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Input & Output Controlled GaN Power Amplifiers

Vince Mallette

Acknowledgements

- We would like to thank Dr Tushar Sharma from Princeton University, Sagar Dhar and Prof Fadhel Ghannouchi from University of Calgary

- Authors would also acknowledge NXP Semiconductors for collaborative work

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Dr. Sharma was a recipient of the Izaak Walton Killam Pre-Doctoral Scholarship, the Alberta Science and Innovation under 30 Future Leader Award, the AITF Doctoral Scholarship, the Alberta Transformative Talent Scholarship, the Academic Excellence Award, and the Research Productivity Award.

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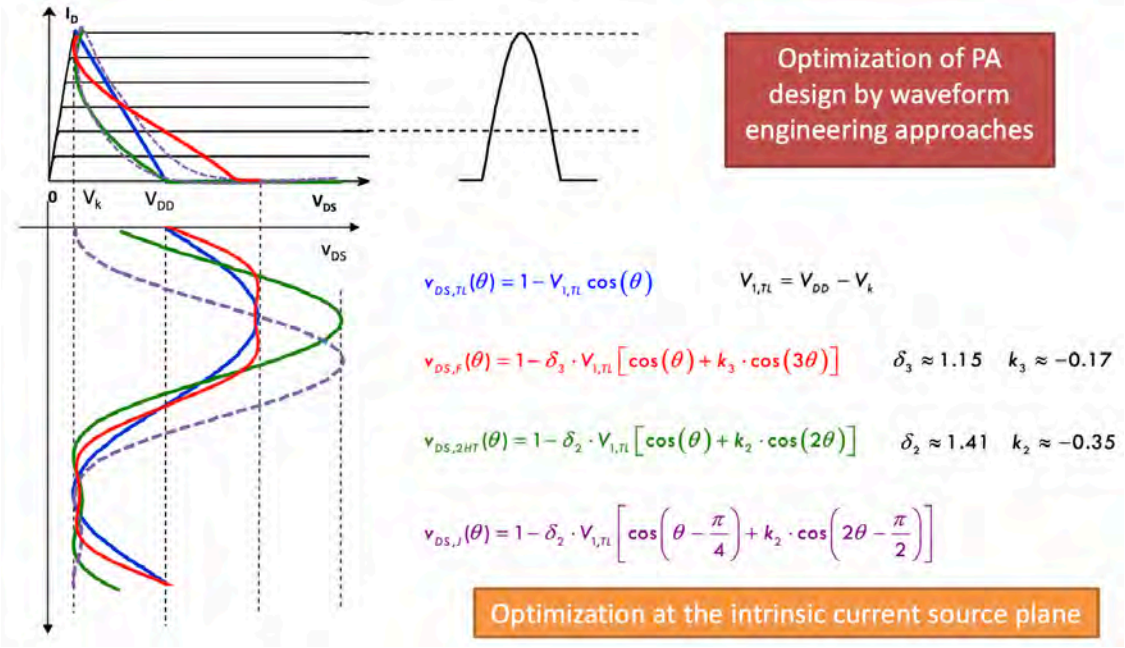
Fadhel M. Ghannouchi (S'84–M'88–SM'93–F'07) held several invited positions at several academic and research institutions in Europe, North America, and Japan. He has provided consulting services to a number of microwave and wireless communications companies. He is currently a Professor, Alberta Innovates/the Canada Research Chair, and the Founding Director of the iRadio Laboratory, Department of Electrical and Computer Engineering, University of Calgary, Calgary, AB, Canada.

He has authored or co-authored over 650 publications. He holds 16 U.S. patents with 4 pending. His current research interests include microwave instrumentation and measurements, nonlinear modeling of microwave devices and communications systems, design of power- and spectrum-efficient microwave amplification systems, and design of intelligent radio frequency (RF) transceivers for wireless and satellite communications.

Waveform Engineering Concept



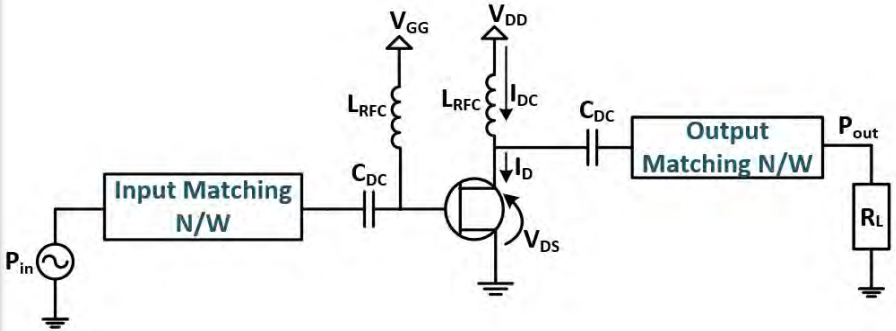
Reference : Low frequency waveform measurements: from theory to power amplifier design
https://intranet.birmingham.ac.uk/eps/documents/public/emuw2/WTh01.pdf

Power Amplifier Classes

Tuned Load (TL) PAs, $Z_{nf} = 0, n > 1$

- Class A
- Class AB
- Class B
- Class C

Efficiency



Second Harmonic Source, $Z_{2S} = 0$

Harmonic Tuned (HT) PAs, $Z_{nf} \neq 0, n > 1$

- Class J
- Class F
- Class F^{-1}

Efficiency

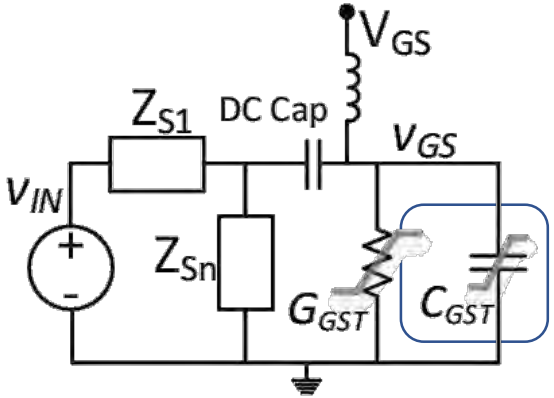
Why Input Nonlinearity Analysis Needed?

- In Broadband design, it cannot be avoided
  - Better be explored and exploited

- Input nonlinearity degrades PA performances
  - Misconceived, need to be properly understood.

- Input nonlinearity could pave the way of understanding a true harmonic tuned broadband PA **IN PRACTICE**.

