# Linearization Techniques for Power Amplifiers at the Device and Circuit Level (invited)

Leo de Vreede

PA Workshop, San Diego 2005

January 30, 2006



DIMES

TU Delft
Delft University of Technology

# Introduction

Improving for the linearity/efficiency trade-off is complex!

(it involves system, circuit & process technology considerations;)

Required:

knowledge of device non-linearities

+

Profound knowledge of RF circuit design

+

Non-linear RF characterization tools & models

||

Improved Circuit & Technology Design for Linearity



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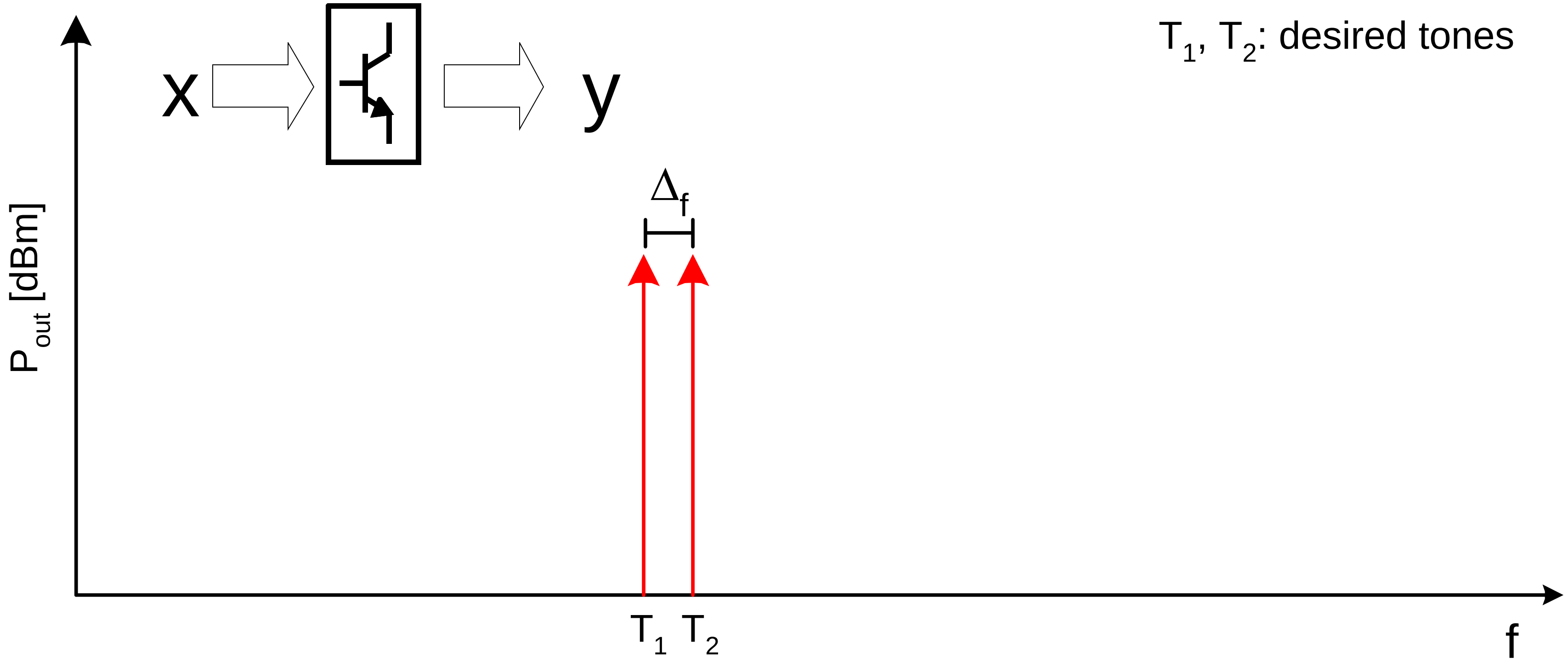
# Introduction: Linearization Basics

$y = a_1 x$ (linear response)

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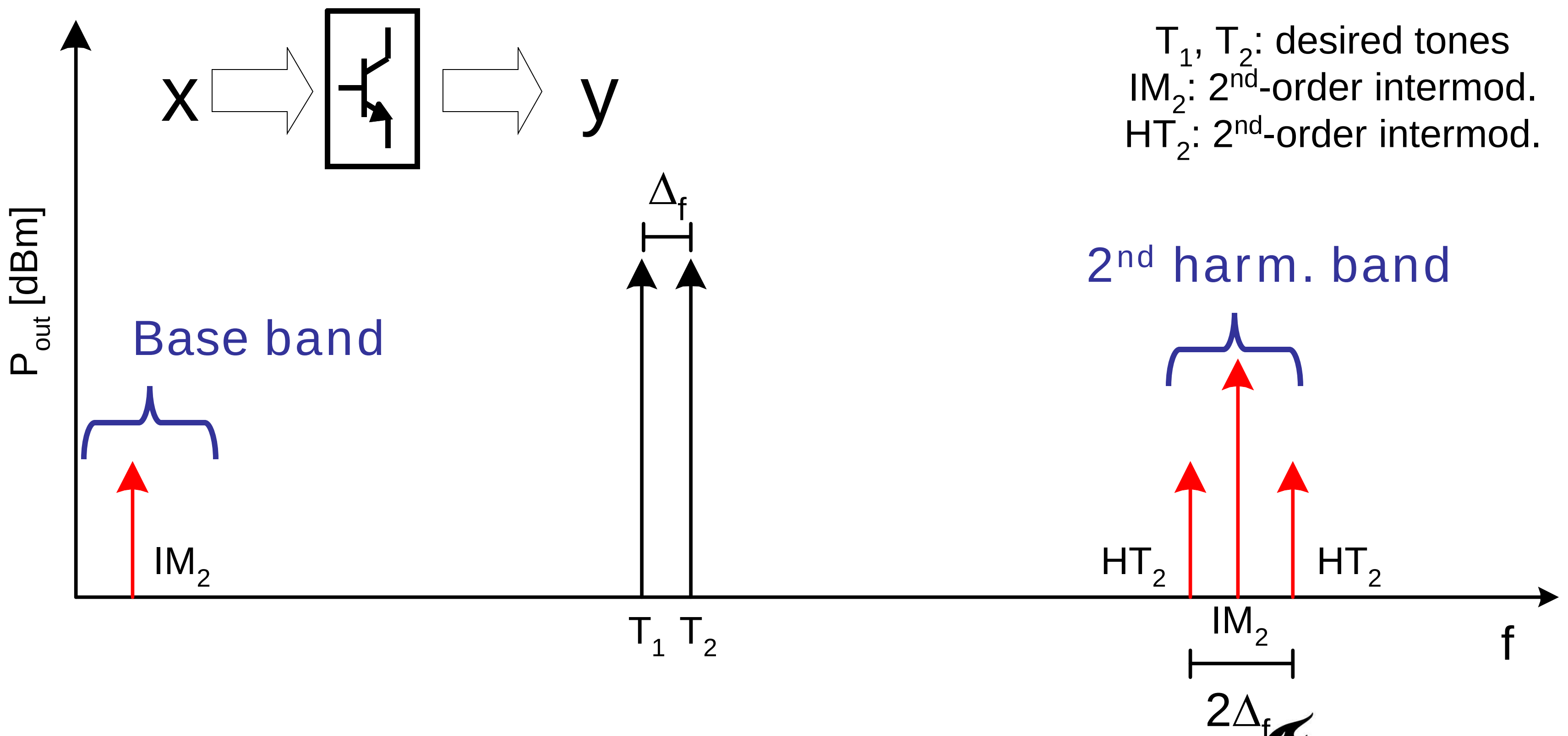
# Introduction: Linearization Basics

$y = ax + a_2 x^2$ (2nd-order intermod.)

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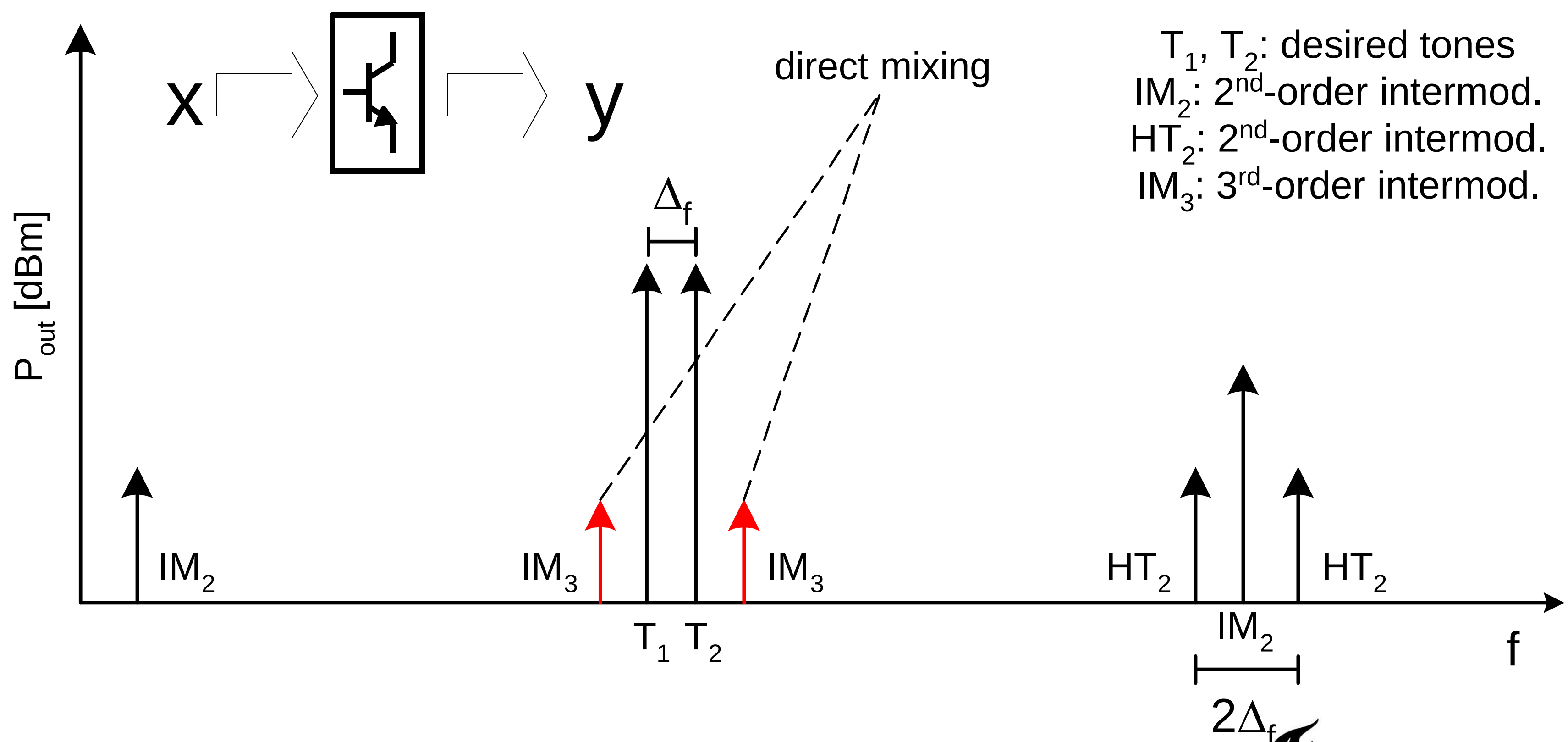
# Introduction: Linearization Basics

$y = ax + a_2x^2 + a^3x^3$ ($3^{rd}$-order intermod.)

