Advanced Power Amplifier Design Using Doherty Configurations

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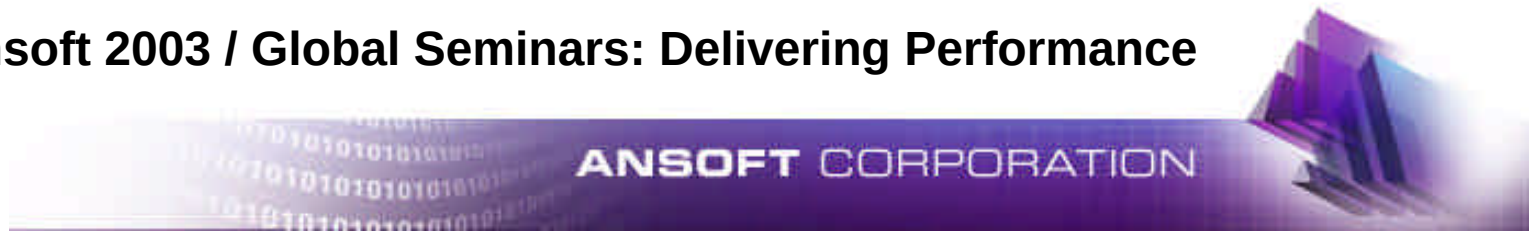
Ansoft Corporation

Ansoft 2003 / Global Seminars: Delivering Performance



Outline

- **Introduction**
- **Motorola MET Model Design Kit in Ansoft Designer**
  - Model consideration and validation
- **Matching Techniques for Power Amplifier Design**
  - Load-pull analysis
  - Lowpass multi section, transmission line, and low Q matching technique
- **Doherty Amplifier Design**
  - Doherty amplifier overview
  - Carrier amplifier design
  - Peak amplifier design
  - 90° hybrid coupler, offset line, and impedance transformer design
- **Balanced Amplifier Design**
- **Doherty and Balanced Amplifier Comparison**
- **Conclusion**
- **References**

Introduction

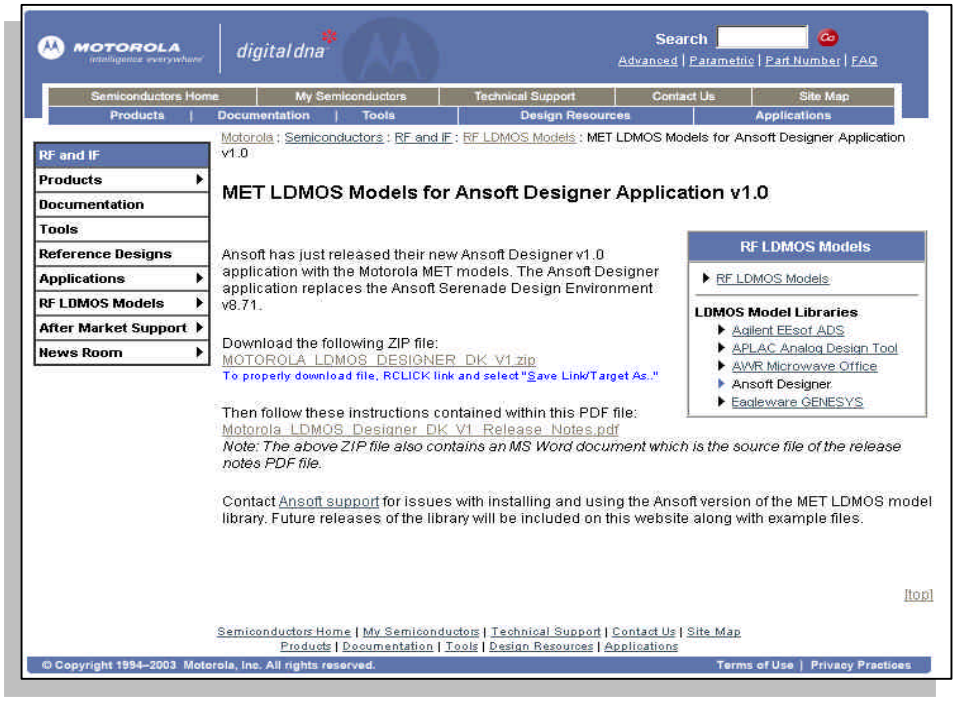
- **Why a power amplifier is important?**
  - Power amplifier is a key element to build a wireless communication system successfully.
  - There is a trade-off between power per cost vs. efficiency and linearity.
  - Digital communications require more peak power for the same bit error rate.
  - To minimize spectral re-growth and interferences, transmitters have to be more linear.
  - Clear modulation scheme requires more higher power and broader bandwidth.
- **What is a solution from Ansoft?**

Ansoft Designer™

- **Power Amplifier Design**
  - DC network analysis
  - Stability analysis
  - Harmonic balanced analysis
  - Transient analysis
  - Convolution analysis
  - Modulation envelop analysis
  - 3D EM analysis
  - Load-pull analysis
  - Motorola MET model
  - Smith-Tool utility
  - Transmission Line Utility

LDMOS MET Model Design Kit

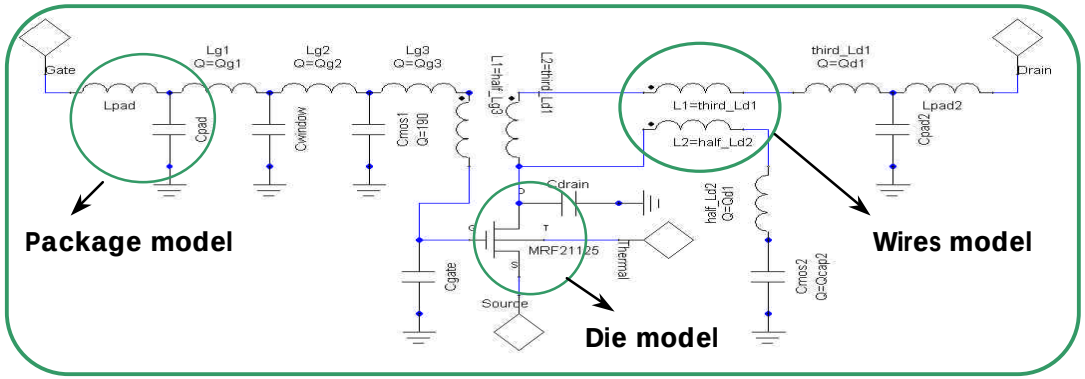
- **MET (Motorola Electro Thermal) Model is available from Ansoft**
  - Nonlinear model for high power RF LDMOS transistor
  - Calculate both electrical and thermal phenomena
- **LDMOS (Laterally Diffused Metal- Oxide- Semiconductor)**
  - Used in making high power, high frequency RF amplifier

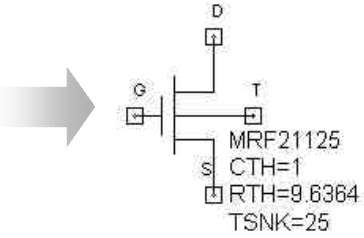


http://www.ansoft.com/products/hf/ansoft_designer

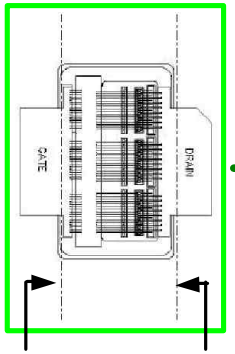
MET Model Considerations

- **Capable of performing**
  - Small and Large Signal HB, Noise, and Transient Simulations
  - More accurate because of its ability to simulate self–heating effects
- **All transistors model include die, package, and bond wire models.**

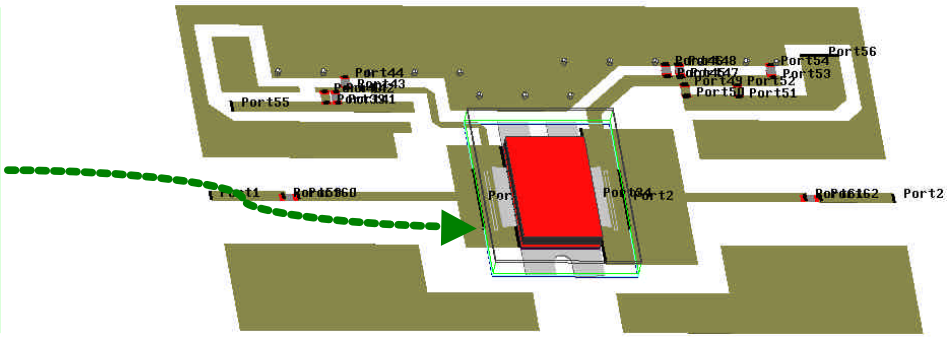




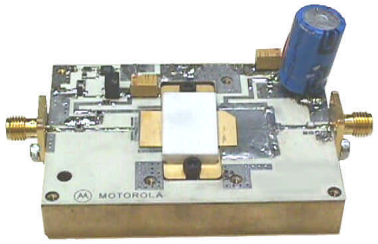
- **Reference planes are defined without leads.**



G_{IN} G_{OUT}



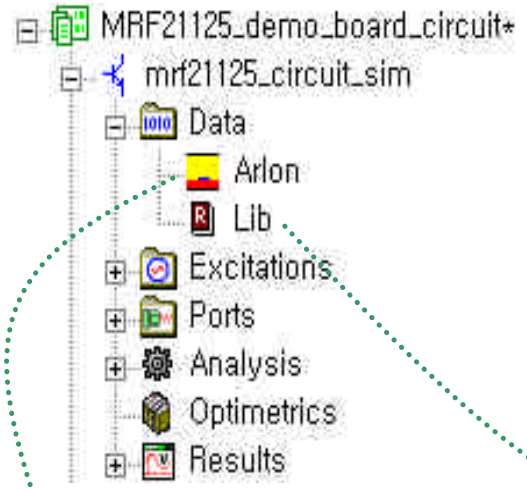
Layout view of Ansoft Designer™

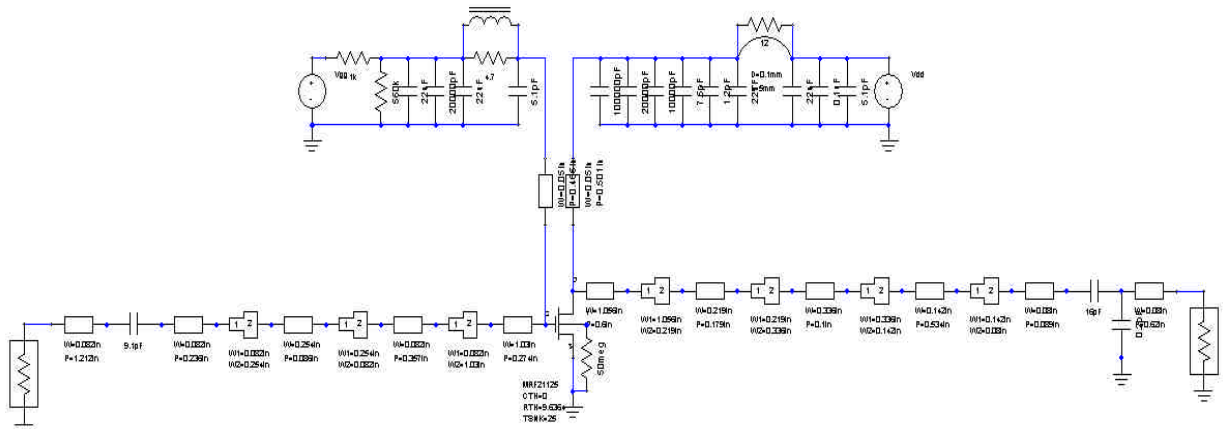


Demo Board

Schematic for MET Model Validation

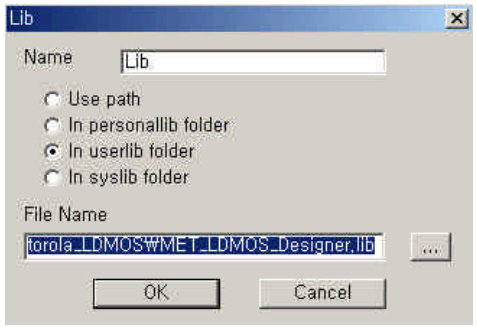
- **Ansoft Designer™ Circuit Simulator is used to valid MET model.**
- **MRF21125 was used.**

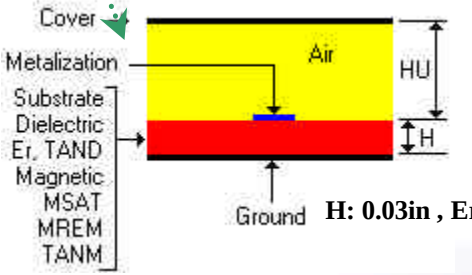




2. Make a technology file for PCB

1. LDMOS library should be installed and included

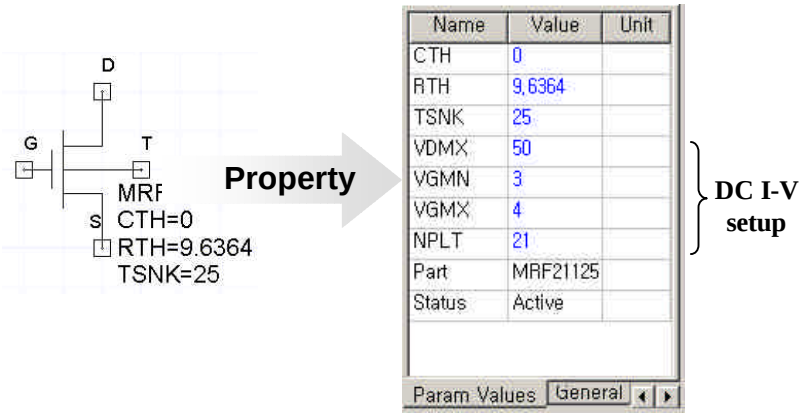


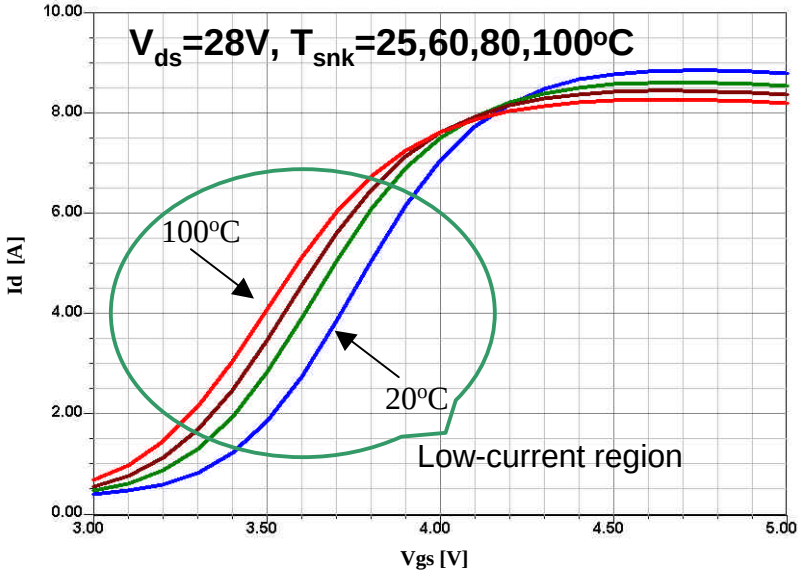


H: 0.03in , Er=2.55,TAND: 0.001

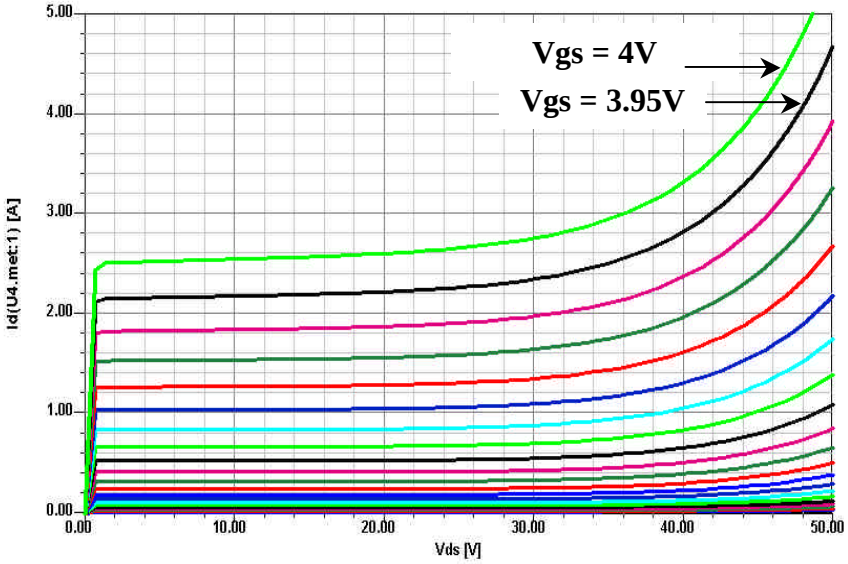
DC I-V Characteristics

- The rise of temperature increases the drain current at a low-current region and decreases it at a high-current region.
- Simulation can predict thermal effects of the LDMOS by tuning T_{snk}.





