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

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Outline & Overview

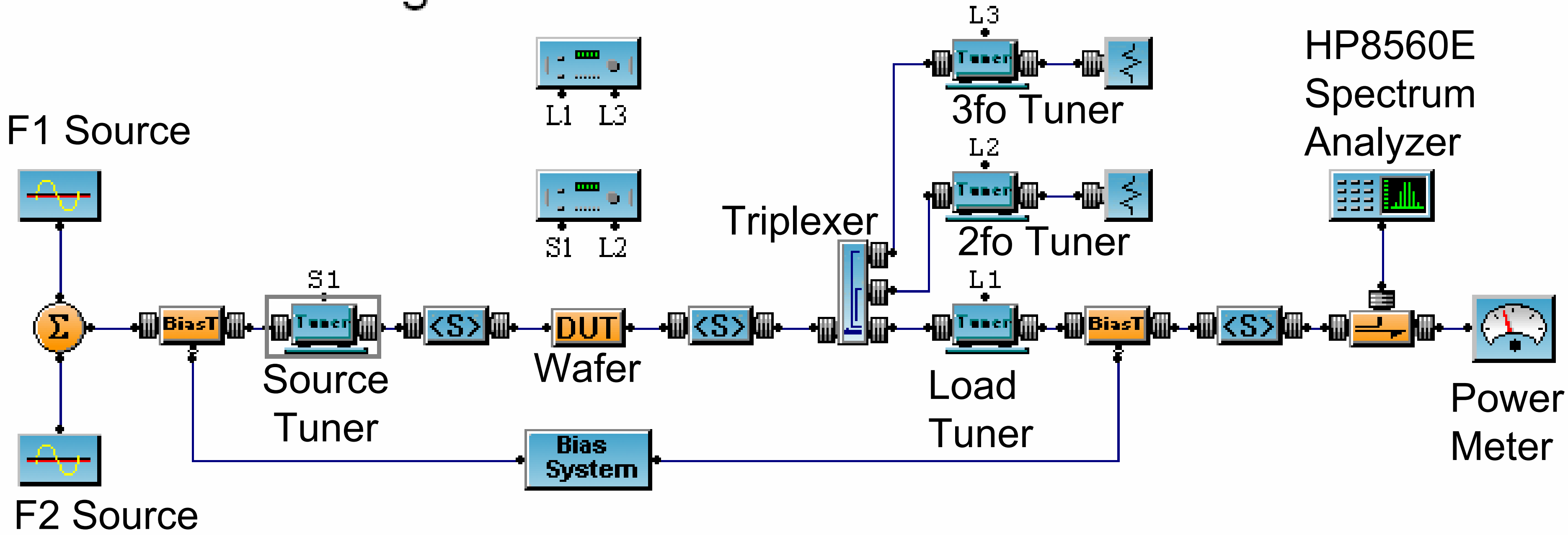
- Intro
- Load Pull Test Setup and Devices Tested
- Small-Signal Comparisons: VNA vs. Load Pull
- VNA vs. Load Pull Compression at 50Ω
- Fundamental TOI Tuning for Po, PAE, and TOI
- Harmonic Load Pull (HLP) TOI tuning results
- Conclusions
- References

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.

Maury Microwave ATS Bench Setup

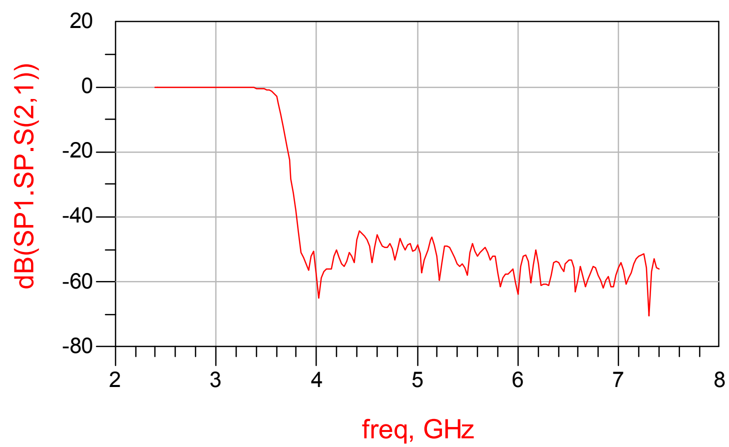
Power Block Diagram

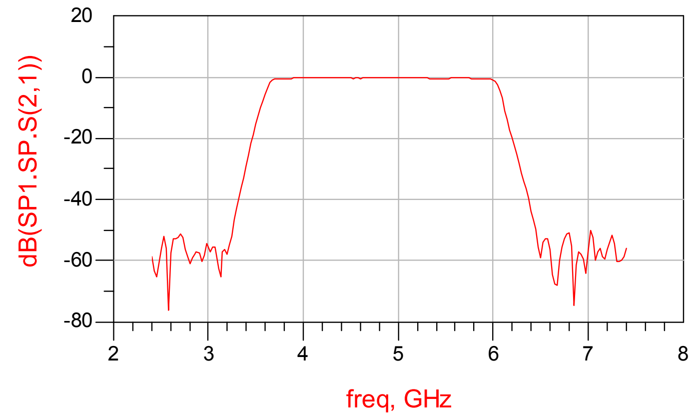


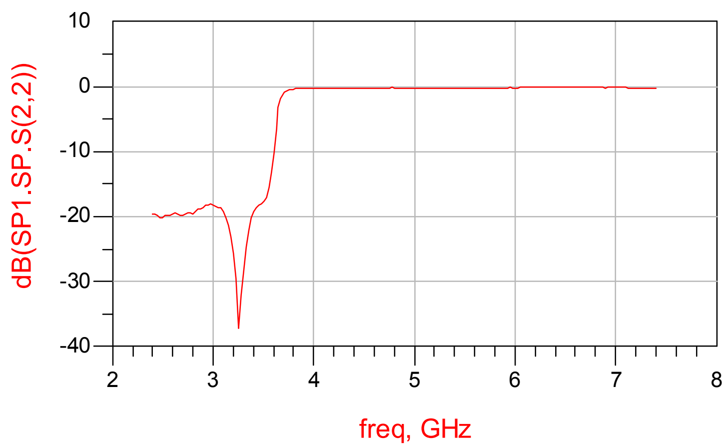
Label: Block Diagram for 2nd and 3rd Harmonic Load Tuning

