Wideband and Energy Efficient Power Amplifiers for Wireless Communications

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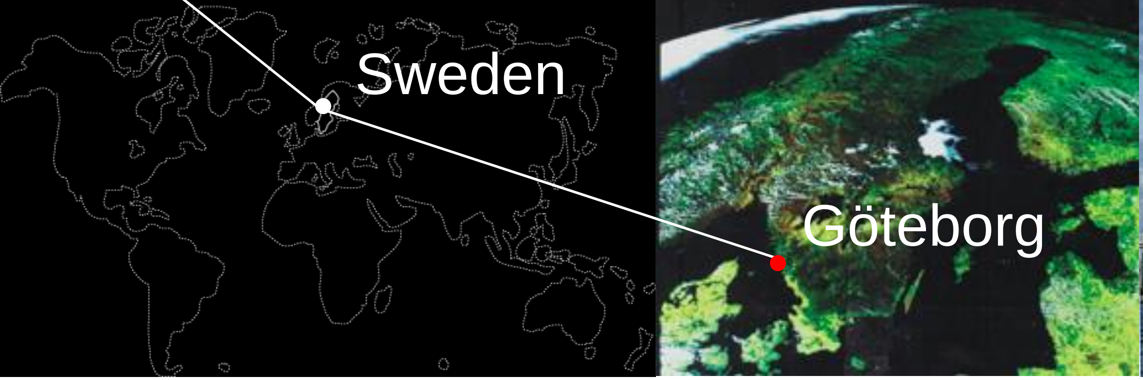
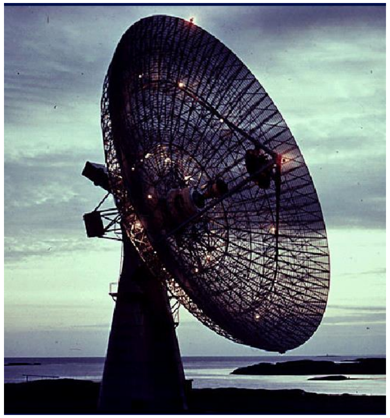


Located by the west cost of Sweden

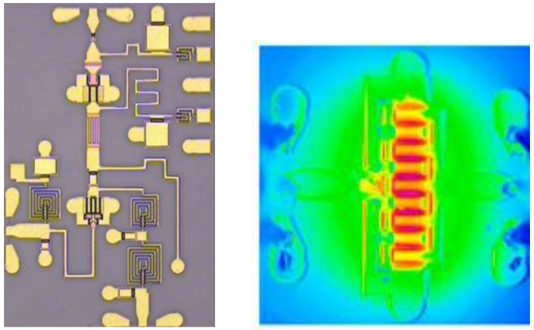
… Founded 1829 by William Chalmers

…11000 students (1150 doctoral students)

…Long tradition in microwaves

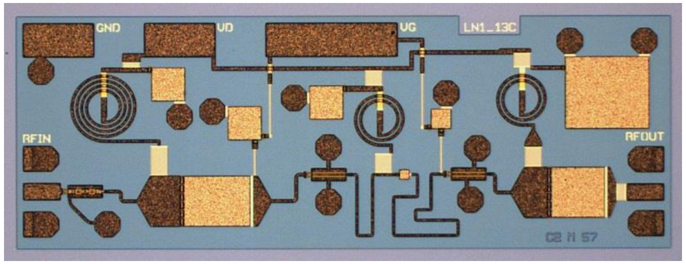


Microwave Technologies at Chalmers



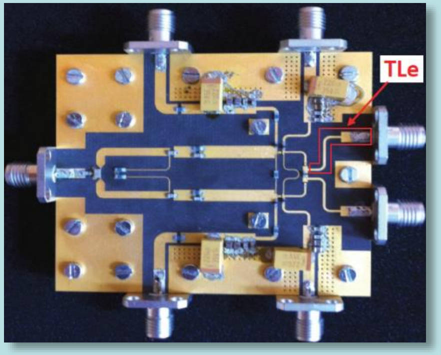
GaN HEMT technology

GaN HEMT MMICs
Robust transceivers, high RF power



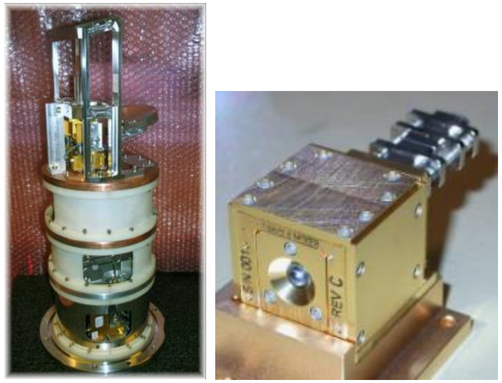
InP HEMT technology

InP and InAs HEMT MMICs
Cryogenic low-noise amplifiers



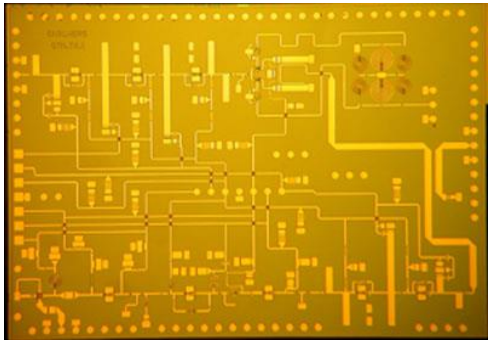
Transmitters for telecom

Power amplifiers
High efficiency and linearization



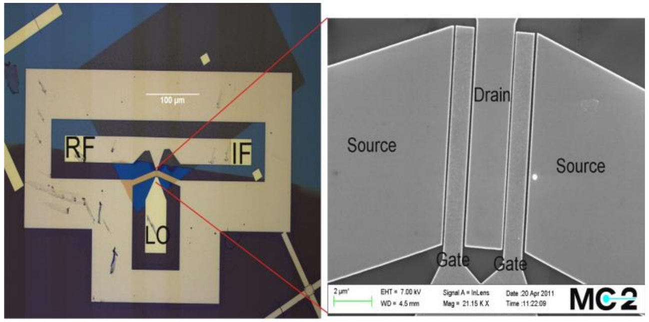
THz devices & instrumentation

Mixers:
Schottky diode, varactors
Hot-electron bolometer SIS
Heterodyne receivers beyond 1 THz



III-V MMIC design

Multifunctional
THz > 300 GHz
Communication > 100 GHz
GaN HEMT VCOs
Mixed signal (>100 Gbps)



Emerging MW components

Graphene HF electronics
Ferroelectric tunable devices

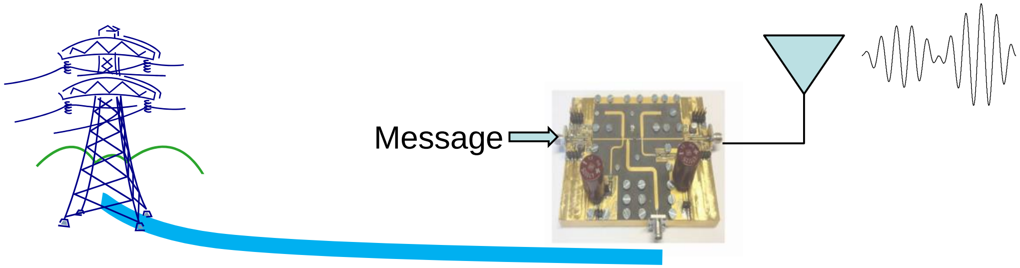
Full Professors: Victor Belitsky, Spartak Gevorgian, Jan Grahn, Jan Stake, Herbert Zirath

Outline

- Background
- Energy efficient wideband transmitter architectures
  - Varactor based dynamic load modulation
  - Doherty power amplifiers (PA)
  - Outphasing PAs
  - Mixed Doherty-outphasing techniques
- Summary

Transmitter Demands

- A radio transmitter generates high power information carrying electromagnetic signals.

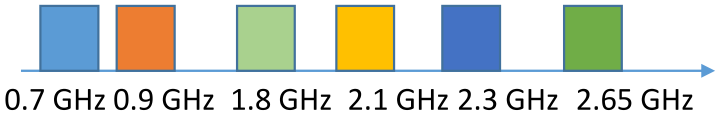


- Most power hungry unit in a radio base station.

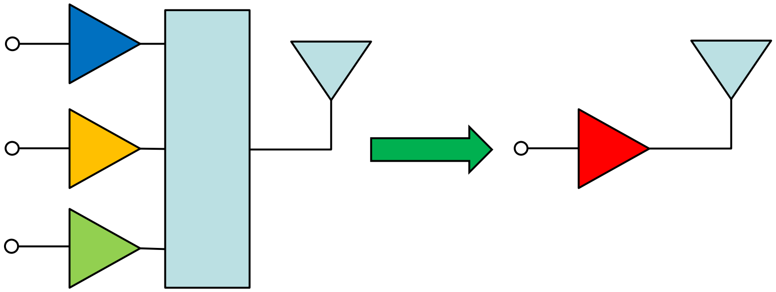
- **Higher transmitter efficiency** for
  - Lower operational costs
  - Smaller environmental footprint

Transmitter Demands

- Strong demand for higher data rates
- Wireless providers allocate more spectrum
  - 44 different bands are utilized in LTE-A

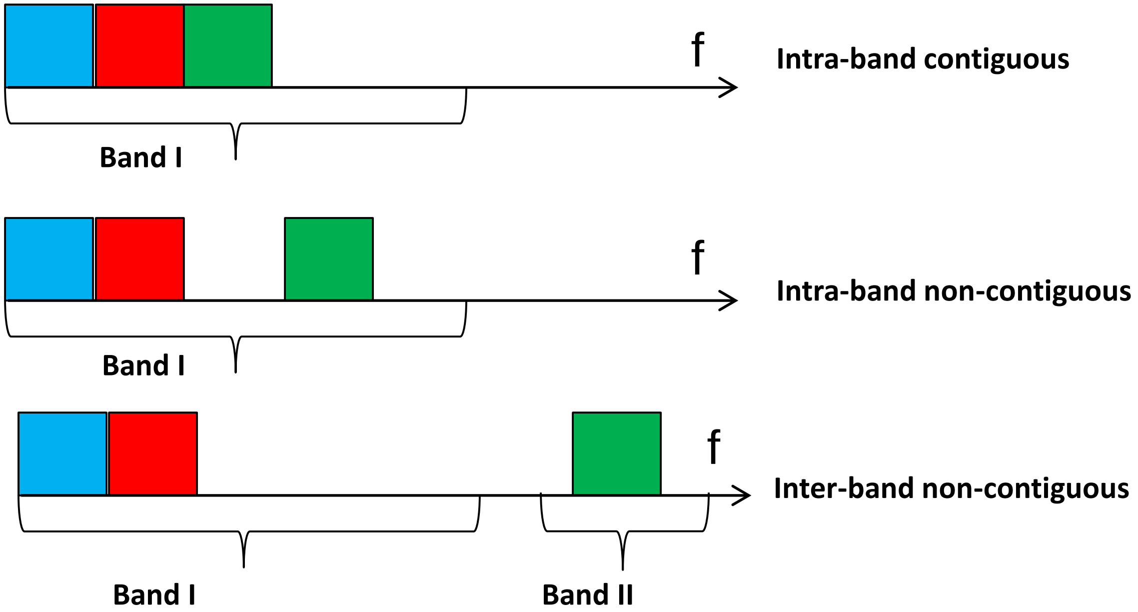


- **Wideband transmitters** enable covering multiple bands with a single unit



Transmitter Demands

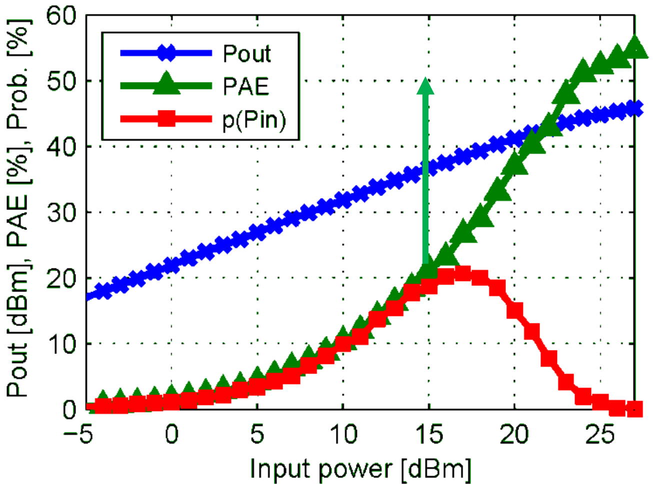
- Carrier aggregation in LTE-A for higher data rates