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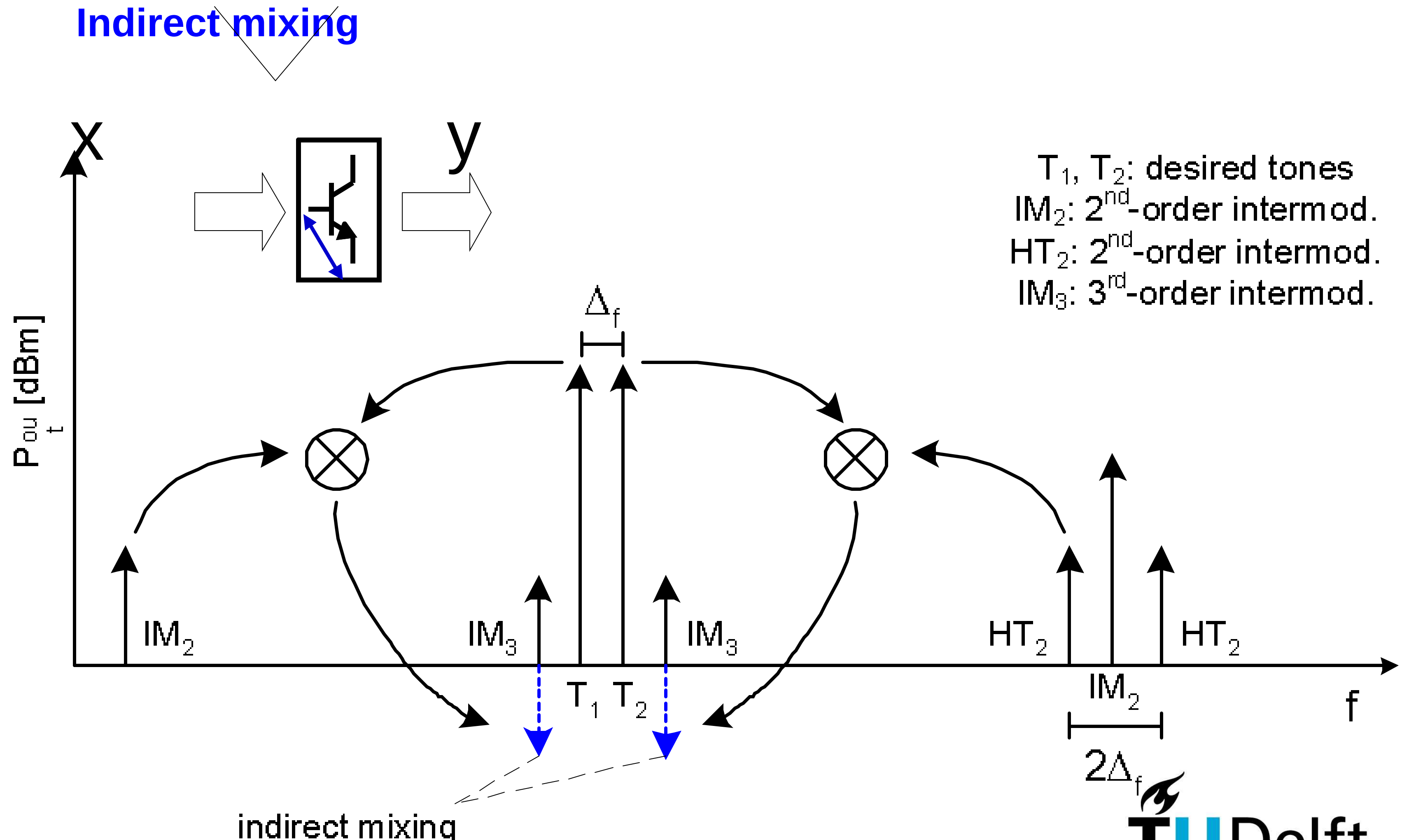
# Introduction: Linearization Basics

$y = ax_1 + a_2x^2 + a^3x^3$

**Indirect mixing**

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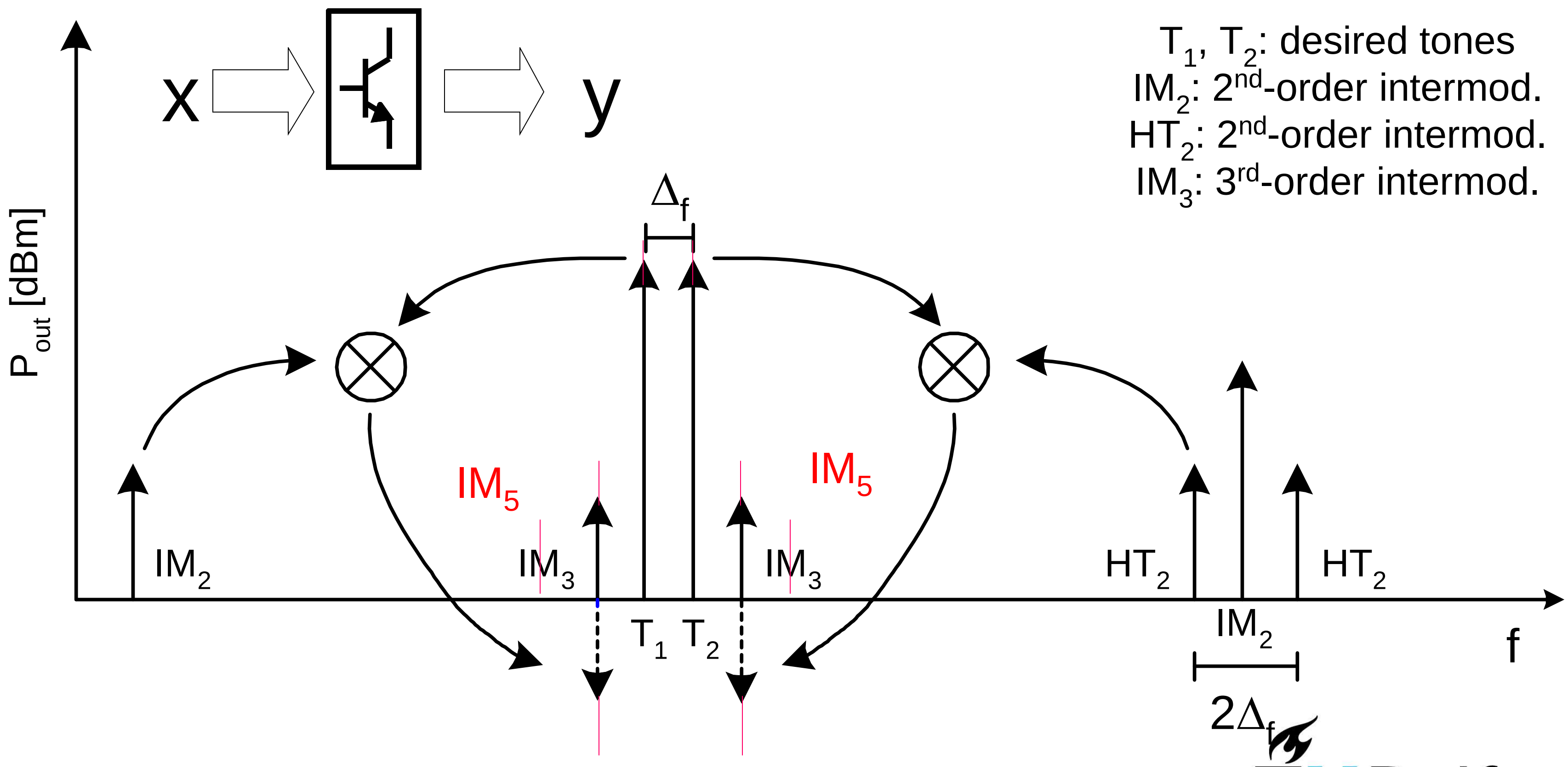
# Introduction: Linearization Basics

$y = ax_1 + a_2x^2 + a^3x^3 + ..$ Higher order terms (x)