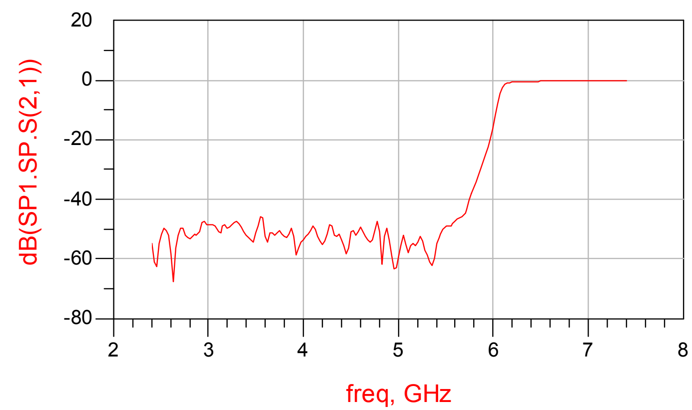
The Triplexer S-Parameters are created by measuring each signal path.
Tuners are characterized at 2.45GHz, 4.9GHz and 7.35 GHz.
S-Parameter blocks <S> accounted for the DUT Probes.
Short Low Loss cables connect Cascade Probes.

2.45 GHz Triplexer Characteristics









Insertion Loss: 0.235 dB at fo, 0.248 dB at 2fo, and 0.196 at 3fo.
Return Loss: 19.77 dB at fo, 25.9 dB at 2fo, and 14.97 dB at 3fo.

Delta-Gt Error Check

HBT Delta-Gt Measurement

Fixed Pull vs Phase
Load Pull at 2.4500 GHz
Label: Triquint_2.45GHz_DeltaGt_0dBm
ΓSource = 0.0299<-143.62
ΓLoad2 = 0.0108< -71.80

Phase degrees	Mag lin	Gt dB	Gt(s) dB	Delta_Gt dB
-179.82	0.838	-5.188	-5.102	-0.086
-175.24	0.352	-0.424	-0.523	0.099
-122.25	0.842	-6.009	-5.403	-0.606
-87.04	0.296	-0.691	-0.458	-0.234
-85.31	0.852	-6.399	-5.774	-0.625
-49.22	0.860	-6.760	-6.061	-0.699
-14.66	0.031	-0.126	-0.025	-0.101
-4.64	0.866	-6.346	-6.204	-0.141
3.01	0.423	-1.259	-0.950	-0.309
52.49	0.861	-5.611	-5.903	0.292
86.94	0.854	-5.056	-5.570	0.515
87.45	0.505	-1.050	-1.225	0.175
127.02	0.844	-4.947	-5.221	0.274
180.18	0.838	-5.188	-5.102	-0.086

pHEMT Delta-Gt Measurement

Fixed Pull vs Phase
Load Pull at 2.4500 GHz
Label: CM10_DeltaGt_aug19
ΓSource = 0.0179< 24.75
ΓLoad2 = 0.0563<-142.89

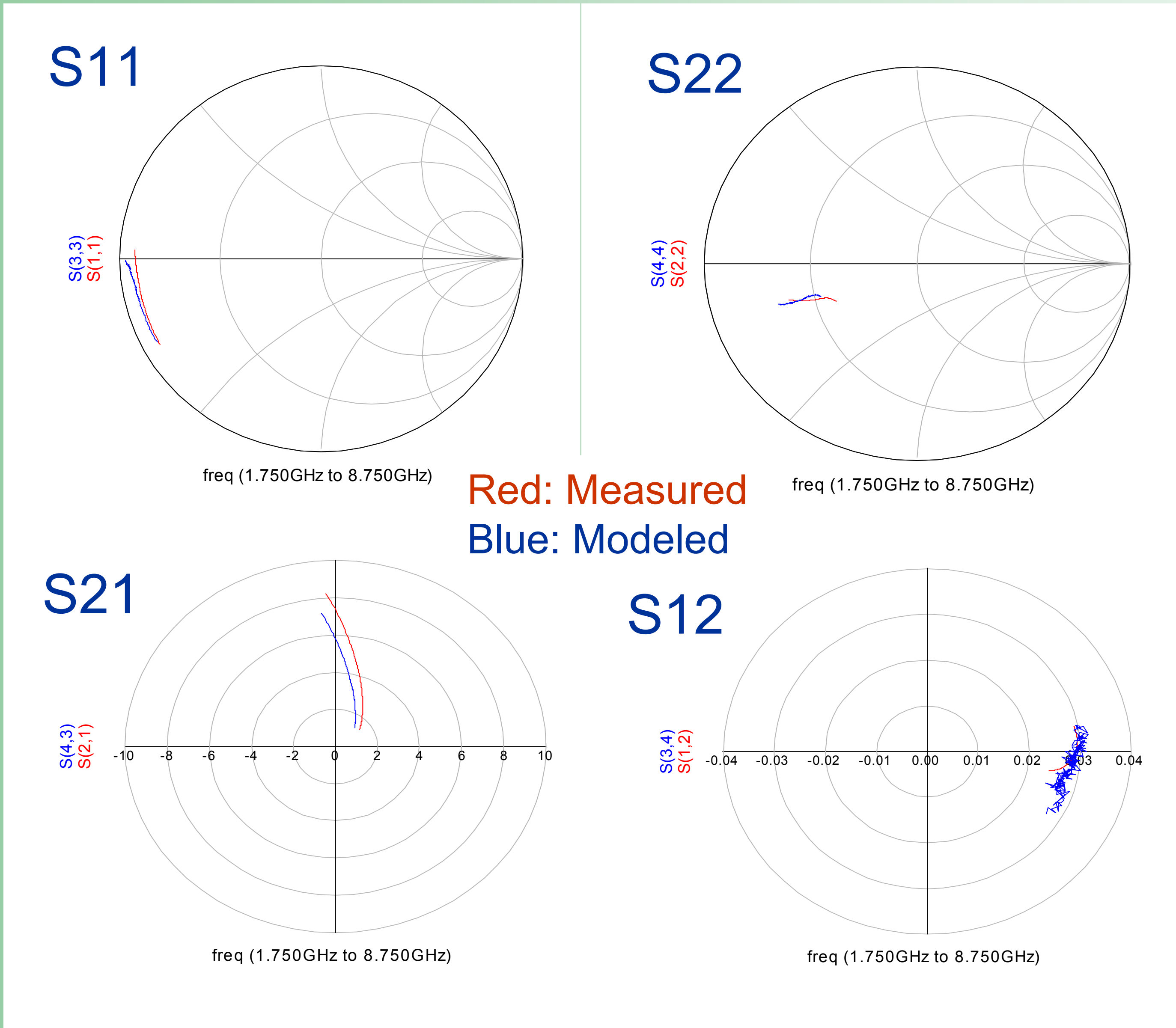
Phase degrees	Mag lin	Gt dB	Gt(s) dB	Delta_Gt dB
-177.52	0.852	-5.746	-5.742	-0.004
-124.75	0.852	-5.323	-5.659	0.336
-97.58	0.372	-0.596	-0.635	0.039
-86.87	0.844	-5.171	-5.374	0.203
-50.21	0.831	-5.095	-4.994	-0.102
-4.99	0.819	-5.137	-4.699	-0.438
7.10	0.282	-0.647	-0.315	-0.332
51.57	0.817	-5.463	-4.722	-0.740
88.17	0.824	-5.615	-4.964	-0.651
91.43	0.032	-0.211	0.000	-0.211
96.37	0.412	-1.253	-0.823	-0.430
129.54	0.837	-5.736	-5.335	-0.402
178.81	0.505	-1.367	-1.346	-0.022
182.48	0.852	-5.746	-5.742	-0.004