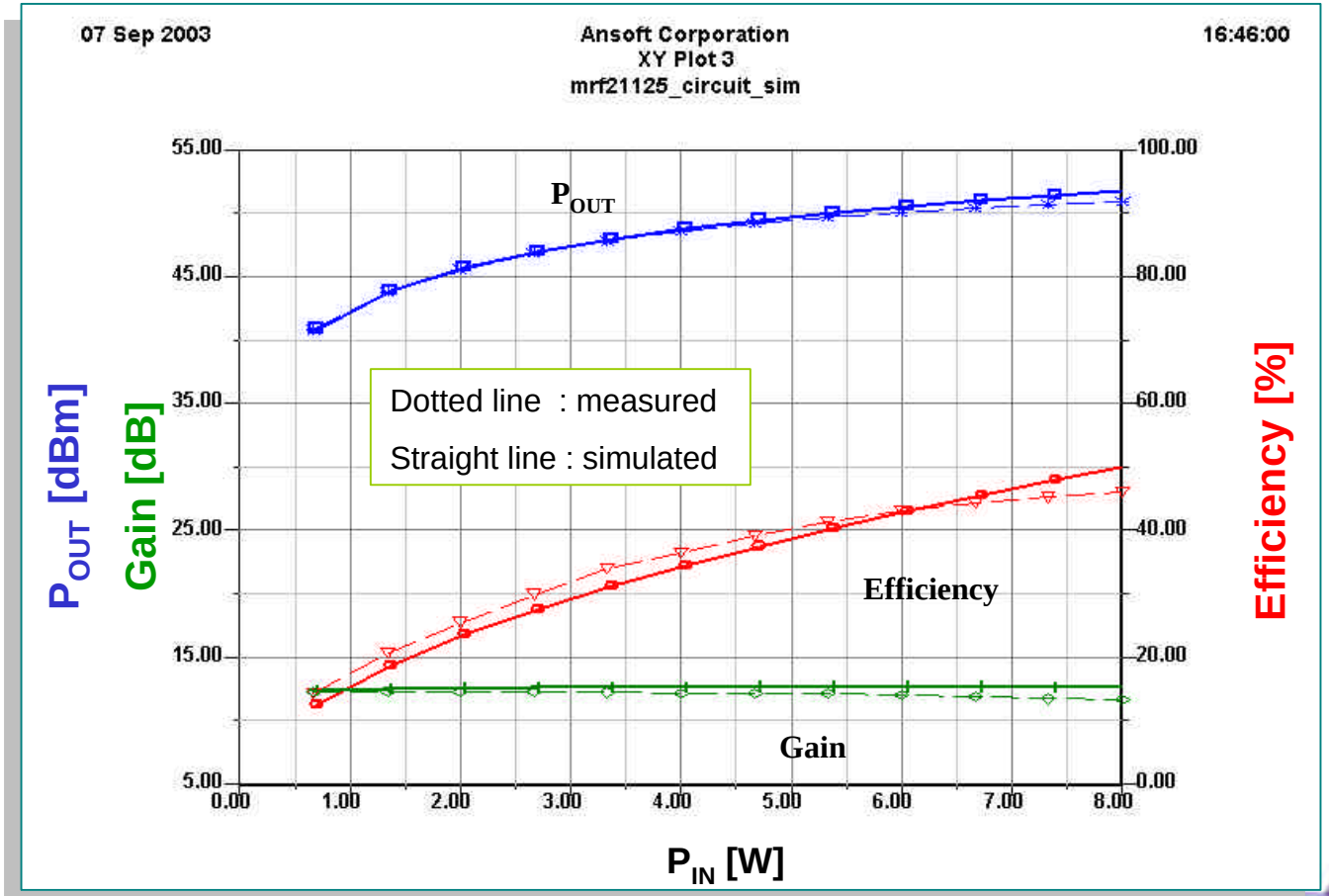
Input Transfer Characteristics



Output Transfer Characteristics

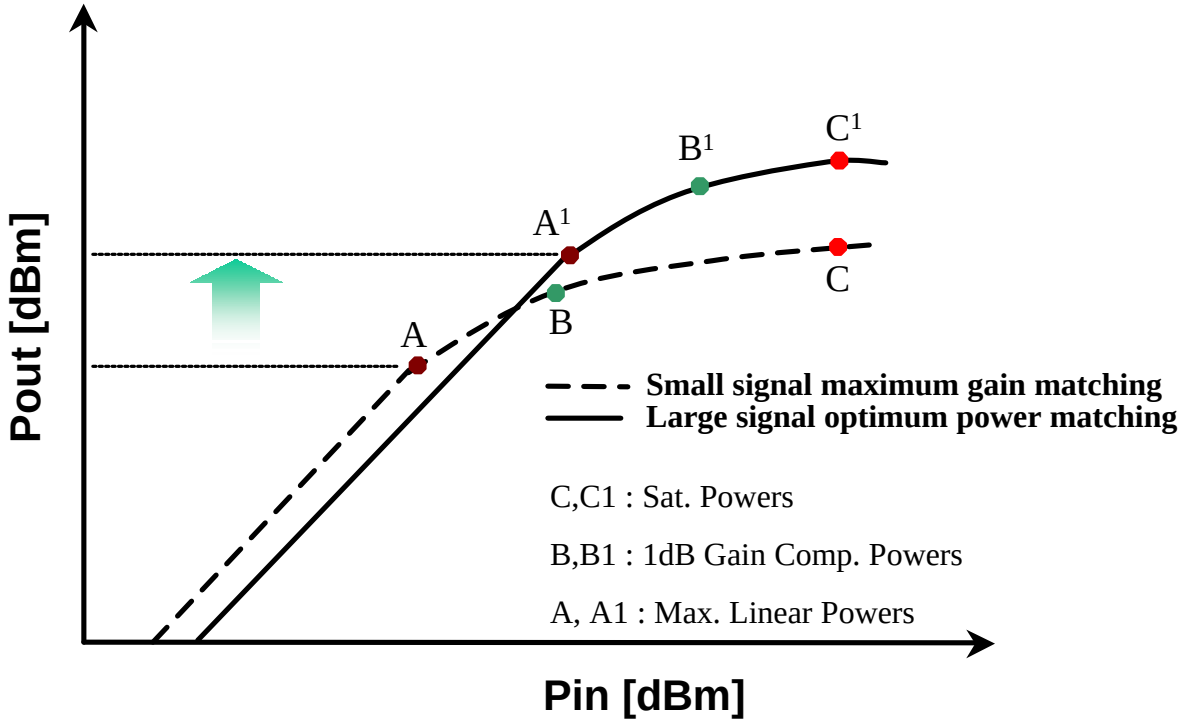
MET Model Validation

- **MRF21125 performances were compared with measurements.**
  - V_{ds}=28V, I_{dq}=1600mA, f = 2120MHz
  - HB1Tone analysis , Linear sweep with Pin

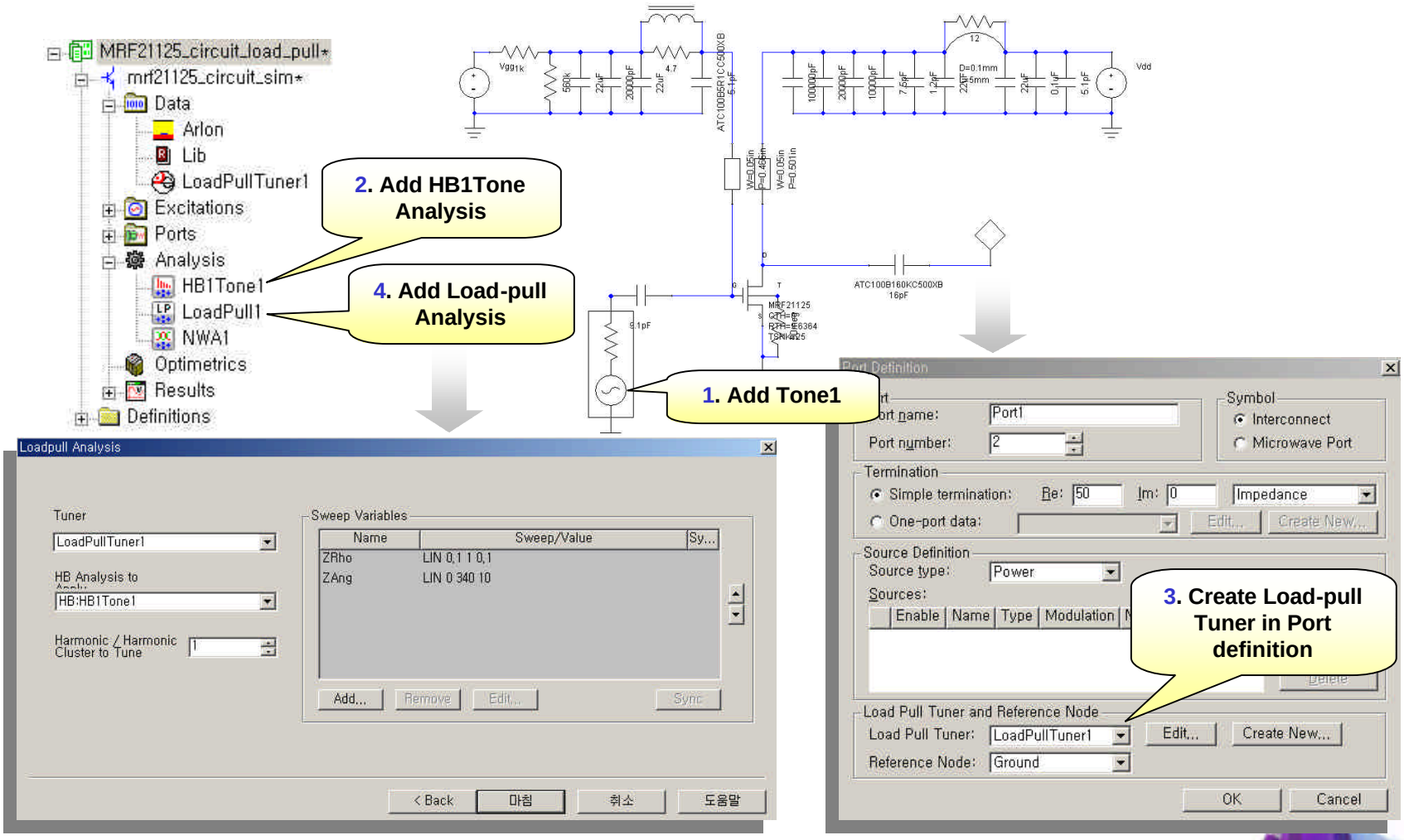


Matching for Power Amplifier

- Maximum gain matching based on the small signal S- parameters is not useful to design power amplifier.
- The information of source and load reflection coefficients as a function of output power is useful to get higher power output.
- **Load-pull Analysis** is a method to obtain an optimum power matching point

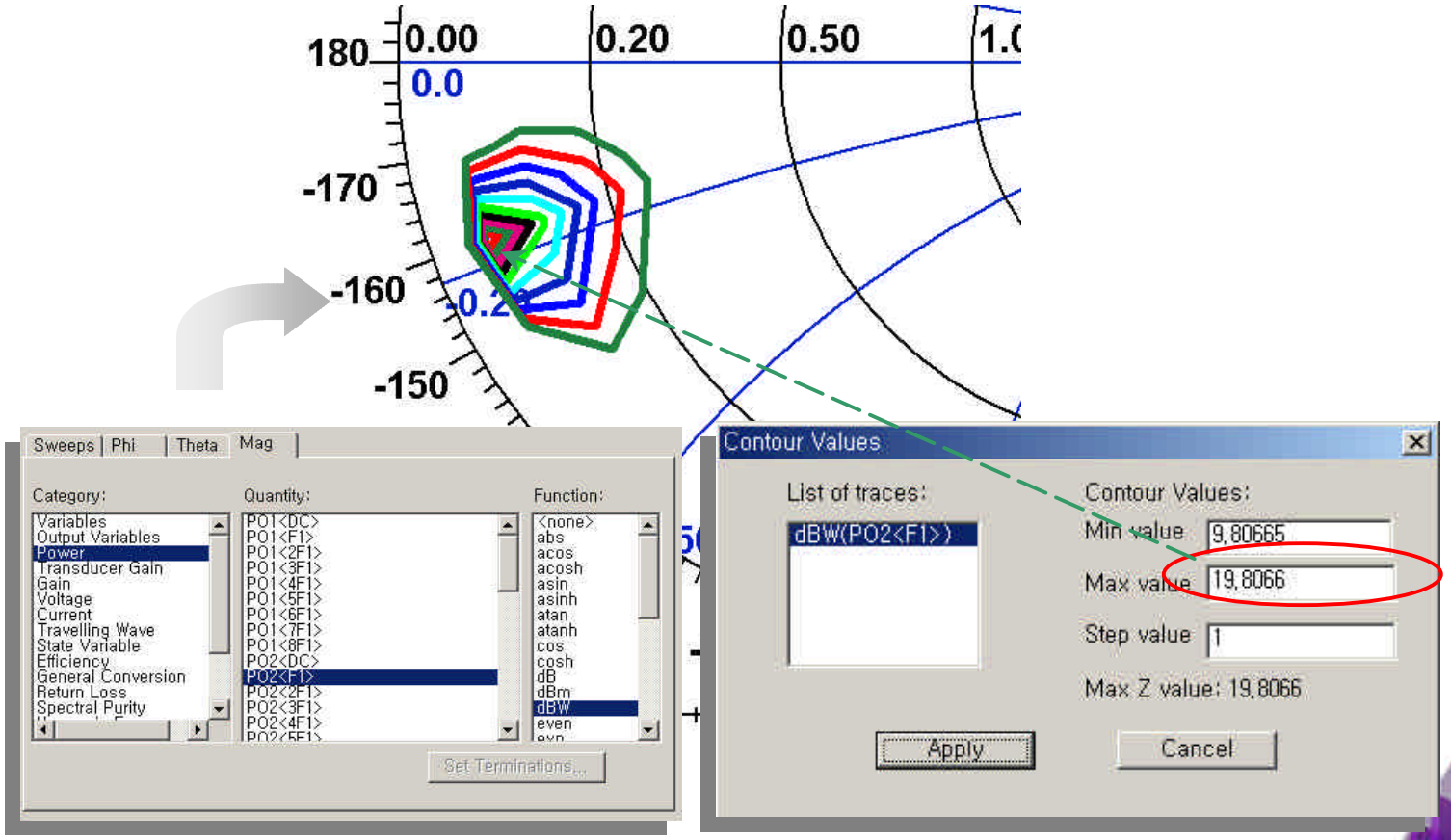


Load-pull Analysis Setup



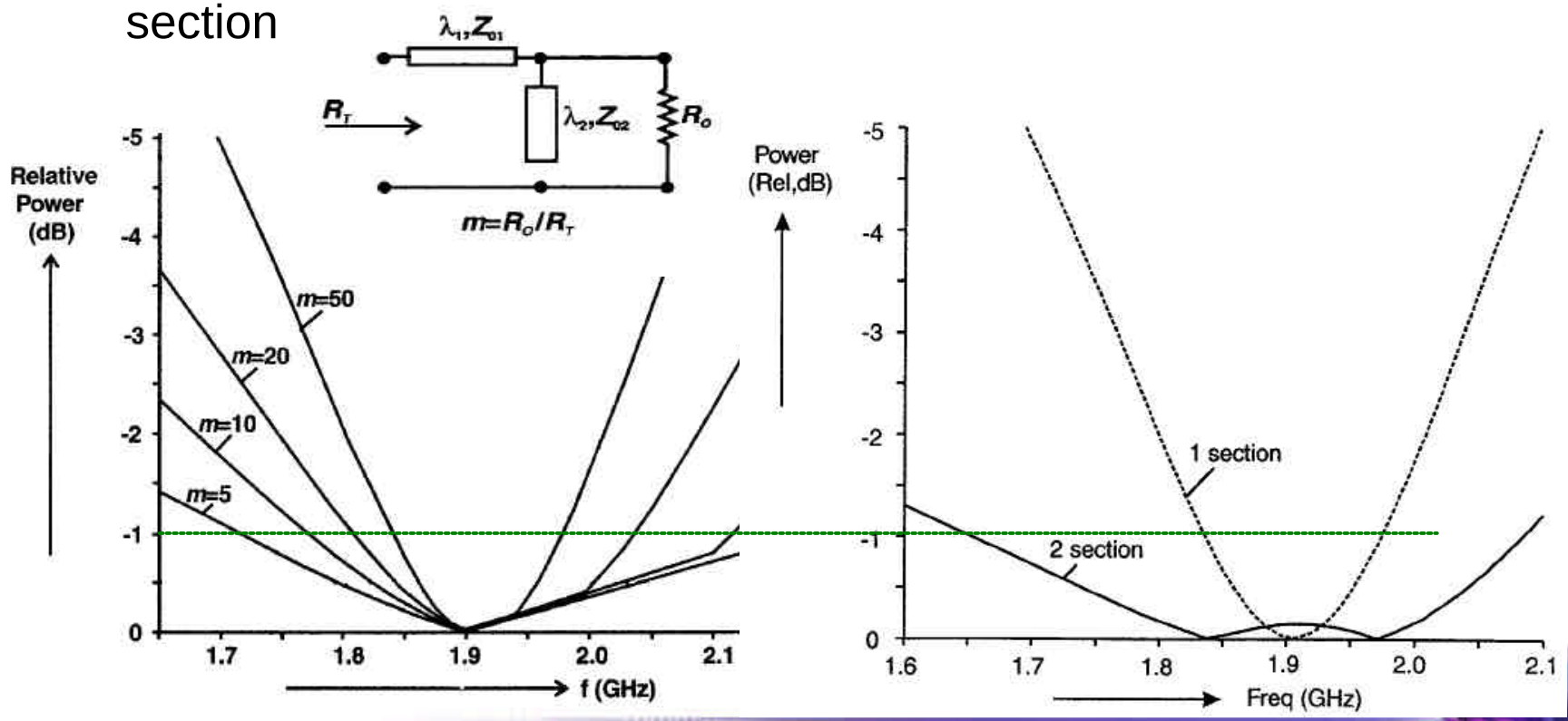
Load-pull Contours

- Output power, efficiency, and harmonic contours can plot
- Max, Min, Step value can be assigned