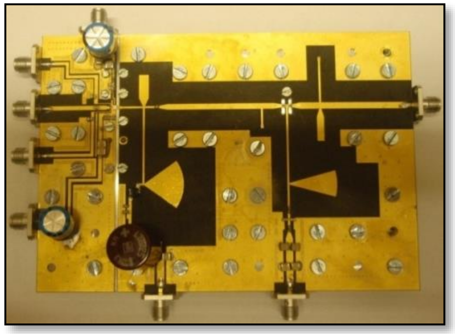


- In summary: **Energy efficient, large RF and signal bandwidth transmitters**

Traditional linear PA operation

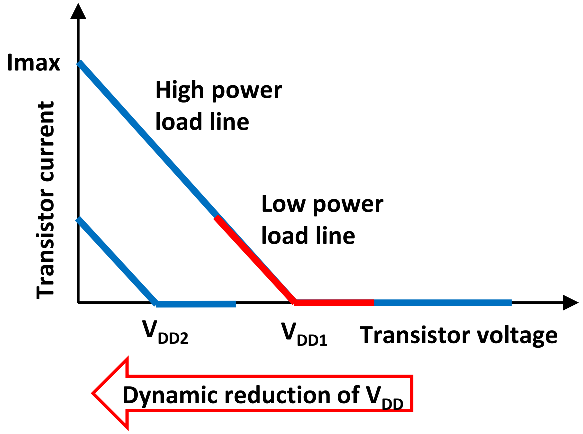
- The peak output power is determined by PA saturation
  - PA efficiency is maximum close to saturation
  - Operating it into compression results in severe distortion

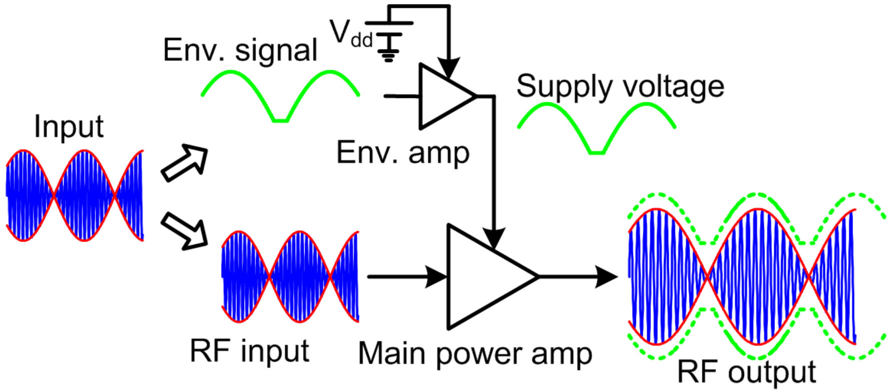


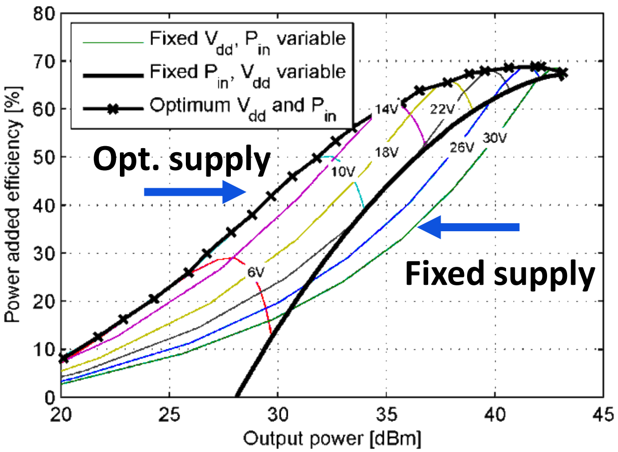


- The total PA efficiency is weighted by the signal input power probability density function
  - For this case: Peak PAE = 55%, total average PAE = 22%

Efficiency enhancement via Supply modulation

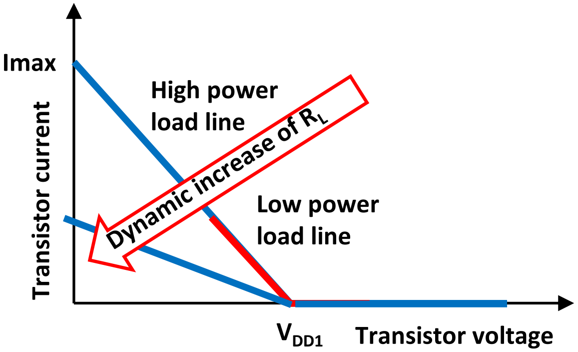


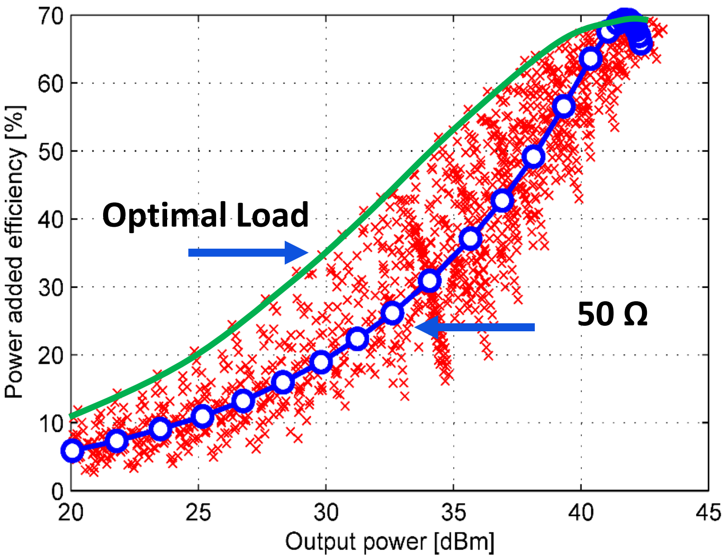


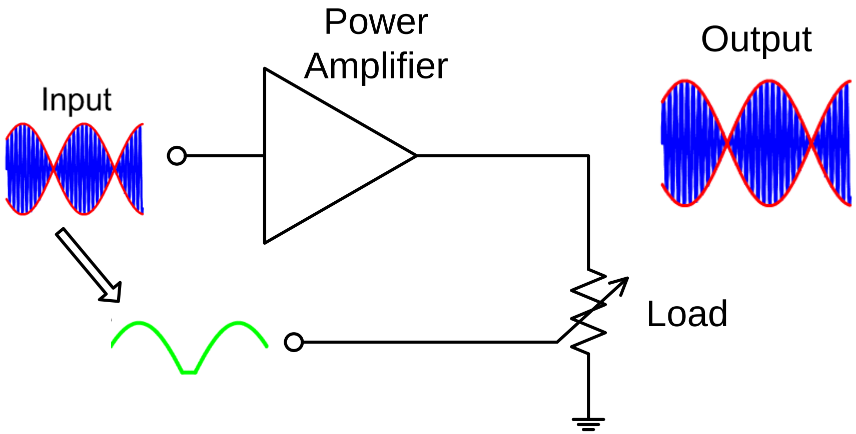


- Provides large RF bandwidth ☺
- Difficult to power scale at large instantaneous signal bandwidths ☹
- More suitable for handsets

Efficiency enhancement via load modulation







- High power realization at large signal bandwidths ☺
- Challenging to achieve large **RF bandwidth ☹**

Outline

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  - Varactor based dynamic load modulation
  - Doherty power amplifiers (PA)
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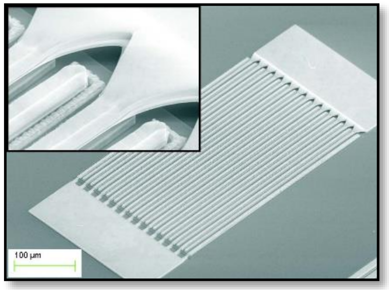
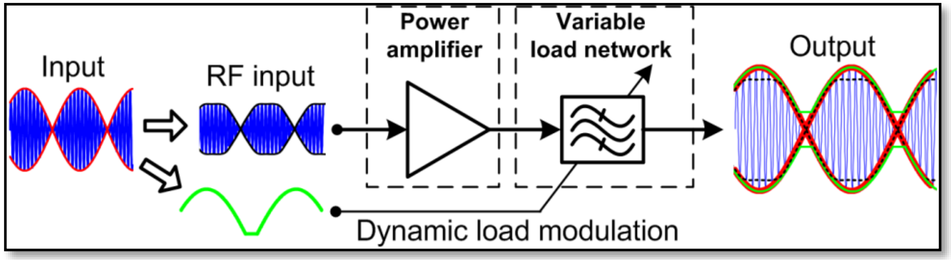
  - Mixed Doherty-outphasing techniques



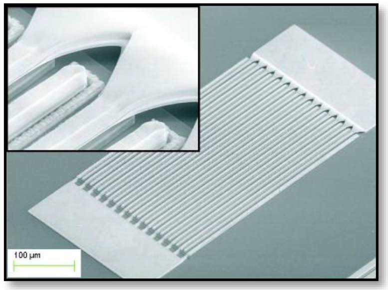
- Summary

Varactor based DLM

- Variation of output power by dynamically tuning the PA load network



Chalmers SiC varactors



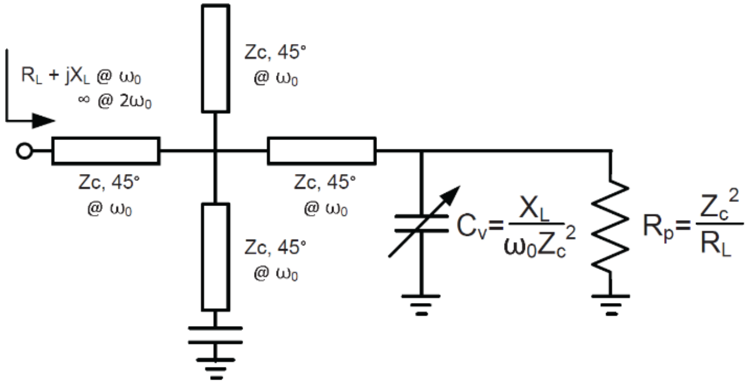
- Varactors typically used as tuneable elements
  - Breakdown voltage > 100V
  - Low series resistance, large tuning range
- Simple and efficient control electronics
  - No need for high power dc converters etc.
  - Potentially wideband modulation