- 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

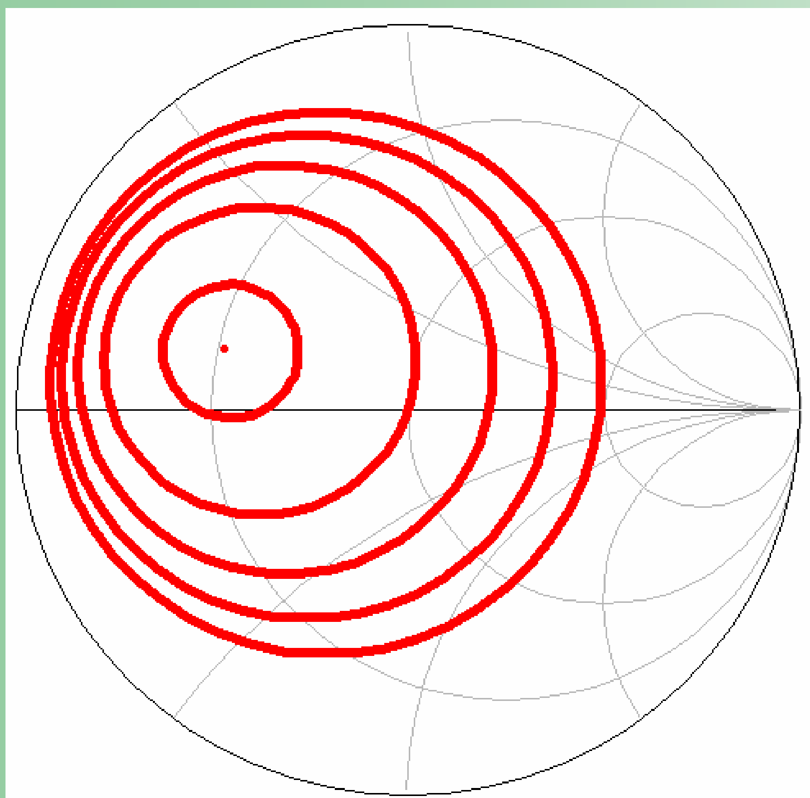
- GaAs pHEMT
  - Class AB: Vds=8V, Ids=165 mA (~25% I_{max})
- InGaP HBT
  - Class AB: Vce=3.3V, Ic=20 mA (~25% I_{max})
  - 2.5kA/cm^2 to 15kA/cm^2 Ae=405sq.um
- Test Environment:
  - Power: P1dB and P-3dB of device.
    - Po, Gp, PAE, and TOI contours plot optimums & trades
    - Final power sweep from Linear to P+6dB saturation.

