# *Amplifier Design and Topology for Microwave Applications*

## *(from LNAs to LPNAs to PAs)*

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AML Communications

# Presentation Outline

- Amplifier requirements – practical view
- Design considerations – multidisciplinary know how
- Examples of practical amplifier designs and their performances

# Amplifier Requirements (Wish list)

- High and flat gain
- Very low noise figure
- High output power and efficiency
- Extremely linear
- Very low phase noise
- No reflections or harmonics
- Super wide dynamic range
- Constant over temperature
- Very small size
- Very high MTBF

# Practical Trade-offs

- General:
  - Gain, NF vs BW
  - BW vs Power
  - Stability vs NF
  - BW, Gain and flatness vs practical matching
  - Linearity vs efficiency
  - Amplifier input/output protection vs NF, BW
  - Performance vs price

# Practical Trade-offs - cont -

- Low Noise Amplifier:
  - Gain, VSWR, stability  vs NF
  - Power, BW, linearity vs NF
- Power Amplifier:
  - Max power vs efficiency
  - Max power vs BW
  - Max power vs linearity & efficiency
  - Power vs environmental

# *Meeting Specifications Dependents On:*

* Design:
  - Active device selection
  - Amplifier topology
  - CAD design tools
* Fab and Testing:
  - Implementation
  - Assy Processes
  - Test methodology
  - Environment

# *What Does It Take to Make a 'perfect' Amplifier ?*

- Know device performance & limitations
- Correct application of amplifier topologies
- Experienced with CAD design tools
- Understand the environmental impact
- Posses world class processes
- Expert in testing techniques
- Verify data vs. environmental specs

# Active Devices

- **Heterojunctions:**
  - Reliable and commercially available
  - HEMTs & HBTs replace MESFETs & BJTs

- **Performance/Advantages depending on:**
  - compound material properties,
  - technology, mainly Gate geometry,
  - device capacitances and access resistances,
  - Attachment in the circuit
  - $

# Material Properties Brief

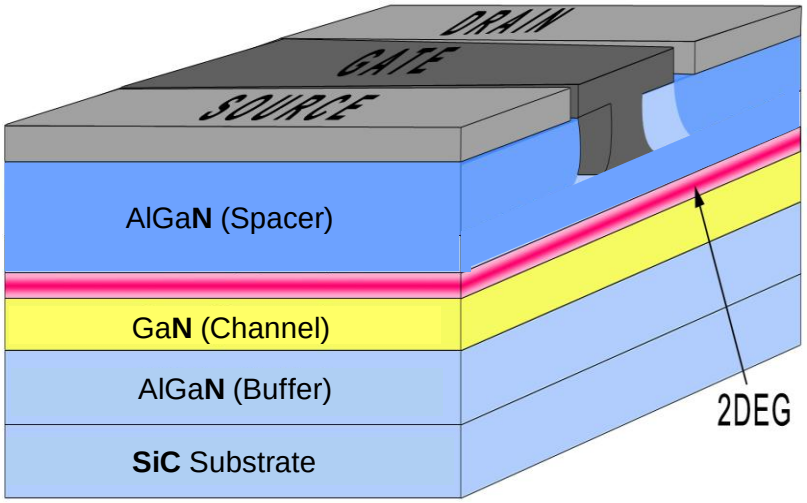
| | Si | GaAs | InGaAs | SiC | GaN |
|---|---|---|---|---|---|
| **Bandgap Energy (eV)** | 1.1 | 1.4 | 0.8 | 3.2 | 3.4 |
| **Breakdown Field (MV/cm)** | 0.3 | 0.4 | 2 | 3.5 | 3.5 |
| **Thermal Conductivity (W/cm*K)** | 1.5 | 0.5 | 0.07 | 2.9 | 1.7 |
| **Electron Mobility ($cm^2$/ V*s)** | 1,350 | 8,500 | 12,000 | 800 | 1,500 |
| **Saturated Electron Velocity (*$10^7$ cm/s)** | 1 | 0.8 | 0.75 | 2 | 2.4 |

# From MESFETs to HEMTs

- HEMTs outperform MESFETs in NF, gain, and also operate to higher frequencies.
- “Heart of HEMT: 2DEG”
- This is due to superior electron transport properties in the channel:
  - higher mobility and density
  - higher transconductance
  - higher cut-off frequency ($f_T$)
  - lower layer resistances

# GaAs HEMT Basic Structure

- The electron channel is confined in a 2DEG layer, just under the Spacer layer
- Size: Channel width << Gate to Channel distance << Gate length



# From BJTs to HBTs

- BJTs: current gain (β) highly dependent on doping level of Base and Emitter
- As for HBTs, β can be substantially increased by Base/Emitter junction bandgap engineering. Advantages:
  - low $C_{BE}$, thus higher frequencies
  - lower $R_B$, easier to match

# Amplifier Performance at X-Band vs Device

| | Vds | NF | Gain | P-1dB | Phase Noise (@ 1 kHz Offset) | Psat | PAE |
|---|---|---|---|---|---|---|---|
| MESFET (GaAs) | 5/10 VDC | Good, (even below 2GHz) (4 dB) | Poor (10 dB) | Good Typ 0.5W/mm (+17dBm) | Good (155dBc/Hz) | typ 2dB above P-1 | <20% |
| | | | | | | | |
| PHEMT (AlGaAs/InGaAs) | 3/8 VDC | Best (2.5 dB) | Good (13 dB) | Good Typ 0.65W/mm (+20dBm) | Poor (140dBc/Hz) | typ 3/5dB above P-1 | 35% |
| | | | | | | | |
| HEMT (AlGaN/GaN) | 28/40 VDC | Good (3 dB) | Good (11 dB) | Very good 5W+/mm (+38 dBm) | Poor (140dBc/Hz) | typ 3/5dB above P-1 | 50% (@ Psat) |
| | | | | | | | |
| HBT (InGaP) (SiGe) | 2/5 VDC | Good (4 dB) | Poor (9 dB) | Low (+16 dBm) | very good (160dBc/Hz) | typ 2dB above P-1 | 30% |

# Amplifier Topologies

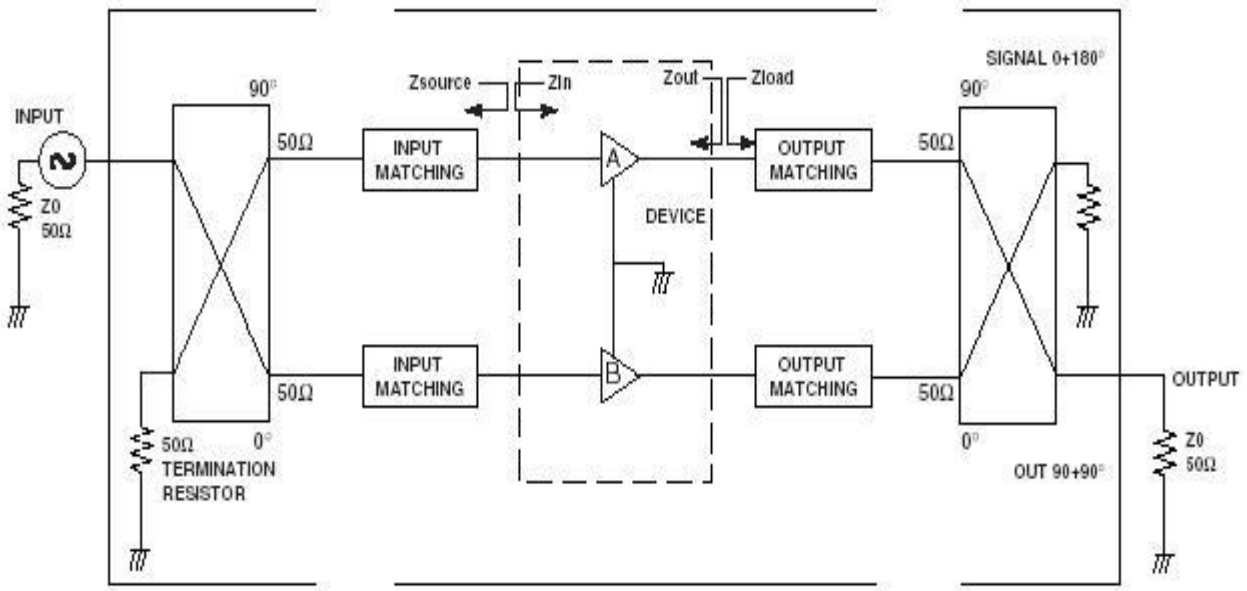
* **Single ended:**

  - best NF, poor VSWR, nominal gain and power, narrow band, difficult to achieve stability

* **Balanced:**

  - best VSWR, good NF, twice the power of single ended, very good stability, covers 1.5 octave, build-in redundancy

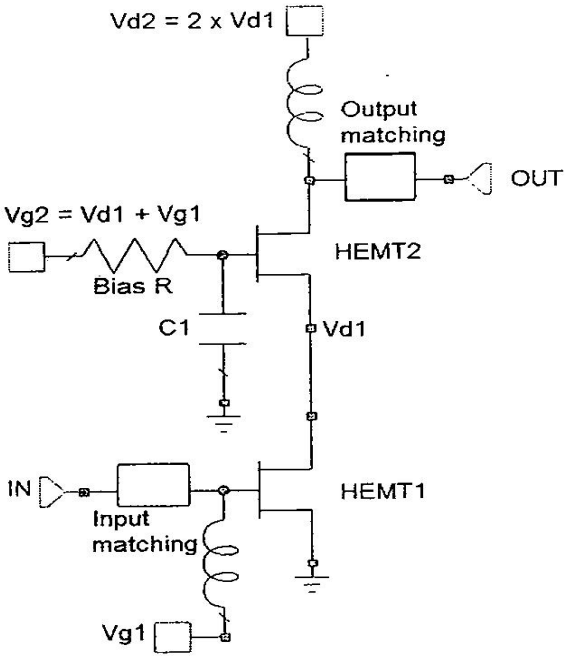
# Balanced Amplifier
# - basic bock diagram -



# Cascode Amplifier Topology

* advantages:
  - high reverse isolation
  - higher gain and BW
  - low power consumption
  - higher input and output impedances vs single device

- Schematic



# Amplifier Topologies (cont)

- **Distributed:**
  - Moderate to high flat gain over broad freqs
  - Moderate NF
  - fair power and linearity
- **Feedback amplifiers:**
  - Flat gain over many octaves
  - Good power and high linearity
  - Suppresses harmonics and spurious signals
  - Poor NF

# Required Design Tools

- Microwave CAD: small and large S-param.
- CAD Harmonic analysis
- 3D EM simulation tool
- Mechanical CAD: 2D and 3D
- Thermal simulation tools
- Reliability tools
- Cascade analysis

