# RF Power Amplifier Simulation with Microwave Office

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http://www.rfpoweramp.com

# Simulation Methods

- A simulator is an equation solver. The models are the equations. Accurate results require accurate models and the skill to apply them.
- Large signal models of power transistors are not very accurate. Simulation should be used for verifying concepts and statistical analysis.
- Several types of simulators are used for PA design. Most all include layout for PCBs and some have RFIC process kits:

  Linear – Simulation of passive networks and linear controlled sources. Prediction of power output using “Cripps Contours”.

  Harmonic Balance – Nonlinear frequency domain analysis. <u>Periodic sources</u> decomposed into harmonics. KVL and KCL solved for user specified number of harmonics and order of products. Good for soft to medium nonlinearities. Fast runtimes for closely spaced tones.

  Spice - Nonlinear time domain analysis. Good for strong nonlinearities. Long runtimes for closely spaced tones. Must handle distributed elements and s-parameters via equivalent circuits or convolution.

  Envelope – Represents modulated waveforms with complex envelope. Nonlinear circuits may be behaviorally modeled, or envelope source sliced into time steps and circuit solved with HB. Amplifiers and mixers may be incorporated into high level systems such as digital communication links, AGC loops, and linearization schemes.

  2.5D EM – Microstrip, stripline, RFICs, multilayer PCBs, thin printed antennas. Primary EM coupling in XY plane.

  3D EM – Packages, wirebonds, waveguide, antennas. Not a substitute for 2.5D (ex. Lange couplers).

# HB Simulation

- Distributed components and s-parameters pose some problems:

  DC is the zero harmonic.

  Closely spaced tones produce low frequency products.

  S-parameter data should have a 0 Hz line or else the simulator will extrapolate a low frequency response or model it as a short, likewise for EM simulations.

  High order products appear at high frequencies. Simulator may extrapolate data.

! Coilcraft 0402CS-10N Chip Inductor

! 29 May 2002
# MHZ S MA R 50

| !Freq | MagS11 | AngS11 | MagS21 | AngS21 | MagS12 | AngS12 | MagS22 | AngS22 |
|---|---|---|---|---|---|---|---|---|
| 0 | 1E-9 | 0 | 0.999999999 | 0 | 0.999999999 | 0 | 1E-9 | 0 |
| 1 | 0.0007713331 | 54.474609 | 0.999552003 | -0.0359838749 | 0.999552003 | -0.0359838749 | 0.000771333108 | 54.474609 |
| 21.7 | 0.0137349967 | 81.4213296 | 0.9980436 | -0.779702275 | 0.9980436 | -0.779702275 | 0.0137349967 | 81.4213296 |
| 42.4 | 0.0266883634 | 82.9323629 | 0.997068075 | -1.52215299 | 0.997068075 | -1.52215299 | 0.0266883634 | 82.9323629 |

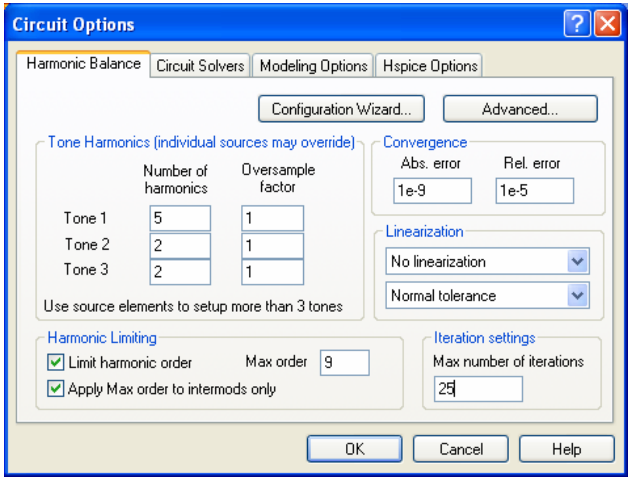
- Hard nonlinearities cause convergence problems. Tricks to achieve convergence:

  Back off power

  Adjust oversample factor.

  Reduce error tolerance.

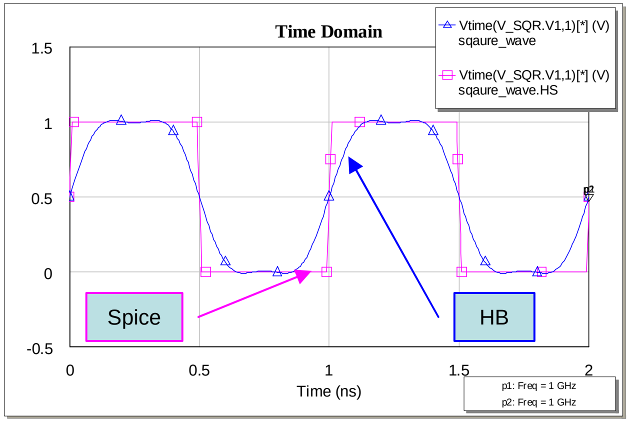
  Turn off breakdown diodes in model or linearize them. Same for nonlinear capacitors.

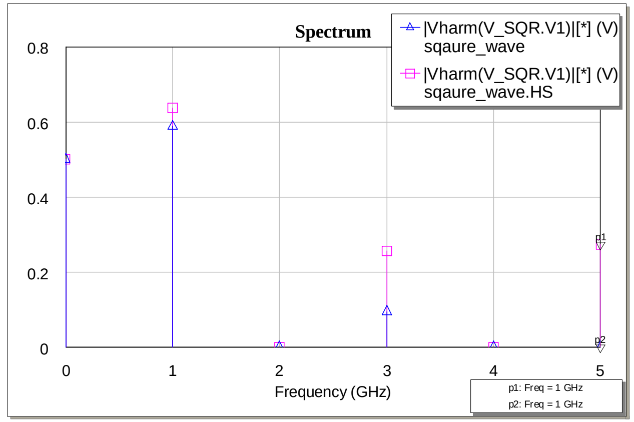


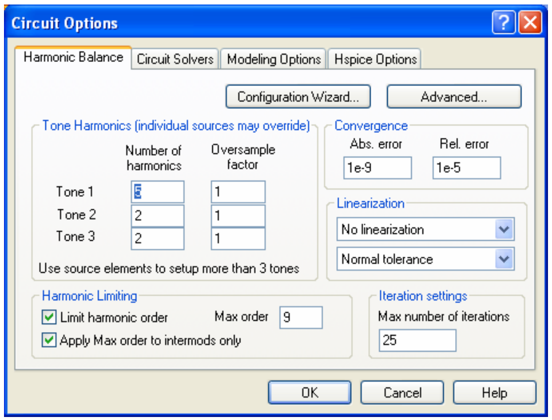

- Good model should be “continuously derivable” meaning there should be a solution (no matter how small) for every harmonic.

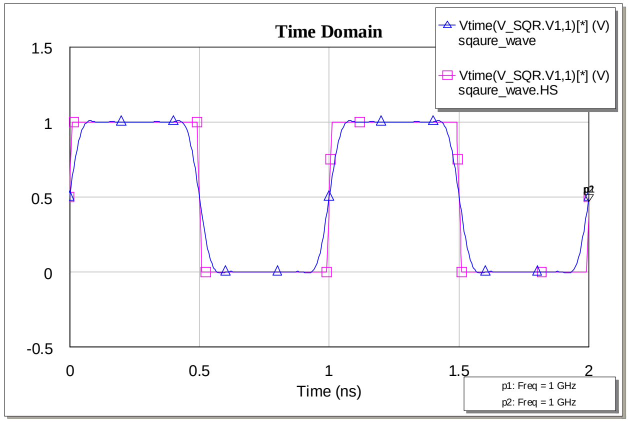
# HB Waveforms

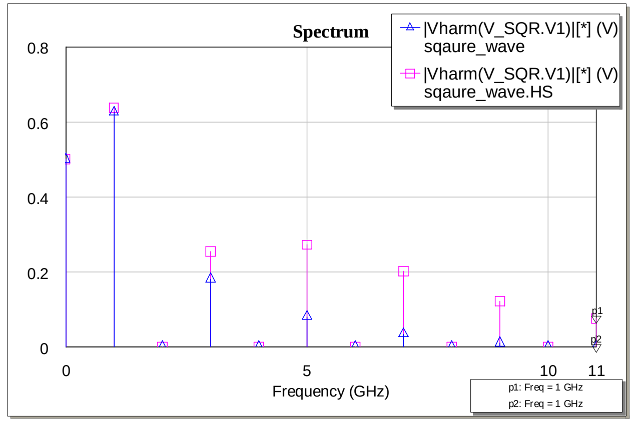
- Sharp transitions difficult to model

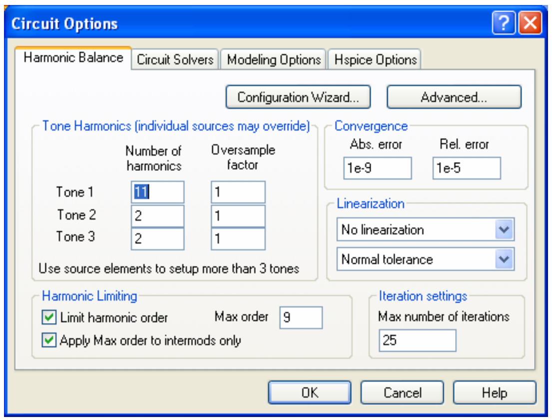


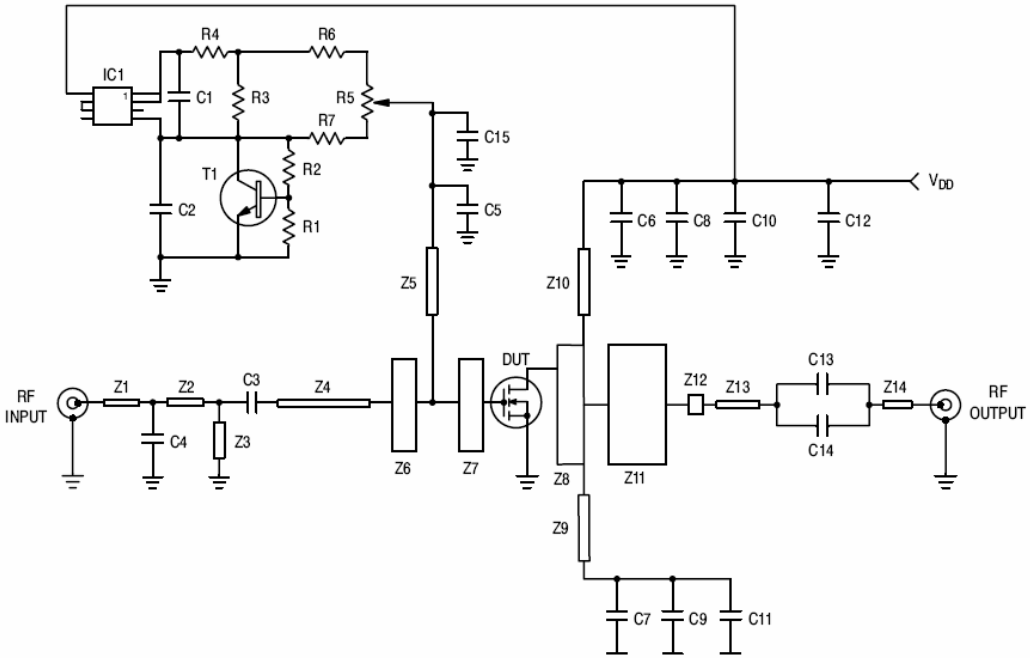



# Example Amplifier

Freescale MRF5S21150H reference design:

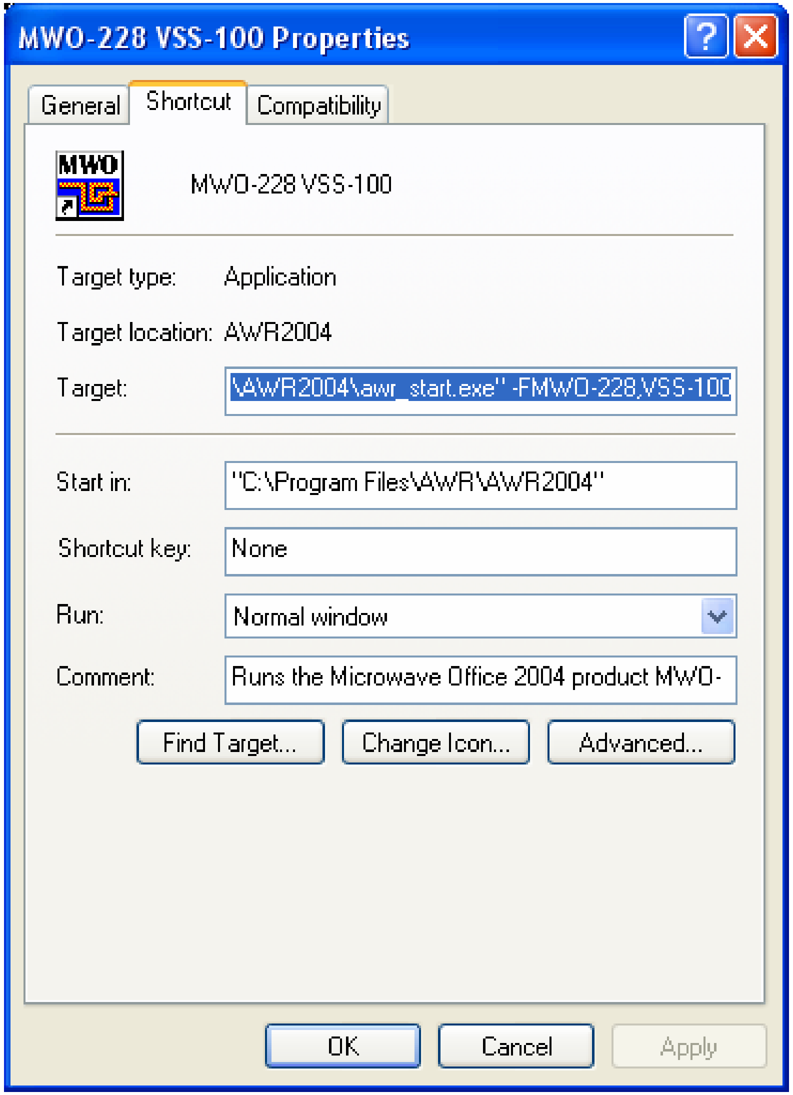
Pout=33 Watts at 2140 MHz, 2 carrier CDMA
Gain=12.5 dB
Eff=25 %
IM3=-37 dBc at 10 MHz offset
VCC=28 V, IDQ=1300 mA




http://www.freescale.com/files/rf_if/hardware_tools/printed_circuit_boards_for_reference_designs/MRF5S21150H_UMTS_RD.pdf

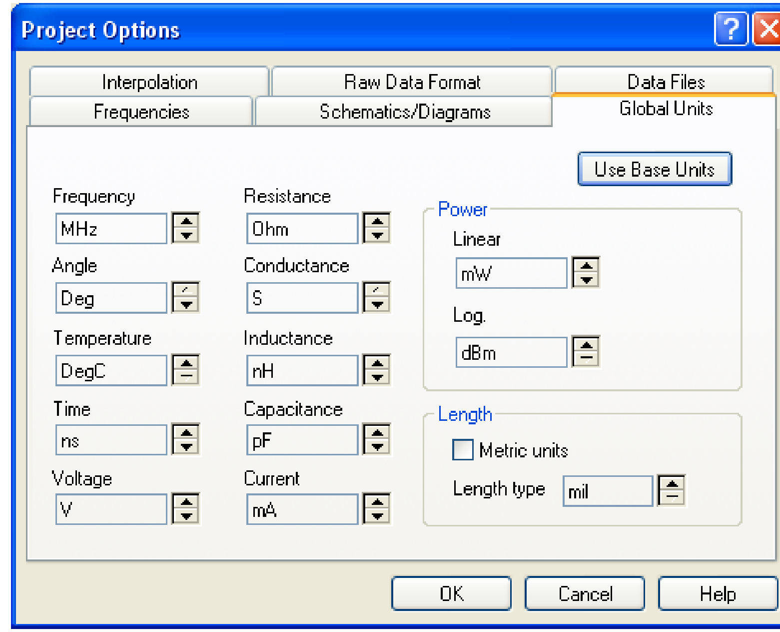
# Launching Microwave Office

- MWO-228, VSS-100 :
    - Linear
    - Harmonic Balance
    - EM
    - Layout
    - System
- May need to edit desktop icon and modify start parameters. May also use MWO-225