Varactor-based DLM

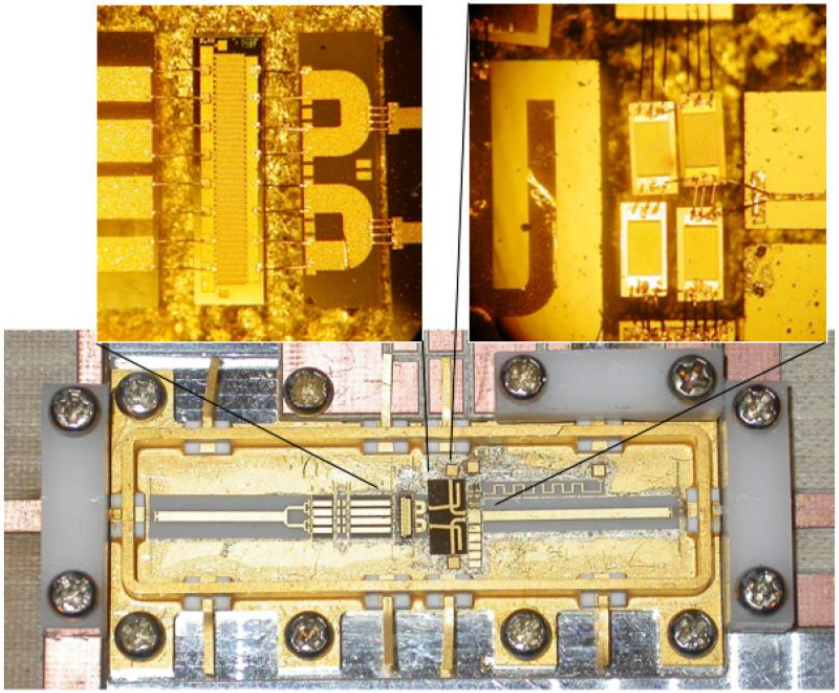
High power demonstrator

[C. M. Andersson, et. al, "A Packaged 86 W GaN Transmitter with SiC Varactor-based Dynamic Load Modulation", EuMC 2013]

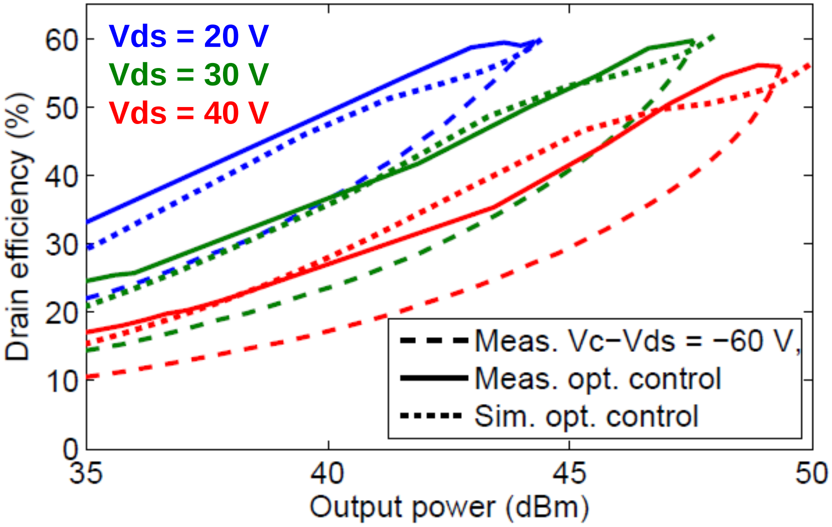
Power scalable load network topology

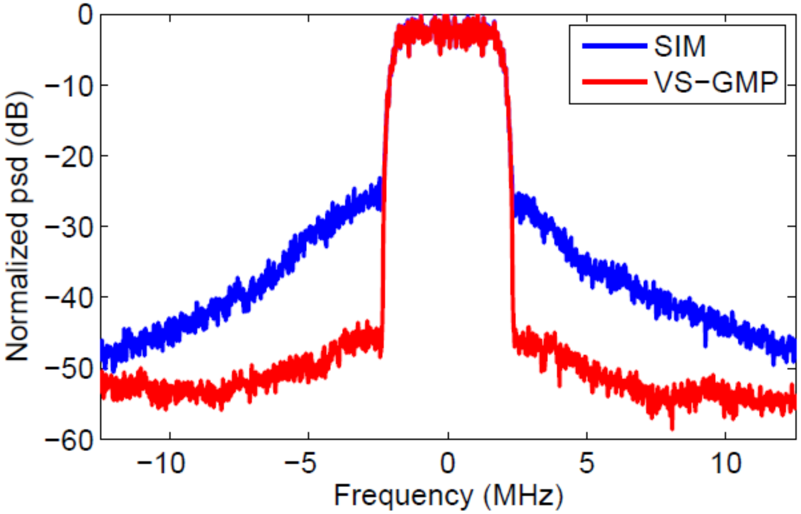


Packaged (40x20mm) 100W GaN demo



Results @ 2.14 GHz



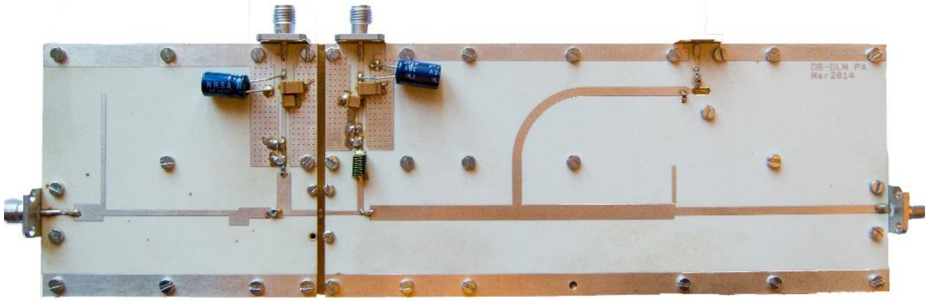


- Peak power = 86W
- 6.7 dB PAPR WCDMA signal
  - ACLR < -46 dBc
  - 34% average efficiency
- Losses in load network limits efficiency enhancement

