KATHOLIEKE UNIVERSITEIT LEUVEN

NMDG LEADING BEYOND S-PARAMETERS

Using Large-Signal Measurements for Transistor Characterization and Model Verification in a Device Modeling Program

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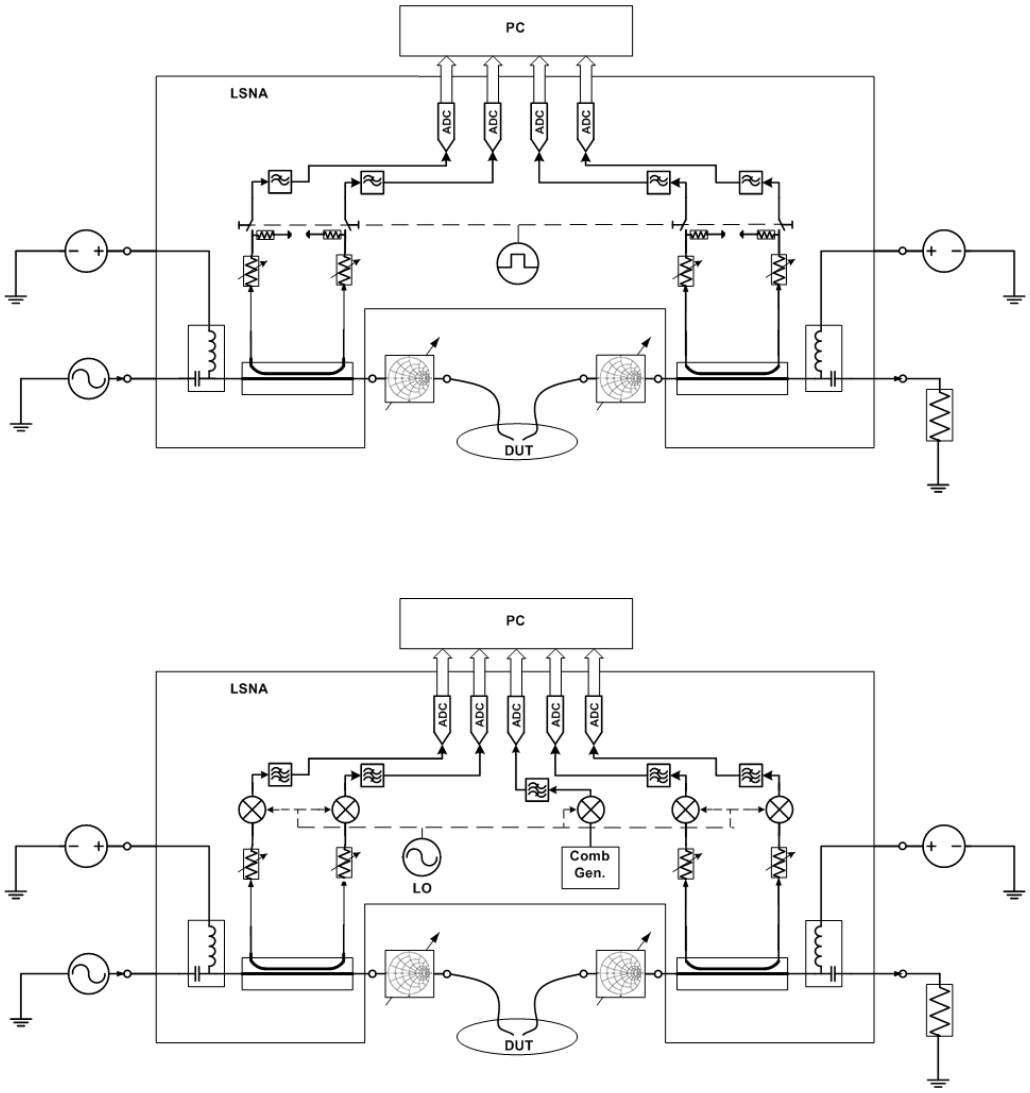
Outline

- Introduction
- Large-signal measurement data in a device modeling program
  - Example: IC-CAP
- Transistor characterization
  - Example: MOSFET
- Model verification
  - Example: Angelov model
- Results
- Conclusions

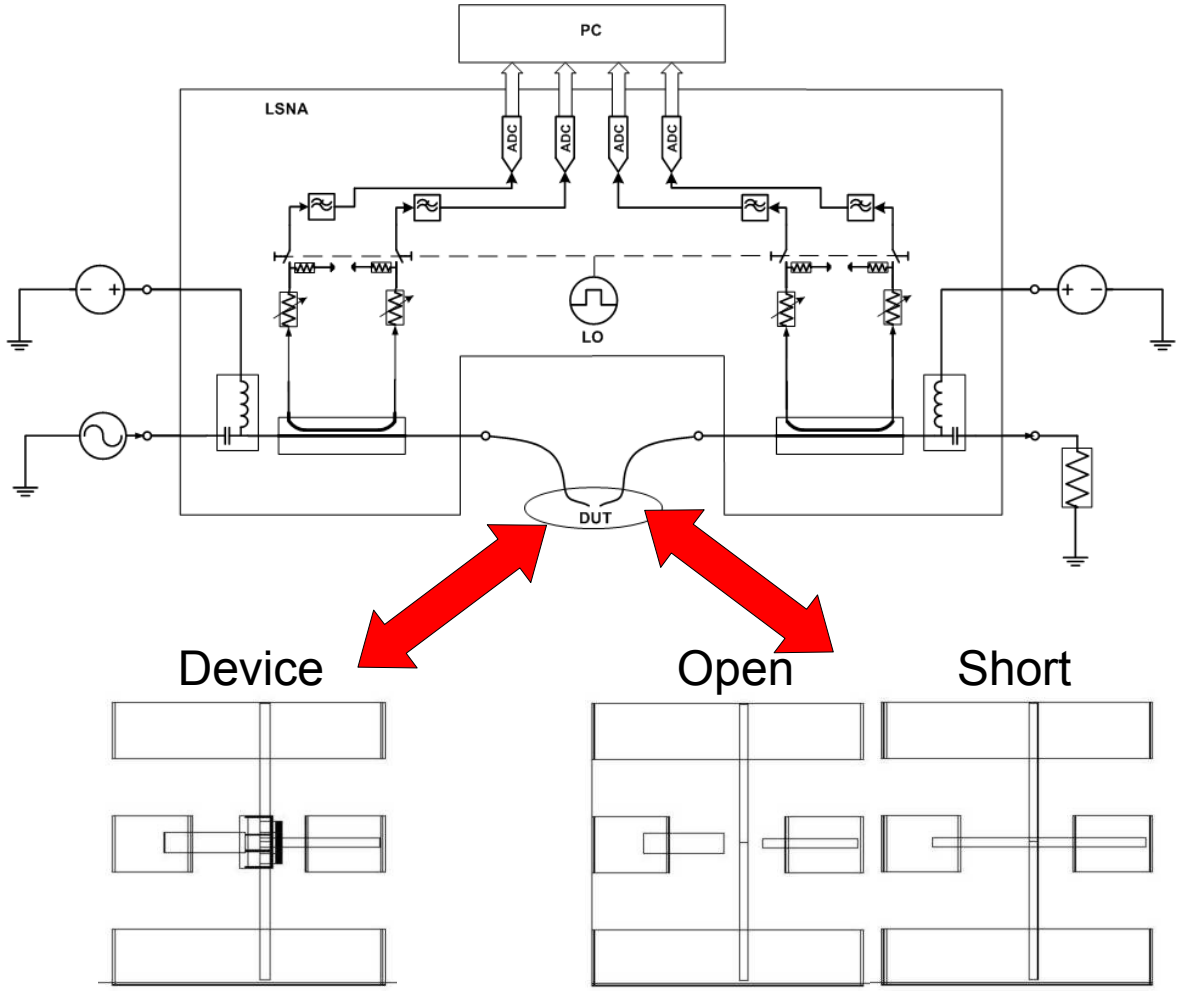
Introduction

- Large-signal network analyzer (LSNA)
  - Amplitude and phase of all harmonics and intermods up to 50 GHz
  - Realistic signals: 1-tone, 2-tone, N-tone up to +40 dBm
    - DC, small-signal, large-signal behavior
  - Non-50 Ω environment
  - Sampler/Mixer-based



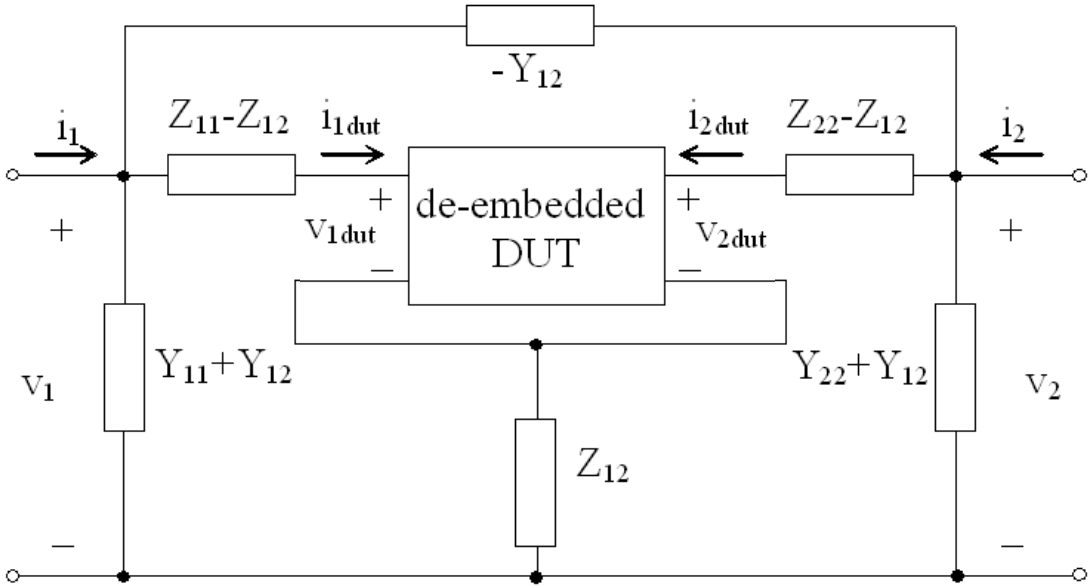
LSNA data in IC-CAP

- Large-signal on-wafer measurements
  - Device:
    - Frequency sweep
    - RF power sweep
    - DC bias sweep
  - De-embedding structures:
    - Frequency sweep



LSNA data in IC-CAP

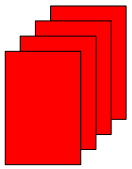
- Large-signal on-wafer measurements
- Data processing
  - De-embedding
  - Transformation to the program specific format



Y_{ij} → Y-parameters of open

Z_{ij} → Z-parameters of short, after de-embedding of open effects.

MDM files



$$i_{1dut} = i_1 - v_1(Y_{11} + Y_{12}) - (v_2 - v_1)Y_{12} = i_1 - v_1Y_{11} - v_2Y_{12}$$

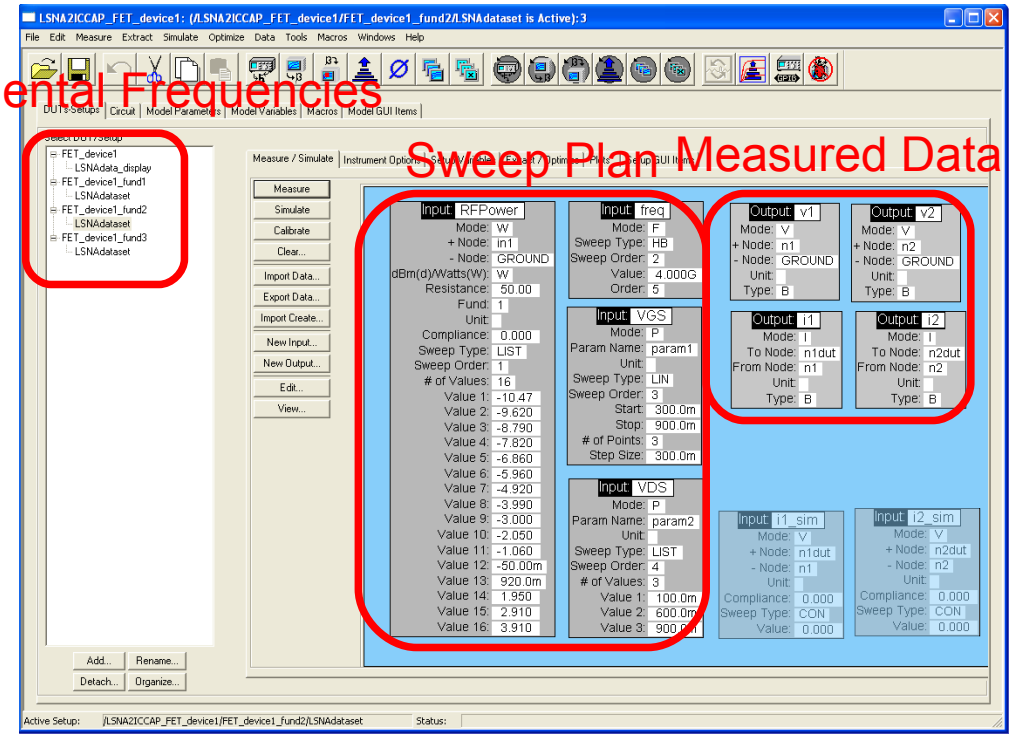
$$i_{2\,dut} = i_2 - v_2(Y_{22} + Y_{12}) - (v_1 - v_2)Y_{12} = i_2 - v_2Y_{22} - v_1Y_{12}$$

$$v_{1dut} = v_1 - i_{1dut}Z_{11} - i_{2dut}Z_{12}$$

$$v_{2\,dut} = v_2 - i_{2dut}Z_{22} - i_{1dut}Z_{12}$$

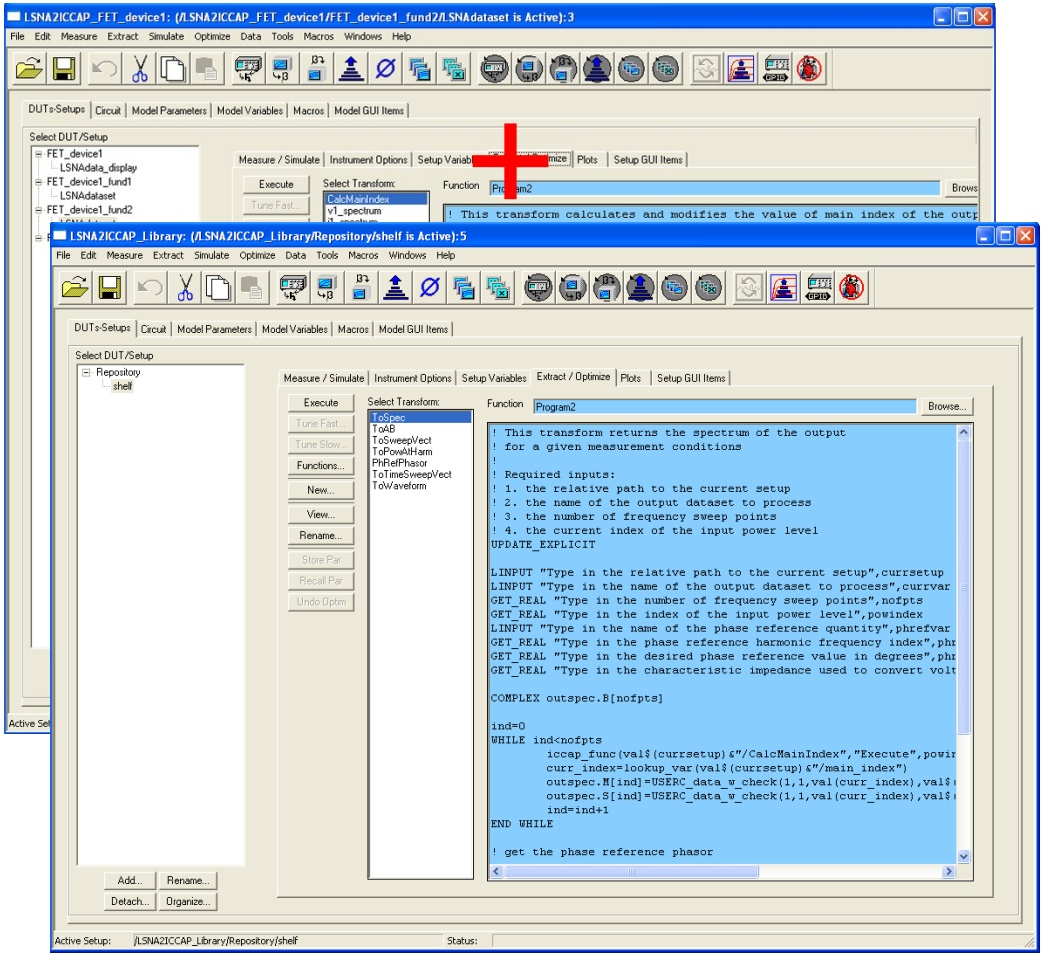
LSNA data in IC-CAP

- Large-signal on-wafer measurements
- Data processing
- Implementation in the device modeling program
  - Measured data