Source of Input Nonlinearity – Pathway to Input Waveform Engineering



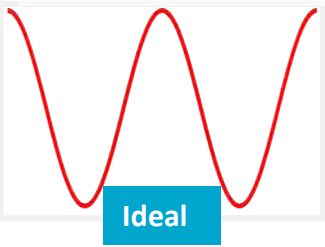
$$V_{IN}(\theta) = V_1 \cos\theta$$

$$v_{GS}(\theta) = V_{GS0} + V_1 \cos\theta + V_2 \cos(2\theta + \varphi_2)$$

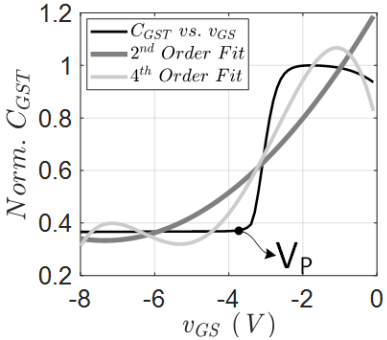
$$v_{GS,\text{norm}}(\theta, \gamma, \varphi_2) = \frac{v_{GS}(\theta) - V_{GS0}}{V_1} \qquad \gamma = V_2/V_1$$

$$= \cos\theta + \gamma \cos(2\theta + \varphi_2)$$

V_{IN}

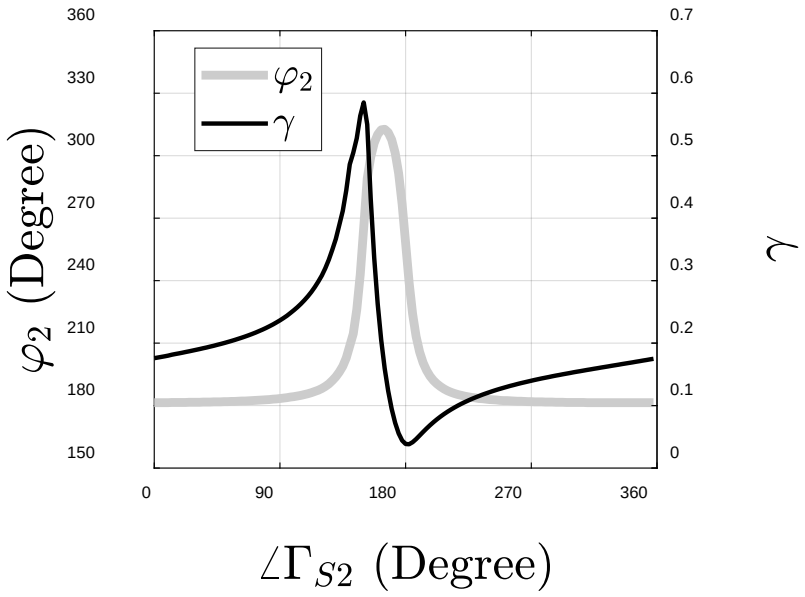


C_{gs} vs Vgs Variation



$V_{GS\_norm}(\gamma, \varphi_2)$

What controls γ and $\boldsymbol{\varphi_2}$?



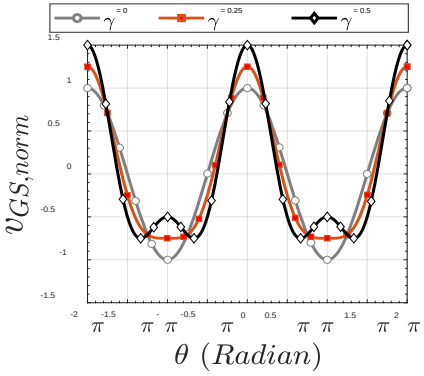
Second Harmonic Source Pull

- The second harmonic source/input impedance determines the magnitude (γ) and phase difference ($\boldsymbol{\varphi_2}$) between second and fundamental harmonic
- $\boldsymbol{\gamma}$ and $\boldsymbol{\varphi_2}$ changes as function of second harmonic source pull and impacts the input waveform at gate of the device
- This is turn impact the drain waveforms and achievable drain efficiencies of the active device under test

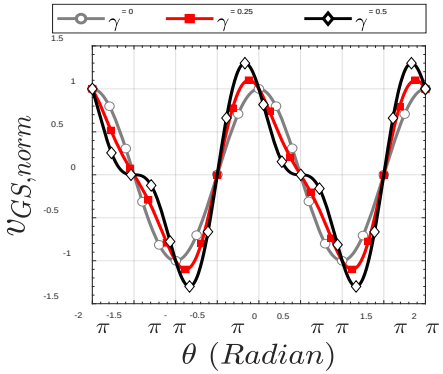
Input Waveform Engineering

- Varying magnitude (γ) and phase difference (φ_2) between **second harmonic** and **fundamental** component at device input results in family of input waveforms