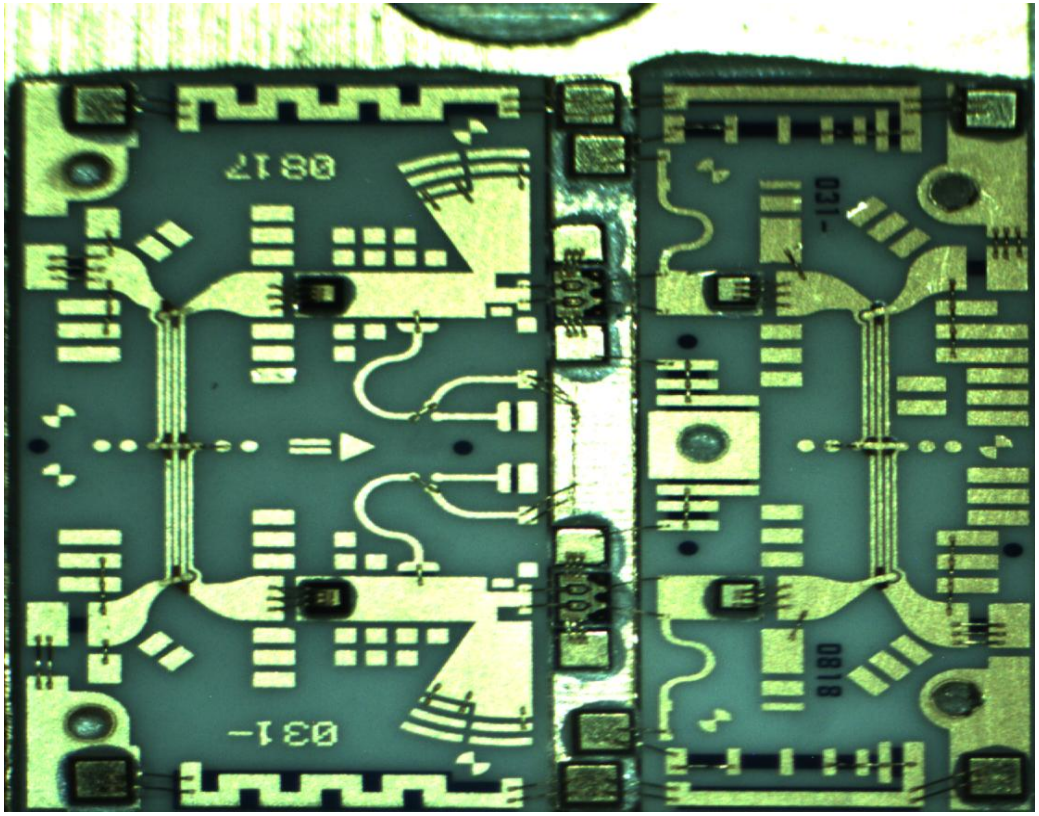
# Amplifier Design Process

1. Select appropriate devices and topology vs requirement
2. CAD design using linear/non-linear simulation tools:
   - solve a matching problem, note that a different criteria is used for different amplifier types
   - depending on the application, optimize for gain, NF, Pout, and/or $VSWR_{in/out}$
   - perform a stability simulation – it is a must!
3. Perform a sensitivity analysis and evaluate design
4. Make circuit layouts,
5. Fab and QC
6. Perform DVT/Qual
7. Implement tuning notes

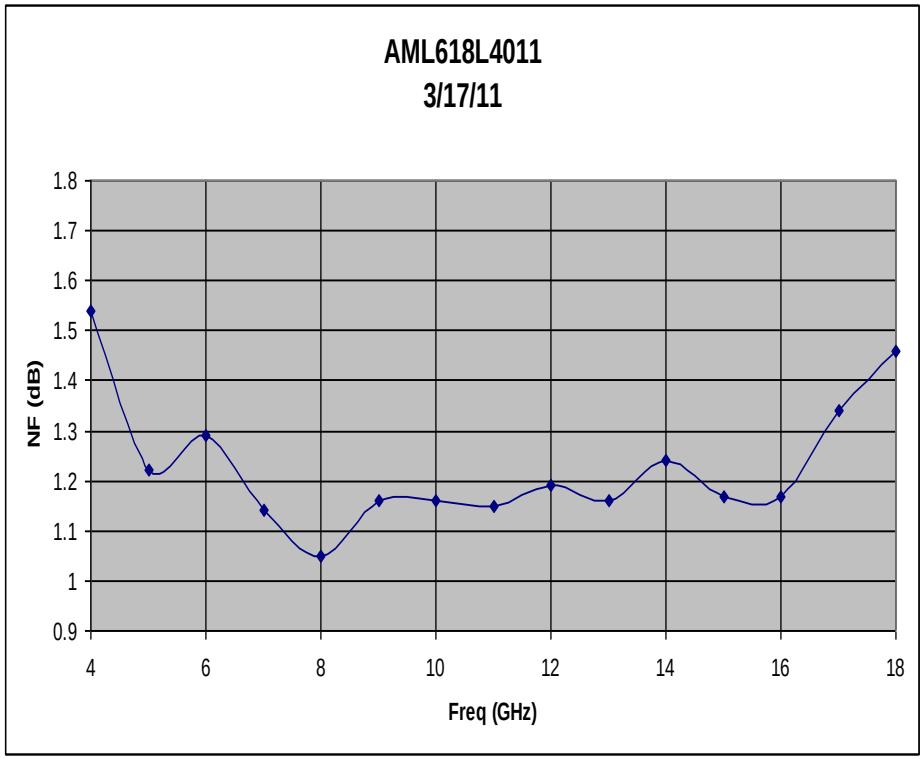
# LNA Design Rules

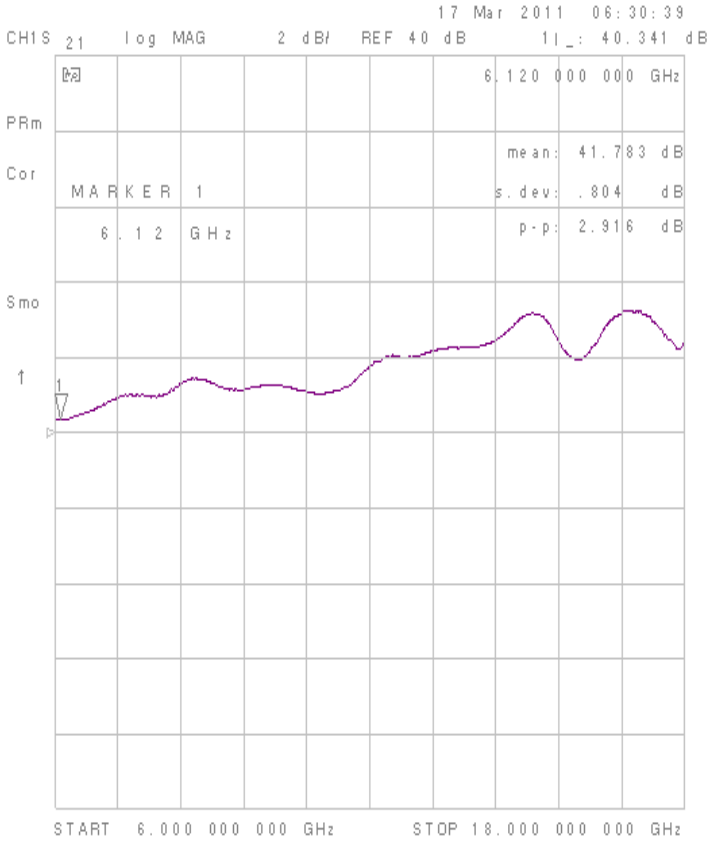
* Select devices that exhibit low NF, high gain, low current consumption in the band of interest
* Expect lower gain due to NF optimization
* Balanced topology is preferred, for stability and $S_{11}$ reasons, and if no other constrains are dictated by requirements
  * Match the input to $\boldsymbol{G}_{opt}$ for min NF and the output to $S_{22}^{*}$, using manufacturer's S-param
  * Verify unconditional stability over a wide BW

