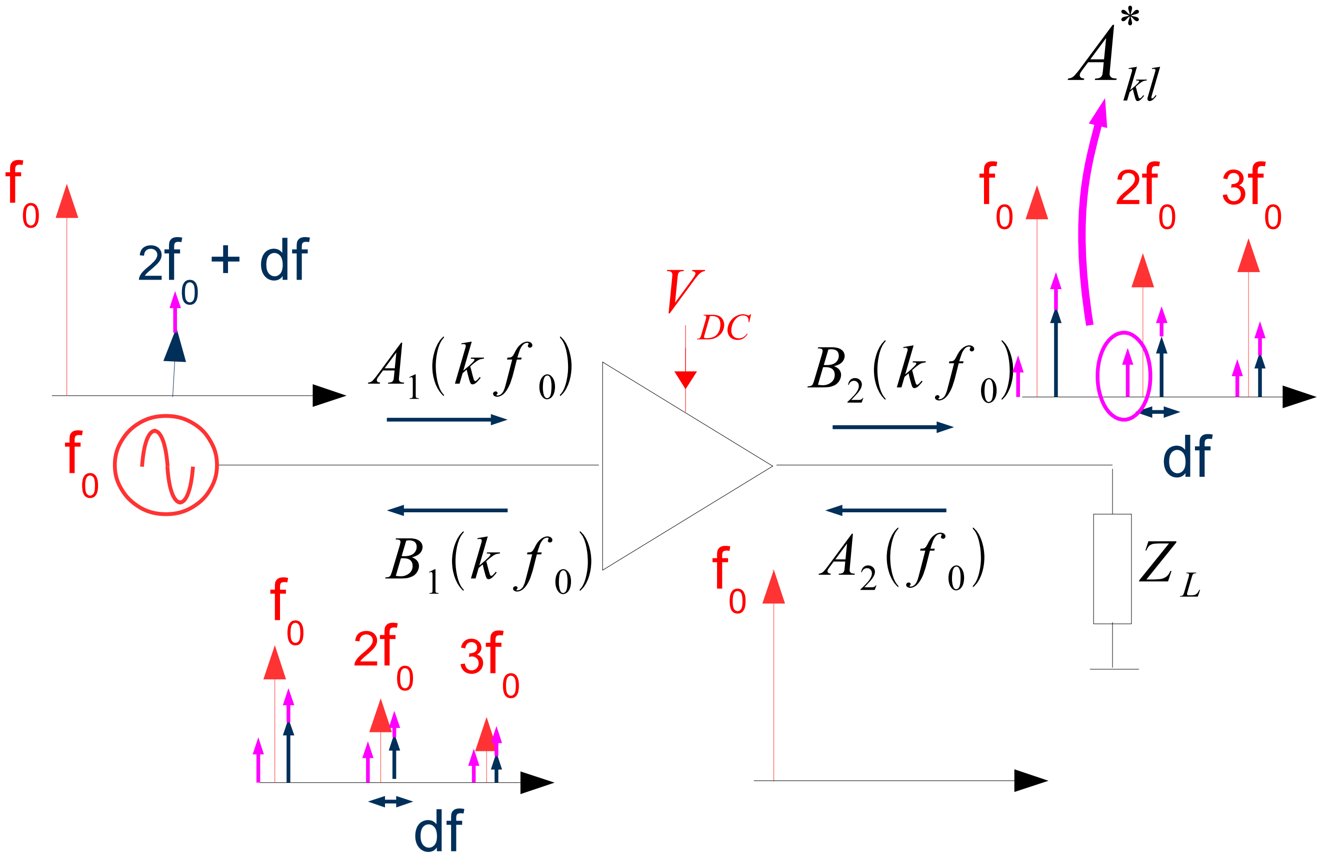
Sfc ???



Sfc ???


f0
2f0 + df
f0
$A_1(k f_0)$
$B_1(k f_0)$
V_{DC}
$B_2(k f_0)$
$A_2(f_0)$
f0
f0
2f0
3f0
df
Z_L
f0
2f0
3f0
df

Sfc ???



A_{kl}^{*}

f0

2f0 + df

V_{DC}

$A_1(k\,f_0)$

$B_2(k\,f_0)$

f0

2f0

3f0

df

f0

$B_1(k\,f_0)$

$A_2(f_0)$

Z_L

f0

f0

2f0

3f0

df

How to extract S-functions?

Select a LSOP and keep it constant

$$B_{mn} = \underbrace{Sf_{mn01}(V_{DC}, A_{11}, A_{21})}_{\text{constant}} + \underbrace{Sf_{mnij}(V_{DC}, A_{11}, A_{21})}_{\text{constant}} \underset{\big\downarrow}{A_{ij}} + \underbrace{Sfc_{mnij}(V_{DC}, A_{11}, A_{21})}_{\text{constant}} \underset{\big\downarrow}{A_{ij}^{*}}$$

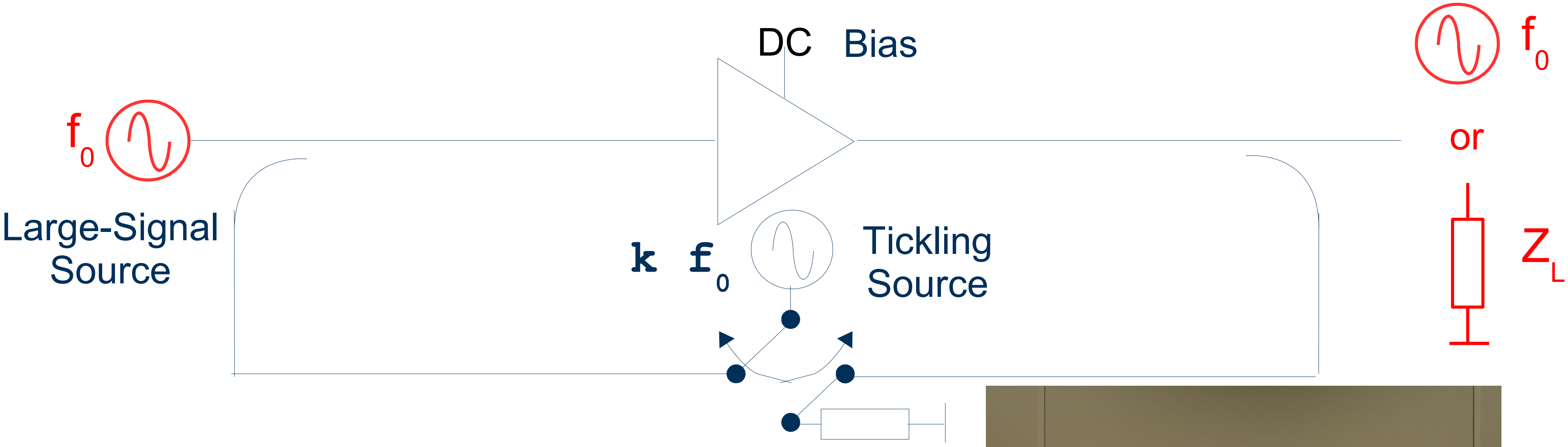
Change the tickle tones

Measure each time A_{ij}, B_{mn}

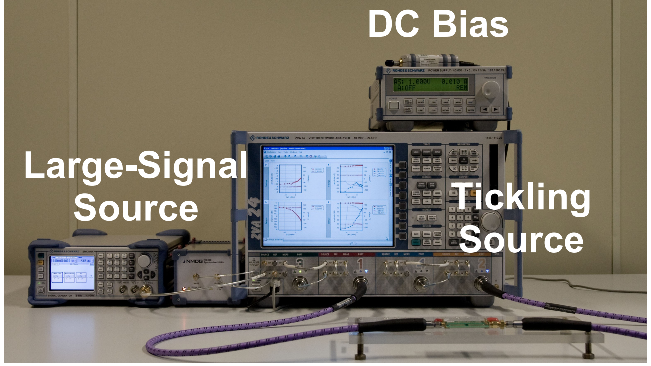
Solve for the S-functions : $Sf_{mnij}(\mathrm{LSOP}), Sfc_{mnij}(\mathrm{LSOP})$

Select a new LSOP and repeat

Extract S-functions for a real device

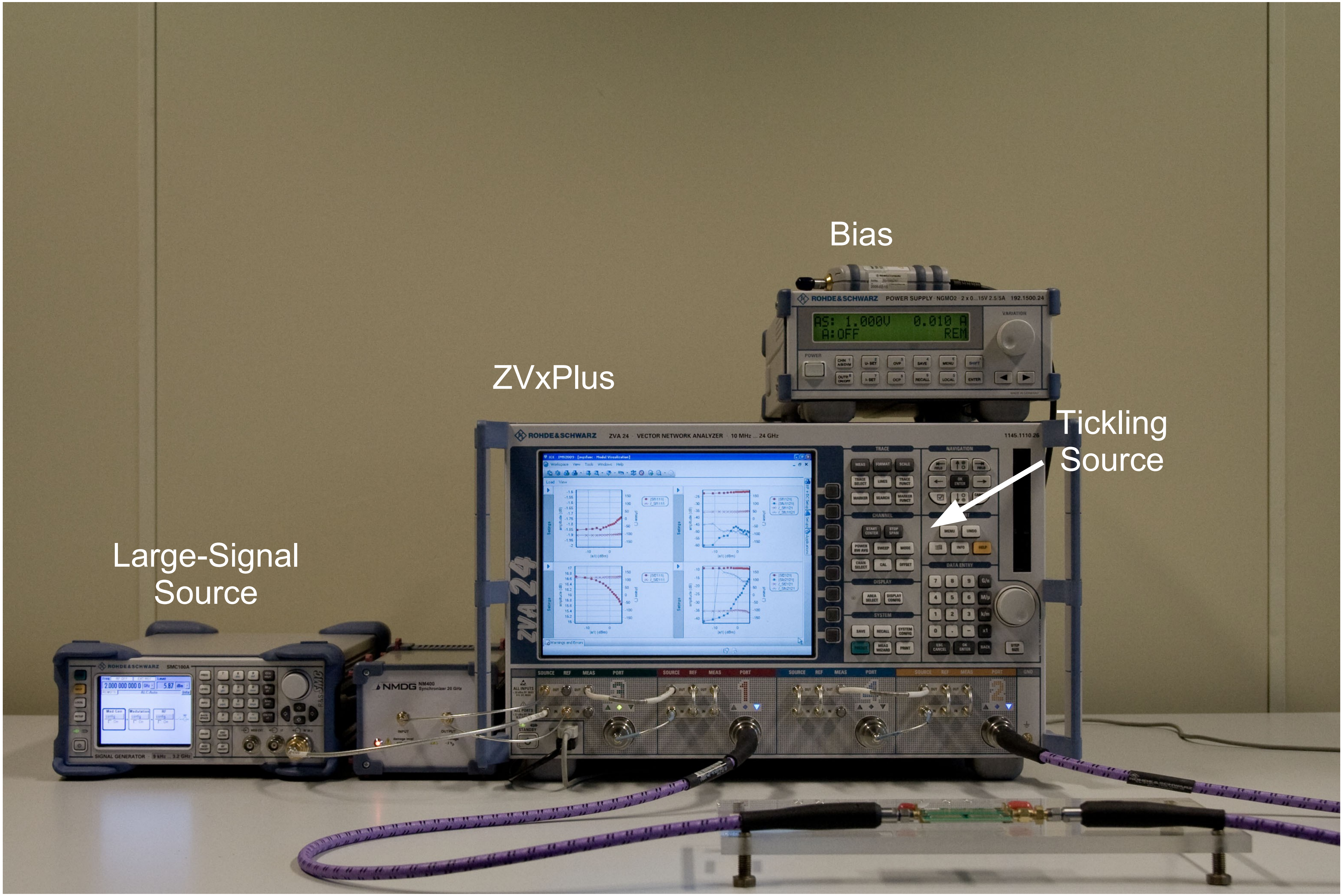


- Repeat the following for all LSOPs of interest
  - Select tickle tones
    - Large enough to be detectable
    - Small enough not to violate linearity assumption

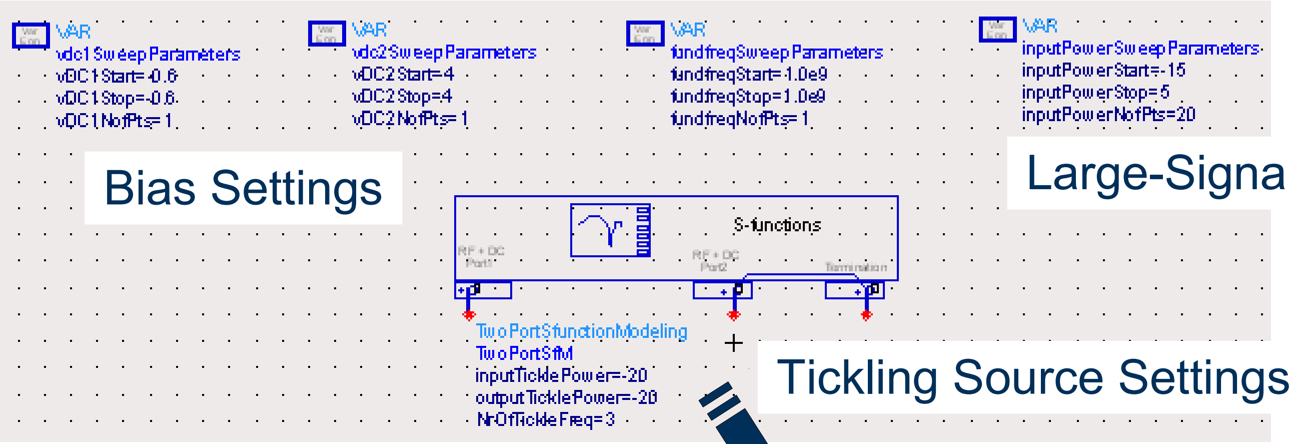


  - **Measure** incident and reflected waves for different tickle tones
  - **Model** by solving for all Sf and Sfc
- Resulting into S-functions

S-functions for Real Devices with ZVxPlus



Extract S-functions for a simulated device



VAR
vdc1SweepParameters
vDC1Start=-0.6
vDC1Stop=-0.6
vDC1NofPts=1

VAR
vdc2SweepParameters
vDC2Start=4
vDC2Stop=4
vDC2NofPts=1

VAR
fundfreqSweepParameters
fundfreqStart=1.0e9
fundfreqStop=1.0e9
fundfreqNofPts=1

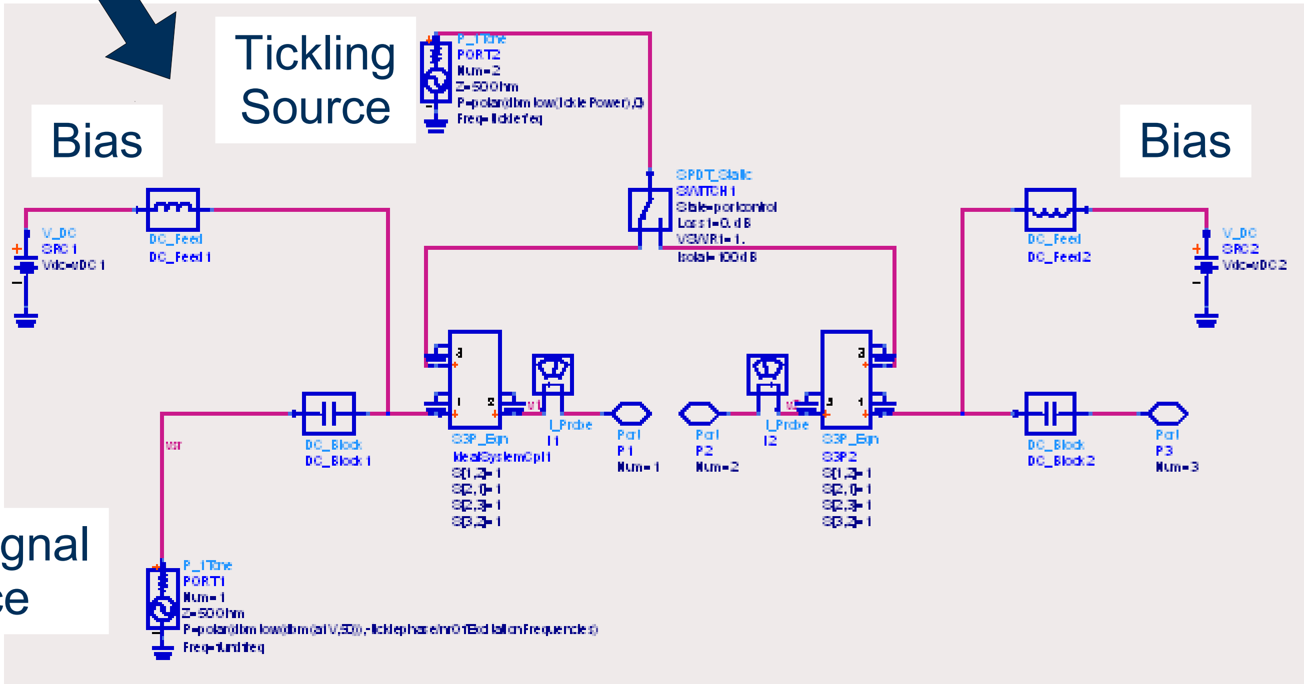
VAR
inputPowerSweepParameters
inputPowerStart=-15
inputPowerStop=5
inputPowerNofPts=20

TwoPortSfunctionModeling
TwoPortSfM
inputTicklePower=-20
outputTicklePower=-20
NrOfTickleFreq=3

Bias Settings

Large-Signal Source Settings

Tickling Source Settings



Vdc=vDC1

Num=1

S[1,2]=1
S[2,1]=1
S[2,3]=1
S[3,2]=1

Num=2

S[1,2]=1
S[2,1]=1
S[2,3]=1
S[3,2]=1

State=portcontrol
Loss1=0. dB
VSWR1=1.
Isolat=100dB

Vdc=vDC2

Num=3

Num=2
Z=50 Ohm
P=polar(dbmtow(TicklePower),0)
Freq=ticklefreq

Num=1
Z=50 Ohm
P=polar(dbmtow(dbm(a1V,50)),-ticklephase/nrOfExcitationFrequencies)
Freq=fundfreq