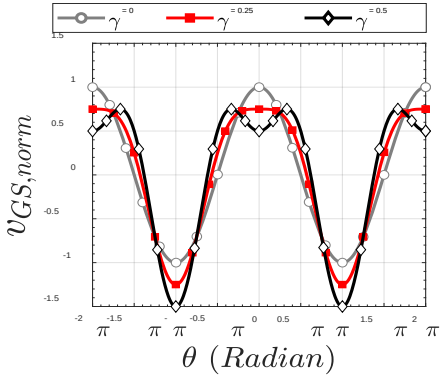
φ_2 = 0



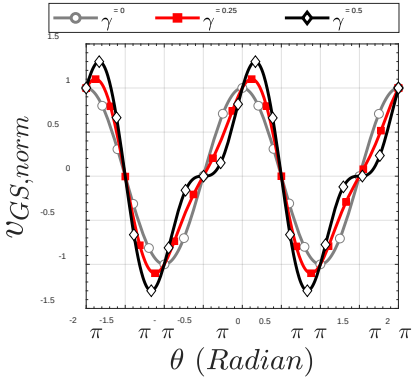
φ_2 = π/2



φ_2 = π

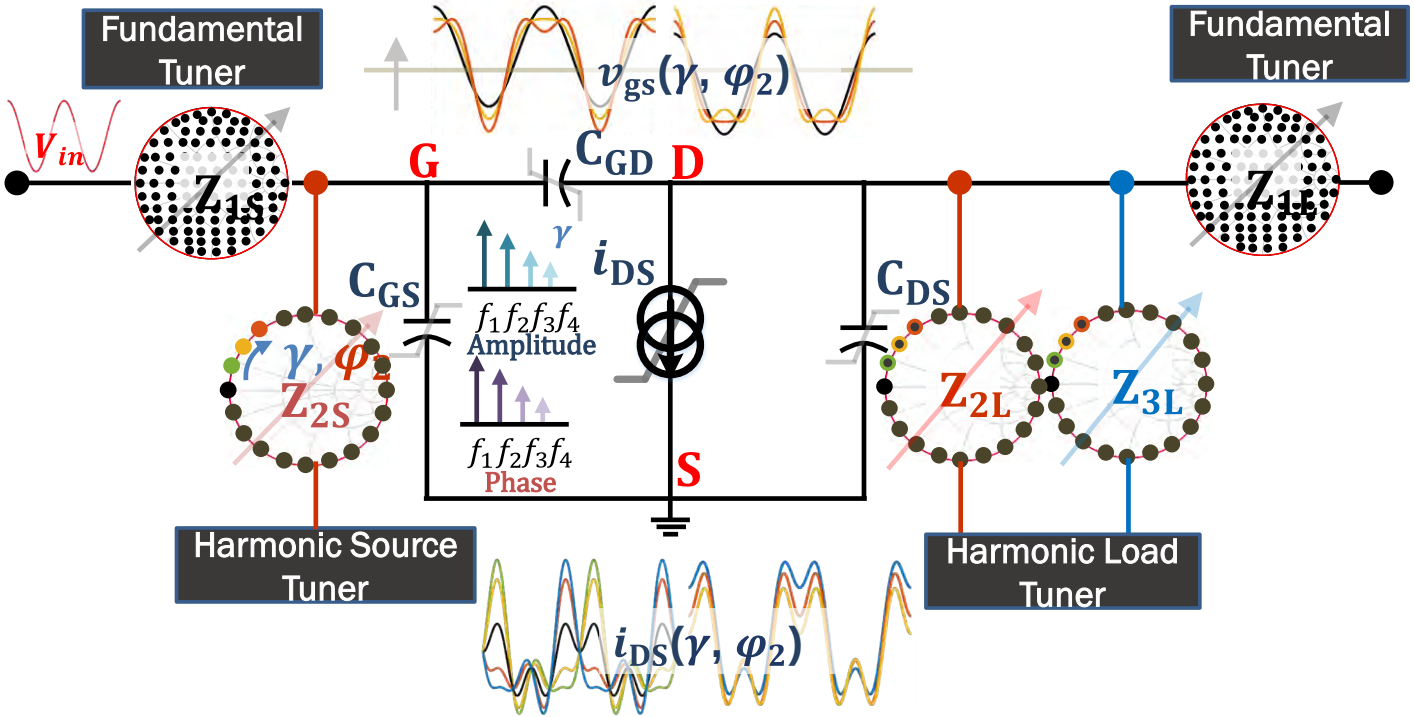


φ_2 = 1.5π



<u>Family of Input Waveforms as function of Input Nonlinearity</u>

Input–Output Controlled Power Amplifier Design



Impact of Input Non Linearity on Drain Waveforms

Modified Conduction Angle: *β*

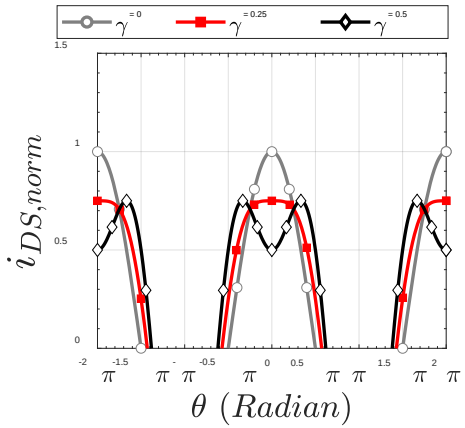
$$i_{DS}\,(\theta,\beta) = \mathrm{I}_{max}[\cos\theta + \gamma cos(2\theta + \phi_2)], \quad -\frac{\beta}{2} \le \theta \le \frac{\beta}{2}$$
$$= 0, \quad otherwise$$

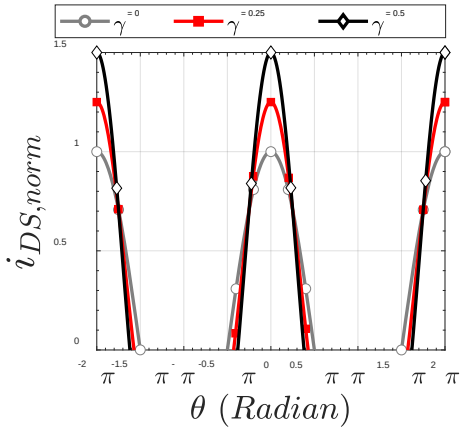
$$\cos\frac{\beta}{2} + \gamma\cos(\beta + \phi_2) = 0$$

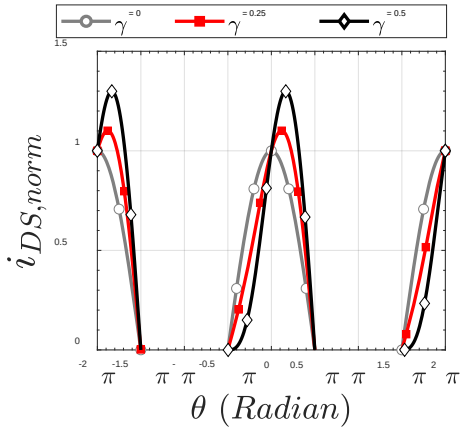
Different ϕ_2

Conduction Angle Expansion

Conduction Angle Contraction

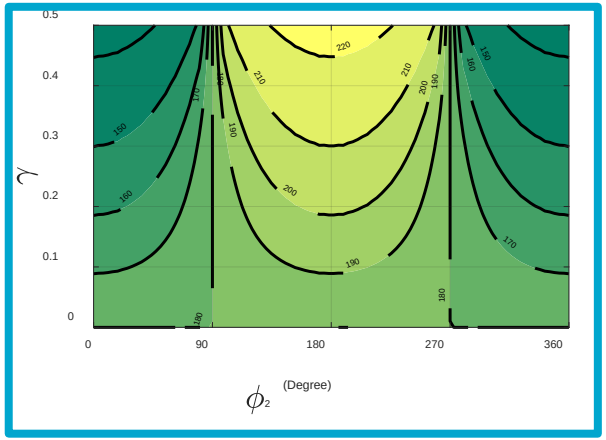




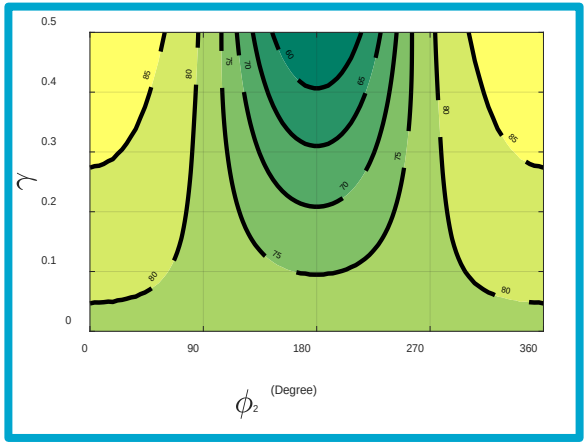


Impact of Input Nonlinearity on Performance – Class B

Conduction Angle



Efficiency (%)