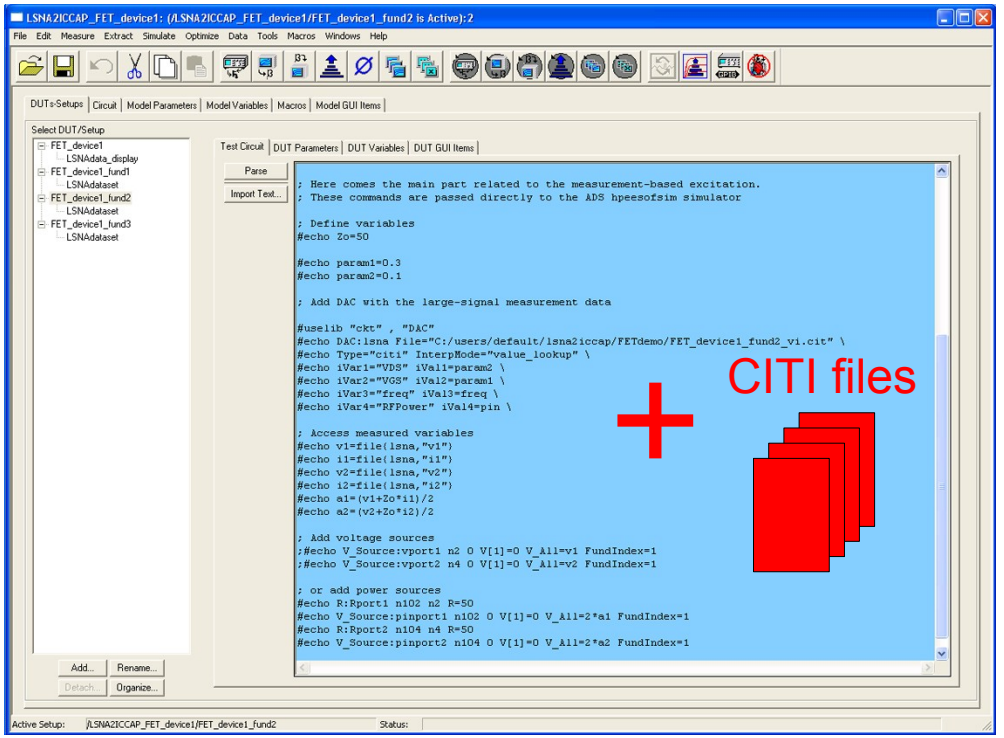
LSNA data in IC-CAP

- Large-signal on-wafer measurements
- Data processing
- Implementation in the device modeling program
  - Measured data
  - Data processing routines



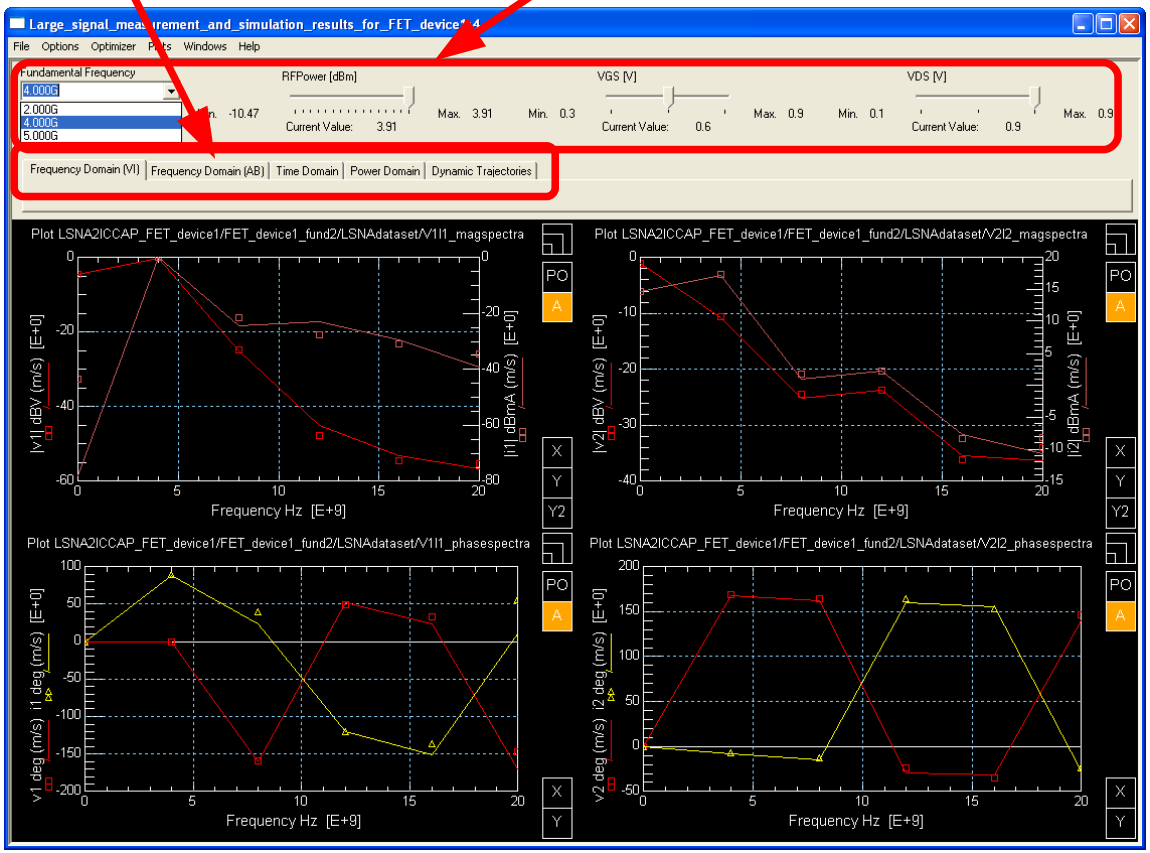
LSNA data in IC-CAP

- Large-signal on-wafer measurements
- Data processing
- Implementation in the device modeling program
  - Measured data
  - Data processing routines
  - Link to simulator



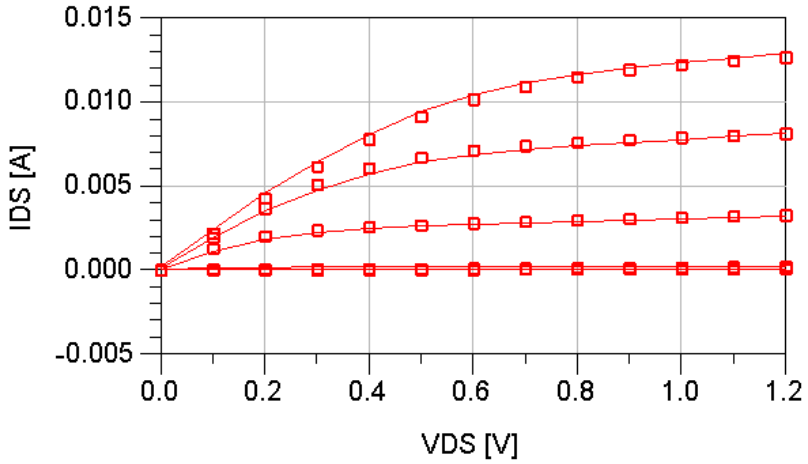
LSNA data in IC-CAP

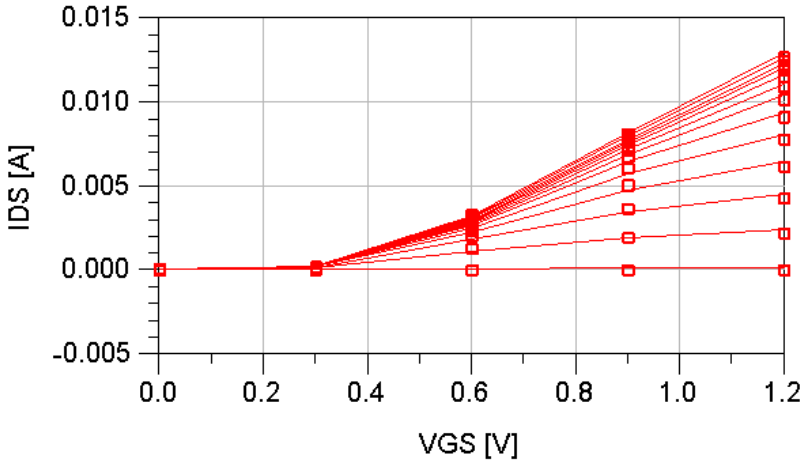
- Large-signal on-wafer measurements
- Data processing
- Implementation in the device modeling program
  - Measured data
  - Data processing routines
  - Link to simulator
  - Graphic user interface



Transistor Characterization

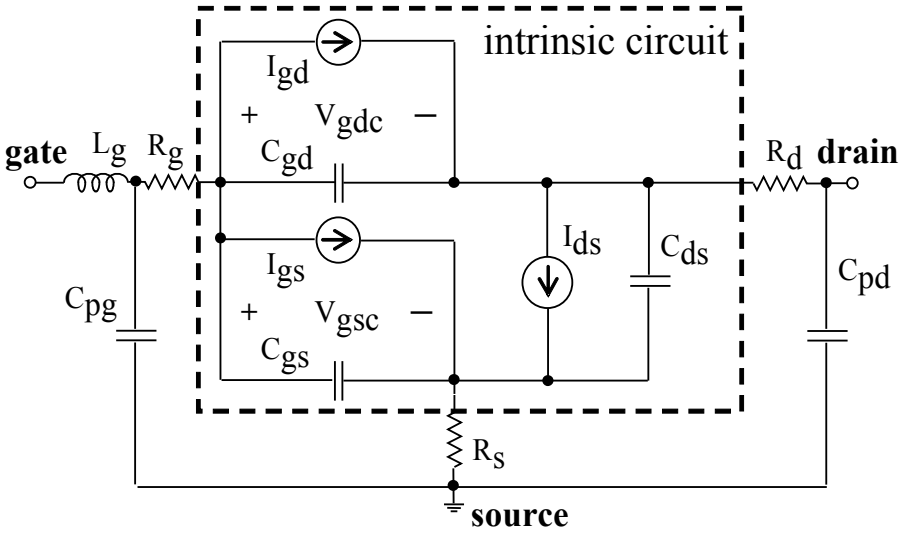
- On-wafer DUT:
  - MOSFET
  - Open & Short de-embedding structures
- LSNA measurements:
  - f_0: 2, 4, 5 GHz
  - P_{in}: -10 → +4 dBm
  - V_{GS}: 0.3, 0.6, 0.9 V
  - V_{DS}: 0.1, 0.6, 0.9 V





Model verification

- Angelov MOSFET model:
  - Neglected self-heating and intrinsic non quasi static effects,
  - Capacitance mode,
  - Extracted from DC and S-parameter measurements
  - Tuned around: V_{GS}=0.6 V, V_{DS}=0.9 V, f_0=4 GHz

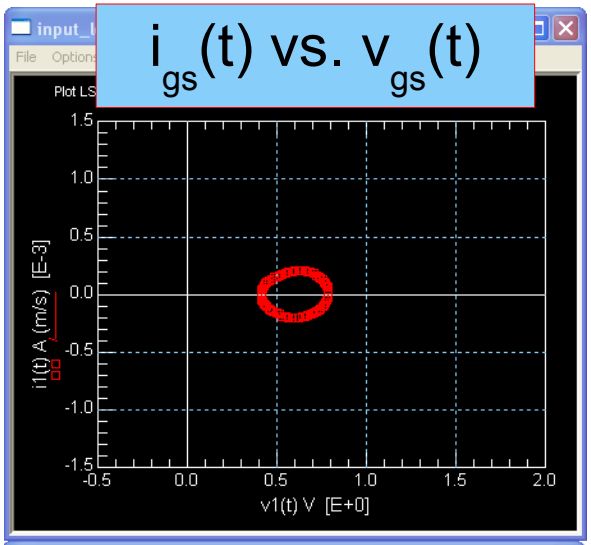


model AngelovM1 Angelov	B1=0	P31=0.54852	Rcmin=0kOhm
Idsmod=1	B2=3.92	P40=1.2	Rc=0kOhm
Igmod=1	Lsb0=0	P41=1.71519	Crf=35.3284fF
Capmod=1	Vtr=4	P111=0.001	Rcin=0kOhm
Ipk0=0.0066	Vsb2=0	Ij=0.0025	Crfin=0fF
Vpks=0.84	Cds=28.331fF	Pg=0.0002	Rth=50
Dvpks=0.027	Cgspi=2.6fF	Vjg=0.9	Cth=0
P1=2.5	Cgs0=5fF	Rg=22.4	Tcipk0=0
P2=0.1	Cgdpi=4.5446fF	Rd=10.7	Tcp1=0
P3=6.2	Cgd0=5.06055fF	Rs=11.2	Tccgs0=0
Alphar=2.5	Cgdpe=0fF	Ri=0	Tccgd0=0
Alphas=0.5	P10=1	Rgd=0	Tclsb0=0
Vkn=0.5	P11=1.71519	Lg=0pH	Tcrc=0
Lambda=0.1	P20=0.2	Ld=0	Tccrf=0
Lambda1=0.07	P21=0.54852	Ls=0	Tnom=25
Lvg=0	P30=0.25	Tau=0ps	

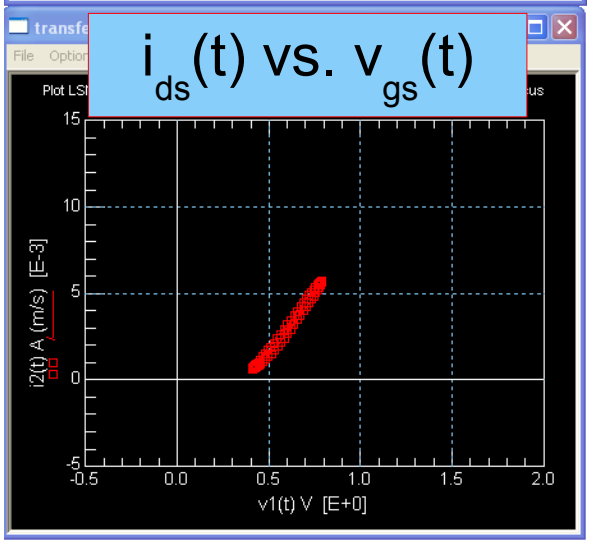
Results

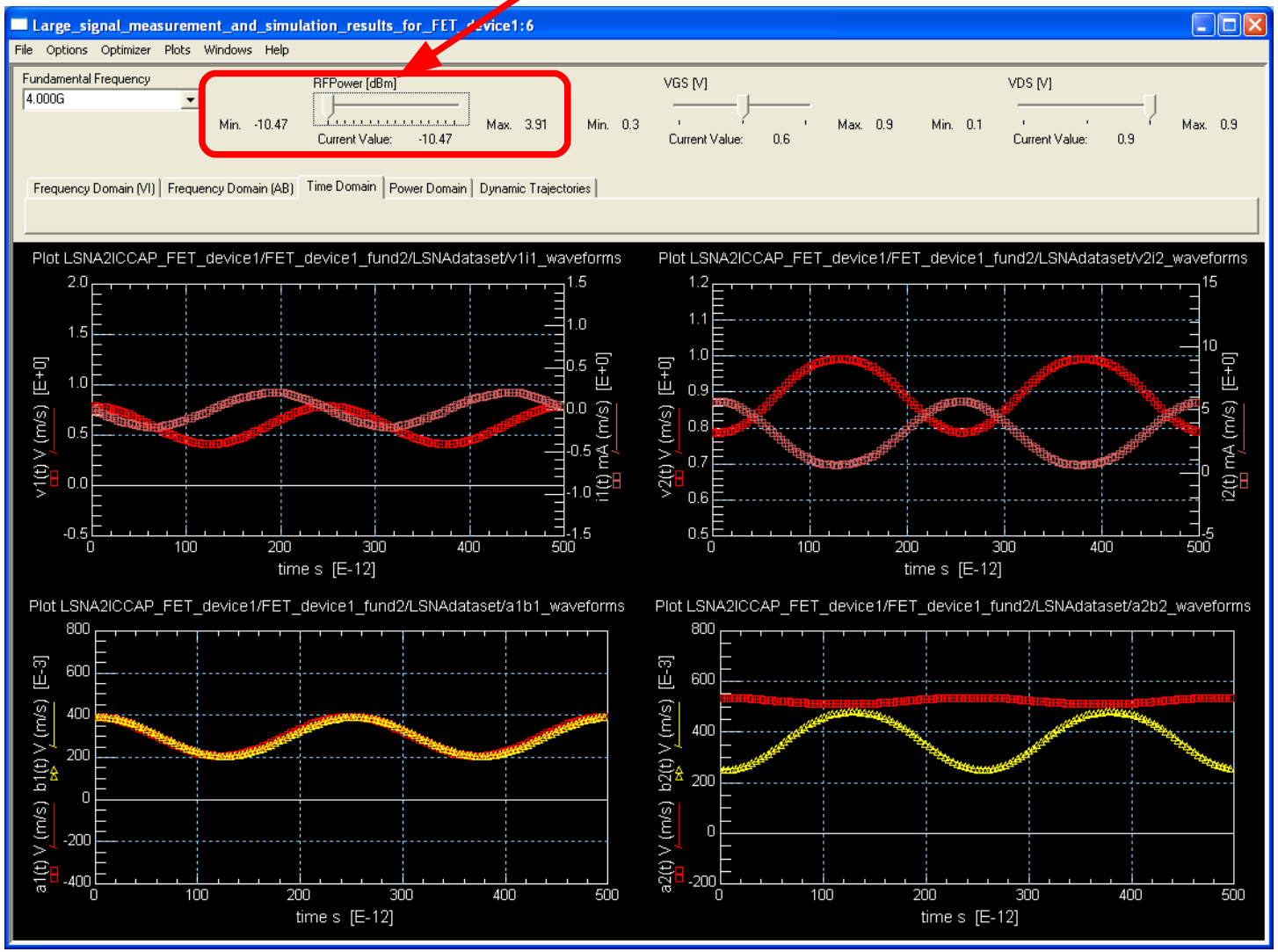
f_0 = 4 GHz, V_{GS} = 0.6 V, V_{DS} = 0.9 V, RF power: -10.47 → +3.91 dBm