Low power High power

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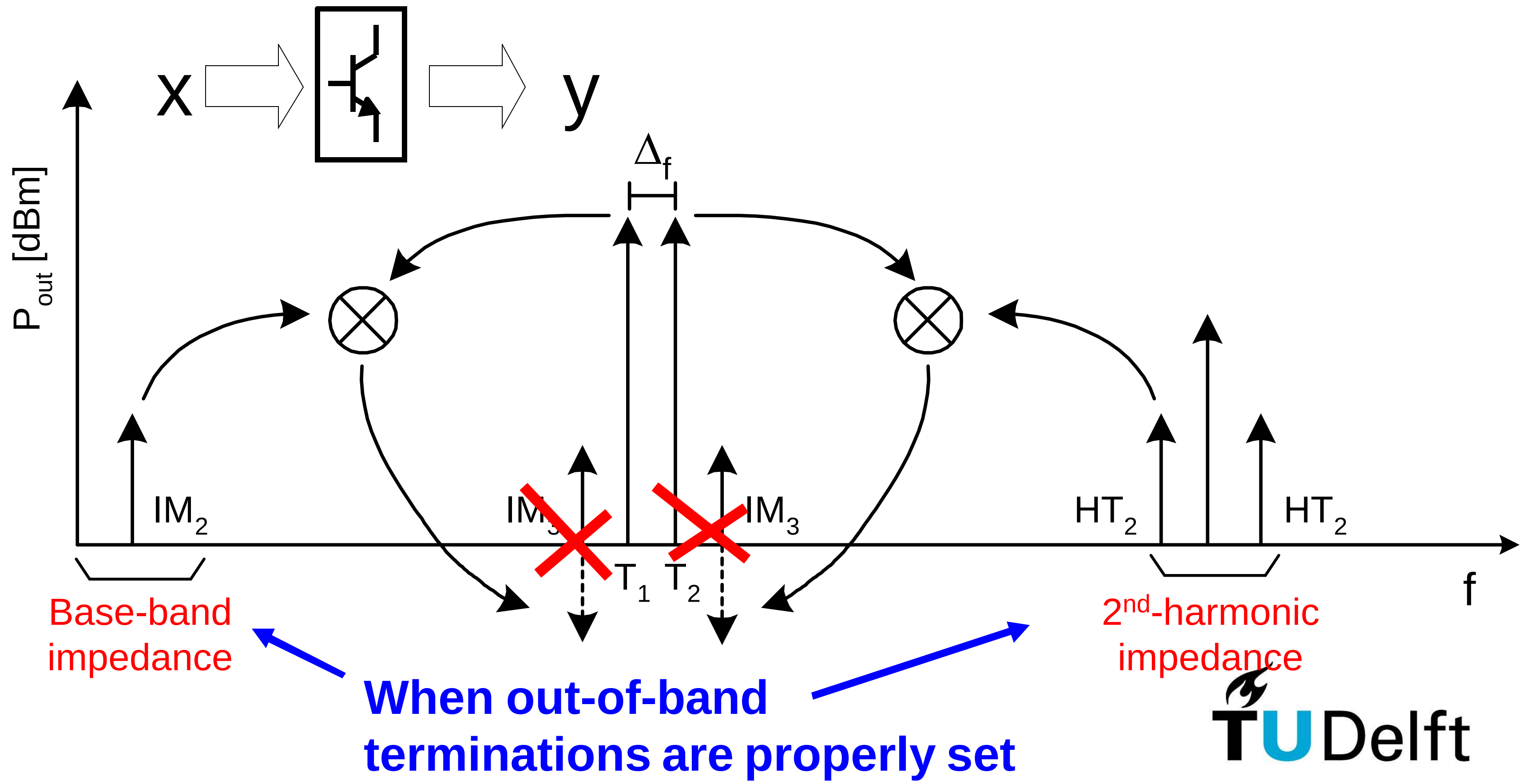
# Introduction: Linearization Basics

- IM$_3$ cancellation is achieved when direct and indirect products have equal amplitude and opposite phase, this can be controlled by the out-of-band impedances.

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# Overview

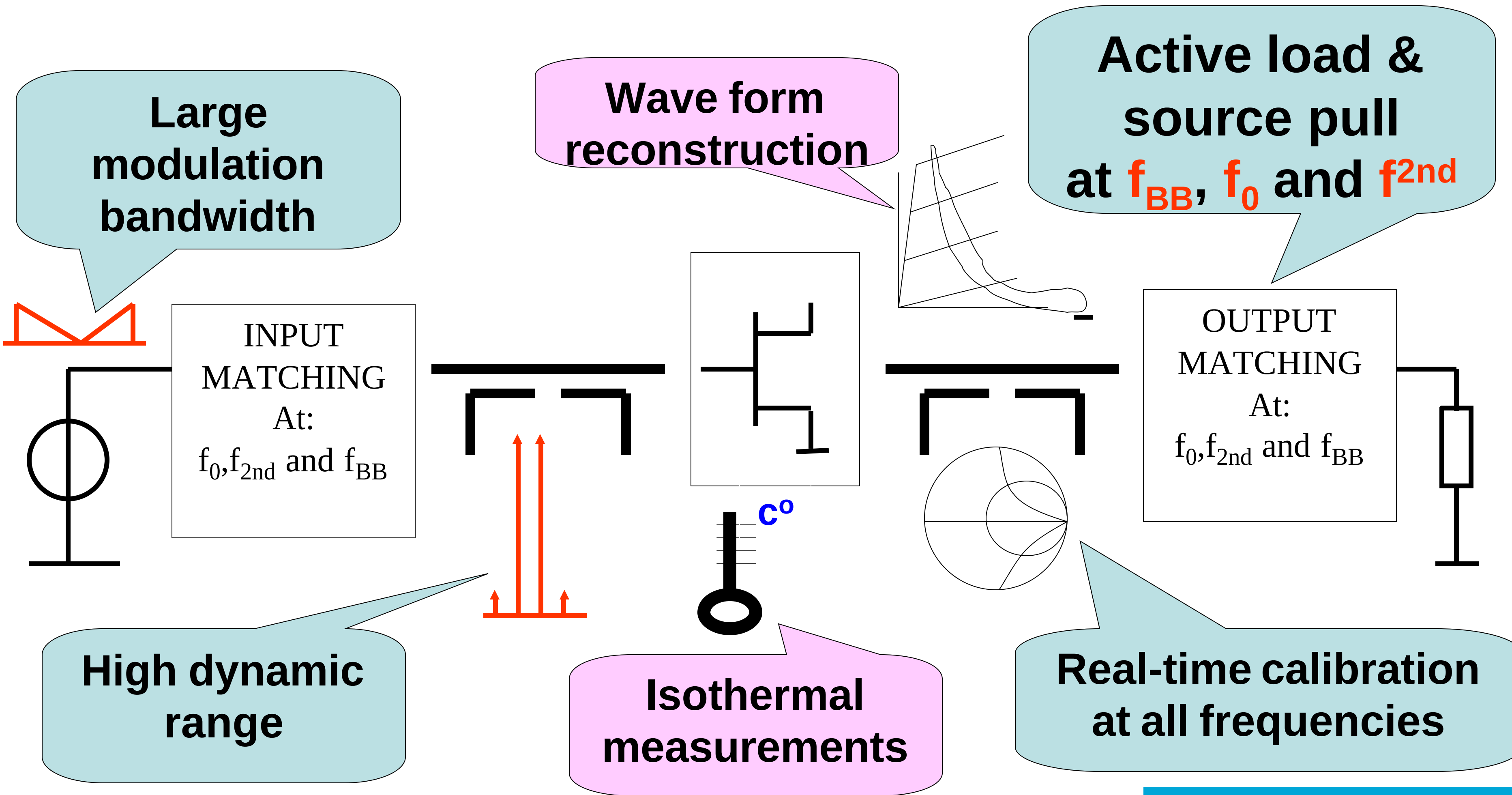
- Introduction
- Characterization
- Predictive Modeling & Device Optimization
- BJT based PA design
- FET based PA design
- Conclusions
- Outlook: Adaptive PA’s
- Acknowledgements

# Characterization

Large Signal Device Characterization setups at the TUDELFT
(custom-built)

- Isothermal measurements
  (Data base model extraction / model verification)
- Differential load-pull measurements
  (testing differential PA’s)
- On-Wafer Active harmonic load-pull measurements
  (Linearity optimization using out-of-band terminations)
  (Evaluation Linearity new process generations)

# Characterization:
# Active Load-Pull setup, Principle




Novel setup for on-wafer non-linear device characterization using optimum circuit conditions



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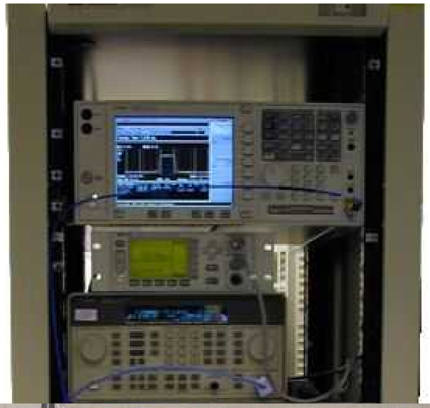
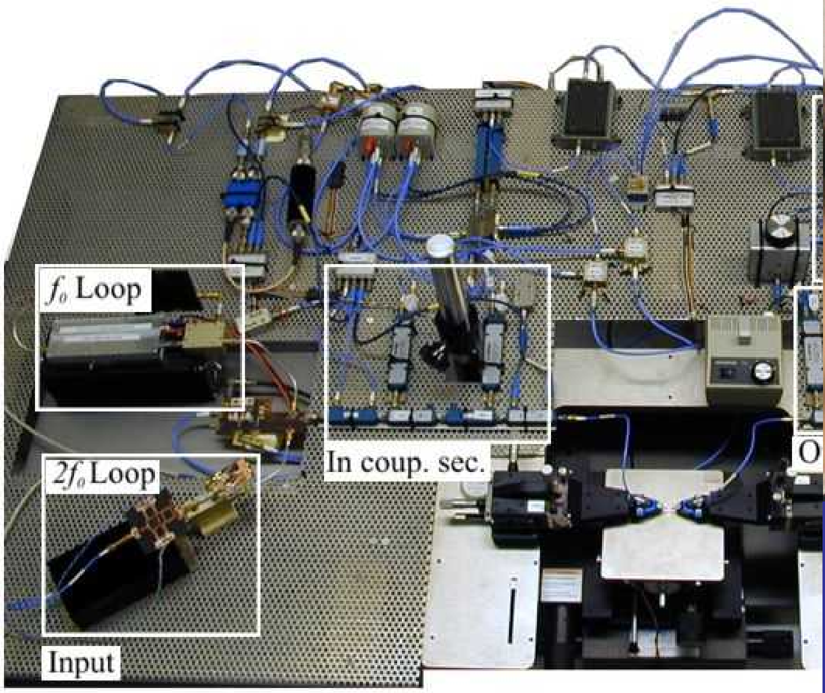
# Characterization:
## Active Harmonic Load-Pull System