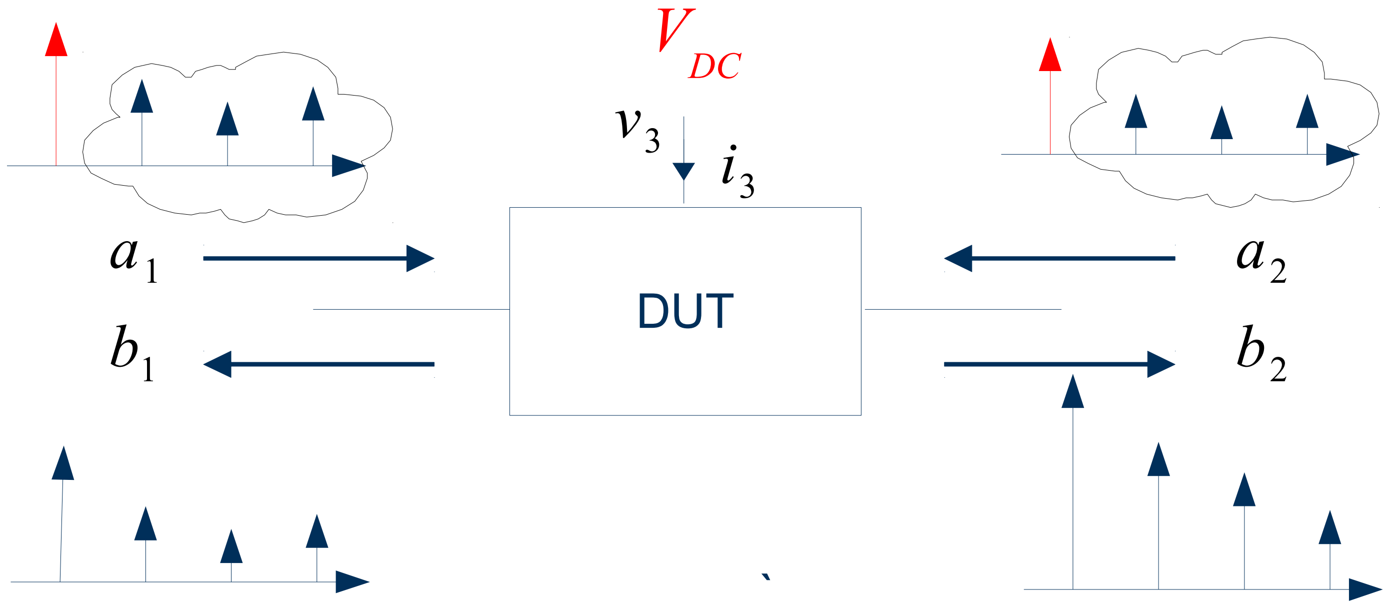
Bias

Tickling Source

Bias

Large-Signal Source

Assumptions of S-functions



$$a_1(k\,f_0),\,a_2(l\,f_0)\,\text{with}\,l,k\neq 0{,}1$$

Is causing only a LINEAR perturbation on the NONINEAR behaviour

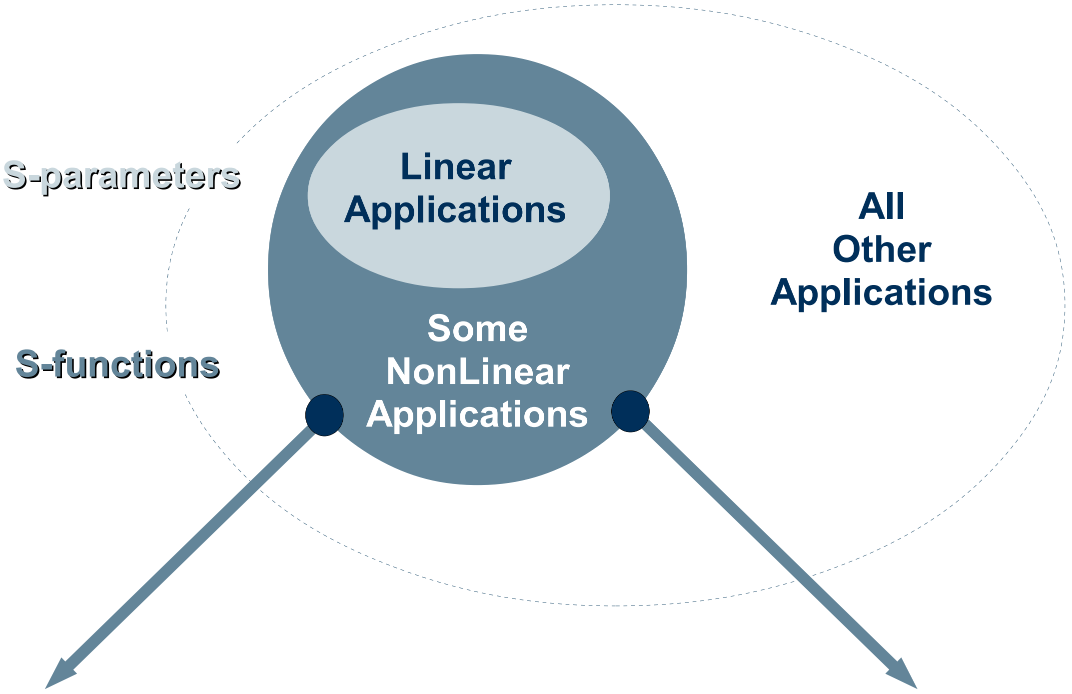
Large-Signal Operating Point (LSOP)

$$a_1(f_0),\,a_2(f_0)\,\text{and}\,v_{dc}$$

Tickle or probing tones

$$a_1(k\,f_0),\,a_2(l\,f_0)\,\text{with}\,l,k\neq 0{,}1$$

The crucial question for S-functions



Mathematically well-defined

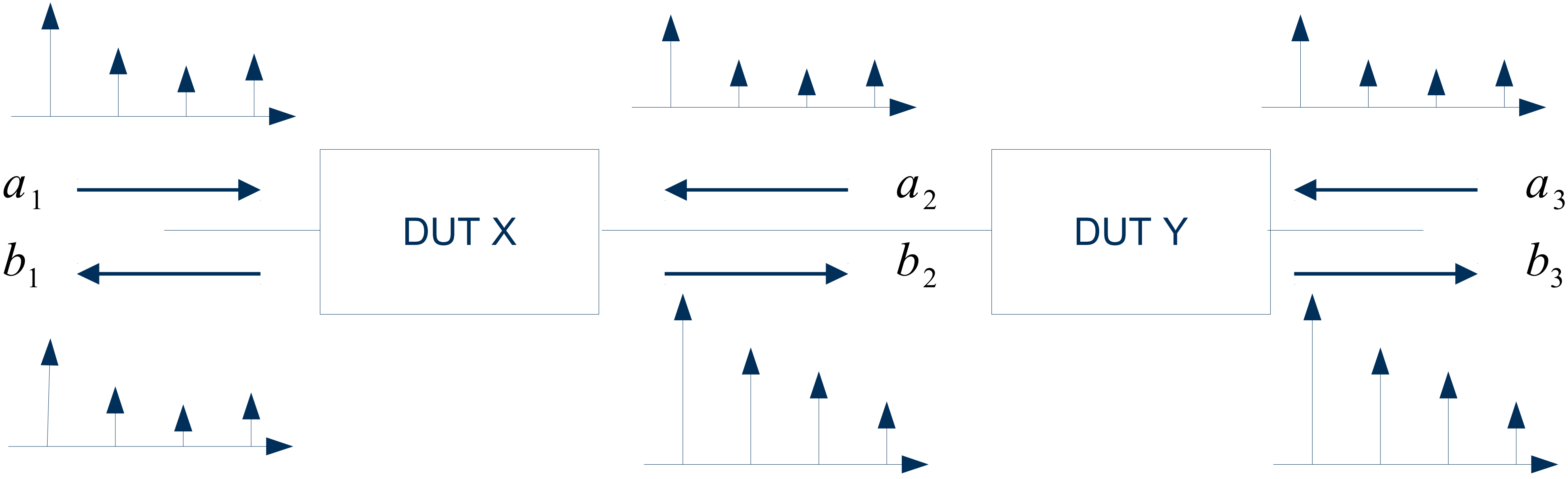
To what applications does it apply?

$a_1(k f_0), a_2(l f_0)$ with $l, k > 1$ SMALL

20 dBc down from main tone

BUT

Applicability of S-functions



Components

- Transistors
- Amplifiers
- Dividers
- Multipliers

Prediction

- Harmonic distortion
- AM – AM and AM – PM
- Source-pull
- Load-pull
- Modulation behaviour (*)
- Intermodulation

(*): The component is assumed to be pseudo-static

S-functions in ICE(*)

- Sweepable Large-Signal Operating Point (LSOP)
- Auto or user-defined tickle signal level
- From simple push-the-button solution to access to expert-level details
- Visualization of component behaviour during data collection
- Easy model verification (no EDA tool required)
- Sanity checks included
- Easy export to and integration in Agilent™ ADS and AWR™ MWO

- Support for mismatched environments
- Harmonics generated by RF sources don't cause any problem
- Simple output prediction does not require EDA tool
- Export to and integration in other EDA tools on request
- Possible to extend the LSOP variables, e.g. temperature

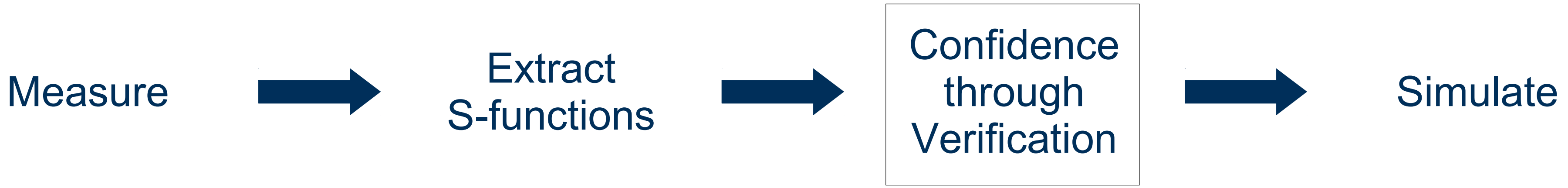
(*) Integrated Component Characterisation Environment

Confidence in S-functions

- Constantness of LSOP
  - All Sf, and Sfc are assumed to be extracted at fixed LSOP
    - e.g. variation in DC drain voltage due to changing current violates this assumption

- Interpolation capability of all Sf, and Sfc
  - LSOP interleaving verification measurements

- Linearity assumption of tickle tones
  - Model verification for different amplitude and phases of tickle tones



Measure

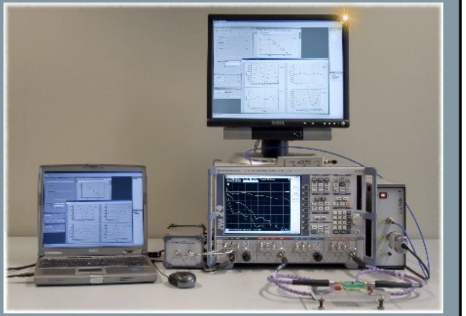
Extract
S-functions

Confidence
through
Verification

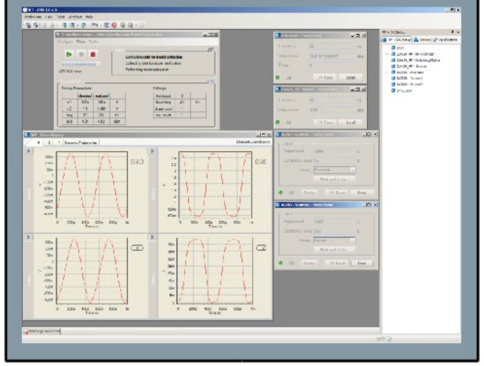
Simulate

Confidence in S-functions through Verification

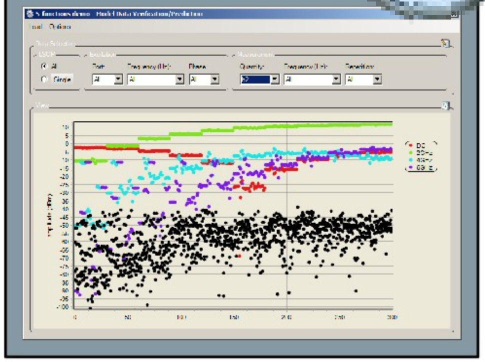
MEASURE



MODEL

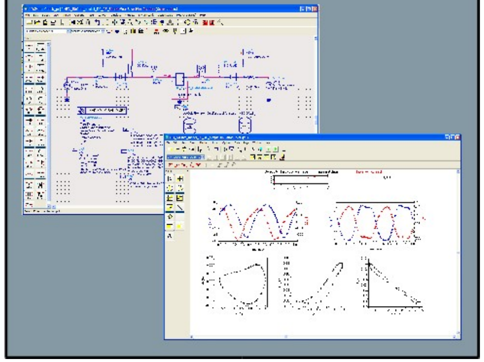


VERIFY



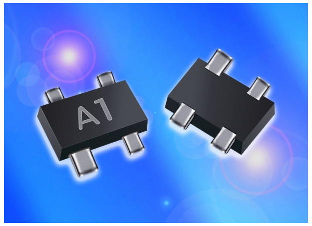
ADS
MWO

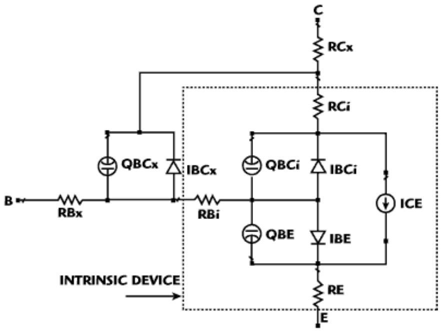
SIMULATE



ADS: Agilent Technologies Advanced Design Systems design software
MWO: AWR Corporation's Microwave Office design software

S-functions for Real and Simulated Components / Circuits

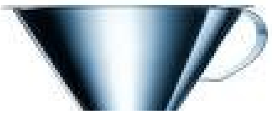




Data Collection

Measurements
on Real Devices
using ICE (*)

Simulations
On Virtual Devices
in Simulation Tool (ADS - MWO)



Extraction

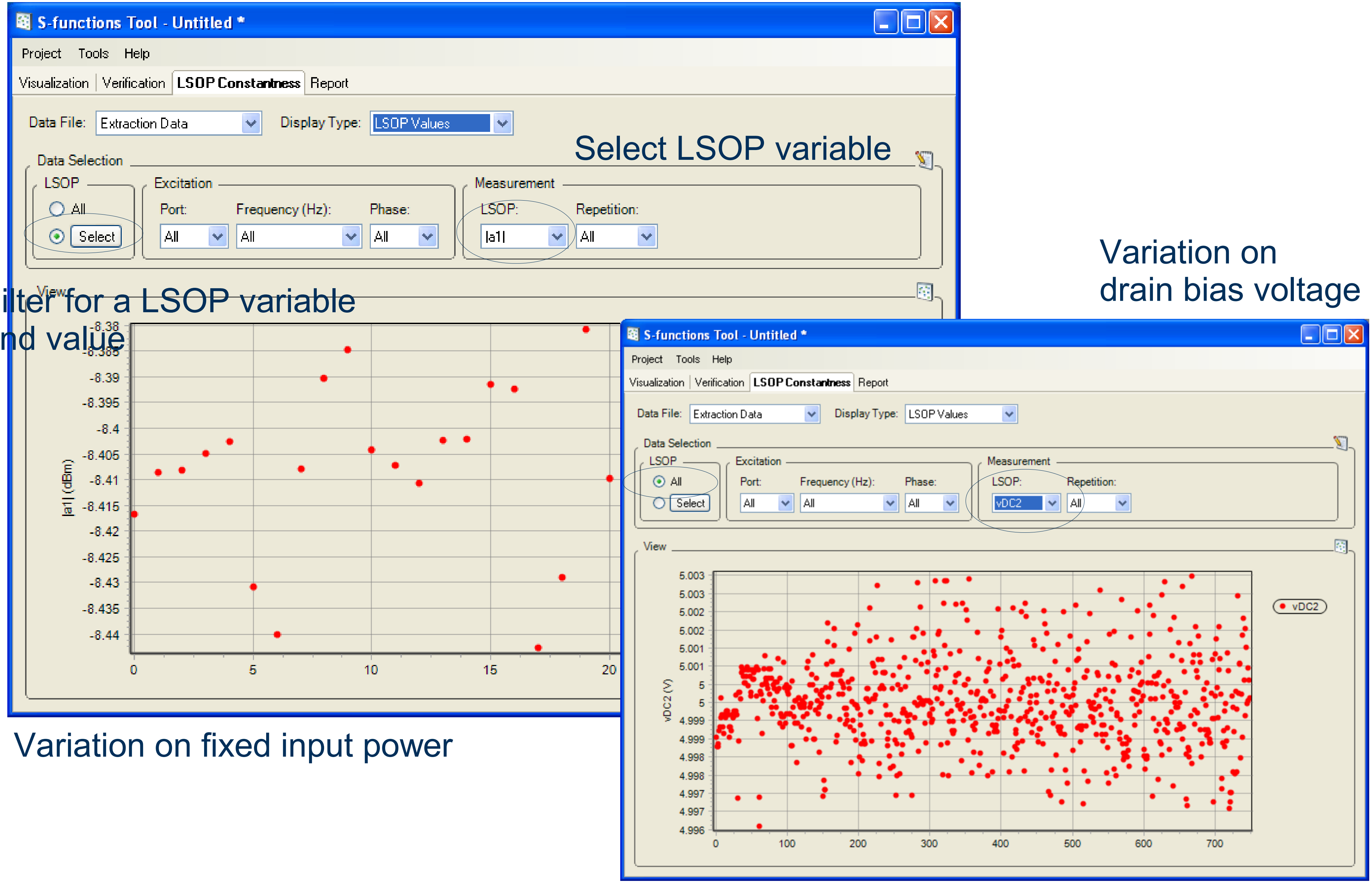
S-functions

S-functions Verifications

Simulators
(ADS - MWO)

S-functions Deployment

S-functions Verification – Constantness of LSOP



Left window:

- Data File: Extraction Data
- Display Type: LSOP Values
- LSOP: Select
- Port: All
- Frequency (Hz): All
- Phase: All
- LSOP: |a1|
- Repetition: All

Right window:

- Data File: Extraction Data
- Display Type: LSOP Values
- LSOP: All
- Port: All
- Frequency (Hz): All
- Phase: All
- LSOP: vDC2
- Repetition: All