# Example of Balanced Ku-Band LNA

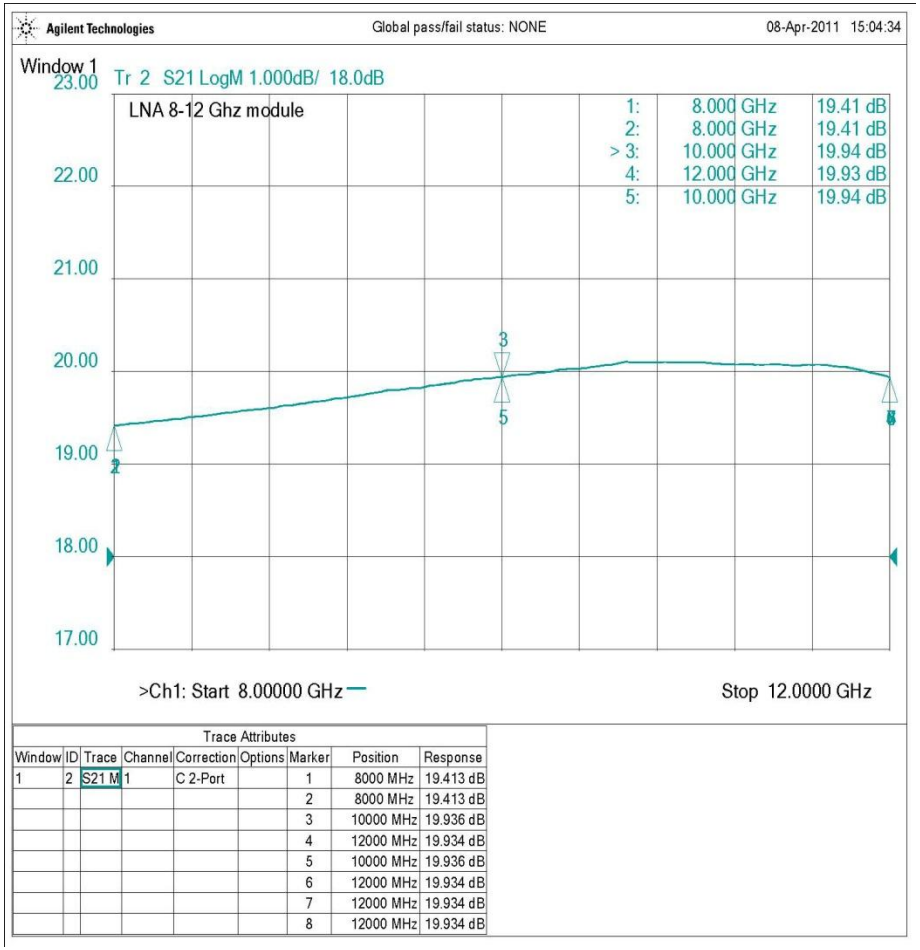


# Balanced Ku Band LNA
# - performance -

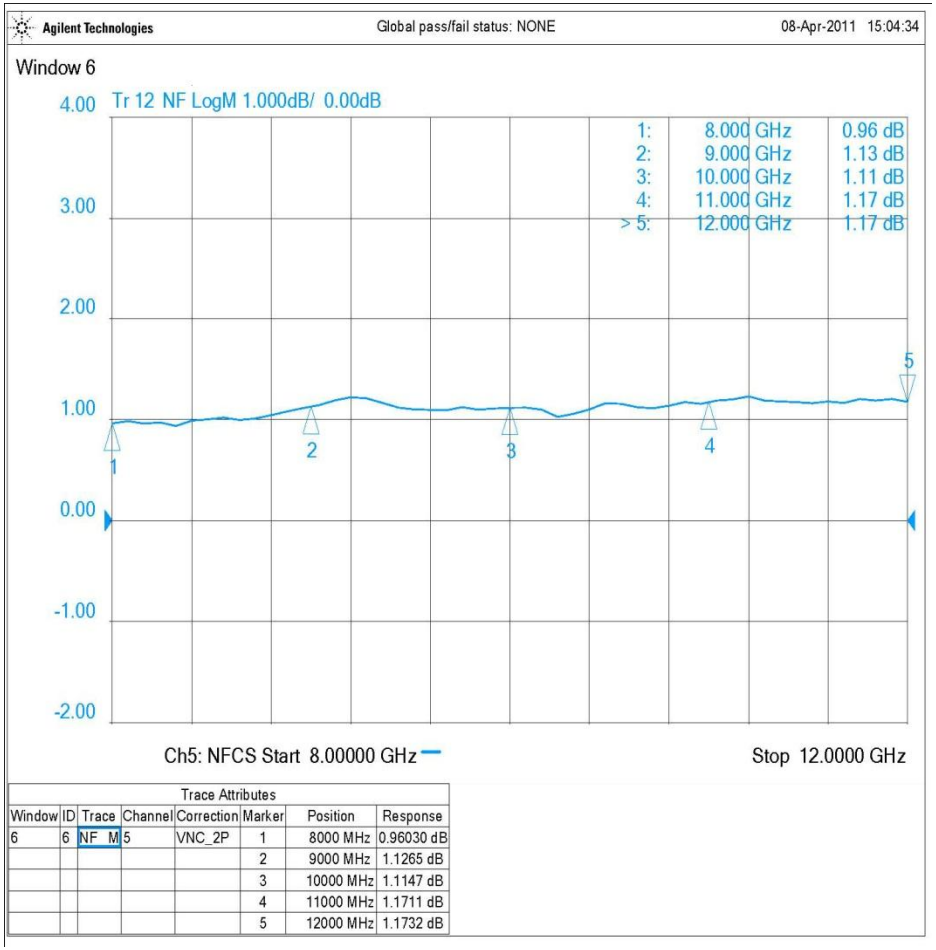


# Single Ended X Band LNA - performance -




| Trace Attributes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Window | ID | Trace | Channel | Correction | Options | Marker | Position | Response |
| 1 | 2 | S21 M | 1 | C 2-Port | | 1 | 8000 MHz | 19.413 dB |
| | | | | | | 2 | 8000 MHz | 19.413 dB |
| | | | | | | 3 | 10000 MHz | 19.936 dB |
| | | | | | | 4 | 12000 MHz | 19.934 dB |
| | | | | | | 5 | 10000 MHz | 19.936 dB |
| | | | | | | 6 | 12000 MHz | 19.934 dB |
| | | | | | | 7 | 12000 MHz | 19.934 dB |
| | | | | | | 8 | 12000 MHz | 19.934 dB |



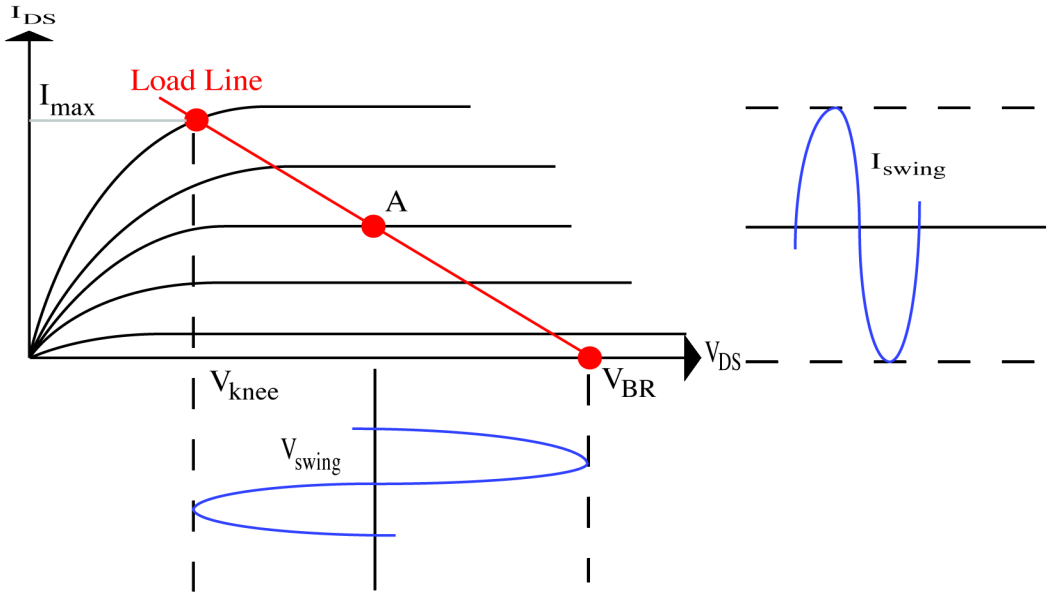

| Trace Attributes | | | | | | | |
|---|---|---|---|---|---|---|---|
| Window | ID | Trace | Channel | Correction | Marker | Position | Response |
| 6 | 6 | NF M | 5 | VNC_2P | 1 | 8000 MHz | 0.96030 dB |
| | | | | | 2 | 9000 MHz | 1.1265 dB |
| | | | | | 3 | 10000 MHz | 1.1147 dB |
| | | | | | 4 | 11000 MHz | 1.1711 dB |
| | | | | | 5 | 12000 MHz | 1.1732 dB |

# GaN Power Amplifiers

## Why GaN ?

- Has higher carrier mobility (than SiC)
- Has highest power density/mm gate

* Reliability verified and commercially available




$P_{out} = I_{max*}(V_{BR}-V_{knee})/8$

$= (V_{BR}-V_{knee})^2/(2*RL)$

thus:

$P_{out}$ is maximized if the operational

voltage is maximized!

**That's the key !**

* Other GaN Characteristics:
- high output impedance
- high efficiency
- high linearity

# Example of Power Amplifier Design

- Requirements over 9.9-10.7 GHz:
  - * Psat > 16W; PAE > 45%
  - * SSG > 11dB; Power Gain > 9dB
  - * VSWR < 1.5:1
  - * DC available: 32V at 1.4A
  - * Stable at any frequency
- Select device: TGF2023-02
- Note: it consists of two 6W unit GaN cells, 1.25mm gate
- Topology: Balanced
- Use S2p & Large Signal Device Model
- Use Gate and Drain pads S4p

# Example of Power Amplifier Design – cont.

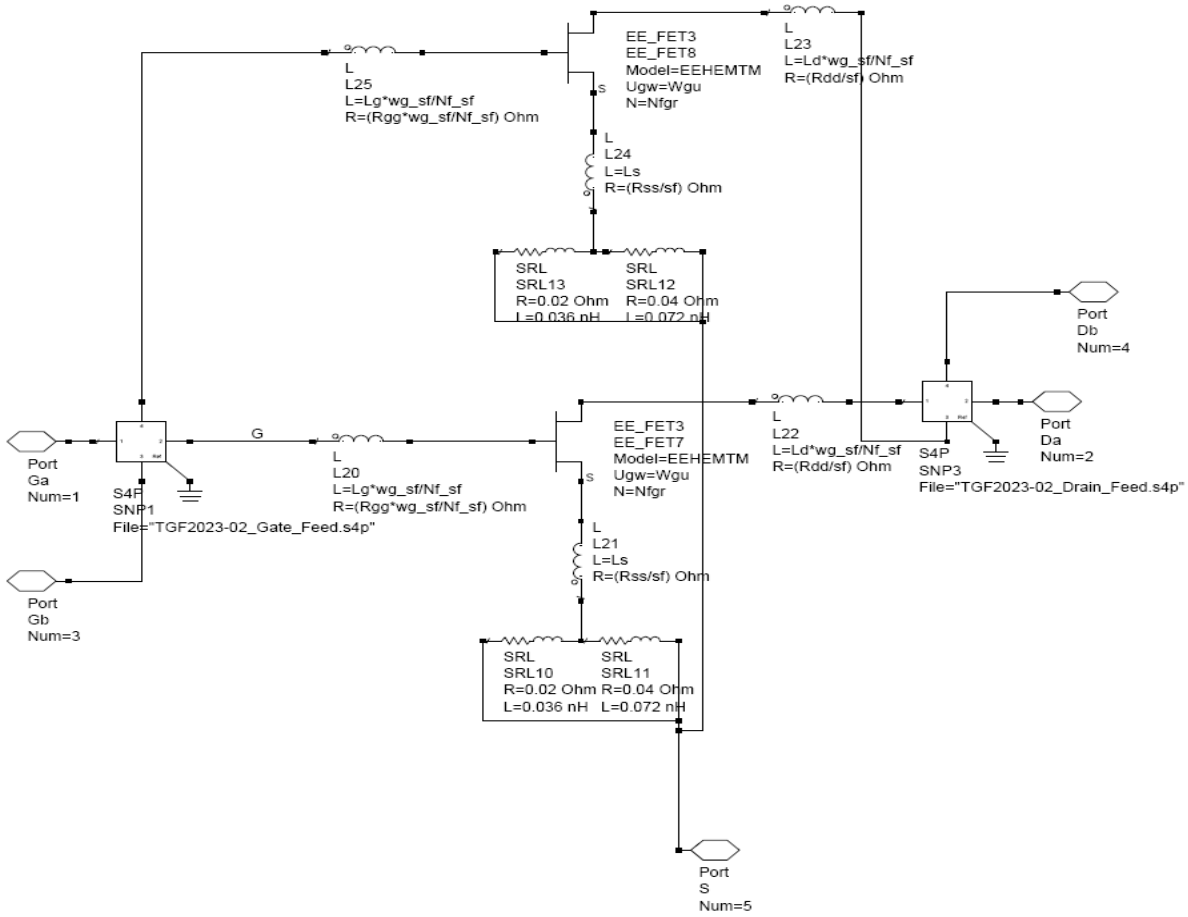
**Design Sequence:**

- Create transistor circuit model: filename TGF2023-02_32V250A
- Add Input and Output matching circuits to the above: filename TGF2023-02_single
- Create the balanced amplifier: filename TGF2023-02_bal