**On wafer large-signal device characterization!!!**







**Happy supporters from Industry**

**Thesis work M. Spirito + support by Marco Pelk**

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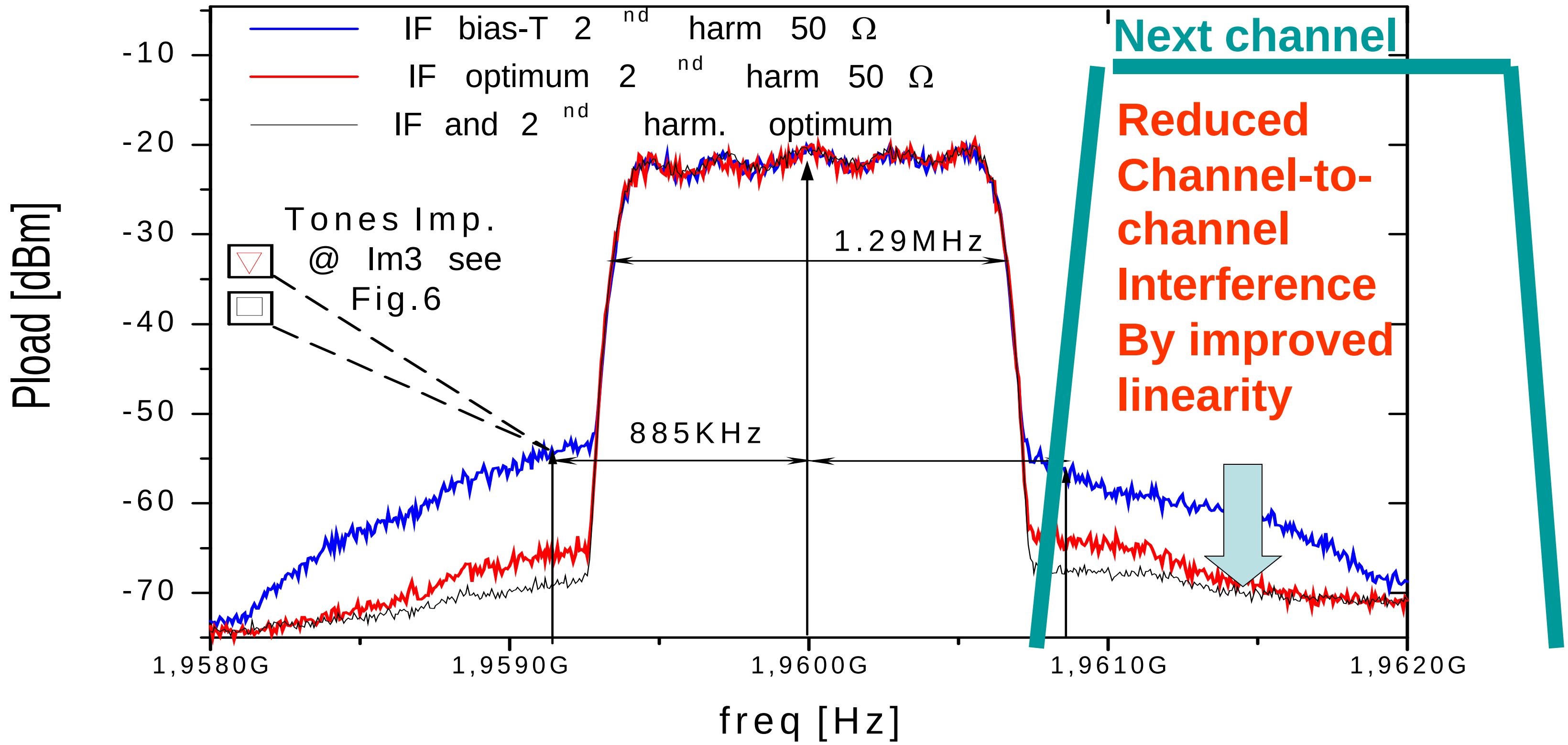
# Characterization:
# Active Harmonic Load-Pull System




Linearity imp. using optimum 2nd and IF impedances for an IS-95 signal.

**On-wafer testing of device linearity using:**

**- optimum harmonic terminations**

**- wideband modulated signals**

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# Predictive Modeling & Device Optimization

Smoothie

| | Compact models | Mixed level models | Database models |
|---|---|---|---|
| Advantages | + Speed<br>+ Accuracy<br>+ Physically based | + Suitable for device innovation<br>+ Physically based | + Device innovation<br>+ Meas./sim. based<br>+ Speed<br>+ Accuracy<br>+ very physical |
| Disadvantages | - Difficult to extract<br>- No device innovation | +/- Accuracy<br>- Not meas. based<br>- Speed | - Speed |

Mextram

MAIDS

Vittorio Cuoco



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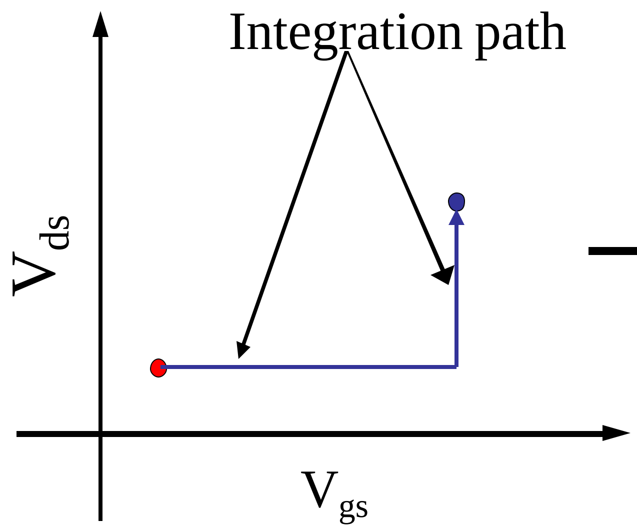
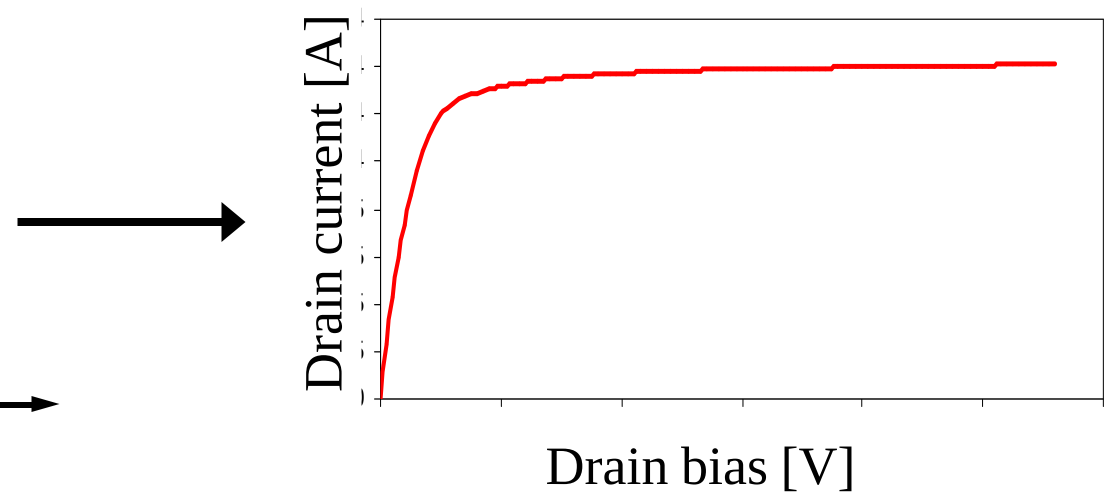
# Predictive Modeling & Device Optimization

## Smoothie model principles: Currents & charges

**as line integral of the y-parameters over bias:**




**✓Consistency between DC, AC and HB simulations!**

**✓Increased order of continuity**

**But what about rotation and thermal effects?**



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# Predictive Modeling & Device Optimization
## The database model Smoothie

Smoothie schematic

Blanked to avoid pre-publication

Large signal equivalent circuit Smoothie, including:

- dynamic thermal effects
- improved freq. dependency

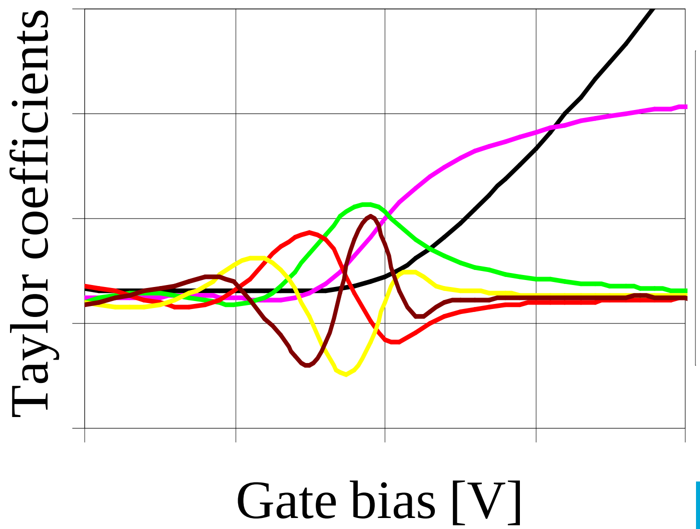
→ Solves for the rotation problem!

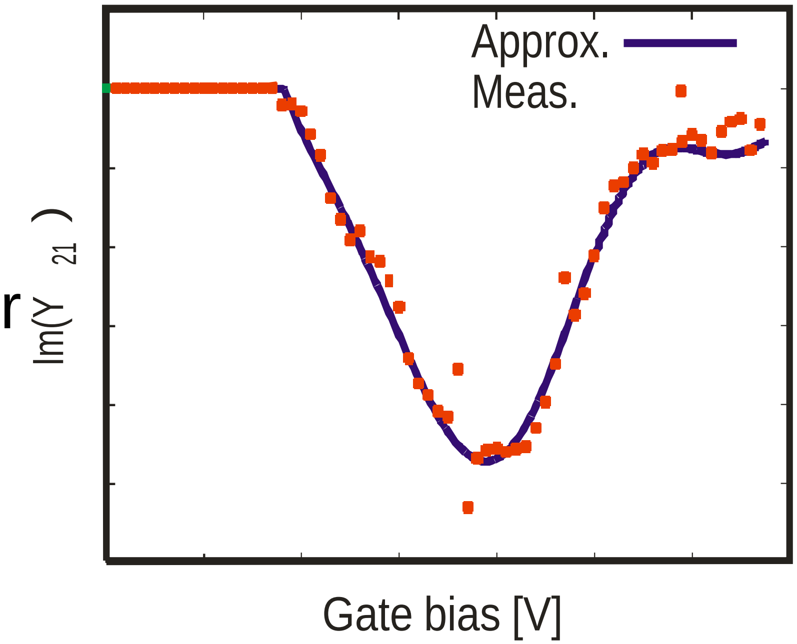
→ No implicit assumptions on the device behavior!