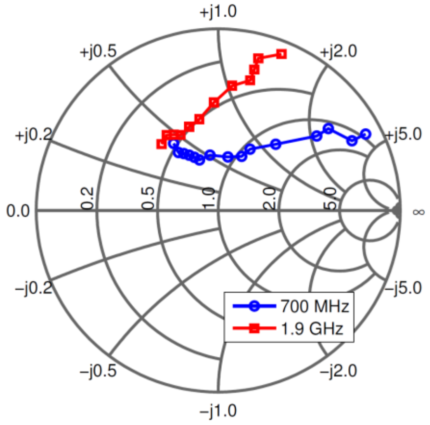
Dual-band Varactor-based DLM

- Dual band operation
  - 700 MHz & 1900 MHz
- Double stub tuner

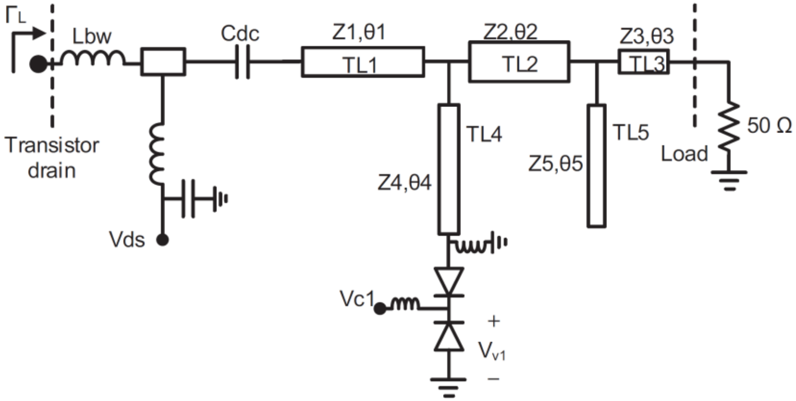
Dual band DLM PA prototype



Optimal load trajectories



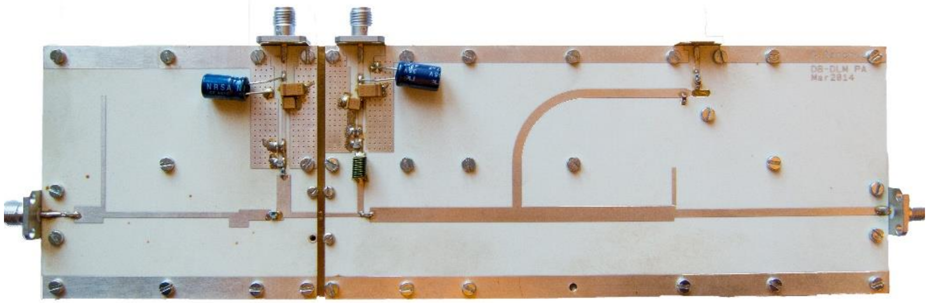
Dual band tunable load network



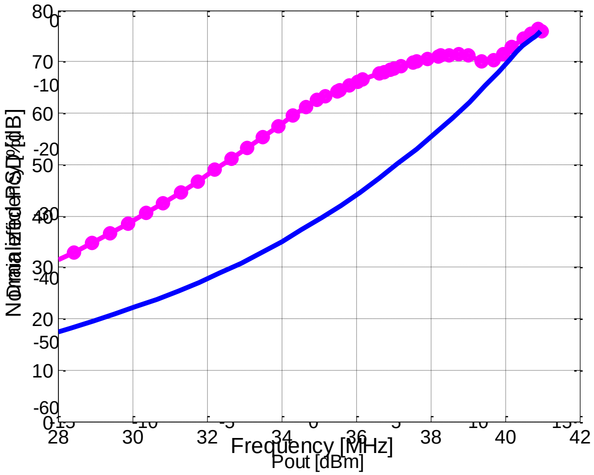
Dual-band Varactor-based DLM

- Dual band operation
  - 700 MHz & 1900 MHz
- Double stub tuner

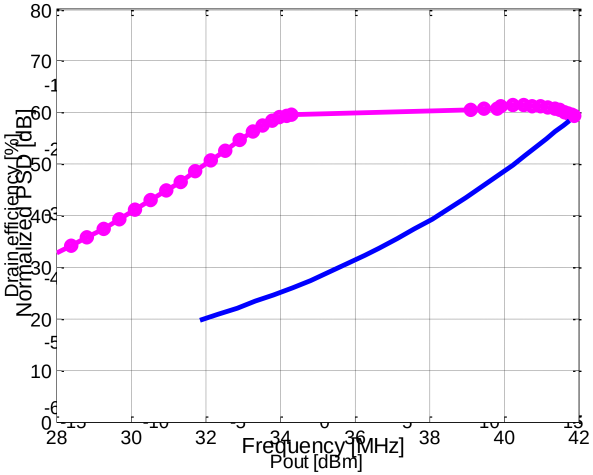
Dual band DLM PA prototype



Lower band



Upper band



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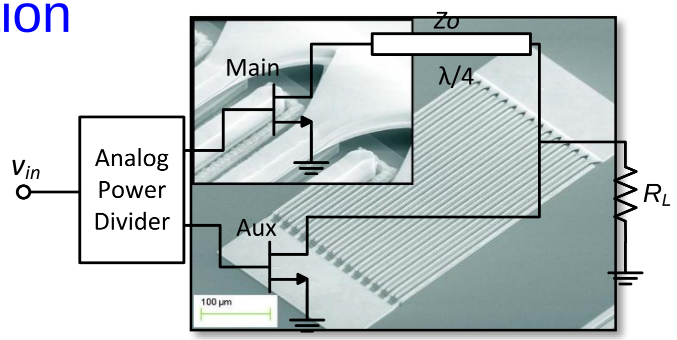
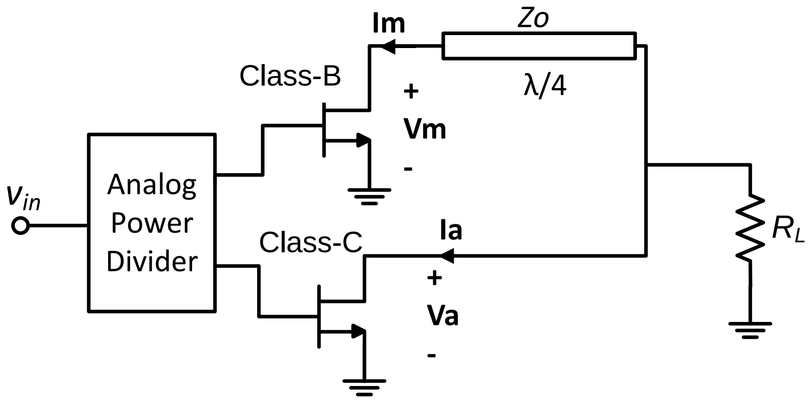
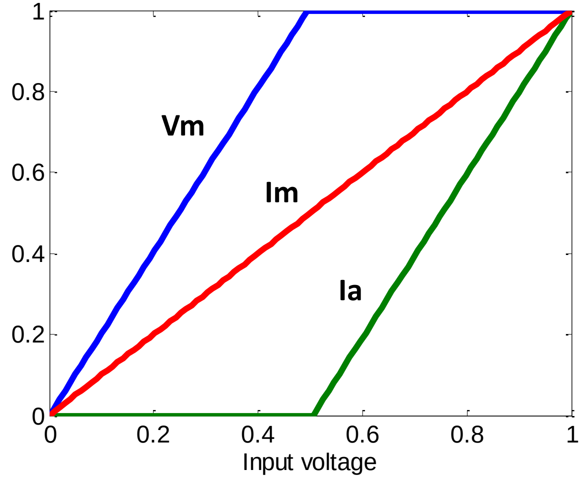


Conventional Doherty PA Concept

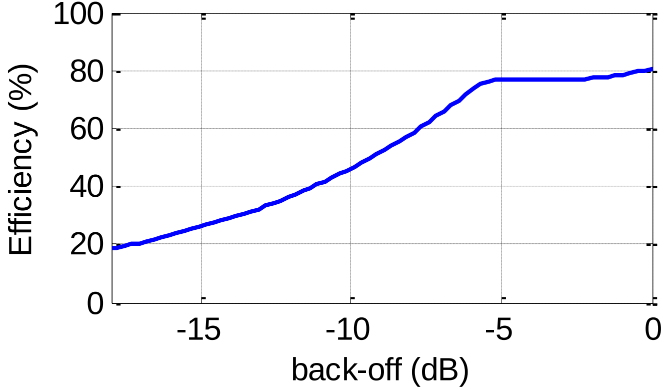
Conventional Doherty PA



Transistor voltages and currents

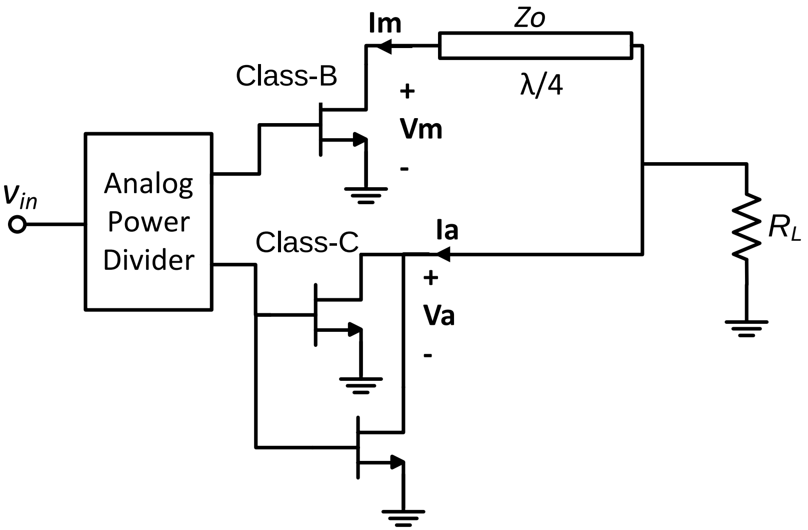


Ideal efficiency

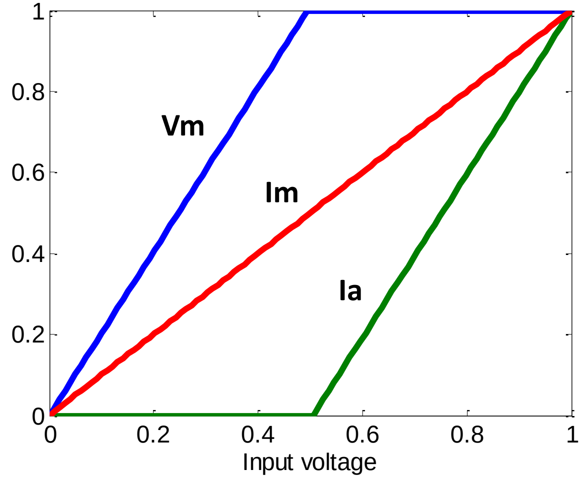


Conventional Doherty PA Concept

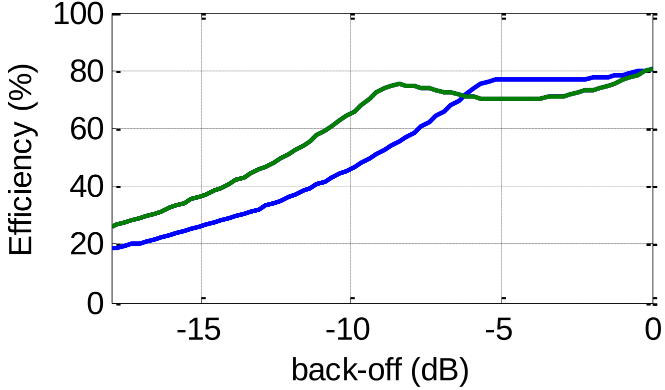
Conventional Doherty PA



Transistor voltages and currents



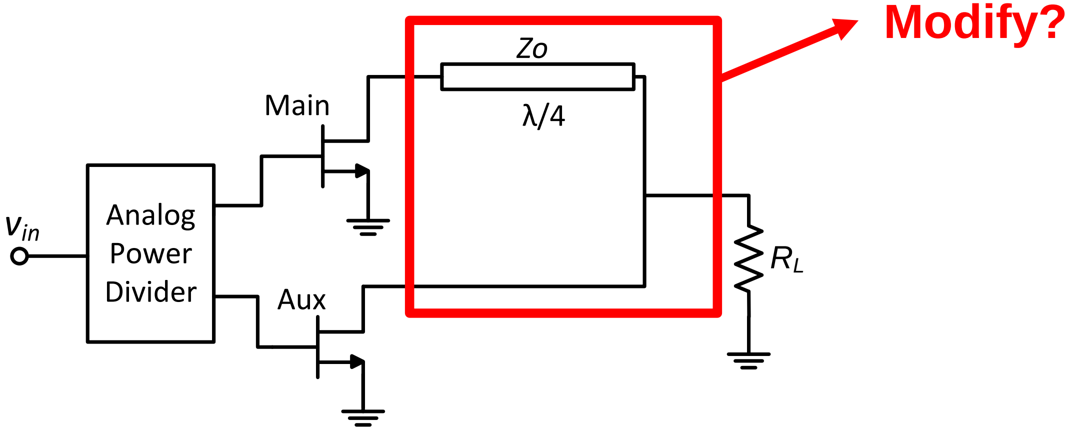
Ideal efficiency



- Higher PAPR→Larger class-C
  - Lower gain and PAE ☹
  - Uneven power division ☹
- Increased manufacturing cost ☹

Hypothesis

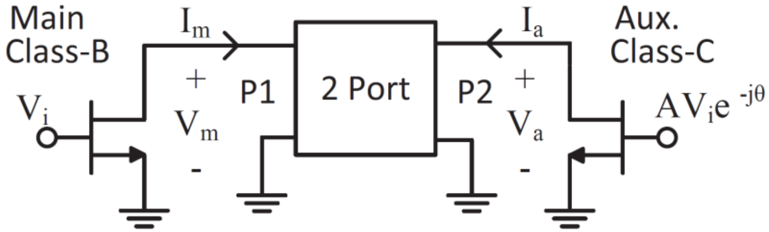
- Large efficiency range (>6 dB) with identical devices?



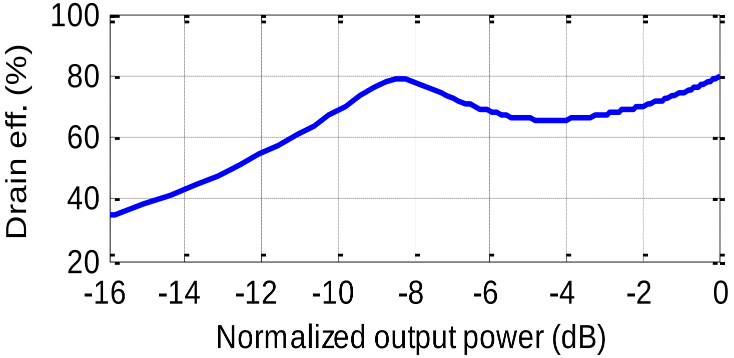
- Devices should be fully utilized
  - Both devices are biased with nominal V_{DD}
  - Use all available current

Novel Symmetrical Doherty PA

Schematic used for the derivations



Efficiency of symmetrical Doherty PA



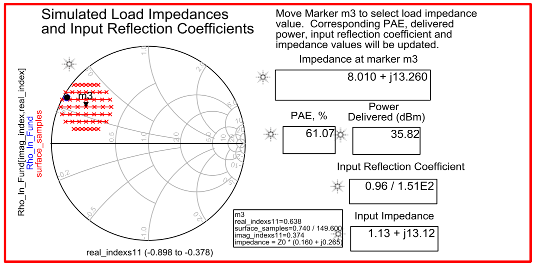
- Calculate the combiner network parameters assuming **identical** devices

Boundary Conditions:

  - Efficiency range (arbitrary)
  - Class-B and class-C impedances at peak power & back-off

Novel Symmetrical Doherty PA

3.5 GHz Hardware Demonstrator



Simulated Load Impedances
and Input Reflection Coefficients

Move Marker m3 to select load impedance value. Corresponding PAE, delivered power, input reflection coefficient and impedance values will be updated.