pHEMT Measured vs. Model S-Parameters



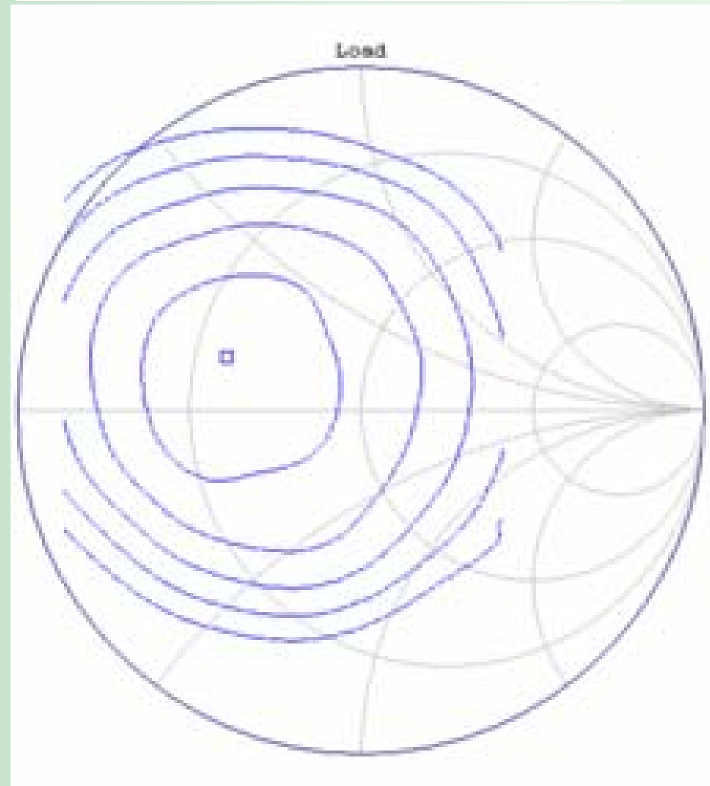
pHEMT Small-Signal Load Conjugate Match

Γload@ 0.496< 161.28



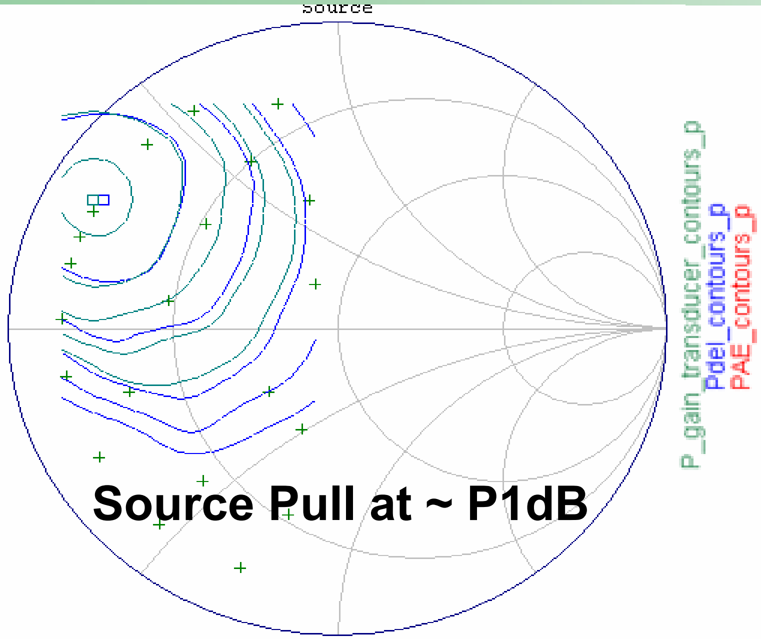
GL circles from S-Par. Meas.

Γload @ 0.4785< 160.15

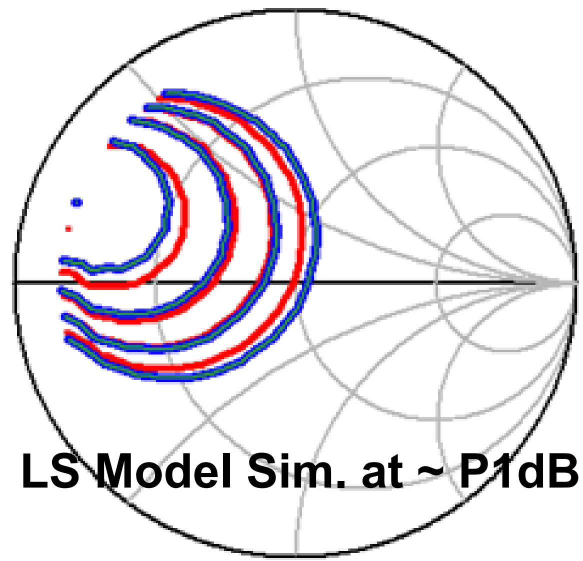


Maury – Low power tune

pHEMT Large-Signal Source Pull



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

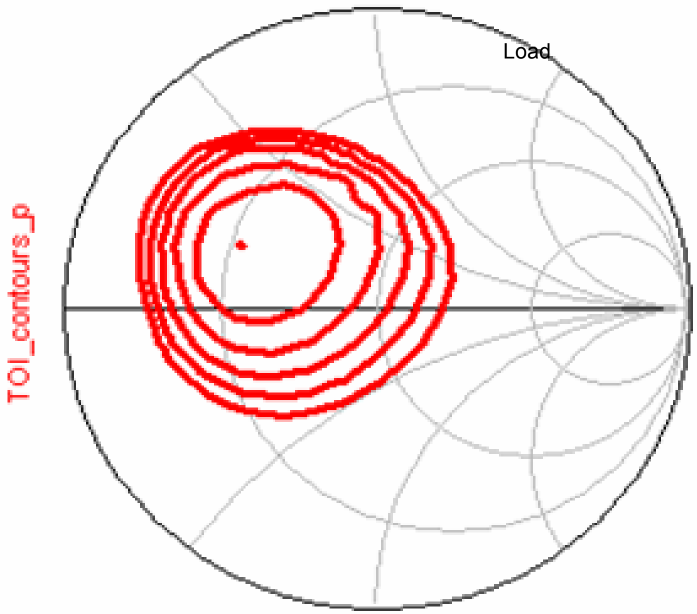


Γ_s=0.83<159.25°

Maximum Power-Added Efficiency, %	Maximum Power Delivered, dBm
38.00	28.46

Maximum Transducer Power Gain, dB	TOI, dBm
15.459	30.746

pHEMT Large-Signal Load Pull



indep(TOI_contours_p) (0.000 to 66.000)