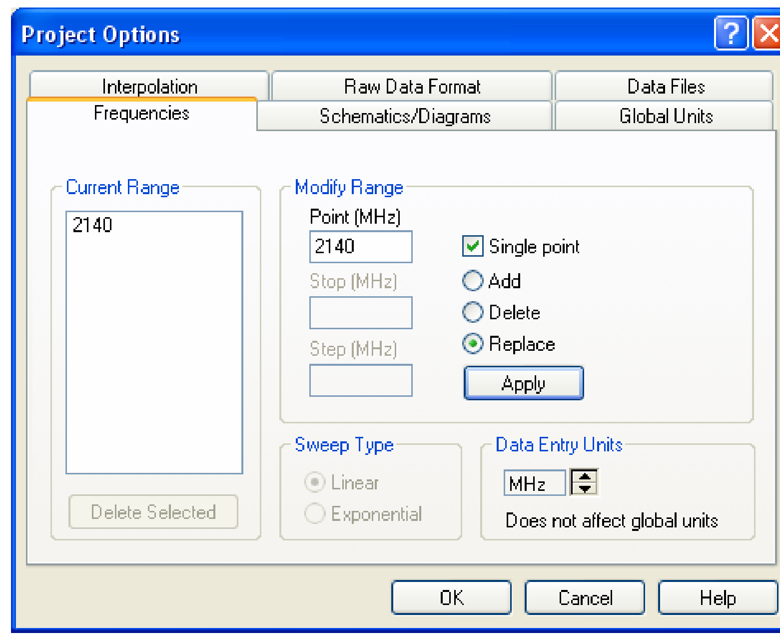


# Project Setup

- Set Project Options, Global Units to:
  - MHz
  - mils

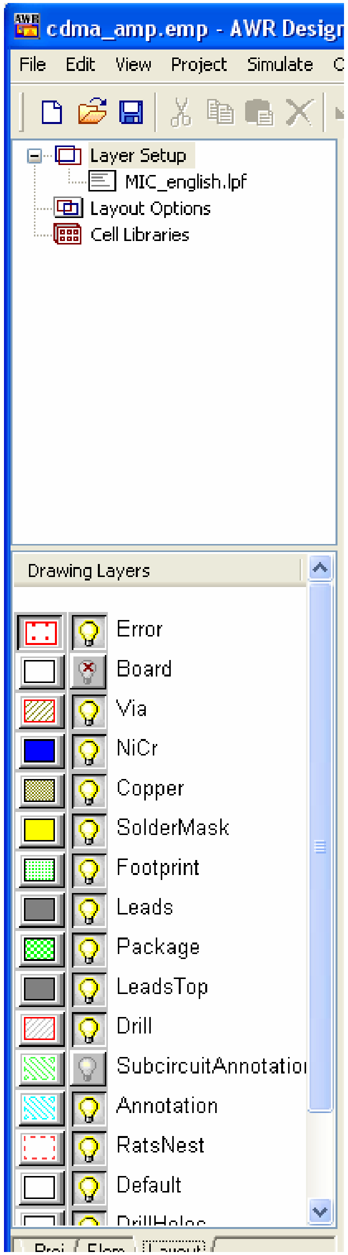



- Set Project Options, Frequencies to:
  - MHz units
  - 2140 MHz single point



# Layout Setup

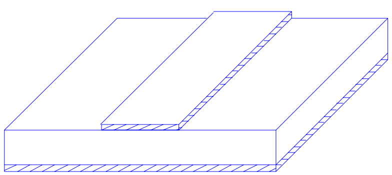
- Setup drawing layers by importing pre-defined Layout Process File “MIC_english.lpf”
- Project, Process Library, Import LPF
- Example process files located in:
  – C:\Program Files\AWR\AWR2004



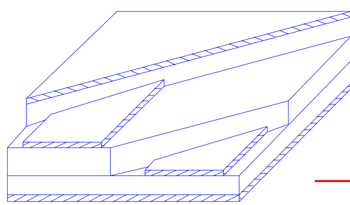
# Global Definitions

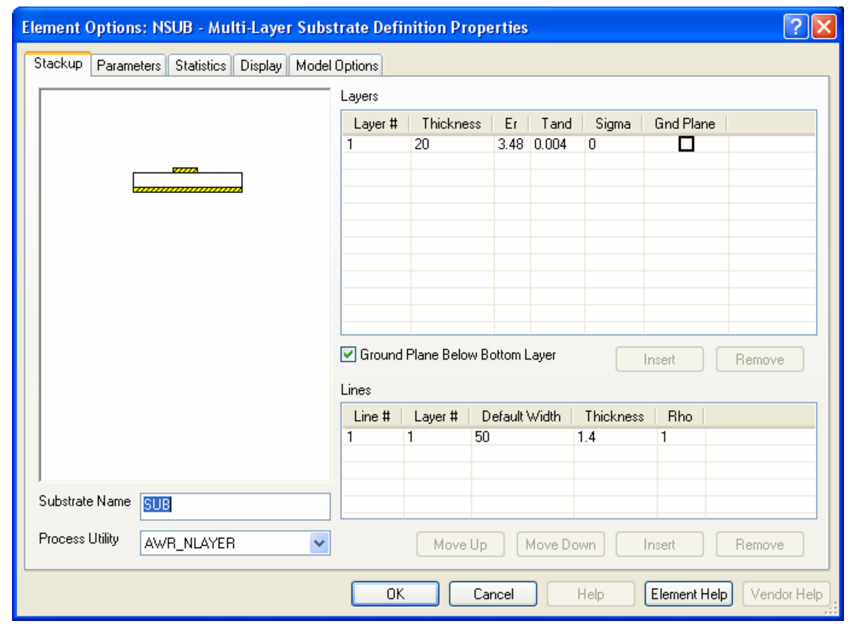
- Substrate information may be placed on Global Definitions page

MSUB
Er=3.48
H=20 mil
T=1.378 mil
Rho=0.7
Tand=0.004
ErNom=3.48
Name=RO/RO4350B



NSUB
HSub=20 mil
Er=3.48
Tand=0.004
ProcUtil="AWR_NLAYER"
Name=SUB



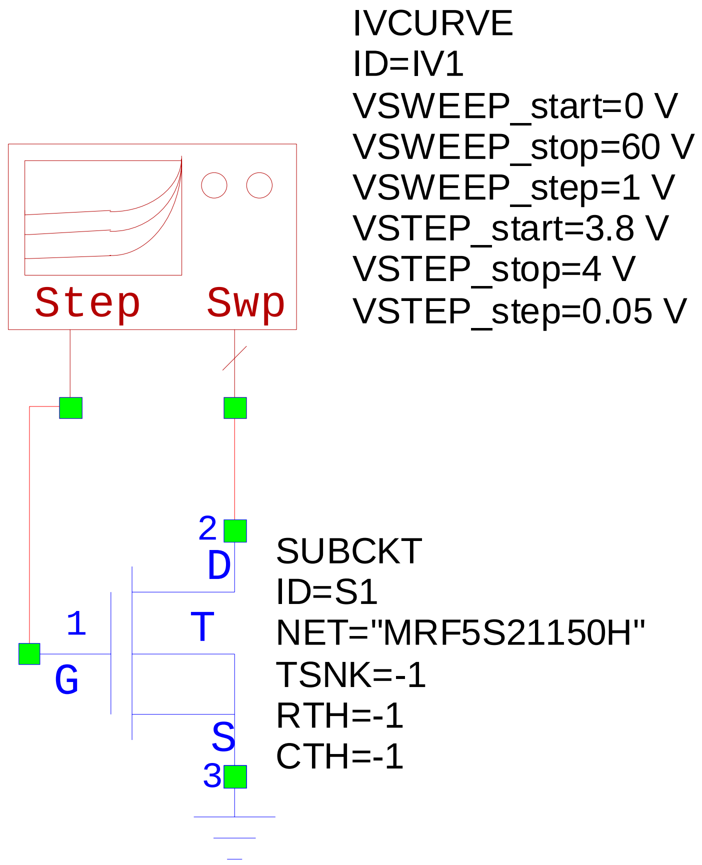



Microstrip substrate from vendor library

Multilayer substrate used for EM extraction

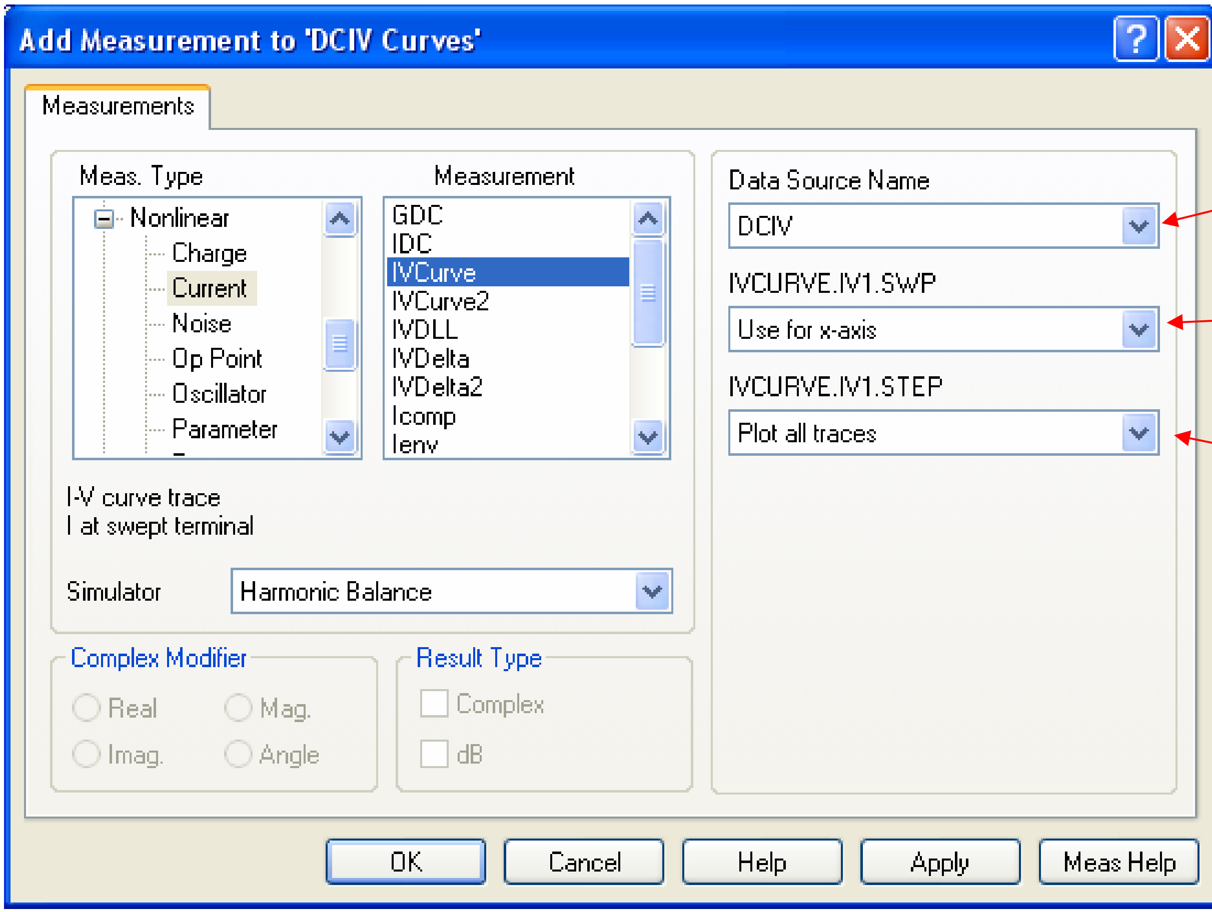
# DCIV Schematic

- Create a circuit schematic named “DCIV” consisting of the non-linear model and IVCURVE measurement device
- Use a curve tracer measurement to find VGS that establishes IDQ=1300 mA at VDD=28 V



# DCIV Measurement

- Create a rectangular graph named “DCIV Curves”
- Add an IVCurve measurement



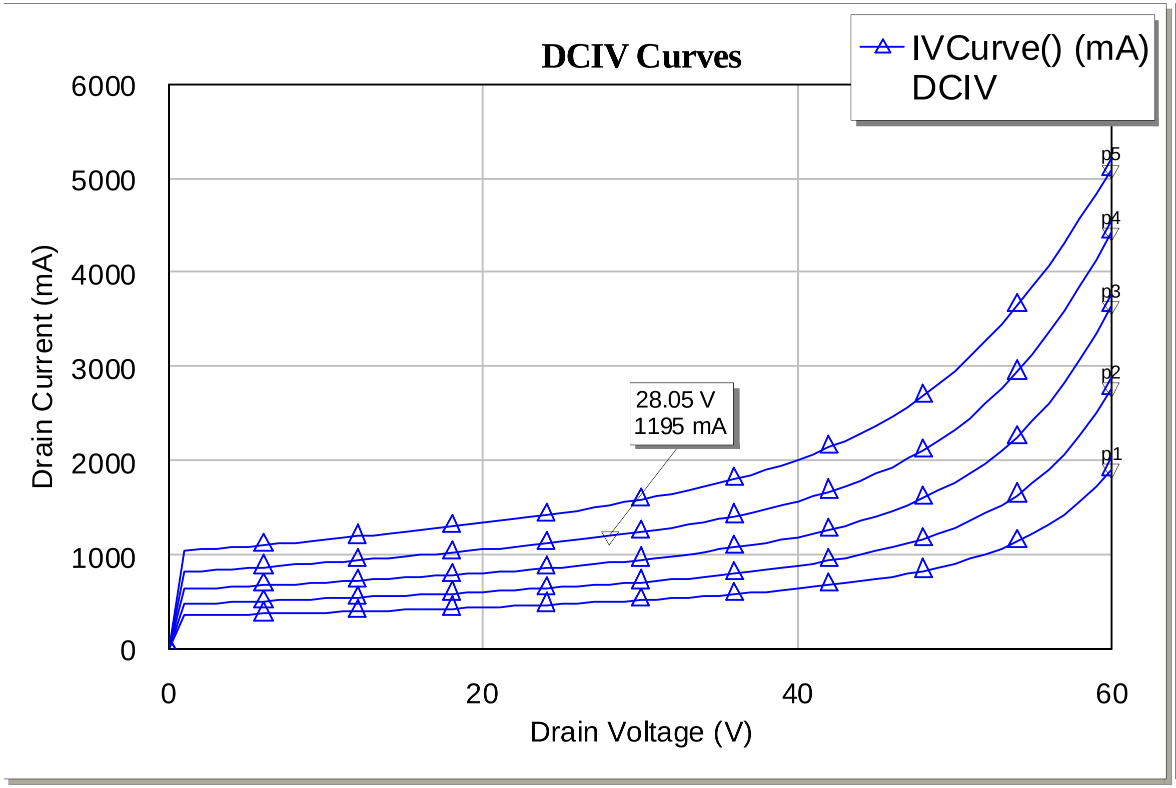

Data Source is either a schematic or data file

The x-axis will be the swept terminal (Drain Voltage)