$i_{gs}(t)$ vs. $v_{gs}(t)$



$i_{ds}(t)$ vs. $v_{gs}(t)$





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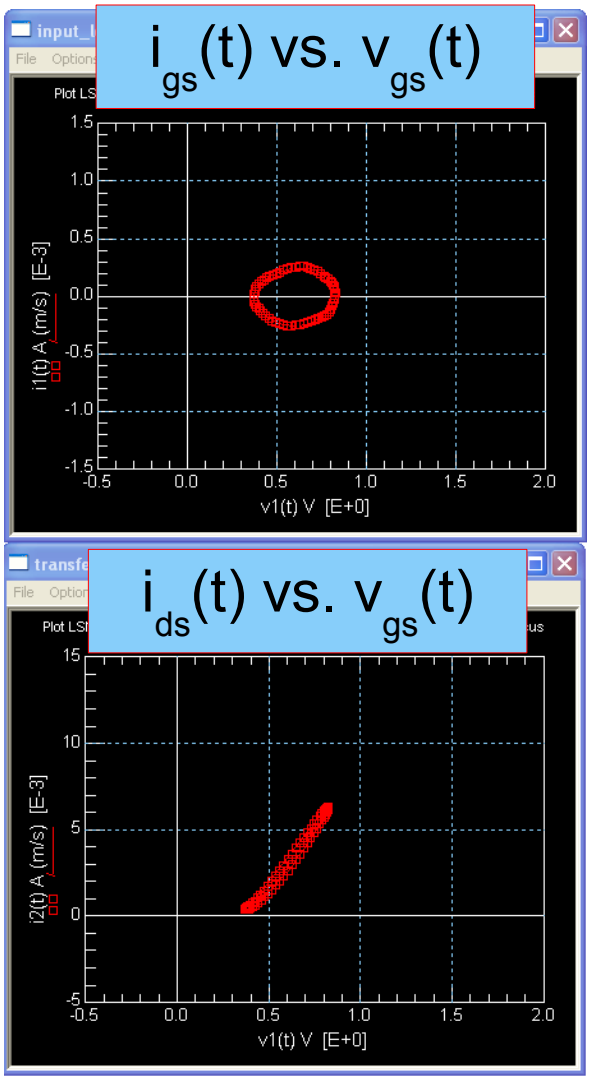

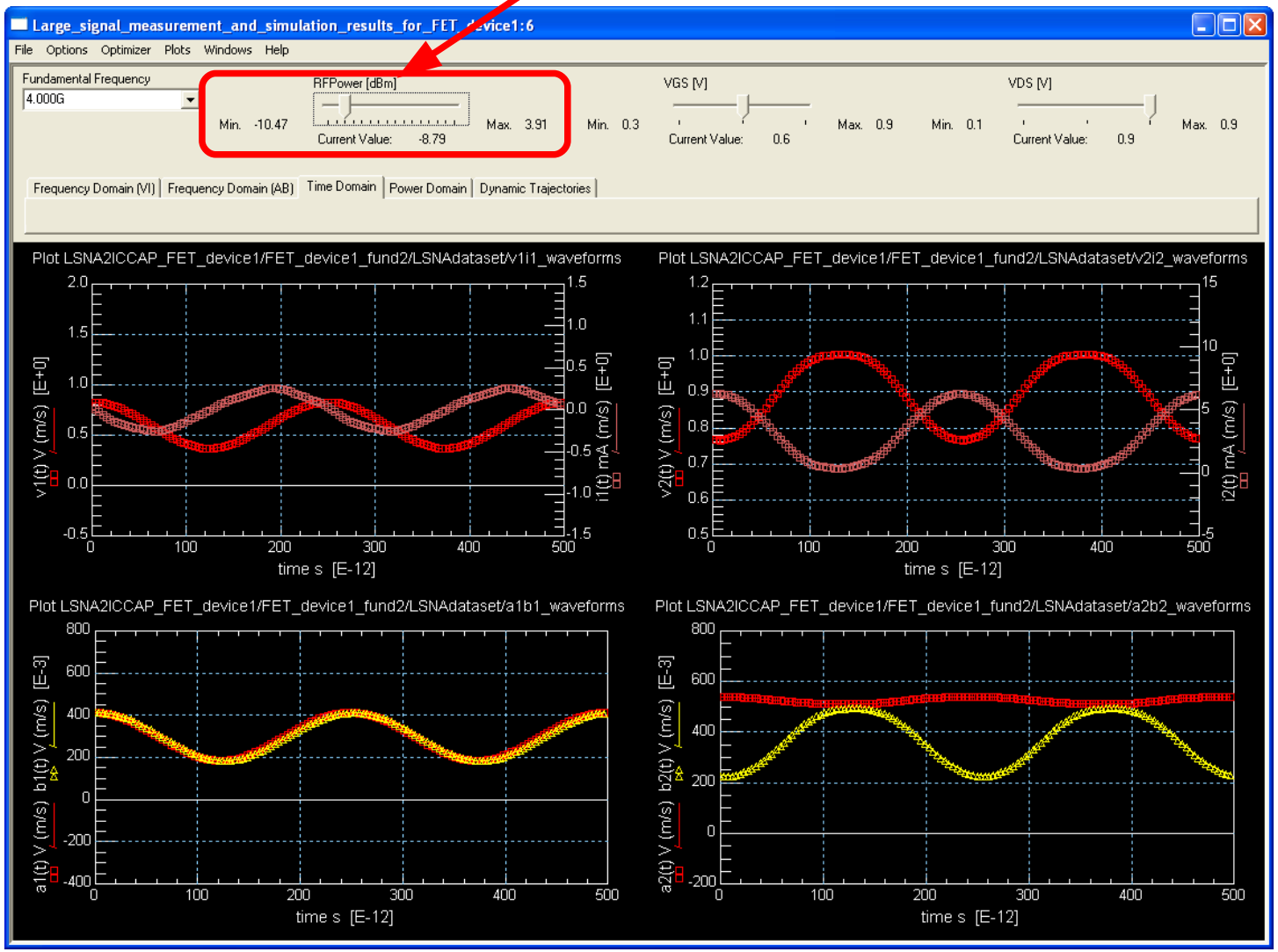

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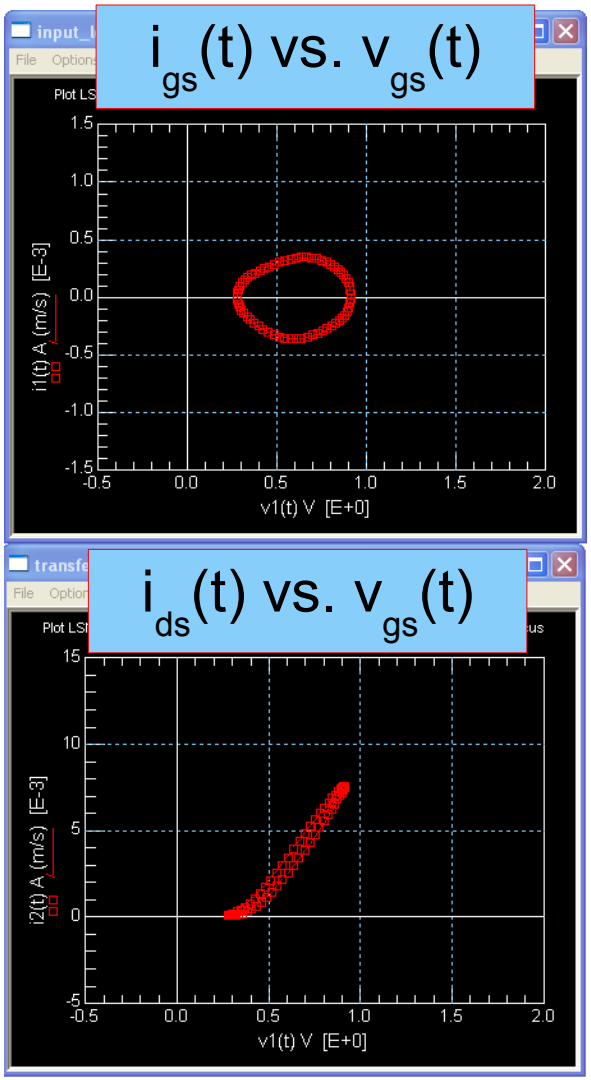

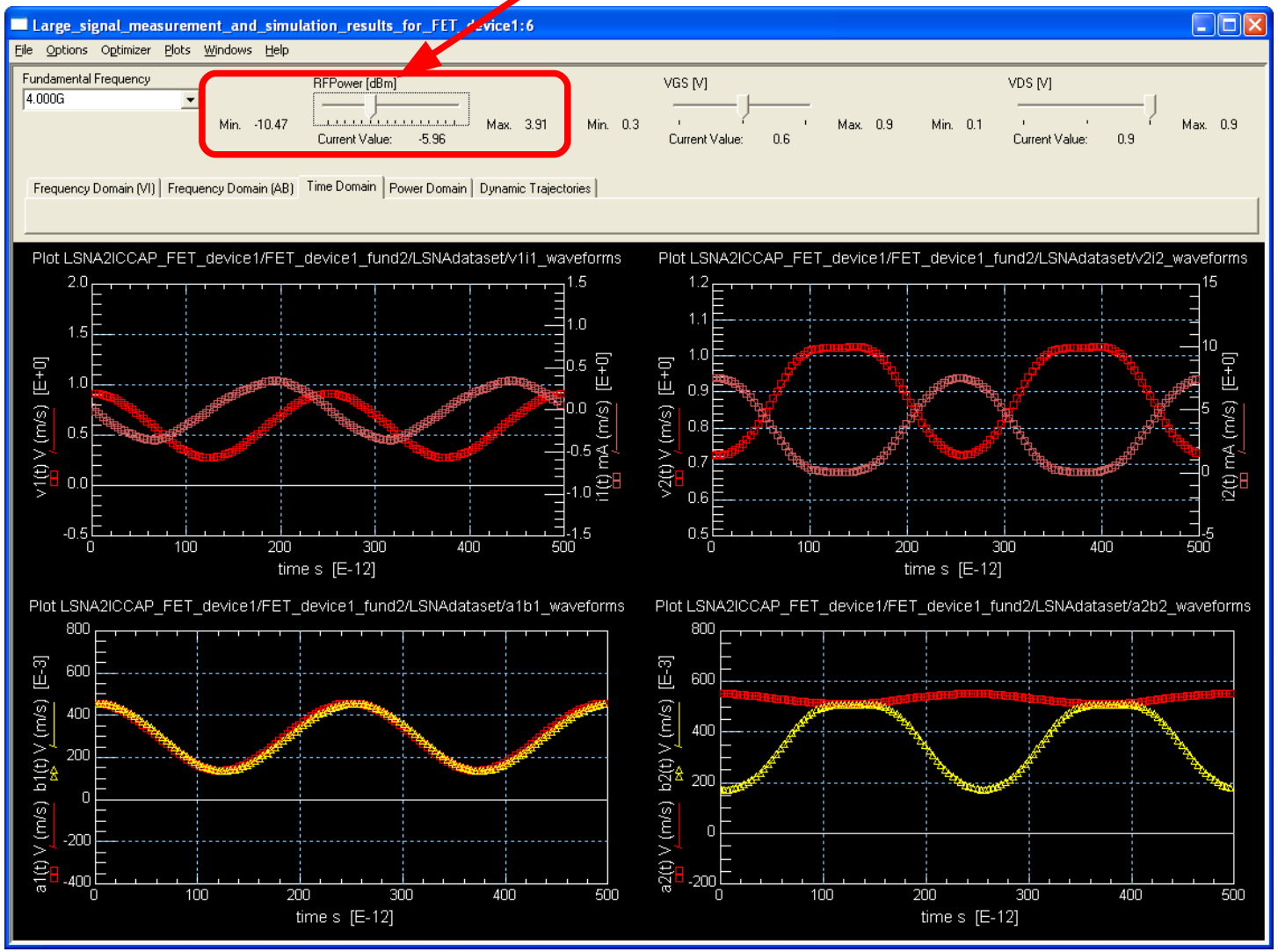

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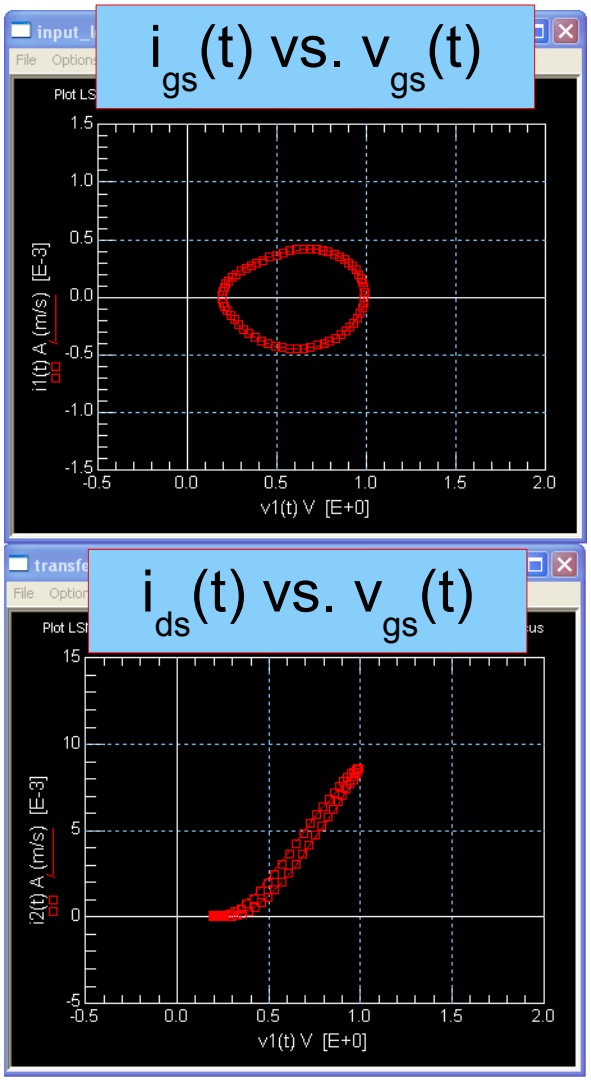