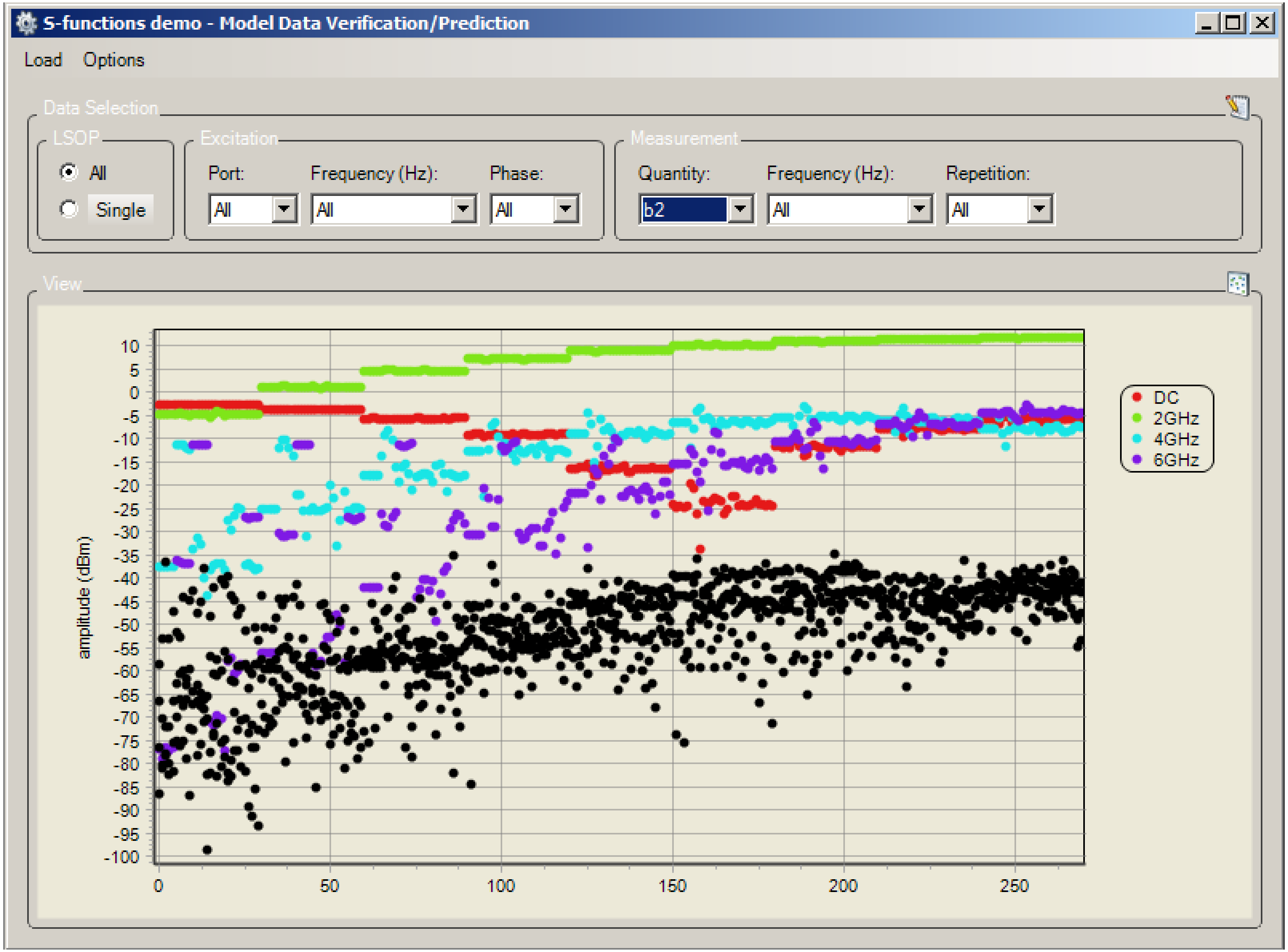
Select LSOP variable

Filter for a LSOP variable and value

Variation on drain bias voltage

Variation on fixed input power

S-functions Verification – Interpolation Capability



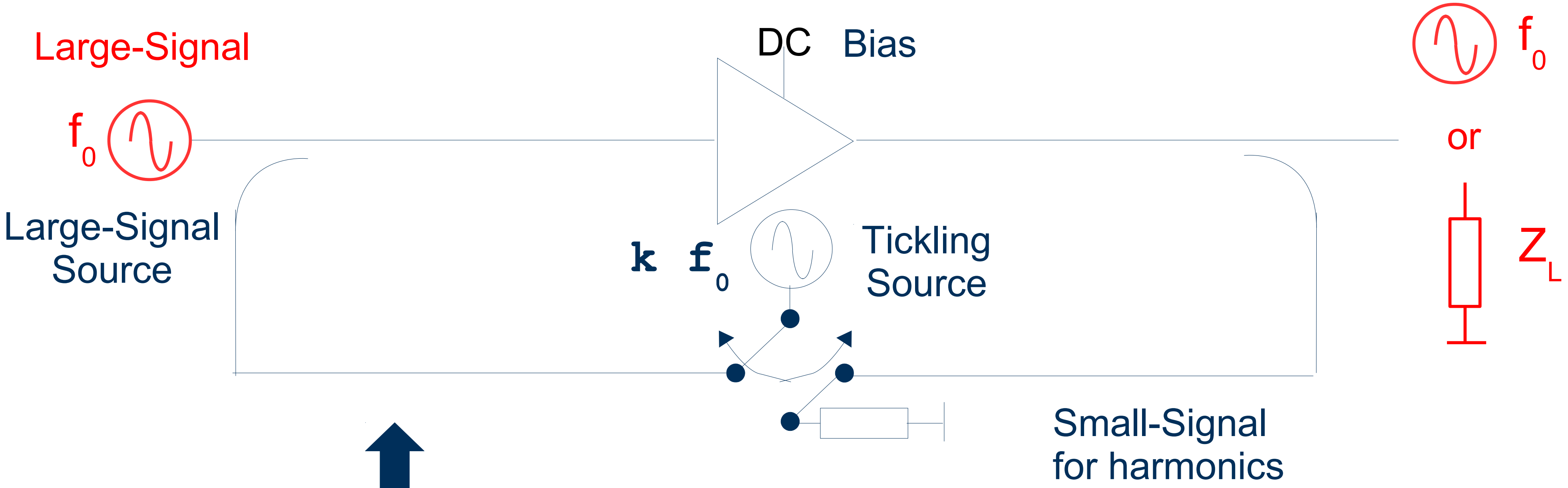
LSOP: ● All ○ Single

Excitation: Port: All; Frequency (Hz): All; Phase: All

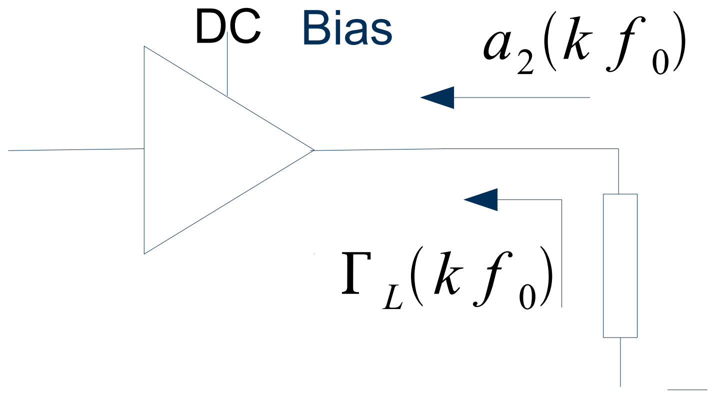
Measurement: Quantity: b2; Frequency (Hz): All; Repetition: All

verify interpolation of b_2 using independent set of measurements

S-functions Verification – Linearity Assumption of Tickle Tones

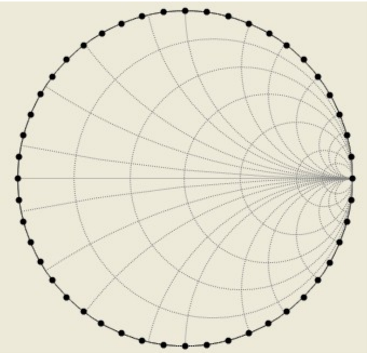


Switching Amplifier design



$\Gamma_L(2\,f_0)$

$\Gamma_L(3\,f_0)$



$a_2(2\,f_0)$

$a_2(3\,f_0)$

Still small signal?

ICEBreaker – Option S-function Verification Tool

ICEBreaker Dataset → Predicted ICEBreaker Dataset → Compare Datasets

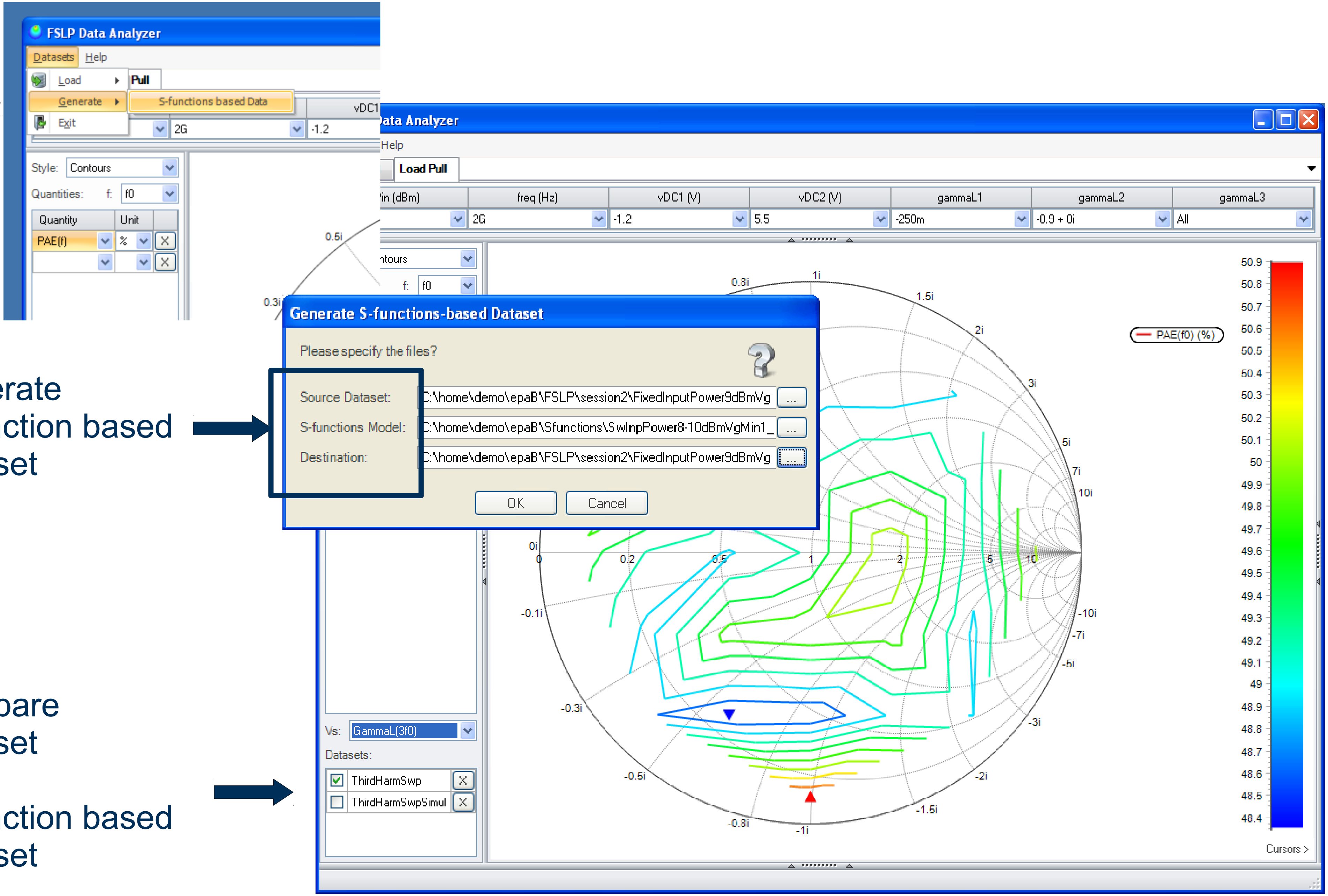
- Measured Data
- Realistic Sweep Plan
- Under multi-harmonic Load-Pull

- Using S-function

- Derived Quantities
- Incident / Reflected Waves
- Voltage and Current
- Absolute Error
- Relative Error

Generation of “S-function Predicted Dataset” in ICEBreaker

Generate
S-function based
Dataset



Generate S-functions-based Dataset

Please specify the files?

Source Dataset: C:\home\demo\epaB\FSLP\session2\FixedInputPower9dBmVg

S-functions Model: C:\home\demo\epaB\Sfunctions\SwInpPower8-10dBmVgMin1_

Destination: C:\home\demo\epaB\FSLP\session2\FixedInputPower9dBmVg

OK Cancel

Style: Contours

Quantities: f: f0

Quantity	Unit
PAE(f)	%

Pin (dBm)	freq (Hz)	vDC1 (V)	vDC2 (V)	gammaL1	gammaL2	gammaL3
	2G	-1.2	5.5	-250m	-0.9 + 0i	All

Vs: GammaL(3f0)

Datasets:

☑ ThirdHarmSwp

☐ ThirdHarmSwpSimul

Compare
Dataset
and
S-function based
Dataset

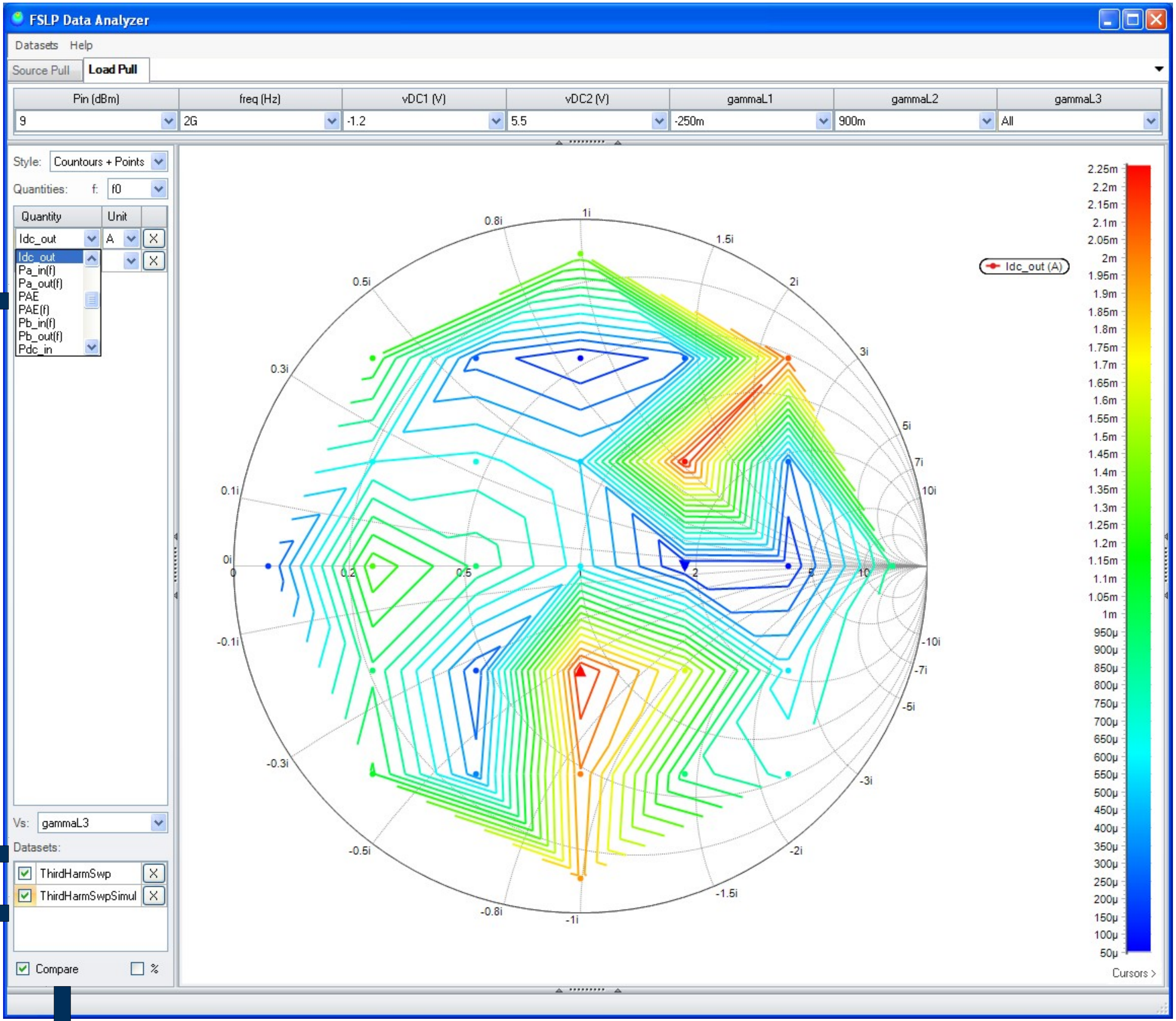
Absolute Comparisons with S-function Predictions

Quantity for which to compare measurement and prediction

- **Derived quantities**
  - Idc_out
  - Gain
  - Pdel_in
  - Pdel_out
  - PAE
  - ..
  - Frequency selection
- **Basic quantities**
  - Incident waves
  - Reflected waves
  - Voltages / Currents
  - Frequency selection

Measurements

S-function Prediction



Pin (dBm)	freq (Hz)	vDC1 (V)	vDC2 (V)	gammaL1	gammaL2	gammaL3
9	2G	-1.2	5.5	-250m	900m	All

Style: Countours + Points

Quantities: f: f0

Quantity	Unit
Idc_out	A

Vs: gammaL3

Datasets:

☑ ThirdHarmSwp

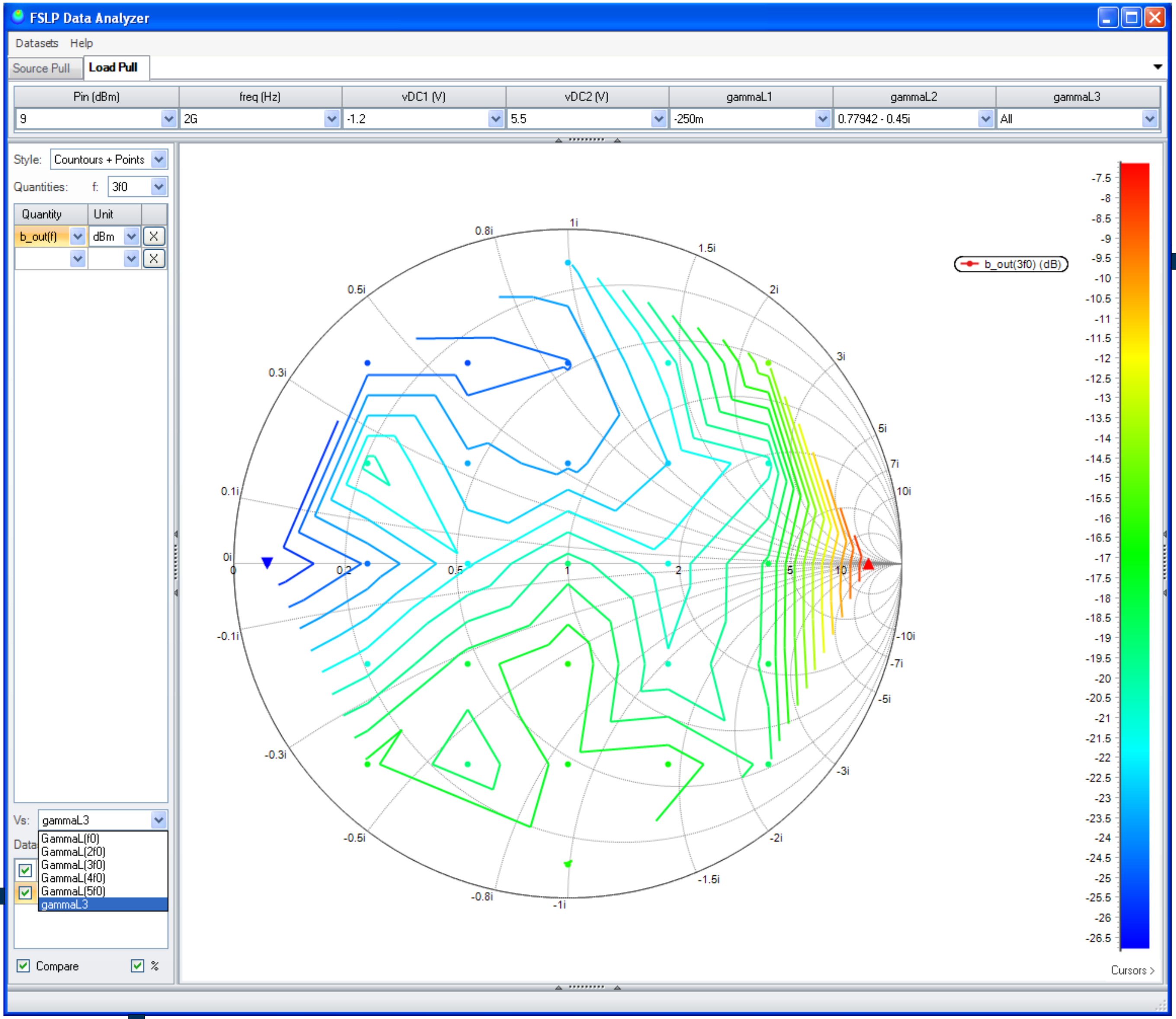
☑ ThirdHarmSwpSimul

☑ Compare ☐ %

Idc_out

Absolute Error

Relative Comparisons with S-function Predictions



Pin (dBm)	freq (Hz)	vDC1 (V)	vDC2 (V)	gammaL1	gammaL2	gammaL3
9	2G	-1.2	5.5	-250m	0.77942 - 0.45i	All