# Predictive Modeling & Device Optimization
## The database model Smoothie

**Advantages of smoothing splines:**

- ➢Immunity to noise
- ➢Smooth derivatives up to 5$^{th}$ order
- ➢Sparse grid




- ➢Reduced extraction time
- ➢Compact model databases



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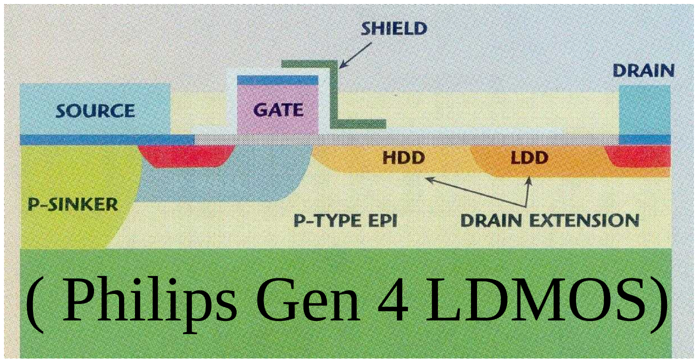
# Predictive Modeling & Device Optimization

## Smoothie used for device engineering




**Definition Device Structure**

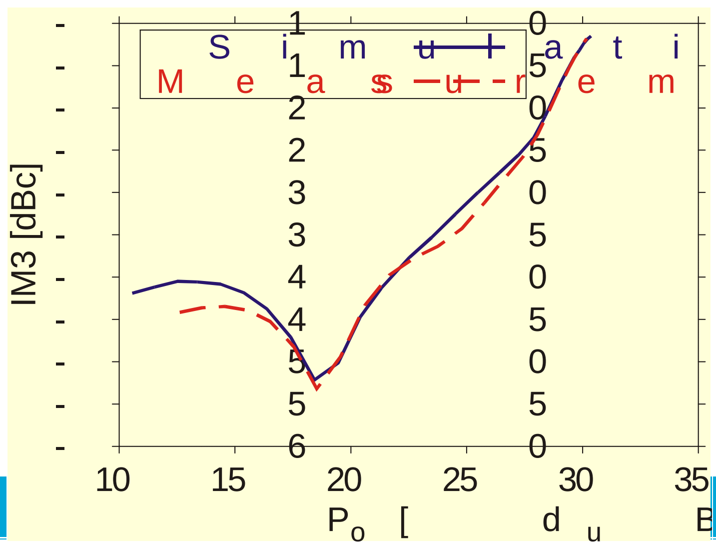
Device simulator (MEDICI)
Layout extractor (Momentum)
Thermal network (FEMLAB)

Smoothie Data base

Thermal Network

Layout parasitics

Circuit simulator (ADS)




**Predicted and measured LDMOS Linearity!**



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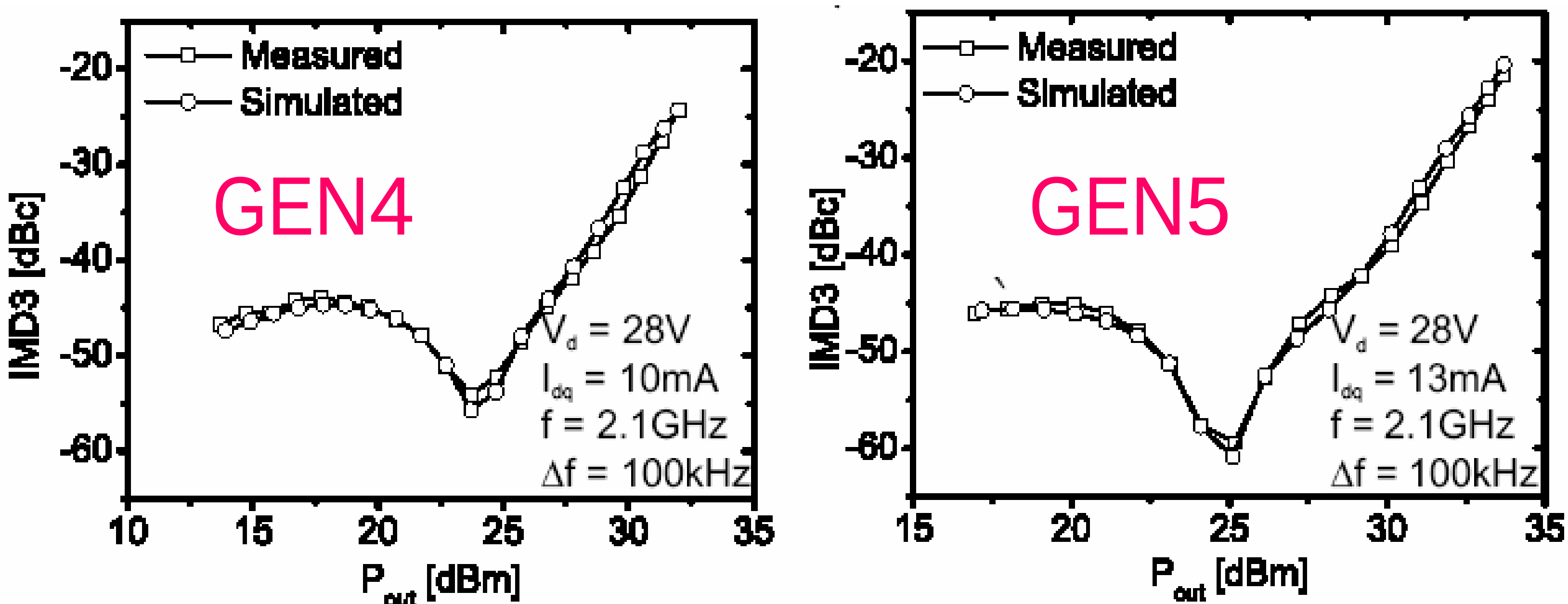
# Predictive Modeling & Device Optimization
## Smoothie results

(Figures on courtesy of V. Cuoco and P. Hammes.)




IMD3

Comparison of predicted (Smoothie) and measured IM3 for the fabricated Philips LDMOS devices GEN4 and GEN5



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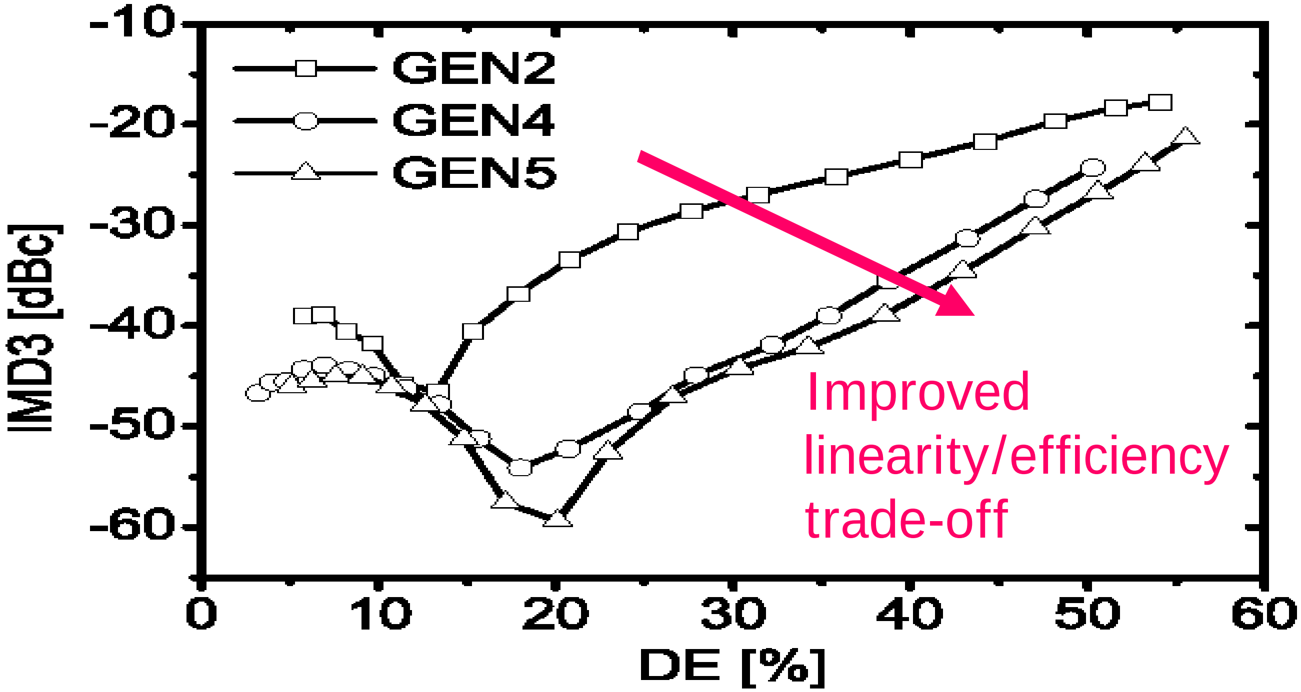
# Predictive Modeling & Device Optimization

## LDMOS Device innovation

(Figure on courtesy of V. Cuoco and P. Hammes.)




Linearity versus efficiency improvements for the Philips LDMOS generations (1-2W devices, on-wafer load-pull measurements).



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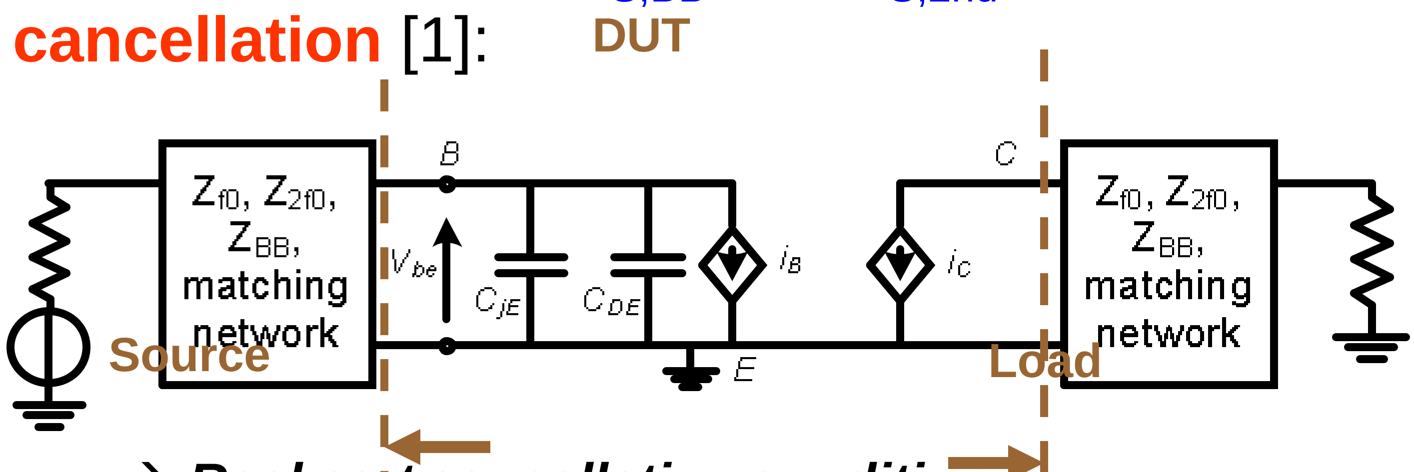
# BJT Based class-AB PA Design