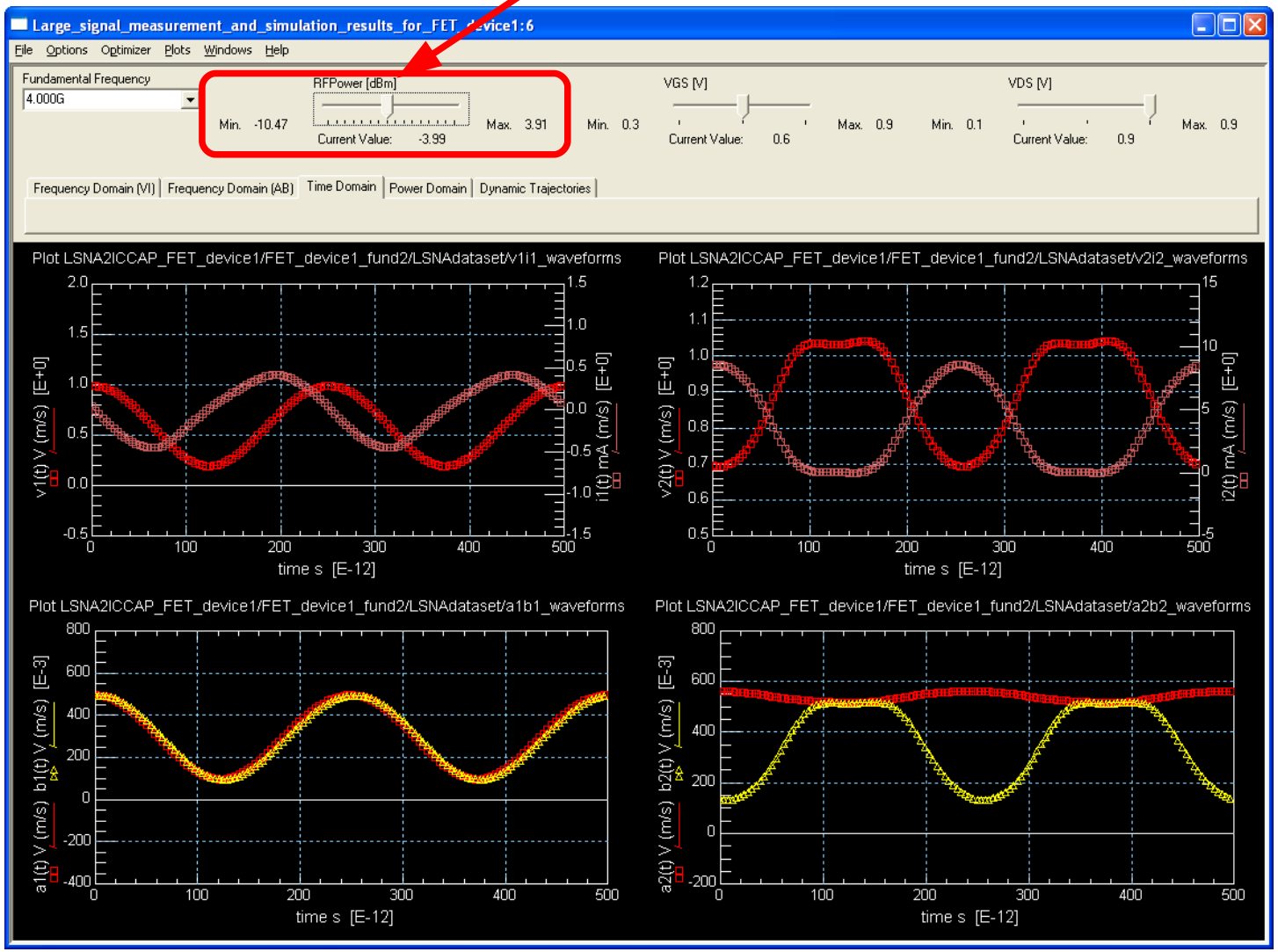

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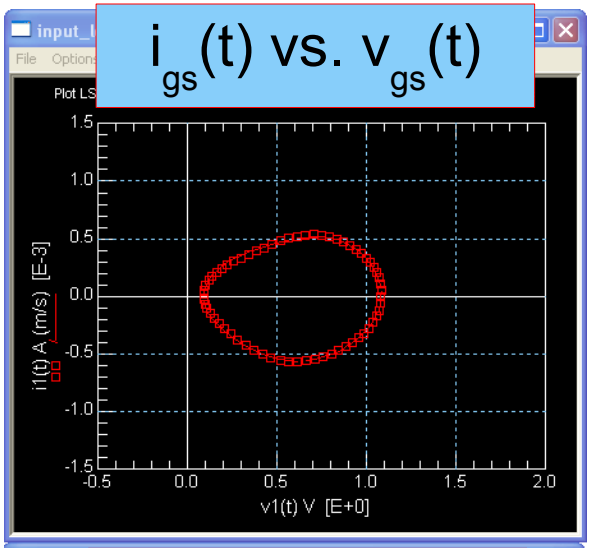
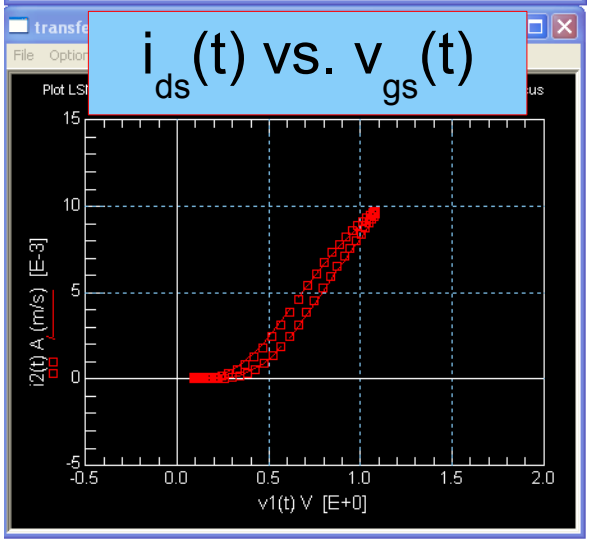
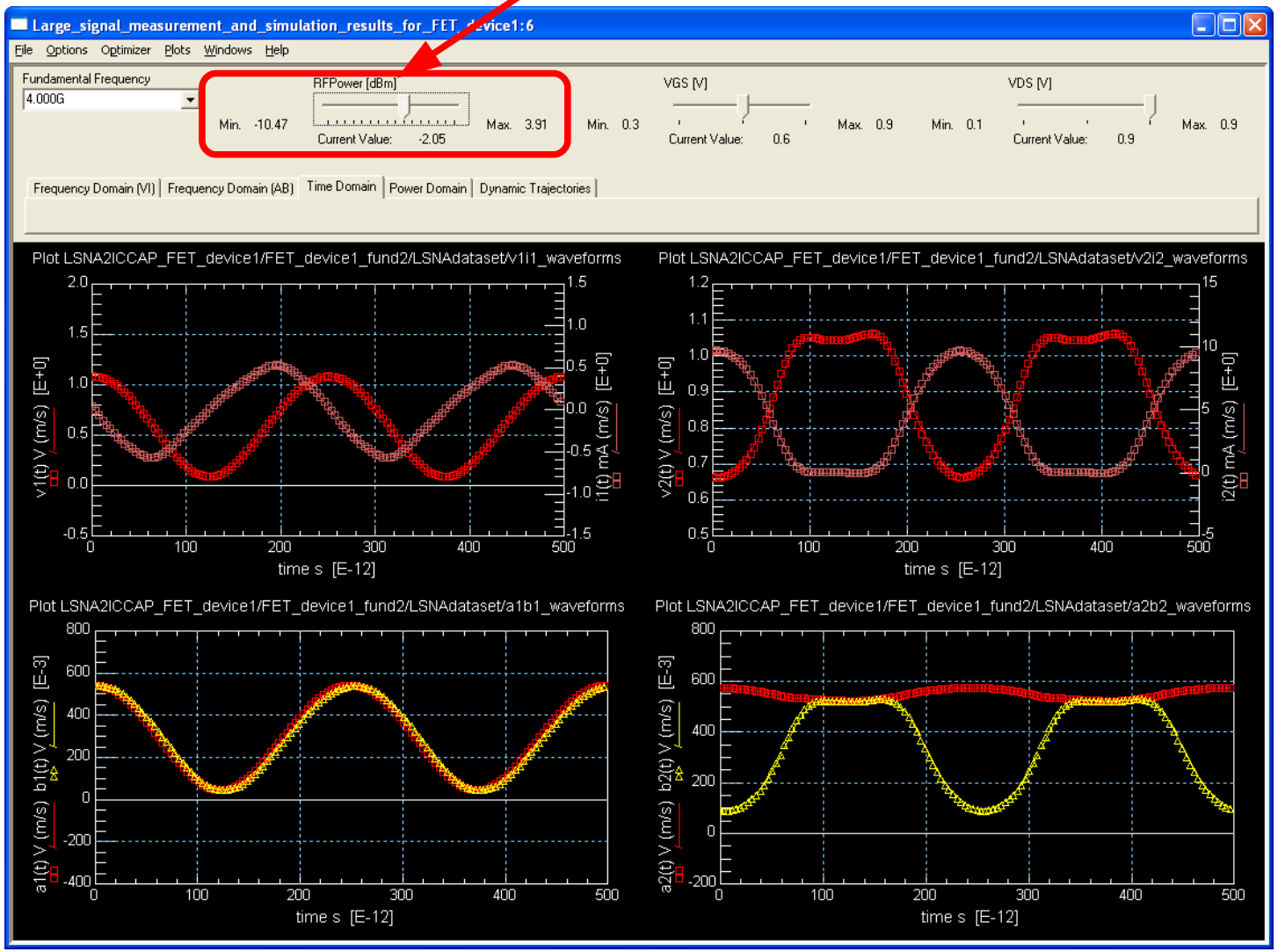


$i_{ds}(t)$ vs. $v_{gs}(t)$





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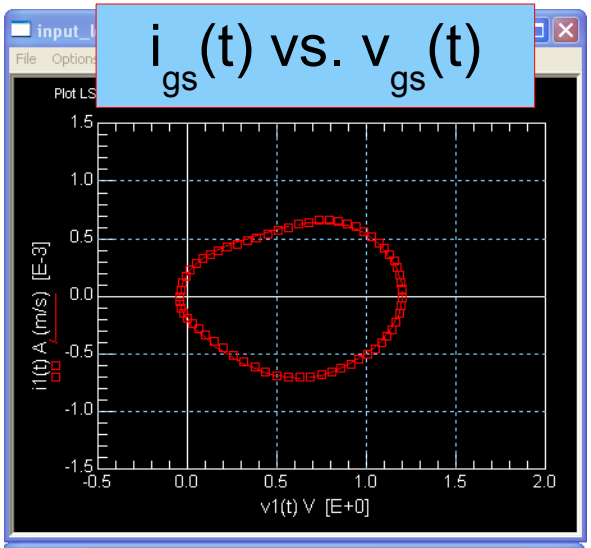

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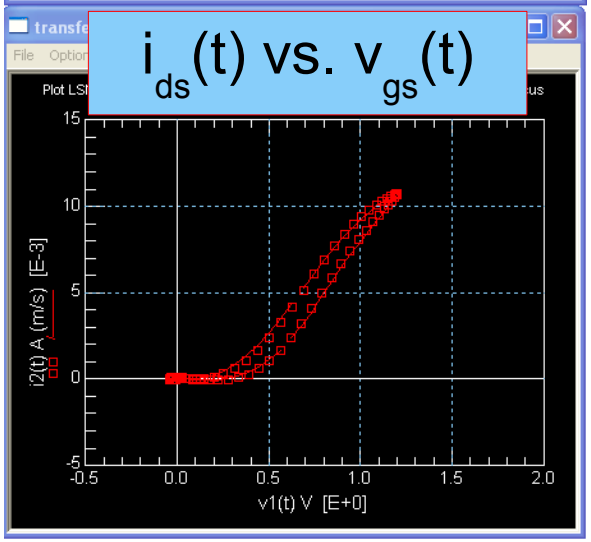

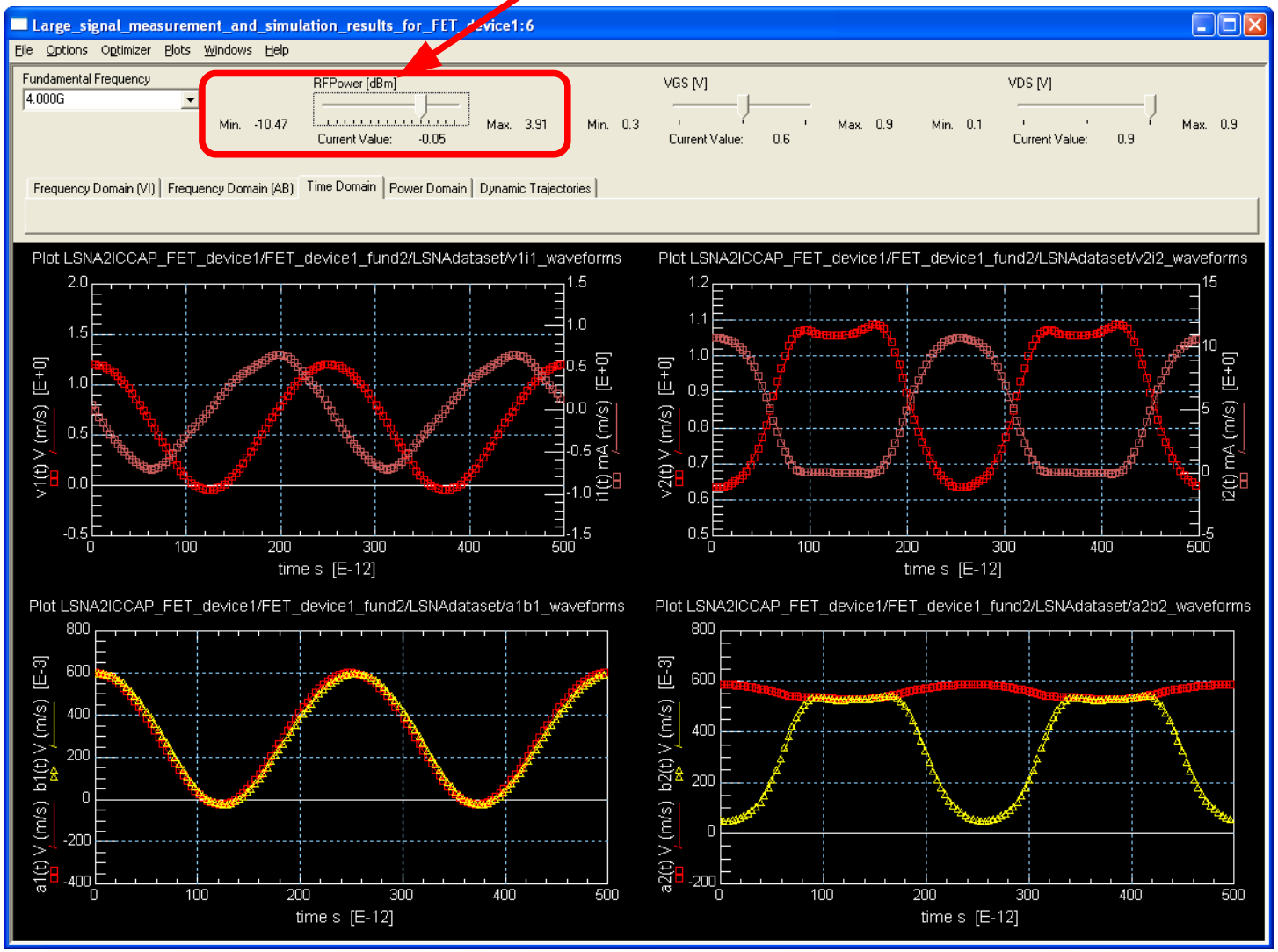

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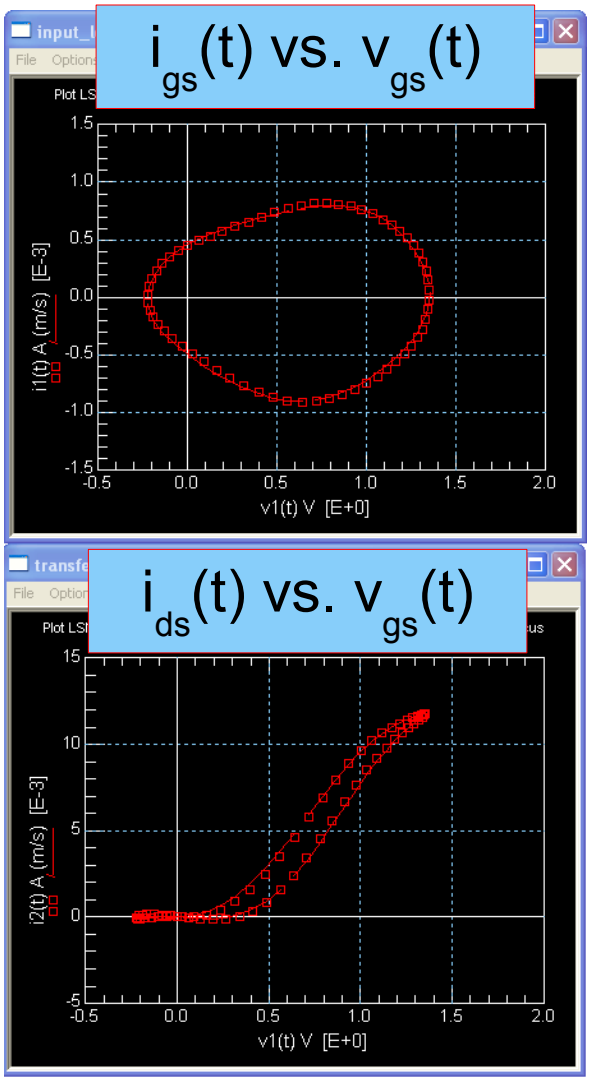