Each step of gate voltage will be plotted on the graph

# Finding the Bias Point

- Simulate then place a marker showing VGS=3.95 V yields (approximately) IDQ=1300 mA at VDD=28 V




p1: Vstep = 3.8 V

p2: Vstep = 3.85 V

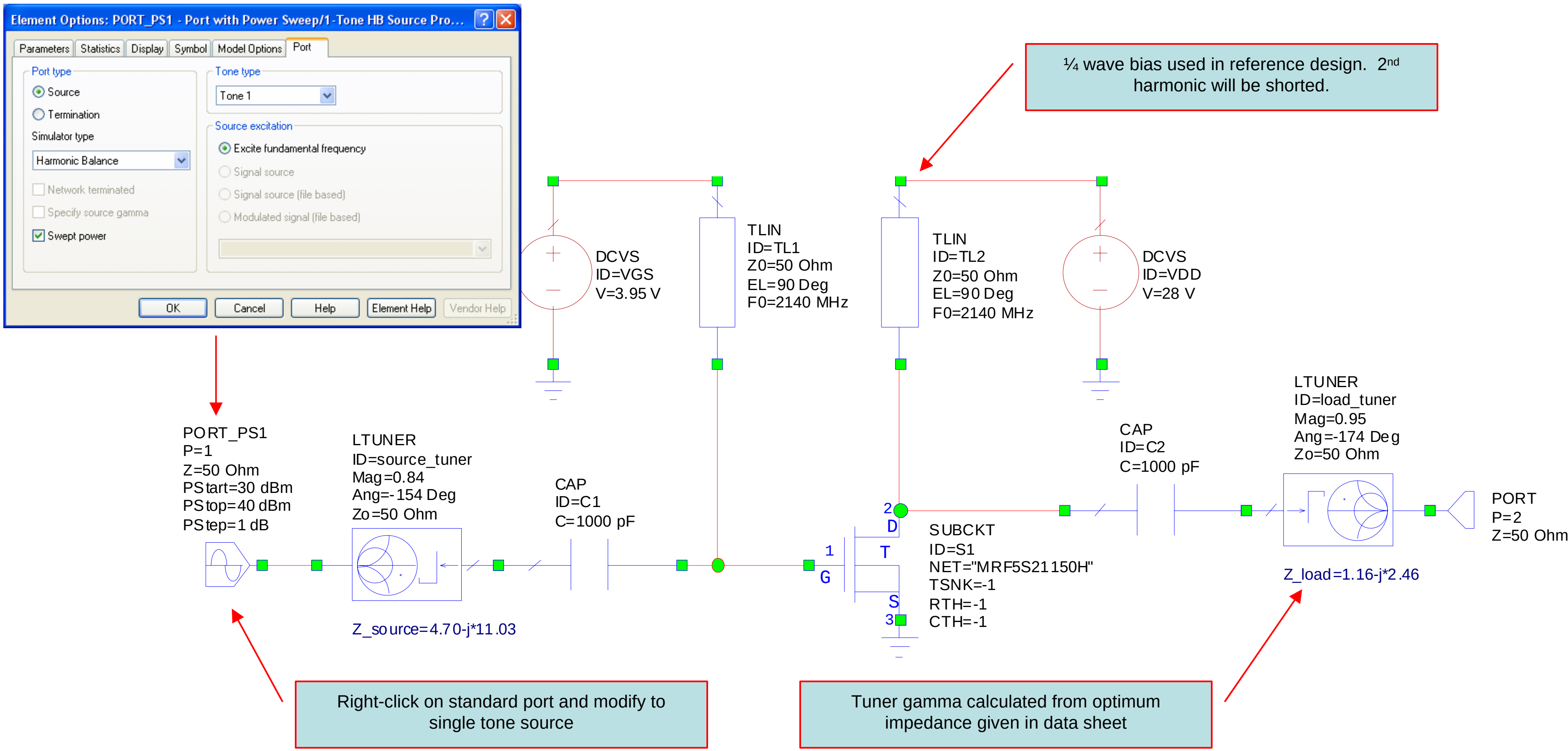
p3: Vstep = 3.9 V

p4: Vstep = 3.95 V

p5: Vstep = 4 V

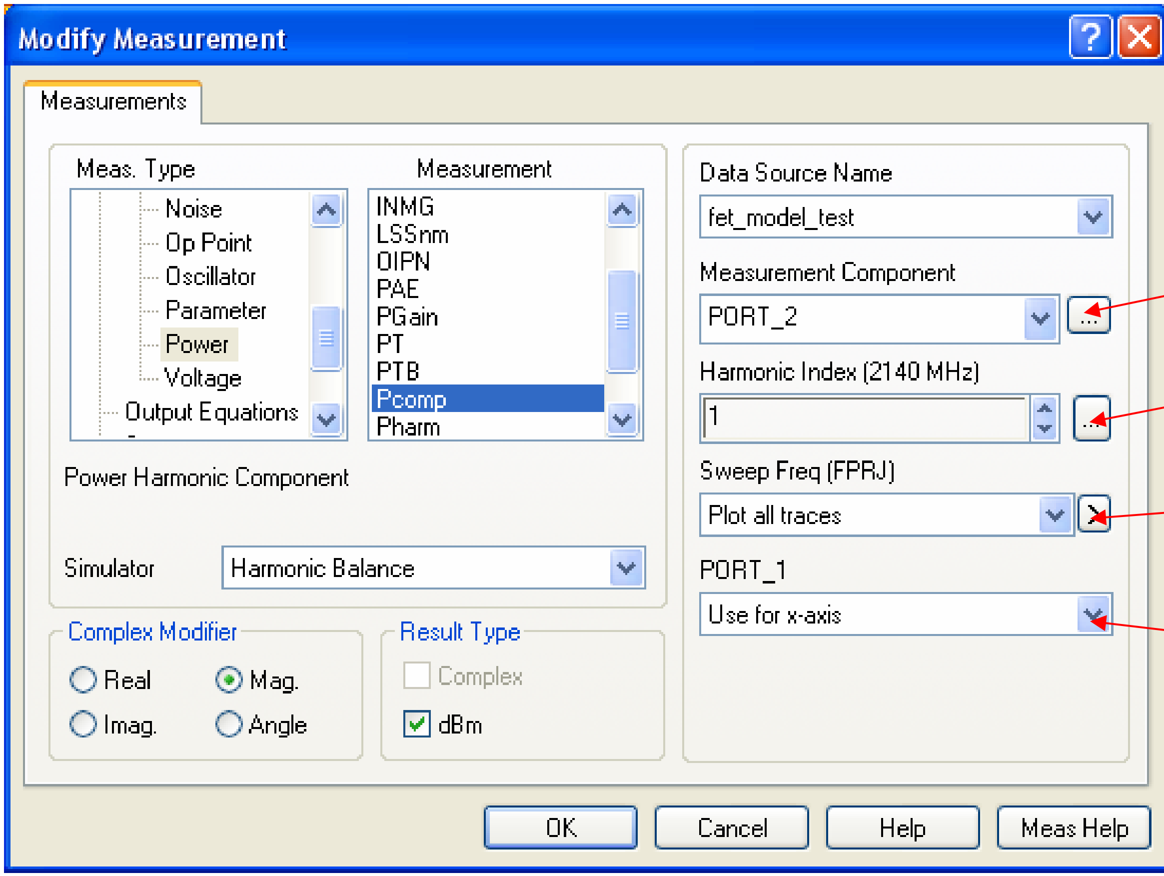
# Model Verification Schematic

- Create a new schematic named “model_test” to verify performance using impedance tuners.



# Model Verification Measurements

- Create a rectangular graph named “FET Model Output Power and Efficiency” and add an Pcomp measurement




Click this button to graphically select the measurement element

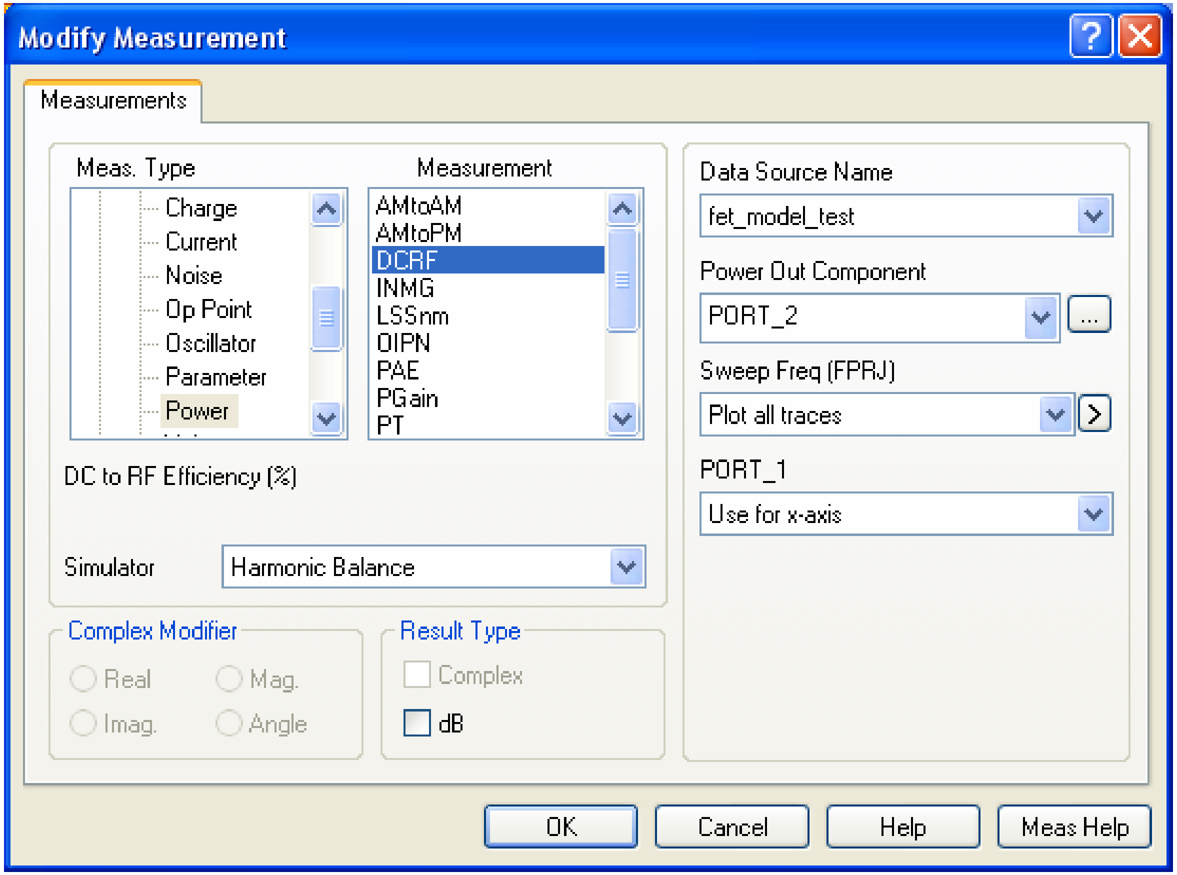
Click this button for “harmonic helper” pop-up window

Click this button to select “Project Frequencies” or “Document Frequencies”

Input power used for x-axis

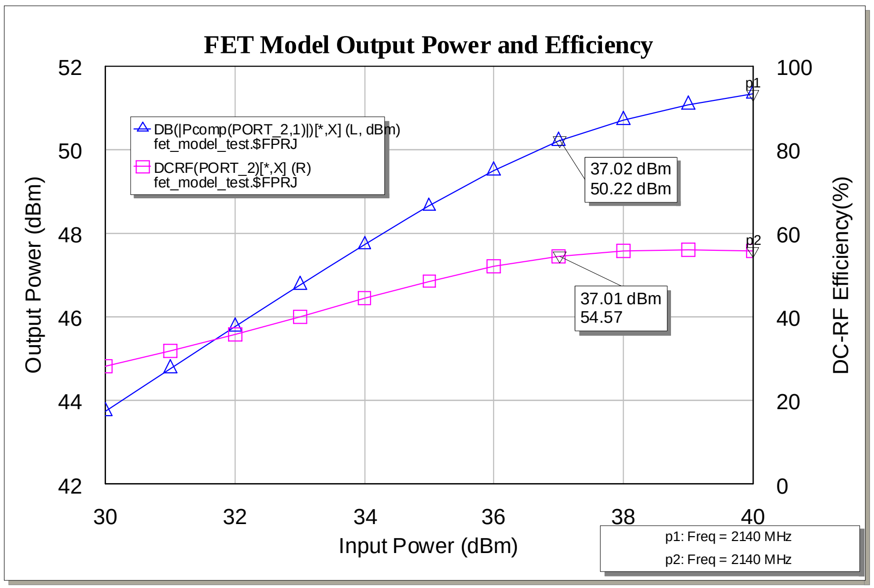
# Model Verification Measurements

- Add a DCRF measurement. The DC input power is calculated from all the DC sources on the schematic.



# Model Verification Results

- Comparison at Pin=5 W (37.0 dBm)
  - Model: Pout=105 W (50.2 dBm), G=13.2 dB, Eff=55 %
  - Measured: Pout=102 W, G=13.1 dB, Eff=42 %



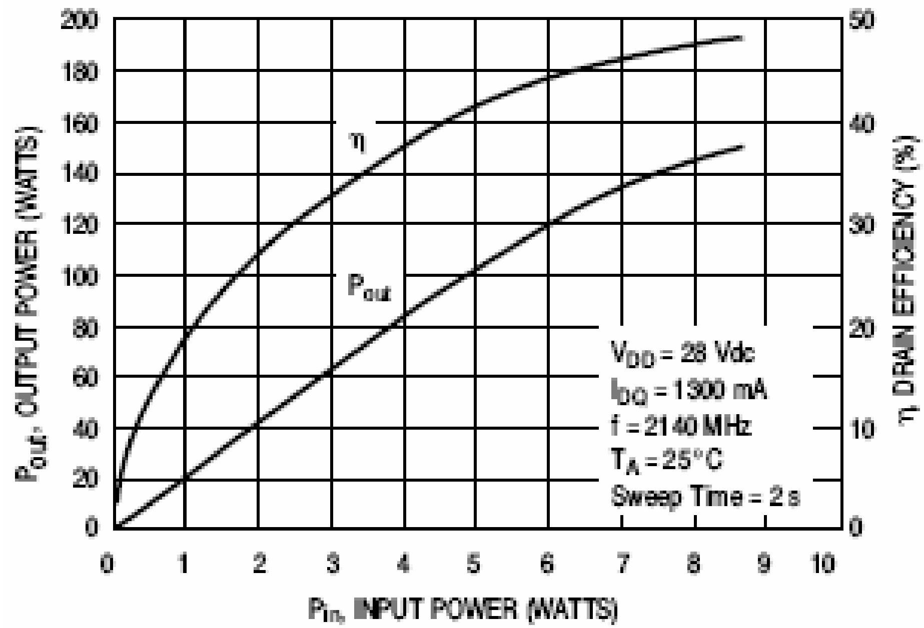
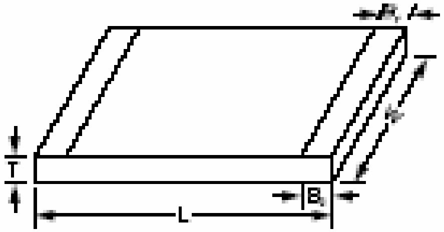




Figure 9. Output Power and Drain Efficiency versus Input Power

# Layout Cell Creation

- Create a new GDS cell library named “RF_footprints”. Create a new cell named “0805_AVX”.
- Use a 10 mil snap grid to draw the footprint and leads on their respective layers.
- Add cell ports (reference planes) at the inside of the pads. Hold down CTRL to snap to geometry.

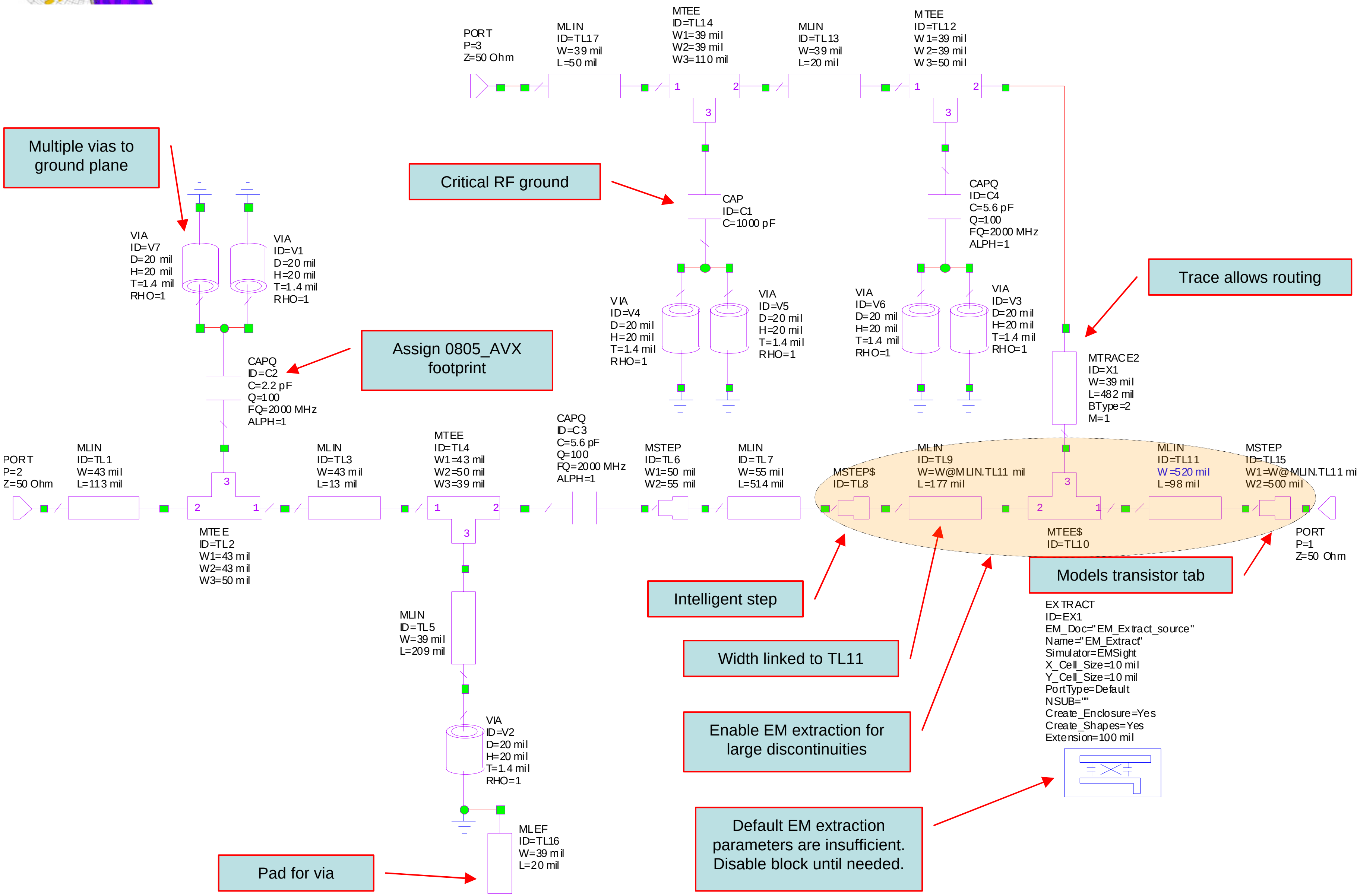

**ACCU-F® *(Signal Type Capacitors)**

| | 0603 | 0805 |
|---|---|---|
| L | 1.60±0.1 (0.063±0.004) | 2.01±0.1 (0.079±0.004) |
| W | 0.81±0.1 (0.032±0.004) | 1.27±0.1 (0.050±0.004) |
| T | 0.63±0.1 (0.025±0.004) | 0.63±0.1 (0.025±0.004) |
| B | 0.30±0.1 (0.012±0.004) | 0.30±0.1 (0.012±0.004) |

*Not recommended for new designs. Accu-P's are recommended.