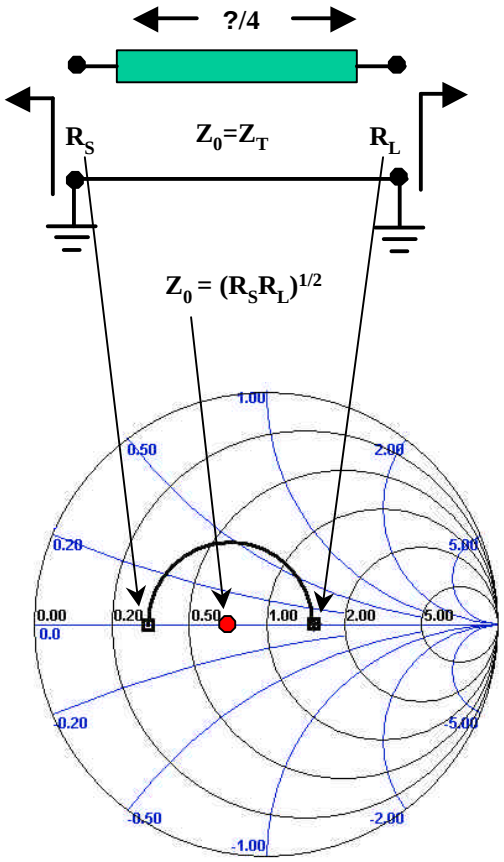
Lowpass Multi Section Matching

- Lowpass networks suppress harmonics and improve linearity
- RF power transistor usually has a small input impedance ($R_T \approx 2$ or 3)
- Large ratio of $m=R_0/R_T$ decrease PA's bandwidth (R_0 is 50ohm)
- Bandwidth of matching networks can be increased by lowpass multi section

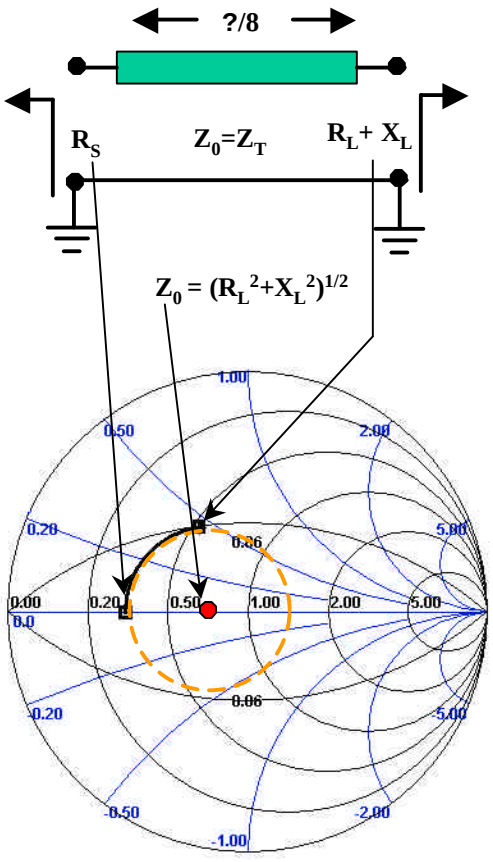


Transmission Line Matching(1)

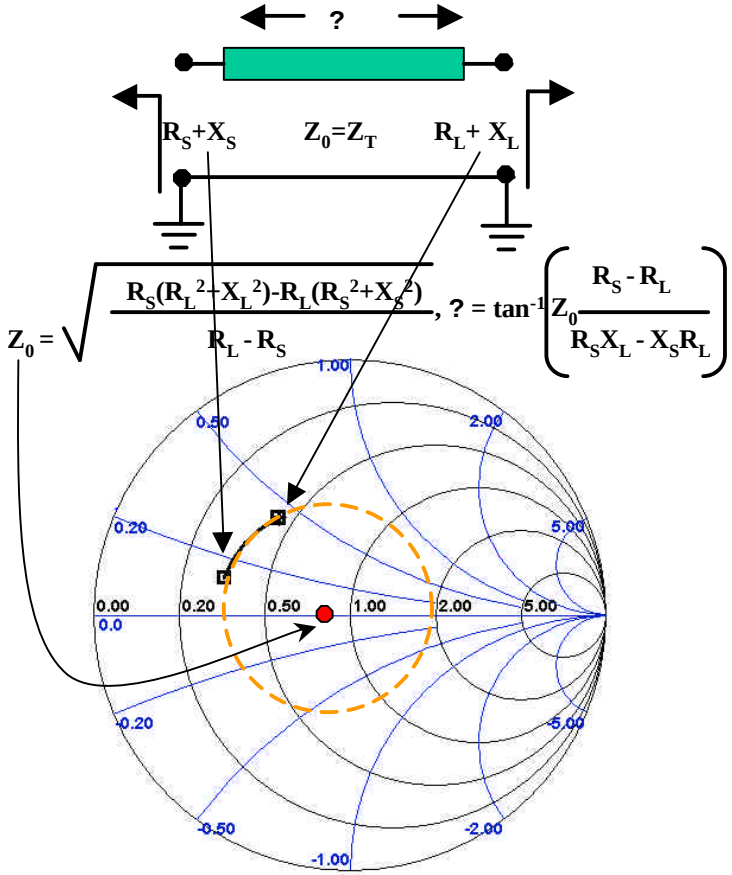
- Matching networks can be realized by using transmission lines such as ?/4, ?/8, and ?/n.



?/4 transformer : any R_S -> any R_L



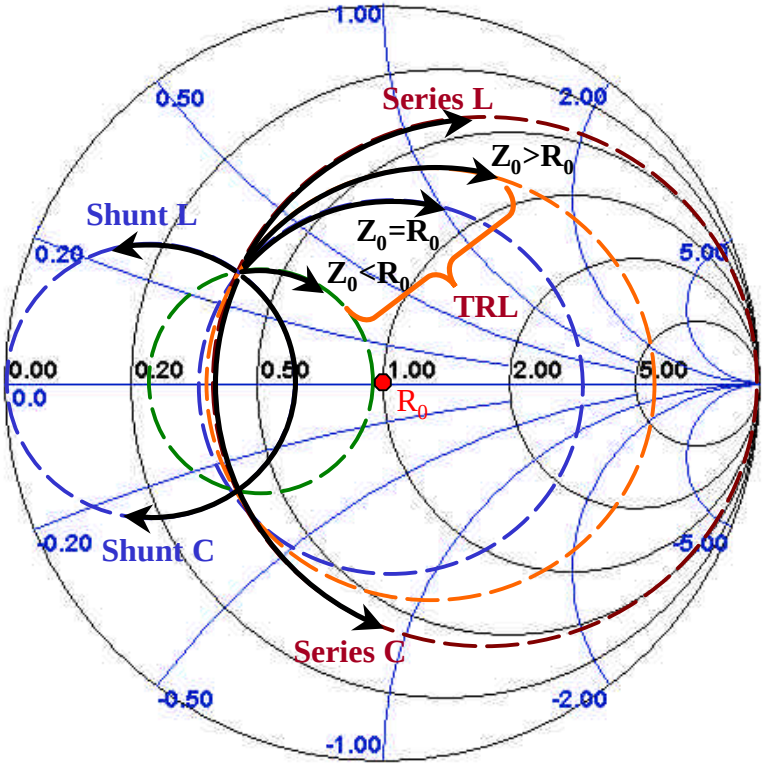
?/8 transformer : any R_S -> any Z_L

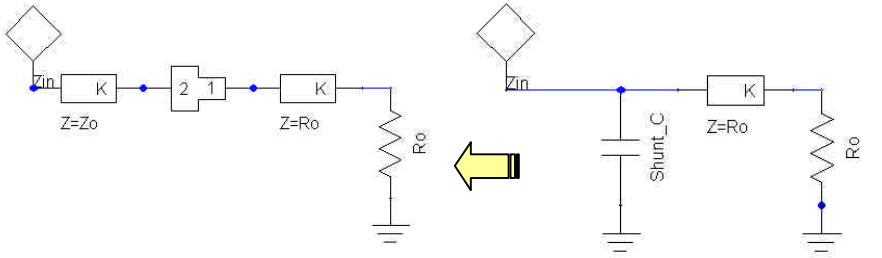


Arbitrary transmission line : any Z_S -> any Z_L

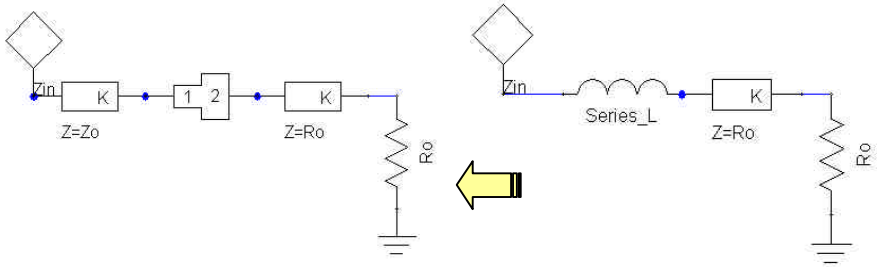
Transmission Line Matching(2)

- Shunt C and Series L can be replaced by series low impedance line and series high impedance line respectively.





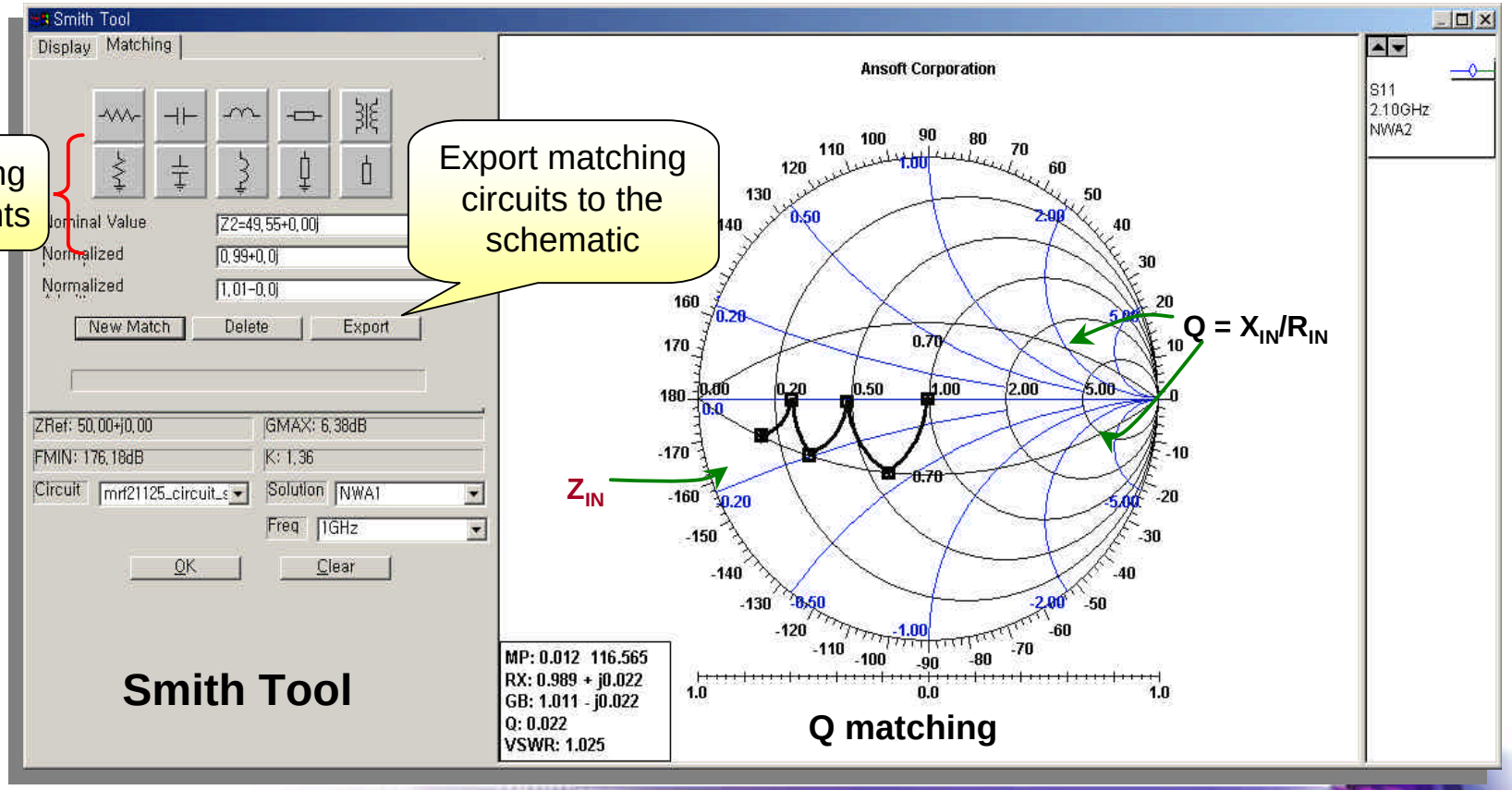
$Z_0 < R_0$: Transmission Line ˜ Shunt C



$Z_0 > R_0$: Transmission Line ˜ Series L

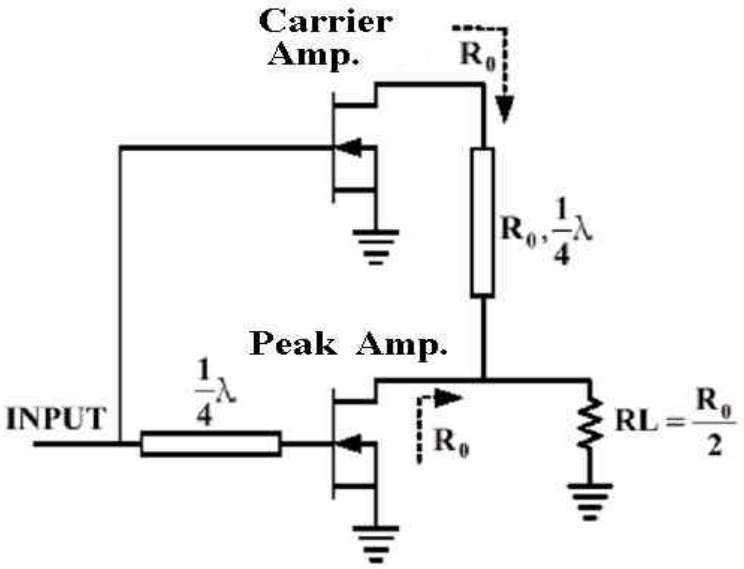
Low Q Matching technique

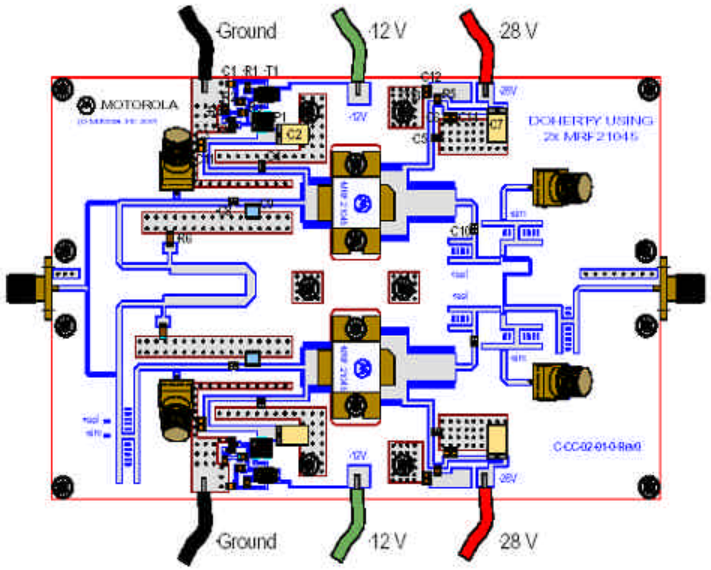
- Conventional approach to design matching circuits which uses analytical equations to calculate the circuits elements is very time consuming.
- Smith Tool in Ansoft Designer™ is a powerful solution to design arbitrary matching networks.



Doherty Amplifier Overview

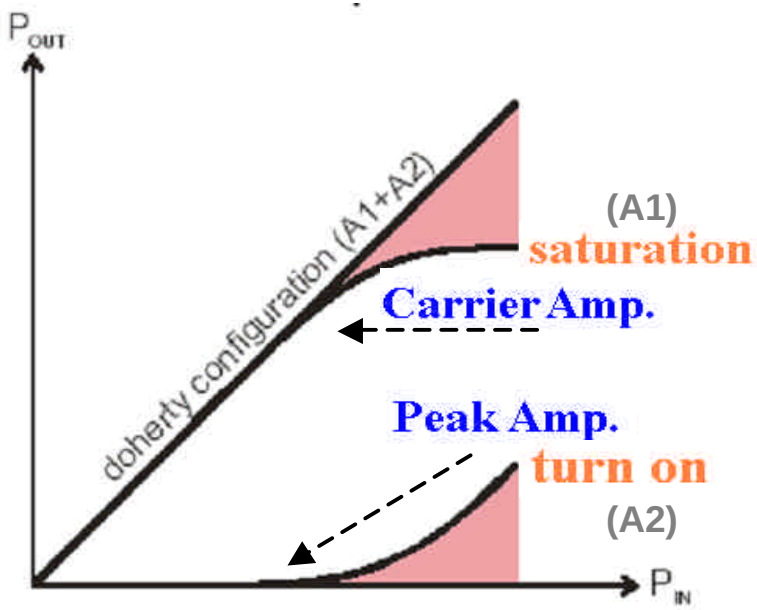
- A Doherty amplifier consists of a carrier and a peak amplifiers.
- There are two quarter-wave transformers: input of the peak amplifier, output of the carrier amplifier.
- **Advantage:** Simple and ease of additional linearization using conventional methods such as feed-forward, envelope, and feed-back.
- **Disadvantage**: Narrow bandwidth and Gain degradation



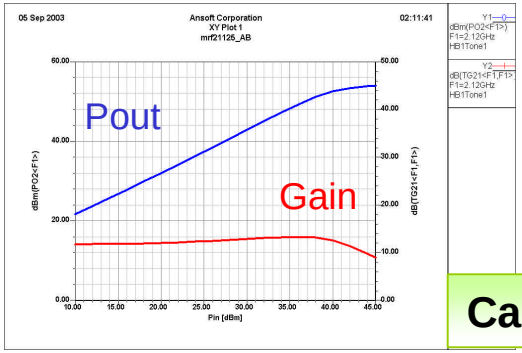


Doherty Amplifier Basic Operation

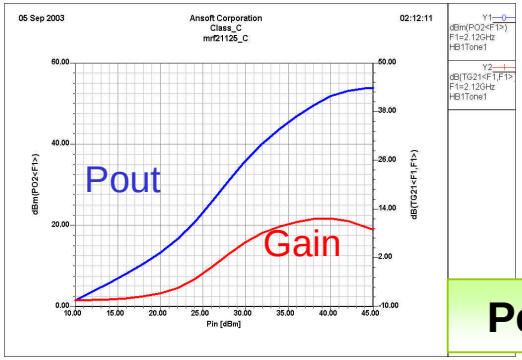
- **Carrier amplifier:** Class AB (Saturates at the high power input)
- **Peak amplifier**: Class C (Turn on at the high power input)
- Doherty configuration improves the linearity at the high power input by complementing the saturation of the carrier amplifier with the turn on characteristics of the peak amplifier.