Impedance at marker m3: 8.010 + j13.260

PAE, %: 61.07

Power Delivered (dBm): 35.82

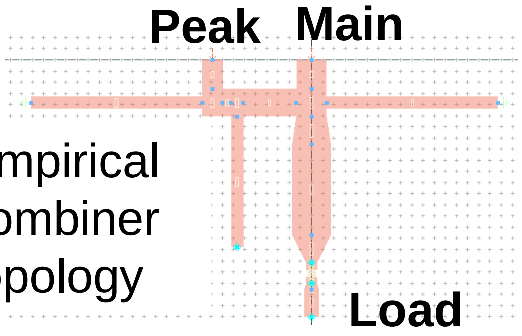
Input Reflection Coefficient: 0.96 / 1.51E2

Input Impedance: 1.13 + j13.12

m3
real_indexs11=0.638
surface_samples=0.740 / 149.600
imag_indexs11=0.374
impedance = Z0 * (0.160 + j0.265)

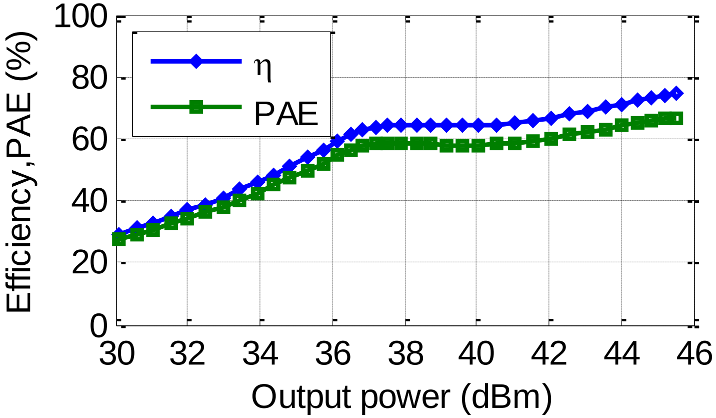
load pull data

- Combiner S-parameters:
  - $S_{11} = -0.81 + j0.24$
  - $S_{21} = -0.022 - j0.38$
  - $S_{22} = -0.27 + j0.24$



Empirical combiner topology

Cut-ready simulation results

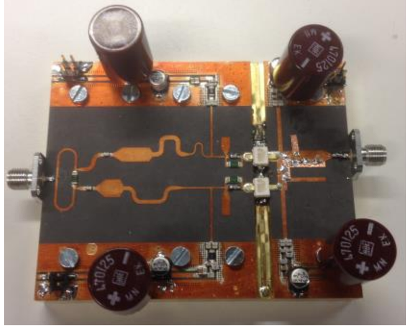


Novel Symmetrical Doherty PA

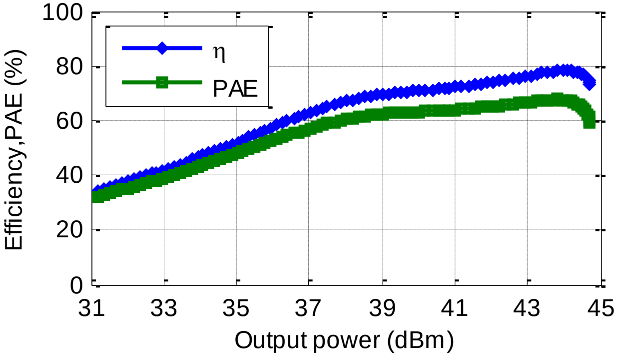
Experimental verification

- A 3.5 GHz 30 watt GaN HEMT symmetical Doherty PA prototype

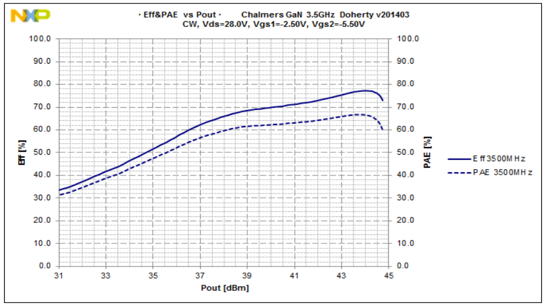
Fabricated prototype



Static efficiency results



Cross-verified at NXP
(Credits Reza Abdoelgafoer)



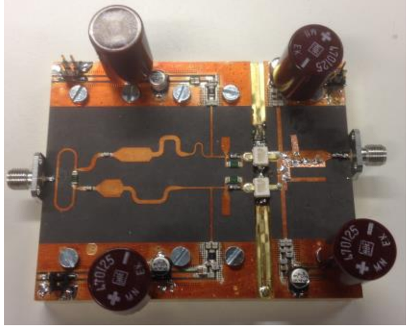
- A **record high PAE** of 55% at 8 dB back-off
  - Symmetrical devices & novel load-pull based combiner design approach

Novel Symmetrical Doherty PA

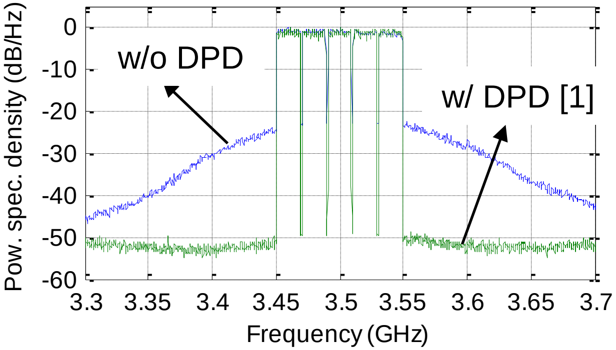
Experimental verification

- Tested with carrier aggregated 100 MHz (5x20) OFDM signals

Fabricated prototype



Output spectrum with 100 MHz OFDM signals

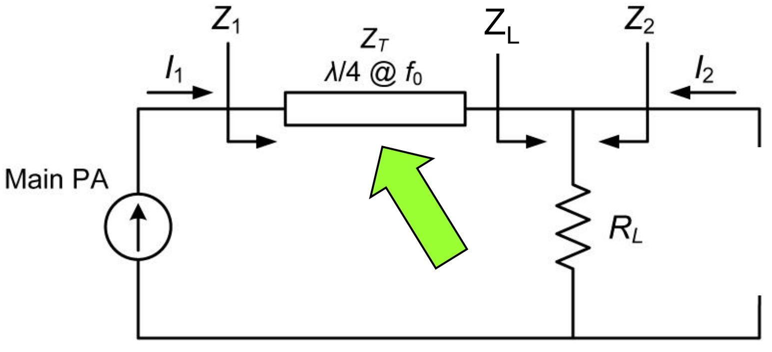


- -50 dBc ACLR with 100 MHz signals.
  - 5 dB margin to spectral mask.
  - **High efficiency with excellent linearity**

[1] S. Afsardoost, T. Eriksson, and C. Fager, "Digital Predistortion Using a Vector-Switched Model," *IEEE T-MTT,* 2012

A Novel Wideband Doherty

[D. Gustafsson et al., "A Modified Doherty Power Amplifier With Extended Bandwidth and Reconfigurable Efficiency," IEEE T-MTT, Jan. 2013]



Doherty PA topology

Frequency response at the peak power

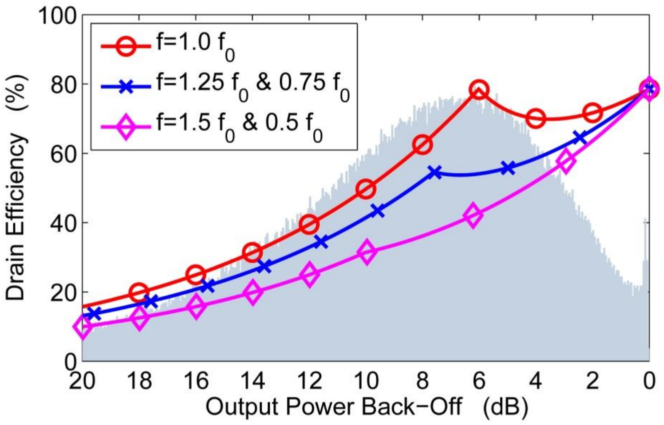
Frequency response at back-off

$$Z_1 = Z_T \frac{Z_L + jZ_T \tan(\frac{\pi}{2}\frac{f}{f_o})}{Z_T + jZ_L \tan(\frac{\pi}{2}\frac{f}{f_o})}$$

$$Z_1 = Z_T \frac{R_L + jZ_T \tan(\frac{\pi}{2}\frac{f}{f_o})}{Z_T + jR_L \tan(\frac{\pi}{2}\frac{f}{f_o})}$$

$$Z_1 = Z_T$$

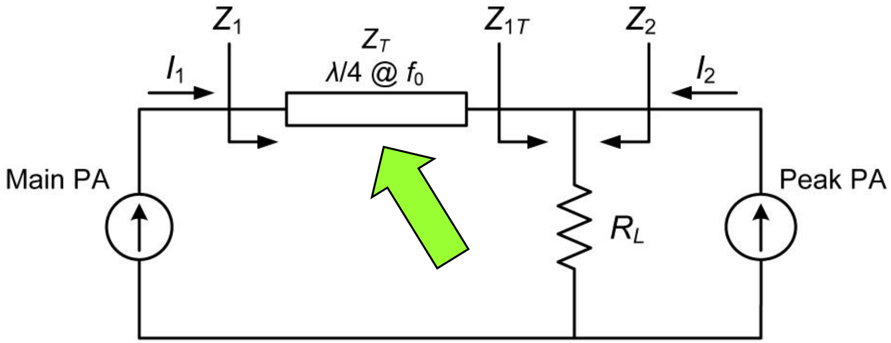
Doherty PA



Back-off efficiency is strongly frequency dependent!