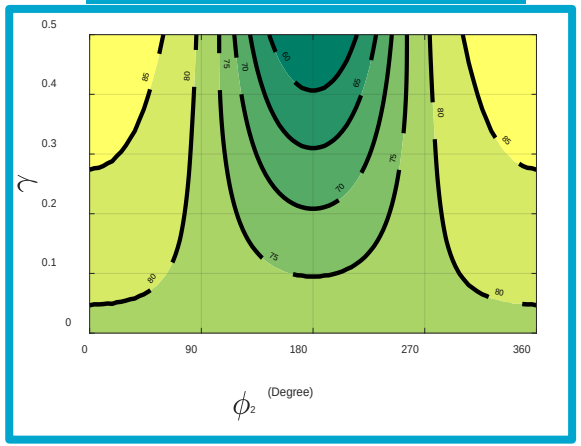


- For combinations of γ and φ_2, the conduction angle goes less than 180° and thus helping in decreasing overlap between current and voltage waveforms
- Possibilities of achieving theoretical efficiency up to 85 % depending on magnitude of γ and φ_2

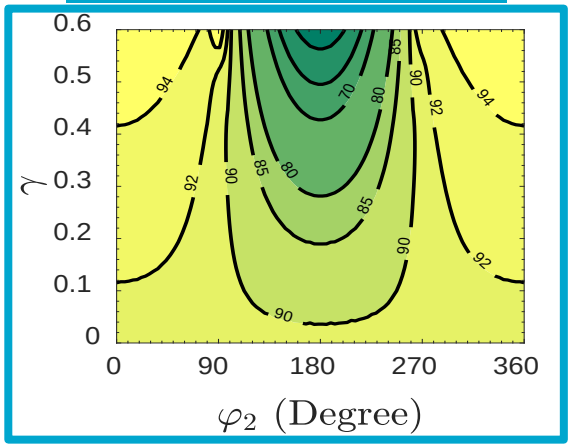
*Assumes no V_{knee}

Harmonic Tuned Classes Vs Input Non Linearity

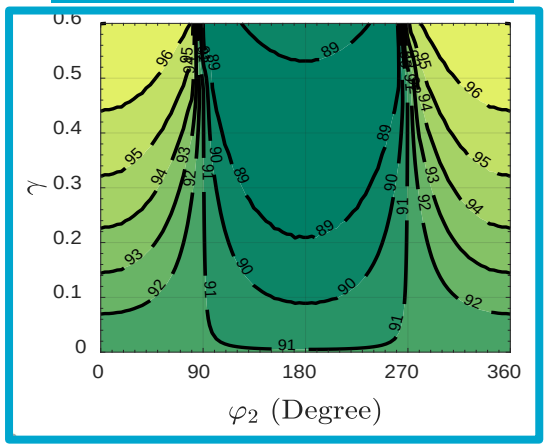
Efficiency(%) – Class B



Efficiency(%) – Class F

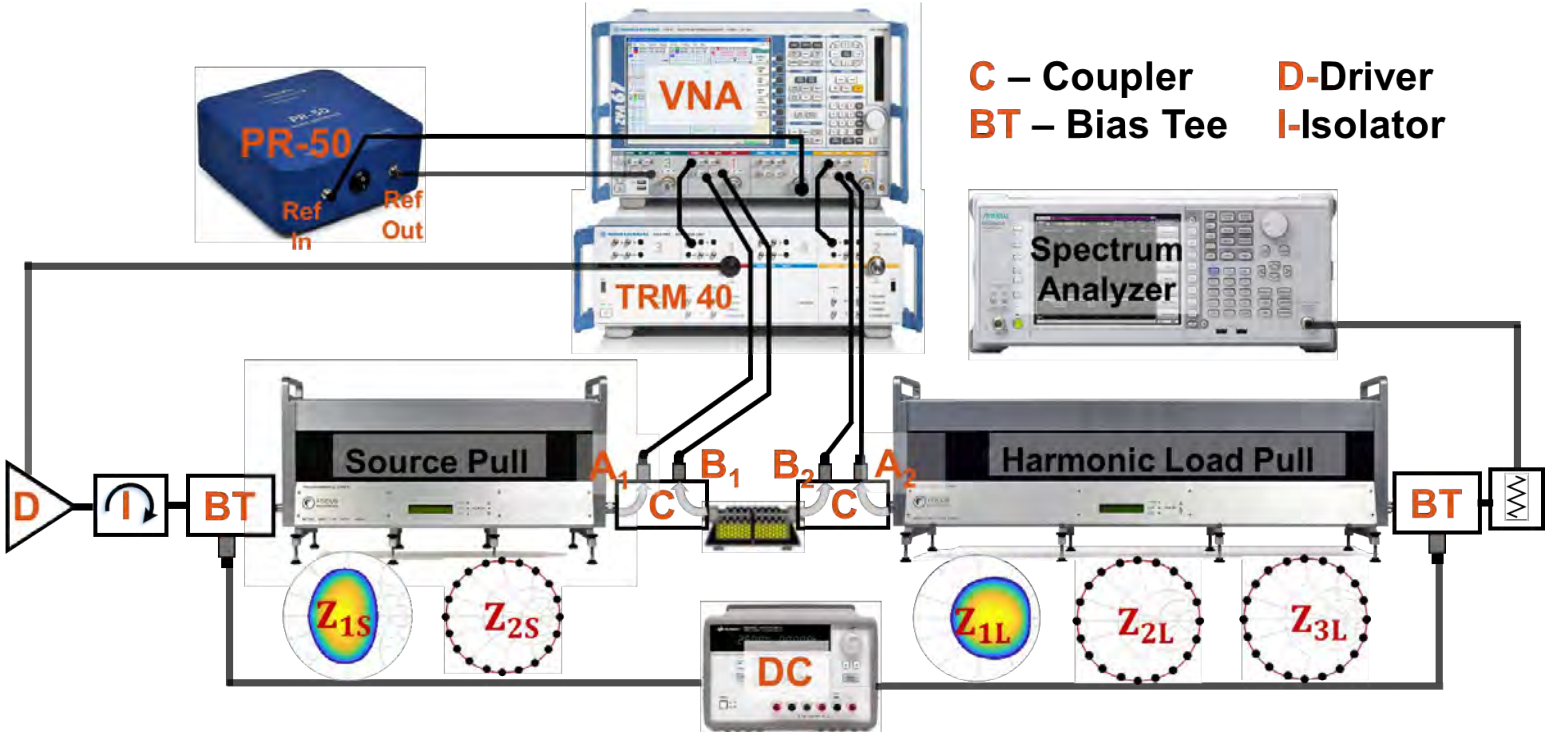


Efficiency(%) – Class F^{-1}

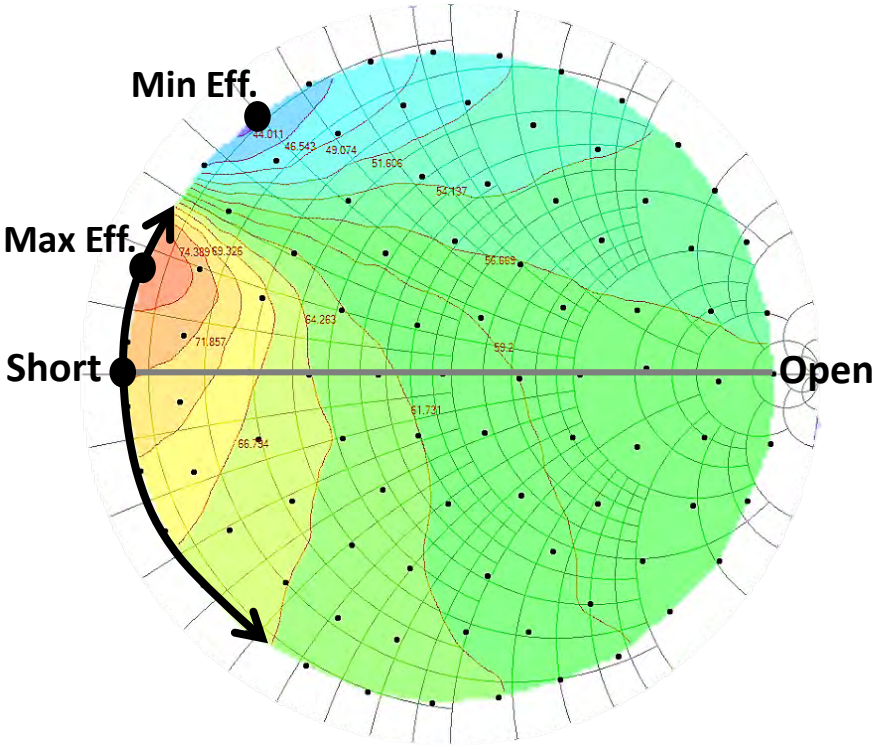


- The maximum and minimum efficiency are function of γ and φ_2 and combination of output harmonics
- Class B/J/F shows big efficiency delta with input non-linearity, however Class F^{-1} is relatively immune to it.