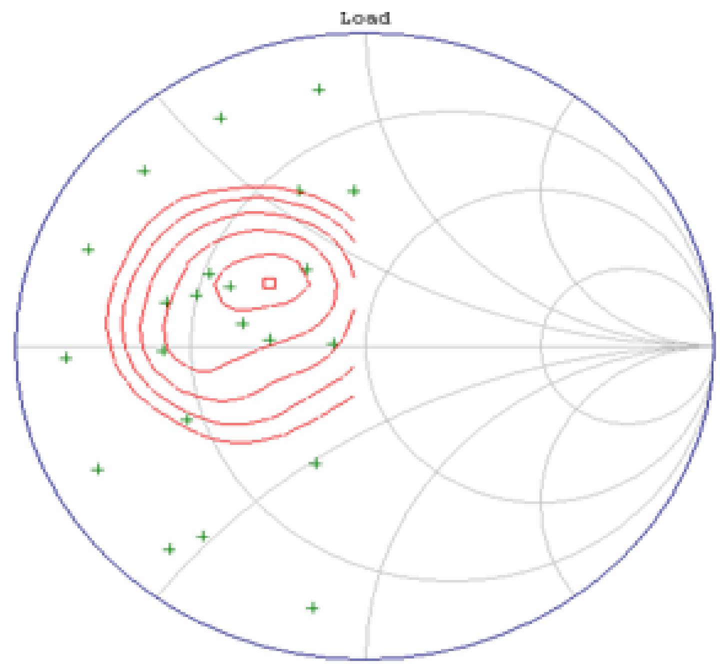
Gt, dB: 14.441

TOI, dBm: 34.579

PAE, %: 31.77

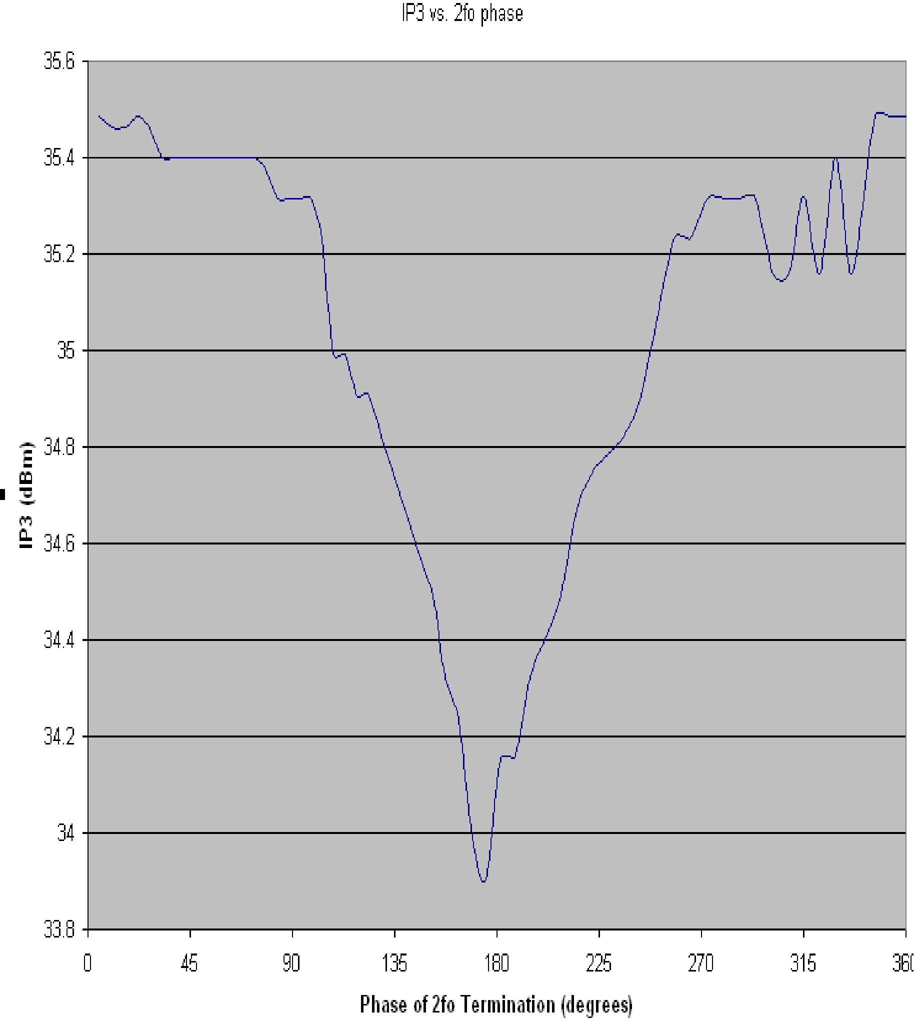
Power Delivered (dBm): 27.44

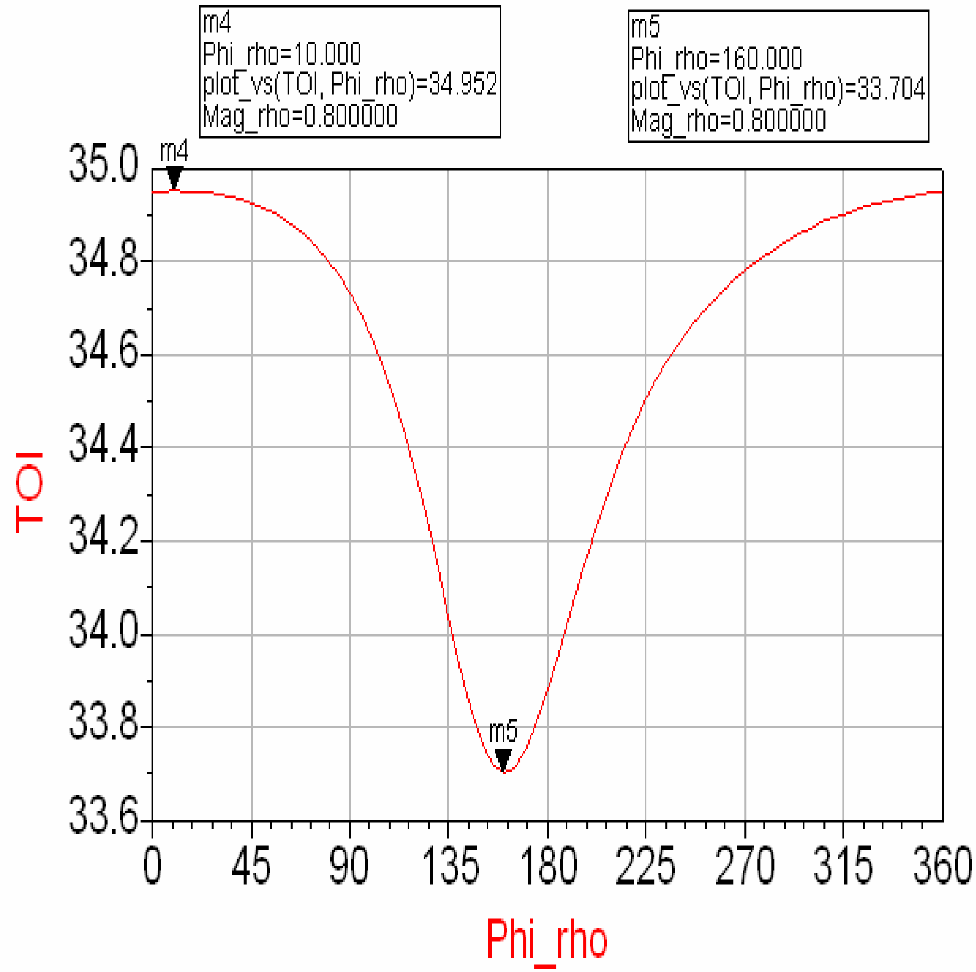
Γ_L=0.486<154.08°



Ip3: 35.19 dBm
0.00 to 50.00 dBm
Gt: 14.27 dB
0.00 to 30.00 dB
Pout: 27.27 dBm
-20.00 to 40.00 dBm
Mag: 0.43 lin
0.00 to 1.00 lin