Style: Countours + Points

Quantities: f: 3f0

Quantity	Unit
b_out(f)	dBm

Vs: gammaL3

Data

GammaL(f0)
GammaL(2f0)
GammaL(3f0)
GammaL(4f0)
GammaL(5f0)
gammaL3

☑ Compare ☑ %

b_out(3f0)

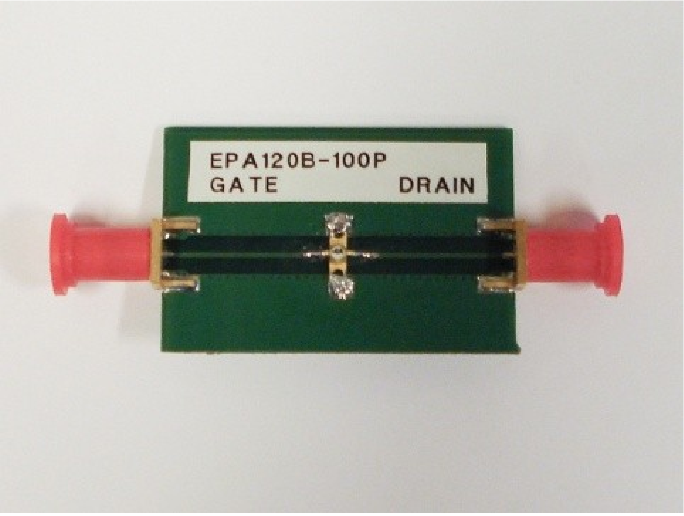
- **Versus**
  - Harmonic index
  - Harmonic refl

Relative Error (dB)

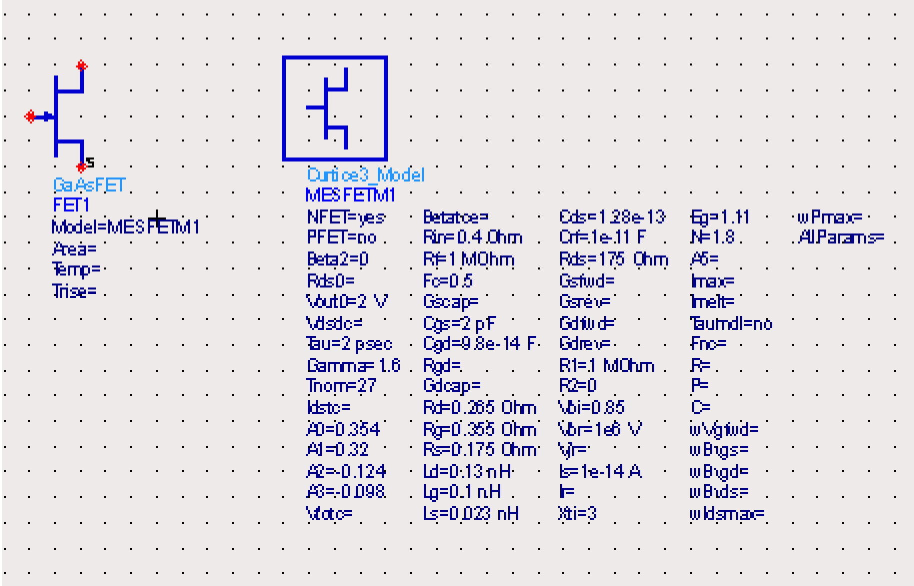
Case Study$^{(*)}$: EPA120B-100P

- EPA120B-100P
  - high efficiency heterojunction power FET
  - power output: + 29.0dBm typ.
  - power gain: 11.5dB typ. @ 12 GHz

Excelics SEMICONDUCTOR



Real Device



```
GaAsFET          Curtice3_Model
FET1             MESFETM1
Model=MESFETM1   NFET=yes      Betatce=         Cds=1.28e-13    Eg=1.11      wPmax=
Area=            PFET=no       Rin=0.4 Ohm      Crf=1e-11 F     N=1.8        AllParams=
Temp=            Beta2=0       Rf=1 MOhm        Rds=175 Ohm     A5=
Trise=           Rds0=         Fc=0.5           Gsfwd=          Imax=
                 Vout0=2 V     Gscap=           Gsrev=          Imelt=
                 Vdsdc=        Cgs=2 pF         Gdfwd=          Taumdl=no
                 Tau=2 psec    Cgd=9.8e-14 F    Gdrev=          Fnc=
                 Gamma=1.6     Rgd=             R1=1 MOhm       R=
                 Tnom=27       Gdcap=           R2=0            P=
                 Idstc=        Rd=0.265 Ohm     Vbi=0.85        C=
                 A0=0.354      Rg=0.355 Ohm     Vbr=1e6 V       wVgfwd=
                 A1=0.32       Rs=0.175 Ohm     Vjr=            wBvgs=
                 A2=-0.124     Ld=0.13 nH       Is=1e-14 A      wBvgd=
                 A3=-0.098     Lg=0.1 nH        Ir=             wBvds=
                 Vtotc=        Ls=0.023 nH      Xti=3           wIdsmax=
```

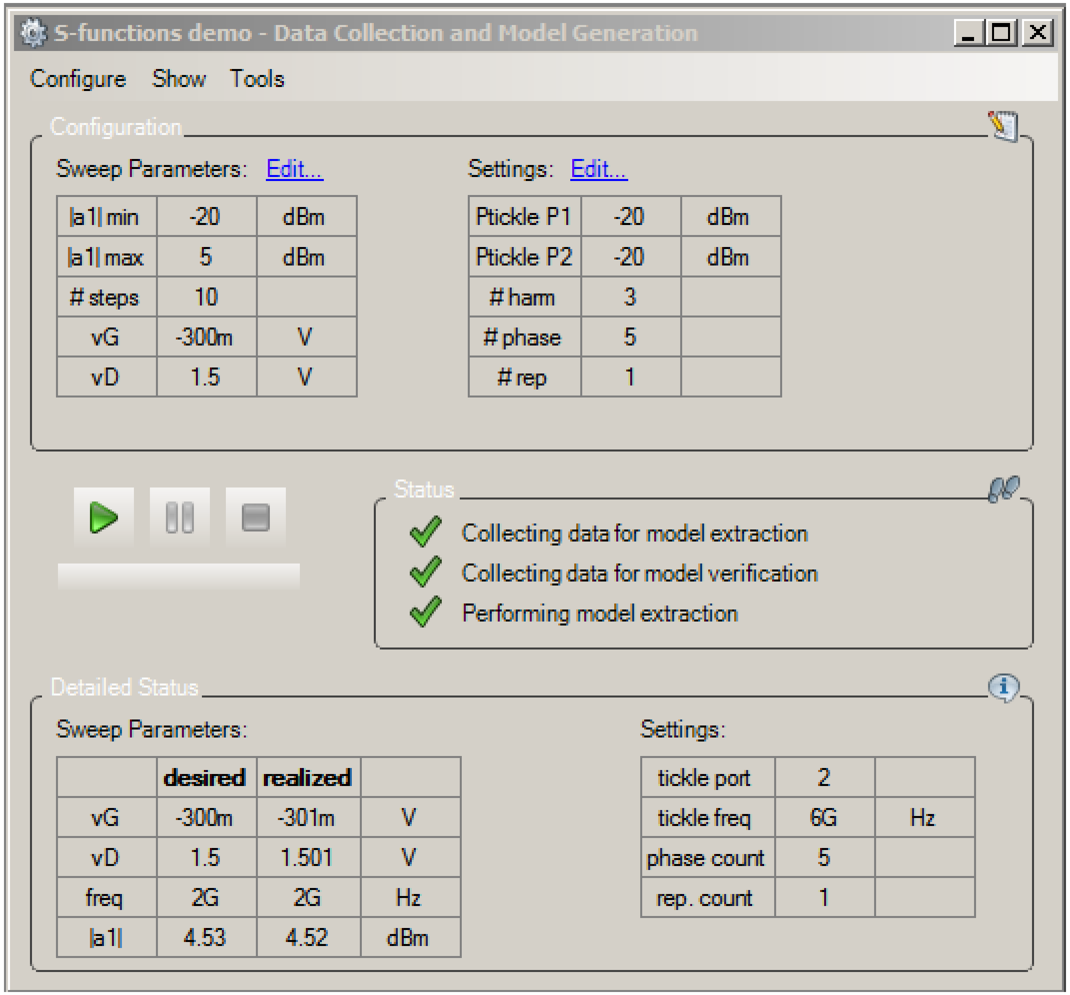
Virtual Device

$^{(*)}$: all results in this slide set are based on S-function extraction and deployment for this device

Data Collection with ZVxPlus

LSOP sweep

“tickle” settings



Sweep Parameters: Edit...

|a1| min	-20	dBm
|a1| max	5	dBm
# steps	10	
vG	-300m	V
vD	1.5	V

Settings: Edit...

Ptickle P1	-20	dBm
Ptickle P2	-20	dBm
# harm	3	
# phase	5	
# rep	1	

✓ Collecting data for model extraction

✓ Collecting data for model verification

✓ Performing model extraction

Sweep Parameters:

	desired	**realized**	
vG	-300m	-301m	V
vD	1.5	1.501	V
freq	2G	2G	Hz
|a1|	4.53	4.52	dBm

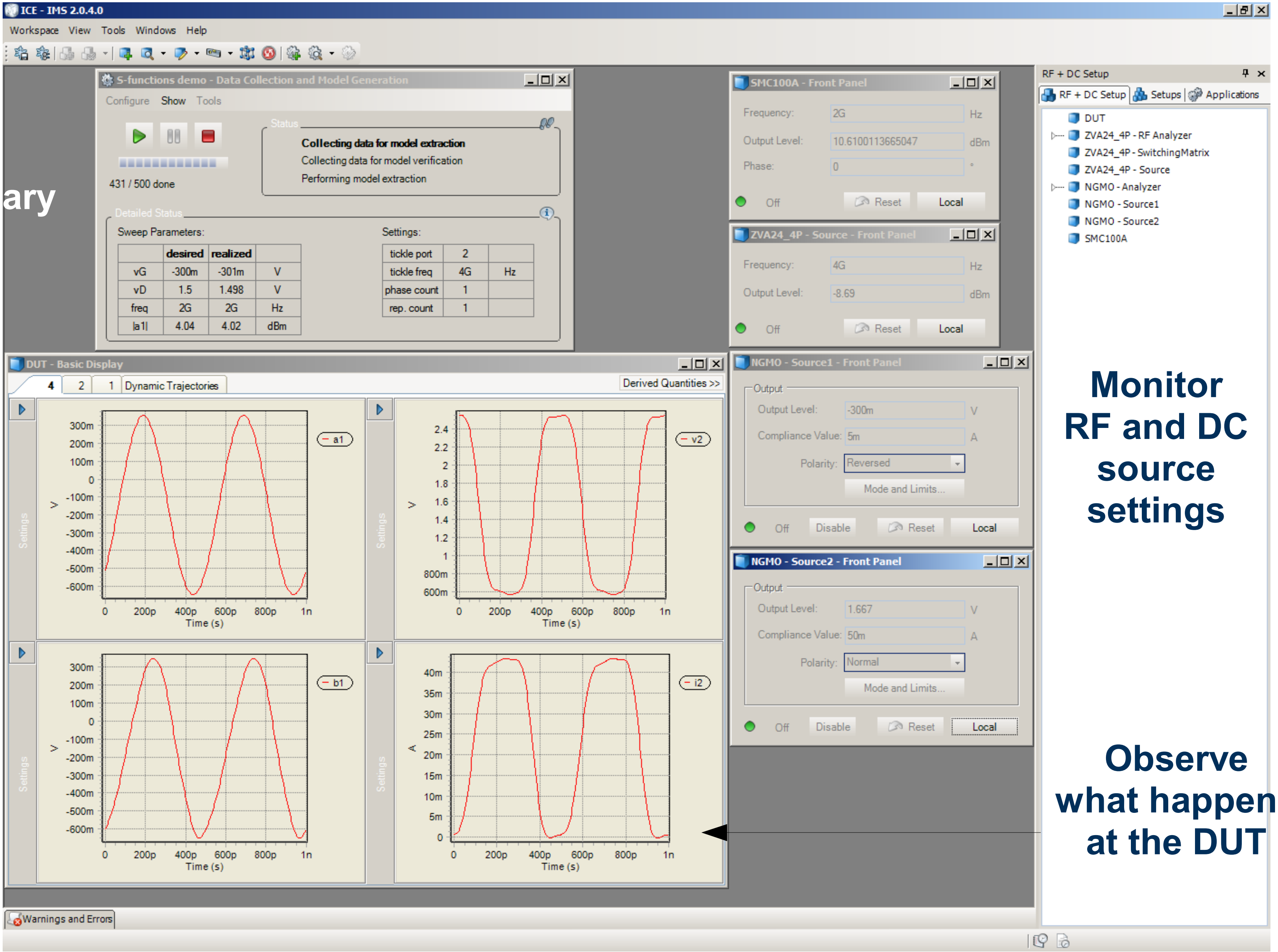
Settings:

tickle port	2	
tickle freq	6G	Hz
phase count	5	
rep. count	1	

detailed feedback of LSOP for actual measurement

detailed feedback on tickle for actual measurement

Expert Details If Desired @ Data Collection



431 / 500 done

Collecting data for model extraction
Collecting data for model verification
Performing model extraction

Sweep Parameters:

	desired	realized	
vG	-300m	-301m	V
vD	1.5	1.498	V
freq	2G	2G	Hz
|a1|	4.04	4.02	dBm

Settings:

tickle port	2	
tickle freq	4G	Hz
phase count	1	
rep. count	1	

SMC100A - Front Panel
Frequency: 2G Hz
Output Level: 10.6100113665047 dBm
Phase: 0 °
● Off Reset Local

ZVA24_4P - Source - Front Panel
Frequency: 4G Hz
Output Level: -8.69 dBm
● Off Reset Local

NGMO - Source1 - Front Panel
Output
Output Level: -300m V
Compliance Value: 5m A
Polarity: Reversed
Mode and Limits...
● Off Disable Reset Local

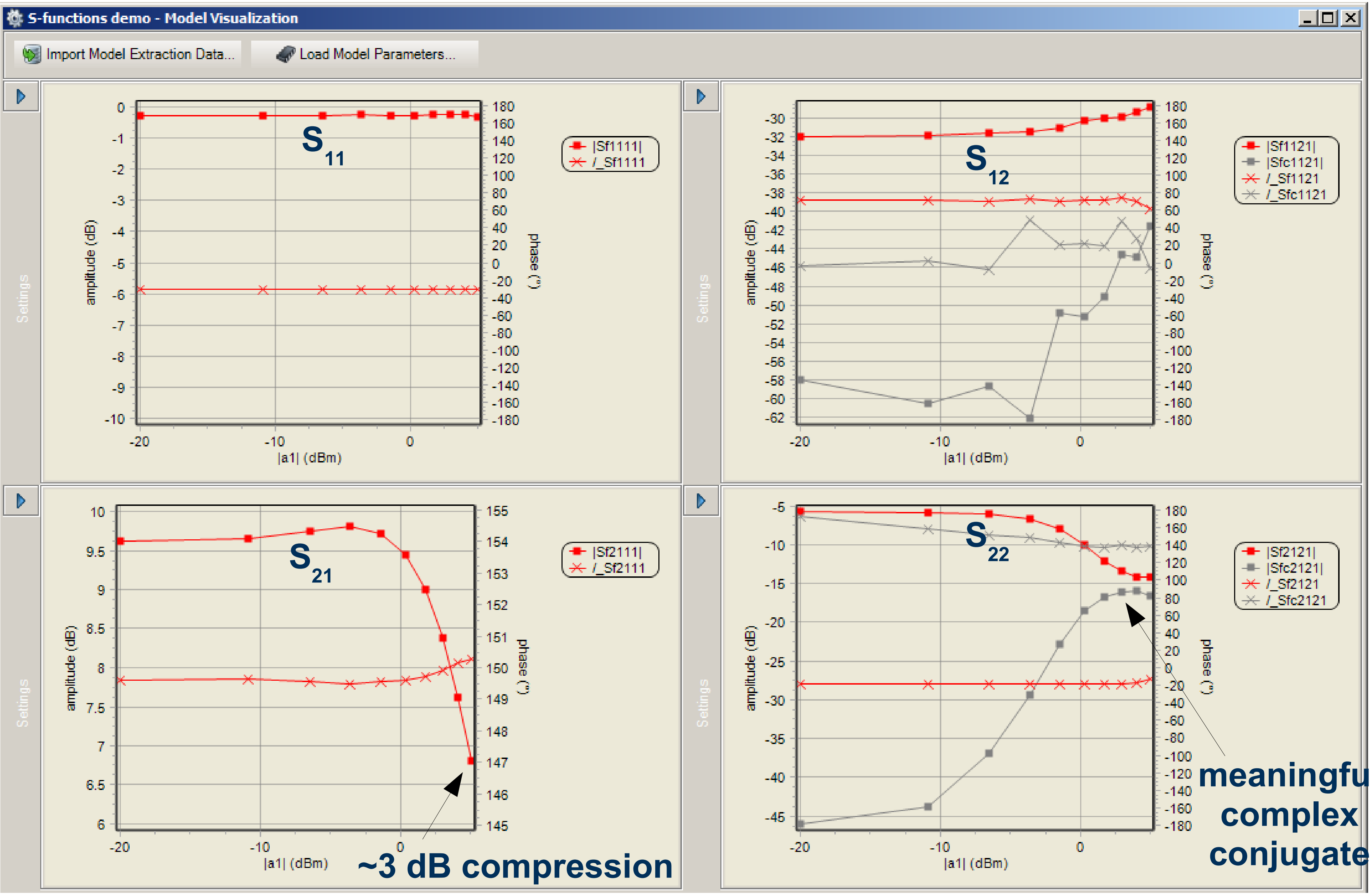
NGMO - Source2 - Front Panel
Output
Output Level: 1.667 V
Compliance Value: 50m A
Polarity: Normal
Mode and Limits...
● Off Disable Reset Local