Input Output Waveform Engineered PA using Focus MPT/MPT Lite Tuners



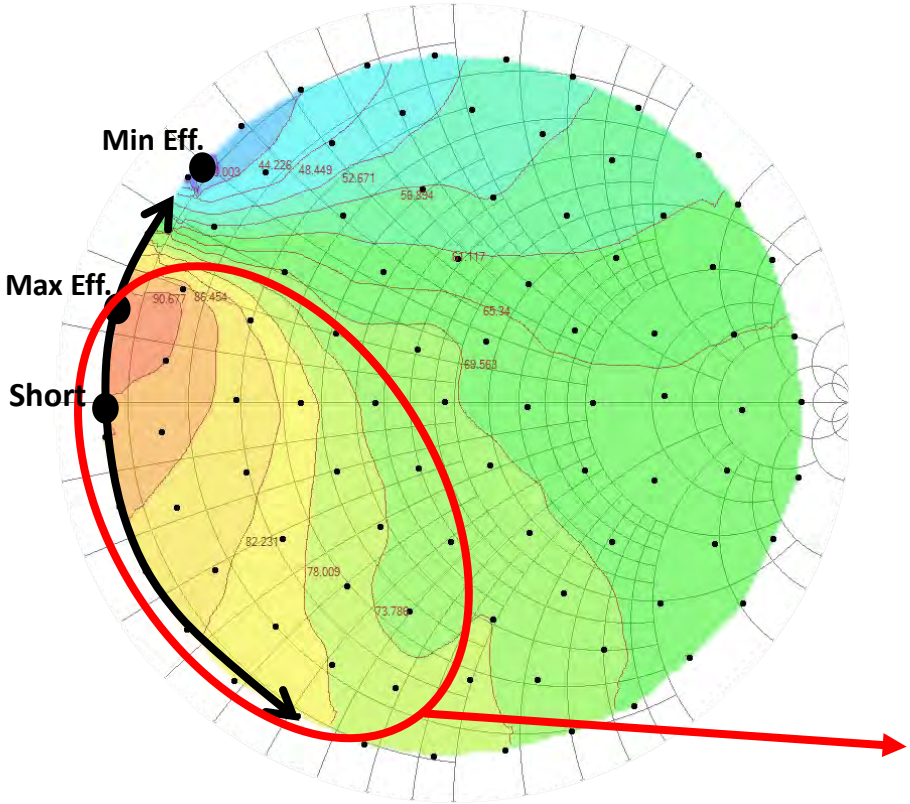
Second Harmonic Source Pull Using MPT – Class B



Z_L	Z_{L2}	Z_{L3}
Max Efficiency	Short	Short

- The maximum efficiency for Class B is a non short termination.
- There is an efficiency “null” region at the source which impact broadband design of harmonic tuned PAs.

Second Harmonic Source Pull – Class F

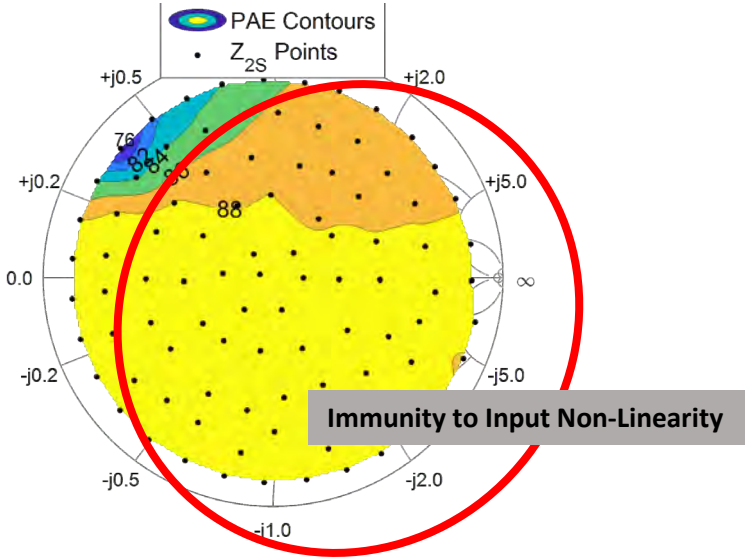


Z_L	Z_{L2}	Z_{L3}
Max Efficiency	Short	Open

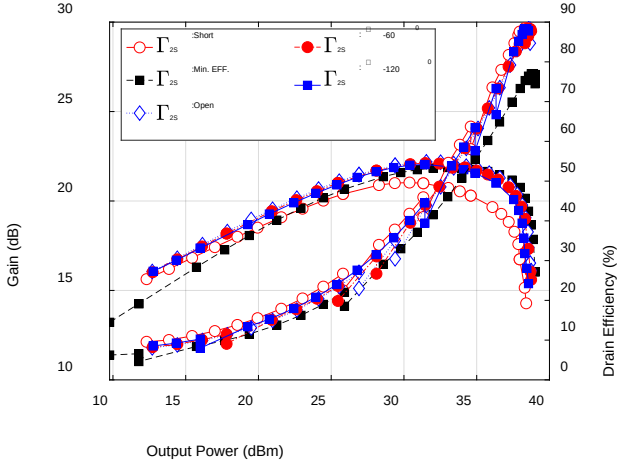
- Class F shows 90% measured peak efficiency with second harmonic control at input of an active GaN die
- Class F shows 30% efficiency delta as function second harmonic source sweep