## Linearity optimization (theory)

Applying a out-of-band short $Z_{L,BB} = Z_{L,2nd} = 0$ at DUT output simplifies analysis and provides $Z_{S,BB}$ and $Z_{S,2nd}$ to enforce **perfect IM3 cancellation** [1]:




→ ***Real part cancellation condition***

$$Z_{S,BB} = Z_{S,2nd} = \frac{\beta_F}{2g_m}$$

→ ***Imaginary part cancellation condition***

$$C_{jE} = 2C_{DE}$$

→ ***Fixed by technology***

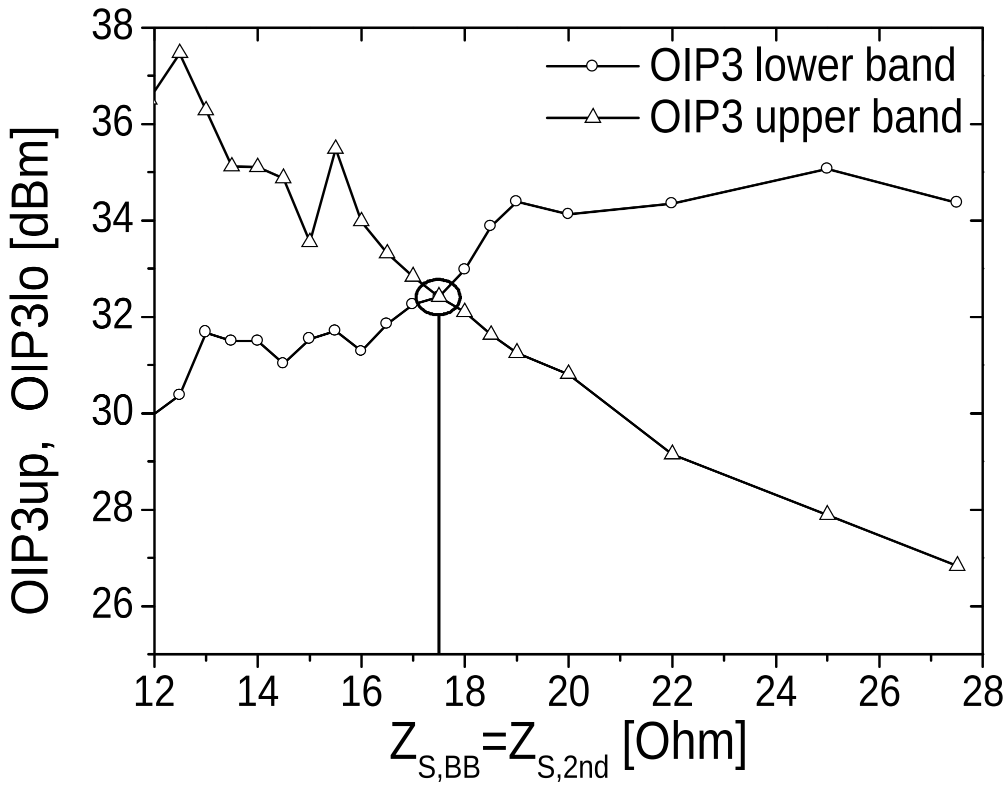
$$I_{c,opt} = V_T \frac{C_{jE}}{2\tau_F}$$

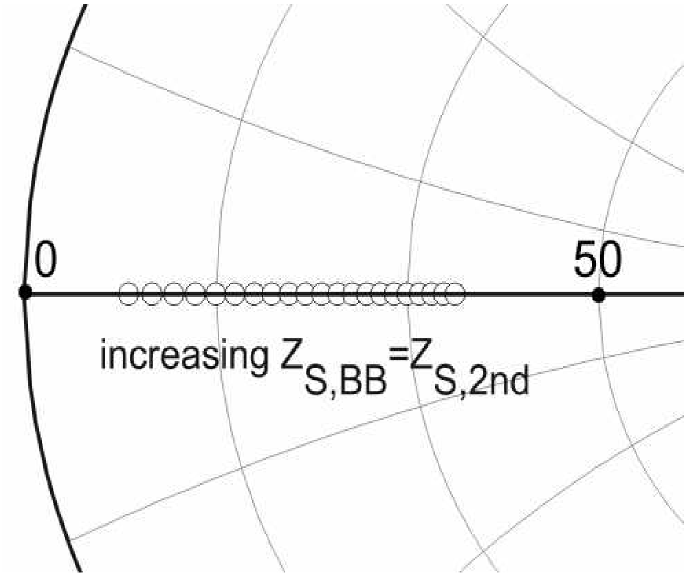

[1] M.P. van der Heijden et al. BCTM 2004

# BJT Based class-AB PA Design

## Low-power Linearity opt.  (measurement)

By <u>sweeping</u> $Z_{S,BB}=Z_{S,2nd}$ we can experimentally find the symmetrical IM3 cancellation condition, and the related optimal quiescent current $I_{cq}$.






M. Spirito,BCTM 2005

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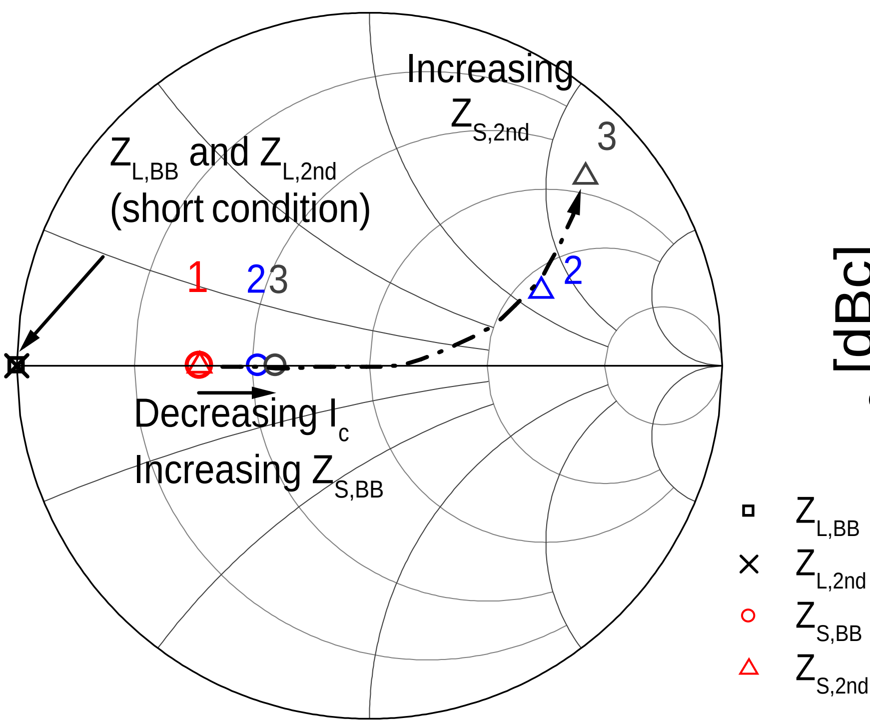
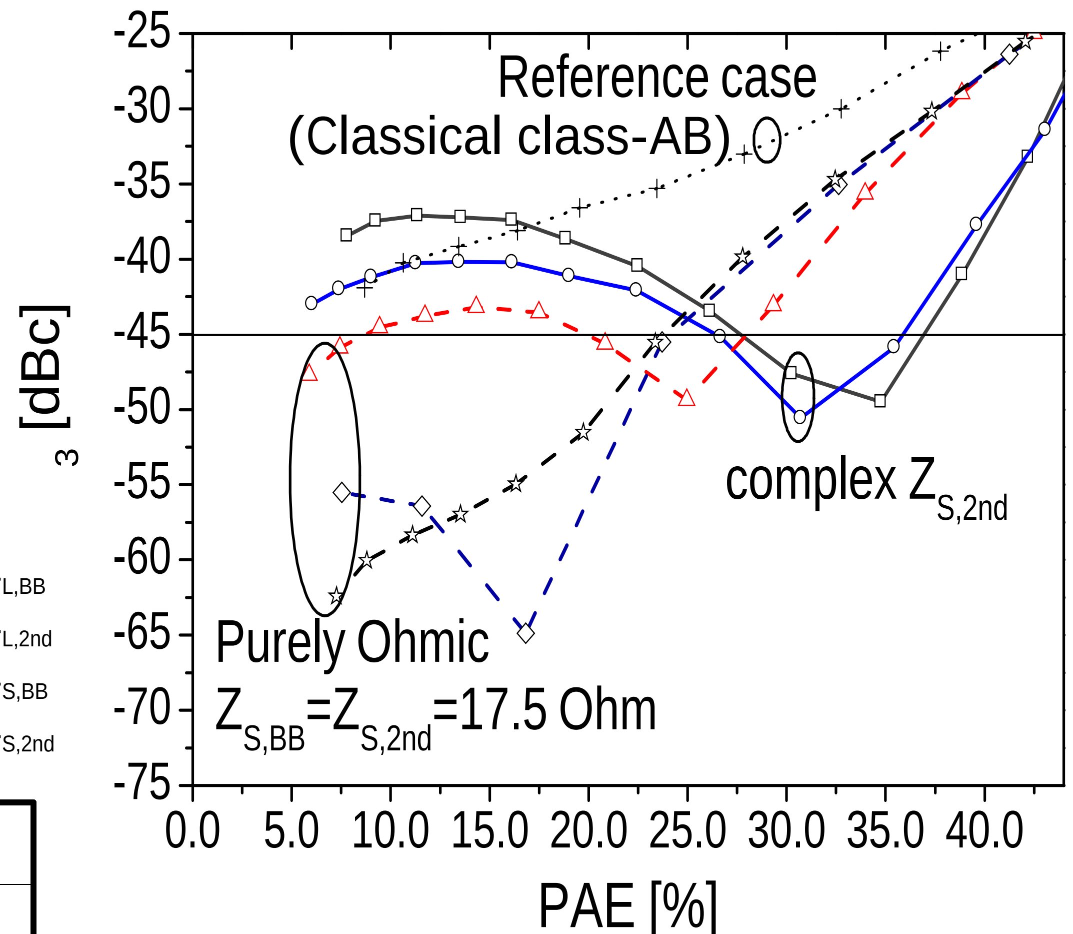
# BJT Based class-AB PA Design

