Using S-Parameter and Load Pull Measurements to Validate Transistor Large-Signal Fundamental and Harmonic Tuning Performance

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Outline & Overview

• Intro
• Load Pull Test Setup and Devices Tested
• Small-Signal Comparisons: VNA vs. Load Pull
• VNA vs. Load Pull Compression at 50Ω
• Fundamental TOI Tuning for Po, PAE, and TOI
• Harmonic Load Pull (HLP) TOI tuning results
• Conclusions
• References
Introduction

• Harmonic Load Pull improves PAE.
  – Linearity effects are now investigated.

• Accuracy of a load pull system needs verification.
  – Delta-Gt method for Load, Source, & Harmonic Tuners.
  – Compare small-signal ANA measurements.
  – Power sweep ANA vs. 50Ω Load Pull compression.
  – CAE linear and non-linear model comparisons.
    • Load Pull results quantify Non-Linear model sims.
The Triplexer S-Parameters are created by measuring each signal path. Tuners are characterized at 2.45GHz, 4.9GHz and 7.35 GHz. S-Parameter blocks <S> accounted for the DUT Probes. Short Low Loss cables connect Cascade Probes.
2.45 GHz Triplexer Characteristics

Insertion Loss: 0.235 dB at $f_o$, 0.248 dB at $2f_o$, and 0.196 at $3f_o$.
Return Loss: 19.77 dB at $f_o$, 25.9 dB at $2f_o$, and 14.97 dB at $3f_o$. 
**Delta–Gt Error Check**

**HBT Delta-Gt Measurement**

<table>
<thead>
<tr>
<th>Phase (degrees)</th>
<th>Mag (lin)</th>
<th>Gt (dB)</th>
<th>Gt (s) (dB)</th>
<th>Delta-Gt (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-179.82</td>
<td>0.838</td>
<td>-5.188</td>
<td>-5.102</td>
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<td>-6.061</td>
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<td>-14.66</td>
<td>0.031</td>
<td>-0.126</td>
<td>-0.025</td>
<td>-0.101</td>
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<td>-4.64</td>
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<td>52.49</td>
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<td>-4.947</td>
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<td>180.18</td>
<td>0.838</td>
<td>-5.188</td>
<td>-5.102</td>
<td>-0.086</td>
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**pHEMT Delta-Gt Measurement**

<table>
<thead>
<tr>
<th>Phase (degrees)</th>
<th>Mag (lin)</th>
<th>Gt (dB)</th>
<th>Gt (s) (dB)</th>
<th>Delta-Gt (dB)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.852</td>
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<td>-5.742</td>
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<td>-0.596</td>
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<td>7.10</td>
<td>0.282</td>
<td>-0.647</td>
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<td>51.57</td>
<td>0.817</td>
<td>-5.463</td>
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<td>88.17</td>
<td>0.824</td>
<td>-5.615</td>
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<td>91.43</td>
<td>0.032</td>
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<td>0.000</td>
<td>-0.211</td>
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<td>96.37</td>
<td>0.412</td>
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<td>-0.430</td>
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<td>129.54</td>
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<td>182.48</td>
<td>0.852</td>
<td>-5.746</td>
<td>-5.742</td>
<td>-0.004</td>
</tr>
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</table>

- Post-calibration Delta Gt check verifies accuracy of Load Pull System S-Parameters.  
  “PA Load Pull Error Limits using Delta G_t Contours,” UCSD PA Workshop, 2003  
- < 1dB is a minimum accuracy for a Harmonic Load Pull System, 0.5dB the goal.  
- Delta-Gt should be run over all gamma points and frequencies during off-shift times.  
- A Delta Gt setup at each of the harmonic paths is required for validation.  
  - The harmonic path is calibrated as the fundamental & verified.
Devices Tested

• GaAs pHEMT
  – Class AB: Vds=8V, Ids=165 mA (\sim 25\% \, I_{\text{max}})

• InGaP HBT
  – Class AB: Vce=3.3V, Ic=20 mA (\sim 25\% \, I_{\text{max}})
  – 2.5\, \text{kA/cm}^2 \text{ to } 15\, \text{kA/cm}^2 \, A_e=405\, \text{sq.um}

• Test Environment:
  – Power: P1dB and P-3dB of device.
    • Po, Gp, PAE, and TOI contours plot optimums & trades
    • Final power sweep from Linear to P+6dB saturation.
pHEMT Measured vs. Model S-Parameters

S11

Red: Measured
Blue: Modeled

S22

freq (1.750GHz to 8.750GHz)

S21

freq (1.750GHz to 8.750GHz)

S12

freq (1.750GHz to 8.750GHz)
pHEMT Small-Signal Load Conjugate Match

GL circles from S-Par. Meas.