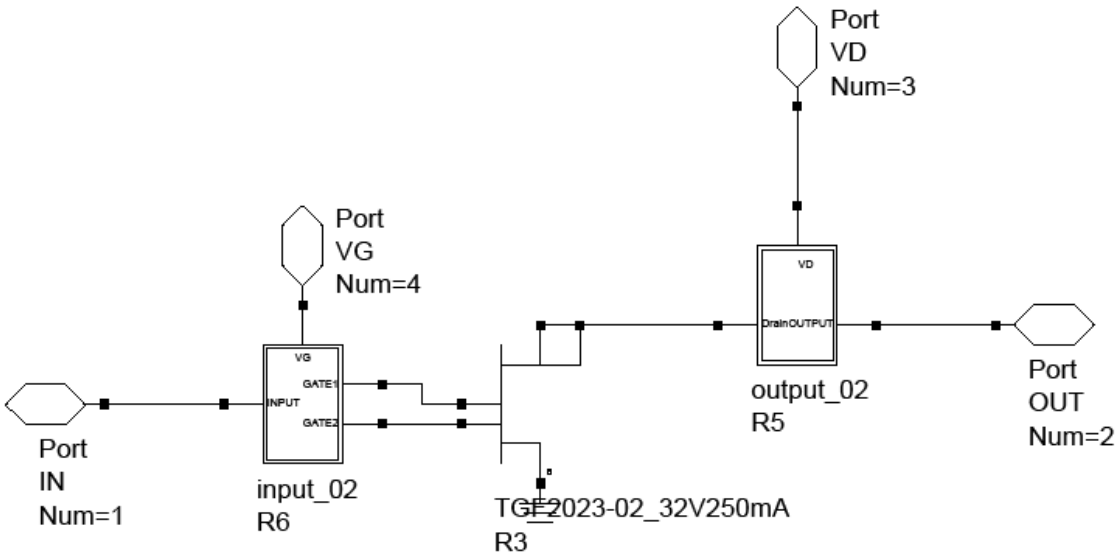
**Simulation:**

1. Derive $\Gamma_s$ using S-param for the Input circuit for, small signal (SS) gain
2. Verify $S_{11}^*$ of FET matches $\Gamma_s$ , and tune the input matching network if necessary; verify stability.
3. Using the load pull method derive $\Gamma_{opt}$ vs. freq for optimum Pout and PAE ,
4. Derive $\Gamma_L$ by looking at the output matching network,
5. Verify that $\Gamma_{opt}$ matches $\Gamma_L$ by using the Smith Chart in SS simulation and tune output matching network if necessary. Verify stability.
6. Check compression, Pout and PAE using HB
7. Tune circuits for $\Gamma_s$ and $\Gamma_L$ for trade-offs in flatness, gain, Pout and PAE in SS,
8. Re-check steps 2 and 5

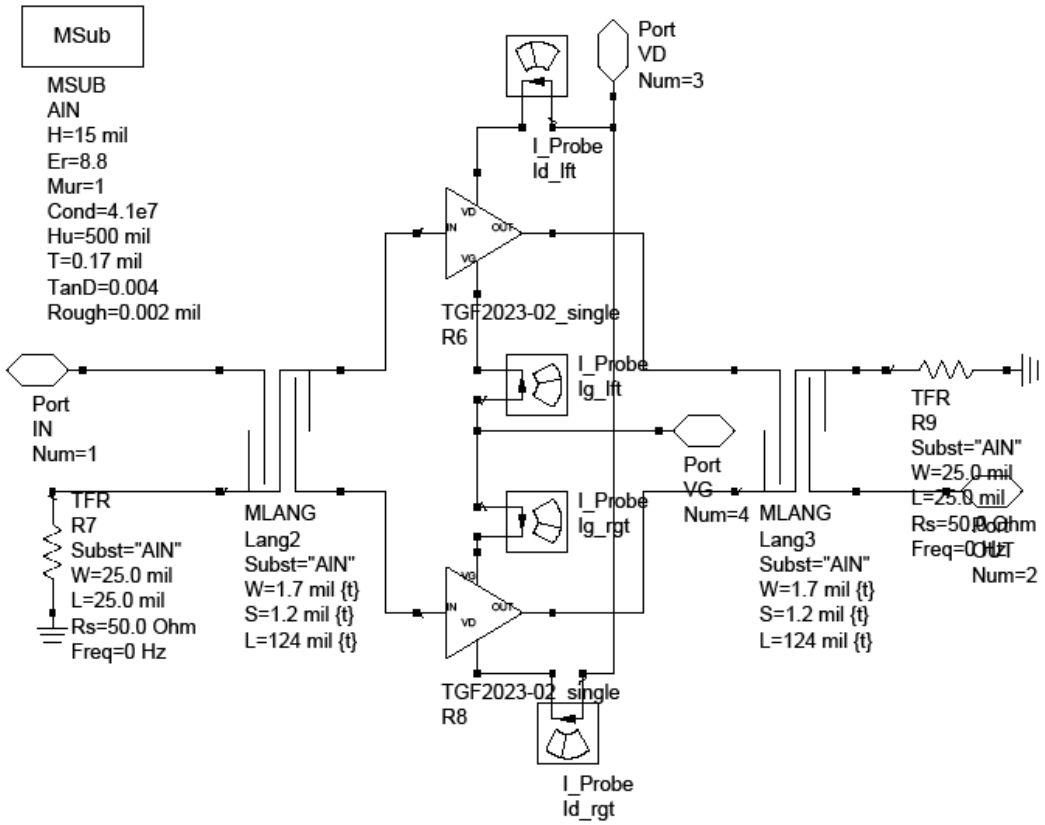
# Circuit schematic for TGF2023-02_32V250A



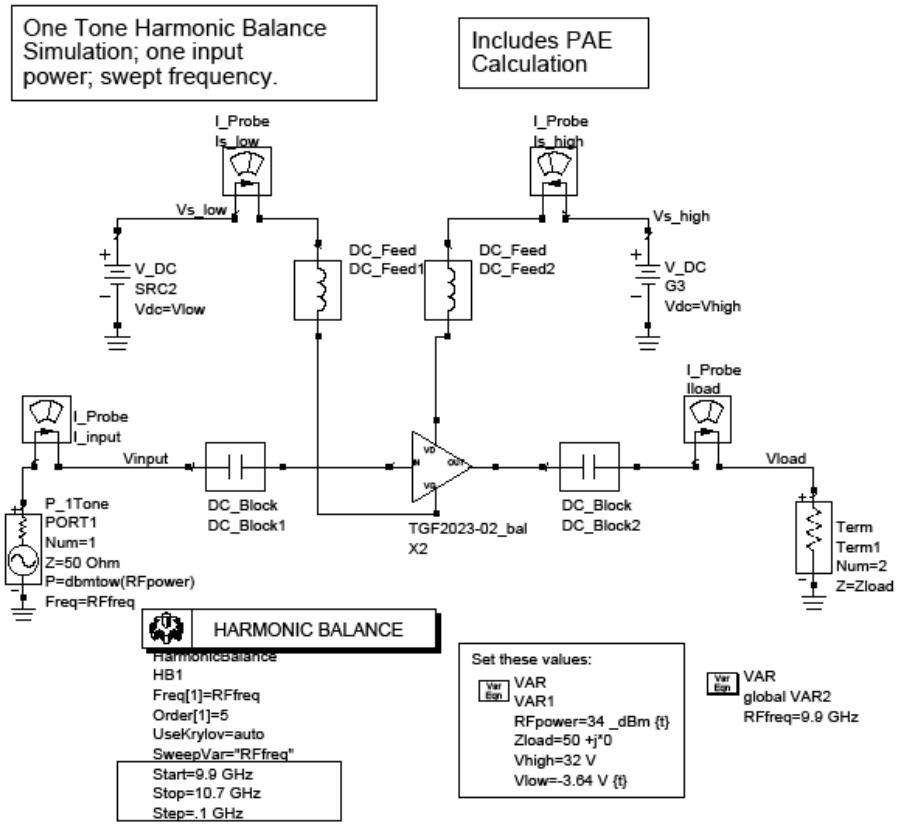
# Circuit schematic for TGF2023-02_single