Basic operation Characteristic

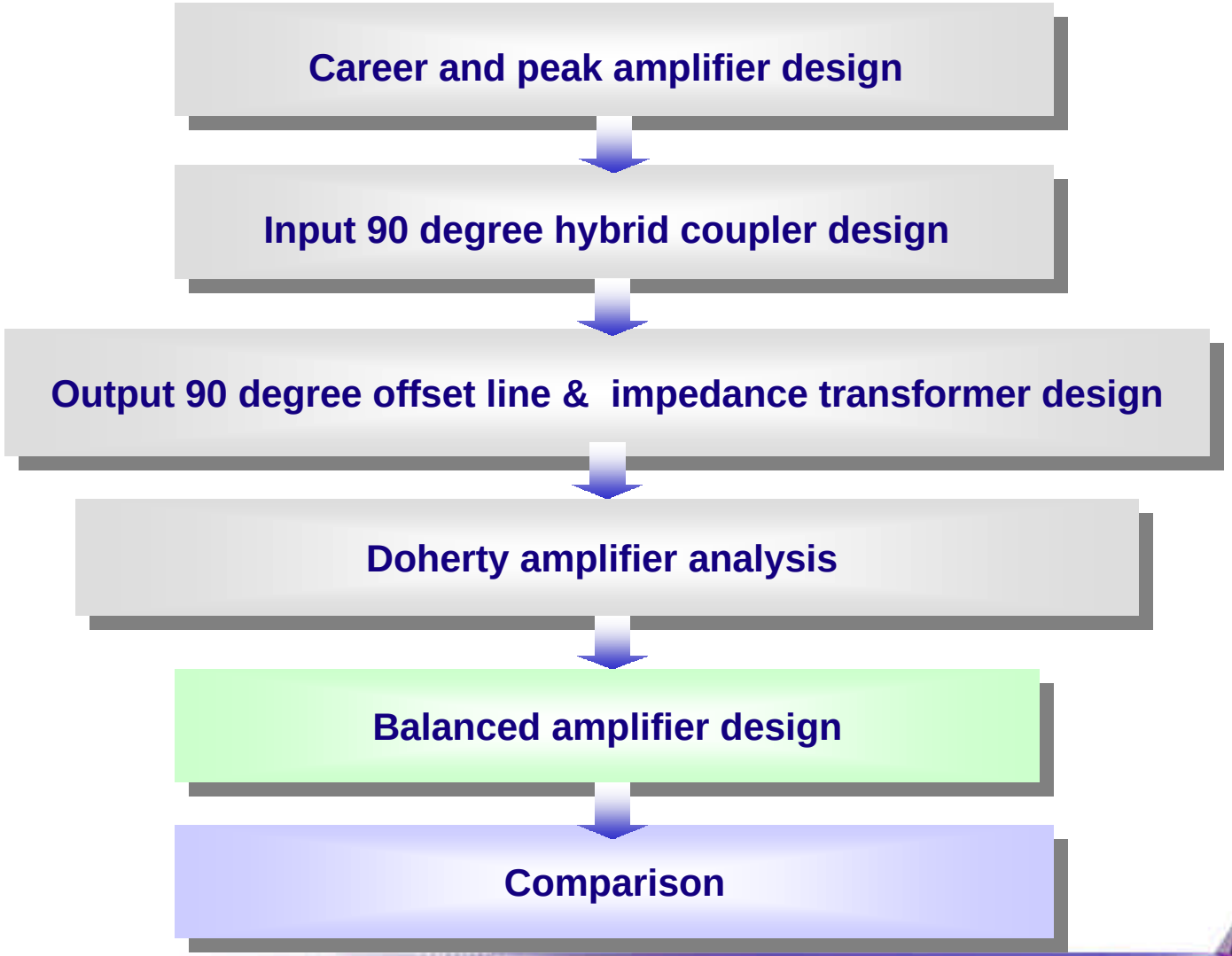


Carrier Amp.



Peak Amp

Doherty Amplifier Design

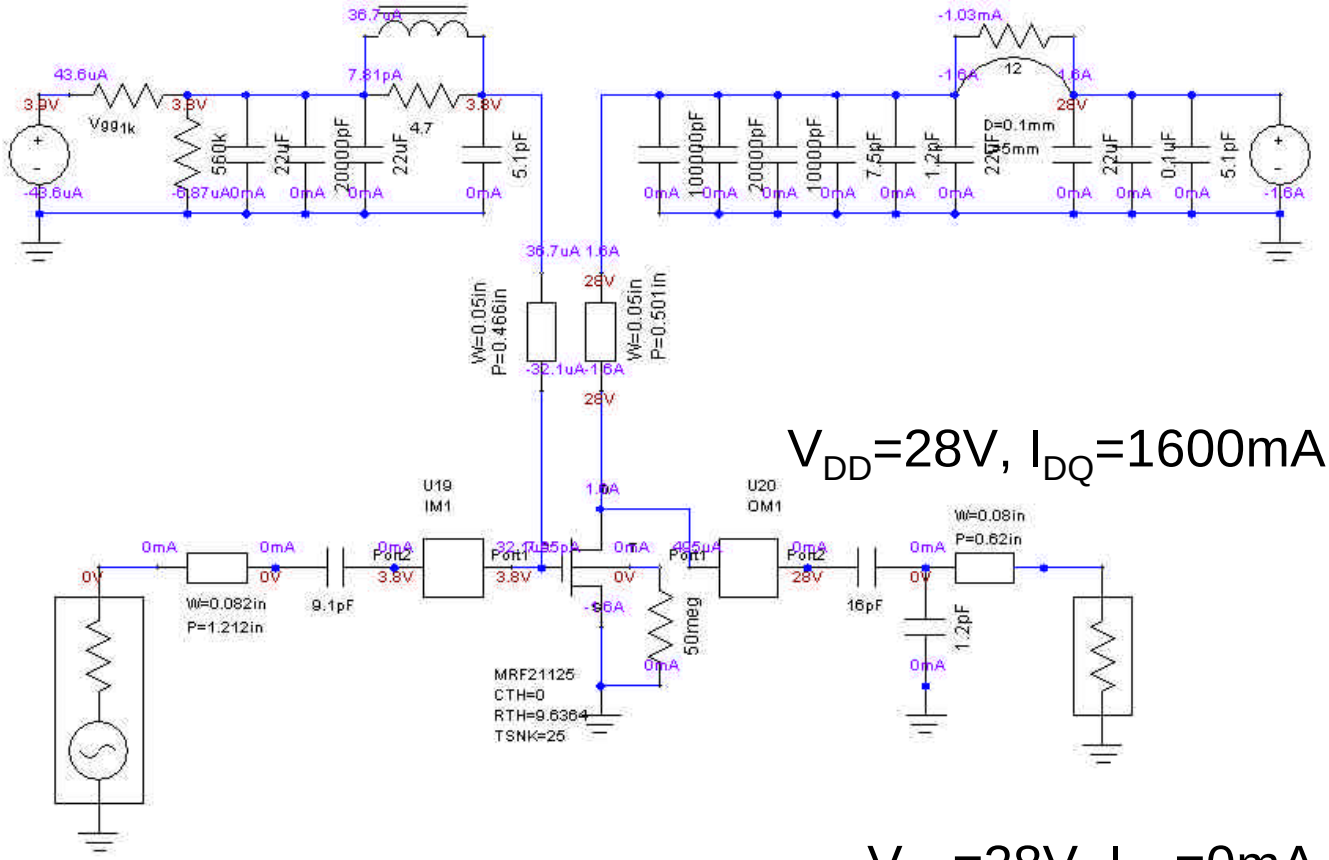


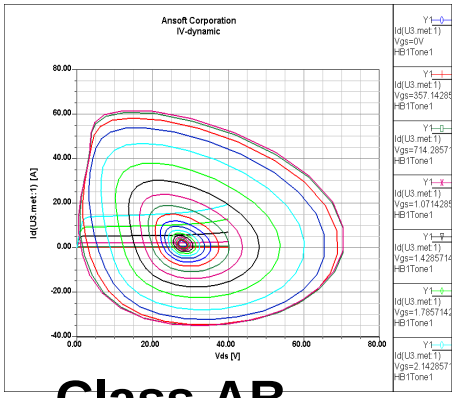
Carrier Amplifier Design Procedure

1. Bias analysis : Class AB operation mode
2. Load-pull analysis : Finding optimum matching point
3. Input & output matching circuit generation
4. EM planar analysis : Matching network verification
5. Modulation envelope analysis
6. Reports (gain, ACPR, Pout, efficiency, PSD)
7. PCB layout

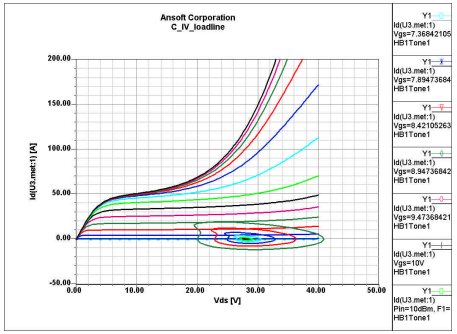
DC Bias Network Analysis

Carrier amplifier IV-curve & dynamic load line





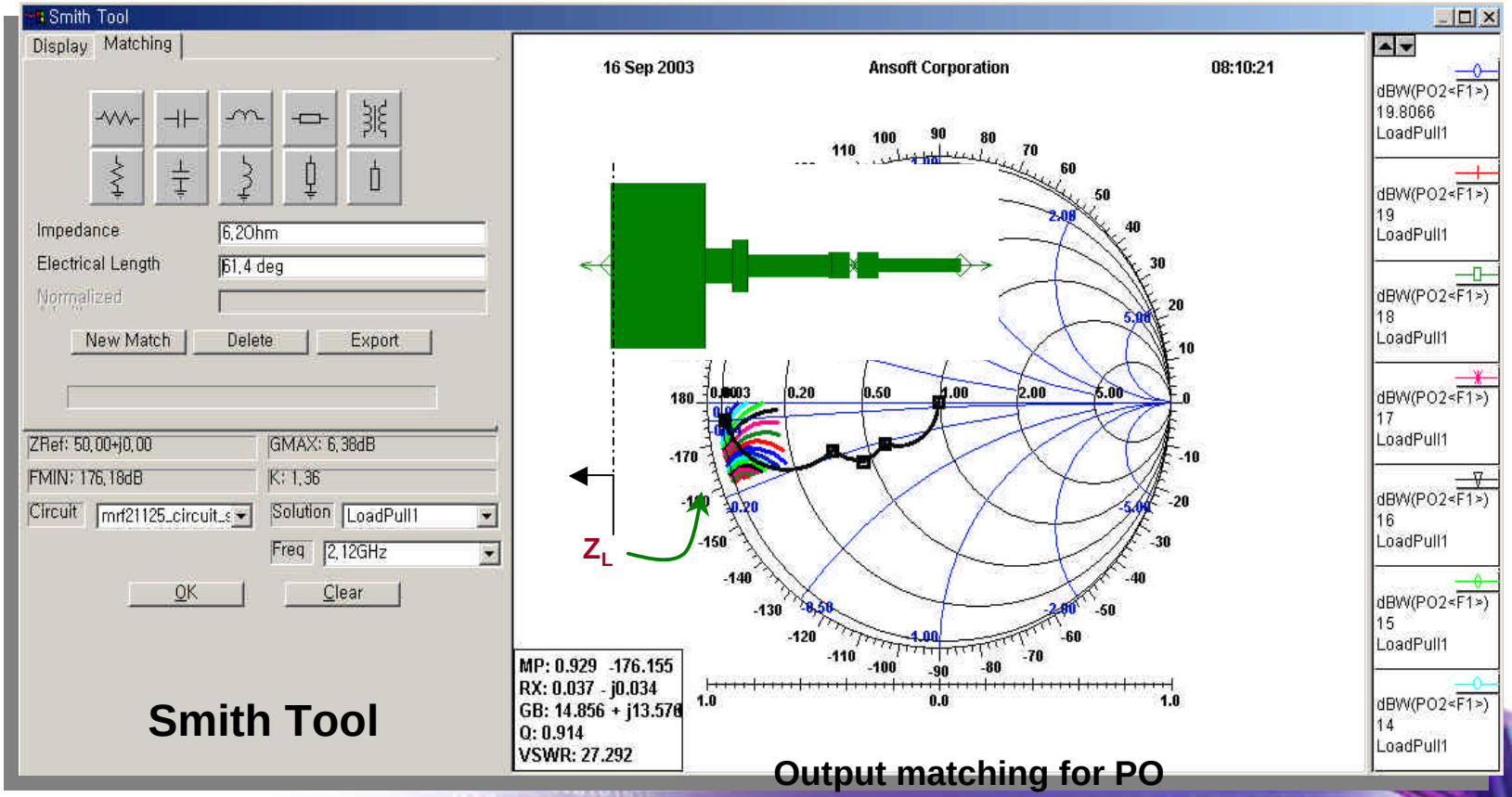
V_{DD}=28V, I_{DQ}=1600mA **Class AB**



V_{DD}=28V, I_{DQ}=0mA **Class C**

Output Matching

- Output matching circuit, V_{DD}=28V, I_{DQ}=1600mA
- Load Impedance matching for optimum PO2<F1>
- Transmission line matching with Smith Tool

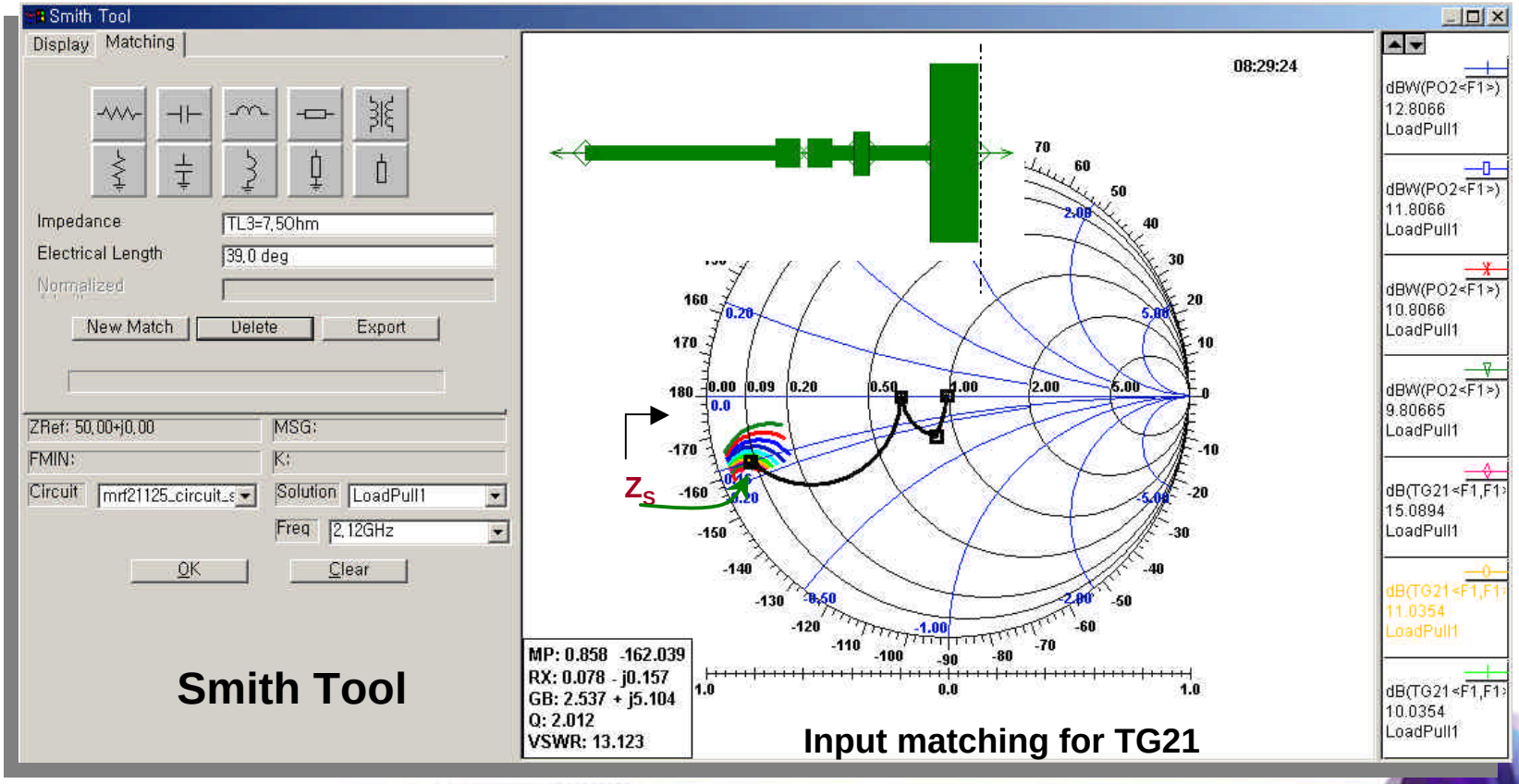


Smith Tool

Output matching for PO

Input Matching

- Input matching circuit, V_{DD}=28V, I_{DQ}=1600mA
- Source Impedance matching for optimum TG21<F1,F1>
- Transmission Line matching with Smith Tool