Good area of design for Broadband application i.e. input controlled continuous Class F PA

Second Harmonic Source Pull – Class F-^{1}



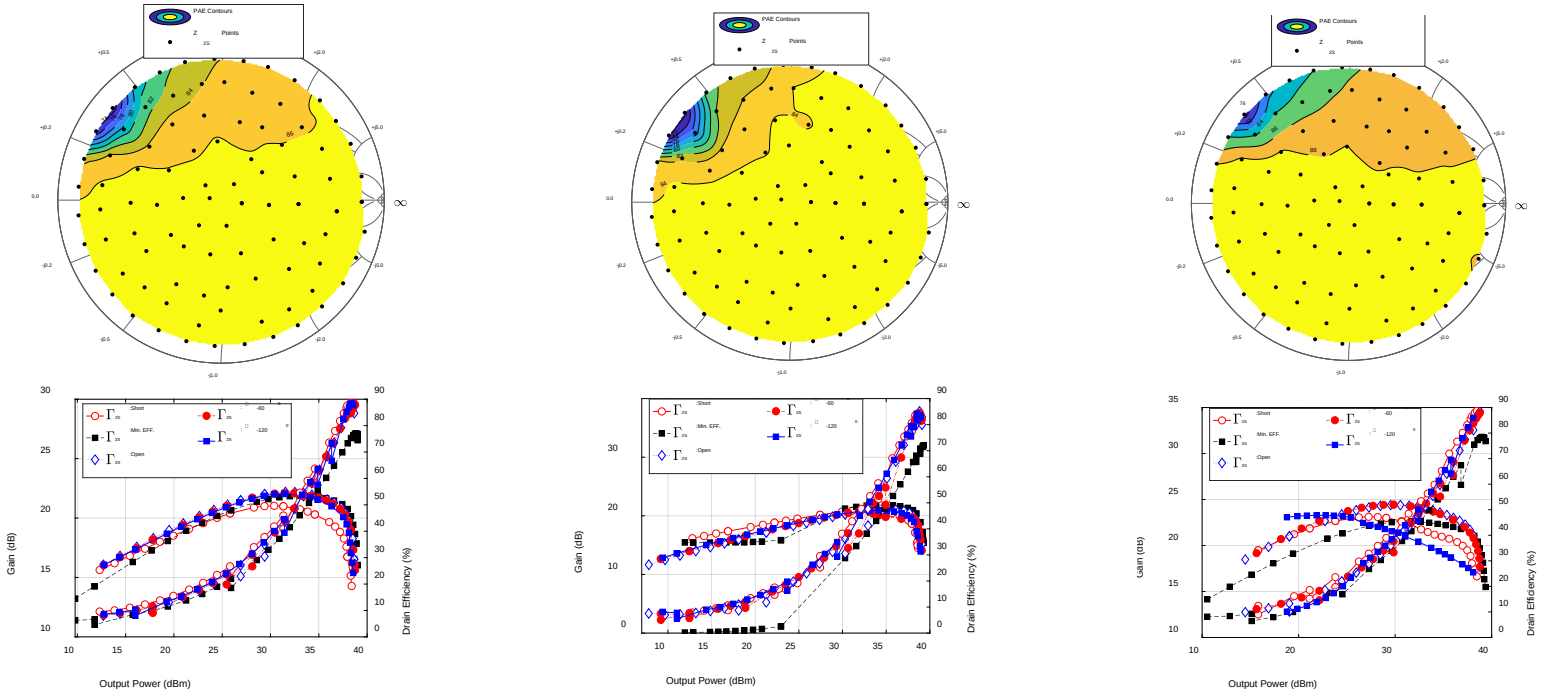
Z_L	Z_{L2}	Z_{L3}
Max Efficiency	Open	Short



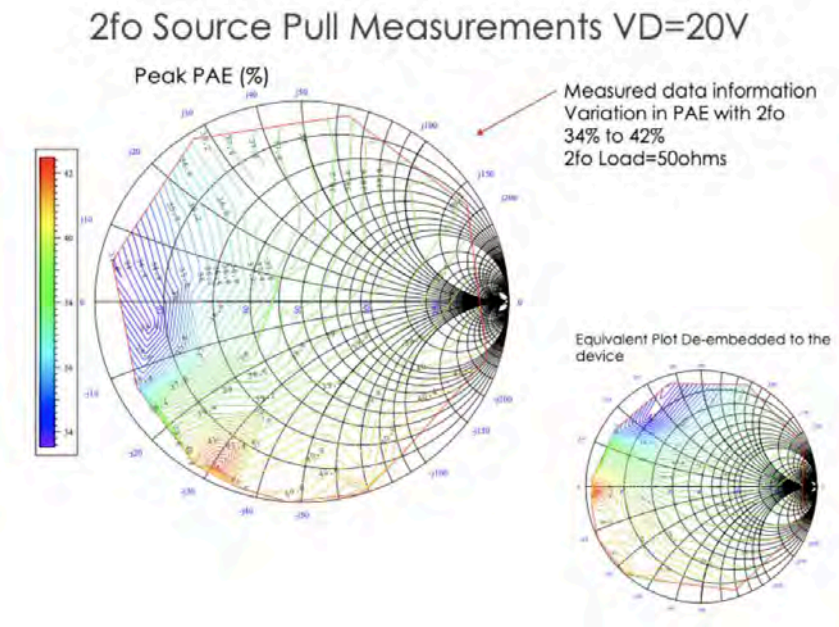
- Efficiency Flatness over second harmonic source sweep. Immunity to input nonlinearities
- Broader design space for high efficiency broadband amplifier design