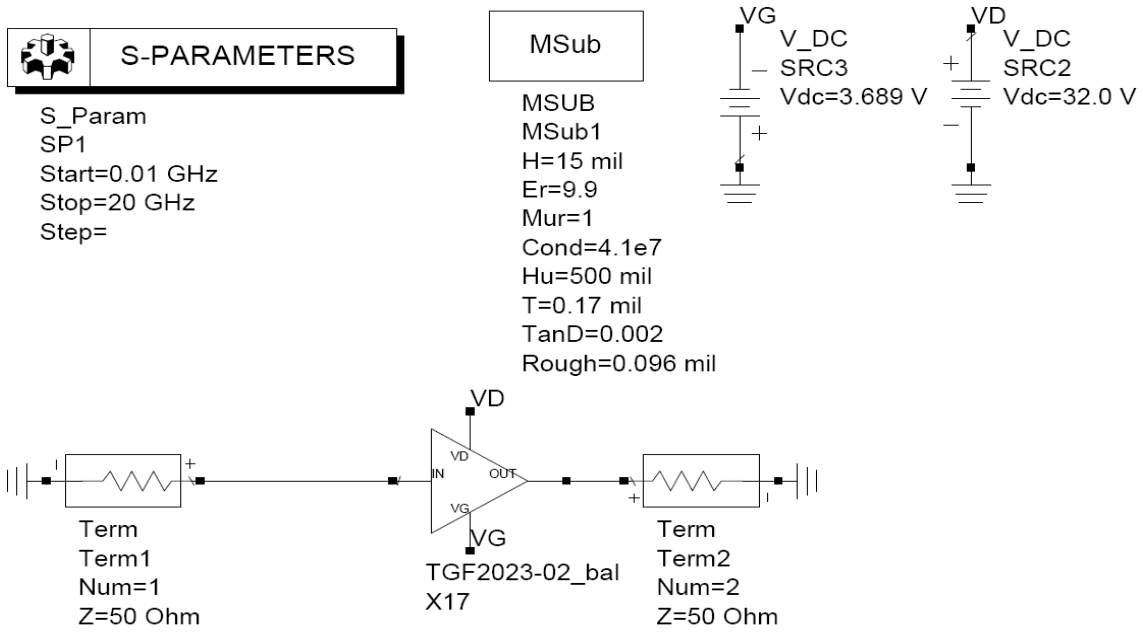
# Circuit schematic for TGF2023-02_bal



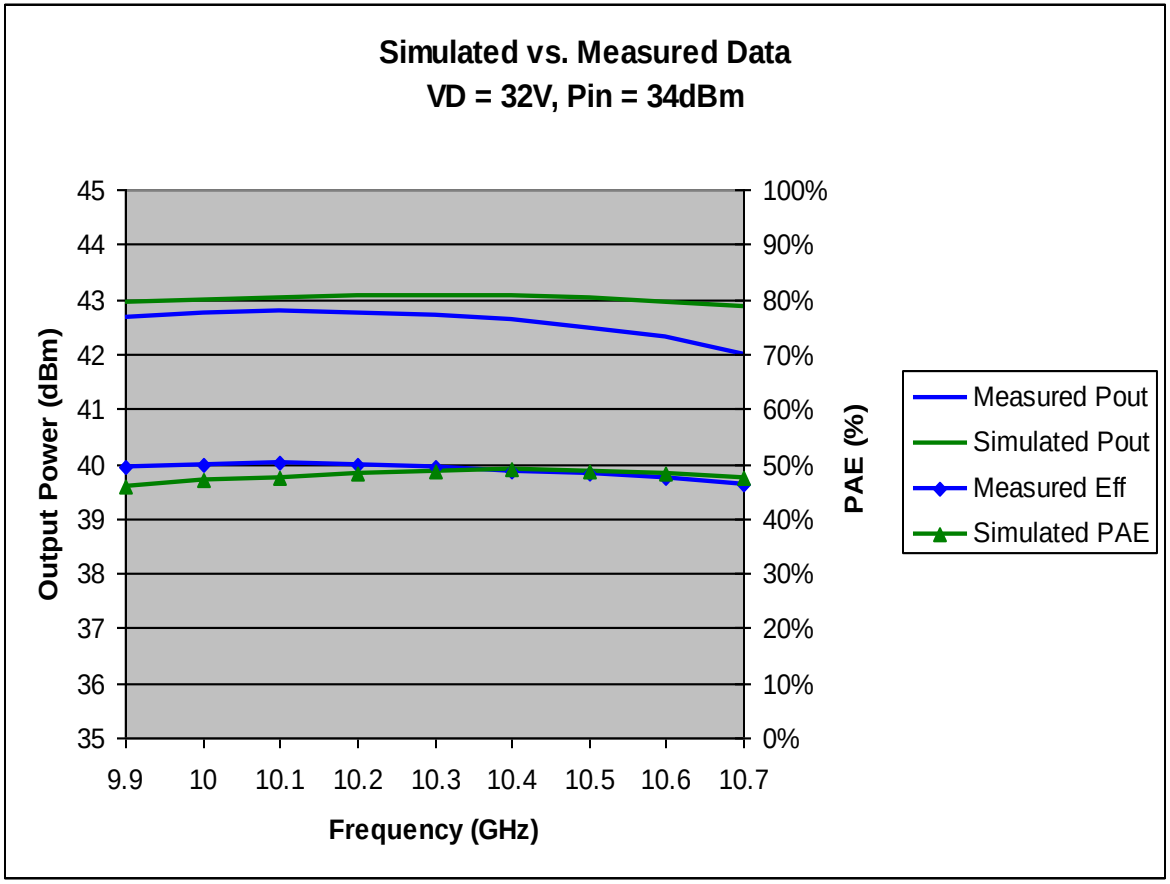
# Circuit schematic for HB simulation



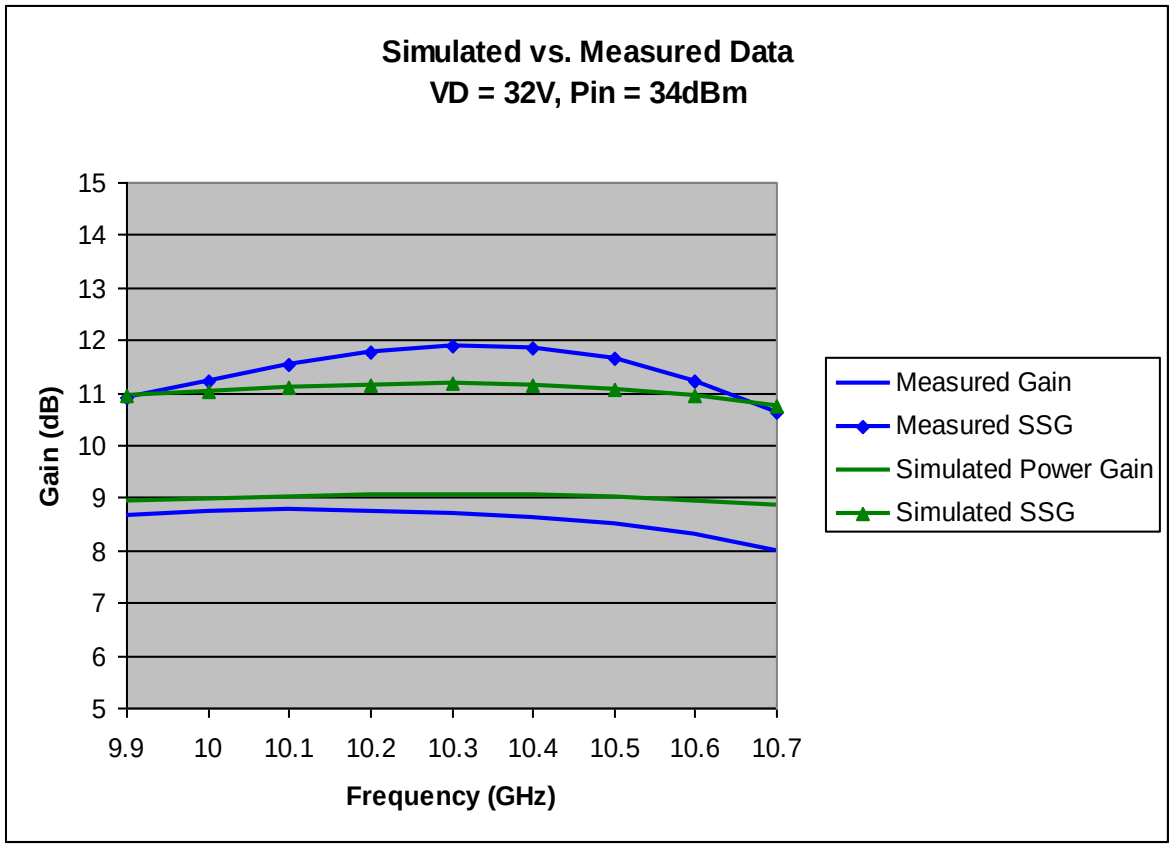
# Circuit schematic for Small Signal simulation



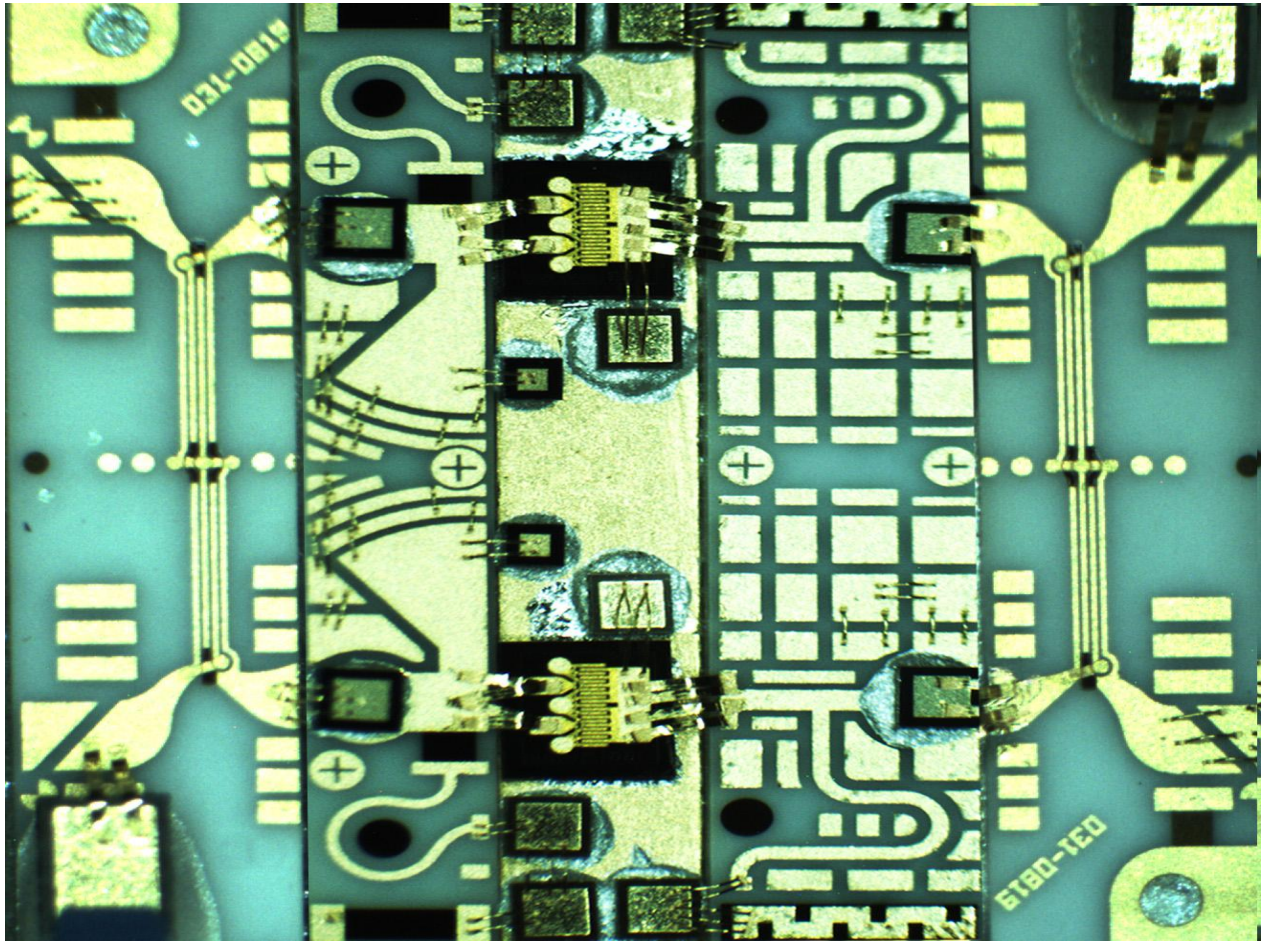
# GaN Module Simulation vs Measured Data



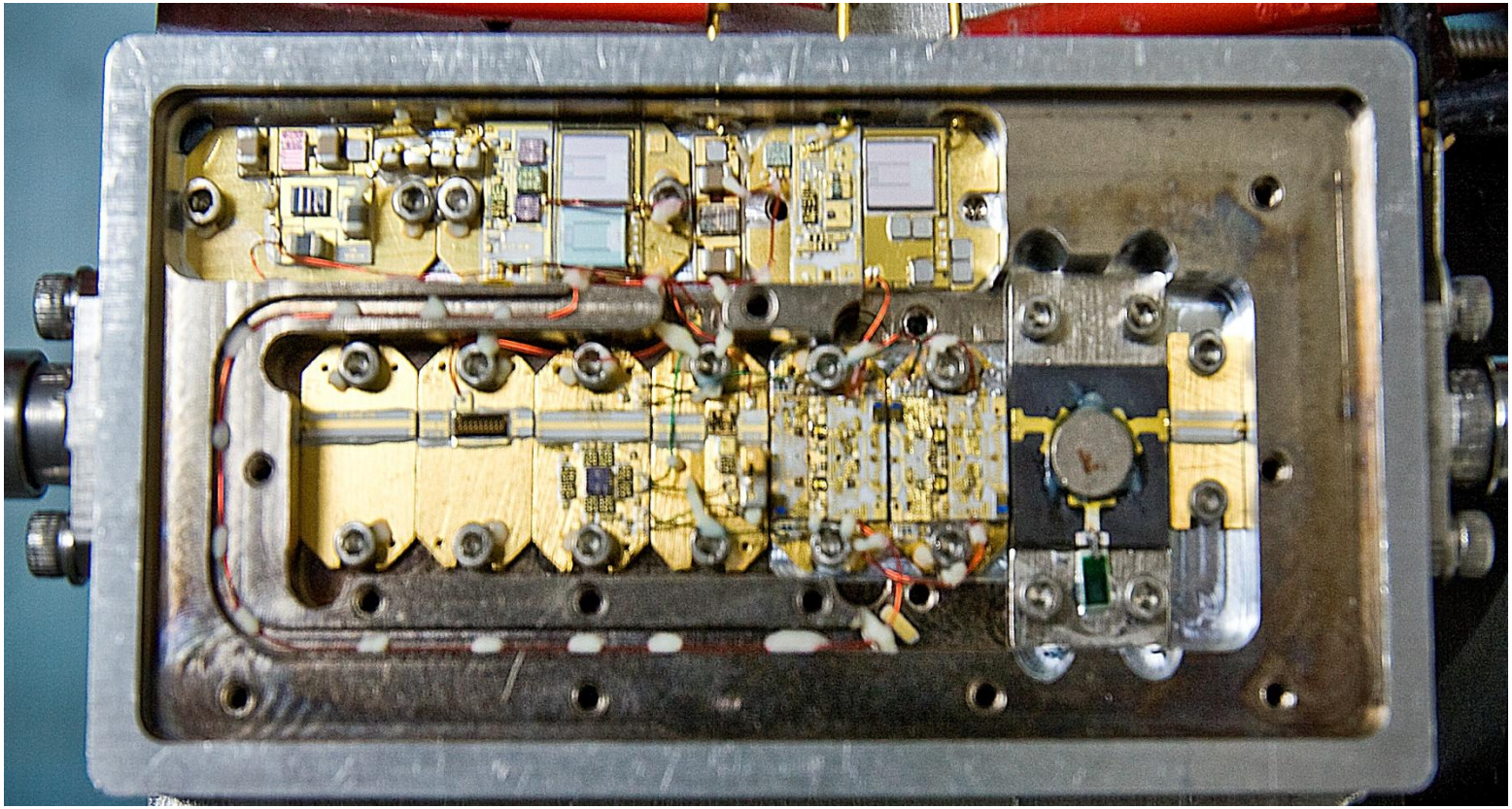
# GaN Module Simulation vs Measured Data