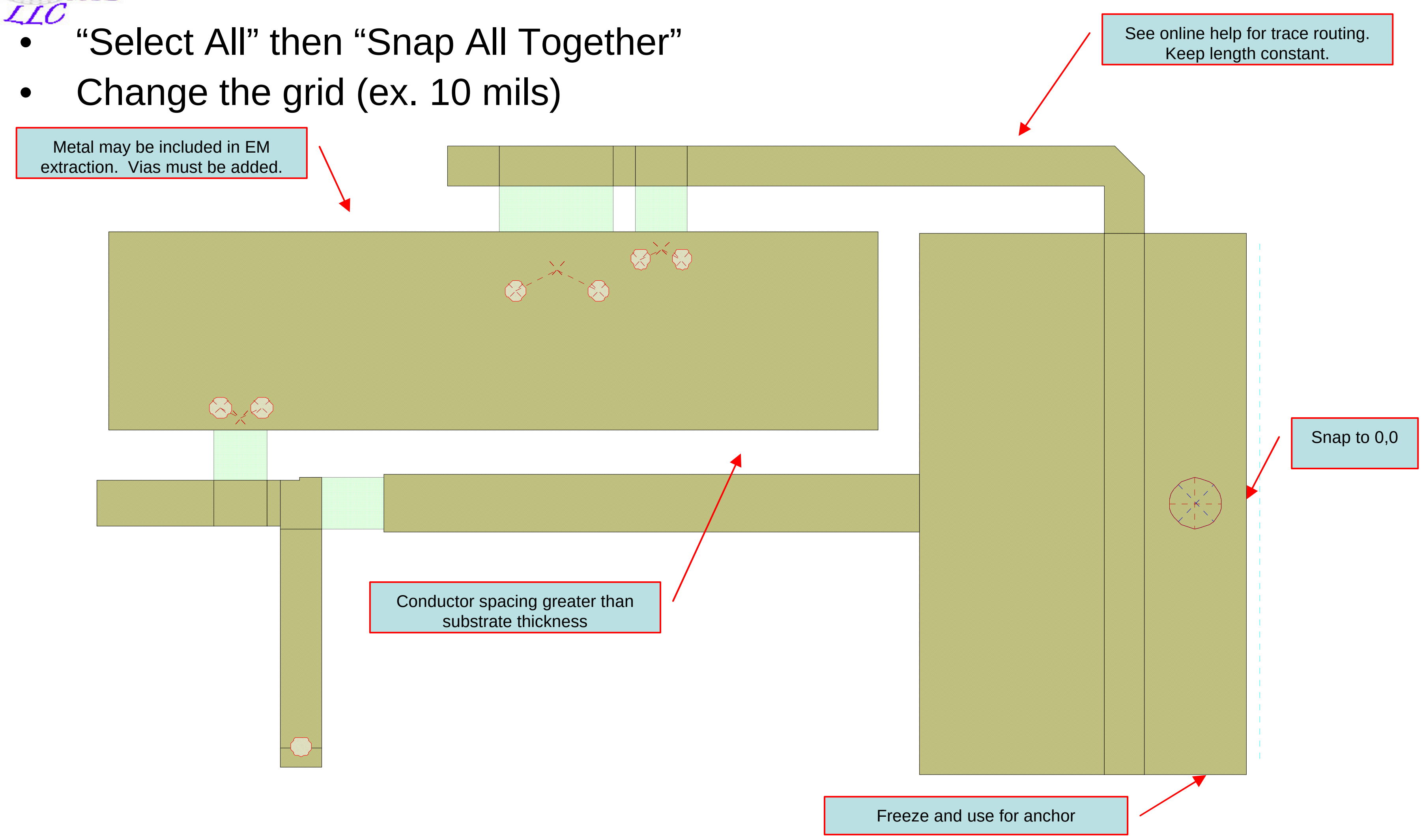
DIMENSIONS: millimeters (inches)

# Source Match Schematic



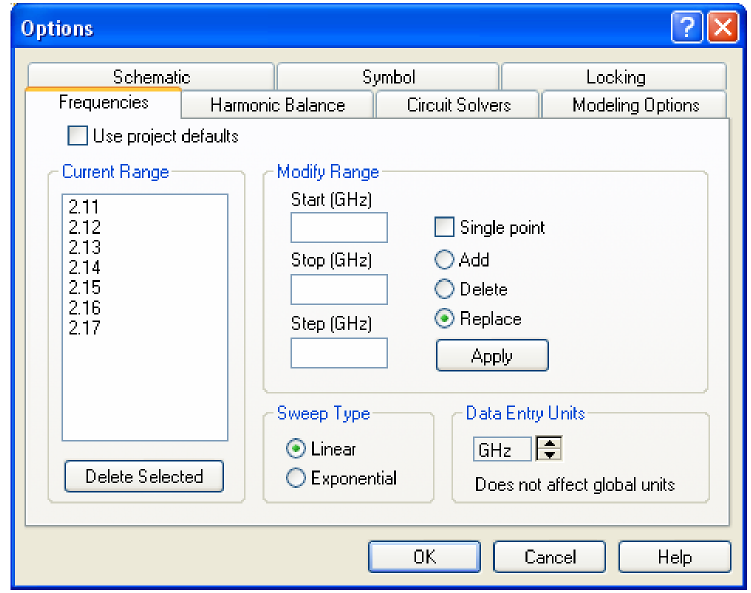
# Source Match Layout

- “Select All” then “Snap All Together”
- Change the grid (ex. 10 mils)

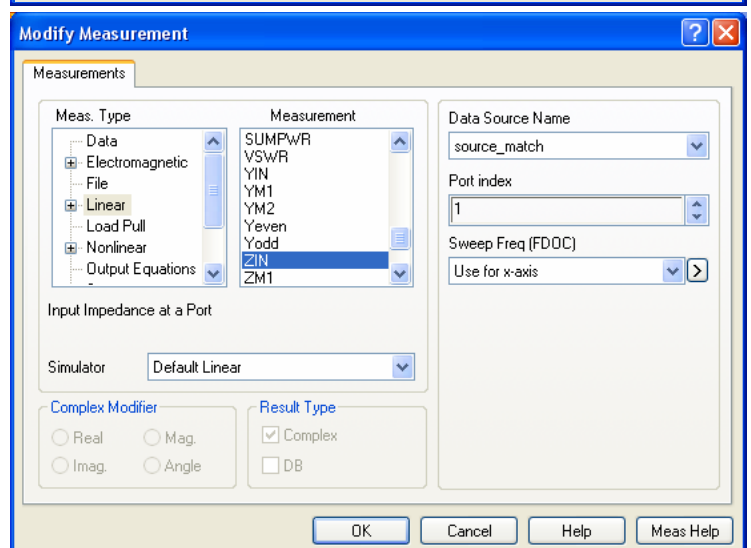


# Source Match Measurements

- Modify the frequency points of "source_match" by right clicking the options in the tree view.

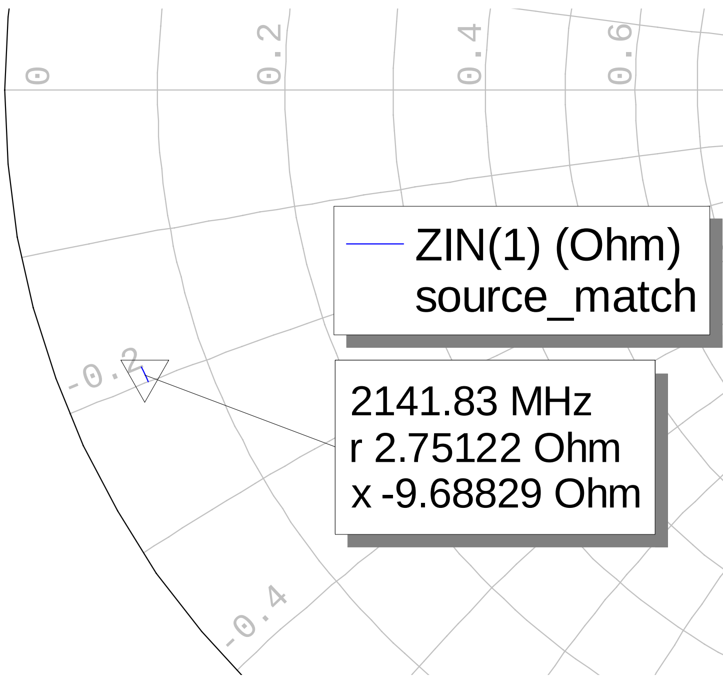


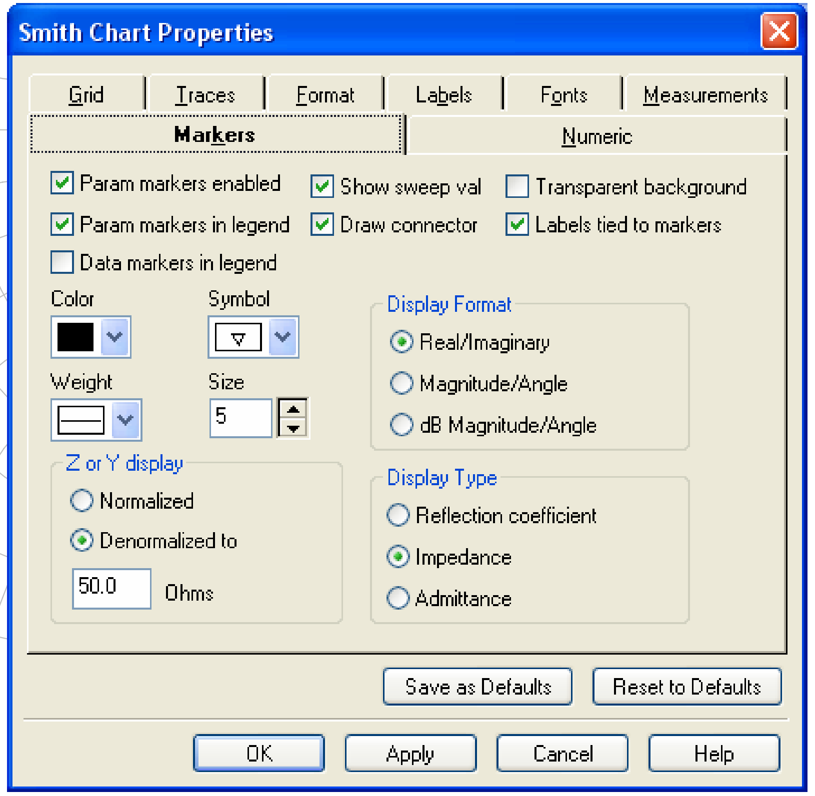

- Create a new Smith Chart graph named "Matching Network Impedances". Add a Zin measurement for Port 1.



# Source Match Results

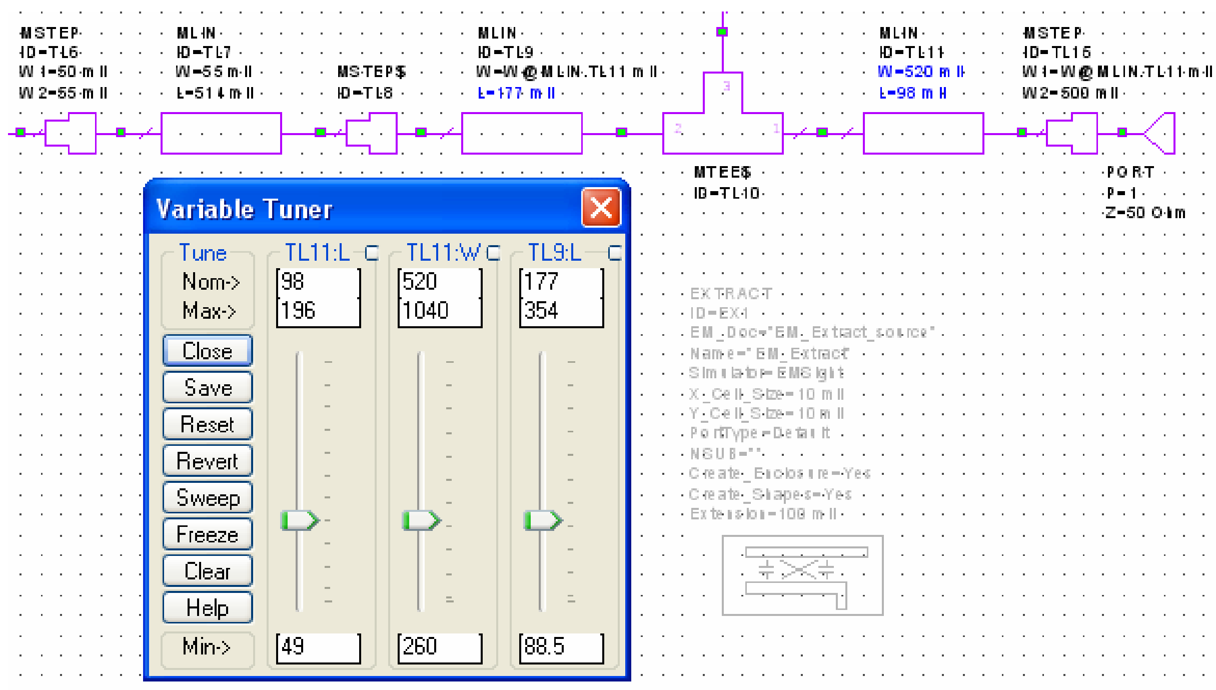
- Simulate then place a marker at 2140 MHz.
- Modify the marker to display impedance



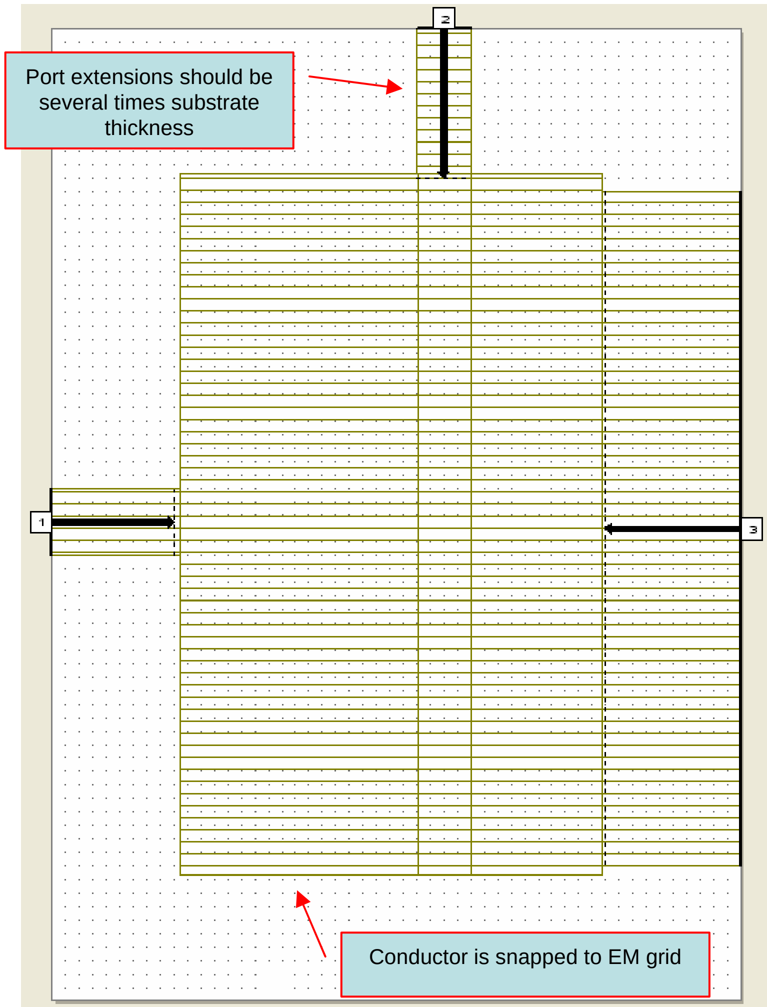



# Source Match Tuning

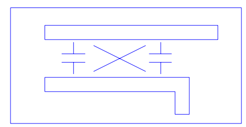
- Is the source impedance close the 4.70–j*11.03 ohms recommended in the data sheet ?
- Tune the circuit to improve the result.
- Enable the EM Extraction element and observe the result.