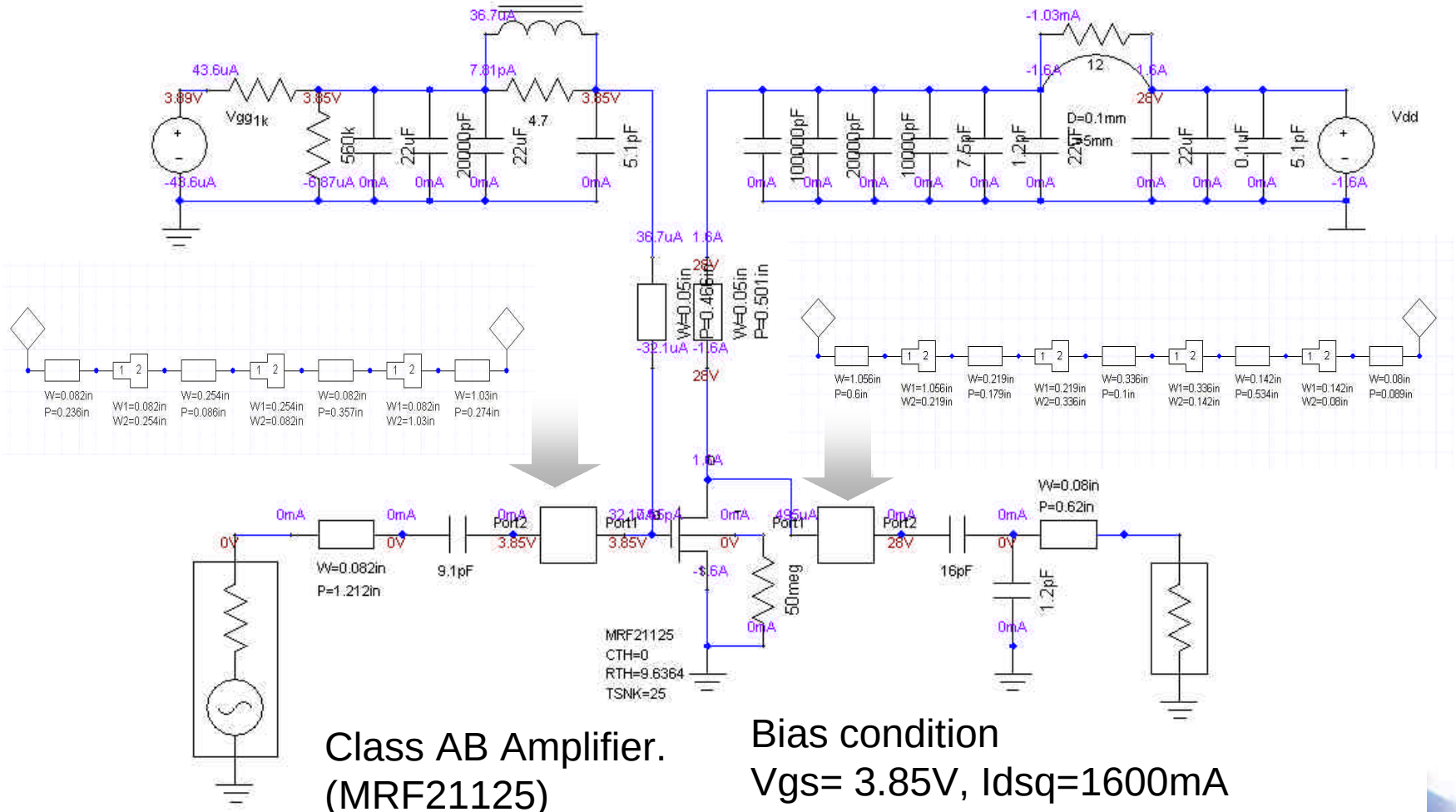


Smith Tool

Input matching for TG21

Carrier Amplifier Analysis

Input and output matching circuits were included



Class AB Amplifier.
(MRF21125)

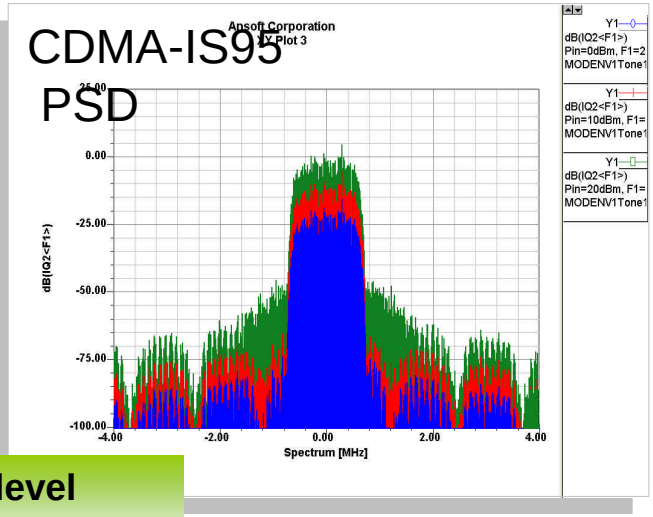
Bias condition
Vgs= 3.85V, Idsq=1600mA

Modulation Analysis

Carrier amplifier characteristics: AB Class operation mode

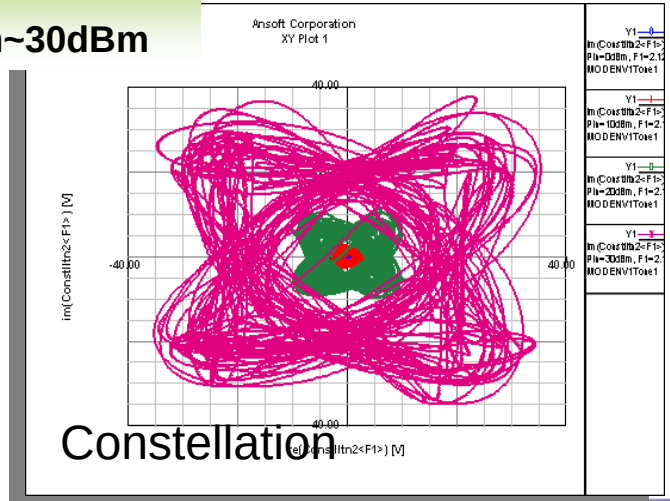
CDMA-IS95

PSD

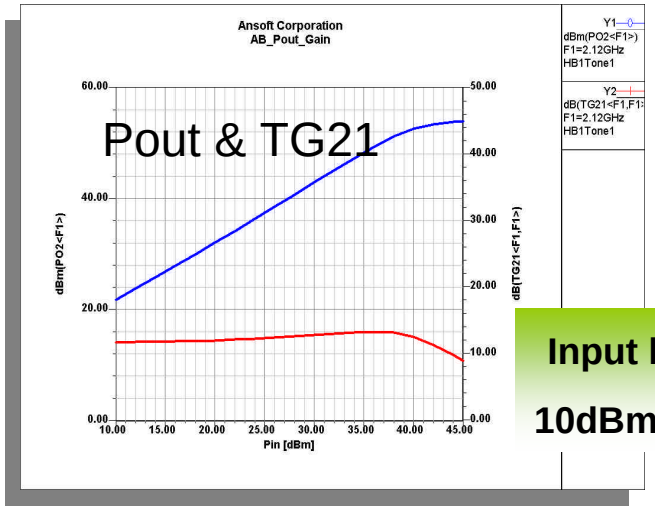


Input level

0dBm~30dBm



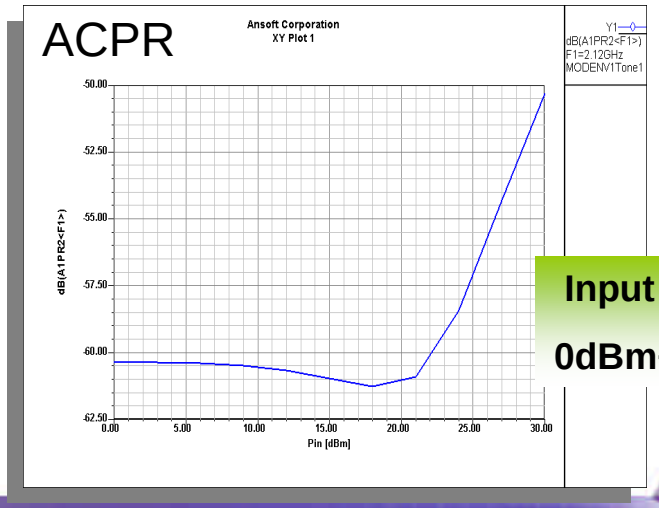
Constellation



Input level

10dBm~45dBm

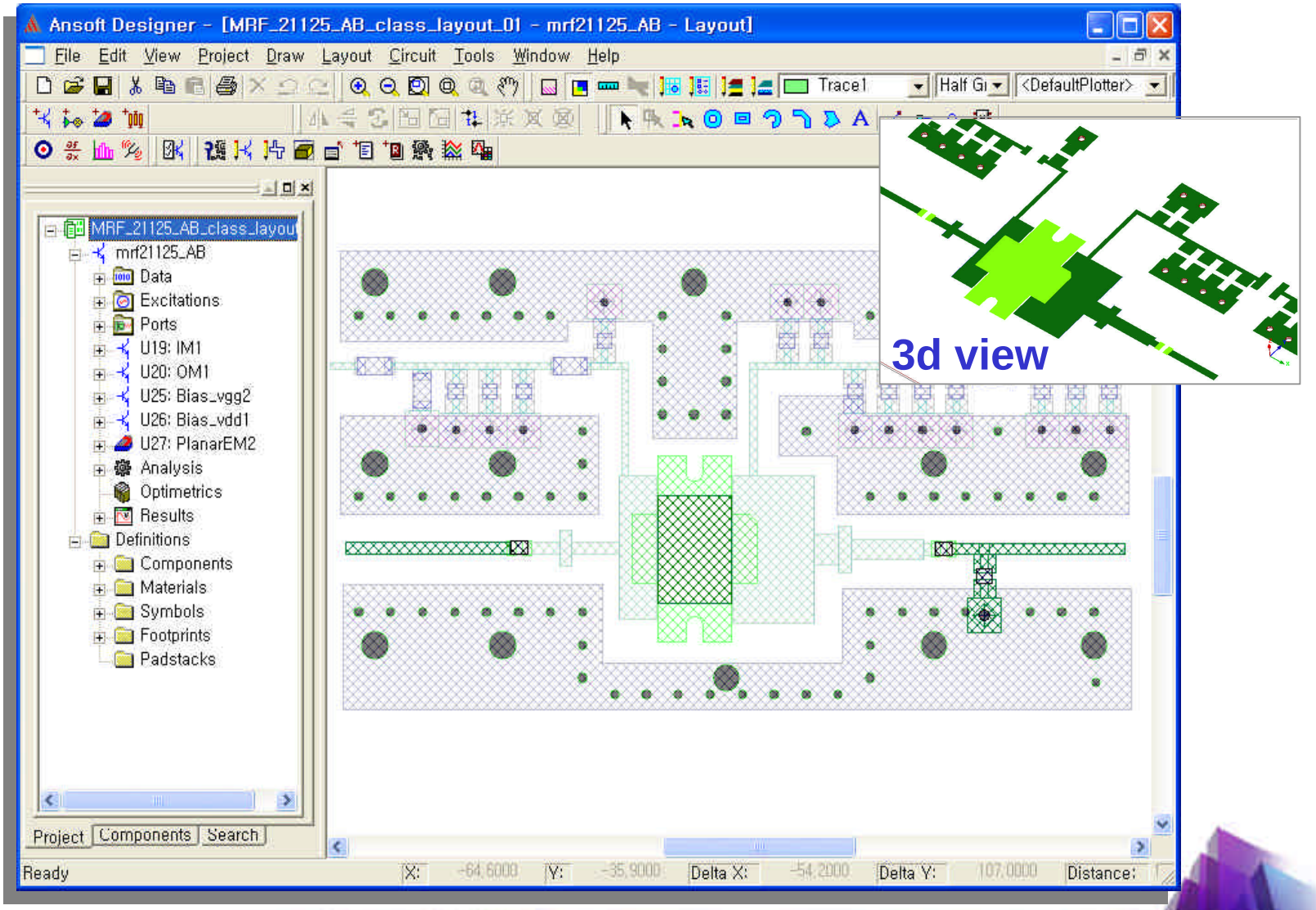
ACPR



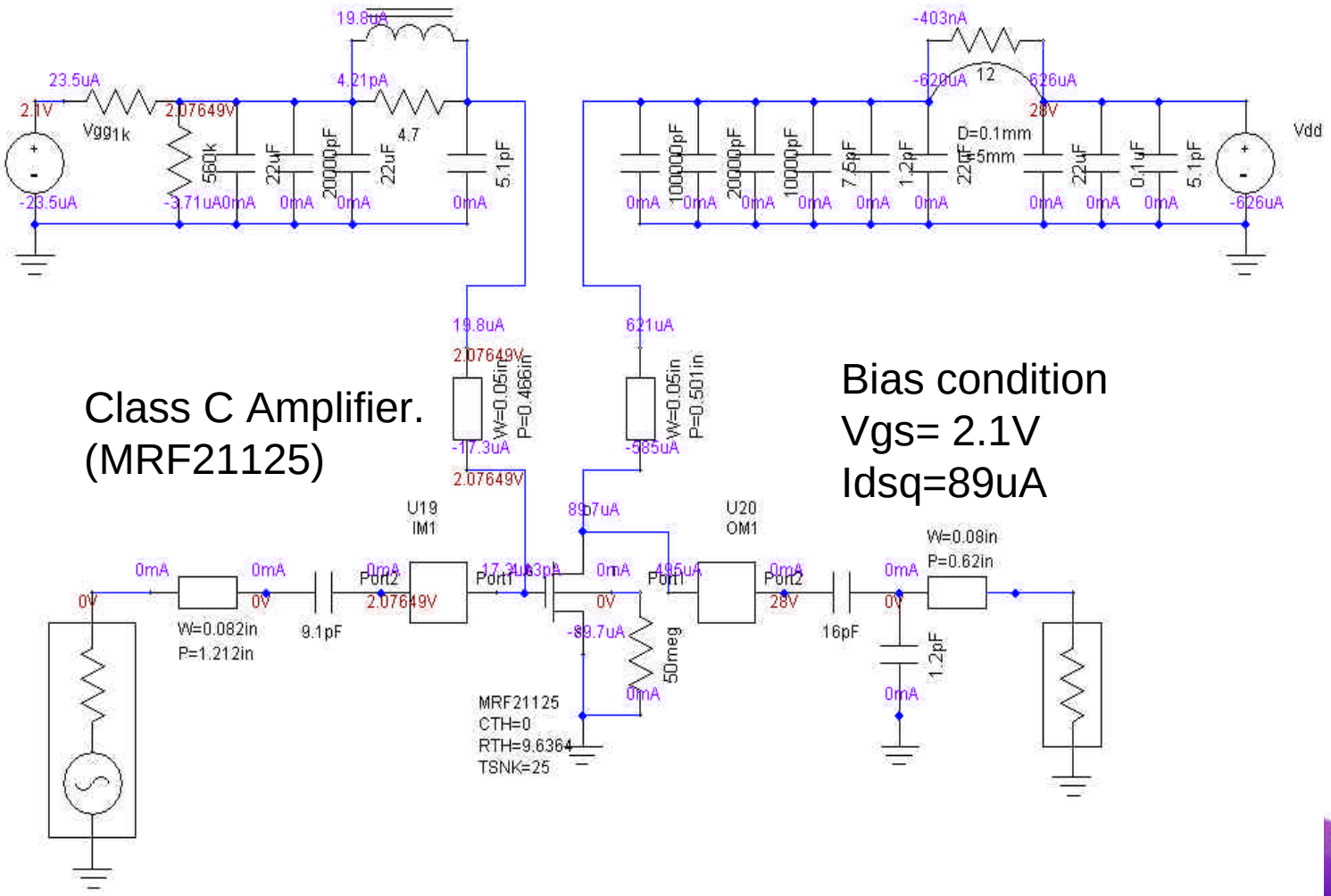
Input level

0dBm~30dBm

Carrier Amplifier PCB Layout



Peak Amplifier Operation



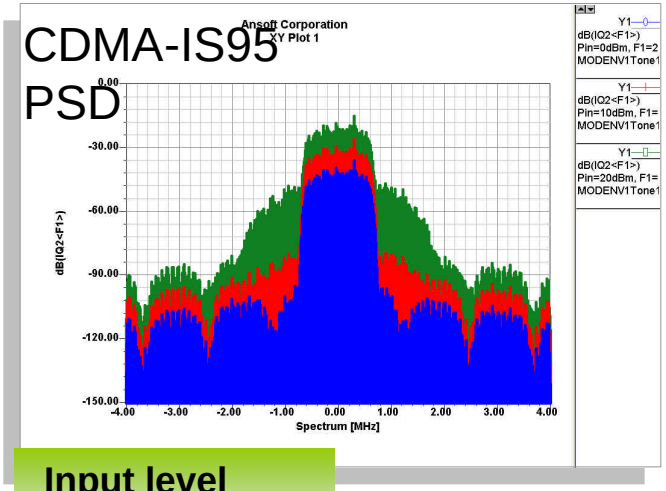
Class C Amplifier.
(MRF21125)