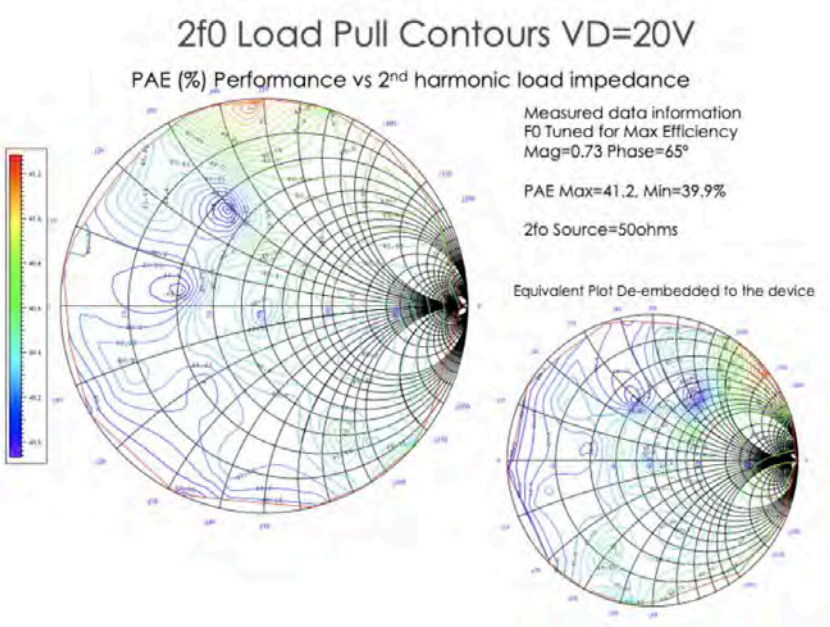
Broadband Input-Output Controlled PA

Second Harmonic Source Pull for Continuous Class F^{-1} PA



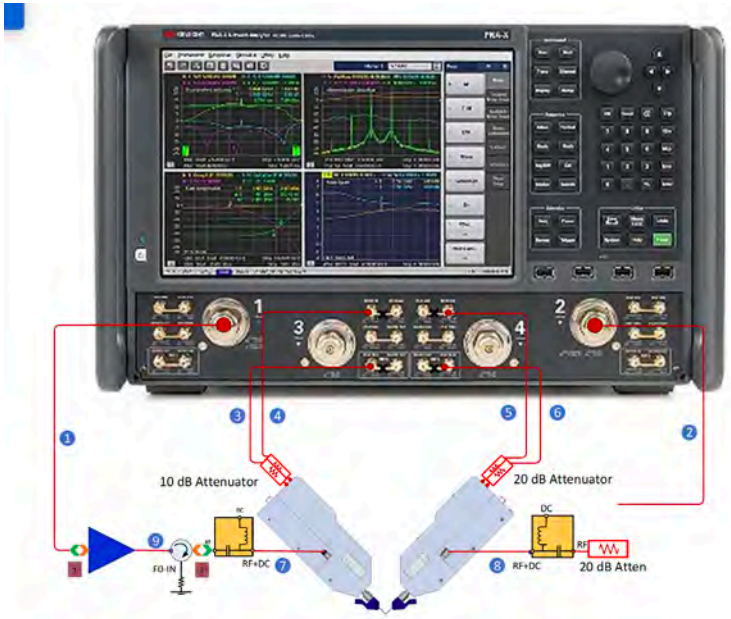
Effects of 2nd harmonic tuning – Source & Load Tuning