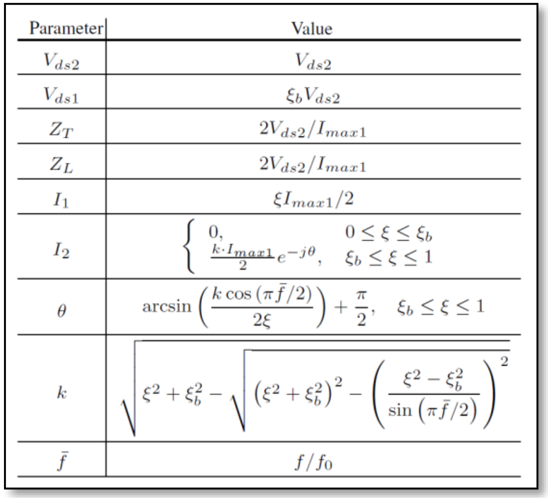
A Novel Wideband Doherty

[D. Gustafsson et al., "A Modified Doherty Power Amplifier With Extended Bandwidth and Reconfigurable Efficiency," IEEE T-MTT, Jan. 2013]



Doherty PA topology

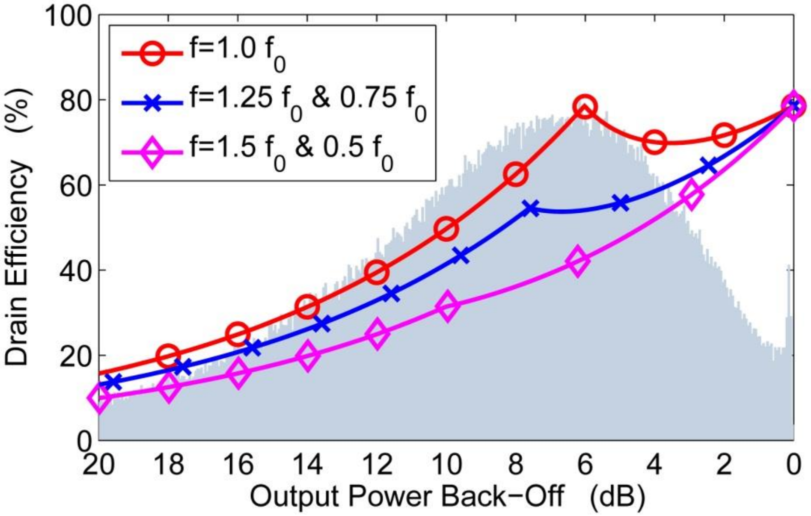
- Doherty PA
  - Backoff efficiency bandwidth limited by λ/4 impedance inverter
  - $Z_T \neq R_L$
- Proposed PA
  - $Z_T \equiv R_L$
  - New drive scheme and biasing



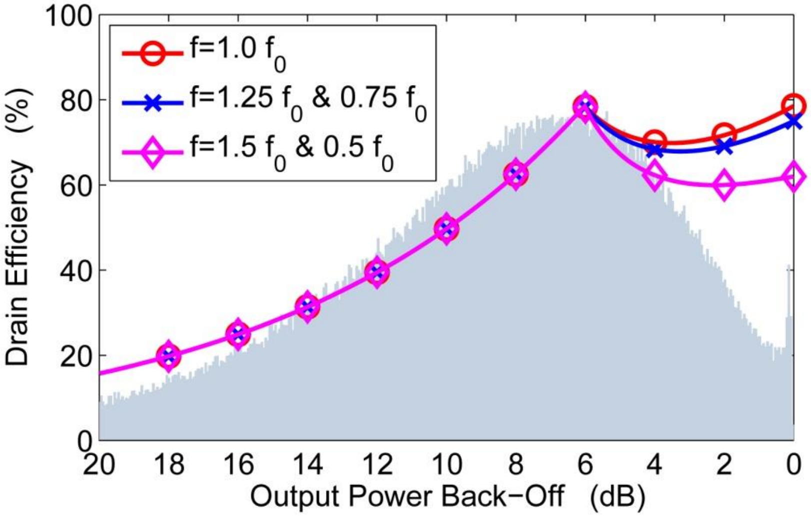
Parameter	Value
V_{ds2}	V_{ds2}
V_{ds1}	$\xi_b V_{ds2}$
Z_T	$2V_{ds2}/I_{max1}$
Z_L	$2V_{ds2}/I_{max1}$
I_1	$\xi I_{max1}/2$
I_2	$\begin{cases} 0, & 0 \leq \xi \leq \xi_b \\ \frac{k \cdot I_{max1}}{2} e^{-j\theta}, & \xi_b \leq \xi \leq 1 \end{cases}$
θ	$\arcsin\left(\frac{k\cos\left(\pi\bar{f}/2\right)}{2\xi}\right) + \frac{\pi}{2}, \quad \xi_b \leq \xi \leq 1$
k	$\sqrt{\xi^2 + \xi_b^2 - \sqrt{\left(\xi^2+\xi_b^2\right)^2 - \left(\frac{\xi^2 - \xi_b^2}{\sin\left(\pi\bar{f}/2\right)}\right)^2}}$
$\bar{f}$	f/f_0

Bandwidth performance

Doherty PA



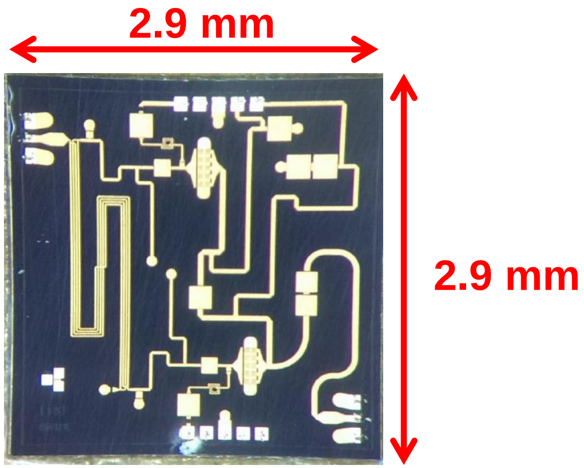
Proposed PA

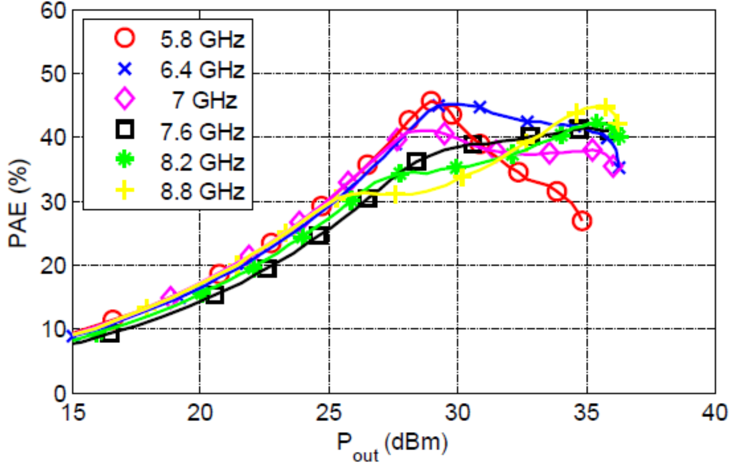


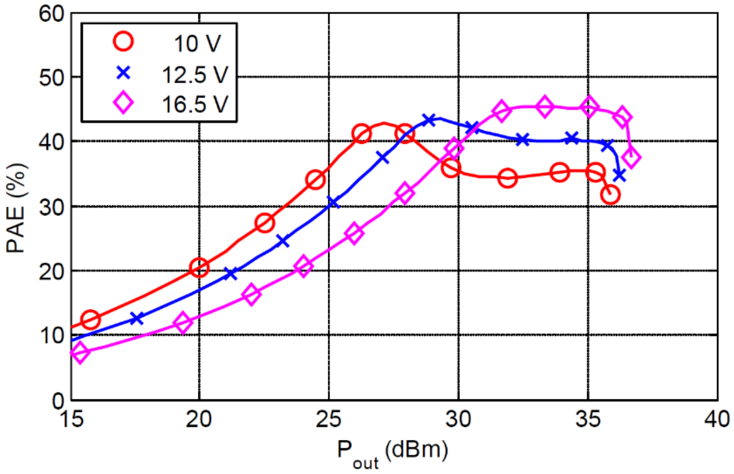
- Frequency independent backoff efficiency
- Extended average efficiency bandwidth

A Novel Wideband Doherty GaN MMIC Demonstrator

- TriQuint 0.25µm GaN process
- 5.7-8.8 GHz (42% bandwidth)
- PAE: 30-39% @ 9 dB BO
- Reconfigurable PAE shape by V_{dd}/V_{gg} adjustments only

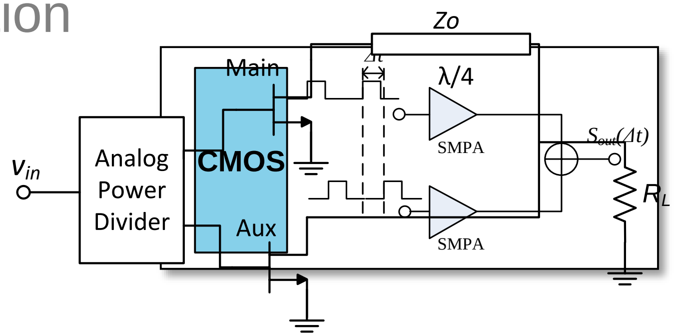



Large PAE bandwidth


Reconfigurable PAE @ 6.4 GHz

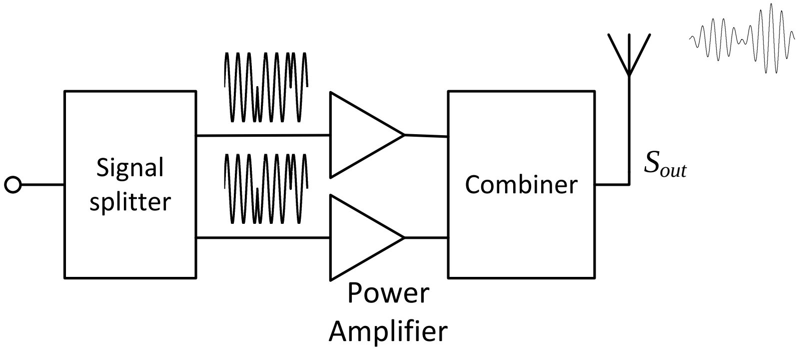
Outline

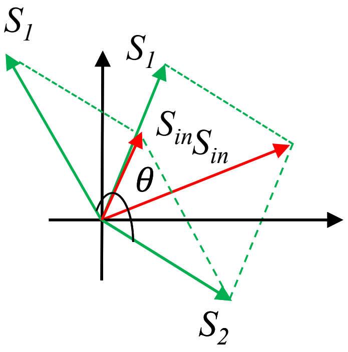
- Background
- Energy efficient wideband transmitter architectures
  - Varactor based dynamic load modulation
  - Doherty power amplifiers (PA)
  - Outphasing PAs
  - Mixed Doherty-outphasing techniques
- Summary



Outphasing Transmitter Architecture

- Two constant envelope signals are summed to achieve amplitude modulation
- Possibility for high efficiency switch mode operation



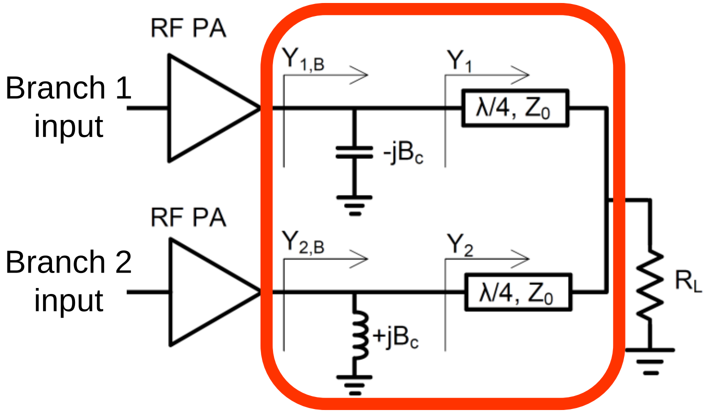


- Combiner determines the interaction between the PAs

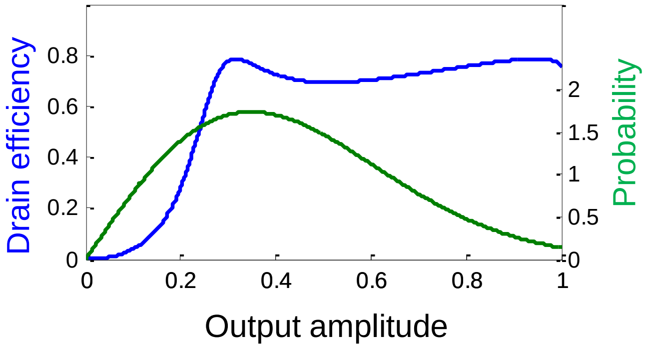
Chireix Outphasing Combiner

- Chireix outphasing combiner enables proper load modulation and thus high efficiency.