Bias condition
Vgs= 2.1V
Idsq=89uA

Modulation Analysis

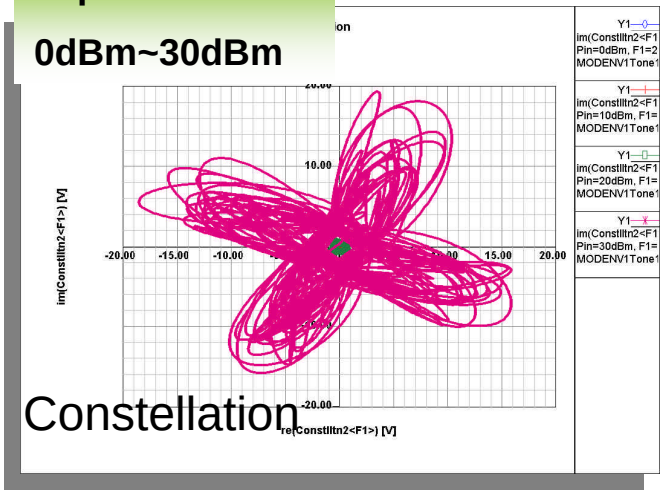
Peak amplifier : Class C operation mode

CDMA-IS95 PSD



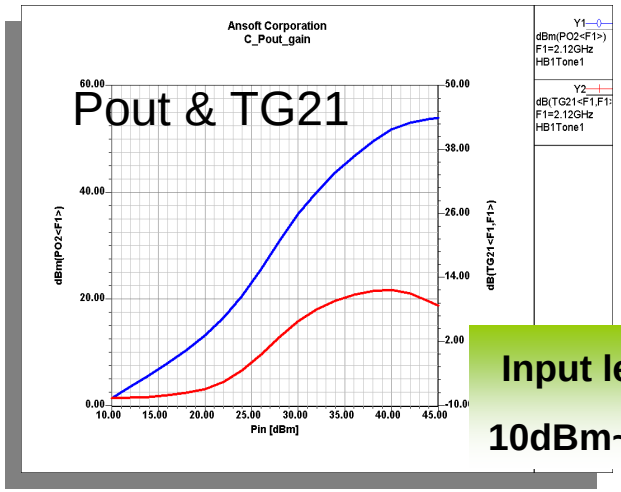
Input level

0dBm~30dBm



Constellation

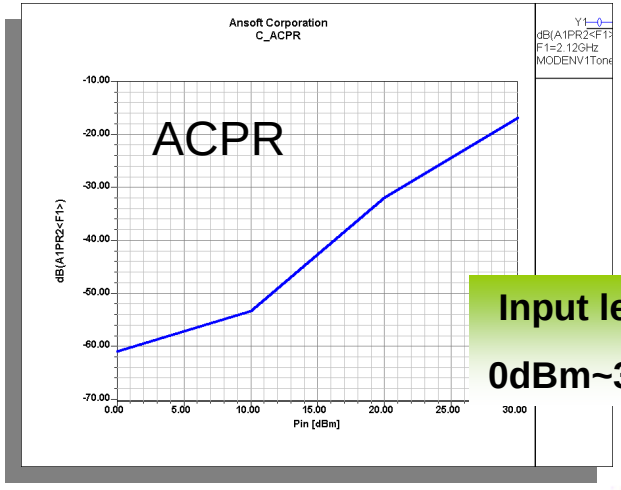
Pout & TG21



Input level

10dBm~45dBm

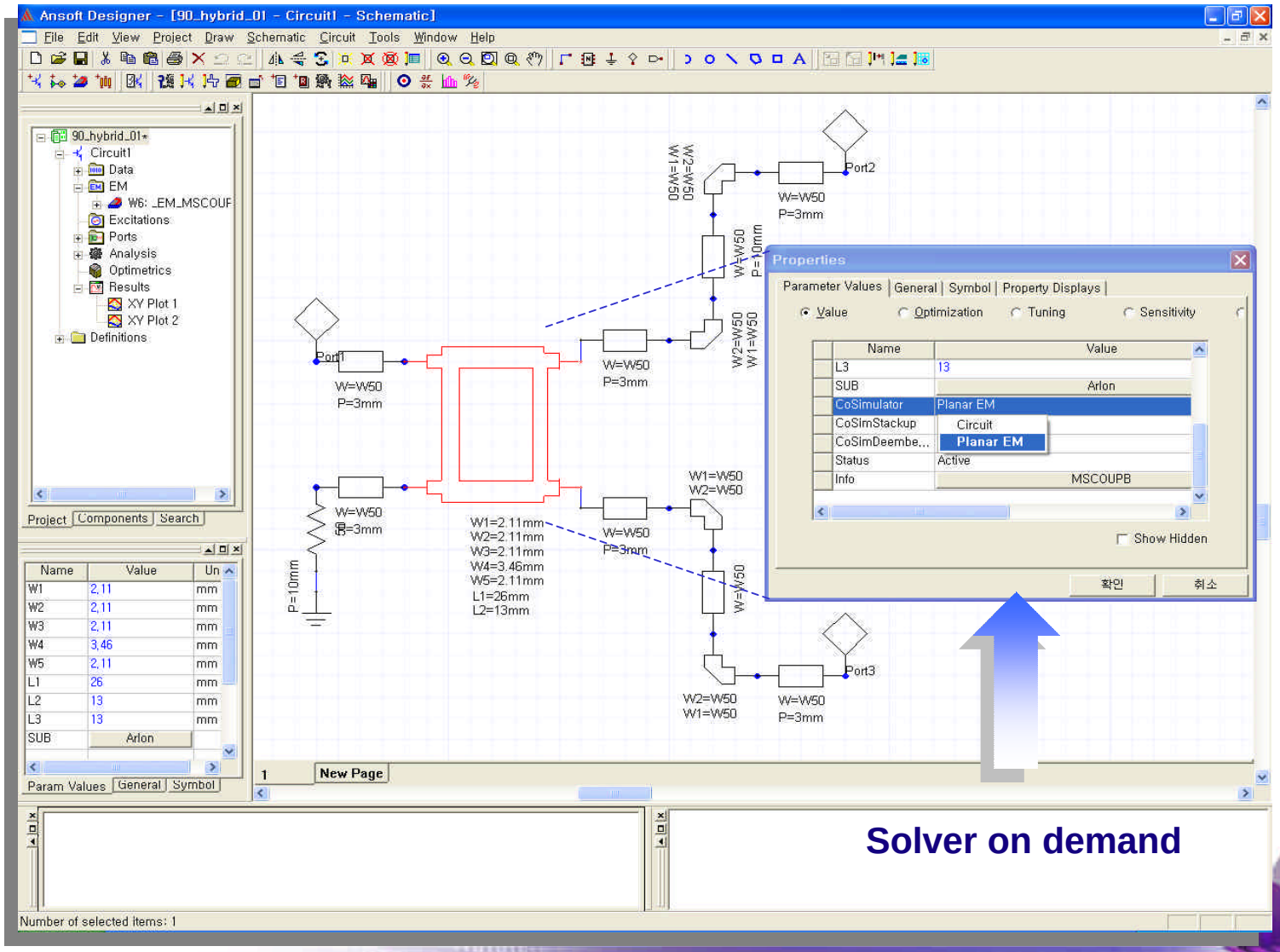
ACPR



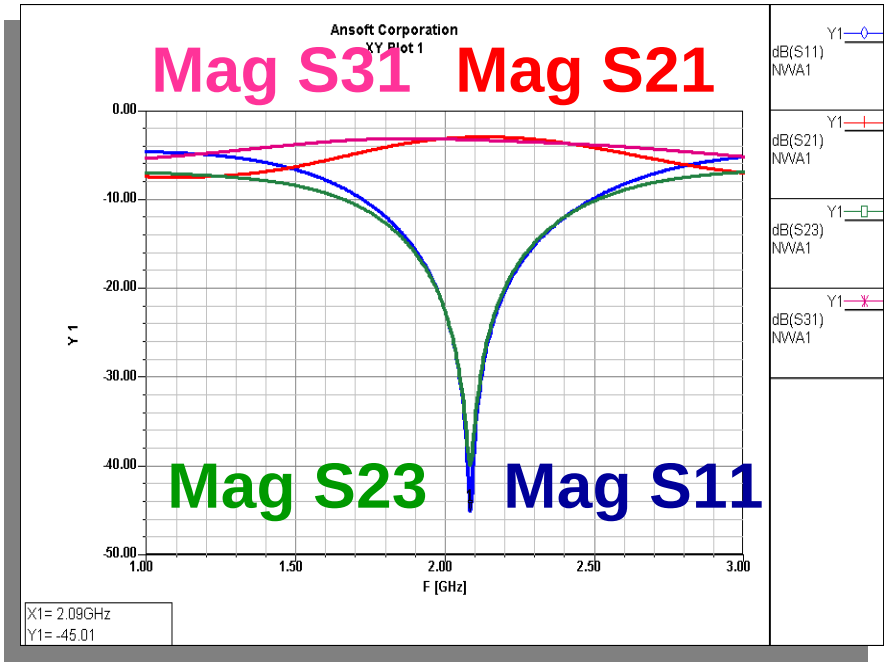
Input level

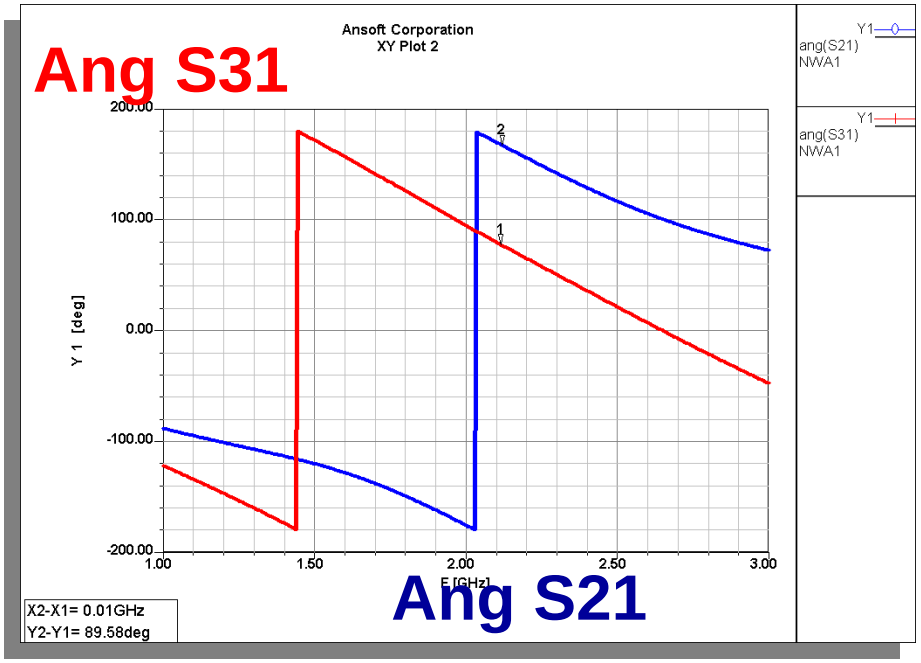
0dBm~30dBm

90º Hybrid Coupler Design

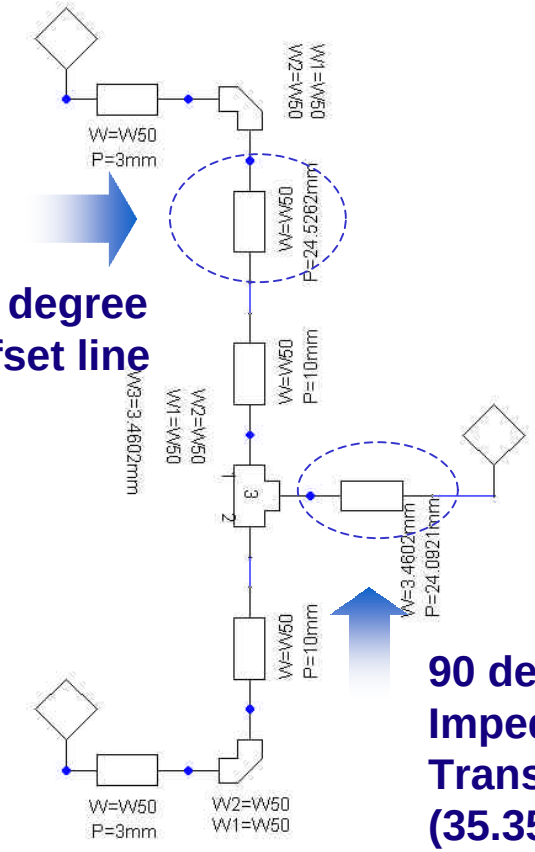


90º Hybrid Coupler Design



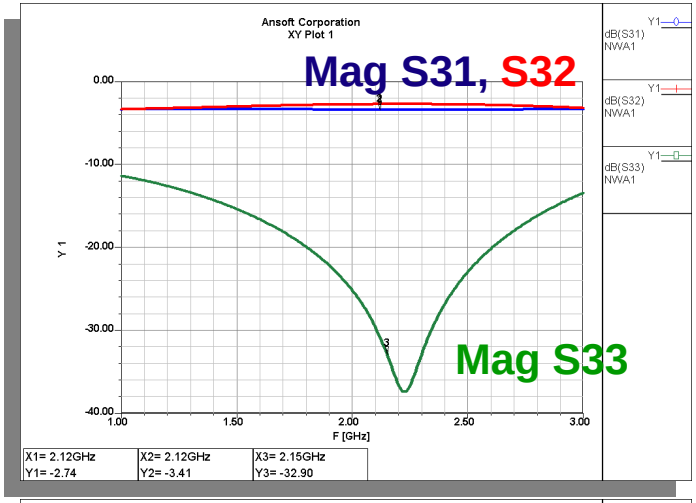


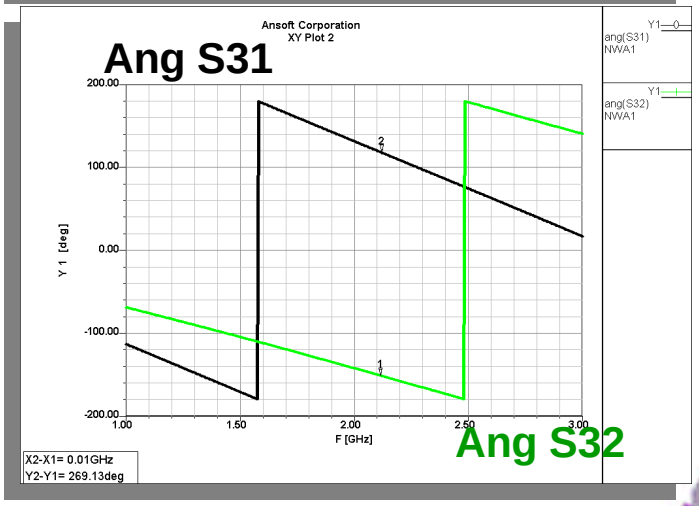
90 º Offset and Transformer Line



90 degree offset line

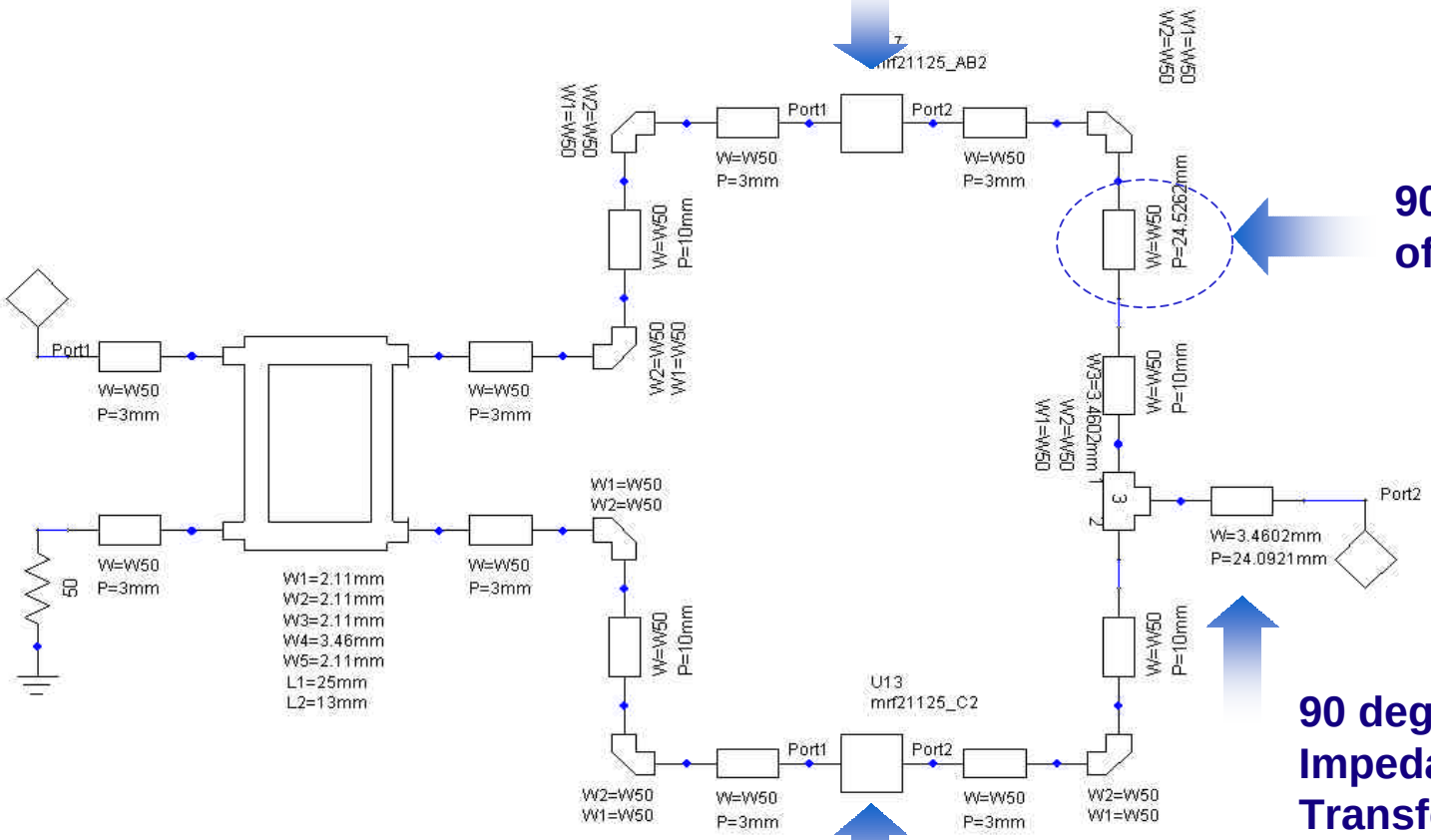
90 degree Impedance Transformer (35.35 Ohm)





Doherty Amplifier Schematic

(Carrier Amp.)