Maury – Low power tune
pHEMT Large-Signal Source Pull

Source Pull at ~ P1dB

Gt: 14.76 dB
10.00 to 30.00 dB
Mag: 0.83 lin
-1.00 to 0.00 lin
Pout: 27.76 dBm
-20.00 to 40.00 dBm
Eff: 37.88 %
0.00 to 100.00 %
Ip3: 29.66 dBm
0.00 to 50.00 dBm
Marker: Phase = 159.02 degrees

LS Model Sim. at ~ P1dB

Γs=0.83<159.25°

Maximum Power-Added Efficiency, %
38.00

Maximum Power Delivered, dBm
28.46

Maximum Transducer Power Gain, dB
15.459

TOI, dBm
30.746
pHEMT Large-Signal Load Pull

\[ \Gamma_L = 0.486 < 154.08° \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gt, dB</td>
<td>14.441</td>
</tr>
<tr>
<td>TOI, dBm</td>
<td>34.579</td>
</tr>
<tr>
<td>PAE, %</td>
<td>31.77</td>
</tr>
<tr>
<td>Power Delivered (dBm)</td>
<td>27.44</td>
</tr>
<tr>
<td>Ip3:</td>
<td>35.19 dBm</td>
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<tr>
<td>0.00 to 50.00 dBm</td>
<td></td>
</tr>
<tr>
<td>Gt:</td>
<td>14.27 dB</td>
</tr>
<tr>
<td>0.00 to 30.00 dB</td>
<td></td>
</tr>
<tr>
<td>Pout:</td>
<td>27.27 dBm</td>
</tr>
<tr>
<td>20.00 to 40.00 dBm</td>
<td></td>
</tr>
<tr>
<td>Mag:</td>
<td>0.43 lin</td>
</tr>
<tr>
<td>0.00 to 1.00 lin</td>
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</tr>
<tr>
<td>Eff:</td>
<td>33.97 %</td>
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<tr>
<td>0.00 to 100.00 %</td>
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<tr>
<td>Marker: Phase:</td>
<td>153.91 degrees</td>
</tr>
</tbody>
</table>

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Modelithics
pHEMT 2\textsuperscript{nd} Harmonic Load Tuning

\[ IP3 \text{ vs. } 2\phi \text{ phase} \]

\[ TP1 \text{ (dBm)} \]

\[ \text{Phase of } 2\phi \text{ Termination (degrees)} \]

\[ \text{Phi}_\rho = 10,000 \]
\[ \text{plot} \text{ vs } (\text{TOI}, \text{Phi}_\rho) = 34.952 \]
\[ \text{Mag}_\rho = 0.80000 \]

\[ \text{Phi}_\rho = 160,000 \]
\[ \text{plot} \text{ vs } (\text{TOI}, \text{Phi}_\rho) = 36.704 \]
\[ \text{Mag}_\rho = 0.80000 \]
## pHEMT 2nd Harmonic Load Tuning

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma(2fo)$</th>
<th>Gain @ $\Gamma(2fo)$</th>
<th>$\text{Pout} @ \Gamma(2fo)$</th>
<th>$\text{PAE} @ \Gamma(2fo)$</th>
<th>TOI @ $\Gamma(2fo)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurements</strong></td>
<td>0.786&lt;4.77°</td>
<td>14.33 dB</td>
<td>27.33 dBm</td>
<td>34.65 %</td>
<td>35.483 dB</td>
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<tr>
<td><strong>Simulations</strong></td>
<td>0.8&lt;10°</td>
<td>14.526 dB</td>
<td>27.526 dBm</td>
<td>32.53 %</td>
<td>34.952 dB</td>
</tr>
</tbody>
</table>
pHEMT Second Harmonic Plot with PAE, TOI

TOI and PAE vs. 2fo Tuning

- TOI (dBm)
- PAE (%)

Phase of 2fo Termination (degrees)
pHEMT Summary & Conclusions

• Reasonable S–Parameter Model Match
  – ADS EE–HEMT extraction was accurate.
• Large Signal Source and Load Pull errors
  – 0.5~0.75dB range also appear reasonable.
• Modeled Power Sweep Po and IP3 are optimistic by up to 5dB at < P1dB.
• System verification means we should take the Load Pull Data as the reference.
  – Model appears accurate for the pHEMT
HBT Small-Signal S-Parameters

- S11
- S22
- S12
- S21

Red: Measured
Blue: Modeled

Freq: 1.750GHz to 15.75GHz
HBT Large-Signal Source Pull

Freq = 2.4500 GHz
Gamma_load: 0.0307 < -14.66
Gamma_load2: 0.0107 < -71.33
Gamma_source @ 0.8231 < 153.88

Gt = 15.338 dB
Pout = 6.338 dBm
Eff = 10.932 %
Ip3 = 16.724 dBm
I3 = -23.936 dBm

Eqn: \( \Gamma_{\text{source}} = 0.8231 < 153.88 \)

\[
\begin{align*}
\text{Gt, dB} & \quad \text{Delivered (dBm)} \\
16.088 & \quad 7.09
\end{align*}
\]

PAE, %

15.05

3rd-Order IMD, dBC

-2143

TOI, dBm

14.739
HBT TOI and PAE vs. 2fo Load Tuning

TOI and PAE vs. 2nd Harmonic Tuning Phase

- **PAE, %**
- **TOI, dBm**

Phase of 2fo Termination
HBT Summary

• Accurate S–Parameter model prediction.
  – Phase within 5°, magnitude within 0.05.
• Power and Gain predicted by <1 dB.
• TOI prediction is optimistic at < P1dB.
• 2fo tuning makes an impact for Class AB.
  – TOI increased 2 dB near open circuit Z.
Conclusions

• Characterization of Maury Harmonic Tuning using Triplexers needs Delta Gt system error validation runs.
  – Harmonic Delta Gt paths should be setup as the primary path fundamental, calibrated, and verified using the Delta Gt technique.

• TOI is a function of Harmonic Tuning
  – Results depend upon device technology.
  – Improvements are not as dramatic as PAE.
References