Summary

Monitor RF and DC source settings

Observe what happens at the DUT

S-functions Extraction



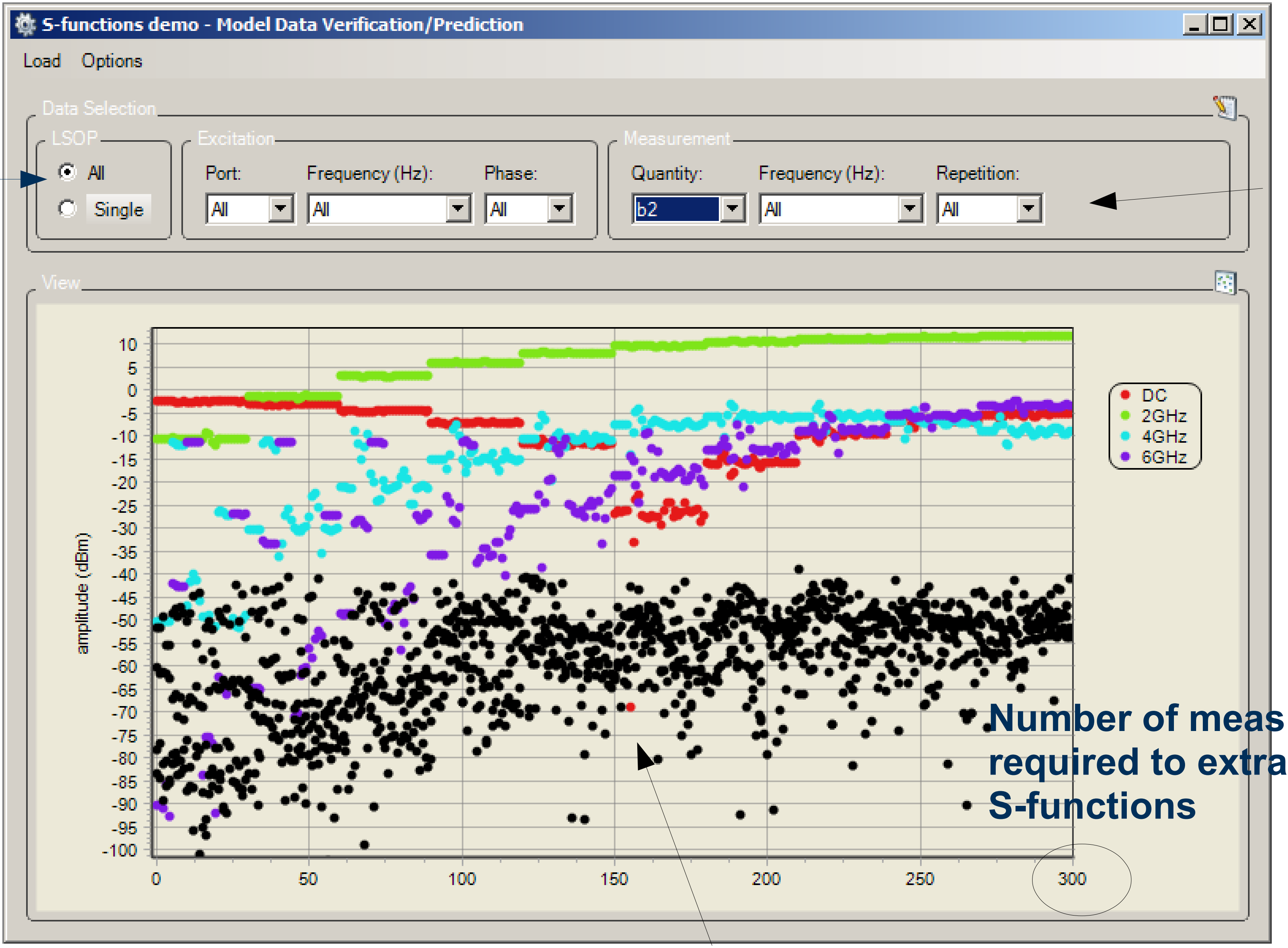
~3 dB compression

meaningful complex conjugate

S-functions Verifications – Residual Error

zoom in on tickling

zoom in on result



S-functions demo - Model Data Verification/Prediction

Data Selection

LSOP: ● All ○ Single

Excitation — Port: All; Frequency (Hz): All; Phase: All

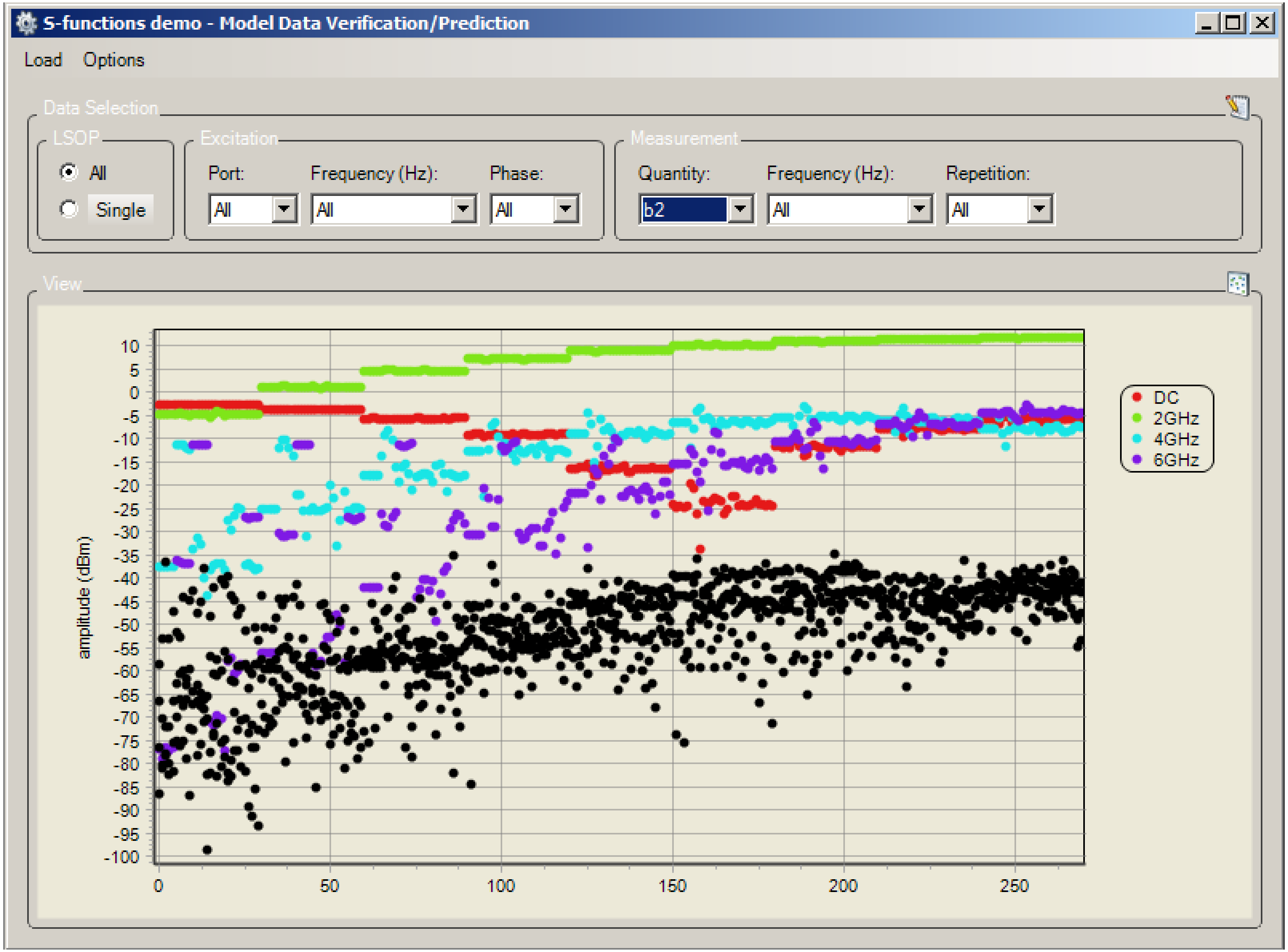
Measurement — Quantity: b2; Frequency (Hz): All; Repetition: All

View

Number of measurements required to extract S-functions

amplitude of complex error for measured and predicted b_2 using extraction data

S-functions Verification – Interpolation Capability



● All
○ Single

Excitation

Port: All

Frequency (Hz): All

Phase: All

Measurement

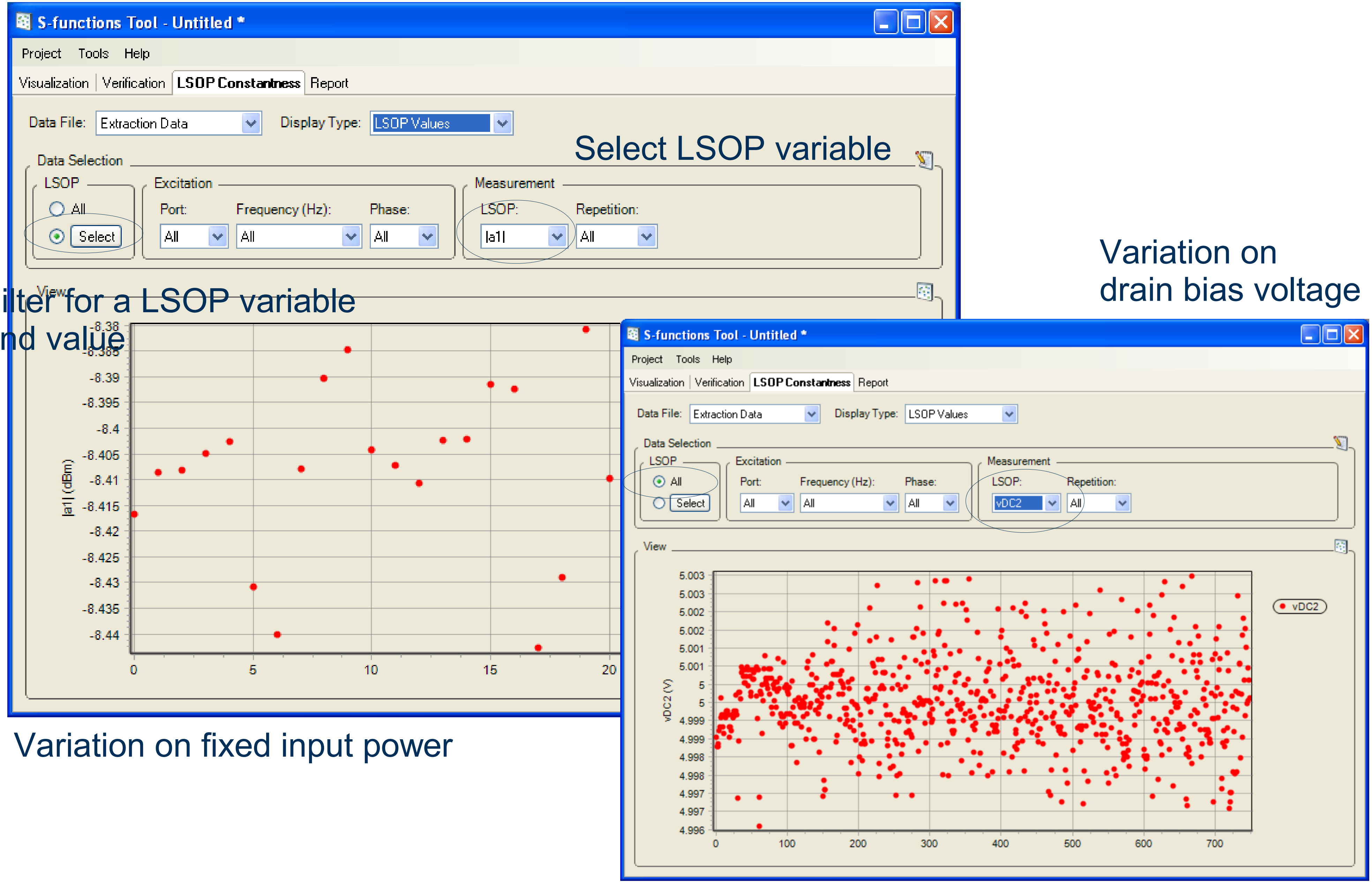
Quantity: b2

Frequency (Hz): All

Repetition: All

verify interpolation of b_2 using independent set of measurements

S-functions Verifications – Constantness LSOP



Select LSOP variable

Filter for a LSOP variable and value

Data File: Extraction Data
Display Type: LSOP Values

Data Selection

LSOP: ○ All ● Select

Excitation — Port: All; Frequency (Hz): All; Phase: All

Measurement — LSOP: |a1|; Repetition: All

Variation on fixed input power

Variation on drain bias voltage

Data File: Extraction Data
Display Type: LSOP Values

Data Selection

LSOP: ● All ○ Select

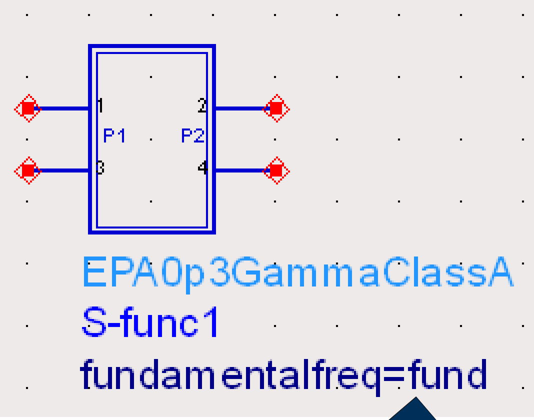
Excitation — Port: All; Frequency (Hz): All; Phase: All

Measurement — LSOP: vDC2; Repetition: All

S-functions in ADS

Acknowledgement:
With the support from Agilent Technologies providing ADS licensing

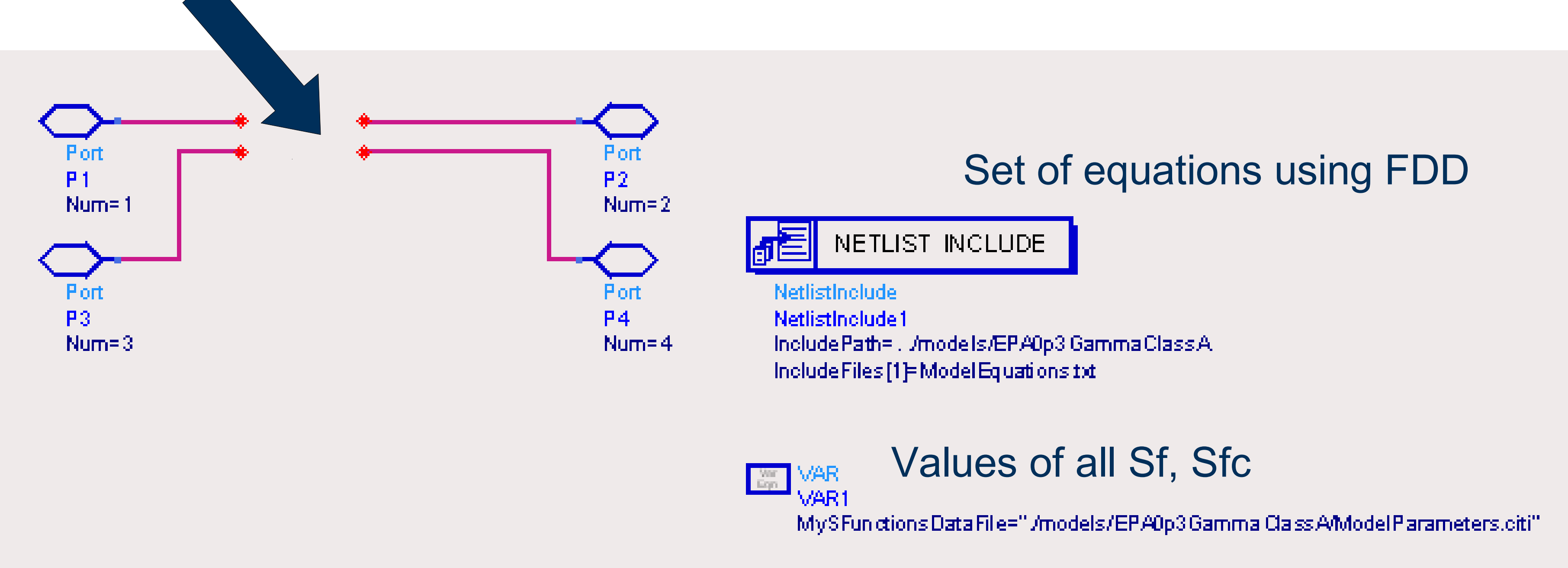
S-functions Useage in Agilent ADS



EPA0p3GammaClassA
S-func1
fundamentalfreq=fund

EPAClassAMediumPower.ael

EPAClassAMediumPower.dsn



Port
P1
Num=1

Port
P3
Num=3

Port
P2
Num=2

Port
P4
Num=4

Set of equations using FDD

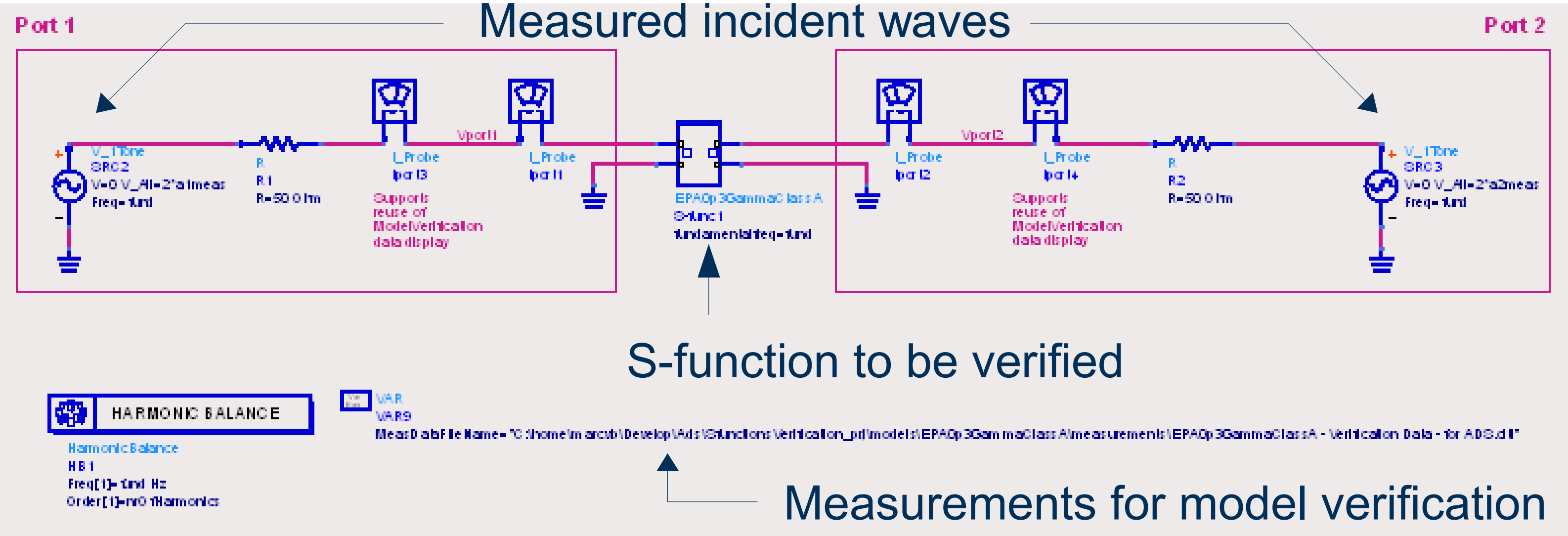
NetlistInclude
NetlistInclude1
IncludePath=../models/EPA0p3GammaClassA
IncludeFiles[1]=ModelEquations.txt