Chireix combiner



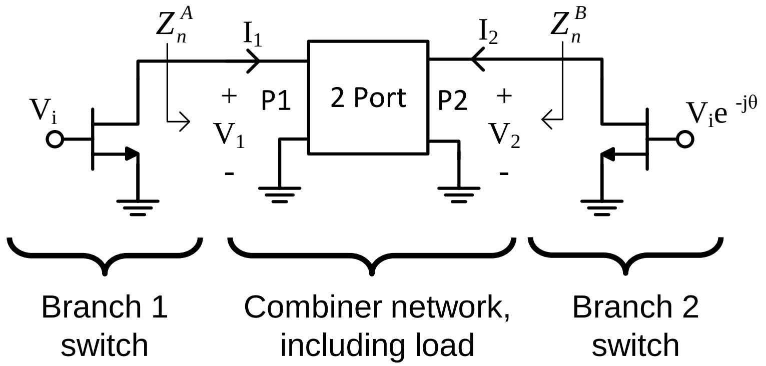
Efficiency of Chireix System



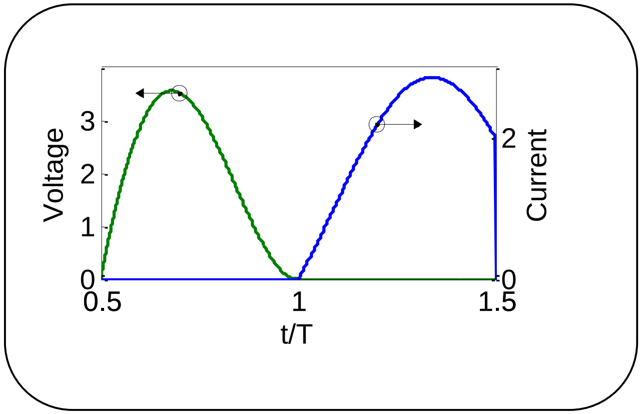
- Combiner is inherently narrowband (~5% efficiency bandwidth).
  - Mainly due to quarter wave transformers.

Novel Outphasing Combiner Design Approach

- Combiner network parameters are derived from the boundary conditions
  - The transistors experience optimal class-E impedances at peak and average power levels

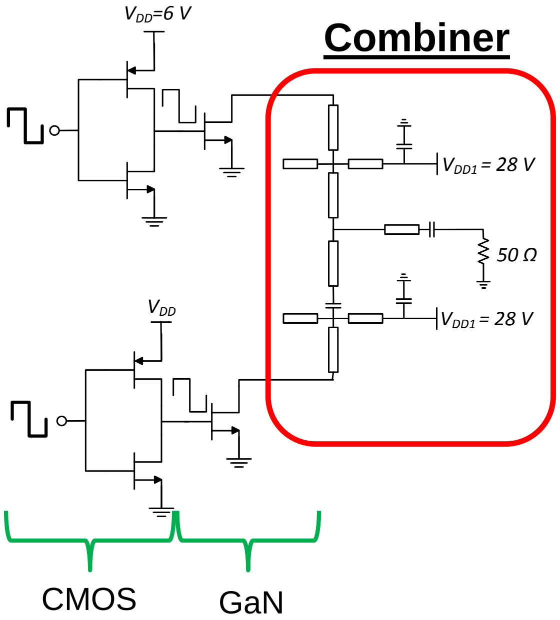


Class-E PA Waveforms

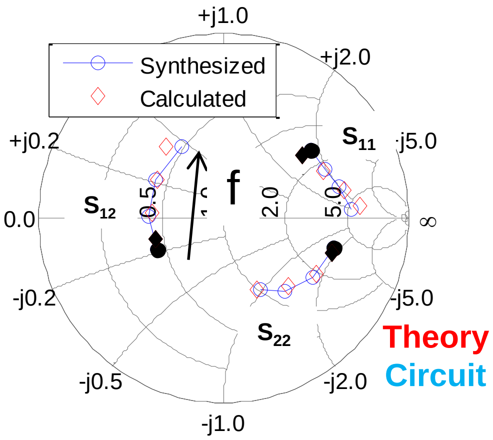


Wideband Outphasing Transmitter Realization

- A 25 W 750-1050 MHz CMOS-GaN HEMT transmitter prototype
  - Combiner S-parameter continuum is mapped to the frequency response of practical network



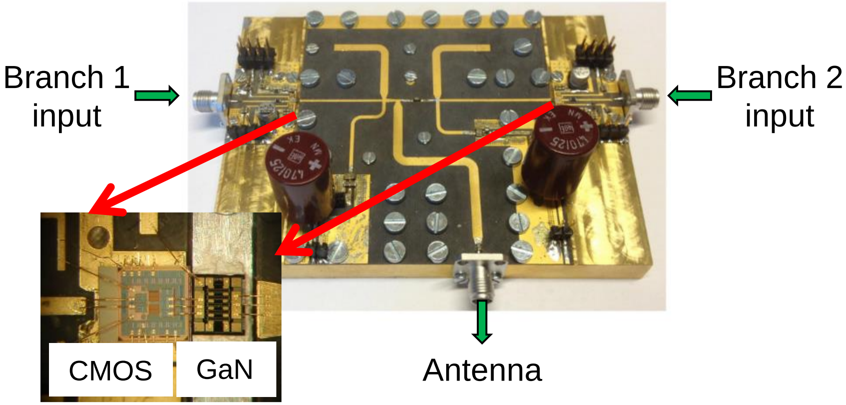
Combiner S-parameters



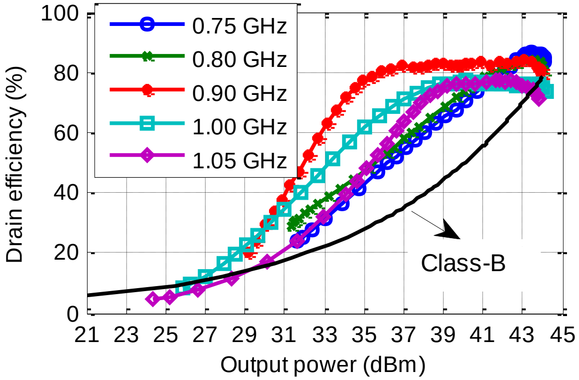
Wideband Outphasing Transmitter

Experimental Results

Fabricated prototype



Measured Drain efficiency



- Efficiency improvement is 20 to 40 percentage units
  - Efficiency enhancement, large RF bandwidth (33%) and possibility for high level of integration

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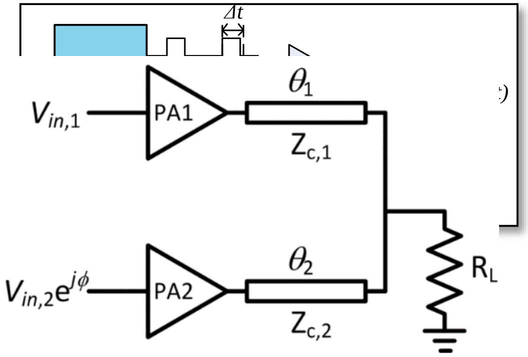
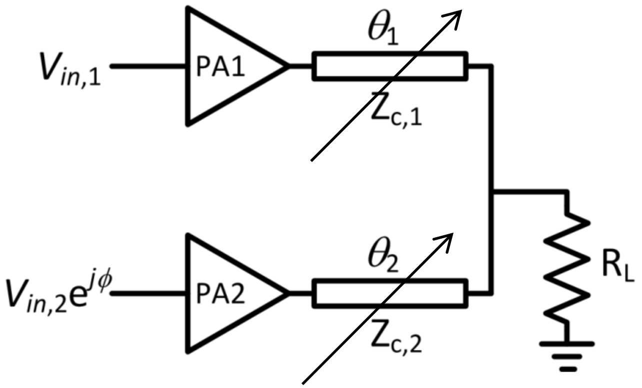
- Summary

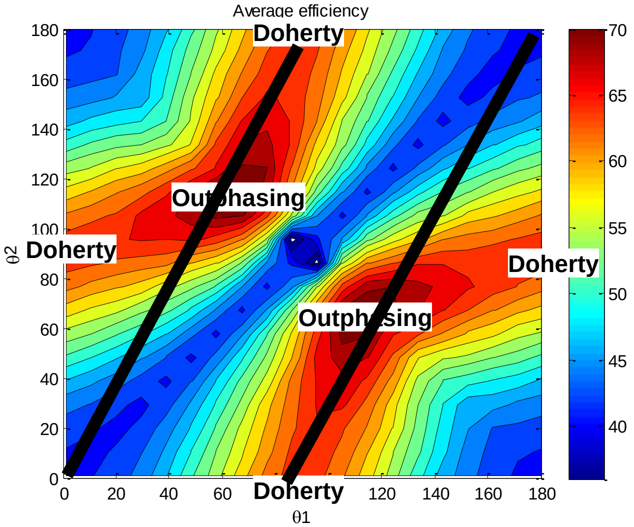


Outphasing/Doherty continuum

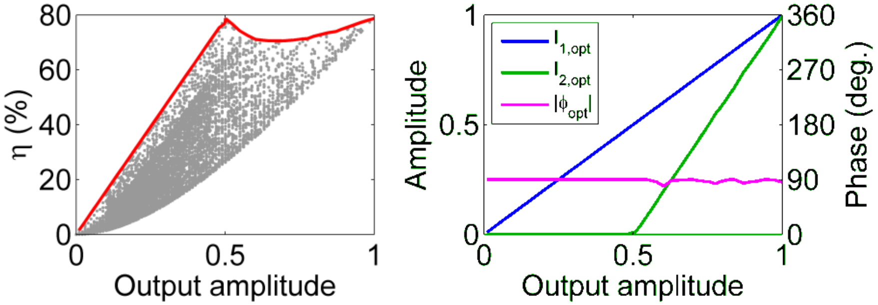
[C. Andersson et al., "A 1–3-GHz Digitally Controlled Dual-RF Input Power-Amplifier Design Based on a Doherty-Outphasing Continuum Analysis," IEEE T-MTT, 2013]