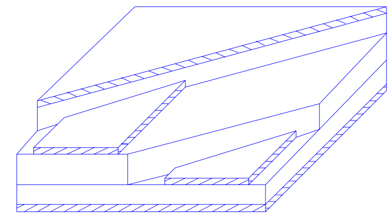
# EM Extraction

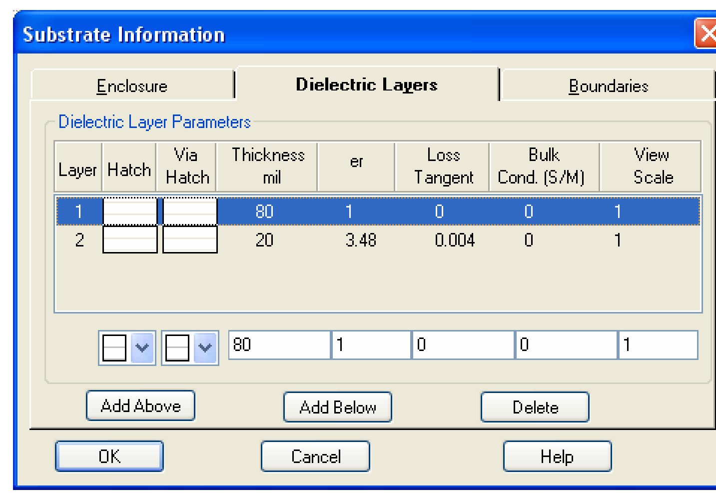



EXTRACT
ID=EX1
EM_Doc="EM_Extract_source"
Name="EM_Extract"
Simulator=EMSight
X_Cell_Size=10 mil
Y_Cell_Size=10 mil
PortType=Default
NSUB=""
Create_Enclosure=Yes
Create_Shapes=Yes
Extension=100 mil



NSUB
HSub=20 mil
Er=3.48
Tand=0.004
ProcUtil="AWR_NLAYER"
Name=SUB

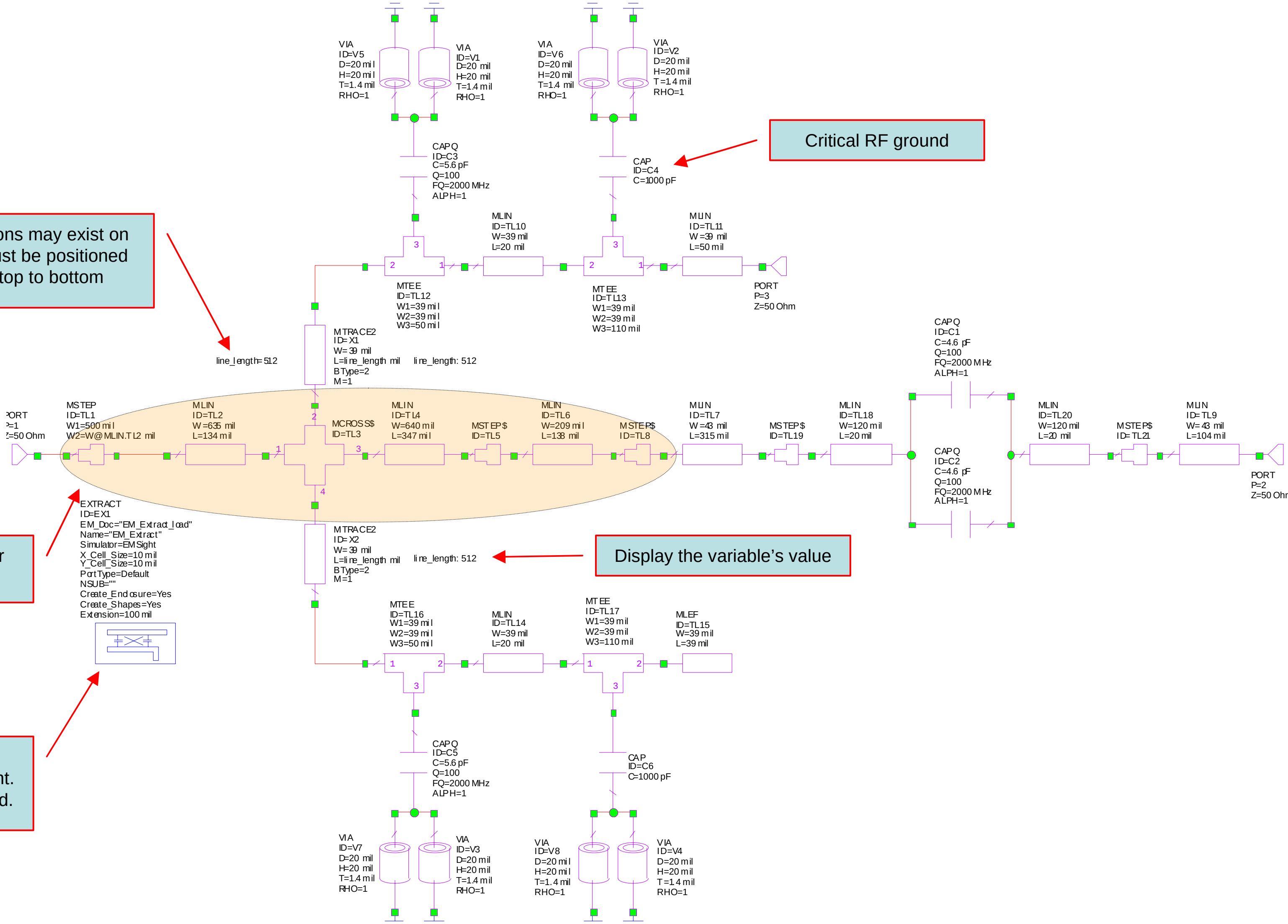




# Load Match Schematic

Variables and equations may exist on the schematic but must be positioned in sequence from top to bottom

Critical RF ground



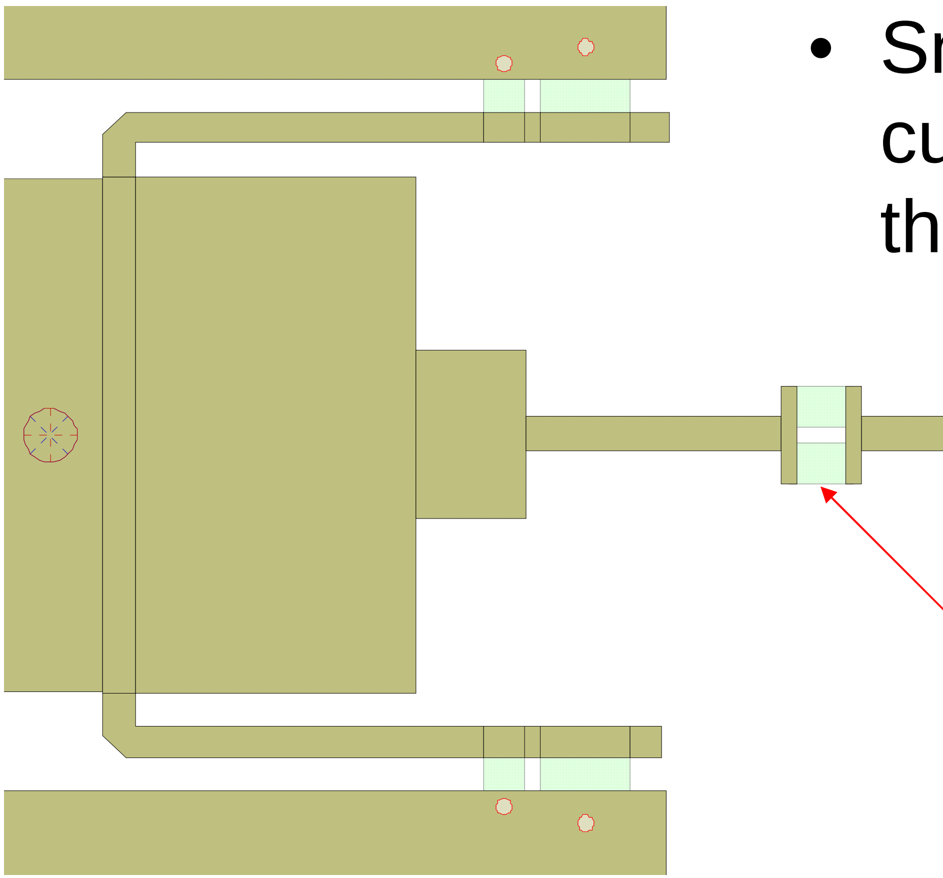

Display the variable's value

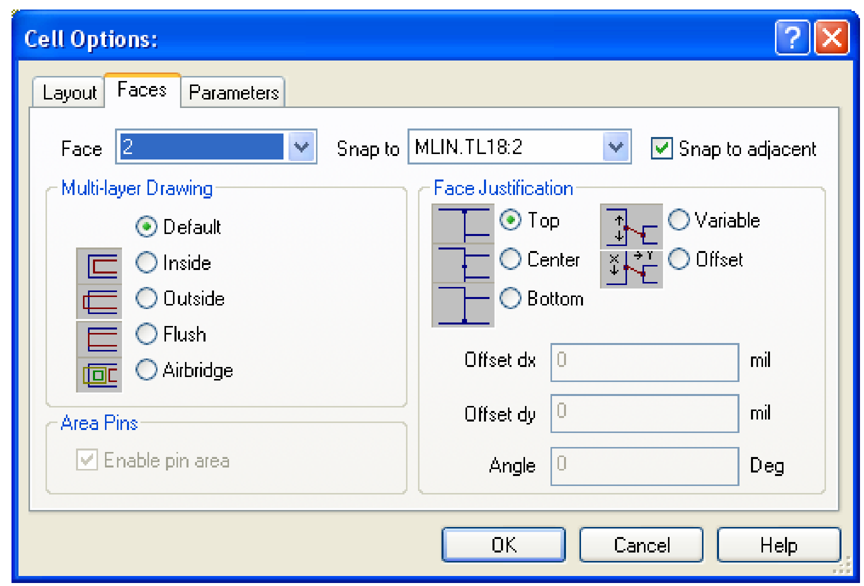
Enable EM extraction for large discontinuities

Default EM extraction parameters are insufficient. Disable block until needed.

# Load Match Layout

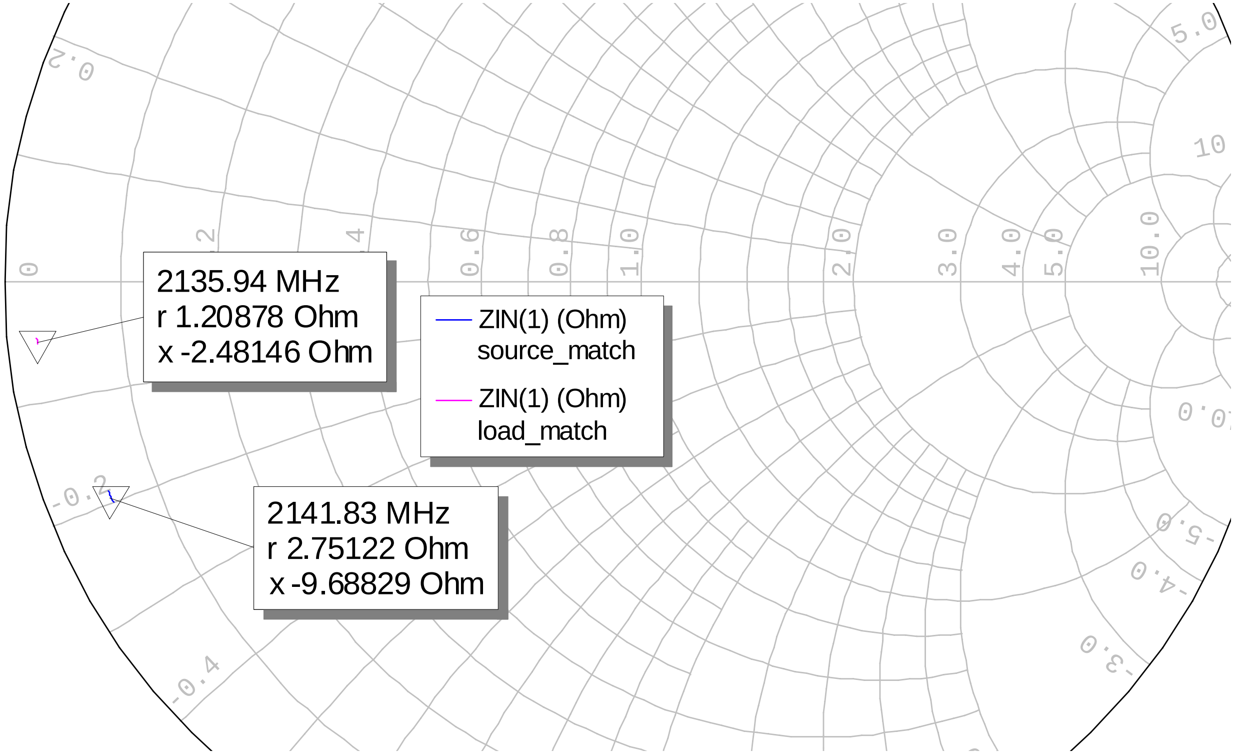
- Snapping may be customized by changing the shape properties.