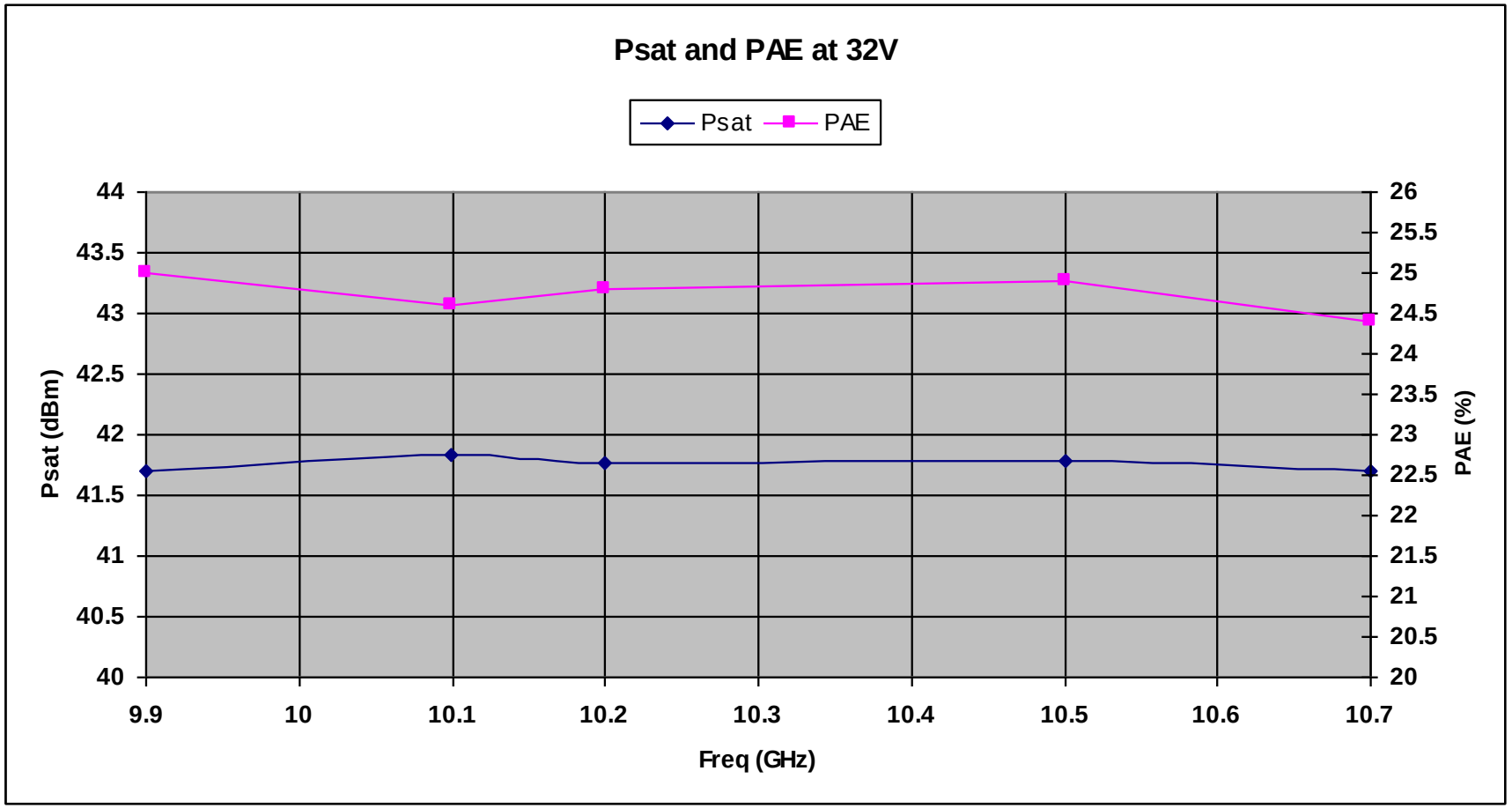
# GaN Module Image (.250x.250)



# Prototype X-Band PA with GaN modules

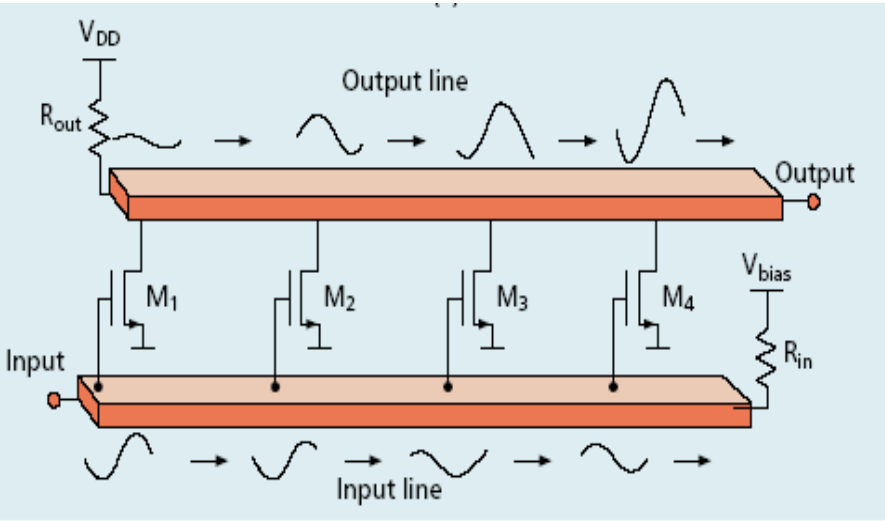


# Prototype PA Performance @ Pin=0dBm



# Distributed Amplifier (DA) - how it works -

- Amplification effect is dominated by the forward wave due to the FET characteristics, where each device adds power in phase at each tap point on the output line.
- The inherent attenuation in both the Gate and Drain lines forces the gain to reach maximum value given an optimum number of HEMTs in the design.

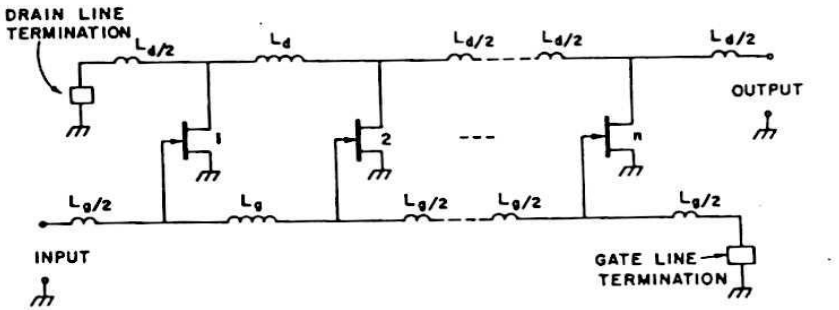


# *Distributed Amplifiers - benefits & limitations -*

- Eliminates gain and BW trade-offs
- Less sensitive to device & ckt. variations
- Achieves flat frequency response, <u>though</u> the upper limit is dictated by:
  - the FETs $f_c$ (solution: adopt non-uniform DA design topology)
  - the cutoff of the Gate line (solution: make Cgs smaller)
  - Drain line atten and loading (choose cascode FET approach)

# Conventional DA
## - BW & Power Limits -

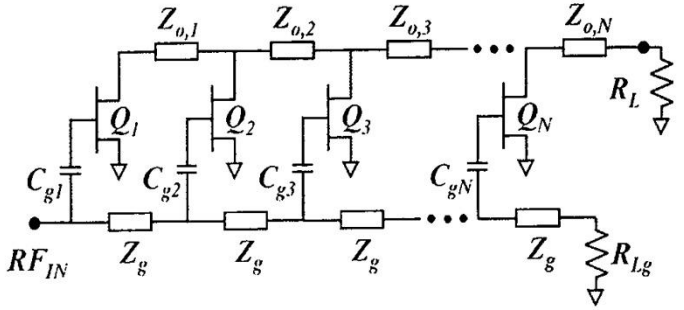
- Schematic (aka Uniform Elements DA):




- Gate and Drain lines are lossy, frequency dependent and loaded, ie both lines have a cutoff freq, and power down the lines is attenuated,
- Output power is also suffering (by 50%) because of the drain line termination,
- The load line for each cell is different due to unmatched capacitances thus power is not maximized in each cell, and not delivered to the output,
- In addition, the power vs frequency is higher or lower from each cell, ie the DA can not achieve a flat output power over the entire BW