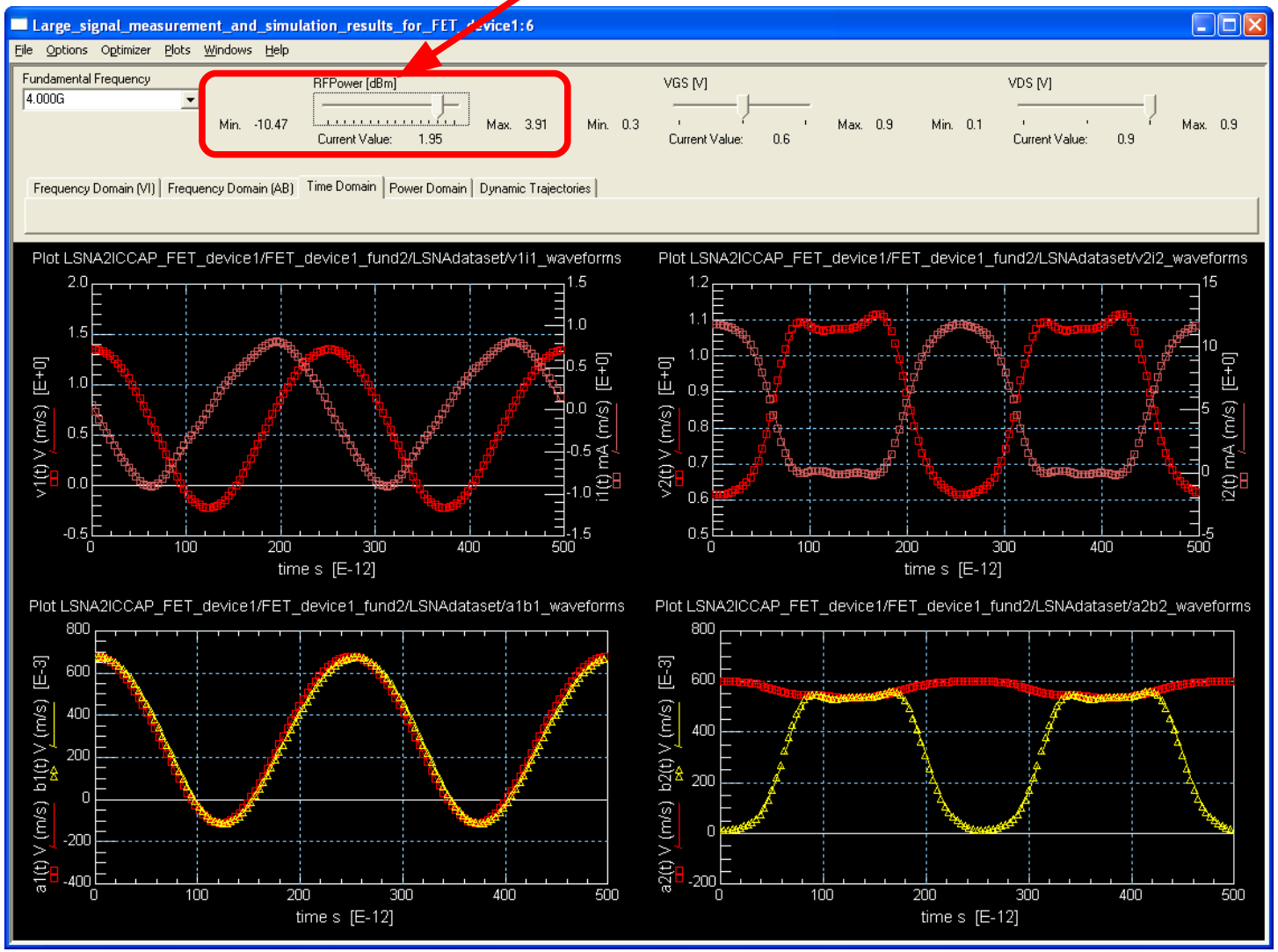

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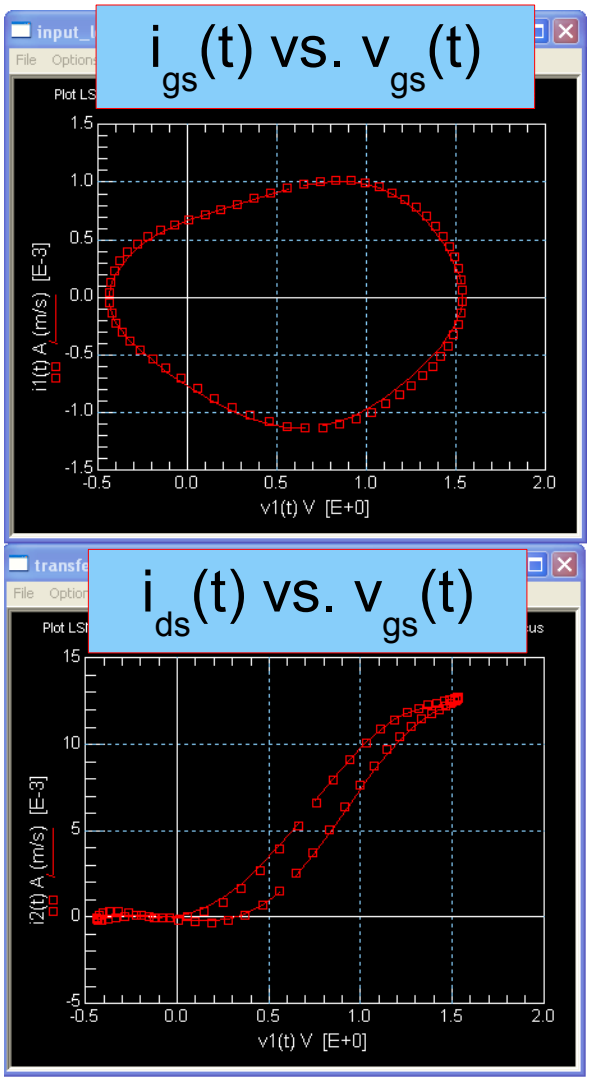
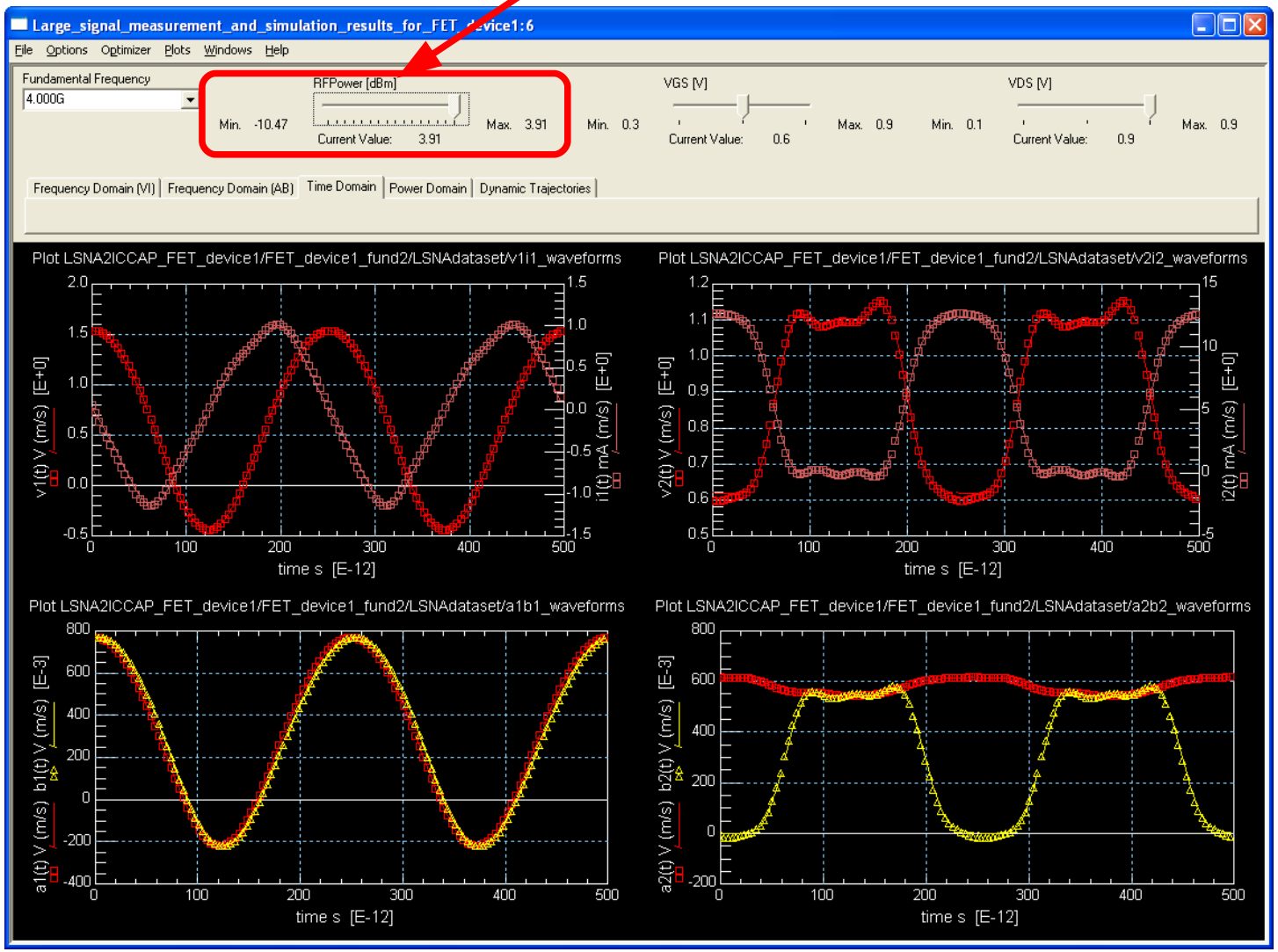
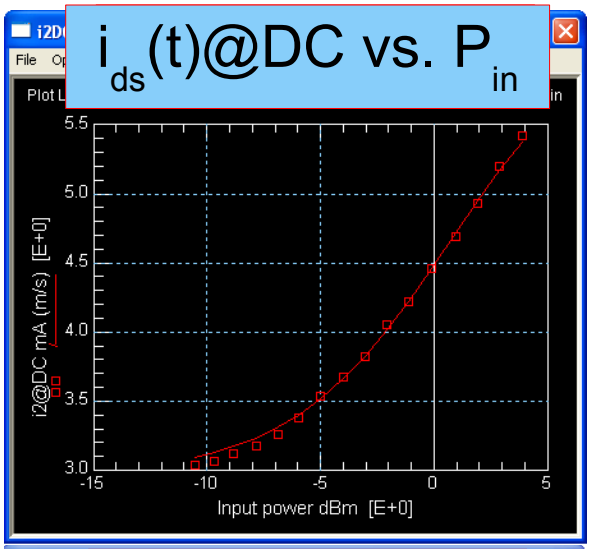
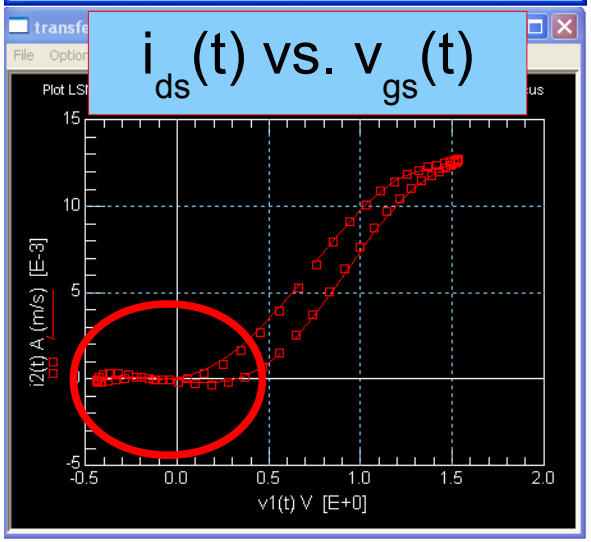