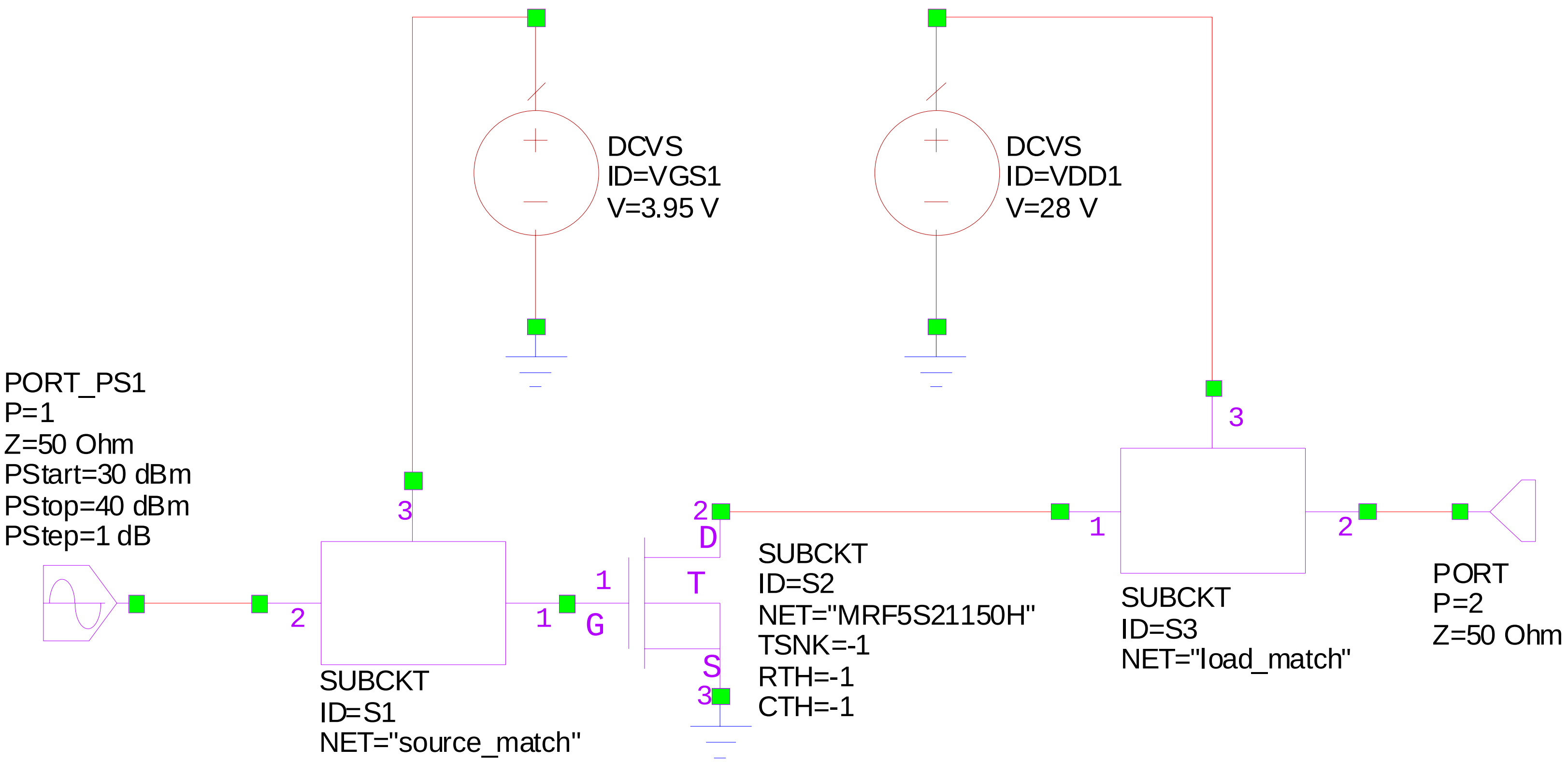


# Load Match Results

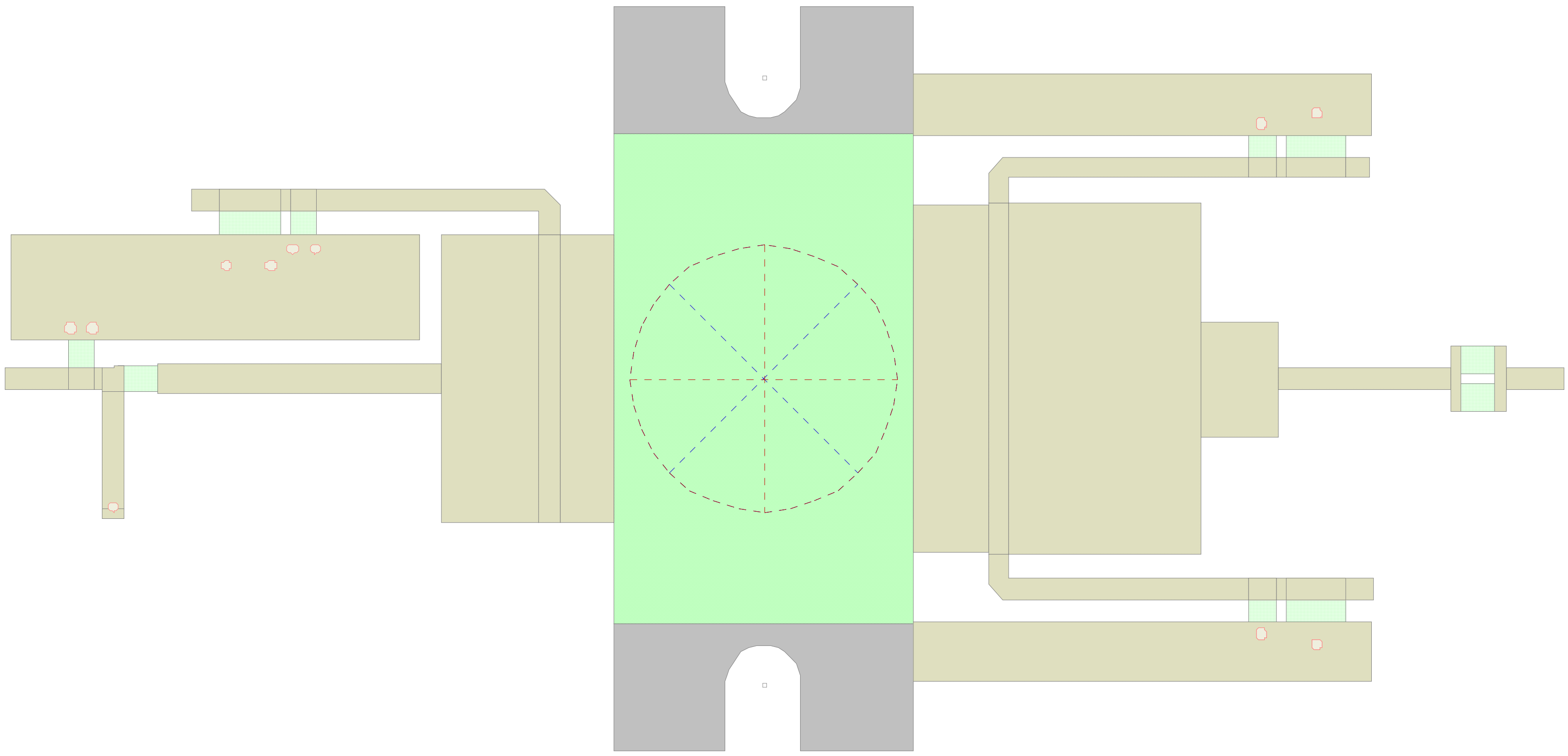
- Is the load impedance close the 1.16–j*2.46 ohms recommended in the data sheet ?
- Tune the circuit to improve the result.
- Enable EM extraction and observe the results.



# Amplifier Schematic

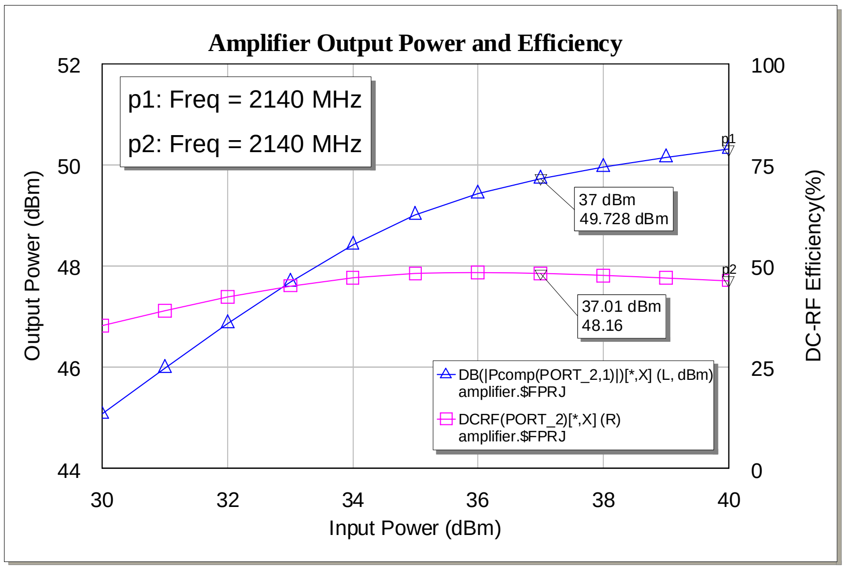


# Amplifier Layout



# Amplifier Pout and Eff

- Comparison at Pin=5 W (37.0 dBm)
  – Model: Pout=93 W (49.7 dBm), G=12.7 dB, Eff=48 %
  – Measured: Pout=102 W, G=13.1 dB, Eff=42 %



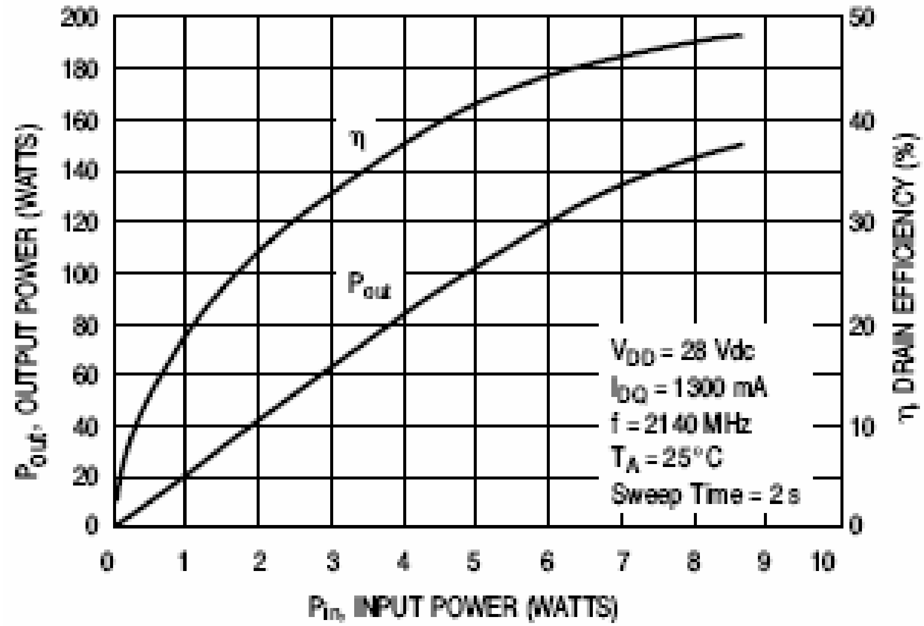
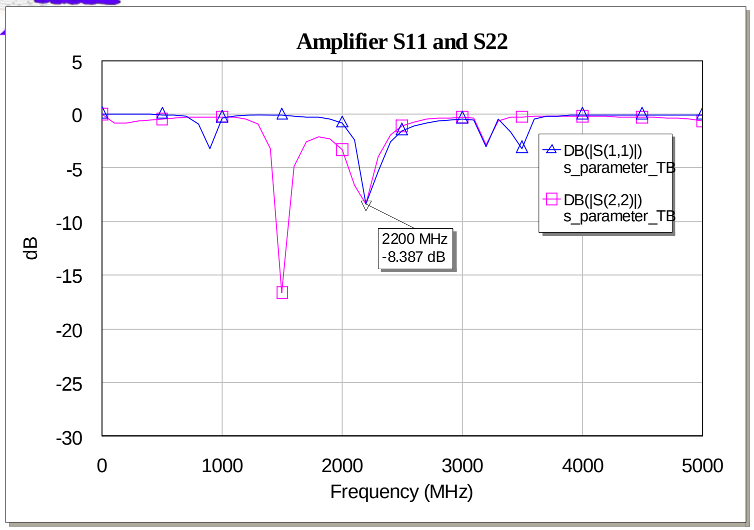
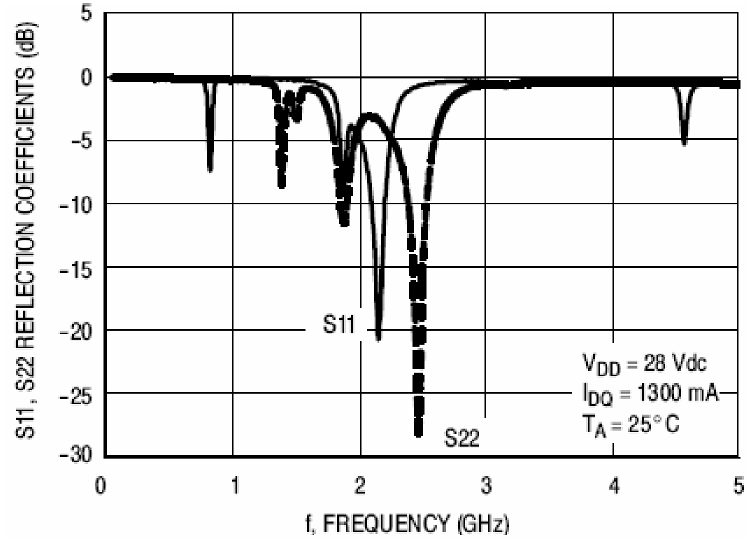
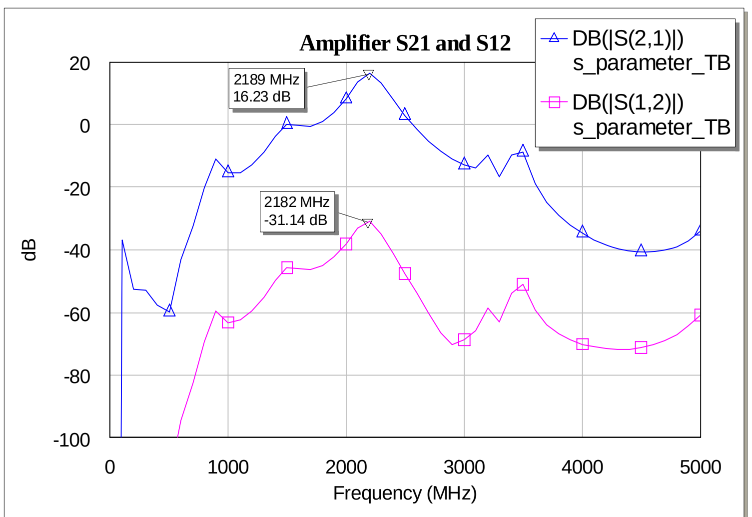



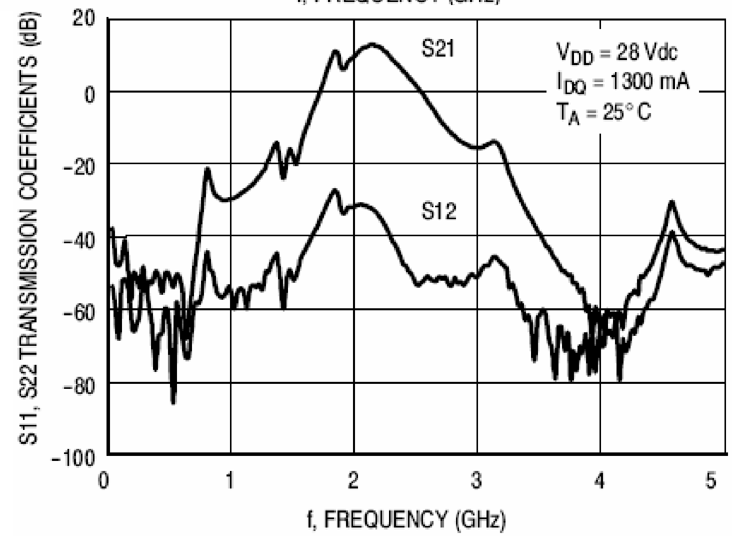

Figure 9. Output Power and Drain Efficiency versus Input Power

# Amplifier S-Parameters



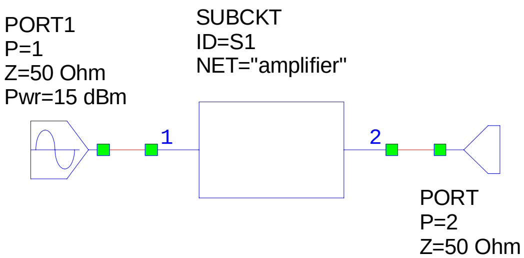



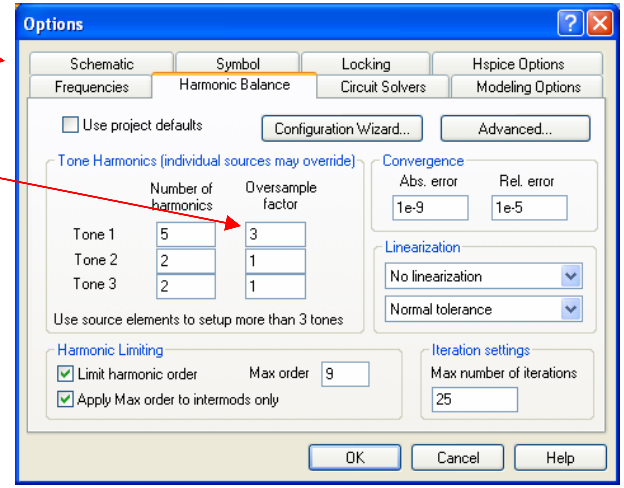



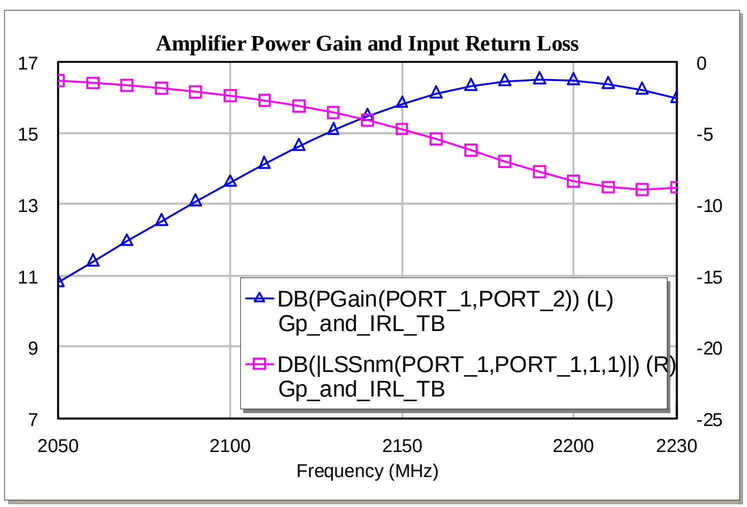
# Amplifier Power Gain and Input Return Loss

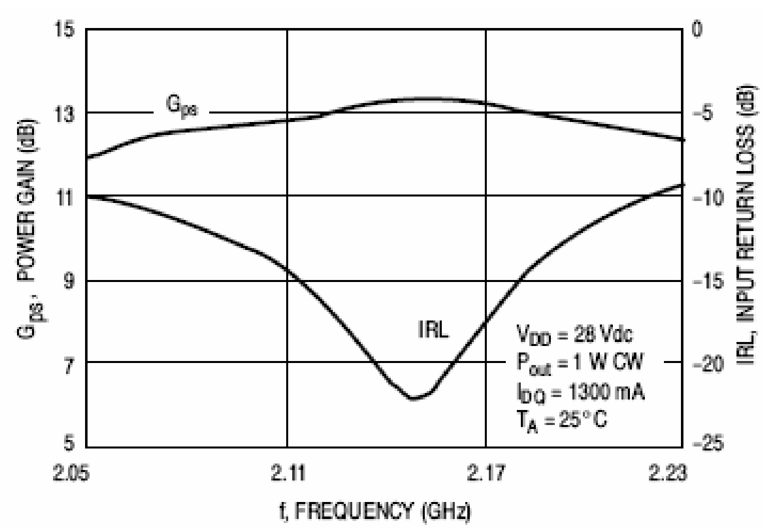
Modify the document options (instead of project options)

Increased to obtain convergence



# Output Equations

- Use output equations to assign measurements to variables.
- Output equations are always in base units
- Data may then be manipulated using a regular equation.