# Non-Uniform DA

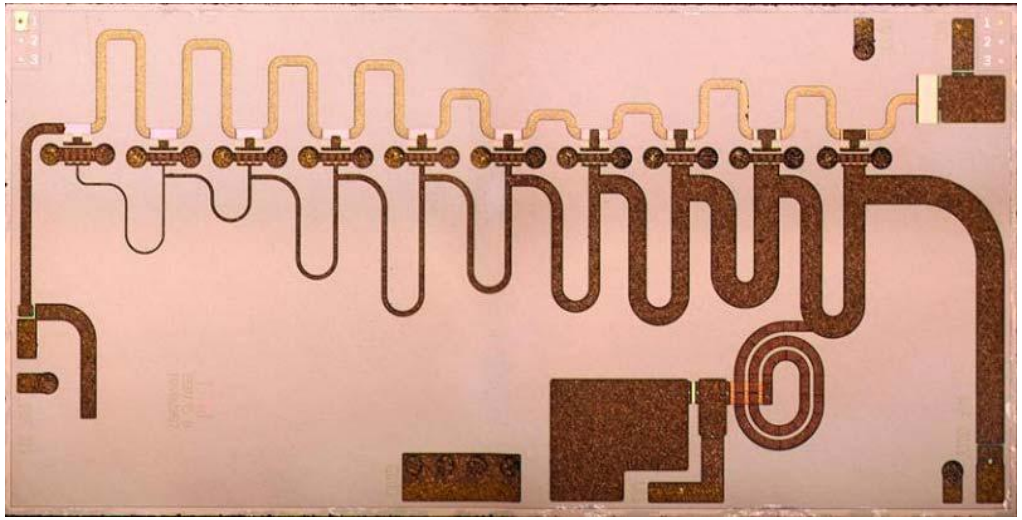
- Schematic




- Increase fc by adding capacitors in series w/ each gate
- Taper drain TL from cell to cell for optimum loads.
- Impedance tapering is to force the backward travelling current to zero. In addition, adjust each drain TL length to add the forward currents in phase
- Absorb each FET output capacitance into the TL

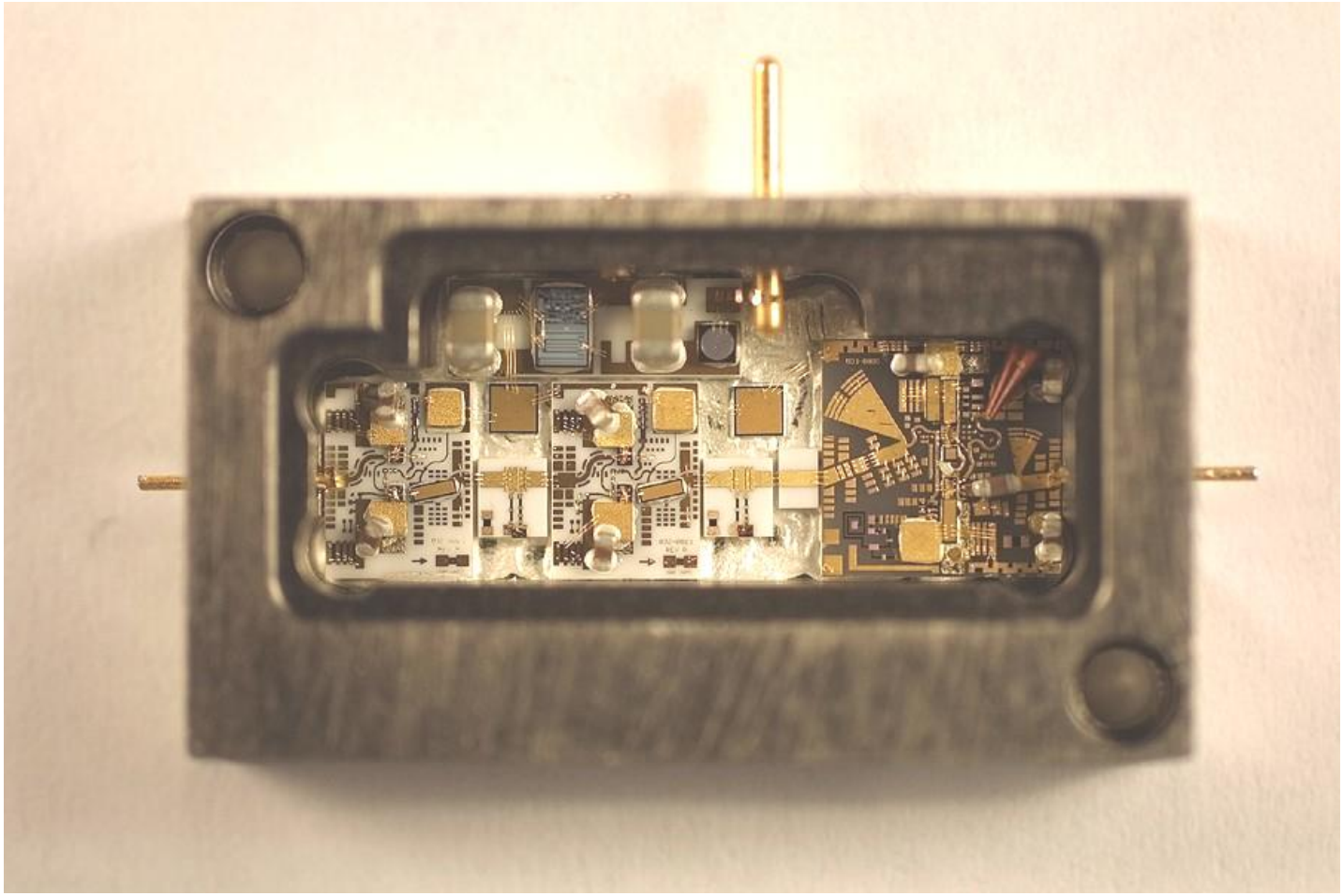
# Non-Uniform MMIC DA - example -

- Triquint TGA2570 : 1.5-17 GHz, 8W output GaN MMIC, size: 2.27x5.54x.10 mm



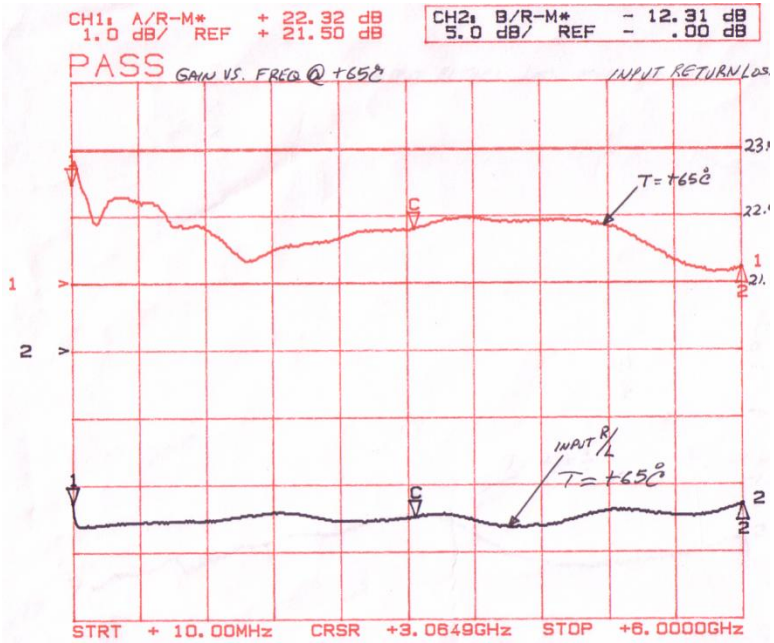
# Uniform 0.05-6 GHz DA

## (1.0x0.5x0.16 inches)

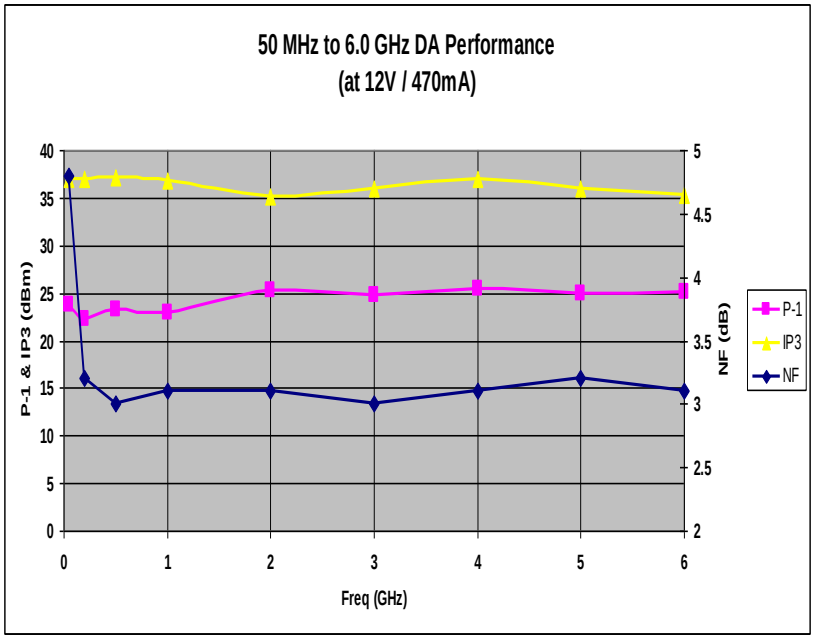


# 0.05-6 GHz DA
## - RF performance -

- Gain & VSWR




- NF & Power



# Low Phase Noise Amp's

- Facts and Theory:

  - Phase noise derives from adding white noise to the RF spectrum around the carrier.

  - Amplifier phase noise is of 1/f type, referred to as flicker noise and it takes place at the microscopic scale

  - By definition, phase noise is the power spectral density of the signal phase fluctuations around the fundamental carrier (PM fluctuations)

# *Low Phase Noise Amp's - design -*

- Experimentation is crucial
- No dedicated CAD simulation exists since the models are developed empirically and not fully supported by experiments
- Accurate measurements are mandatory
- Phase noise designs require a comprehensive understanding of the active device

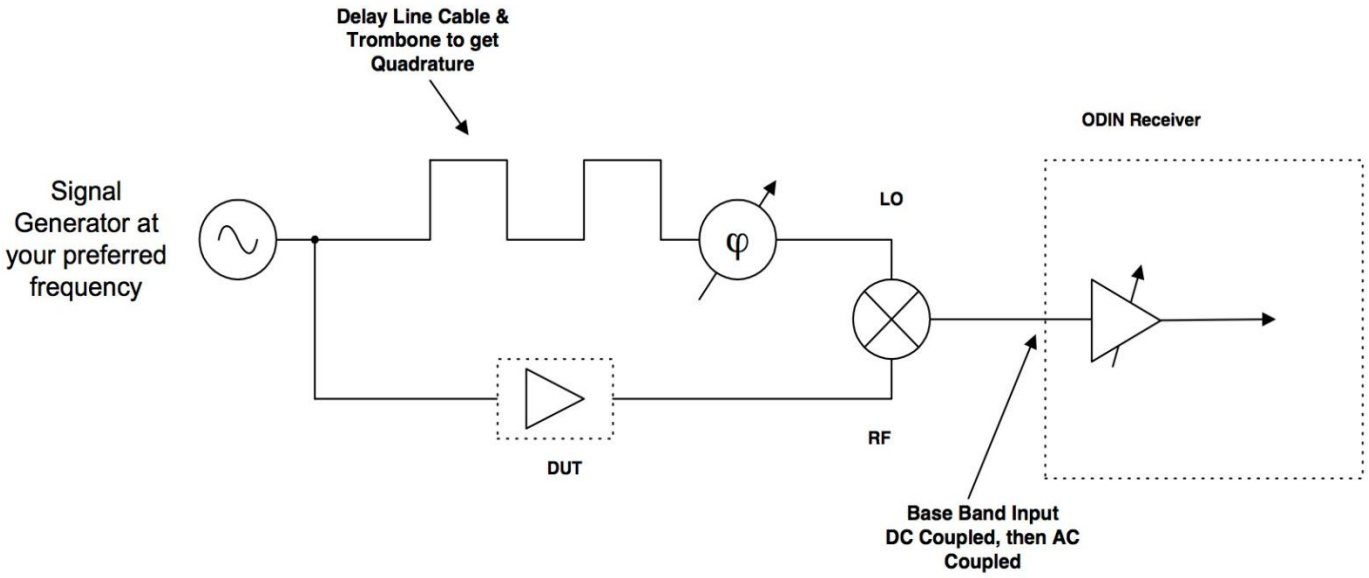
# *Measuring techniques*

- Residual Phase Noise single channel Measurements for amplifiers up to

  -155dBc/Hz at 1kHz (at X-Band)
- Dual channel Cross Correlation Phase Noise method for amplifiers with a phase noise expectation beyond the above number