Values of all Sf, Sfc

VAR
VAR1
MySFunctionsDataFile="./models/EPA0p3GammaClassA/ModelParameters.citi"

S-functions Verification in ADS - Schematic

- Example: Harmonic Balance simulation with measured a1 and a2 spectra
- Excitation: Sweeping through a subset of LSOP points + tickle tones



Measured incident waves

S-function to be verified

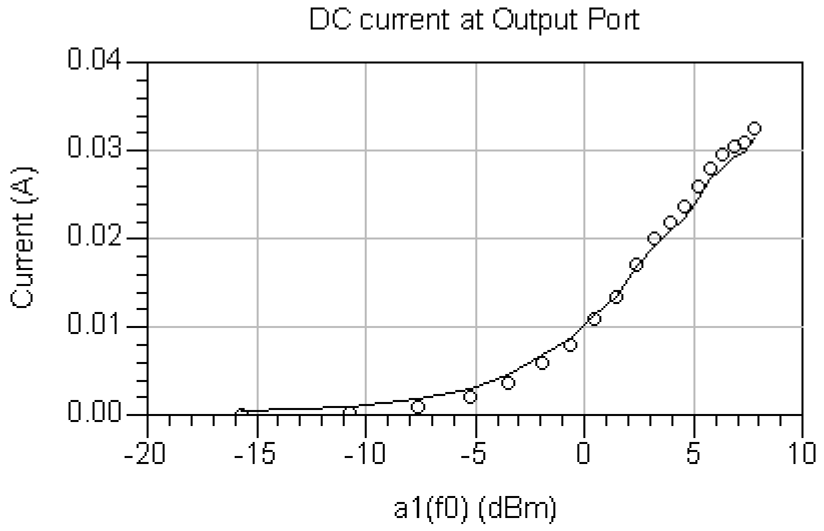
Measurements for model verification

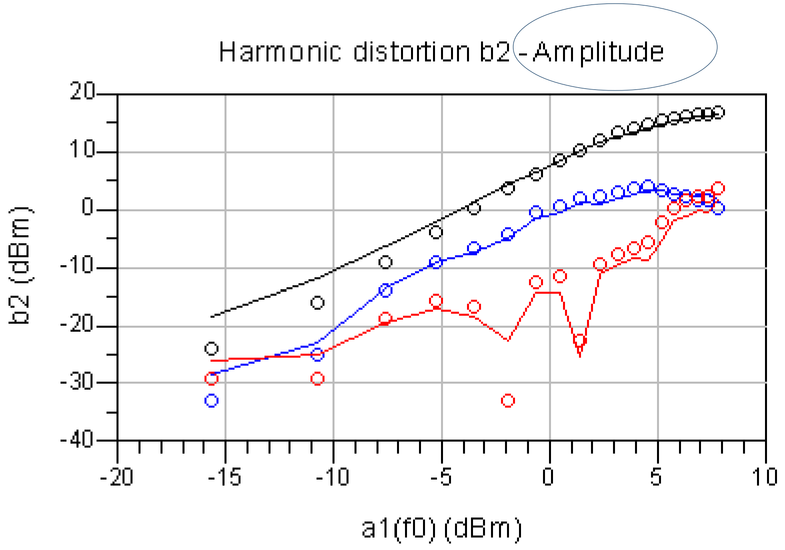
Access to measured data using DAC

Sweeping through subset of LSOP and tickle tones

S-functions Verification in ADS - Frequency Domain

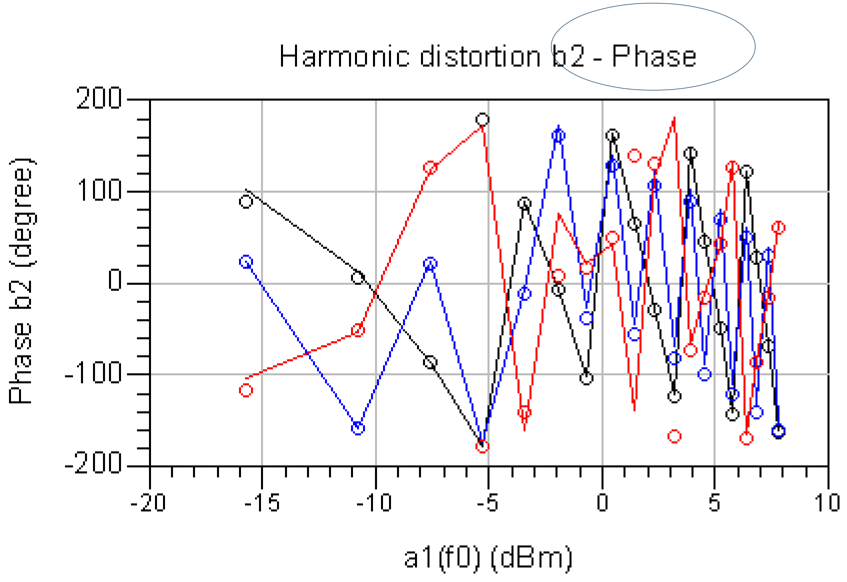
Frequency = 2 GHz, VDC1= -1.3 V, VDC2= +2.0 V





Measurements at <u>different</u> input powers than those which were used for S-functions model extraction!

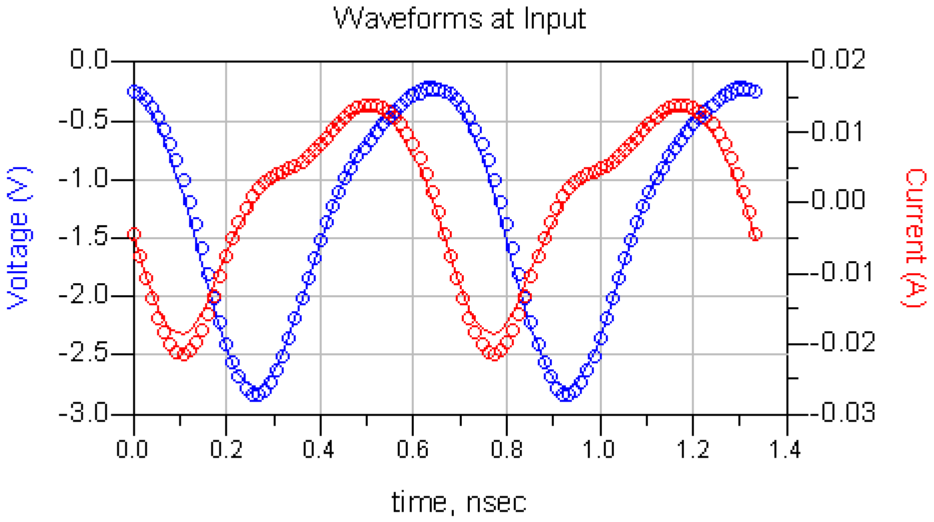
circles – measurements
solid lines - simulations

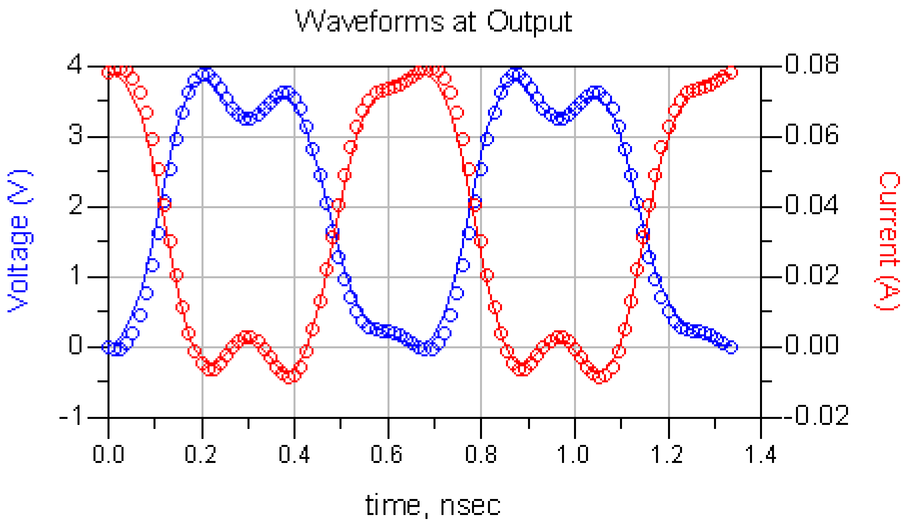


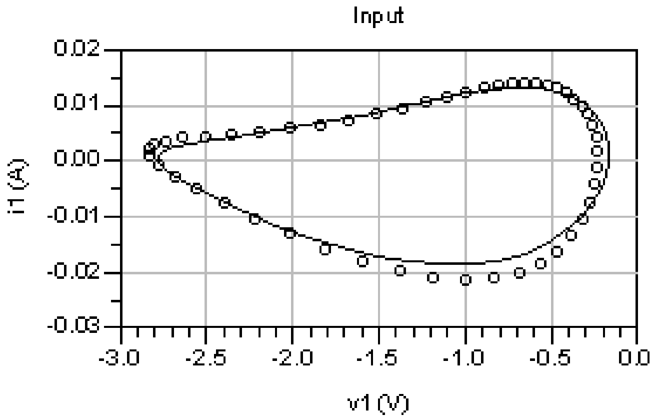
S-functions Verification in ADS - Time Domain

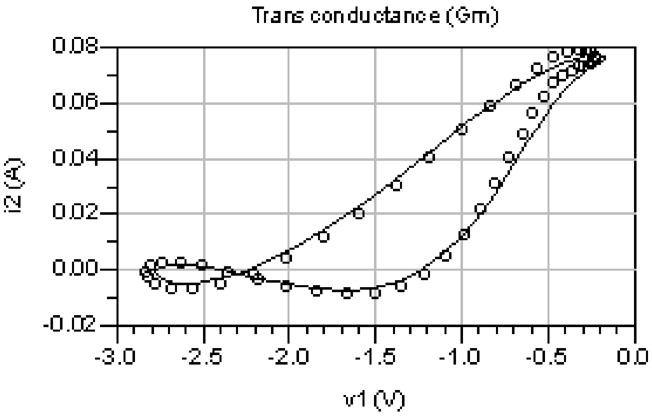
Frequency = 2 GHz, VDC1= -1.3 V, VDC2= +2.0 V, Pa1 = +10.0 dBm

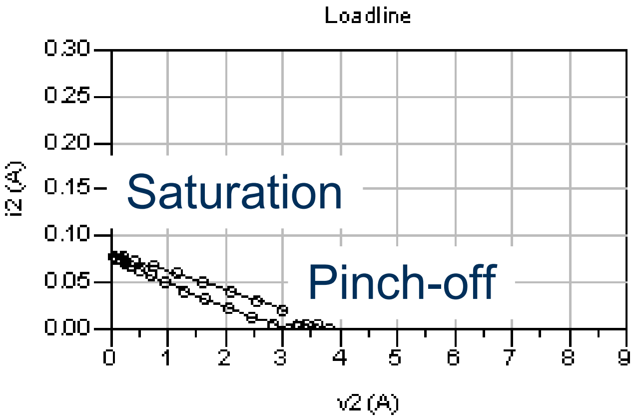
circles – measurements
solid lines - simulations









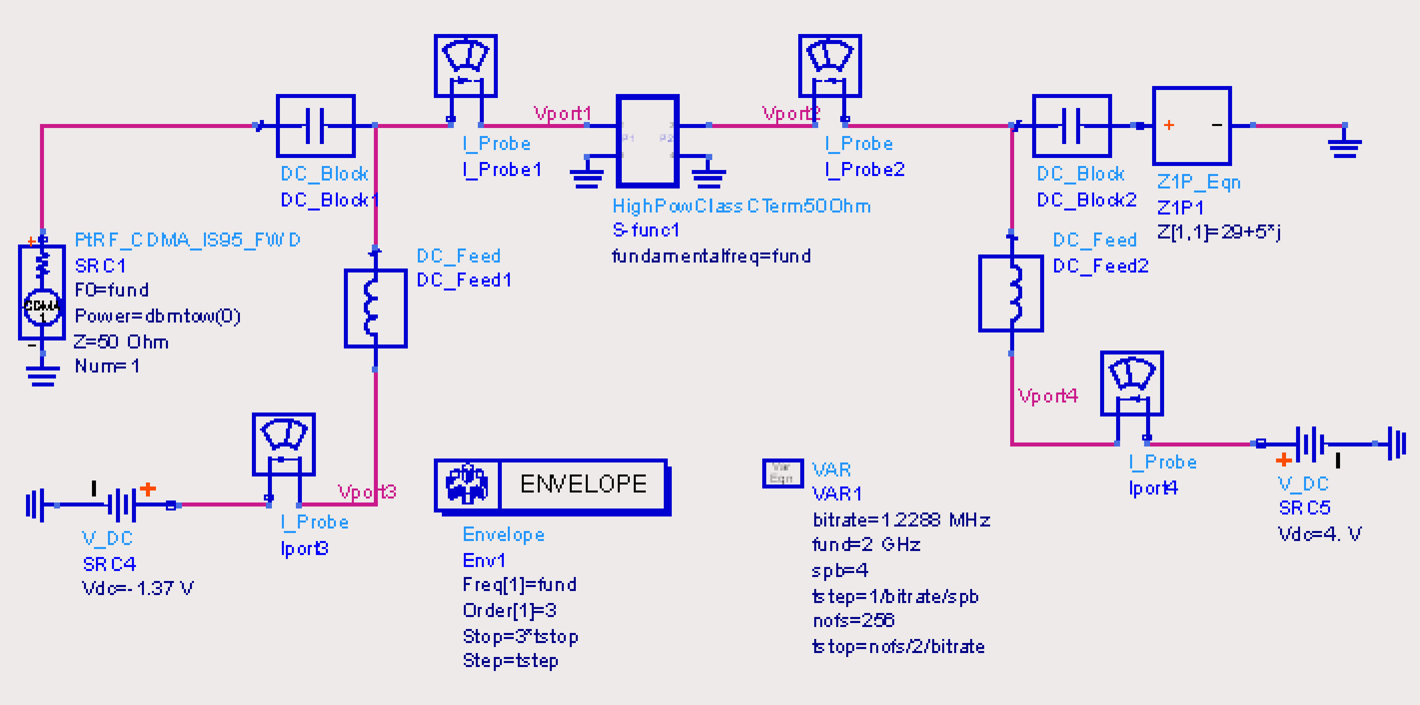


Saturation

Pinch-off

S-functions in ADS – Modulation Prediction - Schematic

Frequency = 2 GHz, VDC1= -1.37 V, VDC2= +4.0 V, Pa1 = +0.0 dBm – Class C



SRC1
F0=fund
Power=dbmtow(0)
Z=50 Ohm
Num=1

S-func1
fundamentalfreq=fund

Z1P1
Z[1,1]=29+5*j

SRC4
Vdc=-1.37 V

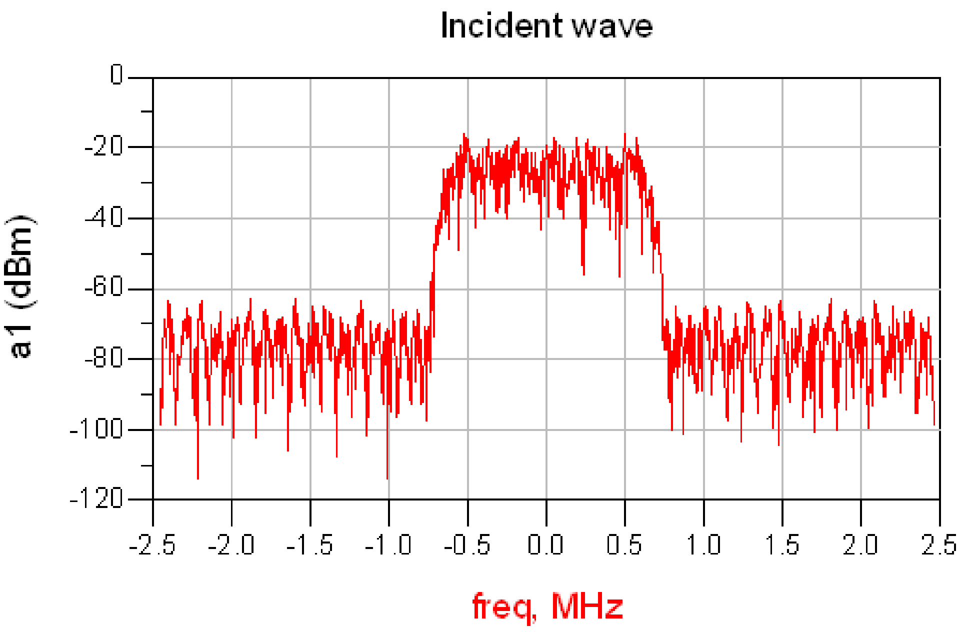
Env1
Freq[1]=fund
Order[1]=3
Stop=3*tstop
Step=tstep