Eff: 33.97 %
0.00 to 100.00 %
Marker: Phase = 153.91 degrees

pHEMT 2nd Harmonic Load Tuning

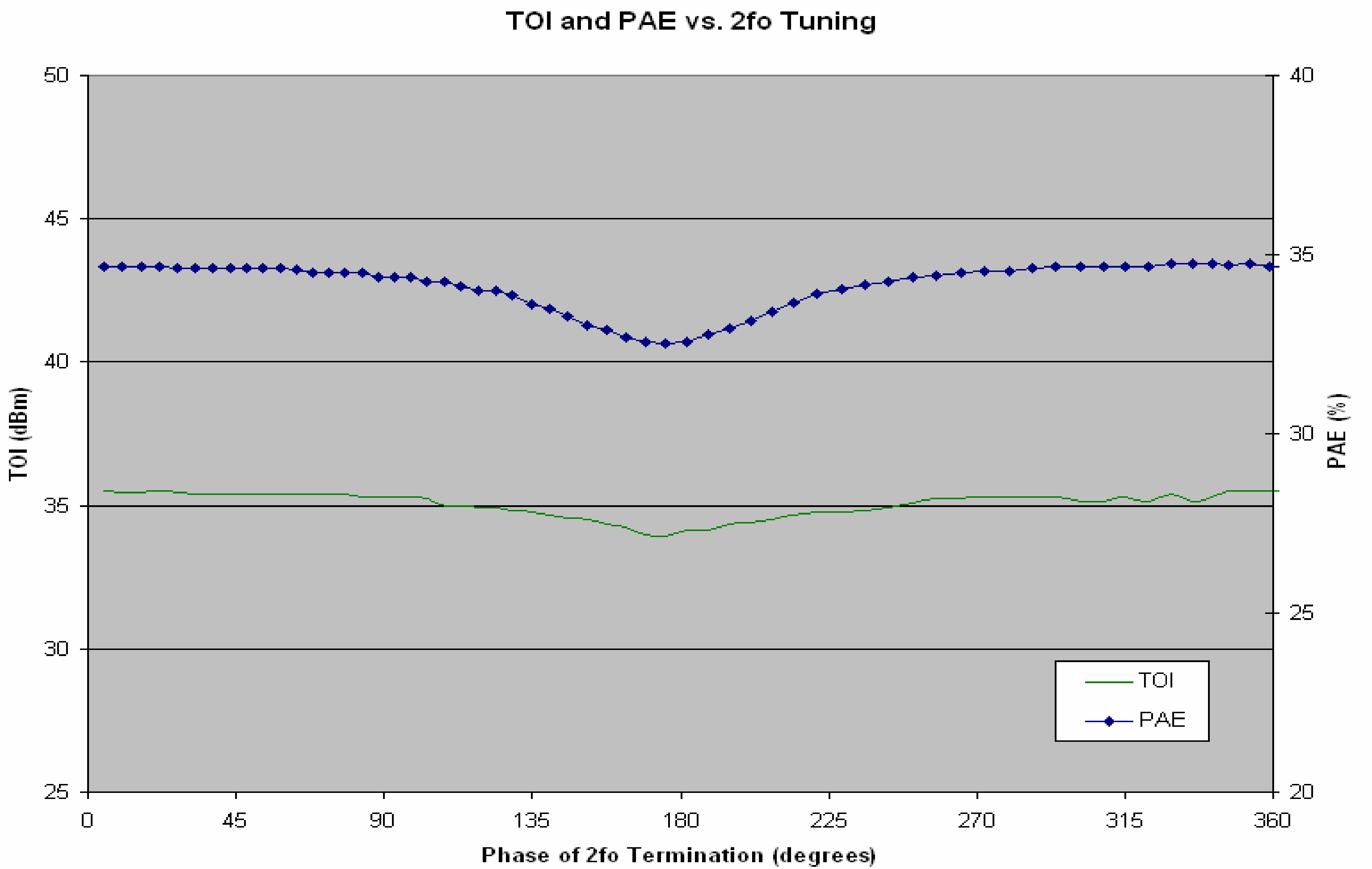




pHEMT 2nd Harmonic Load Tuning

	Γ(2fo)	Gain @ Γ(2fo)	Pout @ Γ(2fo)	PAE @ Γ(2fo)	TOI @ Γ(2fo)
Measurements	0.786<4.77°	14.33 dB	27.33 dBm	34.65 %	35.483 dB
Simulations	0.8<10°	14.526 dB	27.526 dBm	32.53 %	34.952 dB