Waveform engineering at mmW - Possible

67GHz diagram

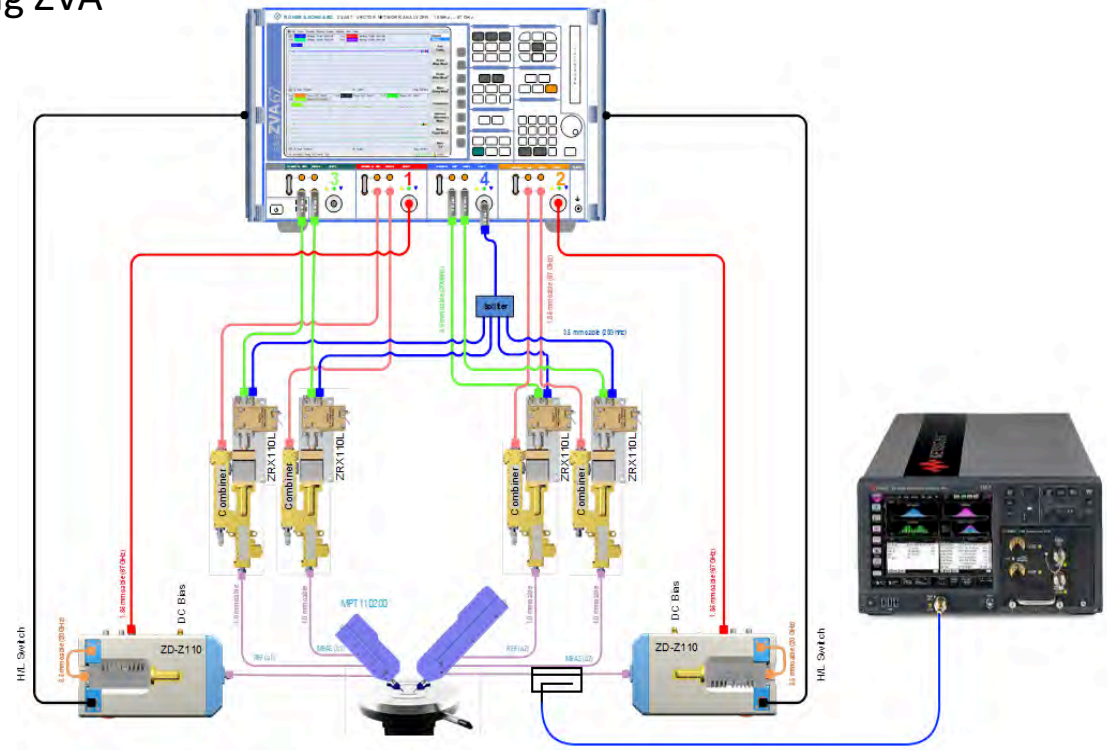


67 GHz Vector LP Setup

110GHz Diagram

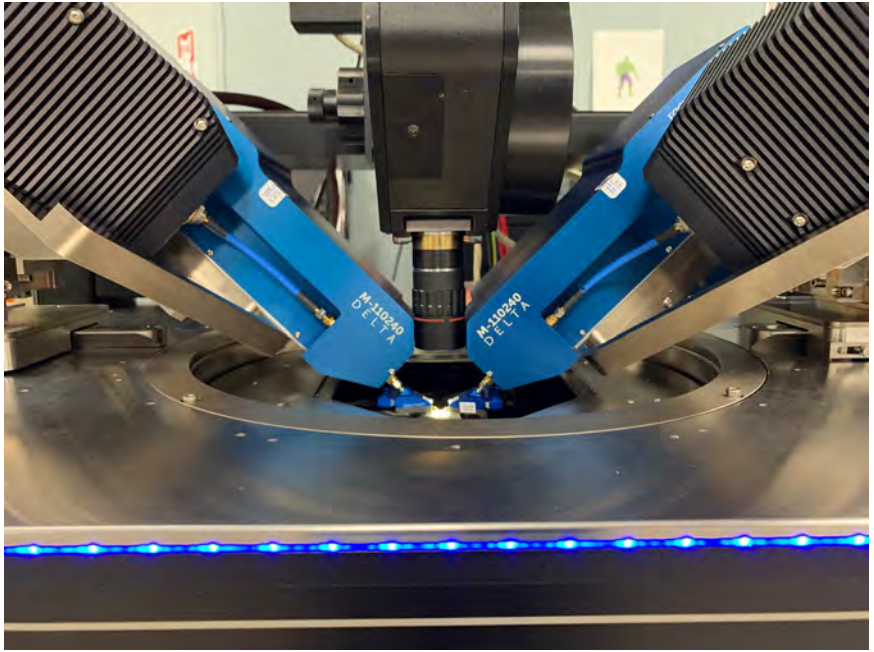
Waveform engineering at mmW - Possible

- 110GHz Setup Using ZVA

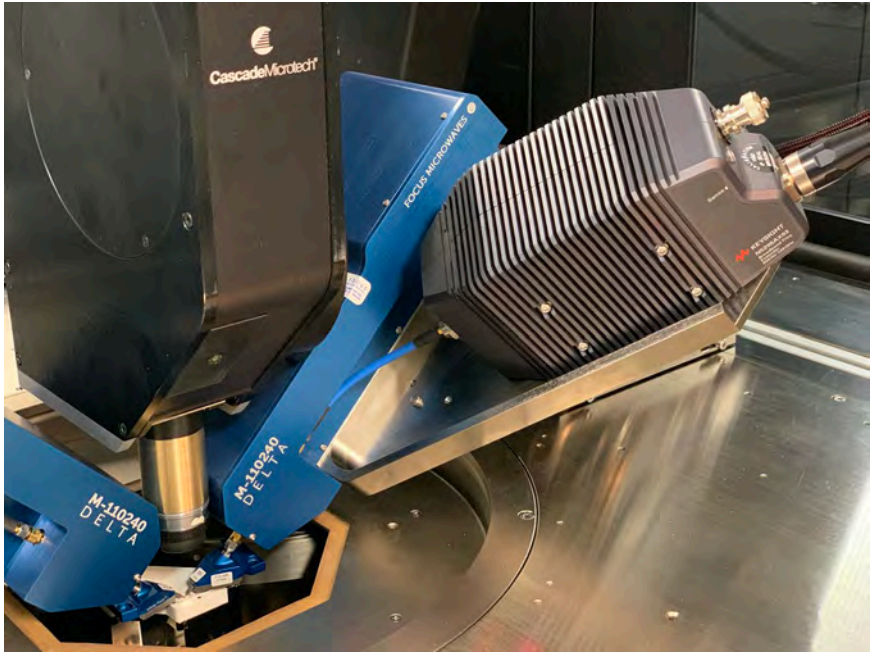


Integrating DELTA tuners CM300

Front view

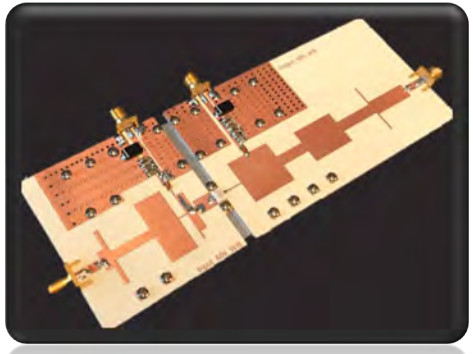


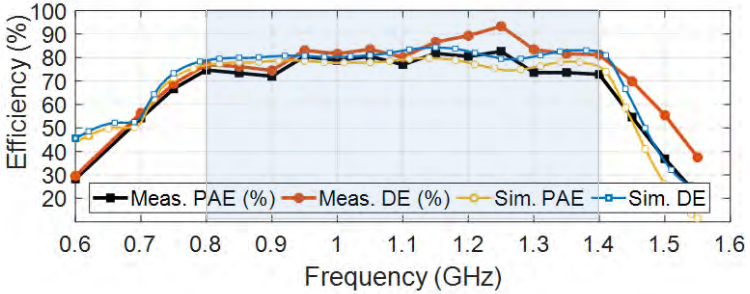
ISO view



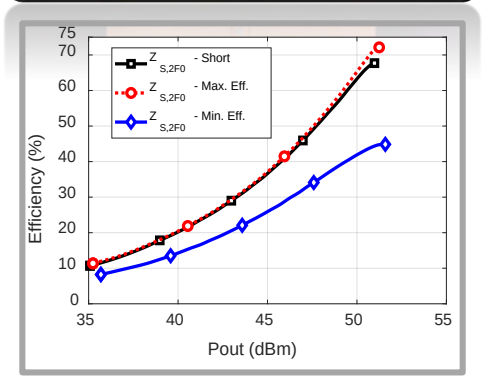
Input-Output Controlled Harmonic Tuned PAs

Low Power (40 dBm)

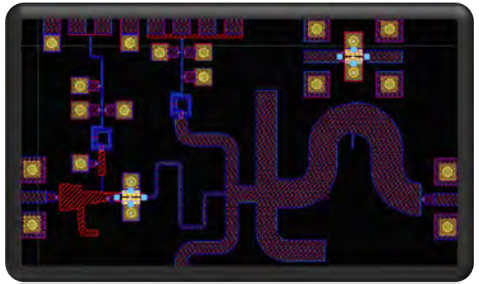


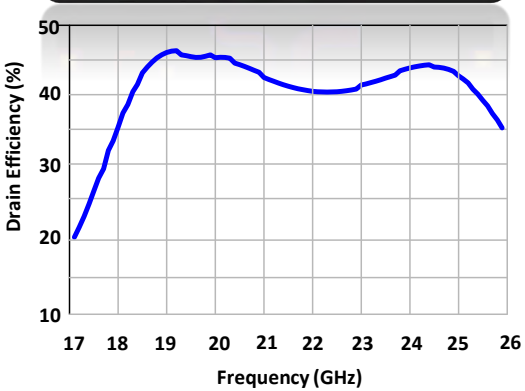


High Power (>50 dBm)



High Frequency (MMIC)





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- T. Sharma*, et al., "*Novel High Efficiency Power Amplifier Mode Using Open Circuit Harmonic Loading*," in IMS 2019.*
- T. Sharma, J. Roberts, S. K. Dhar, *et al.*, "On the Efficiency and AM/AM Flatness of Inverse Class-F Power Amplifiers," in *IMS 2019*.
- T. Sharma *et al.*, "High-Efficiency Input and Output Harmonically Engineered Power Amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. PP, no. 99, pp. 1–13, 2017.
- S. K. Dhar *et al.*, "Investigation of Input-Output Waveform Engineered Continuous Inverse Class F Power Amplifiers," *IEEE Trans. Microw. Theory Tech.*, pp. 1–15, 2019
- S. K. Dhar, T. Sharma, N. Zhu, D. Holmes, R. Darraji, and F. M. Ghannouchi, "Comprehensive Analysis of Input Waveform Shaping for Efficiency Enhancement in Class B Power Amplifiers," in *IMS* 2019, pp. 1164–1167