Output Equation (green text)

P_fund = two_tone_power_sweep:|Pcomp(PORT_2,0_1)|[*,X]

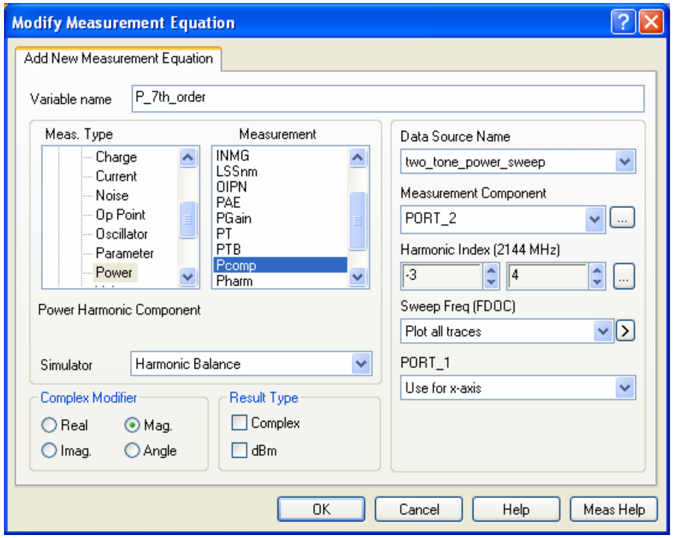
P_PEP=P_fund*4    The Peak Envelope Power for a balanced 2-tone signal is approximately 4 times the single tone
http://en.wikipedia.org/wiki/Peak_envelope_power

Regular Equation

P_3rd_order = two_tone_power_sweep:|Pcomp(PORT_2,-1_2)|[*,X]

P_5th_order = two_tone_power_sweep:|Pcomp(PORT_2,-2_3)|[*,X]

P_7th_order = two_tone_power_sweep:|Pcomp(PORT_2,-3_4)|[*,X]




IMD3=plot_vs(10*log10(P_3rd_order/P_PEP),P_PEP)

IMD5=plot_vs(10*log10(P_5th_order/P_PEP),P_PEP)

IMD7=plot_vs(10*log10(P_7th_order/P_PEP),P_PEP)

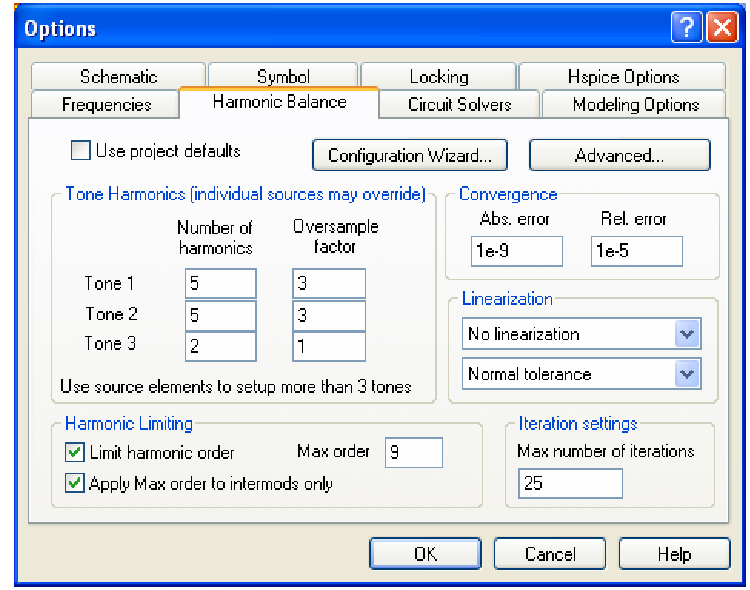
# Amplifier IMD

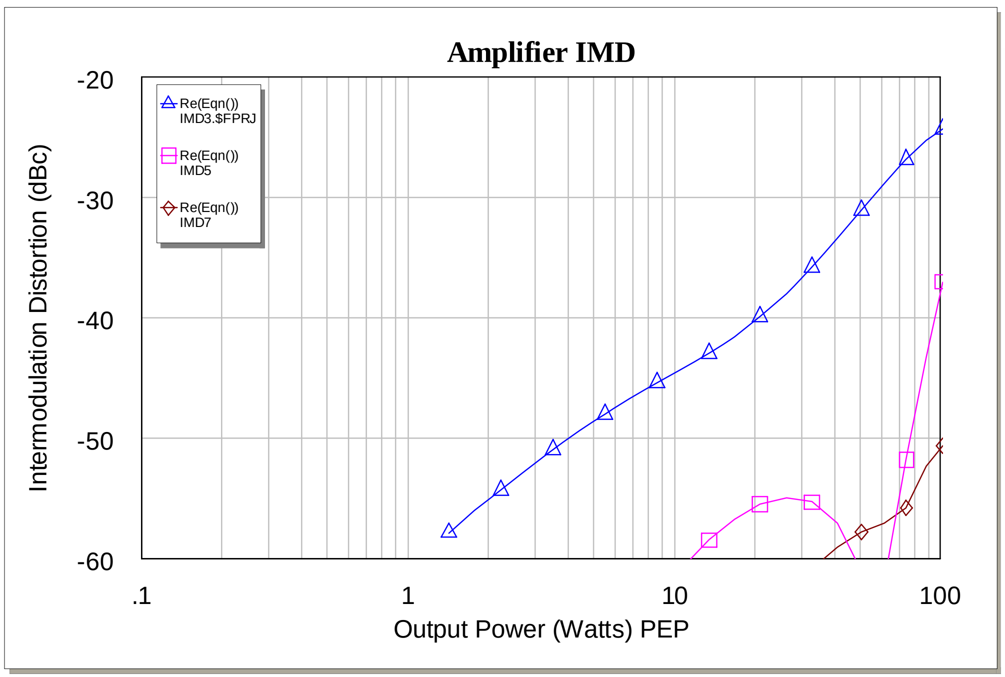
PORT_PS2
P=1
Z=50 Ohm
Fdelt=1 MHz
PStart=10 dBm
PStop=36 dBm
PStep=1 dB

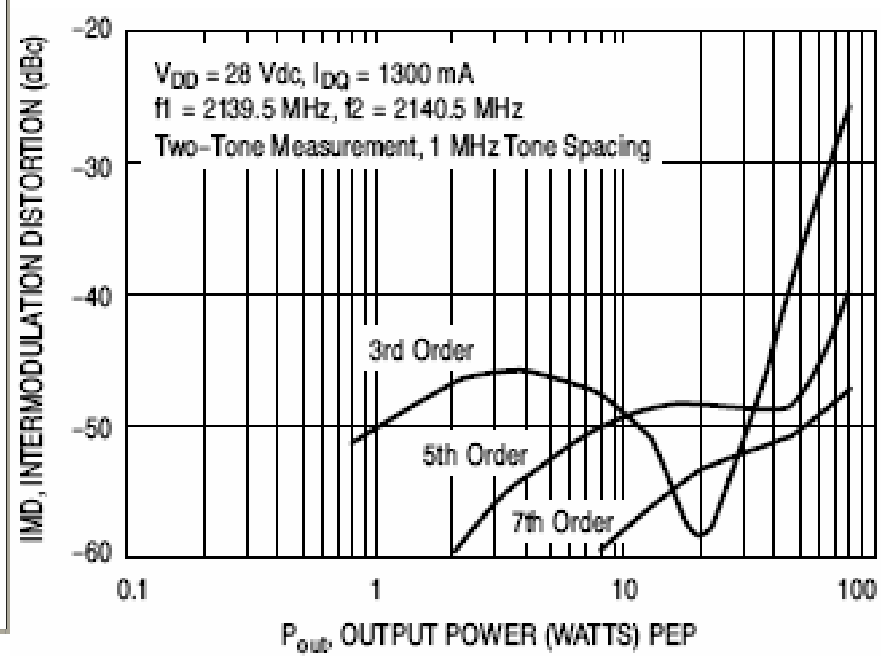
Default HB settings for document must be changed

SUBCKT
ID=S1
NET="amplifier"


PORT
P=2
Z=50 Ohm



# Visual System Simulator

- VSS is a time domain simulator that uses both real samples and complex envelope representation.
- Complex envelope representation allows baseband waveforms to be up-converted and simulated at RF.
- VSS is very powerful however the manual should be read to fully understand it.
- See example vss_data.emp for examples of sources.

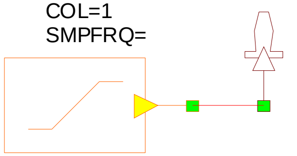
A real signal x(t)=1

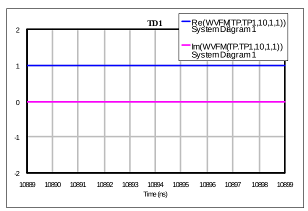
Re[x(t)]=xc(t)=1
Im[x(t)]=xs(t)=0

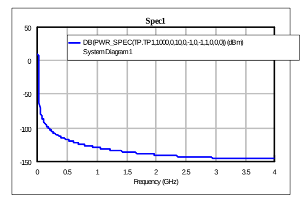
Power at DC

SRC_R
ID=A1
VAL=1
COL=1
SMPFRQ=

TP
ID=TP1





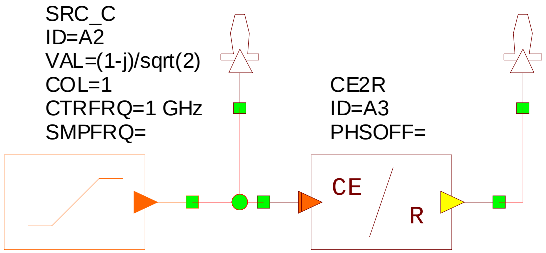

c(t)=(1-j)/sqrt(2), fc=1 GHz

TP
ID=TP2

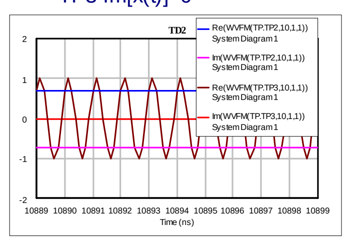
TP
ID=TP3

SRC_C
ID=A2
VAL=(1-j)/sqrt(2)
COL=1
CTRFRQ=1 GHz
SMPFRQ=

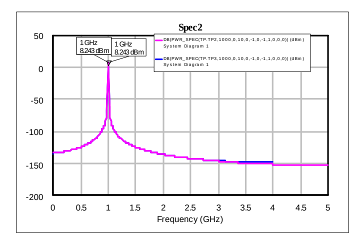
CE2R
ID=A3
PHSOFF=




TP2 Re[c(t)]=xc(t)=1/sqrt(2)
TP2 Im[c(t)]=xs(t)=-1/sqrt(2)
TP3 Re[x(t)]=cos(A+PI/4)
TP3 Im[x(t)]=0

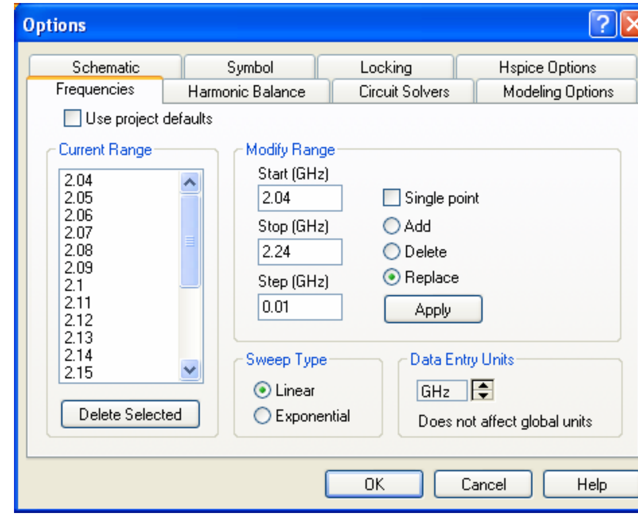


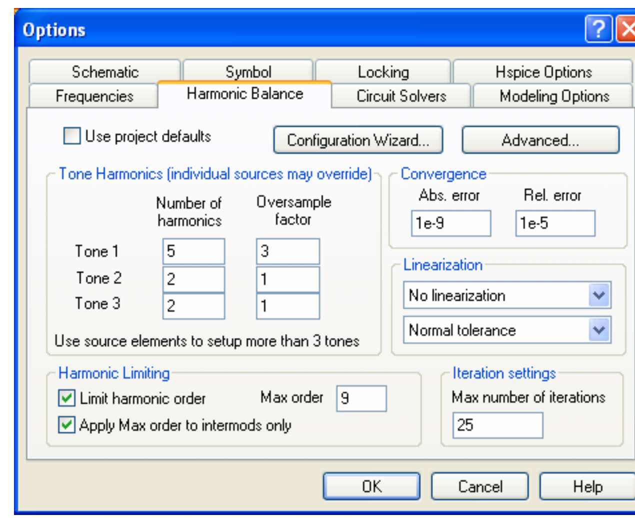

TP2 c(t) is shifted by Fc
TP3 x(t) is a real spectrum



# Behavioral Modeling

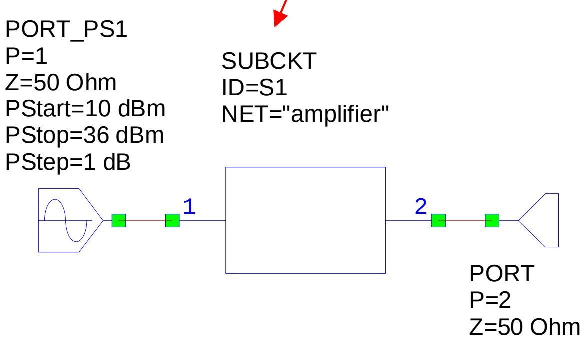
- VSS uses AM-AM and AM-PM results from HB analysis to obtain a behavioral model.
- Strong nonlinearities may not model well.
- HB simulation document “Bmodel_TB” must be configured for power ranges and frequencies desired in system simulation.