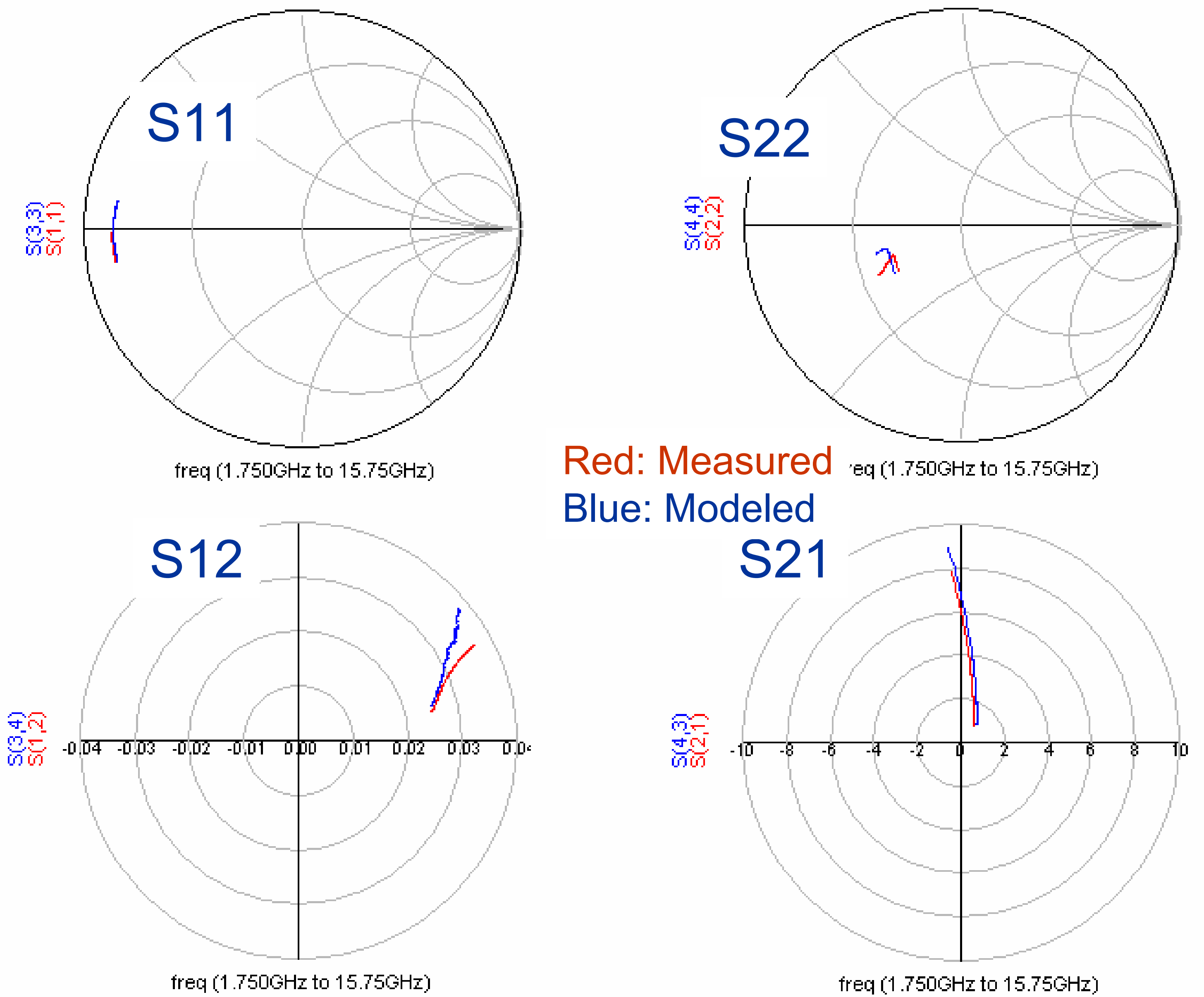
pHEMT Second Harmonic Plot with PAE, TOI