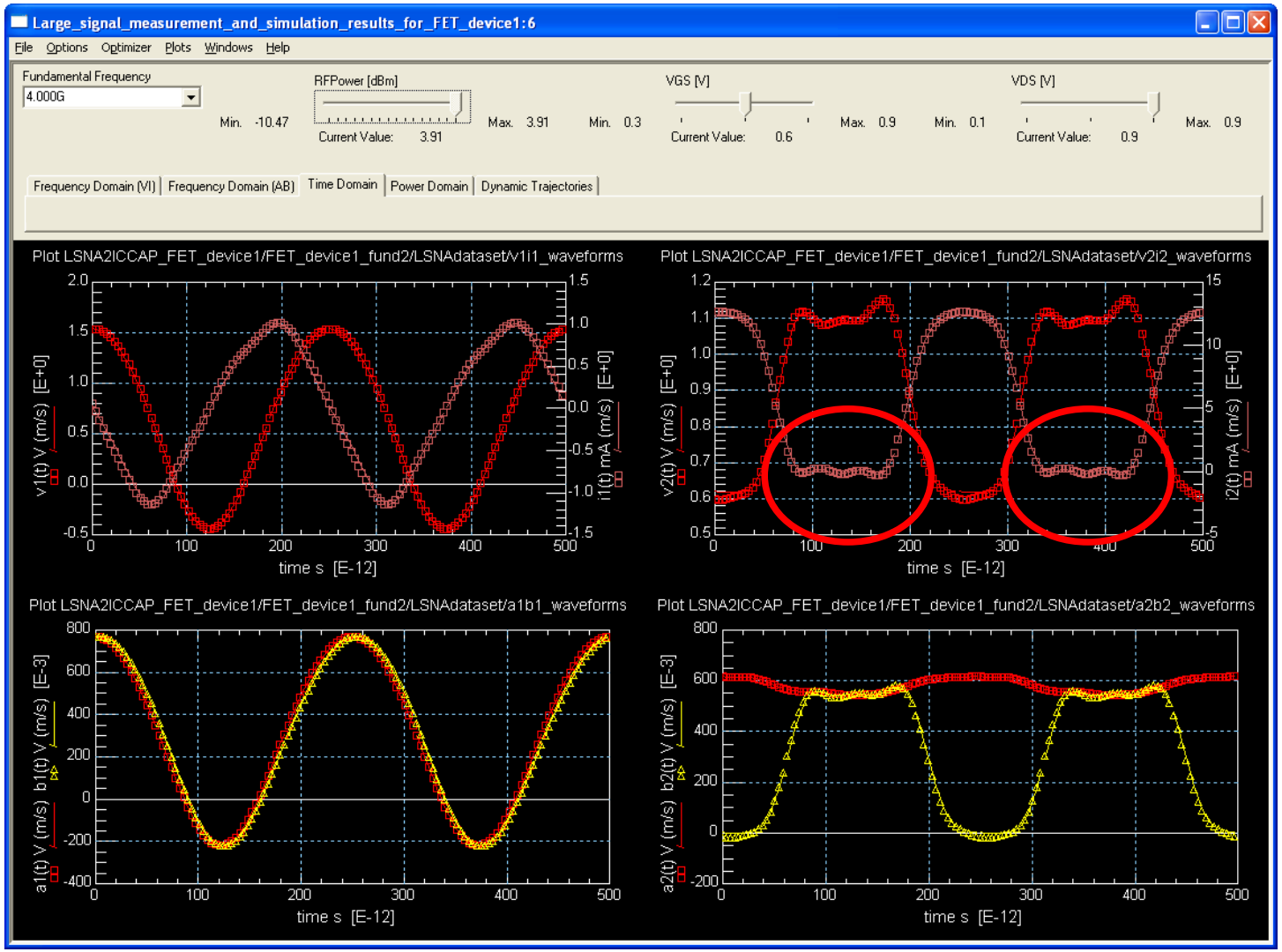


Results

Self biasing effect





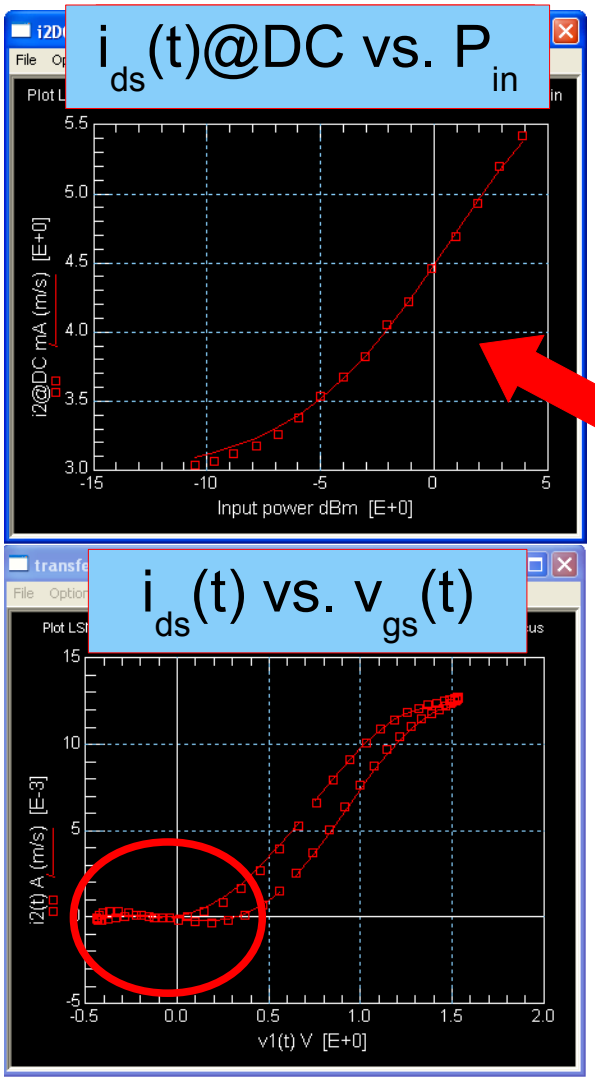


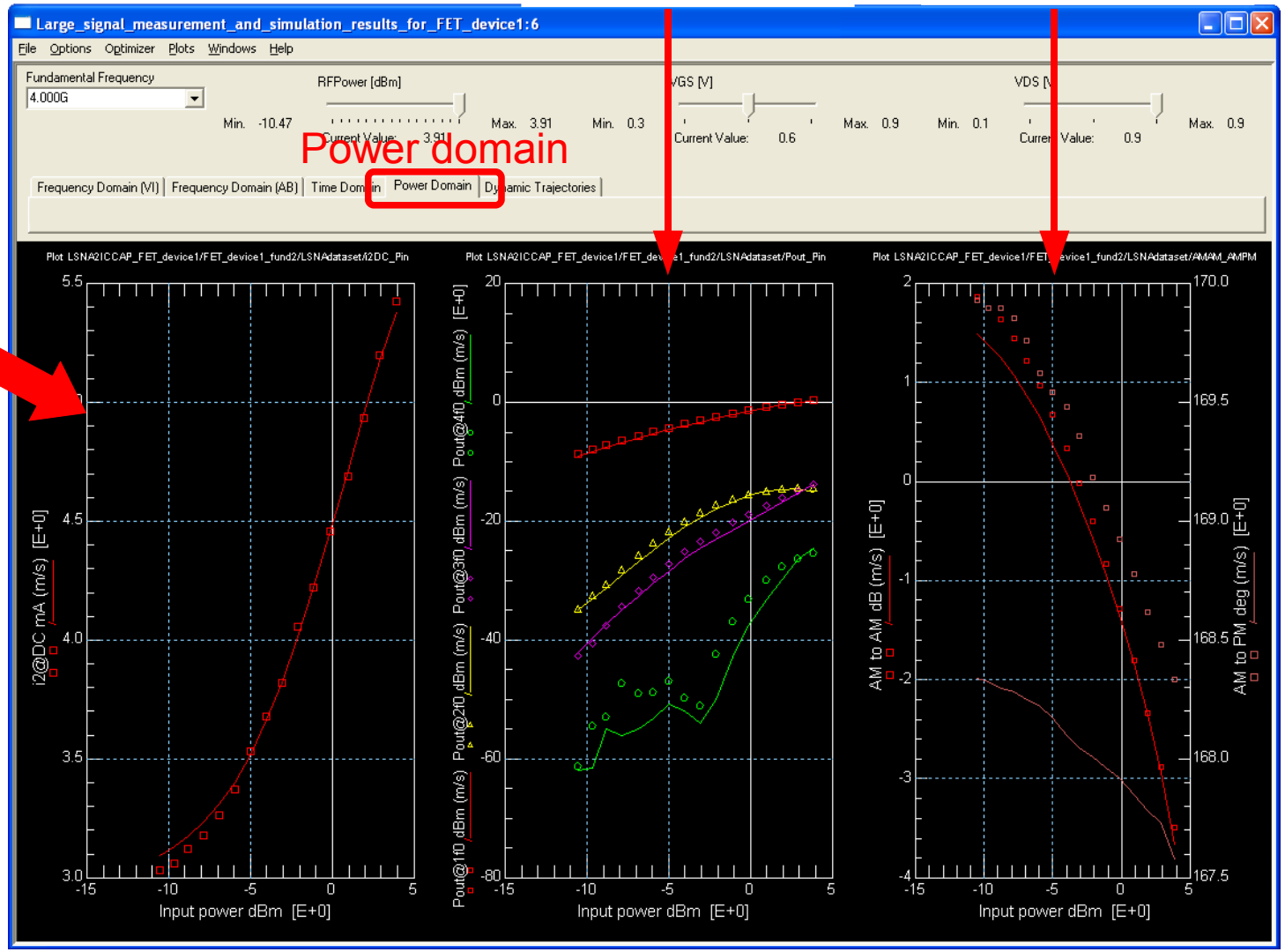
Results

Self biasing effect

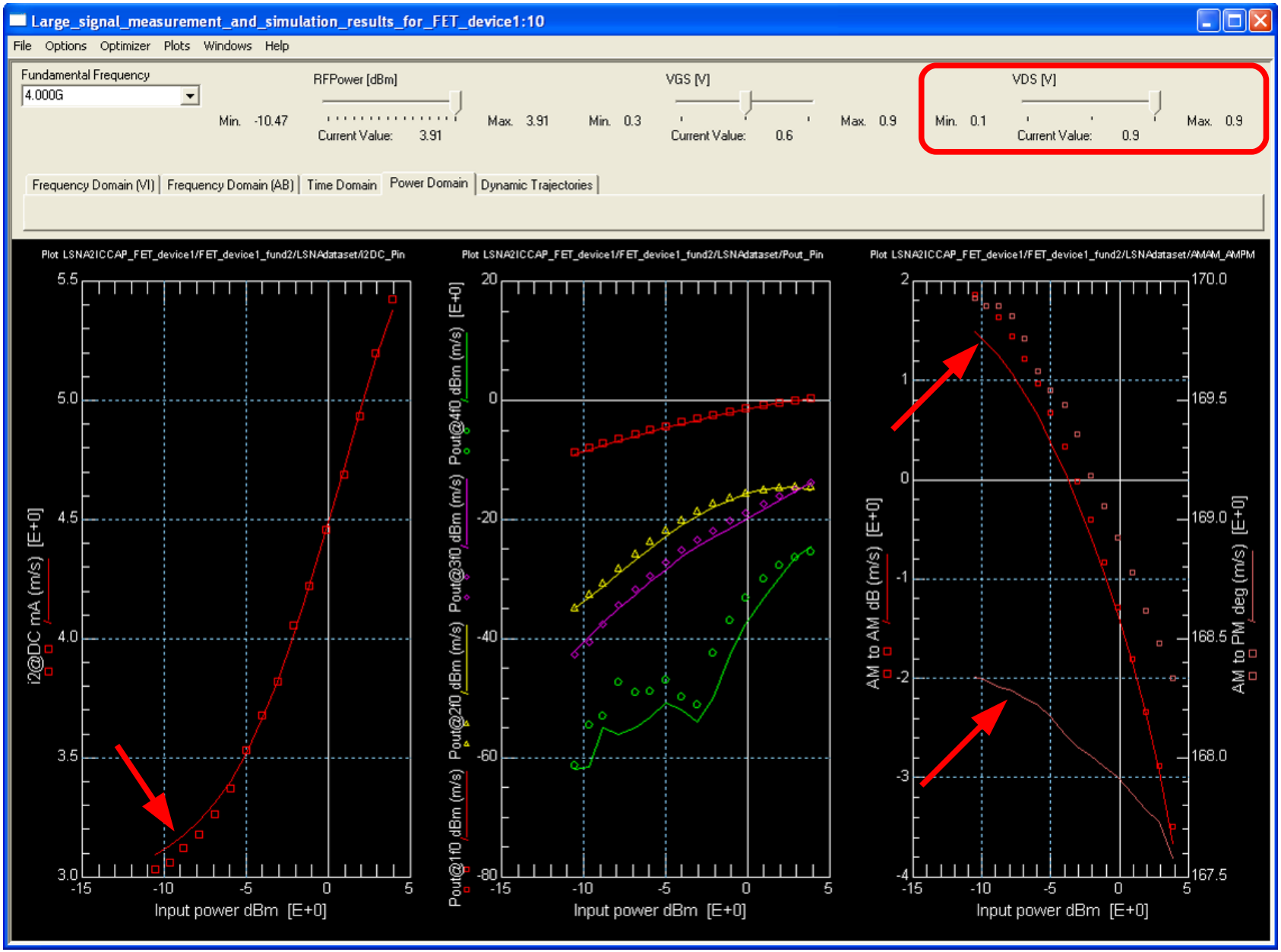
Harmonic distortion

AM-AM AM-PM

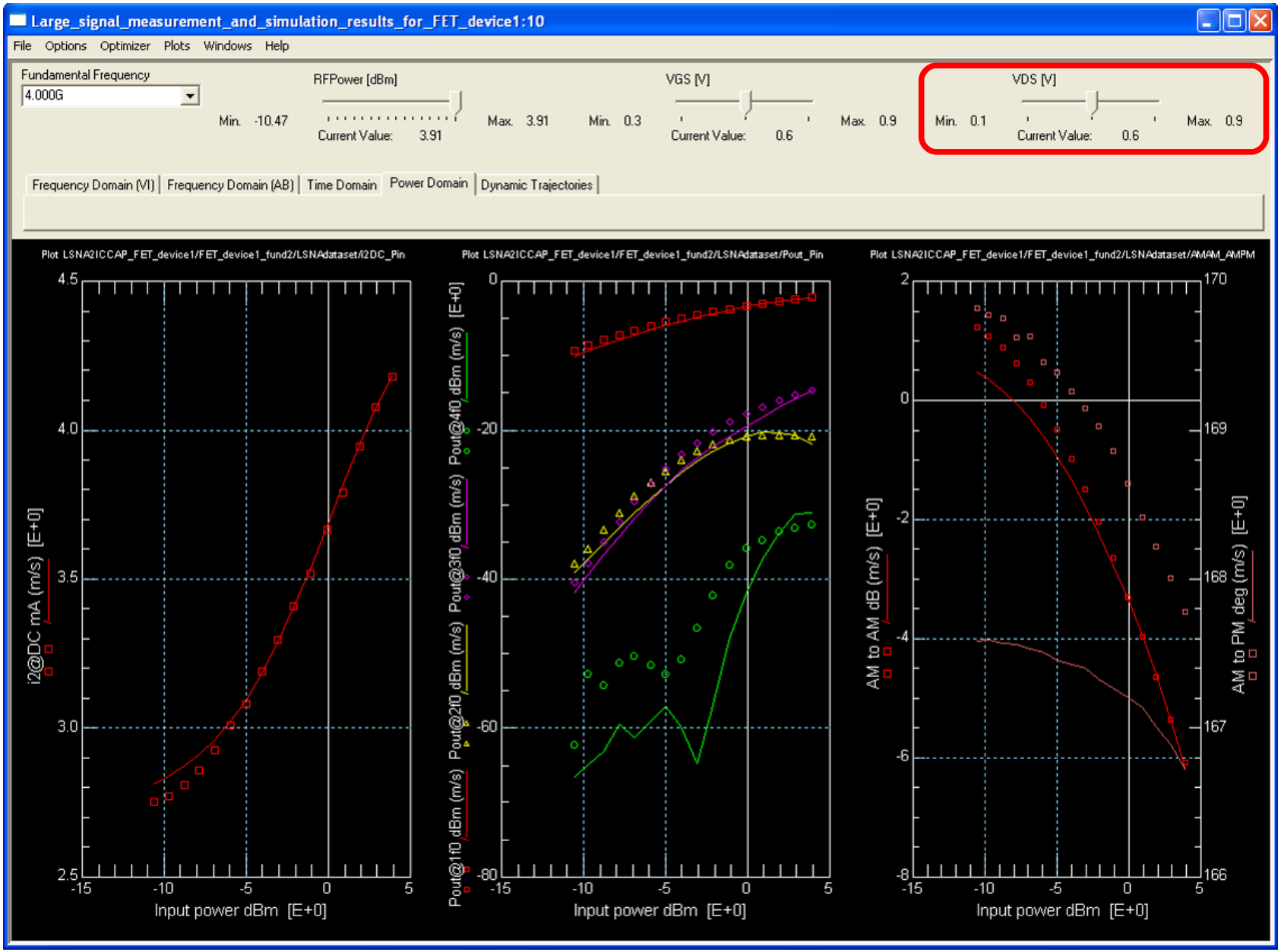




Results


Large_signal_measurement_and_simulation_results_for_FET_device1:10
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47 Max. 3.91
Current Value: 3.91
VGS [V]
Min. 0.3 Max. 0.9
Current Value: 0.6
VDS [V]
Min. 0.1 Max. 0.9
Current Value: 0.9
Frequency Domain (VI) Frequency Domain (AB) Time Domain Power Domain Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/i2DC_Pin
i2@DC mA (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/Pout_Pin
Pout@1f0 dBm (m/s) Pout@2f0 dBm (m/s) Pout@3f0 dBm (m/s) Pout@4f0 dBm (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/AMAM_AMPM
AM to AM dB (m/s) [E+0]
AM to PM deg (m/s) [E+0]
Input power dBm [E+0]

Results


Large_signal_measurement_and_simulation_results_for_FET_device1:10
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47 Max. 3.91
Current Value: 3.91
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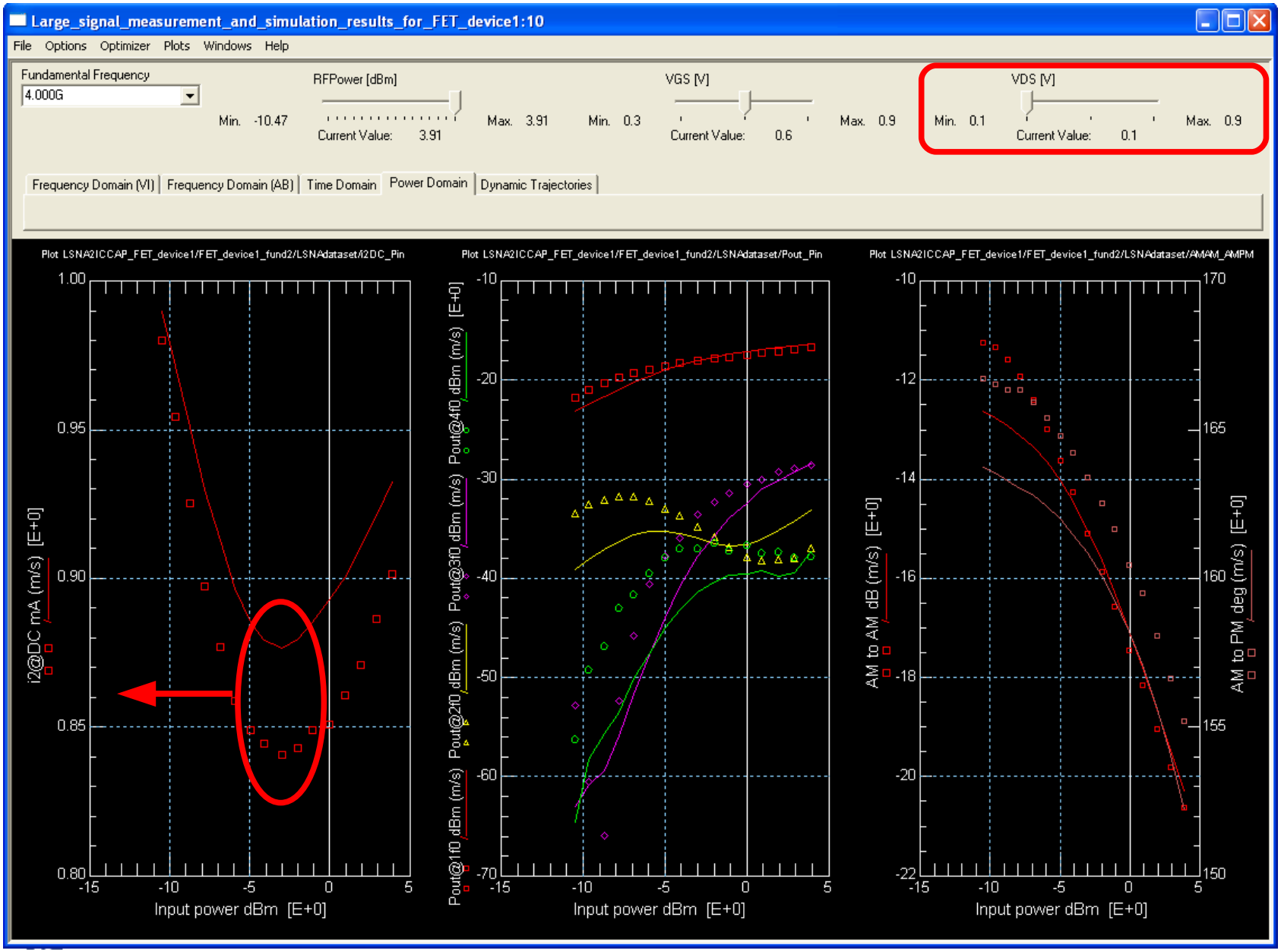
Current Value: 0.6
VDS [V]
Min. 0.1 Max. 0.9
Current Value: 0.6
Frequency Domain (VI) Frequency Domain (AB) Time Domain Power Domain Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/i2DC_Pin
i2@DC mA (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/Pout_Pin
Pout@1f0 dBm (m/s) Pout@2f0 dBm (m/s) Pout@3f0 dBm (m/s) Pout@4f0 dBm (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/AMAM_AMPM
AM to AM dB (m/s) [E+0]
AM to PM deg (m/s) [E+0]
Input power dBm [E+0]

Results


Large_signal_measurement_and_simulation_results_for_FET_device1:10
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47 Current Value: 3.91 Max. 3.91
VGS [V]
Min. 0.3 Current Value: 0.6 Max. 0.9
VDS [V]
Min. 0.1 Current Value: 0.1 Max. 0.9
Frequency Domain (VI) Frequency Domain (AB) Time Domain Power Domain Dynamic Trajectories
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i2@DC mA (m/s) [E+0]
Input power dBm [E+0]
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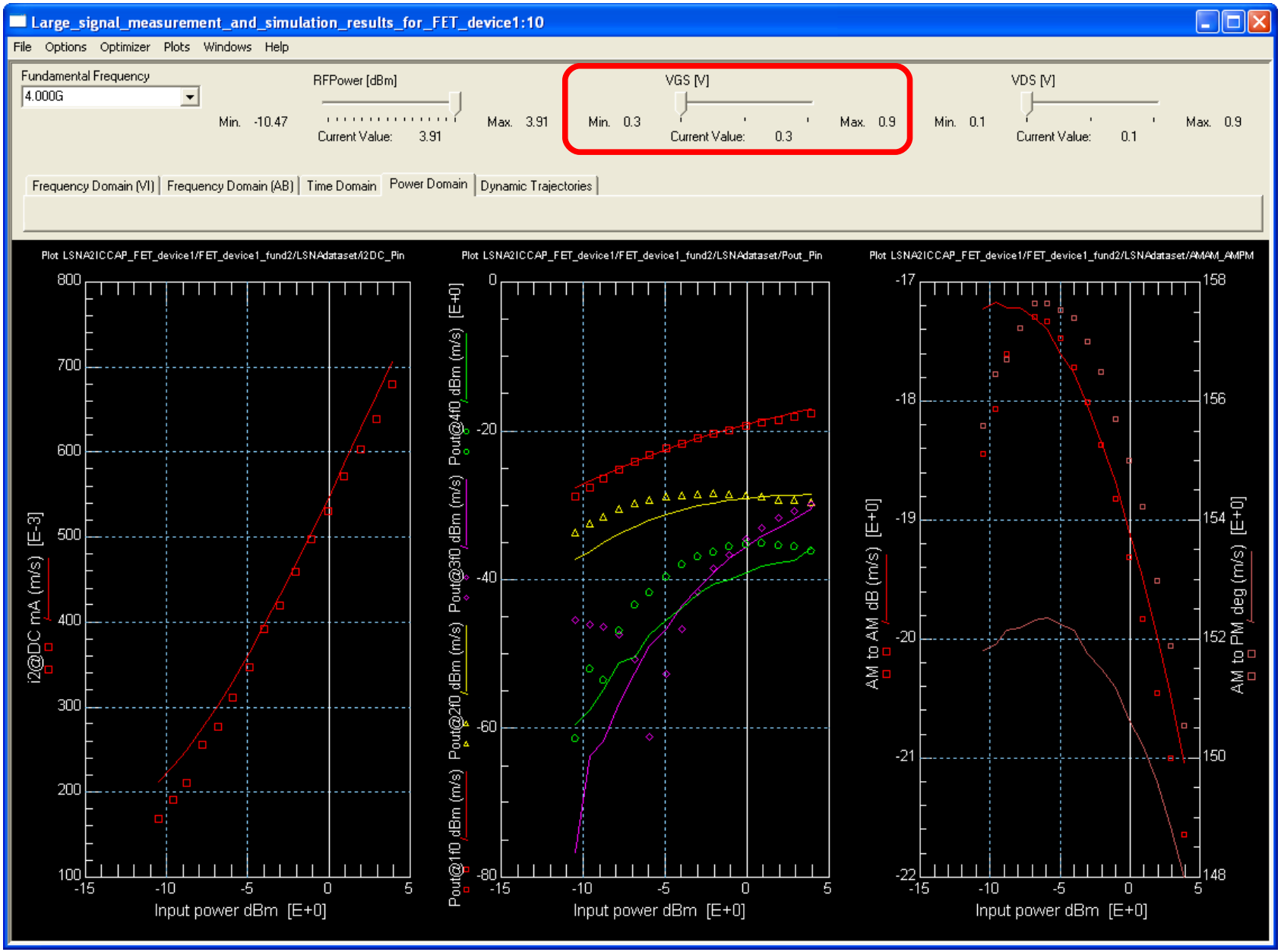
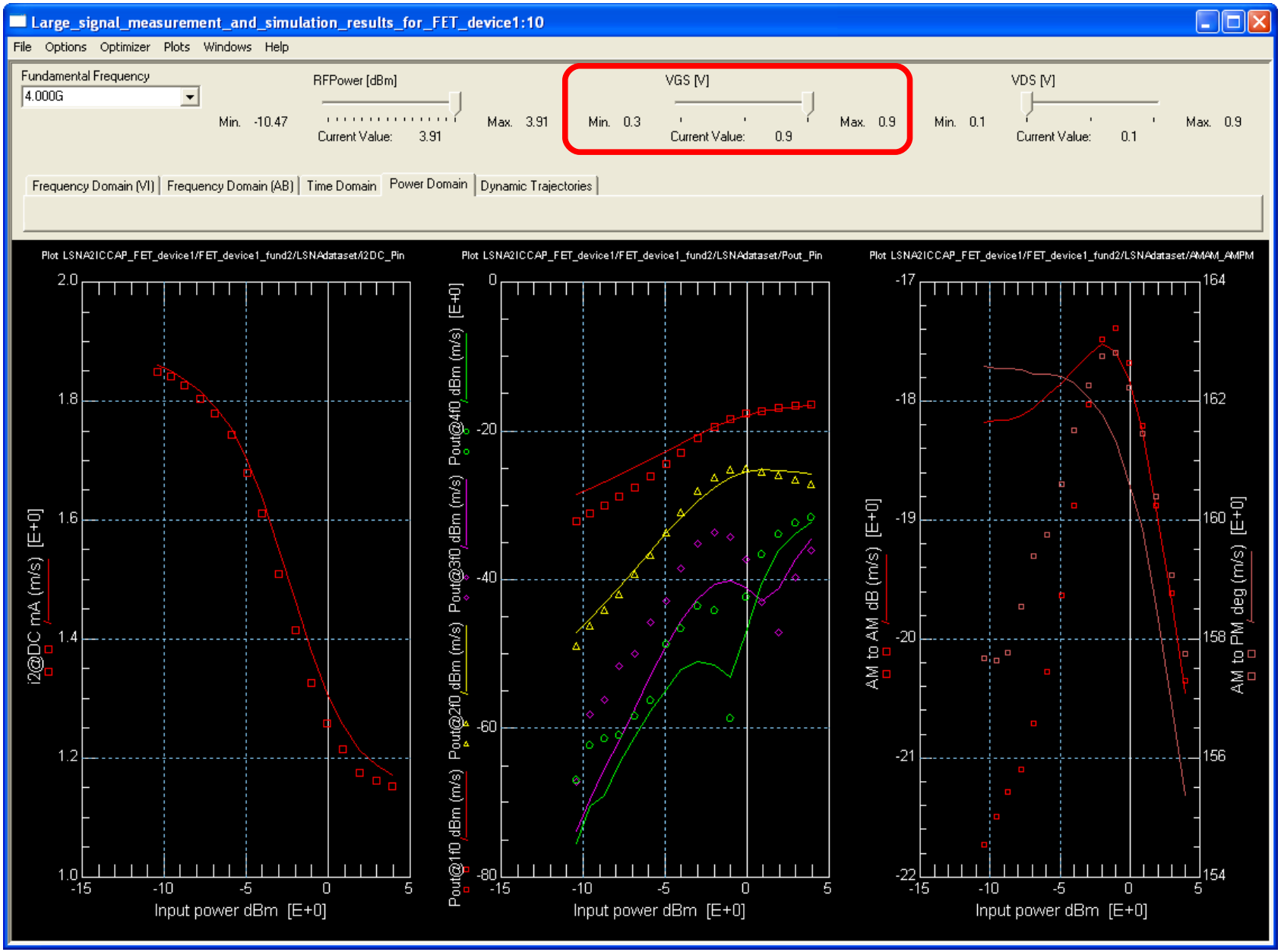
Pout@1f0 dBm (m/s) Pout@2f0 dBm (m/s) Pout@3f0 dBm (m/s) Pout@4f0 dBm (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/AMAM_AMPM
AM to AM dB (m/s) [E+0]
AM to PM deg (m/s) [E+0]
Input power dBm [E+0]