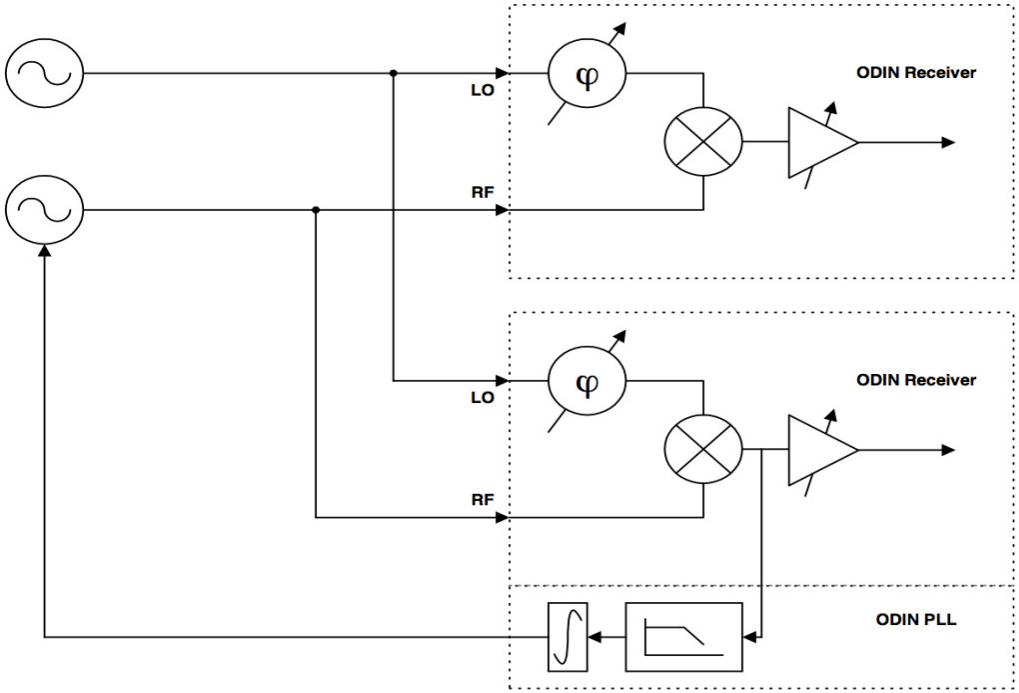
# Single channel set-up

- Using one ODIN Rcvr form PSI

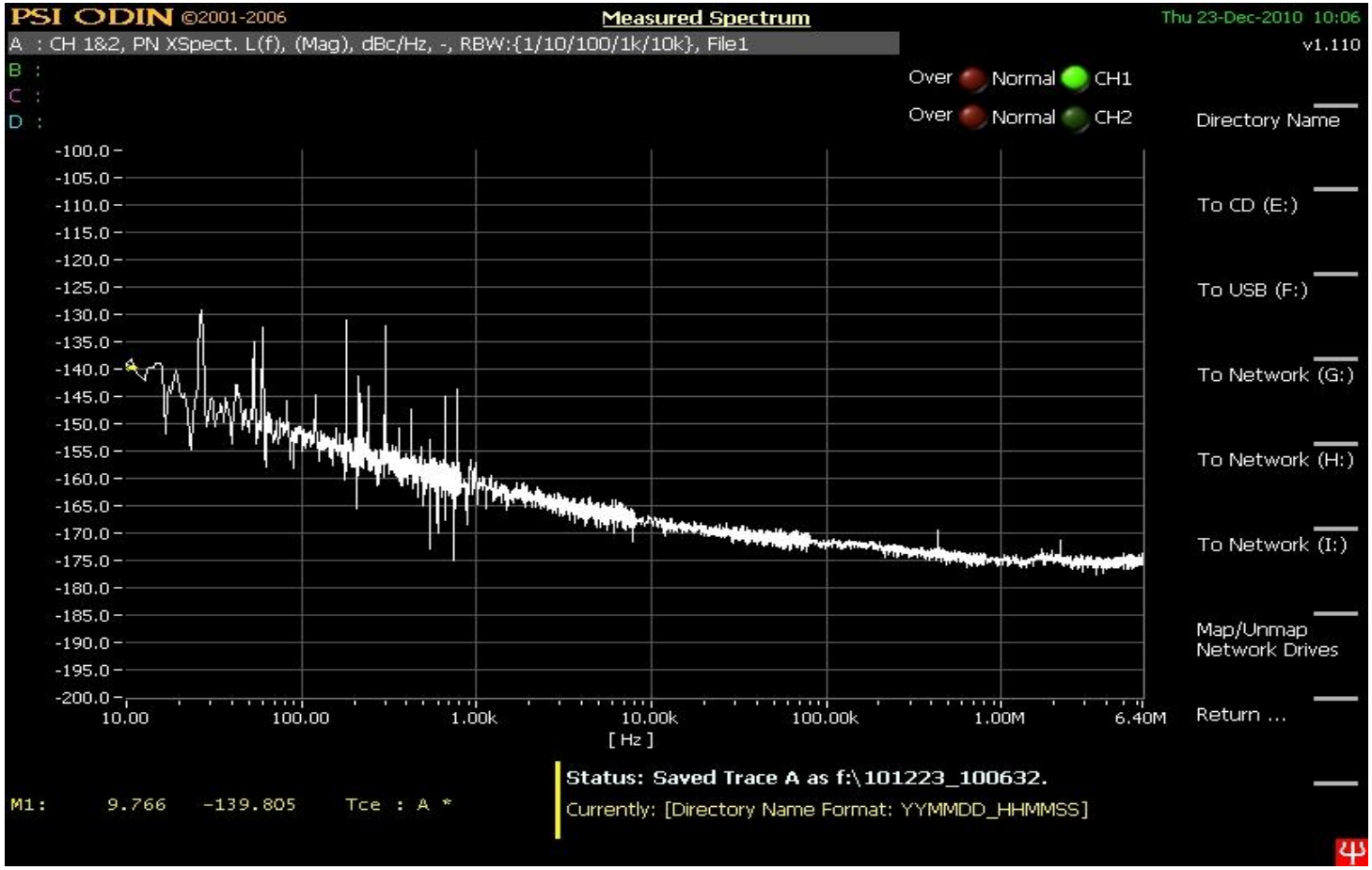


# Dual channel set-up

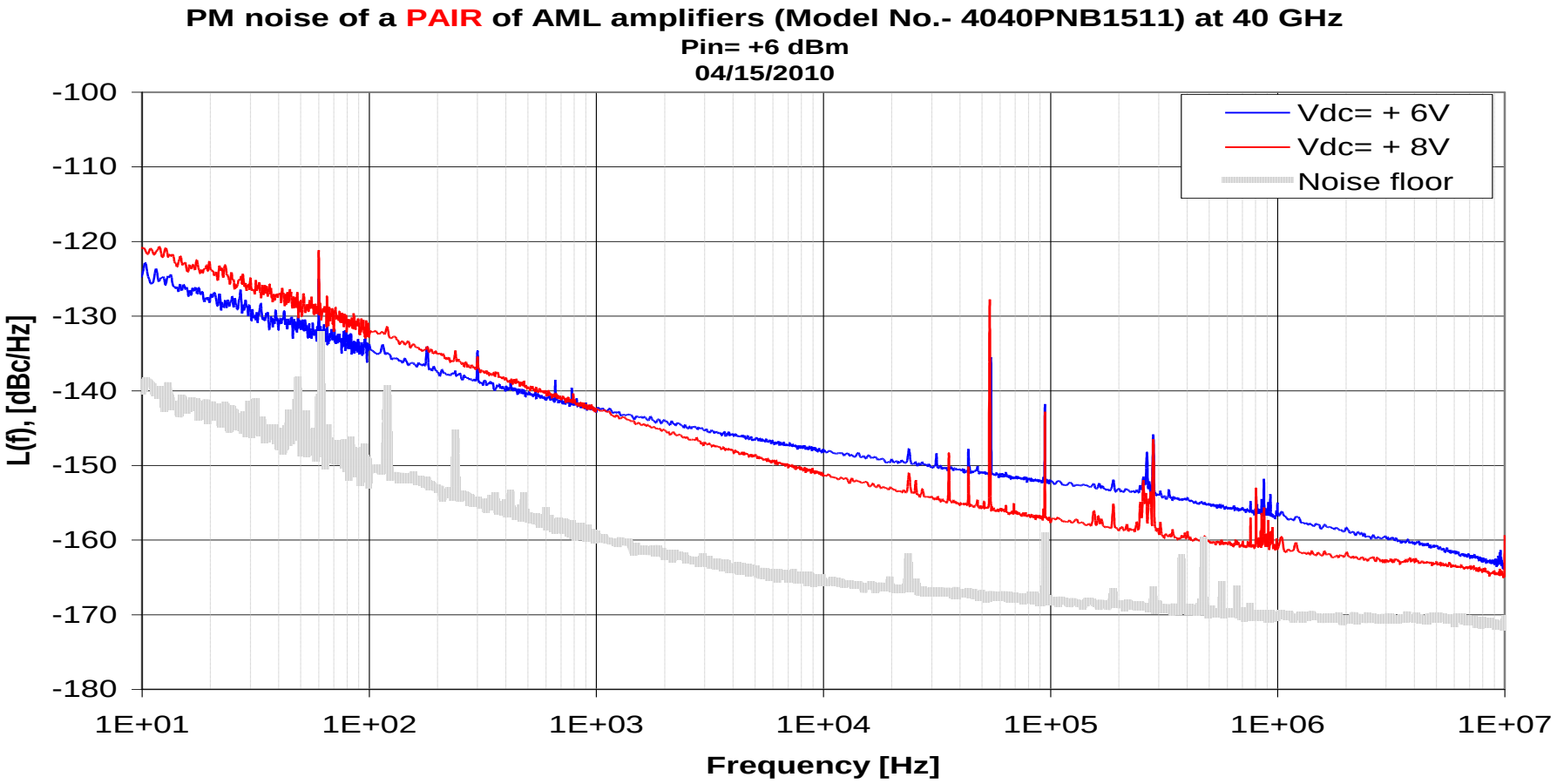
- Using two ODIN Rcvrs from PSI



# X-Band: 163 dBc/Hz at 1 kHz



# 40GHz: 142 dBc/Hz at 1kHz



# AML Reference Data

- Practiced all designs and
- Maintains reference data on 2400 amplifiers at

www.amlj.com