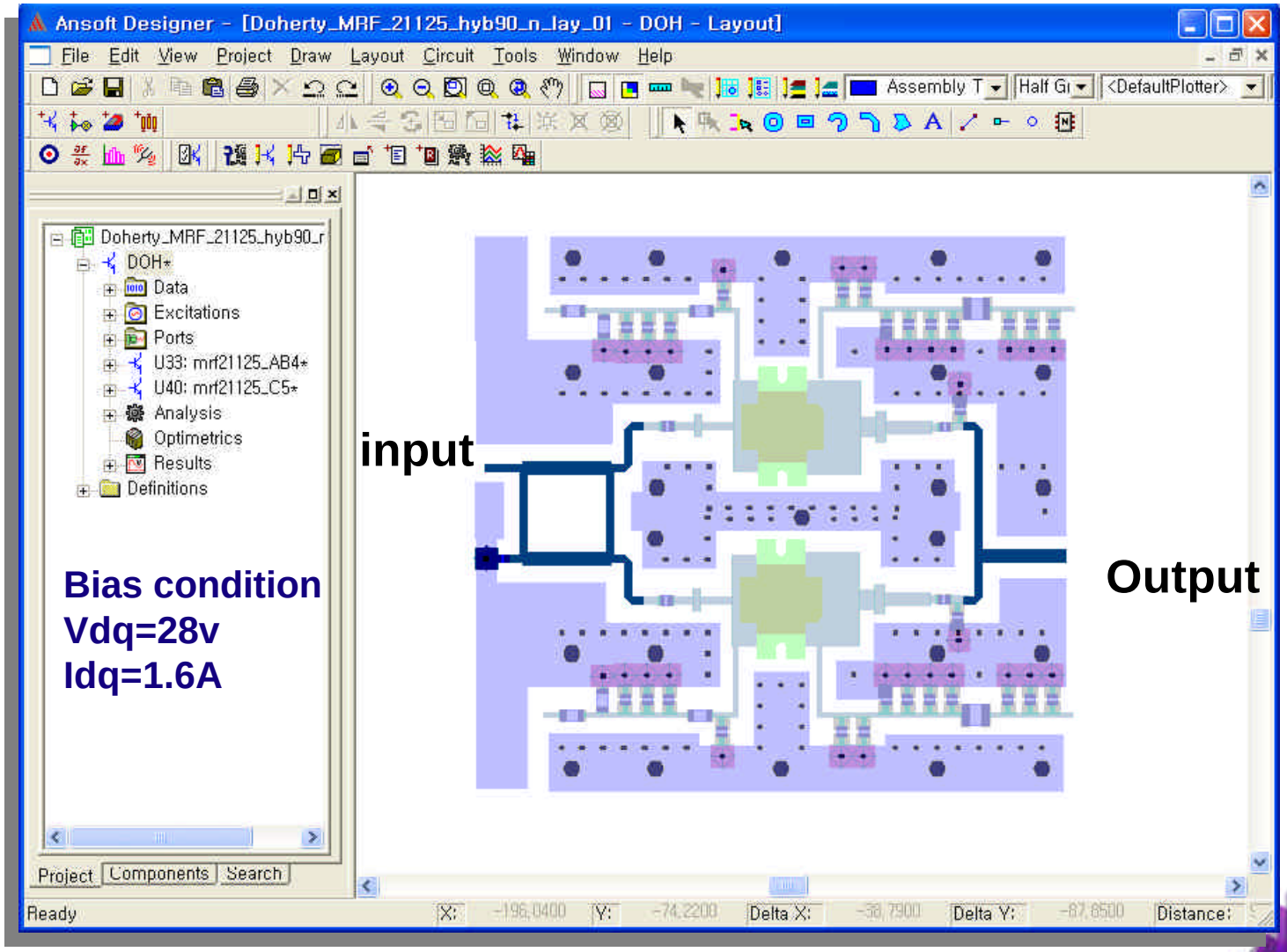


90 degree offset line

90 degree Impedance Transformer

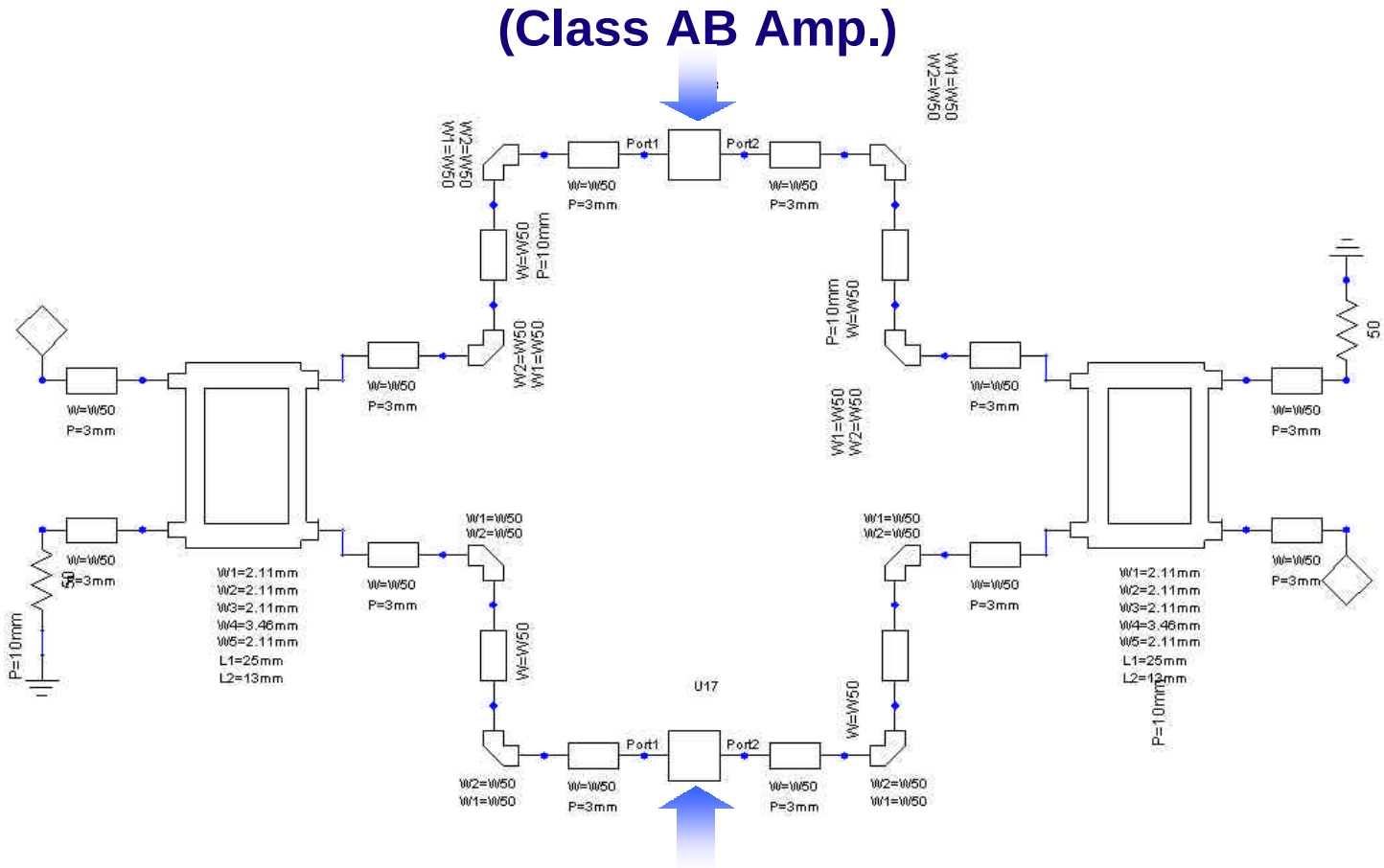
(Peak Amp.)

Doherty Amplifier Layout

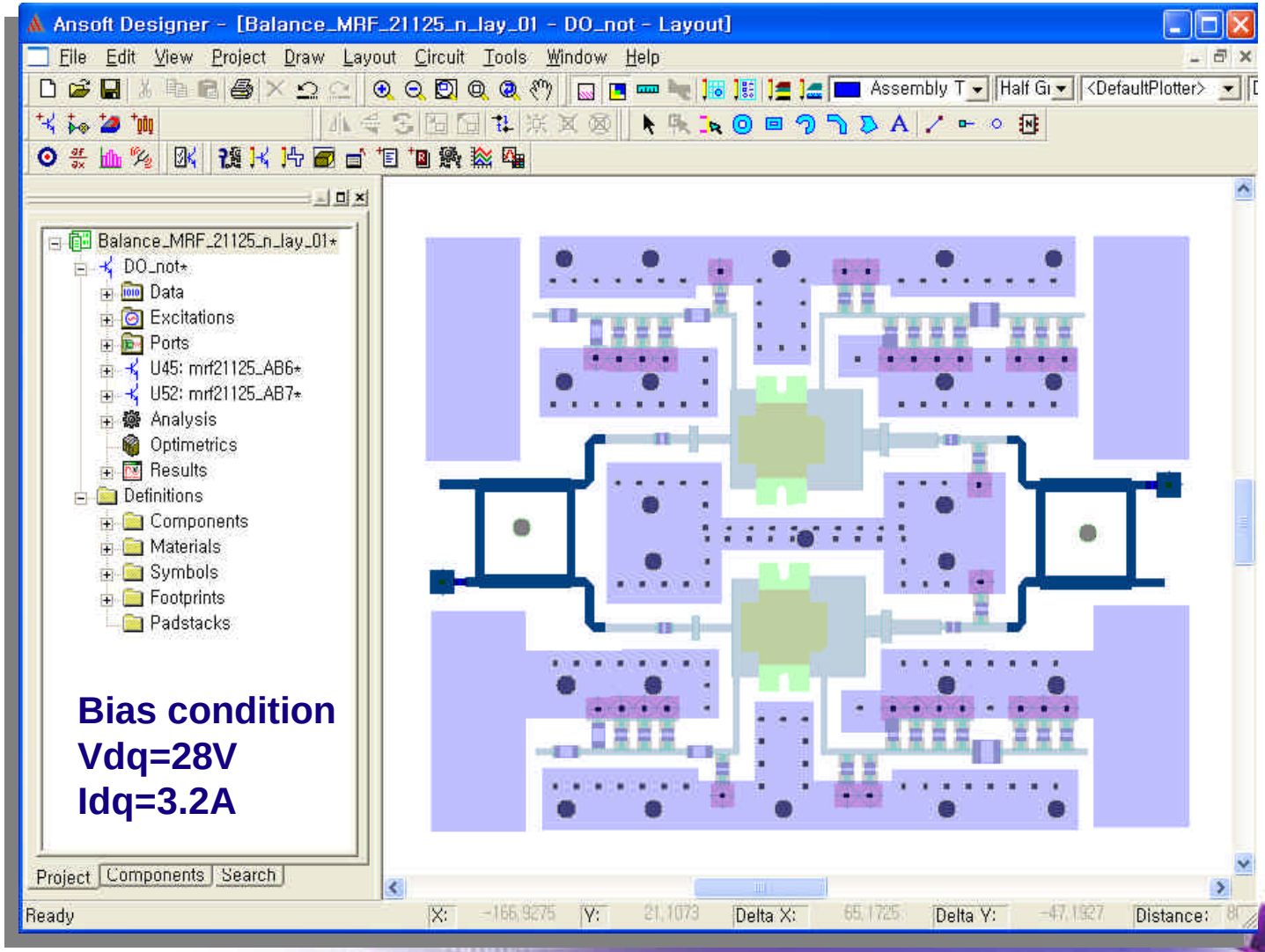


Balanced Amplifier Schematic

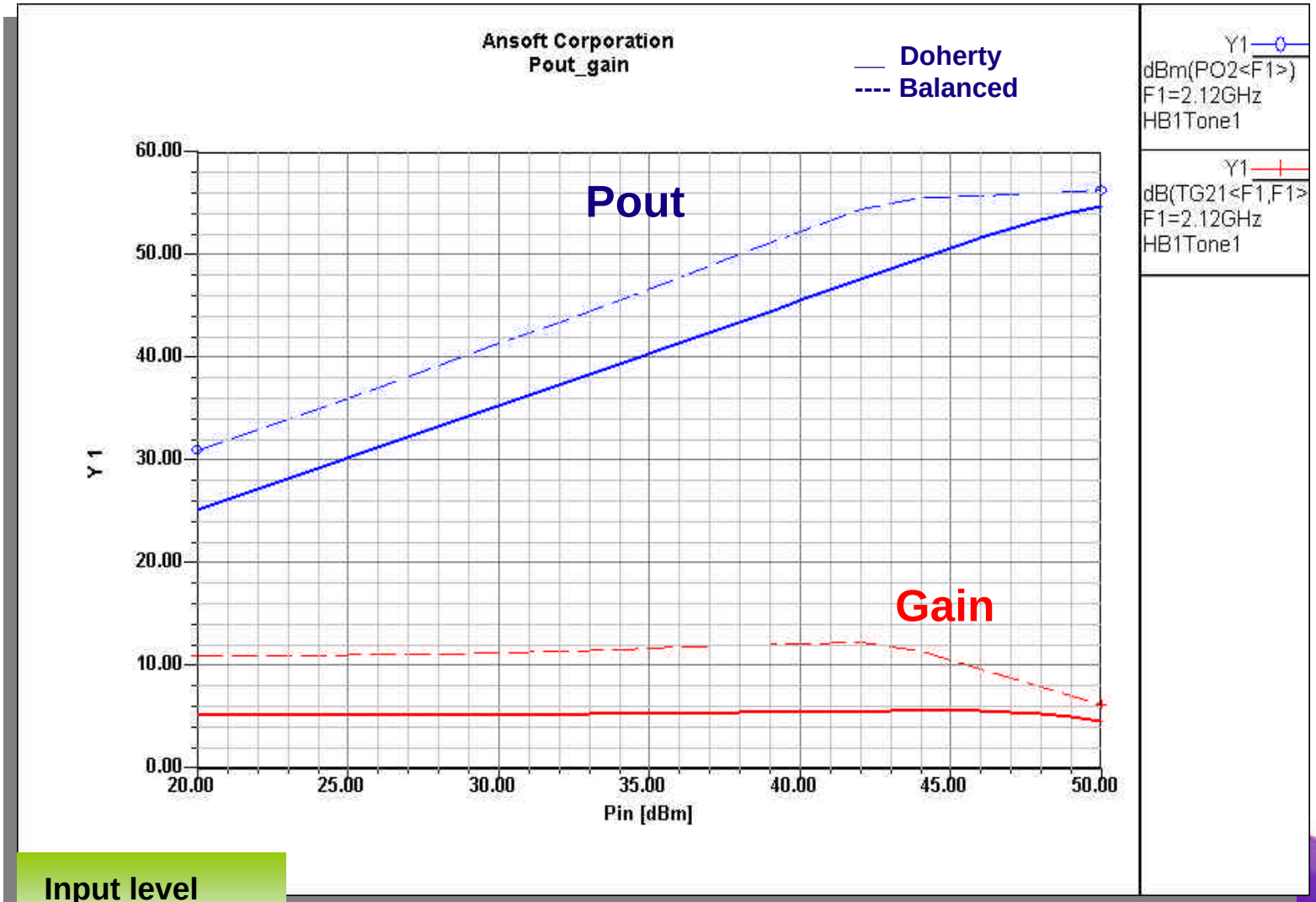
- Conventional balanced amplifier can be realized by combining two class AB amplifiers as shown below.