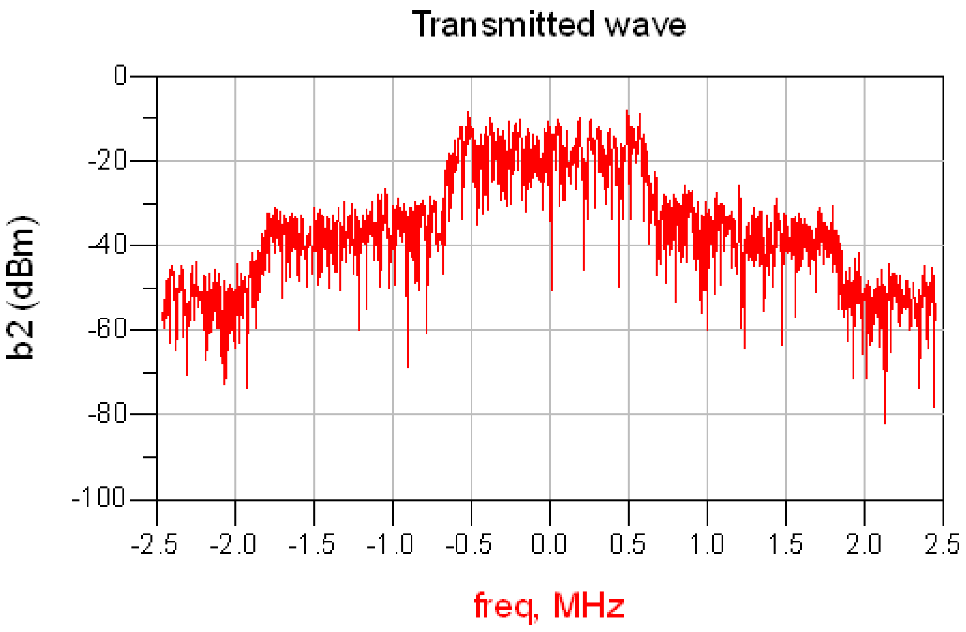
VAR1
bitrate=1.2288 MHz
fund=2 GHz
spb=4
tstep=1/bitrate/spb
nofs=256
tstop=nofs/2/bitrate

SRC5
Vdc=4. V

S-functions in ADS – Modulation Prediction - Display

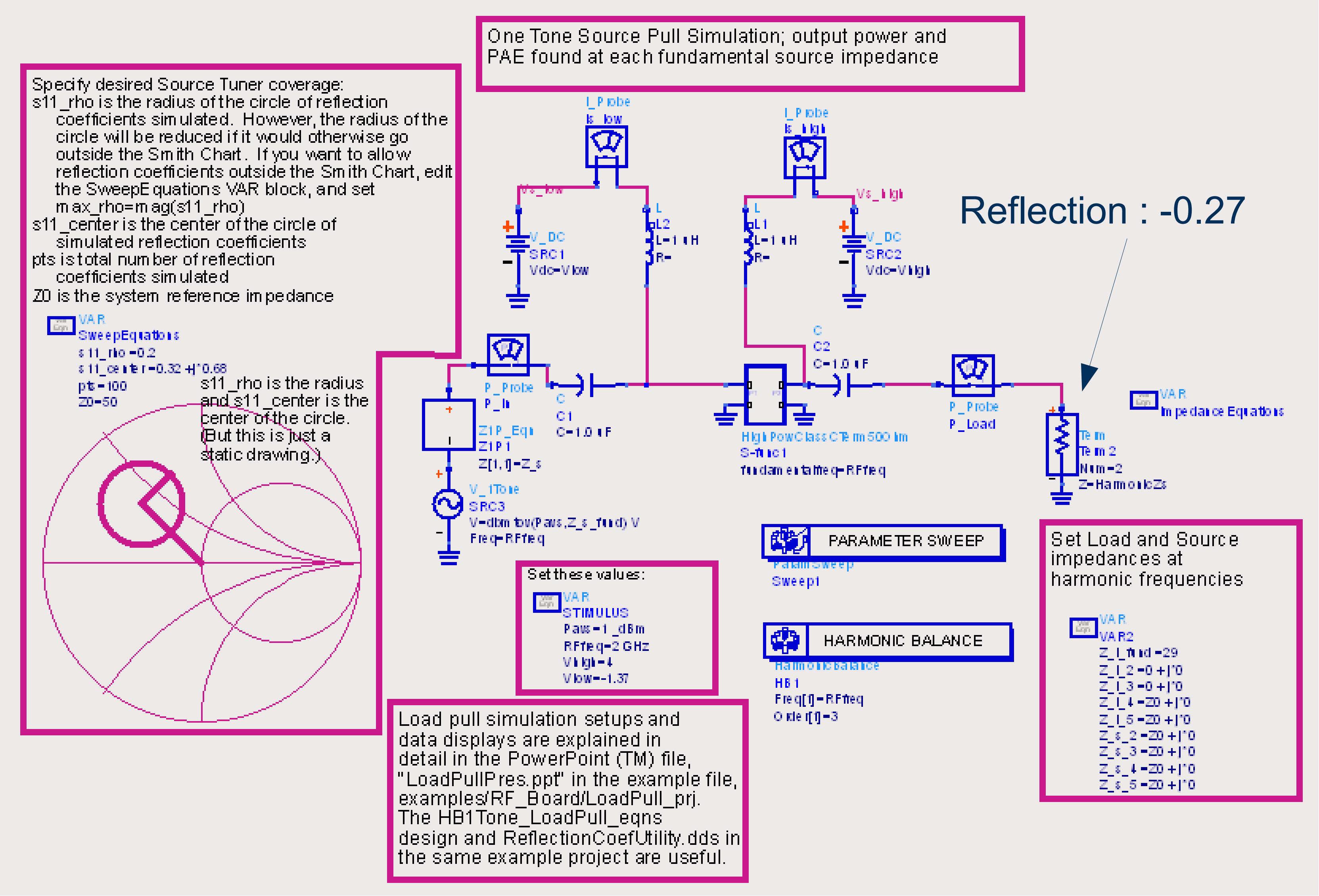
Frequency = 2 GHz, VDC1= -1.37 V, VDC2= +4.0 V, Pa1 = +0.0 dBm – Class C


Incident wave


Transmitted wave

S-functions in ADS – Source-Pull - Schematic

Frequency = 2 GHz, VDC1= -1.37 V, VDC2= +4.0 V, Pav = +1.0 dBm – Class C



Specify desired Source Tuner coverage:
s11_rho is the radius of the circle of reflection coefficients simulated. However, the radius of the circle will be reduced if it would otherwise go outside the Smith Chart. If you want to allow reflection coefficients outside the Smith Chart, edit the SweepEquations VAR block, and set max_rho=mag(s11_rho)
s11_center is the center of the circle of simulated reflection coefficients
pts is total number of reflection coefficients simulated
Z0 is the system reference impedance

VAR
SweepEquations
s11_rho=0.2
s11_center=0.32+j*0.68
pts=100
Z0=50

s11_rho is the radius and s11_center is the center of the circle. (But this is just a static drawing.)

One Tone Source Pull Simulation; output power and PAE found at each fundamental source impedance

Set these values:

VAR
STIMULUS
Pavs=1 _dBm
RFfreq=2 GHz
Vhigh=4
Vlow=-1.37

Load pull simulation setups and data displays are explained in detail in the PowerPoint (TM) file, "LoadPullPres.ppt" in the example file, examples/RF_Board/LoadPull_prj. The HB1Tone_LoadPull_eqns design and ReflectionCoefUtility.dds in the same example project are useful.

PARAMETER SWEEP
ParamSweep
Sweep1

HARMONIC BALANCE
HarmonicBalance
HB1
Freq[1]=RFfreq
Order[1]=3

Set Load and Source impedances at harmonic frequencies

VAR
VAR2
Z_l_fund=29
Z_l_2=0+j*0
Z_l_3=0+j*0
Z_l_4=Z0+j*0
Z_l_5=Z0+j*0
Z_s_2=Z0+j*0
Z_s_3=Z0+j*0
Z_s_4=Z0+j*0
Z_s_5=Z0+j*0

VAR
ImpedanceEquations

I_Probe
Is_low
Vs_low
V_DC
SRC1
Vdc=Vlow

L
L2
L=1 uH
R=

I_Probe
Is_high
Vs_high
L
L1
L=1 uH
R=
V_DC
SRC2
Vdc=Vhigh

P_Probe
P_In
C
C1
C=1.0 uF
Z1P_Eqn
Z1P1
Z[1,1]=Z_s
V_1Tone
SRC3
V=dbmtov(Pavs,Z_s_fund) V
Freq=RFfreq

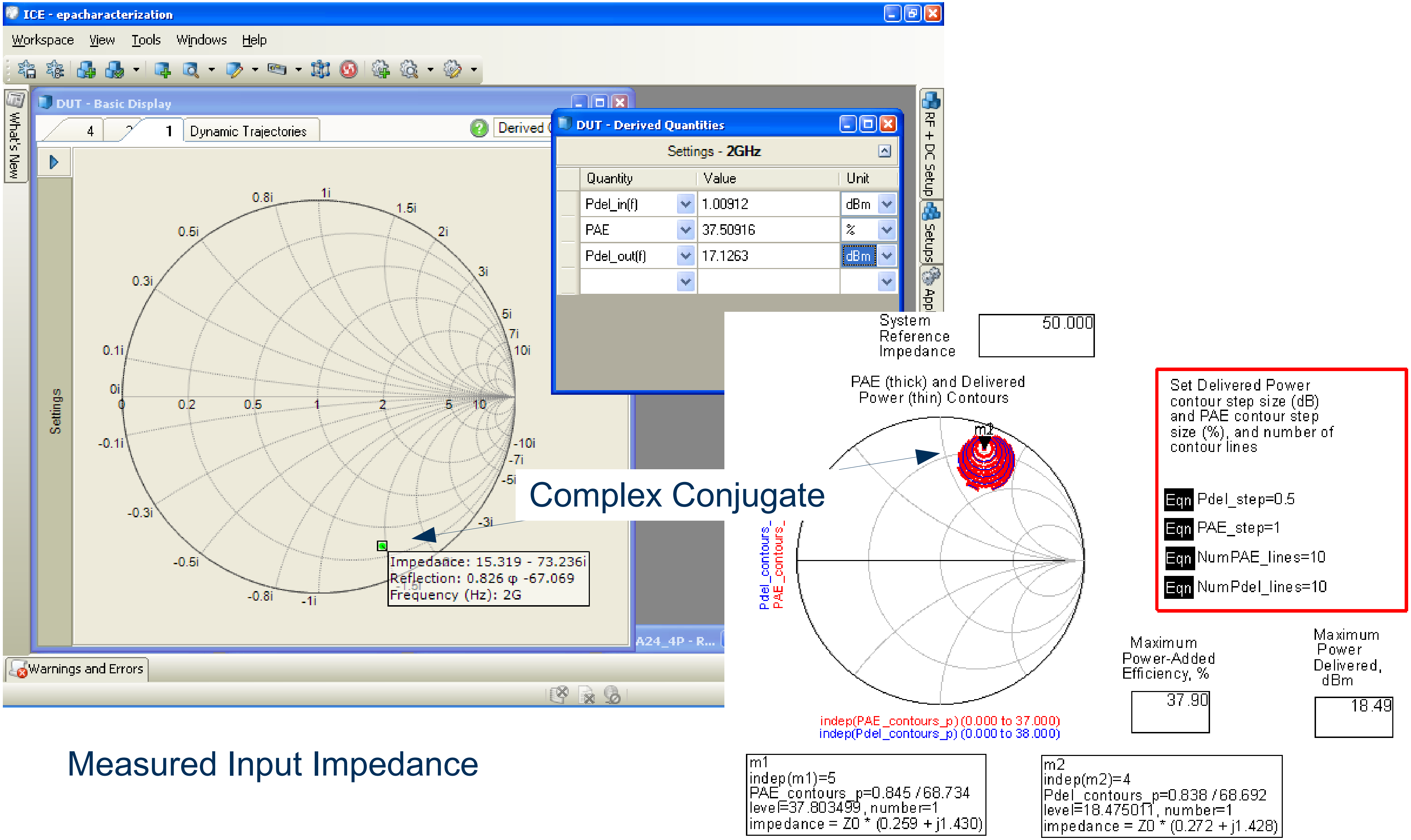
HighPowClassCTerm50Ohm
S-func1
fundamentalfreq=RFfreq

C
C2
C=1.0 uF
P_Probe
P_Load
Term
Term2
Num=2
Z=HarmonicZs

Reflection : -0.27

S-functions in ADS – Source-Pull - Schematic

Frequency = 2 GHz, VDC1= -1.37 V, VDC2= +4.0 V, Pav = +1.0 dBm – Class C



DUT - Derived Quantities

Settings - 2GHz

Quantity	Value	Unit
Pdel_in(f)	1.00912	dBm
PAE	37.50916	%
Pdel_out(f)	17.1263	dBm

Impedance: 15.319 - 73.236i
Reflection: 0.826 φ -67.069
Frequency (Hz): 2G

Complex Conjugate

Set Delivered Power contour step size (dB) and PAE contour step size (%), and number of contour lines

Eqn Pdel_step=0.5
Eqn PAE_step=1
Eqn NumPAE_lines=10
Eqn NumPdel_lines=10

m1
indep(m1)=5
PAE_contours_p=0.845 / 68.734
level=37.803499, number=1
impedance = Z0 * (0.259 + j1.430)

m2
indep(m2)=4
Pdel_contours_p=0.838 / 68.692
level=18.475011, number=1
impedance = Z0 * (0.272 + j1.428)

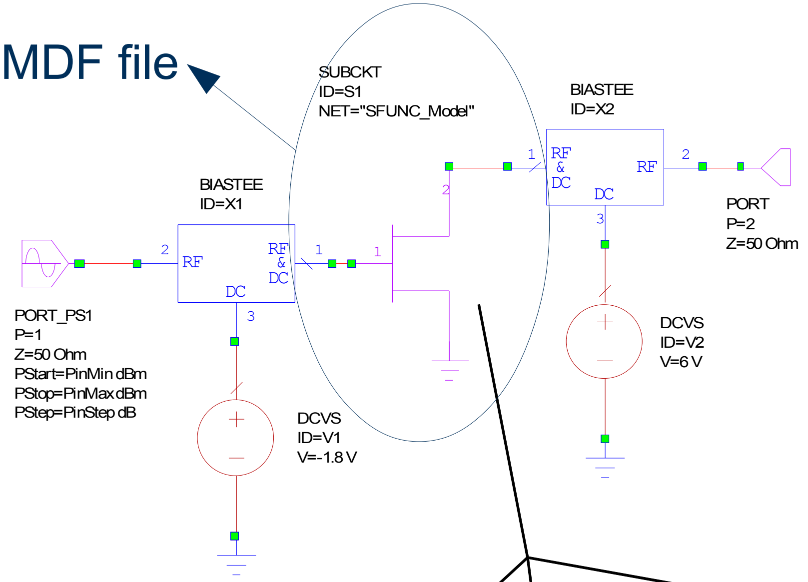
Measured Input Impedance

S-functions in MWO

Acknowledgement:
With the support from AWR providing MWO / VSS licensing

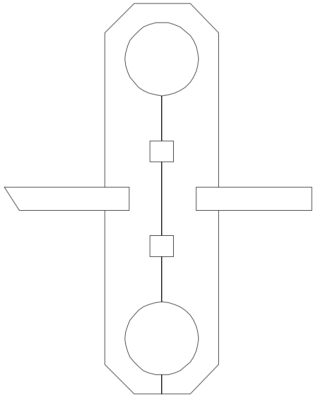
S-functions Usage in AWR MWO

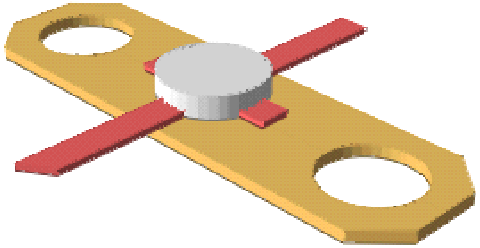
MDF file



Model data

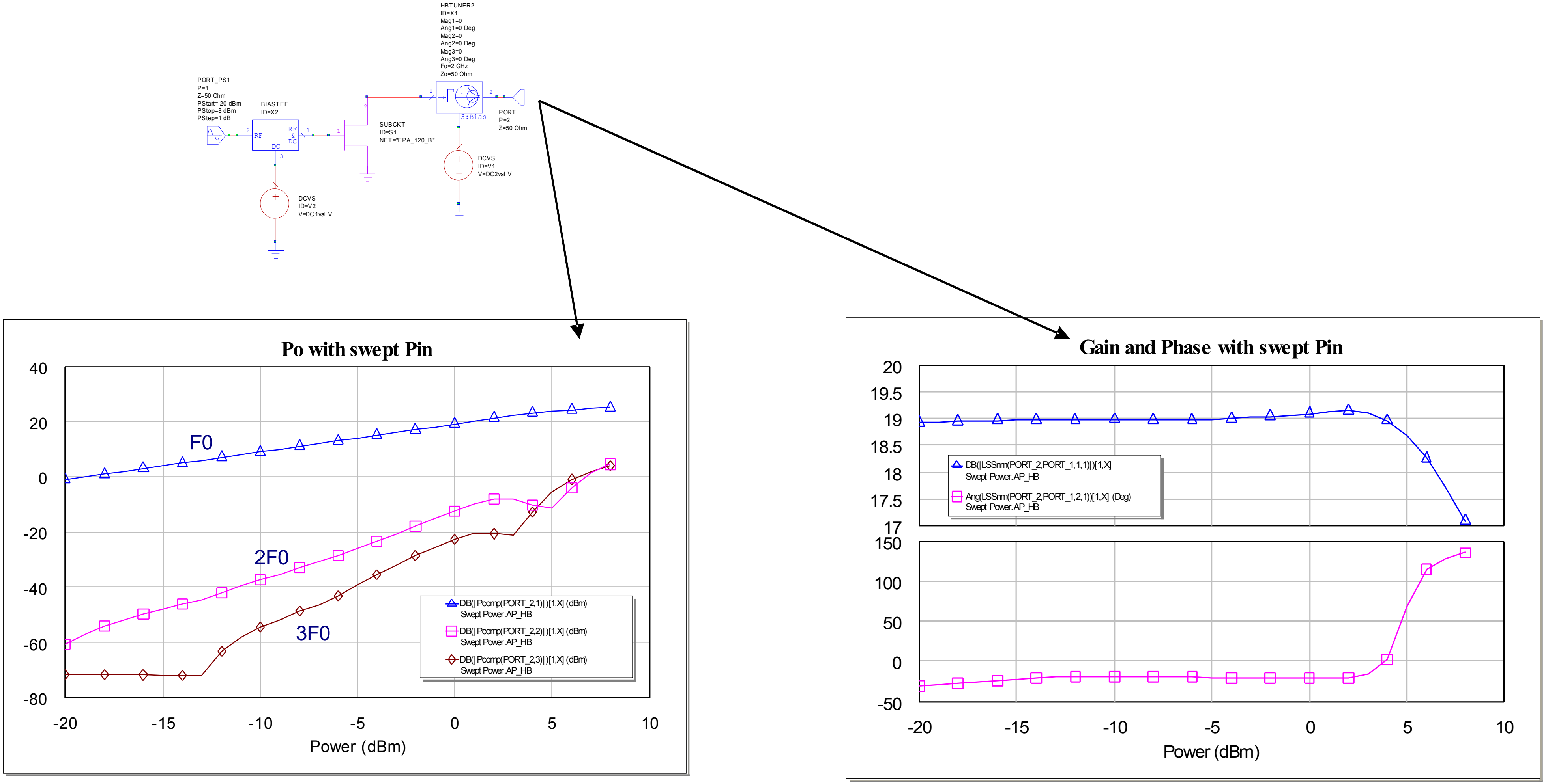
```
..
..
1.16226472890446E-16,-1.35308431126191E-16
-3.15025783237388E-15,4.72191730160887E-15
9.71445146547012E-17,-2.37310171513627E-15
1.51267887105178E-15,1.07899800205757E-15
-2.98198965520413E-15,1.59594559789866E-15
-5.759281940243E-16,-1.97758476261356E-16
-1.83880688453542E-15,1.92901250528621E-15
-5.06539254985228E-16,2.94209101525666E-15
-2.50494069931051E-15,-6.73072708679001E-16
-8.60422844084496E-16,2.65412691824451E-16
-2.019218126037E-15,2.7373936450914E-15
-2.28289609438548E-15,1.70870262383715E-15
1.08246744900953E-15,-6.78276879106932E-16
-1.02955838299224E-15,-1.31578775652841E-15
5.45570533194706E-16,3.99333344169861E-15
-3.62904151174348E-15,-1.74860126378462E-15
-2.00100352953925E-15,-5.68989300120393E-16
2.14975606760426E-15,-5.53376788836601E-16
-1.16226472890446E-15,-2.44942954807925E-15
2.08166817117217E-16,2.4980018054066E-15
1.04372118124342E-05,-1.36061371223614E-05
2.85882428840978E-15,3.11556336285435E-15
-2.15105711021124E-16,1.37390099297363E-15
9.71445146547012E-16,9.95731275210687E-16
-1.69309011255336E-15,2.33146835171283E-15
4.27435864480685E-15,3.3584246494911E-15
-1.08246744900953E-15,-8.60422844084496E-16
…
```