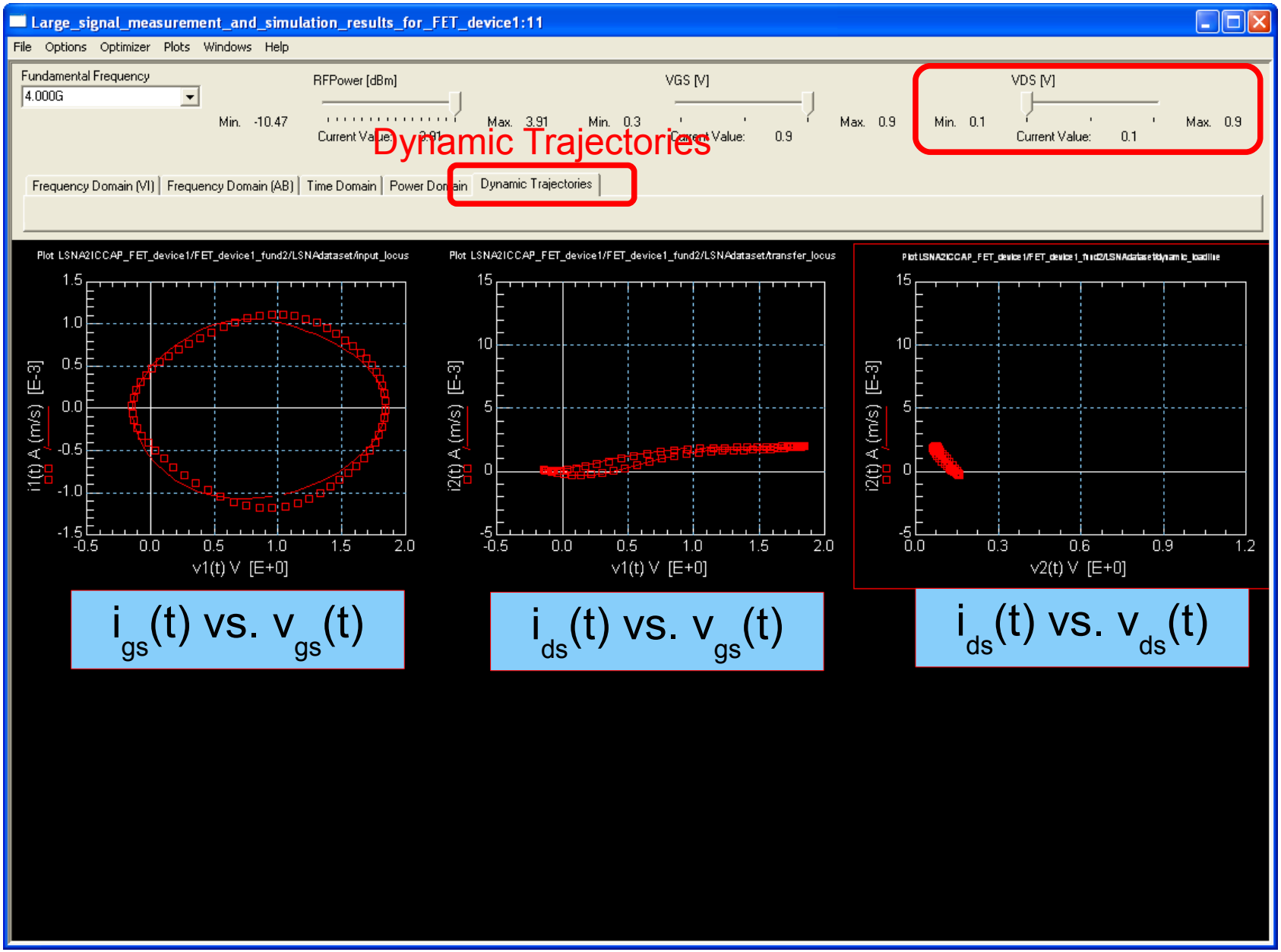
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:10
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Current Value: 3.91
Max. 3.91
VGS [V]
Min. 0.3
Current Value: 0.3
Max. 0.9
VDS [V]
Min. 0.1
Current Value: 0.1
Max. 0.9
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/i2DC_Pin
i2@DC mA (m/s) [E-3]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/Pout_Pin
Pout@1f0 dBm (m/s) Pout@2f0 dBm (m/s) Pout@3f0 dBm (m/s) Pout@4f0 dBm (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/AMAM_AMPM
AM to AM dB (m/s) [E+0]
AM to PM deg (m/s) [E+0]
Input power dBm [E+0]

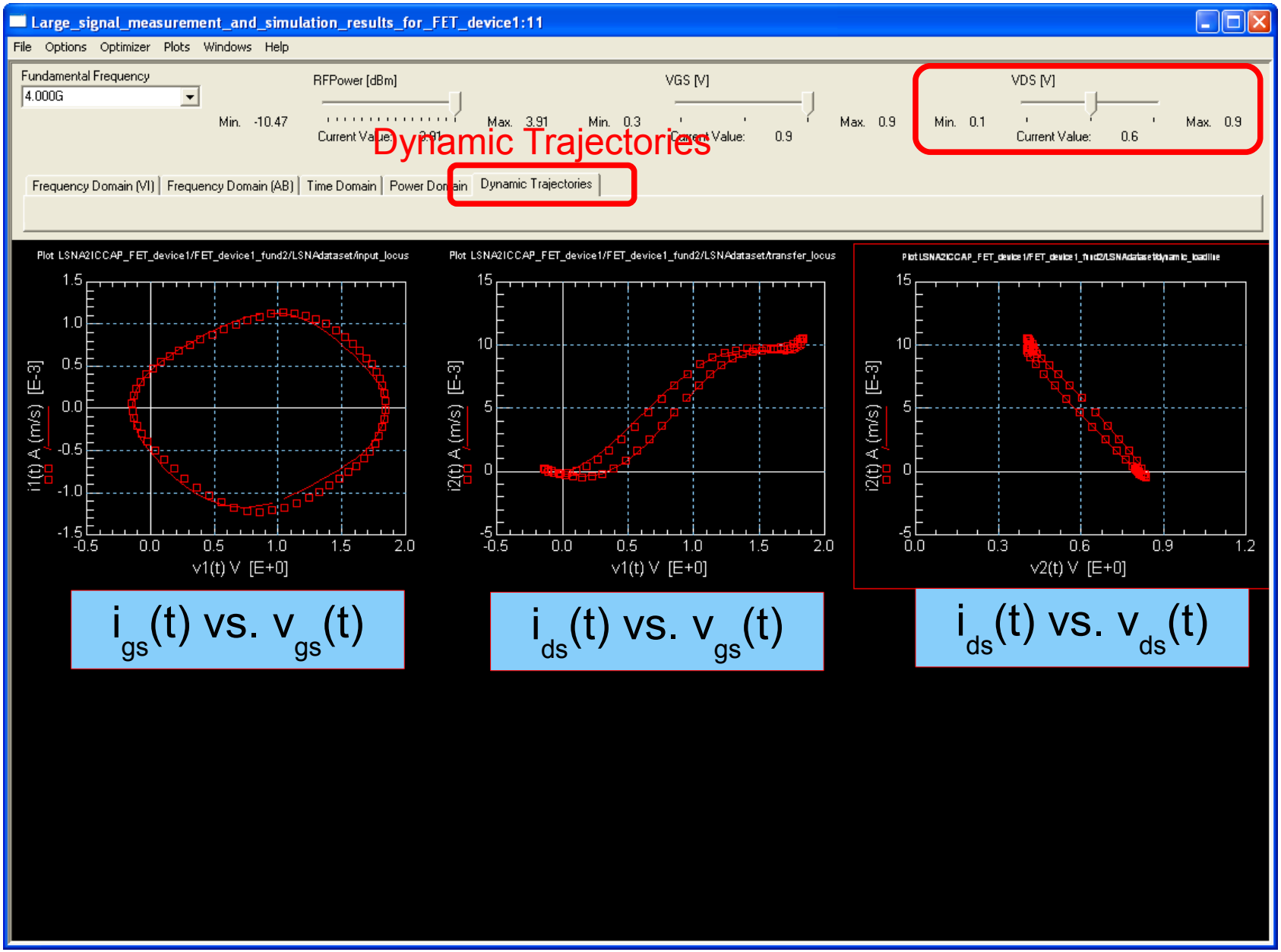
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:10
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Current Value: 3.91
Max. 3.91
VGS [V]
Min. 0.3
Current Value: 0.9
Max. 0.9
VDS [V]
Min. 0.1
Current Value: 0.1
Max. 0.9
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/i2DC_Pin
i2@DC mA (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/Pout_Pin
Pout@1f0 dBm (m/s) Pout@2f0 dBm (m/s) Pout@3f0 dBm (m/s) Pout@4f0 dBm (m/s) [E+0]
Input power dBm [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/AMAM_AMPM
AM to AM dB (m/s) [E+0]
AM to PM deg (m/s) [E+0]
Input power dBm [E+0]

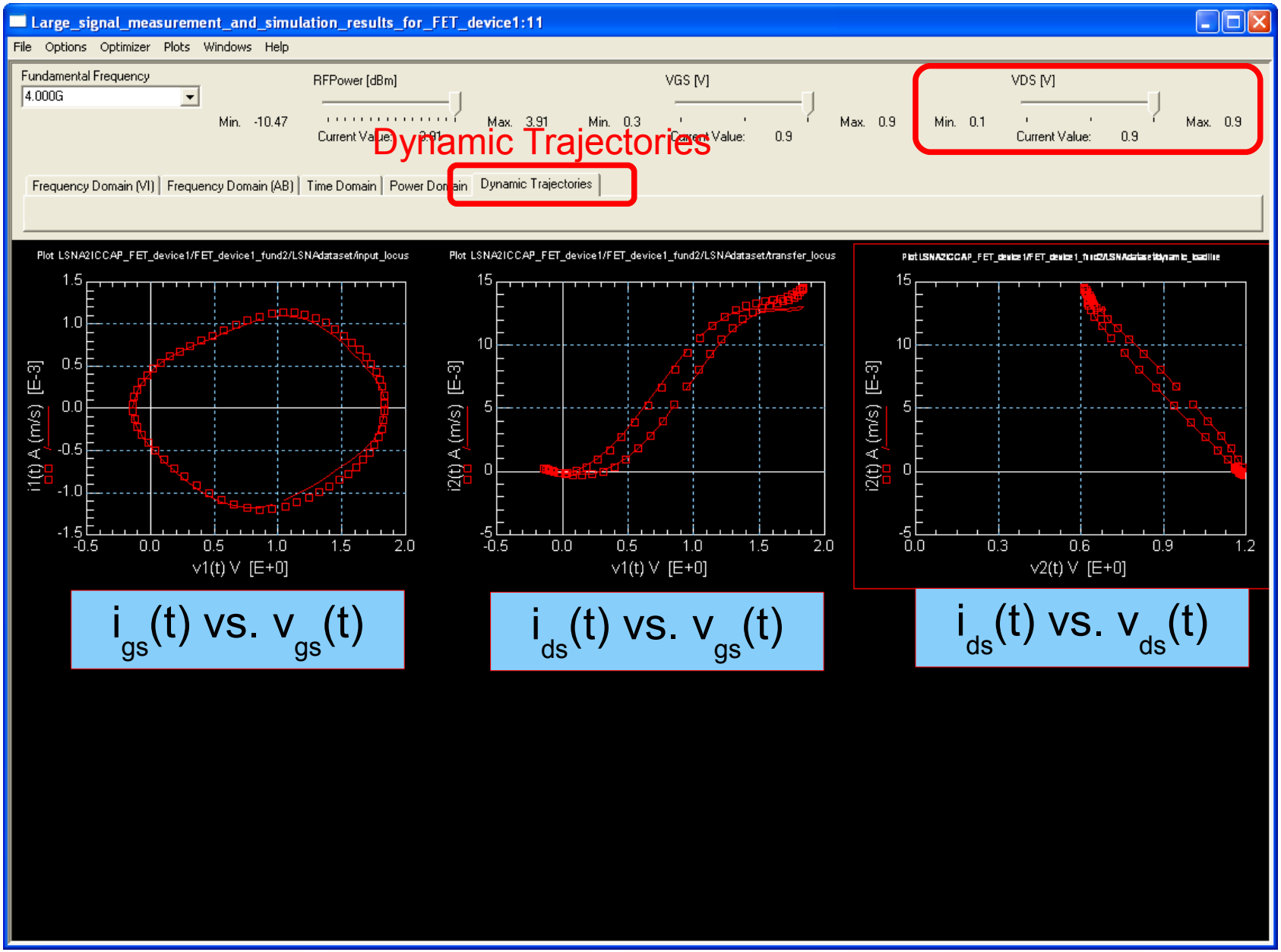
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Max. 3.91
Current Value: 3.91
VGS [V]
Min. 0.3
Max. 0.9
Current Value: 0.9
VDS [V]
Min. 0.1
Max. 0.9
Current Value: 0.1
Dynamic Trajectories
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/input_locus
i1(t) A (m/s) [E-3]
v1(t) V [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/transfer_locus
i2(t) A (m/s) [E-3]
v1(t) V [E+0]
i2(t) A (m/s) [E-3]
v2(t) V [E+0]
i_gs(t) vs. v_gs(t)
i_ds(t) vs. v_gs(t)
i_ds(t) vs. v_ds(t)