General dual-input PA

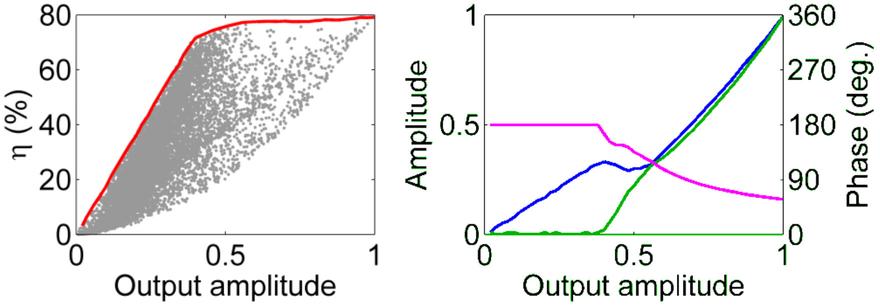




Doherty (θ_1 = 90°, θ_2 = 0°)



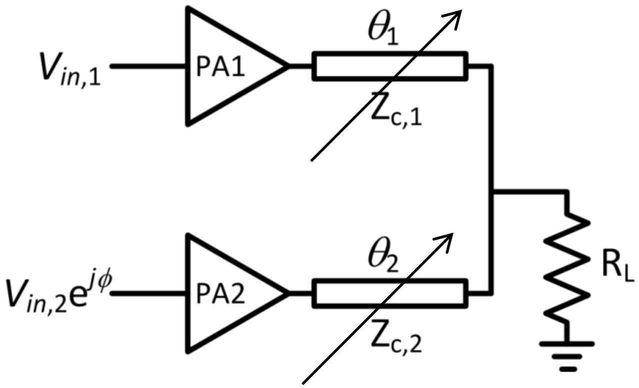
Outphasing (θ_1 = 114°, θ_2 = 57°)

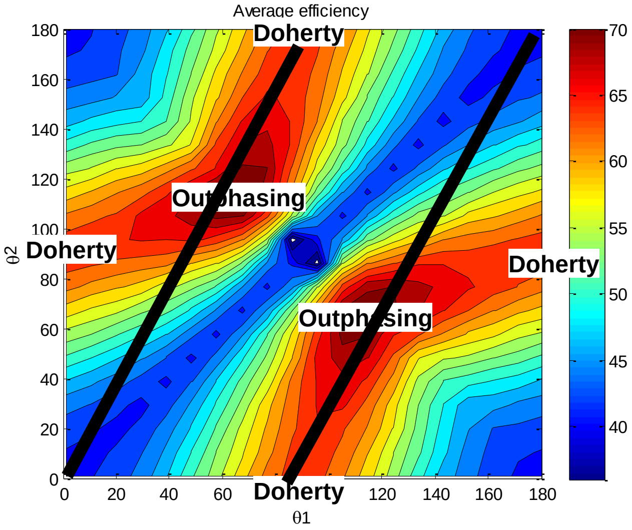


Outphasing/Doherty continuum

[C. Andersson et al., "A 1–3-GHz Digitally Controlled Dual-RF Input Power-Amplifier Design Based on a Doherty-Outphasing Continuum Analysis," IEEE T-MTT, 2013]

General dual-input PA

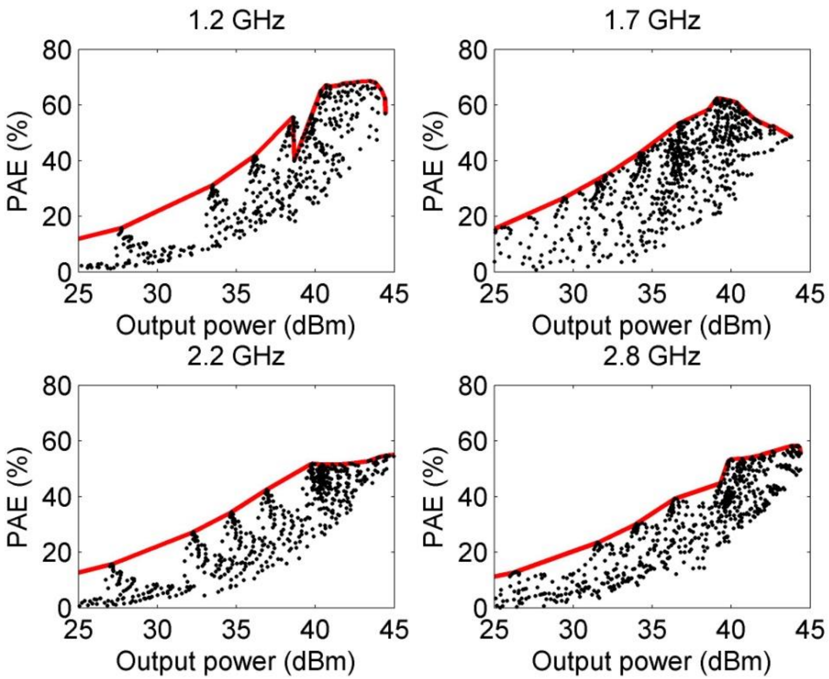




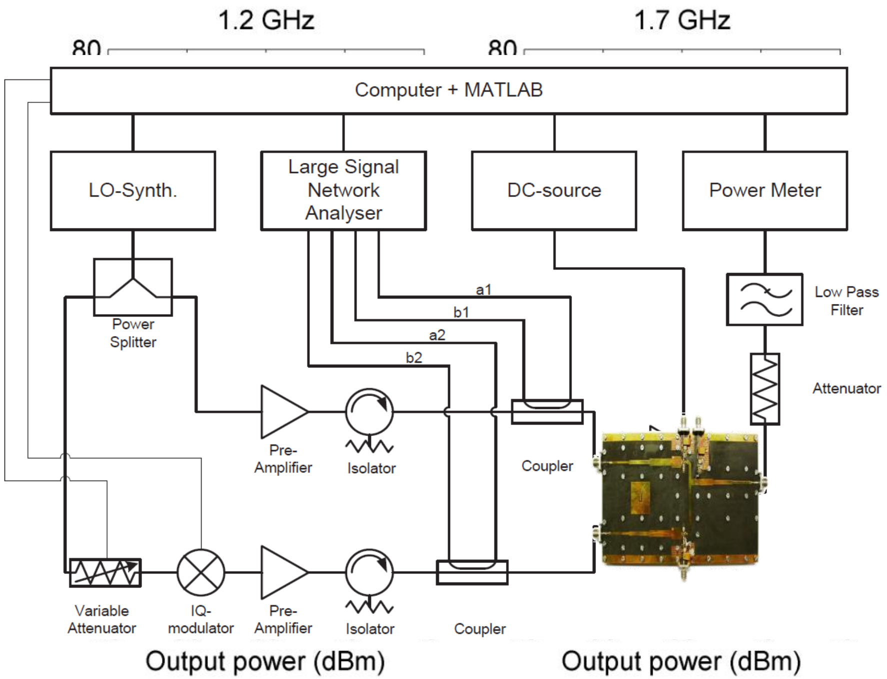
- Continuum between Doherty and outphasing operation
- Potential for >octave bandwidth and efficient operation
  - Class B (short circuited harmonics) assumed

Demonstrator results

ADS simulations

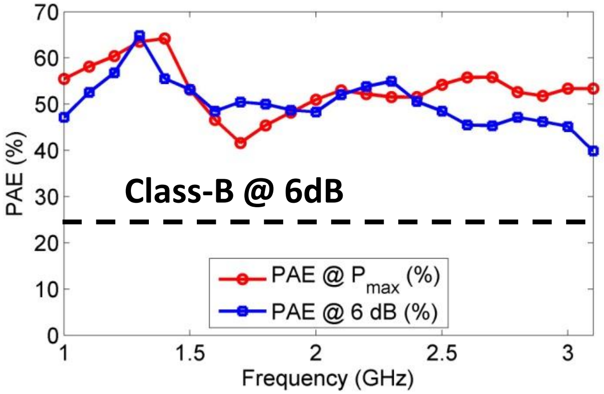


Measurements

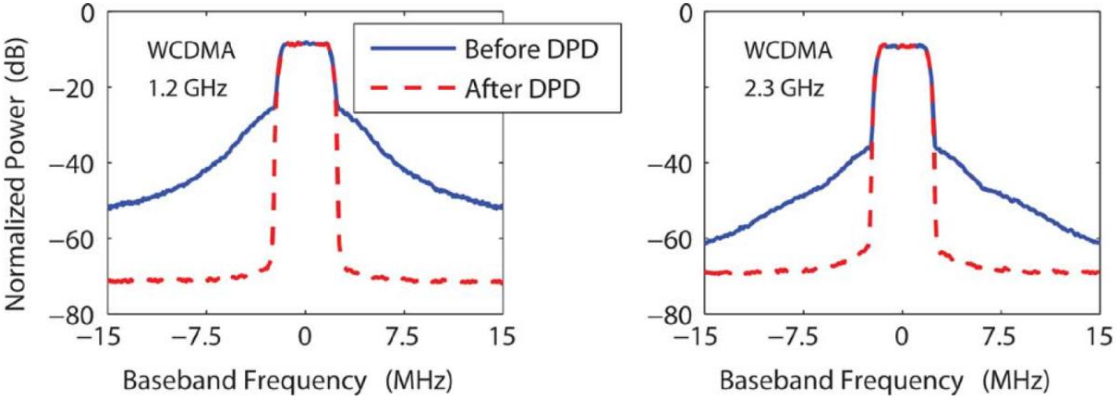


Excellent 1-3 GHz performance

- CW measurements
  - P_{max} = 44 ± 0.9 dBm
  - >45 % PAE at 6 dB OPBO from 1.0 – 3.0 GHz



- DPD linearized measurements
  - 5 MHz WCDMA
  - ACPR < -57 dBc
  - PAE > 40/50%



Summary

- Dynamic load modulation architectures
  - Varactor-based dynamic load modulation
  - Doherty PA
  - Outphasing PA
  - Mixed Doherty and outphasing techniques

- New circuits and design techniques
  - Enabling large RF bandwidhts (1-3 GHz)
  - Excellent linearity with 100 MHz carrier agg. OFDM signals
  - Reduced cost solutions (Symmetrical Doherty)

Acknowledgments

- …past and present power amplifier research collaborators


C. Fager
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T. Eriksson
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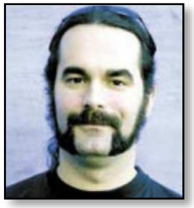
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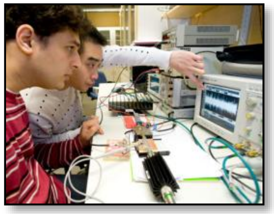
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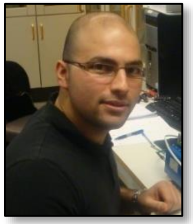
& Dr. H. Cao (Ericsson)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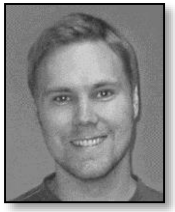
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F. Johansson
(MSc stud)

- Companies and research funding agencies

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