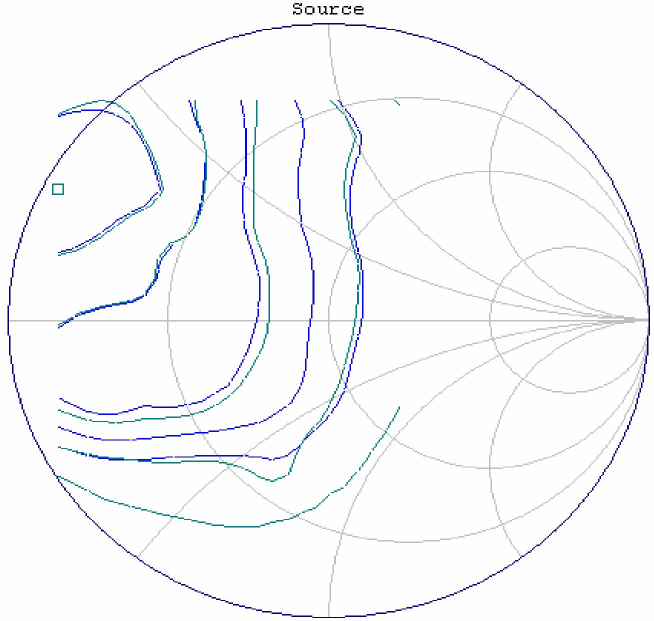
pHEMT Summary & Conclusions

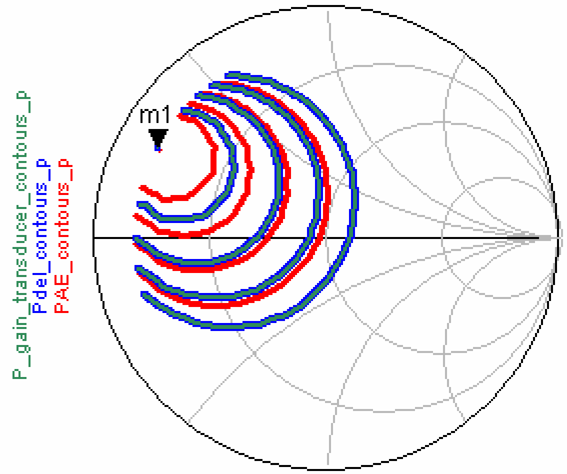
- Reasonable S-Parameter Model Match
  - ADS EE-HEMT extraction was accurate.
- Large Signal Source and Load Pull errors
  - 0.5~0.75dB range also appear reasonable.
- Modeled Power Sweep Po and IP3 are optimistic by up to 5dB at < P1dB.
- System verification means we should take the Load Pull Data as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

HBT Small-Signal S-Parameters



HBT Large-Signal Source Pull





Freq = 2.4500 GHz
ΓLoad: 0.0307< -14.66
ΓLoad2: 0.0107< -71.33
Γsource @ 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_s=0.82<151.821

Gt, dB: 16.088

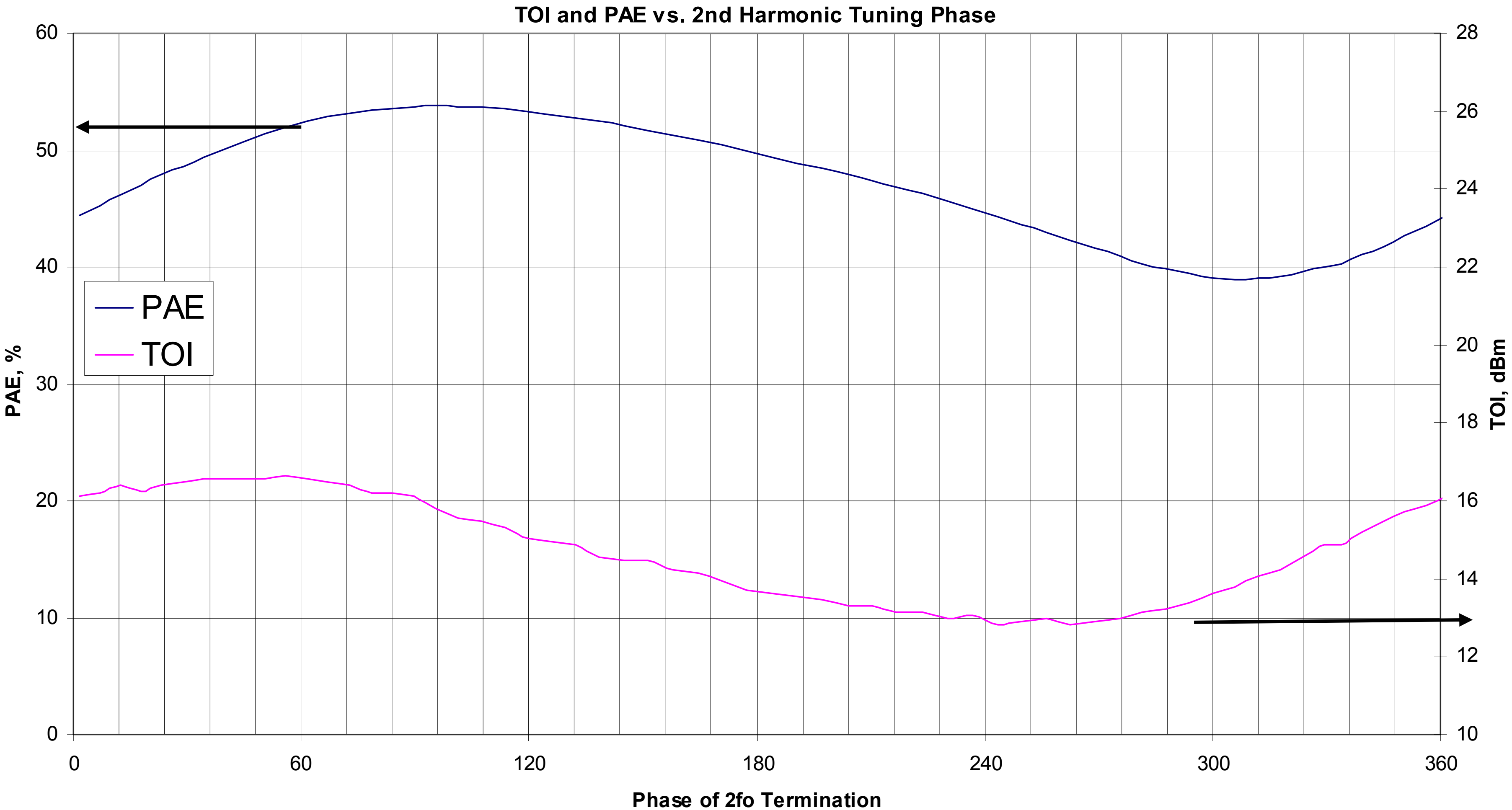
Delivered (dBm): 7.09

PAE, %: 15.05

3rd-Order IMD, dBc: -21.43

TOI, dBm: 14.739

HBT TOI and PAE vs. 2fo Load Tuning



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.

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