Balanced Amplifier Layout



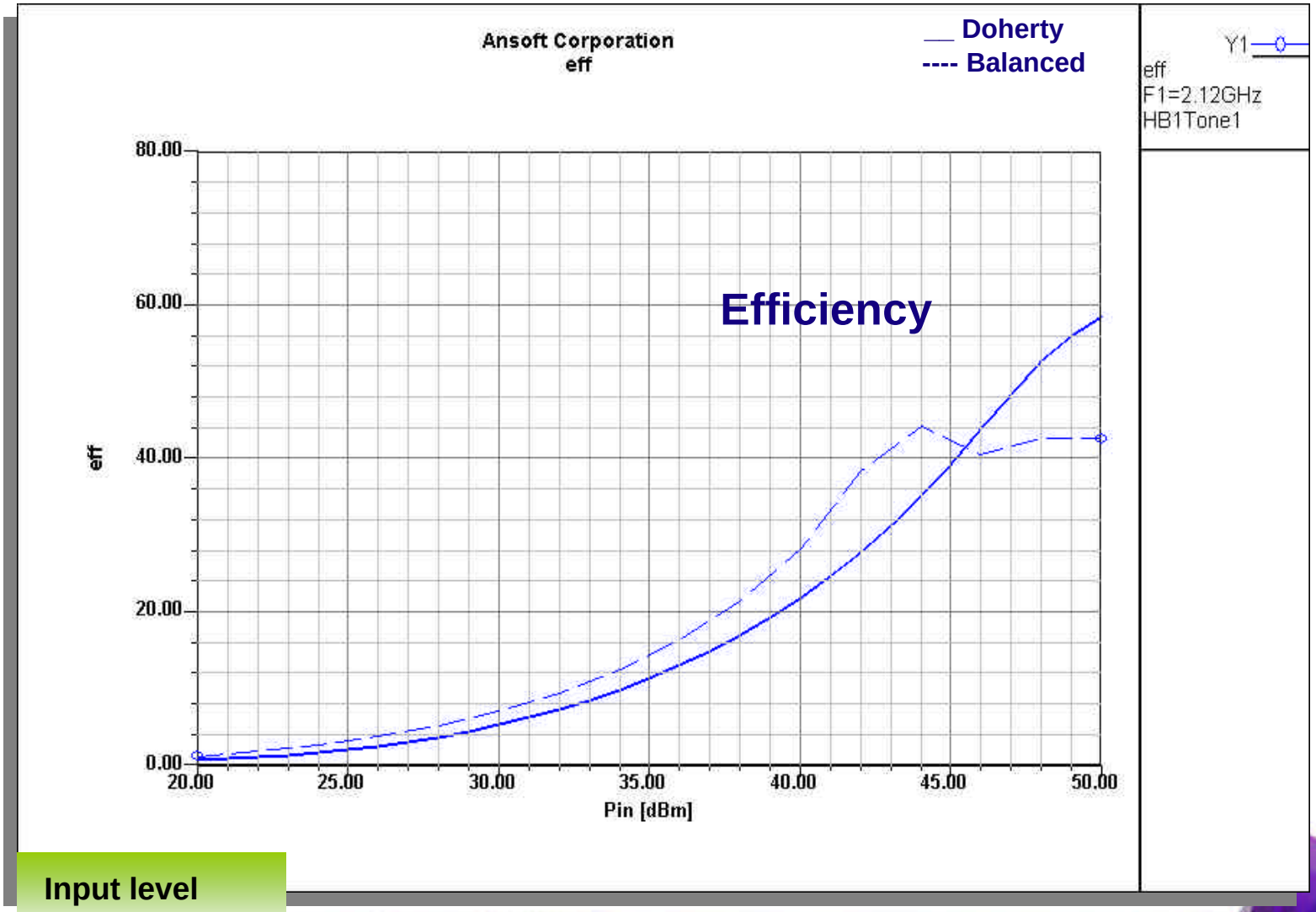
Pout and Gain Comparison



Input level

20dBm~50dBm

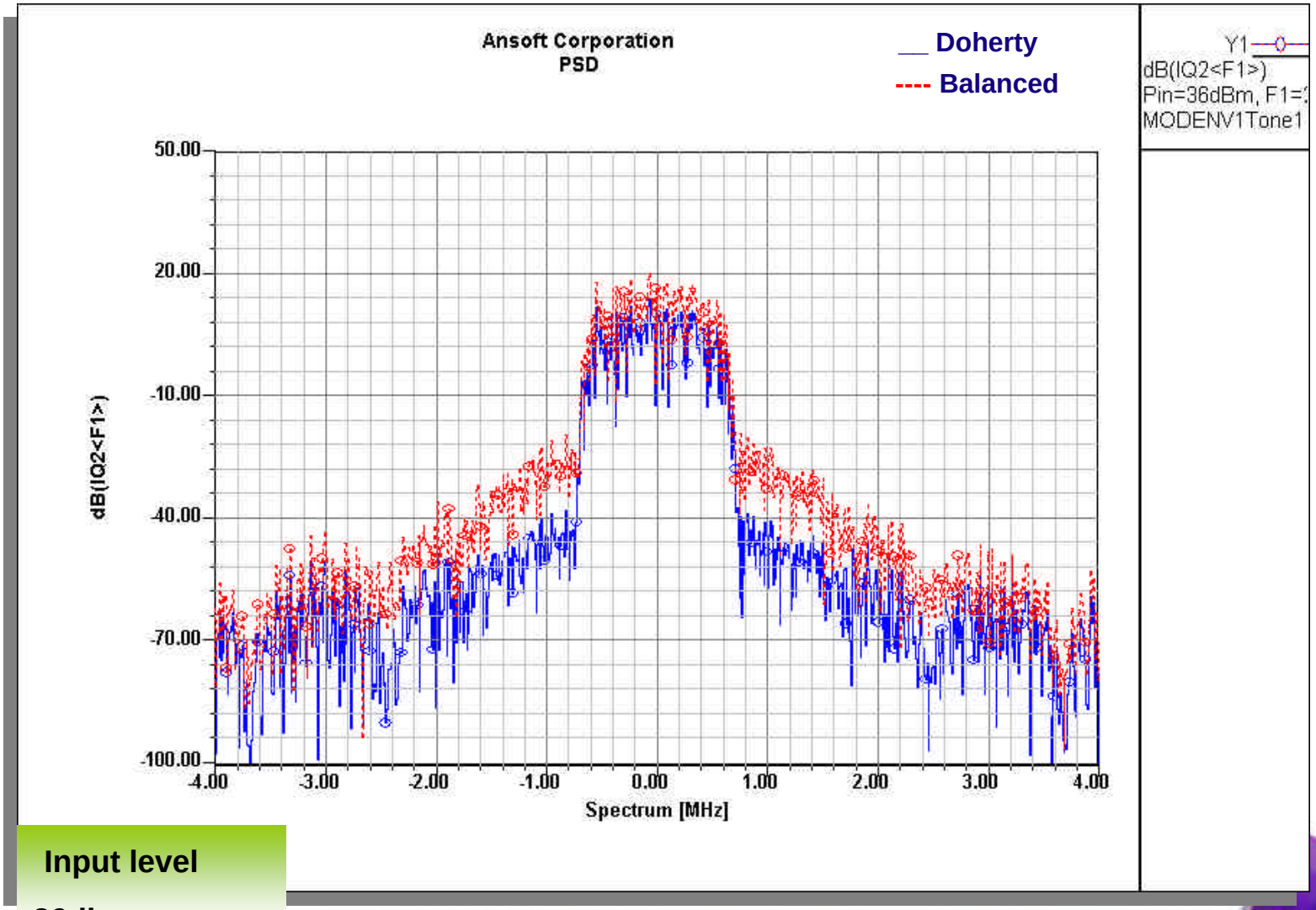
Efficiency Comparison



Input level

20dBm~50dBm

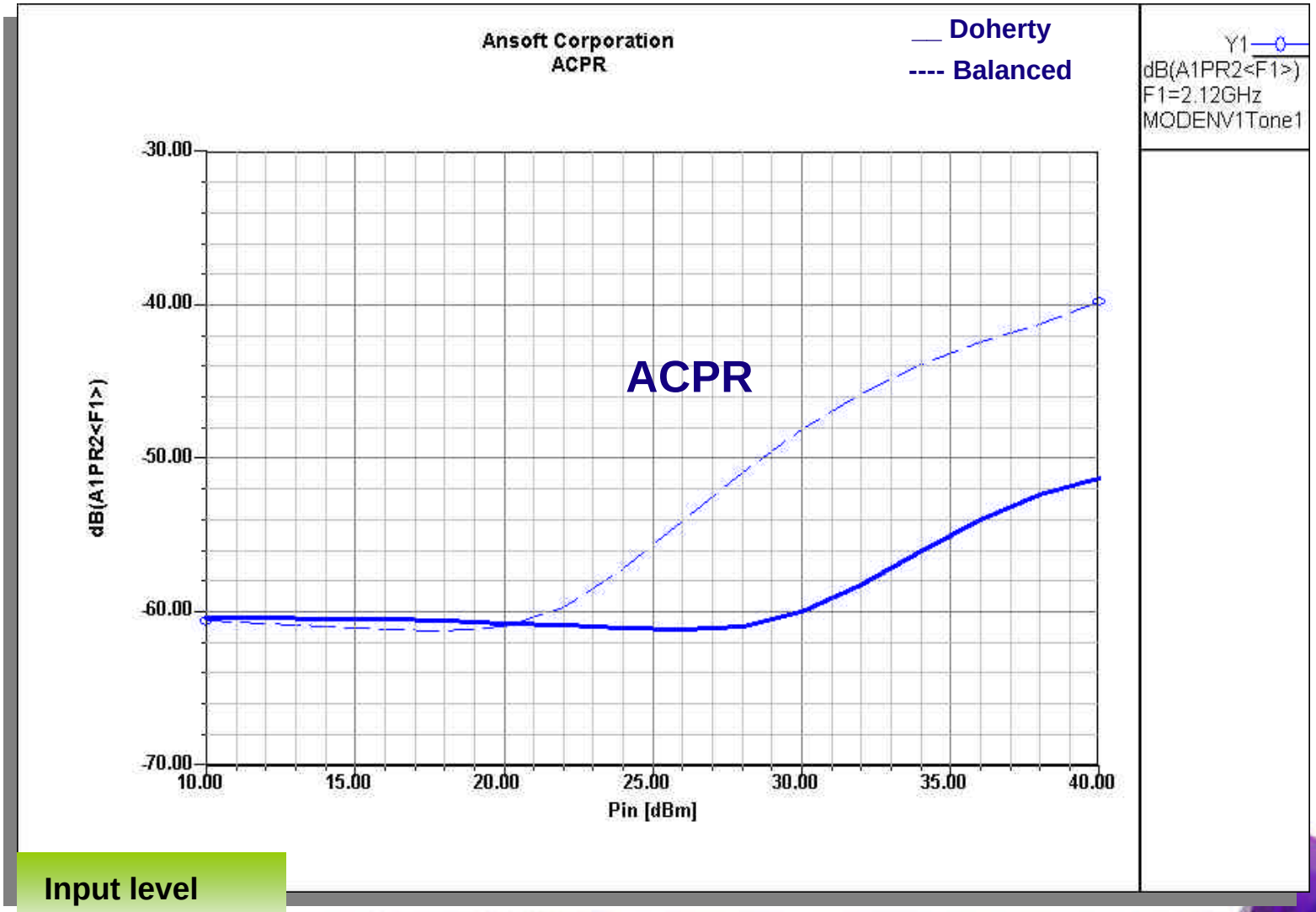
PSD Comparison



Input level

36dbm

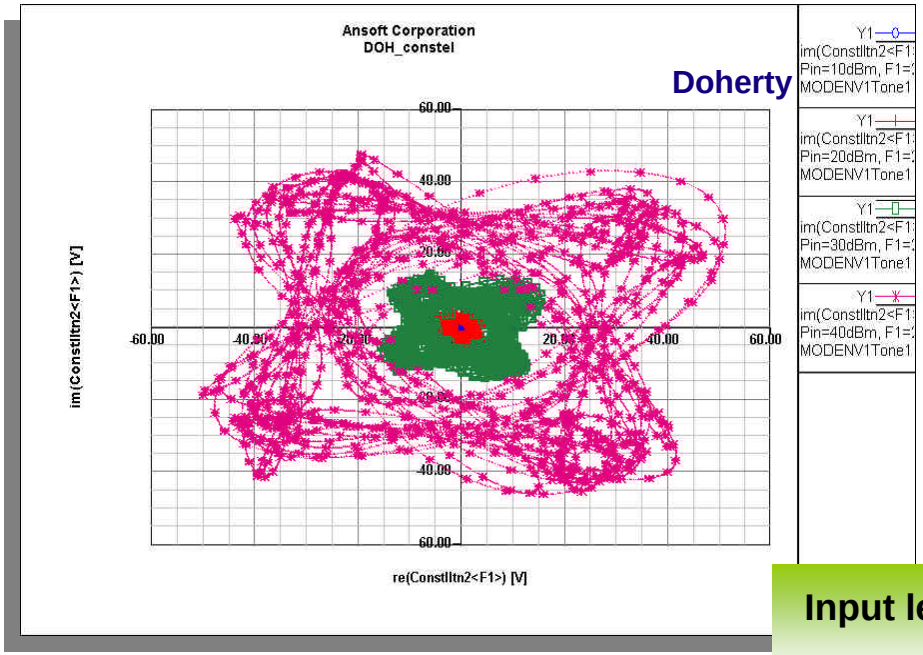
ACPR Comparison

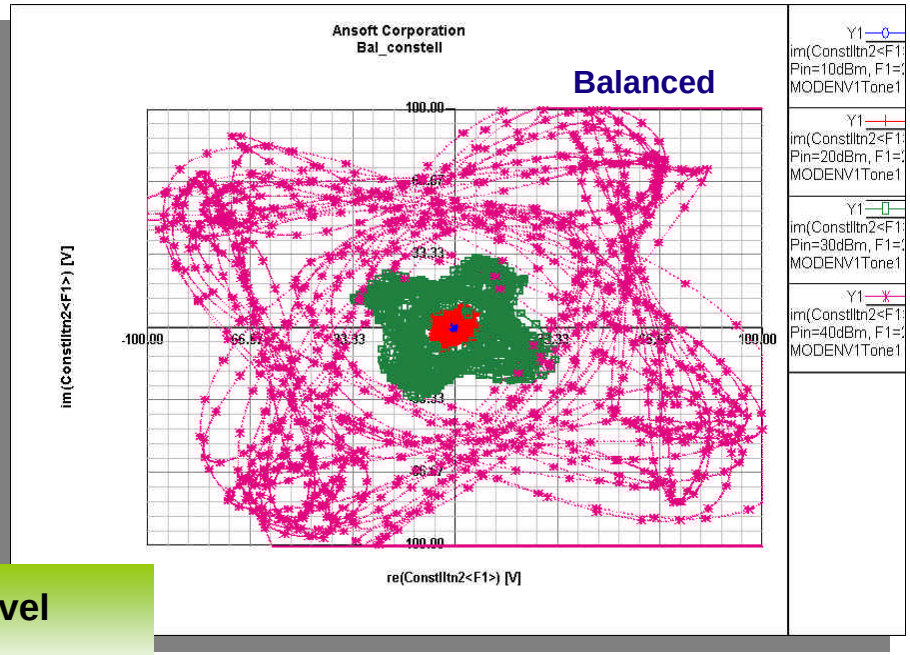


Input level

10dBm~40dBm

Constellation Comparison





Input level

10dBm~40dBm

Conclusion

- **Technical Summary**
  - Motorola MET model validation was checked
  - Various matching techniques were presented.
  - Load-pull analysis was shown in Ansoft Designer.
  - Doherty amplifier was designed using Motorola MET model in Ansoft Designer ™
  - Results of the Doherty amplifier were compared with conventional balanced power amplifier

- **Power Amplifier Design Solution :** Ansoft Designer ™
  - Motorola MET models are available
  - DC, Stability, Load-pull, harmonic balanced, and transient analysis
  - Smith Tool, Transmission line utility
  - Automated tuning, parameter-sweep, optimization, and post-processing
  - Dynamic link between schematic and layout
  - Integrated design environment with Planar EM, Circuit, System, and HFSS

- **Ansoft Products applied in this presentation**
  - Ansoft Designer ™ Planar EM
  - Ansoft Designer ™ Circuit
  - Ansoft Designer ™ System

References

[1] Andrei V. Grebennikov, “Create Transmission-Line Matching Circuits For Power Amplifiers” MICROWAVES & RF OCTOBER 2000

[2] Antoine Rabany, “Accuracy of LDMOS model Measurement versus simulation” , Motorola , January 2003, rev0

[3] Steve C. Cripps, “RF Power Amplifiers for Wireless Communications”, Artech House, 1999.

[4] W.H. Doherty, “A New High Efficiency Power Amplifier for Modulated Waves,” Proc. IRE, Vol. 24, No. 9, pp. 1163-1182, 1936.

[5] S. C. Cripps, RF Power Amplifiers for Wireless Communications.Norwood, MA: Artech House, 1999.

[6] P.B. Kenington, “High-Linearity RF Amplifier Design,” Artech House Inc.,2000.

[7] C.P. Campbell, “A Fully Integrated Ku-Band Doherty Amplifier MMIC,” IEEE Microwave and Guided Wave Letters, Vol. 9, No. 3, 1999.

[8] C.P. McCarroll, et al, “A 20GHz Doherty Power Amplifier MMIC with High Efficiency and Low Distortion Designed for Broad Band Digital Communication Systems,” IEEE MTT-S Int. Microwave Sympo. Dig., pp. -, 2000.

[9] B. Kim, Y. Yang, J. Yi, J. Nam, Y. Y. Woo, and J. Cha, “Efficiency enhancement of linear power amplifier using load modulation technique,” in Int. Microwave and Optical Technology Symp. Dig., June 2001, pp.505–508.

[10] Y. Yang, J. Yi, Y. Y. Woo, and B. Kim, “Optimum design for linearity and efficiency of microwave Doherty amplifier using a new load matching technique,” Microwave J., vol. 44, no. 12, pp. 20–36, Dec. 2001.