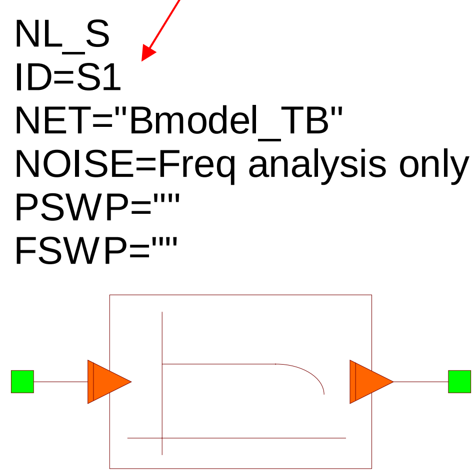



Behavioral system model

Nonlinear circuit model



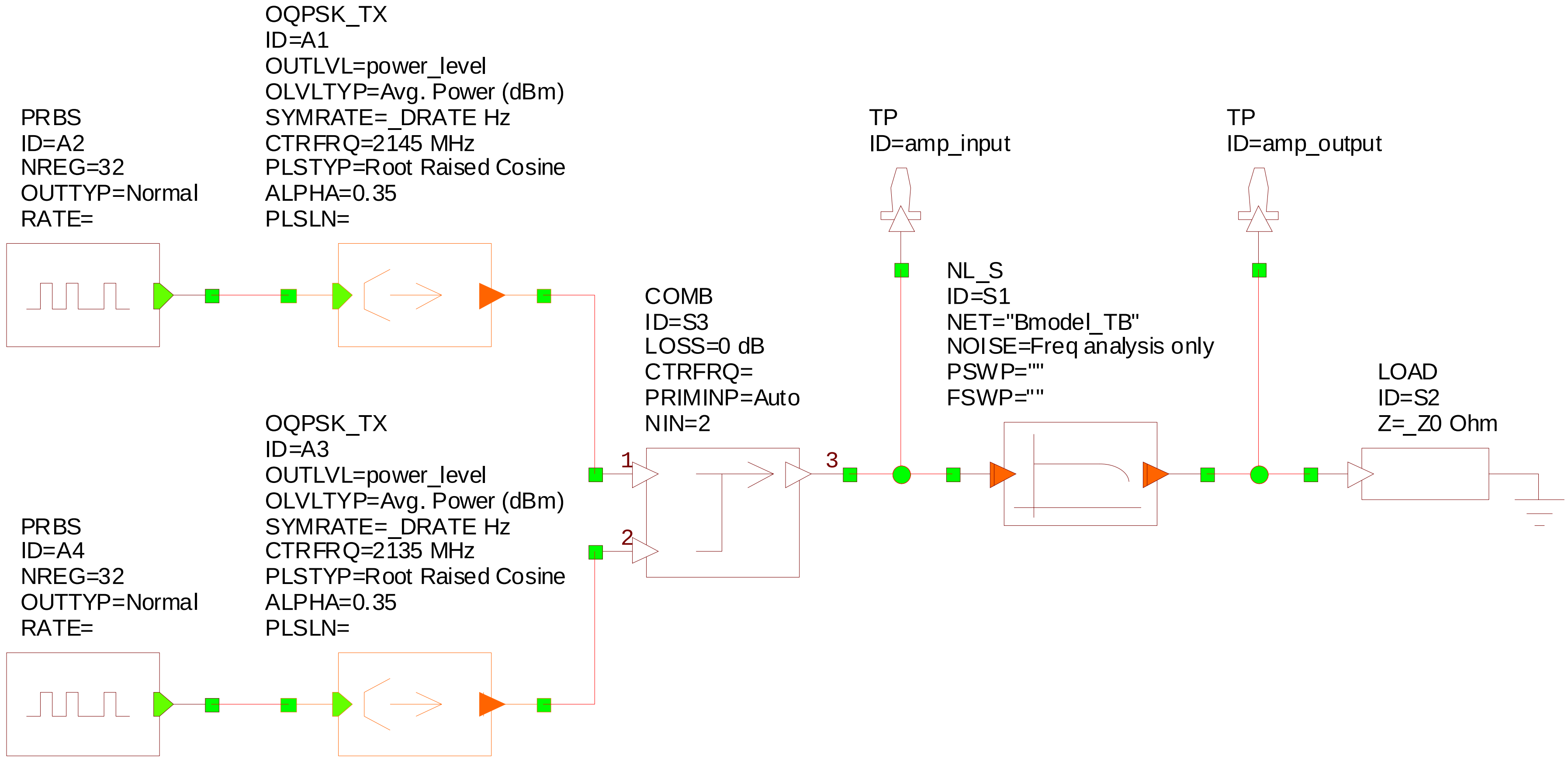



# OQPSK Transmitter

power_level=0

+12 dBm power_level yields +30 dBm out of amplifier

Add 10*log(3.84 MHz)=65.8 dBHz to power spectral density graph for total power



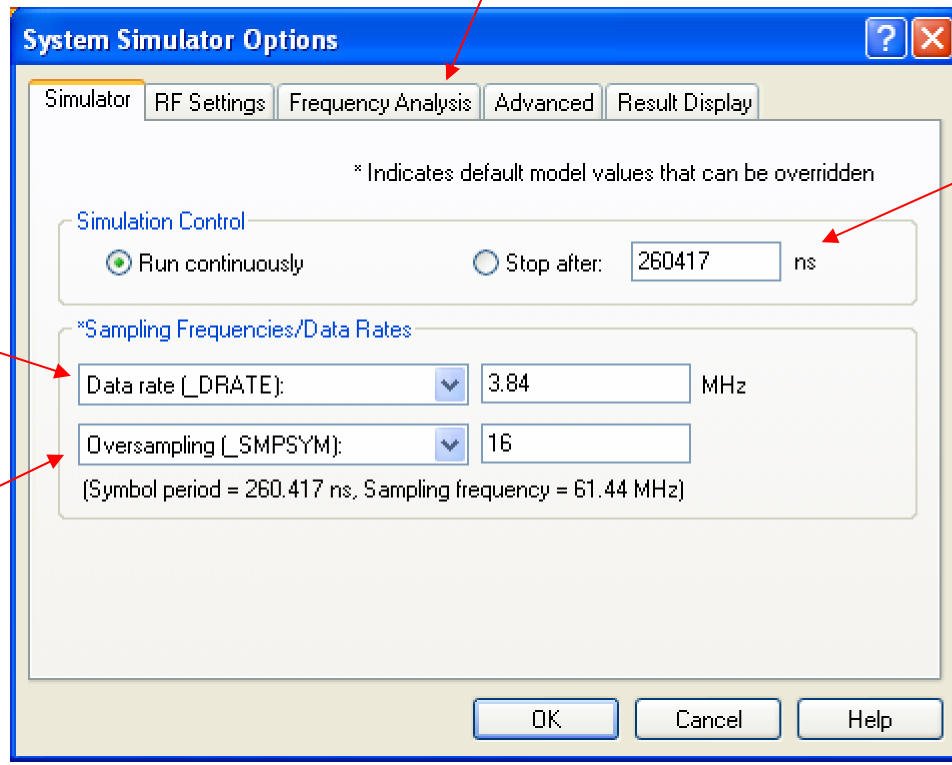
# Default System Options

Used for budget analysis of RX & TX chains

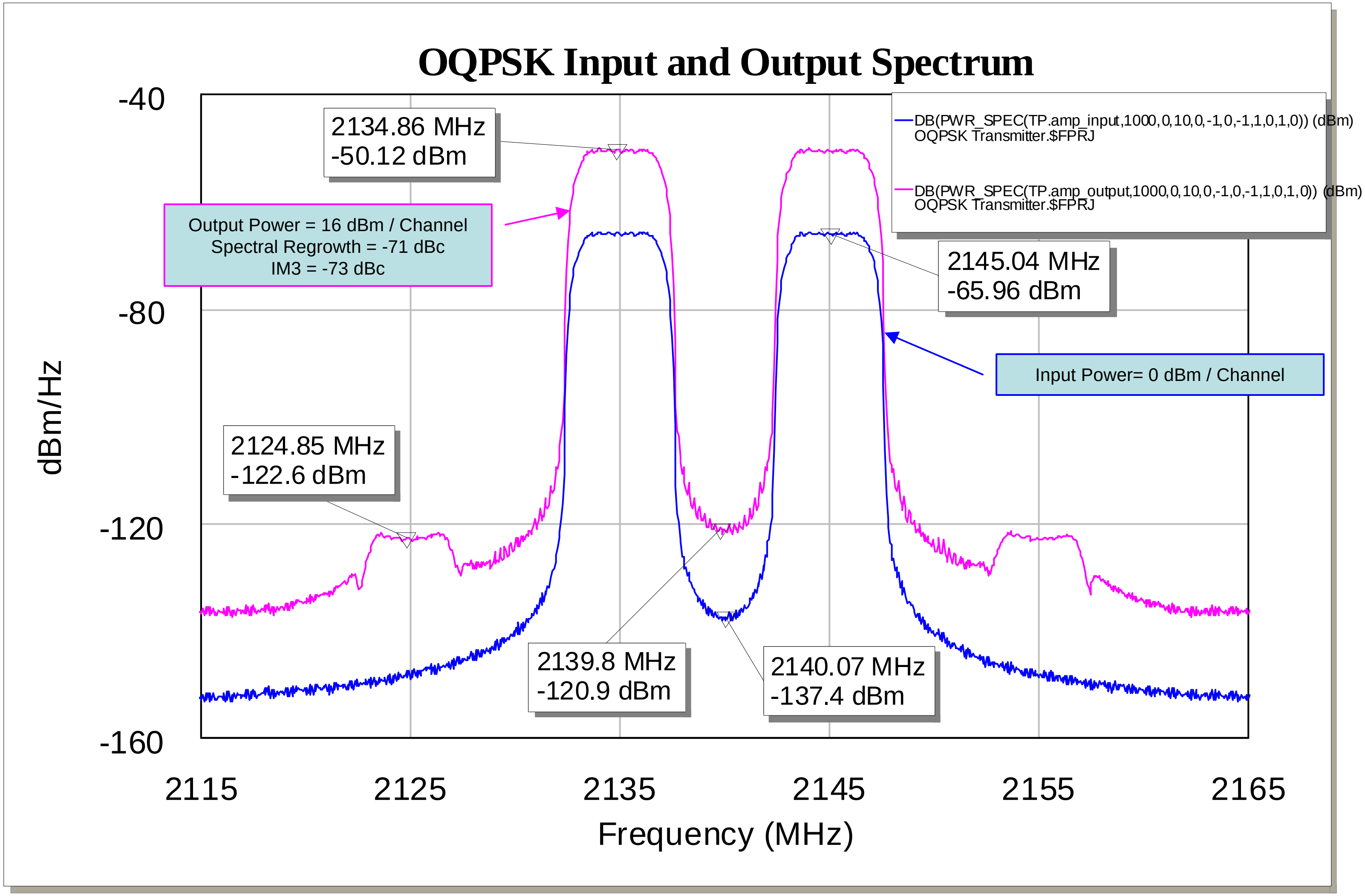
Stop after 1000 bits (not enough for smooth spectrum)

Max data rate in system

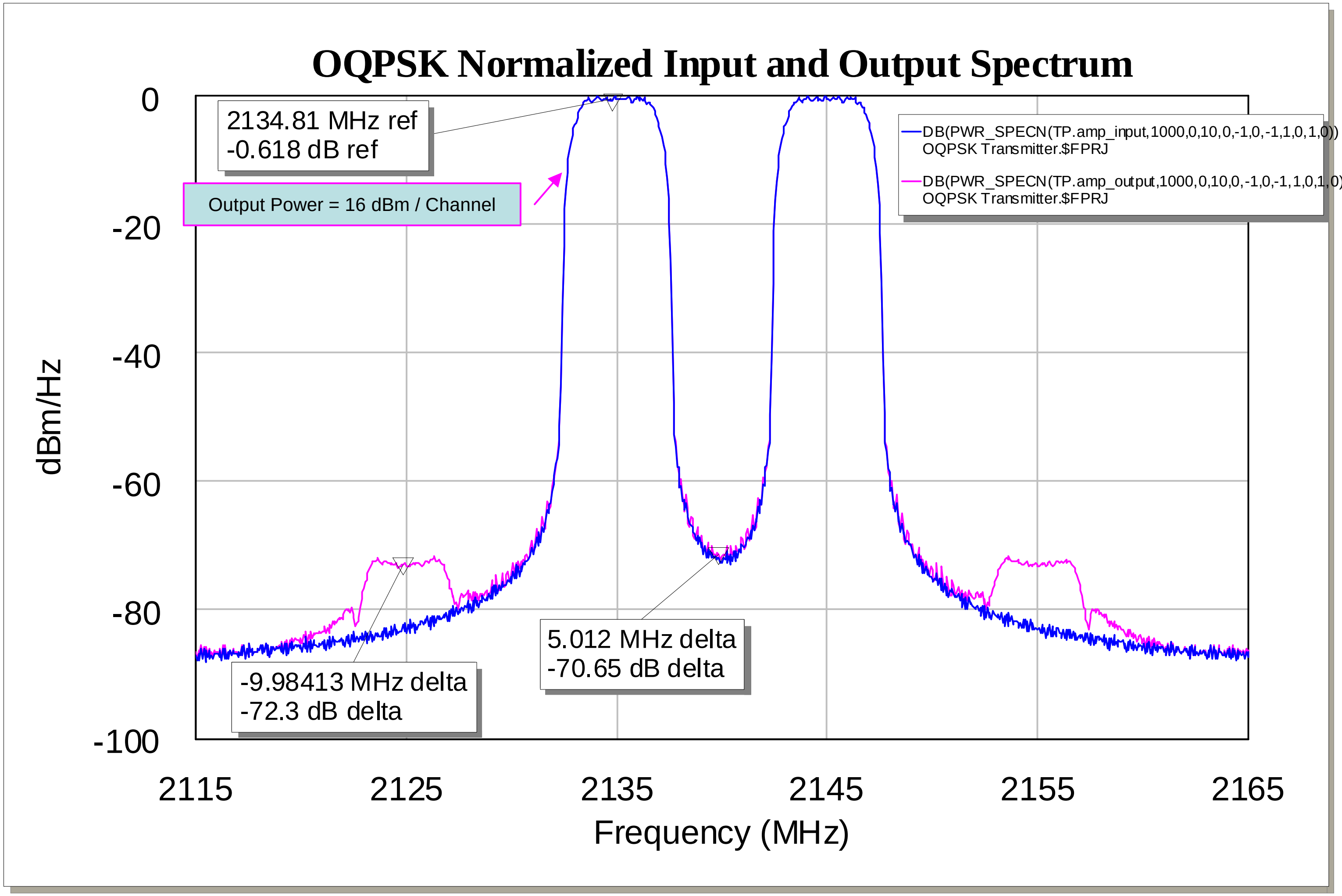
Increase oversampling to allow for wider bandwidth analysis



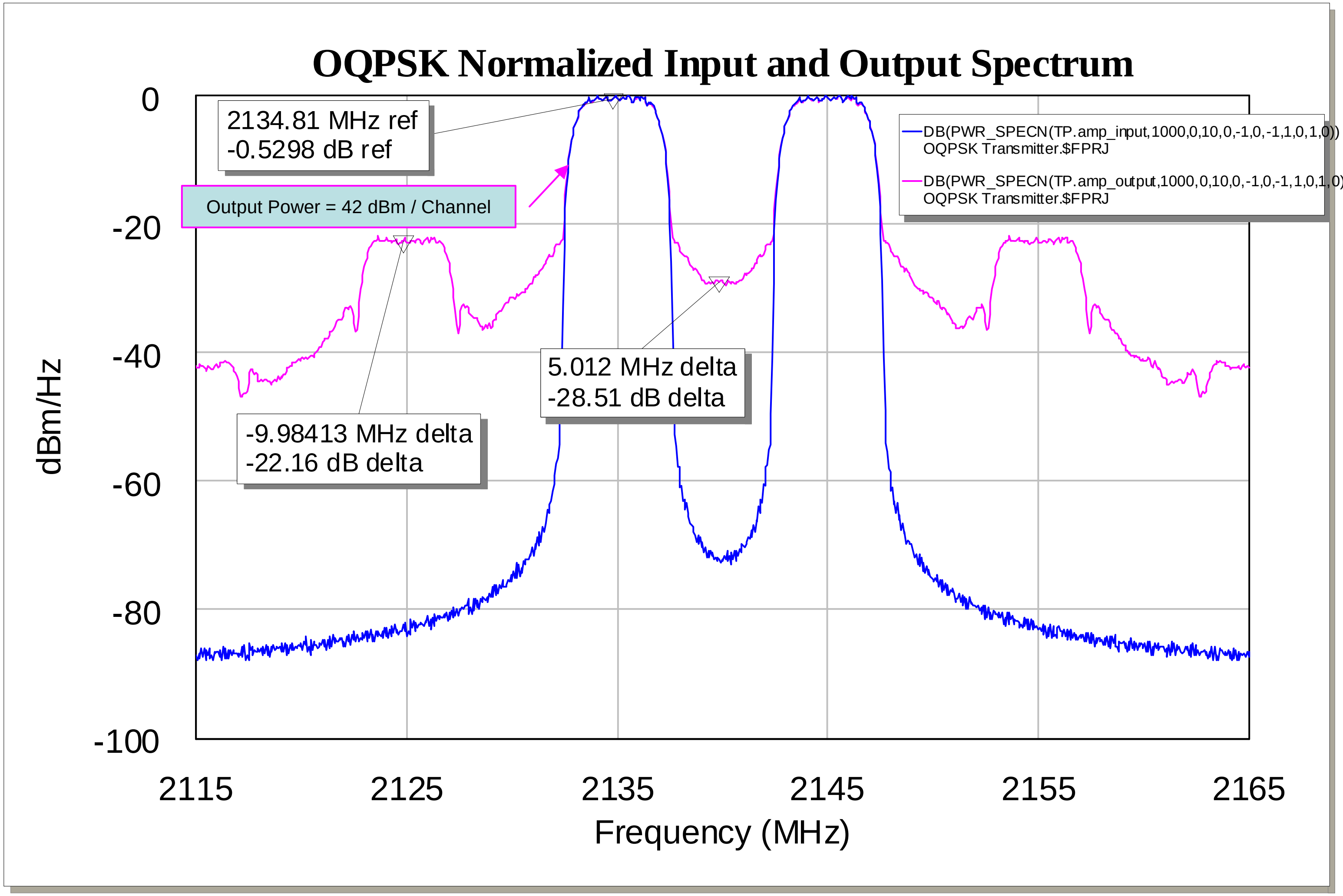
# OQPSK Spectrum (PSD)



# OQPSK Normalized Spectrum (PSD)



# OQPSK Normalized Spectrum (PSD)



# References

MRF5S21150H Reference Design

http://www.freescale.com/files/rf_if/hardware_tools/printed_circuit_boards_for_reference_designs/MRF5S21150H_UMTS_RD.pdf

MRF5S21150H Data Sheet

http://www.freescale.com/files/rf_if/doc/data_sheet/MRF5S21150H.pdf

Applied Wave Research’s Microwave Office & Visual System Simulator

http://www.appwave.com/