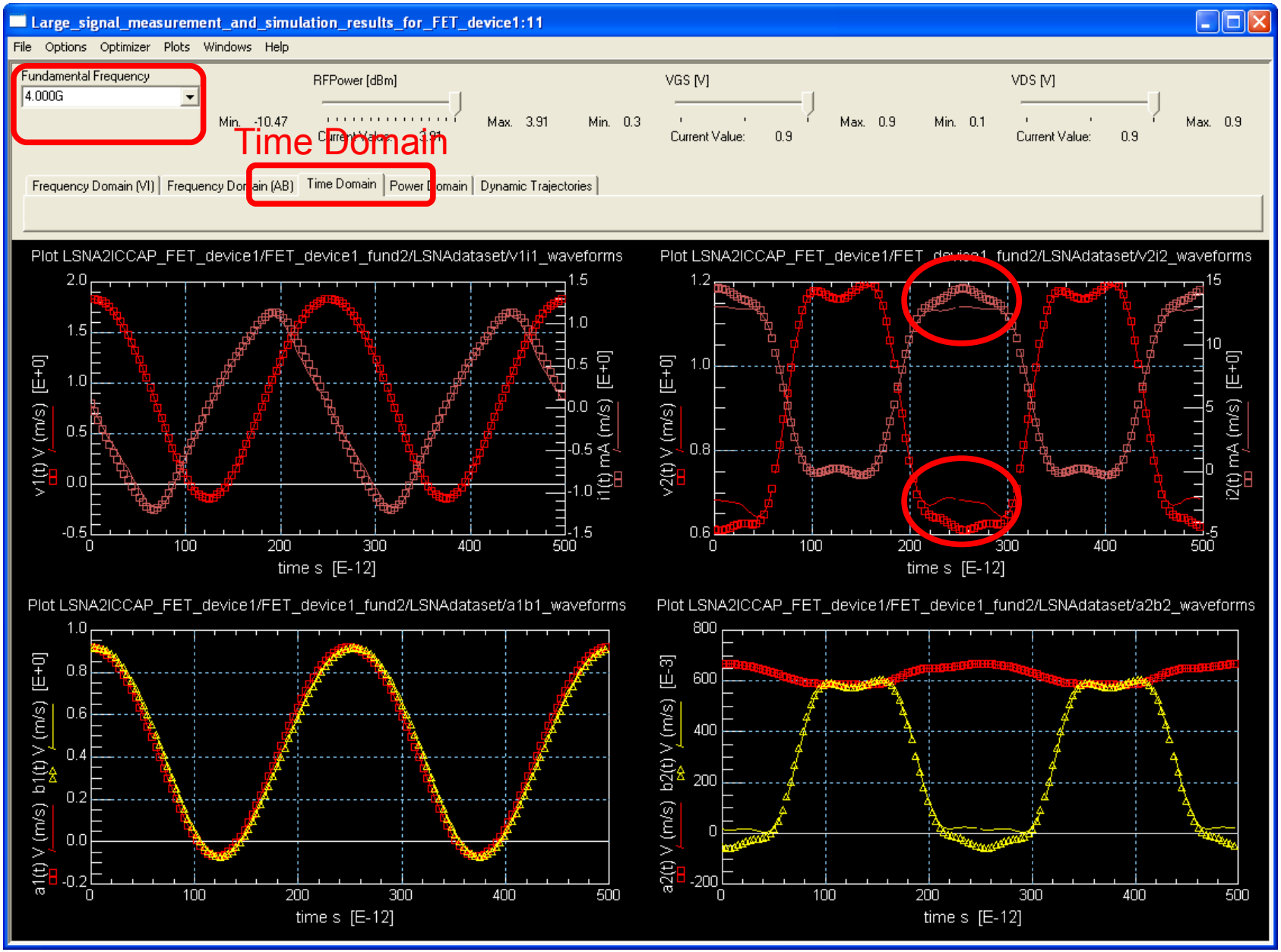
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Max. 3.91
Current Value: 3.91
VGS [V]
Min. 0.3
Max. 0.9
Current Value: 0.9
VDS [V]
Min. 0.1
Max. 0.9
Current Value: 0.6
Dynamic Trajectories
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/input_locus
i1(t) A (m/s) [E-3]
v1(t) V [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/transfer_locus
i2(t) A (m/s) [E-3]
v1(t) V [E+0]
i2(t) A (m/s) [E-3]
v2(t) V [E+0]
i_gs(t) vs. v_gs(t)
i_ds(t) vs. v_gs(t)
i_ds(t) vs. v_ds(t)

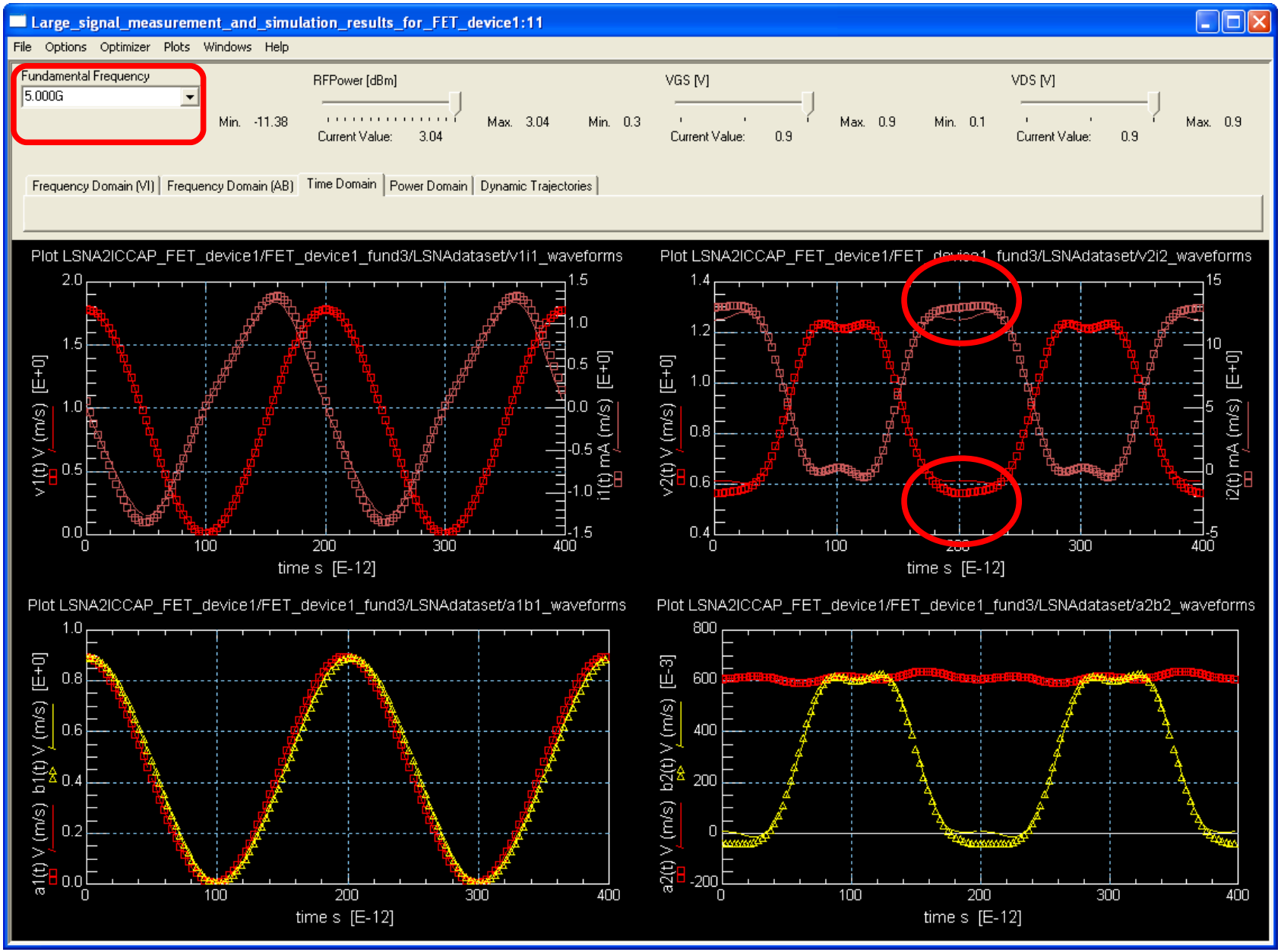
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Max. 3.91
Current Value: 3.91
VGS [V]
Min. 0.3
Max. 0.9
Current Value: 0.9
VDS [V]
Min. 0.1
Max. 0.9
Current Value: 0.9
Dynamic Trajectories
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/input_locus
i1(t) A (m/s) [E-3]
v1(t) V [E+0]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/transfer_locus
i2(t) A (m/s) [E-3]
v1(t) V [E+0]
i2(t) A (m/s) [E-3]
v2(t) V [E+0]
i_gs(t) vs. v_gs(t)
i_ds(t) vs. v_gs(t)
i_ds(t) vs. v_ds(t)

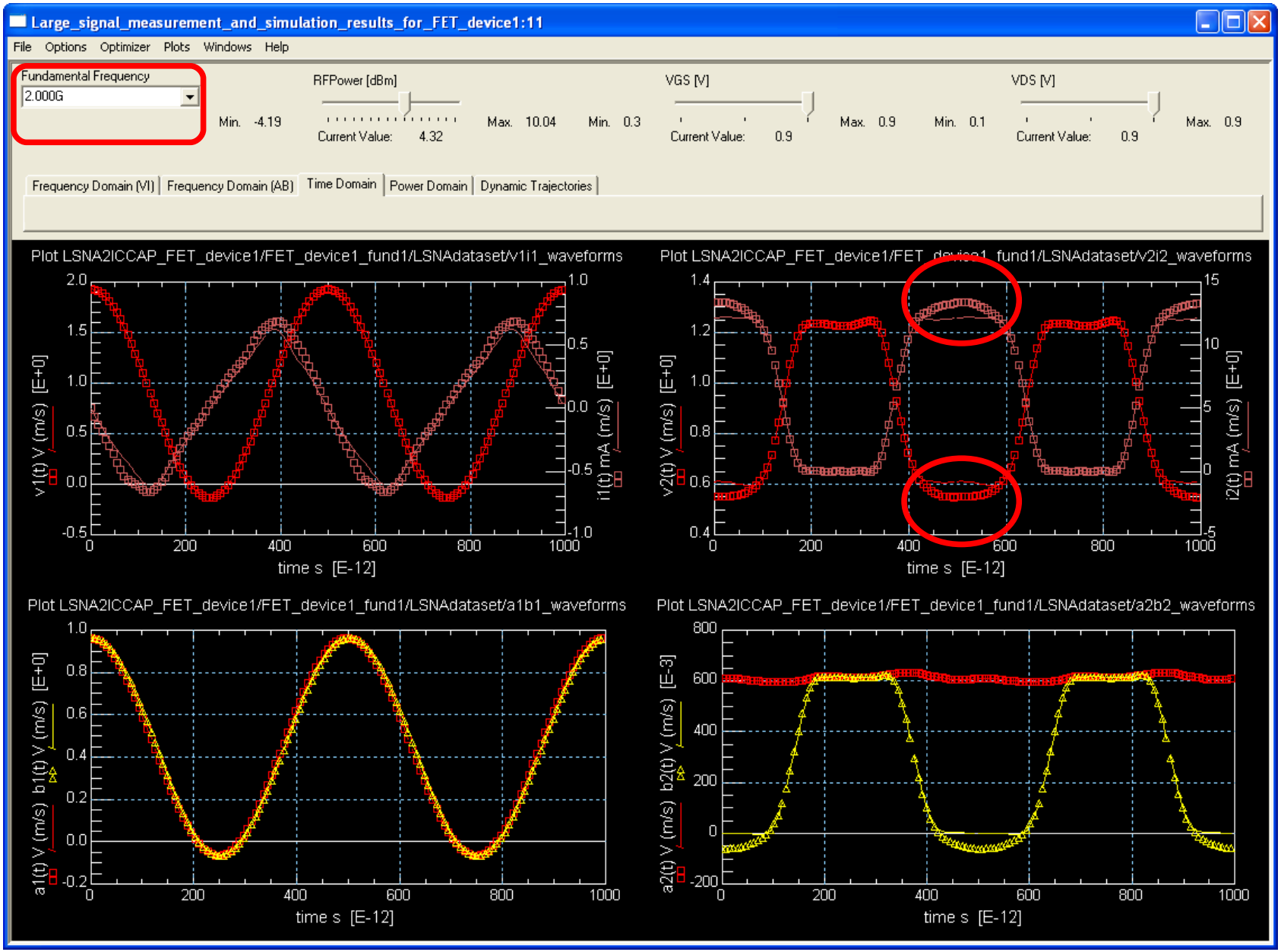
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
4.000G
RFPower [dBm]
Min. -10.47
Max. 3.91
VGS [V]
Min. 0.3
Max. 0.9
Current Value: 0.9
VDS [V]
Min. 0.1
Max. 0.9
Current Value: 0.9
Time Domain
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/v1i1_waveforms
v1(t) V (m/s) [E+0]
i1(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/v2i2_waveforms
v2(t) V (m/s) [E+0]
i2(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/a1b1_waveforms
a1(t) V (m/s) b1(t) V (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund2/LSNAdataset/a2b2_waveforms
a2(t) V (m/s) b2(t) V (m/s) [E-3]
time s [E-12]

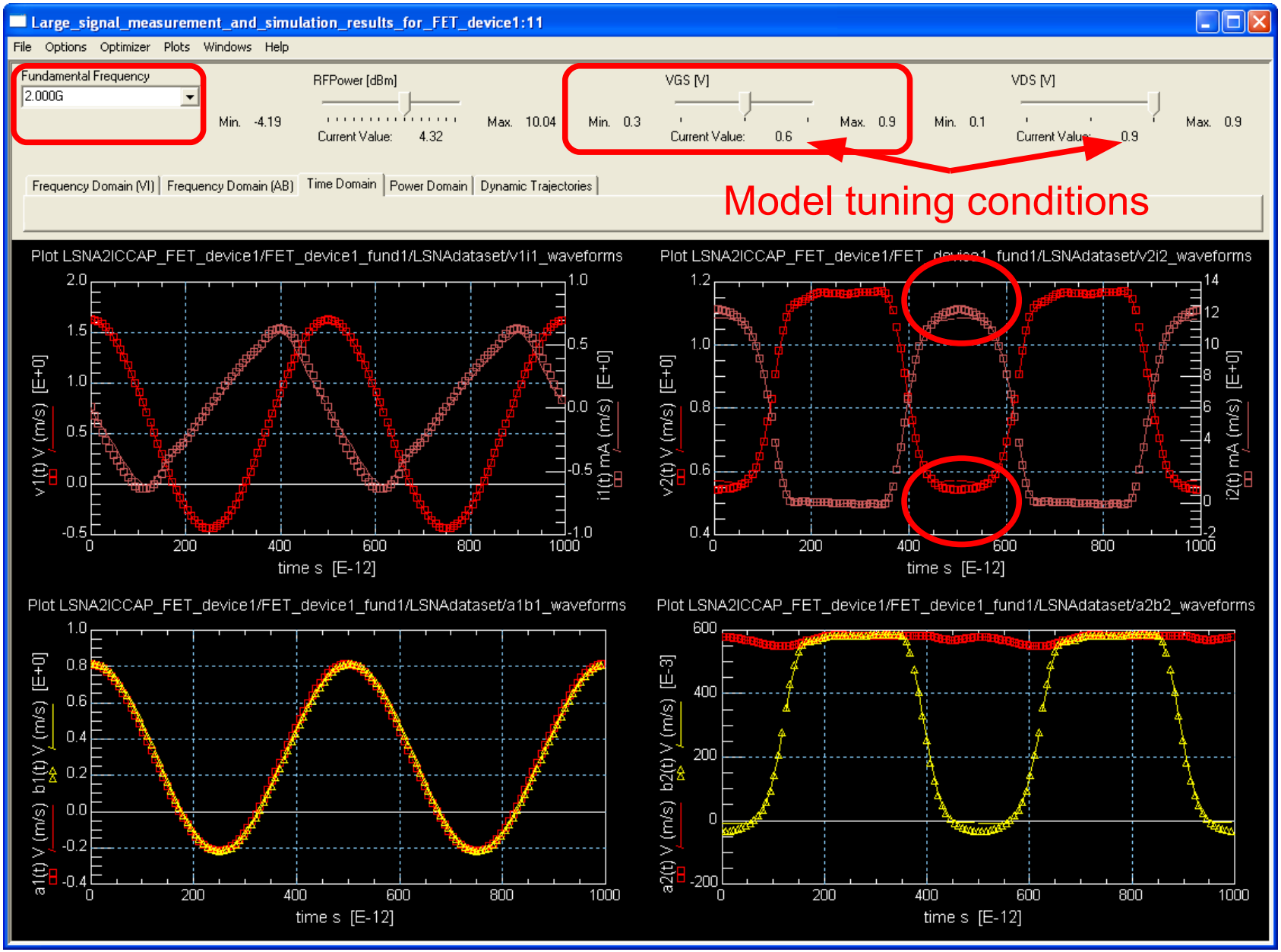
Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
5.000G
RFPower [dBm]
Min. -11.38 Max. 3.04
Current Value: 3.04
VGS [V]
Min. 0.3 Max. 0.9
Current Value: 0.9
VDS [V]
Min. 0.1 Max. 0.9
Current Value: 0.9
Frequency Domain (VI) Frequency Domain (AB) Time Domain Power Domain Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund3/LSNAdataset/v1i1_waveforms
v1(t) V (m/s) [E+0]
i1(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund3/LSNAdataset/v2i2_waveforms
v2(t) V (m/s) [E+0]
i2(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund3/LSNAdataset/a1b1_waveforms
a1(t) V (m/s) b1(t) V (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund3/LSNAdataset/a2b2_waveforms
a2(t) V (m/s) b2(t) V (m/s) [E-3]
time s [E-12]

Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
2.000G
RFPower [dBm]
Min. -4.19
Current Value: 4.32
Max. 10.04
VGS [V]
Min. 0.3
Current Value: 0.9
Max. 0.9
VDS [V]
Min. 0.1
Current Value: 0.9
Max. 0.9
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/v1i1_waveforms
v1(t) V (m/s) [E+0]
i1(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/v2i2_waveforms
v2(t) V (m/s) [E+0]
i2(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/a1b1_waveforms
a1(t) V (m/s) b1(t) V (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/a2b2_waveforms
a2(t) V (m/s) b2(t) V (m/s) [E-3]
time s [E-12]

Results


Large_signal_measurement_and_simulation_results_for_FET_device1:11
File Options Optimizer Plots Windows Help
Fundamental Frequency
2.000G
RFPower [dBm]
Min. -4.19
Current Value: 4.32
Max. 10.04
VGS [V]
Min. 0.3
Current Value: 0.6
Max. 0.9
VDS [V]
Min. 0.1
Current Value: 0.9
Max. 0.9
Frequency Domain (VI)
Frequency Domain (AB)
Time Domain
Power Domain
Dynamic Trajectories
Model tuning conditions
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/v1i1_waveforms
v1(t) V (m/s) [E+0]
i1(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/v2i2_waveforms
v2(t) V (m/s) [E+0]
i2(t) mA (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/a1b1_waveforms
a1(t) V (m/s) b1(t) V (m/s) [E+0]
time s [E-12]
Plot LSNA2ICCAP_FET_device1/FET_device1_fund1/LSNAdataset/a2b2_waveforms
a2(t) V (m/s) b2(t) V (m/s) [E-3]
time s [E-12]

Conclusions

- Large-signal measurements + device modeling program =
  - Complete large-signal device characterization and model accuracy assessment under realistic signals,
  - Simple access and improved usability of the measured data,
  - Model comparison and optimization.