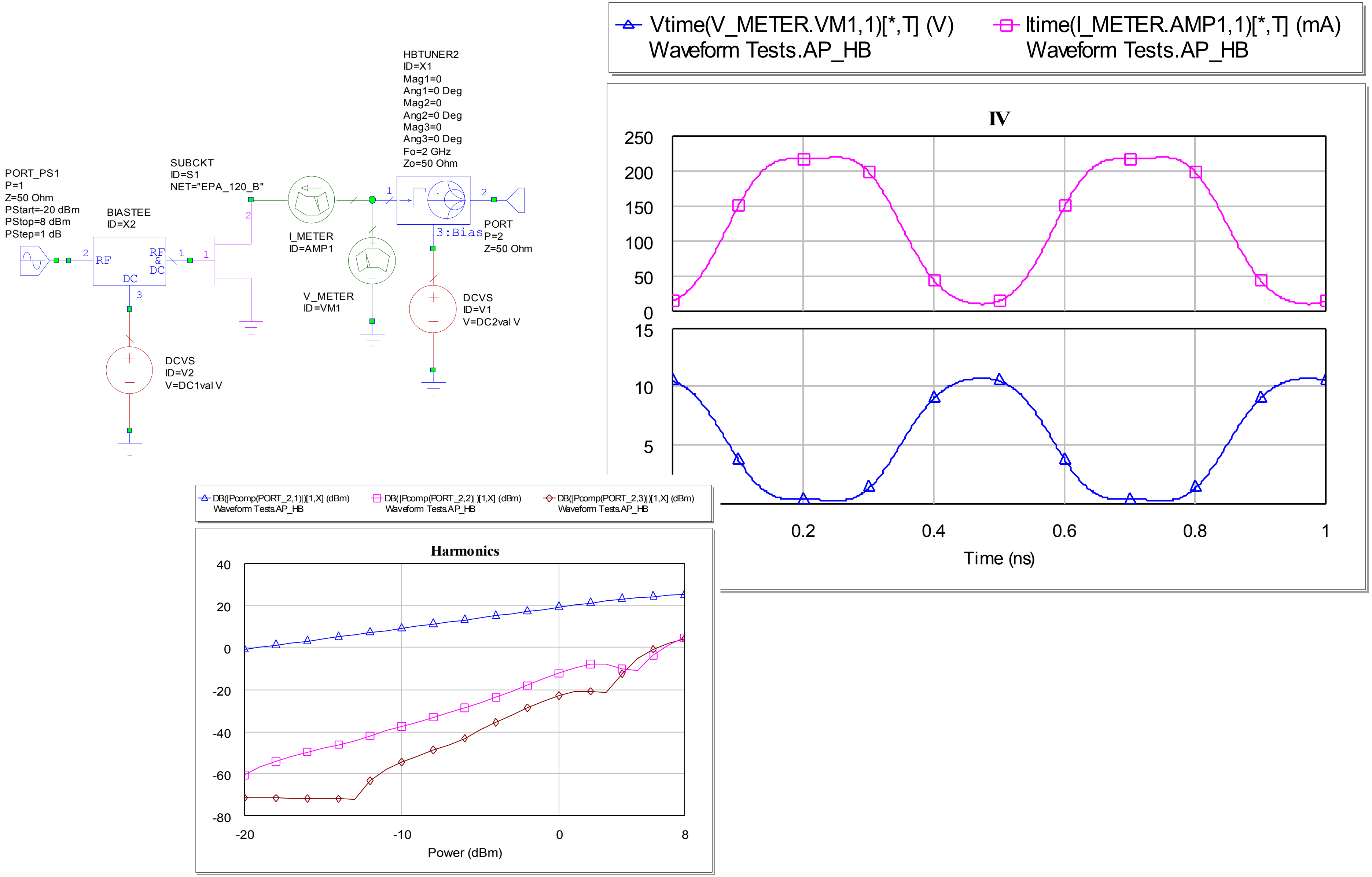


2D and 3D package data

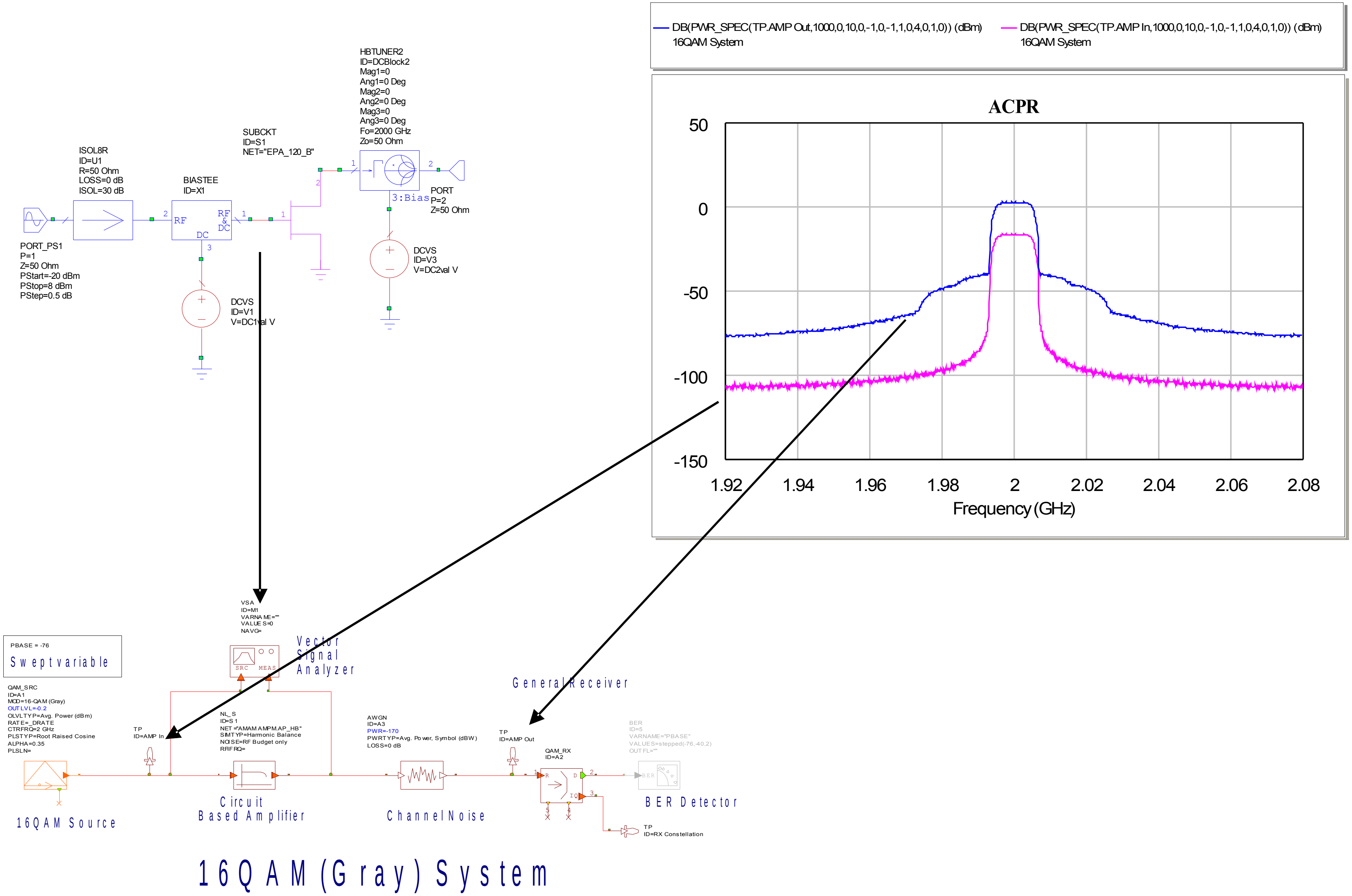
S-functions Verification in MWO - Frequency Domain



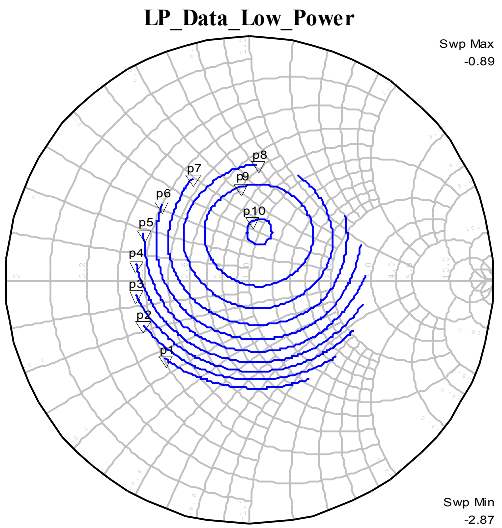
S-functions Verification in MWO - Time Domain



S-functions in MWO – Modulation Prediction - Schematic

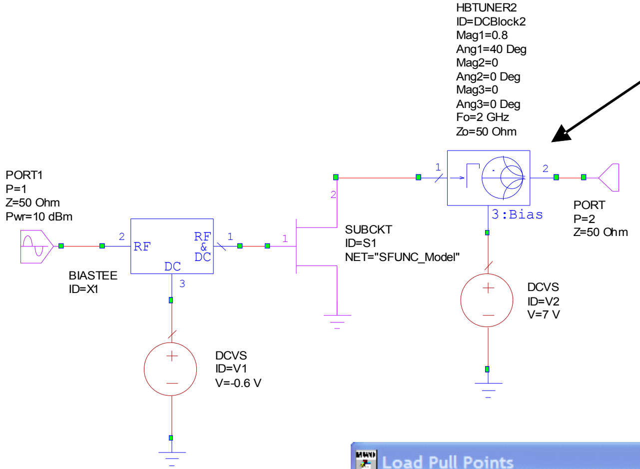


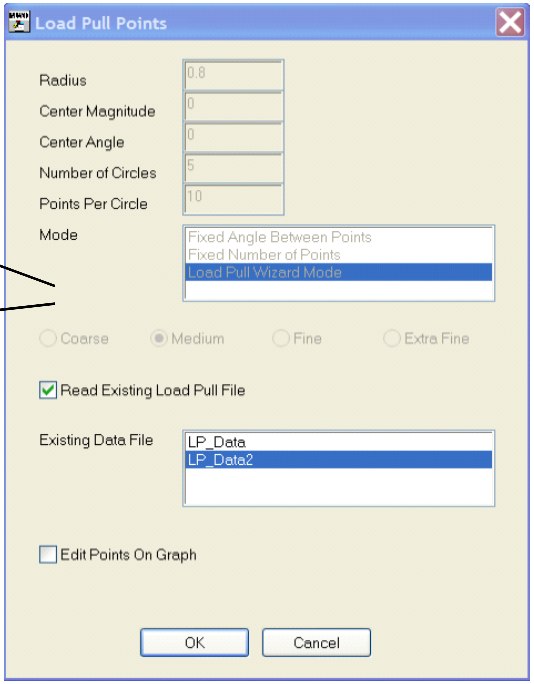
S-functions in MWO – Load-Pull



p1: Pcomp_PORT_2_1_M_DB = -2.87
p2: Pcomp_PORT_2_1_M_DB = -2.65
p3: Pcomp_PORT_2_1_M_DB = -2.43
p4: Pcomp_PORT_2_1_M_DB = -2.21
p5: Pcomp_PORT_2_1_M_DB = -1.99
p6: Pcomp_PORT_2_1_M_DB = -1.77
p7: Pcomp_PORT_2_1_M_DB = -1.55
p8: Pcomp_PORT_2_1_M_DB = -1.33
p9: Pcomp_PORT_2_1_M_DB = -1.11
p10: Pcomp_PORT_2_1_M_DB = -0.89

Load Tuner (and bias)





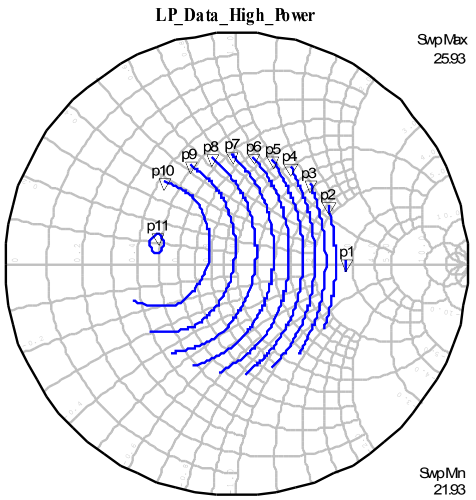
Radius 0.8
Center Magnitude 0
Center Angle 0
Number of Circles 5
Points Per Circle 10
Mode
Fixed Angle Between Points
Fixed Number of Points
Load Pull Wizard Mode

○ Coarse ● Medium ○ Fine ○ Extra Fine

☑ Read Existing Load Pull File

Existing Data File
LP_Data
LP_Data2

☐ Edit Points On Graph



p1: Pcomp_PORT_2_1_M_DB = 21.93
p2: Pcomp_PORT_2_1_M_DB = 22.33
p3: Pcomp_PORT_2_1_M_DB = 22.73
p4: Pcomp_PORT_2_1_M_DB = 23.13
p5: Pcomp_PORT_2_1_M_DB = 23.53
p6: Pcomp_PORT_2_1_M_DB = 23.93
p7: Pcomp_PORT_2_1_M_DB = 24.33
p8: Pcomp_PORT_2_1_M_DB = 24.73
p9: Pcomp_PORT_2_1_M_DB = 25.13
p10: Pcomp_PORT_2_1_M_DB = 25.53
p11: Pcomp_PORT_2_1_M_DB = 25.93

S-functions Strengths

- S-functions are completely public
- S-functions are transparent
- S-functions are connected into ADS and MWO and can be connected in other tools on request, e.g. Matlab
- S-functions are closely integrated with load-pull in general and especially with tuners from Focus Microwave
- S-functions extraction tool has a verification capability for LSOP constantness and interpolation capability, investigating quality of model, without needing a simulation tool
- The source- and load-pull software ICEBreaker from NMDG allows S-function verification, related to the linearity assumption
- Customers can explore the capabilities of S-functions via NMDG services

S-Functions - Key Capabilities

- **Natural extension of S-parameters**
  - Reduce to S-parameters for small-signal excitation
  - S-parameters are cascadeable, S-Functions are cascadeable too
  - e.g. Transistors, amplifiers, dividers, multipliers

- **Predict harmonic behaviour of components under different impedances**
  - Source – Pull
  - Load – Pull
  - Harmonic distortion, Waveforms

- **Predict modulation behaviour of components under different impedances**
  - When no long-term memory effects

- **Valid for multi-ports, applicable to differential components**

References

- F. Verbeyst and M. Vanden Bossche, “VIOMAP, the S-parameter equivalent for weakly nonlinear RF and microwave devices”, published in the *Microwave Symposium Digest of IEEE 1994 MTT-S International* and published in the *1994 Special Symposium Issue of the MTT Transactions*, vol. 42, no. 12, pp. 2531 – 2535.
- F. Verbeyst and M. Vanden Bossche, “VIOMAP, 16QAM and Spectral Regrowth: Enhanced Prediction and Predistortion based on Two-Tone Black-Box Model Extraction”, published in the *Proceedings of the 45th ARFTG Conference*, Orlando, June 1995 and winner of the “Best Conference Paper Award”.
- J. Verspecht and P. Van Esch, “Accurately characterizating of hard nonlinear behaviour of microwave components by the Nonlinear Network Measurement System: introducing the nonlinear scattering function,” *Proc. International Workshop on Integrated Nonlinear Microwave and Millimiterwave Circuits* (INMMiC), October 1998, pp.17-26.
- J. Verspecht, “Scattering functions for nonlinear behavioral modeling in the frequency domain,” *IEEE MTT-S Int. Microwave Symp. Workshop*, June 2003.
- J. Verspecht and D.E. Root “Polyharmonic Distortion Modeling,” *IEEE Microwave Magazine*, vol.7 no.3, June 2006, pp.44-57.
- D.E. Root, J. Horn, L. Betts, C. Gillease, and J. Verspecht, ”X-Parameters: The new paradigm for measurement, modeling, and design of nonlinear RF and microwave components,” *Microwave Engineering Europe*, December 2008, pp. 16-21.

Conclusion

- S-functions are a natural extension to S-parameters for nonlinear behaviour
- S-functions aren't much more complex than S-parameters
- S-functions are accurate when assumptions are not violated
    - Linearity assumption
- S-function extraction is supported on R&S network analysers
- S-functions can be coupled into ADS and MWO
- S-functions can be used to compress or hide specifics of nonlinear circuits in ADS and MWO

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