## IM3 vs. PAE optimization




| | Case 1 | Case 2 | Case3 |
|---|---|---|---|
| $I_{cq}$ | 12 mA | 7 mA | 6.2 mA |
| $Z_{S,BB}$ | 17.5 Ω | 26 Ω | 29 Ω |
| $Z_{S,2nd}$ | 17.5 Ω | 116.5 +68.5 j | 38.8 +122.5j |

M. Spirito,BCTM 2005

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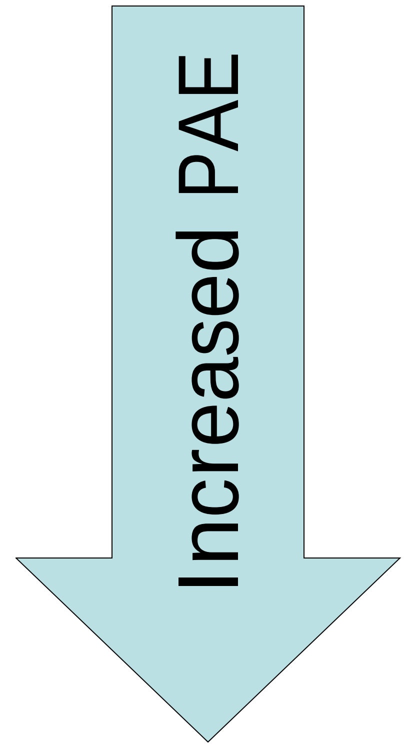
# FET Based Design: Lowering $P_{back\text{-}off}$ while still meeting the linearity spec.

- Derivative superposition method
  (most effective in back-off region)
  M.v.d. Heijden, IMS2001
- Derivative superposition
  + 2nd harmonic input tuning
  (Effective up to close to compression)
  E.W. Neo, EuMC2004
- 2nd harmonic input and output tuning
  (Effective up to the compression region)
  D. Hartskeerl, RFIC2005



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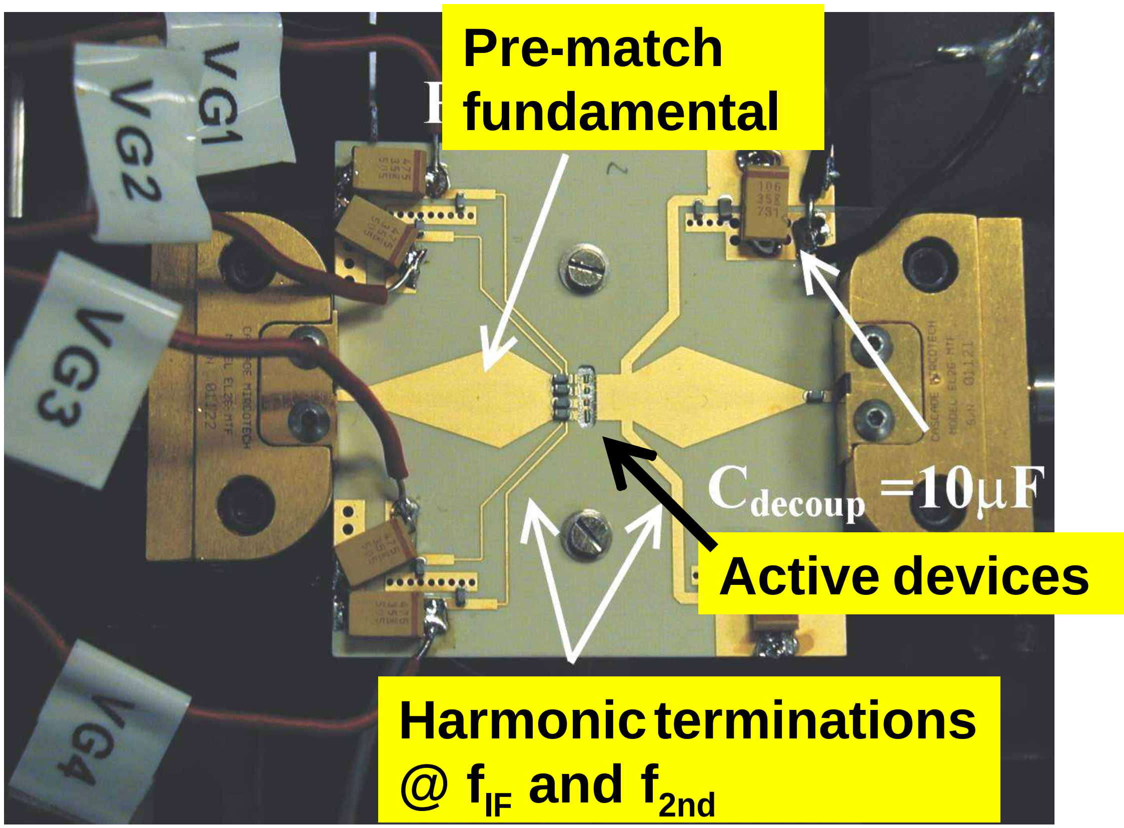
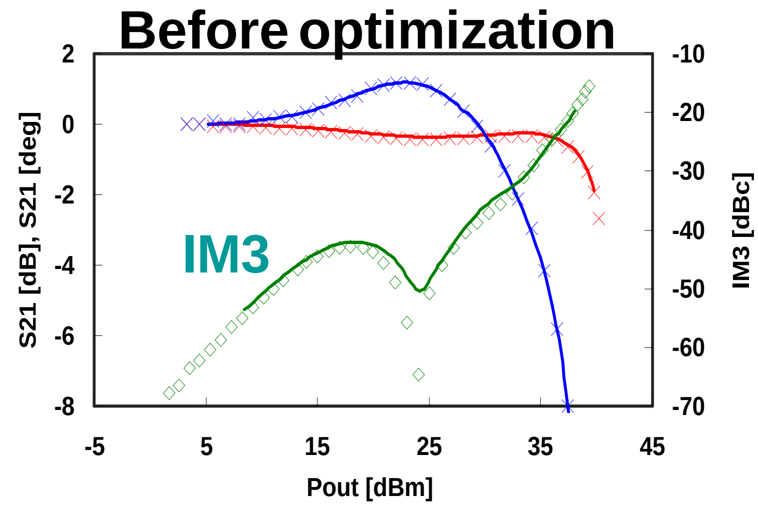
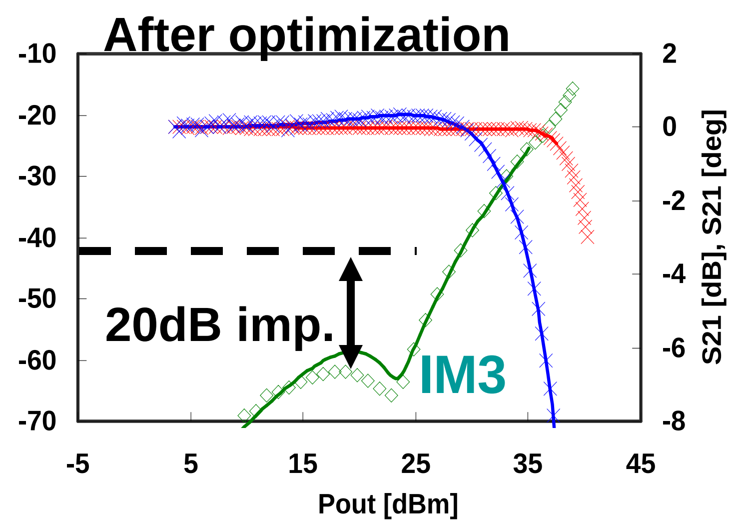
# FET Based Design:

## A Square-Law Optimized Class-AB LDMOS Power Amplifier




**LDMOS amplifier with trans-conductance shaping using VG-offsets**

(M. P. Heijden, Honorable mention at MTT-S2001)

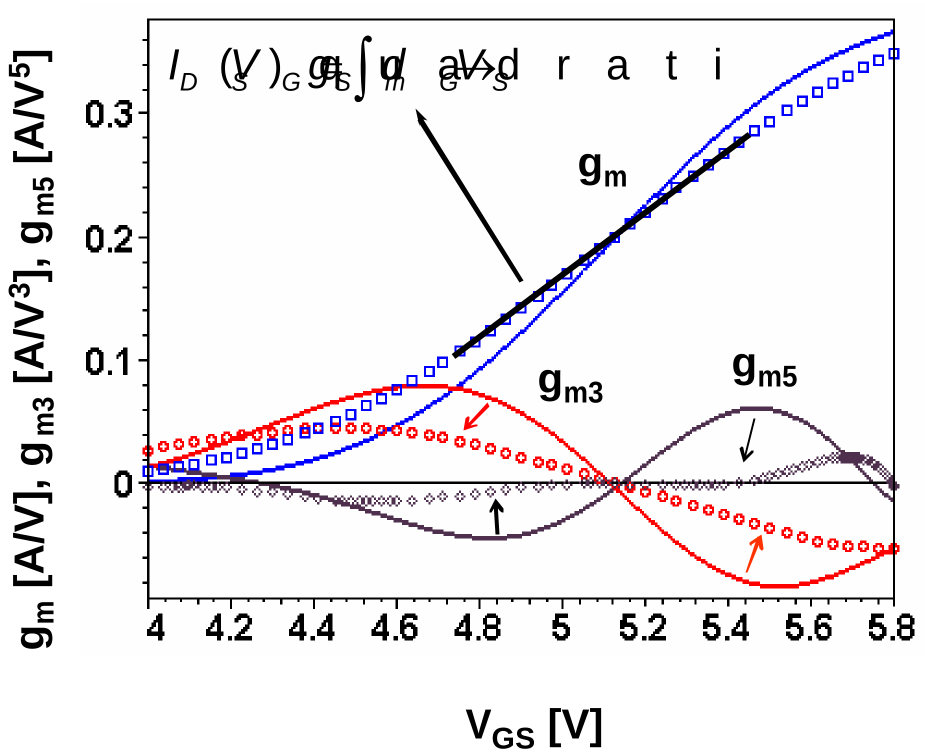
# FET Based Design:

A Square-Law Optimized Class-AB LDMOS Power Amplifier

## Transconductance Optimization

**Linearity optimization by controlling the higher order derivatives of the active device, through:**

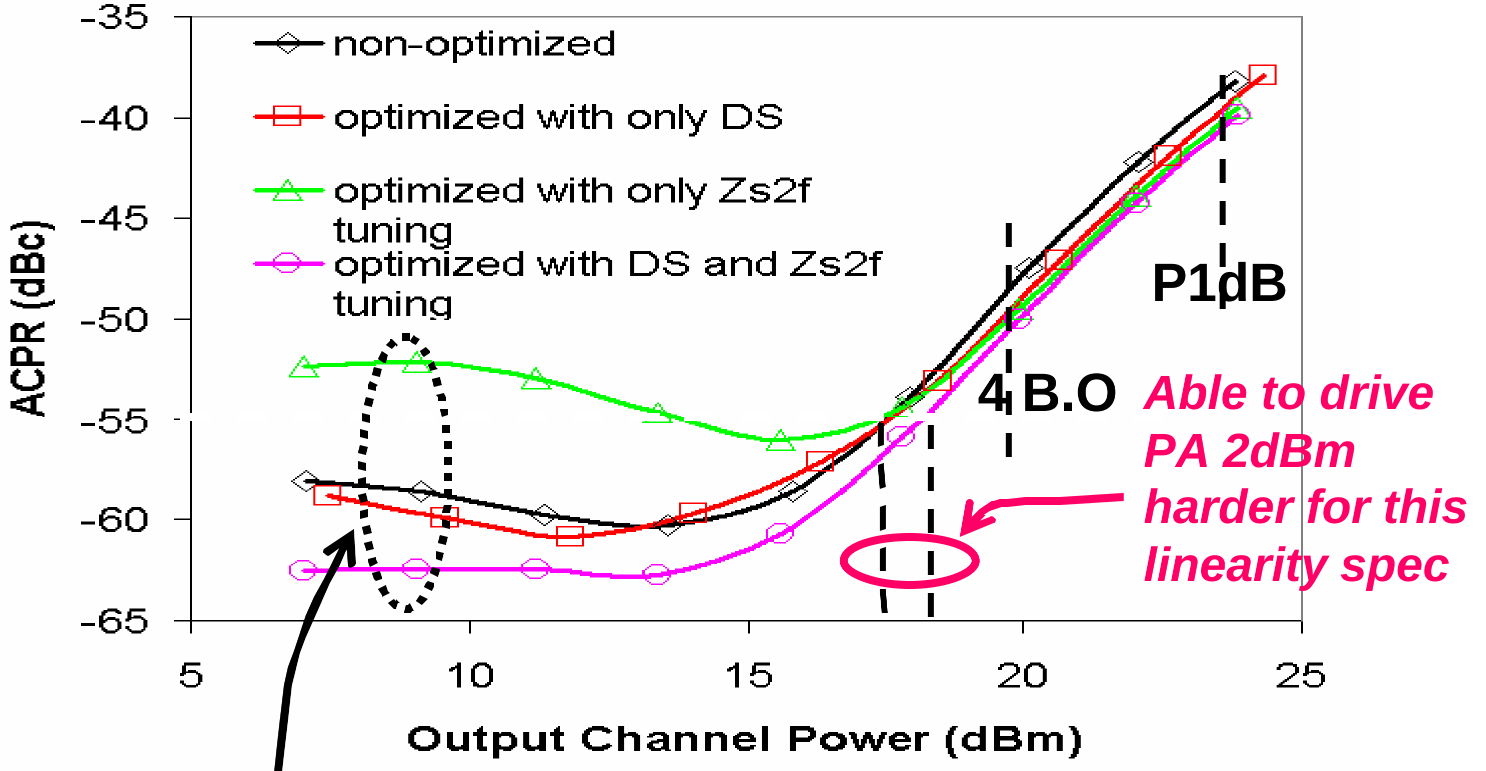
- **$V_{gs}$ offsets (biasing)**
- **$V_T$ shifts (build-in)**




**NEW LDMOS generation with build-in optimized Transconductance, introduced at MTT-S 2003**

# FET Based Design
## DS & 2nd Harmonic Input Tuning#

- IS-95 CDMA signal on Philips GEN 3 LDMOS




***Better linearity achieved in B.O***



#Edmund Neo, EuMC2004

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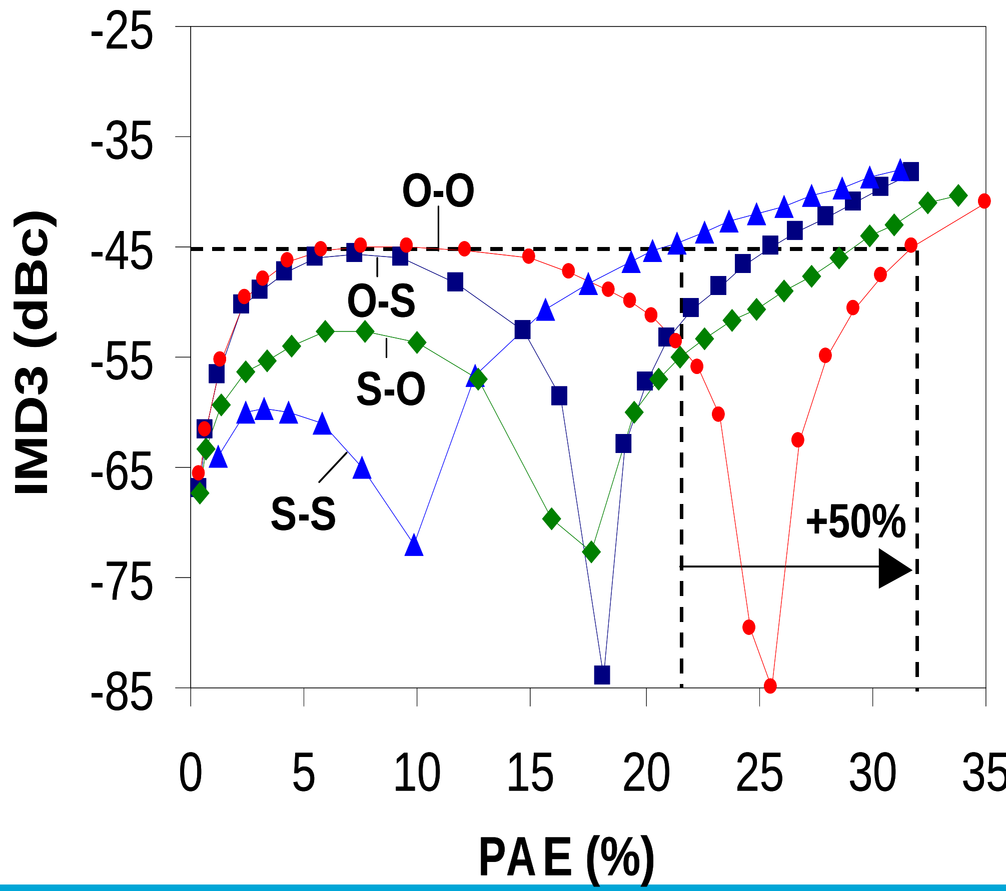
# FET Based PA Design
## $2^{nd}$ Harmonic input & output tuning

Measured PAE linearity trade-off for 2mm LDMOS device using:

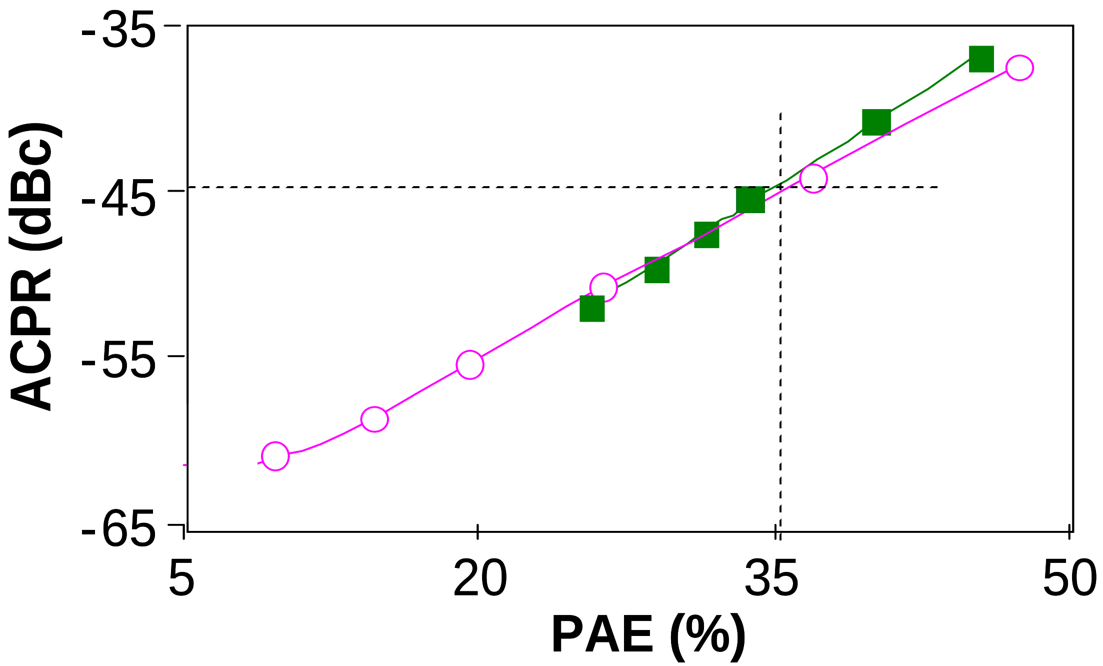
- Open-Short (squares)
- Open-Open (circles)
- Short-Short (triangles)
- Short-Open (diamonds)

2nd harm. terminations
at the device in- and output

(Dave Hartskeerl, RFIC 2005)



# FET Based PA Design
## 2nd Harmonic input & output tuning




Measured using the TUDELFT Active Harmonic Load Pull System

Single carrier IS-95 CDMA signal (open symbols) and single carrier 3GPP WCDMA signal (closed symbols). (D. Hartskeerl, RFIC2005).



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# Conclusions

- A research strategy for improve device performance at the TUDelft has been presented, yielding:
  - Unique Measurement equipment
  - Predictive database models
  - Linearity & PAE device optimization strategies

- As result Modified “Class-AB” device operation is still a competitive option for commercial applications providing high linearity performance at a very reasonable PAE level, while being:
  - Low cost,
  - Reliable,
  - Simple........
- But →Current research fields at the TUDelft also include:
  Device and Circuit Innovation for Doherty PA’s,
  Adaptive / Dynamic Load line PA’s, and Polar PA’s

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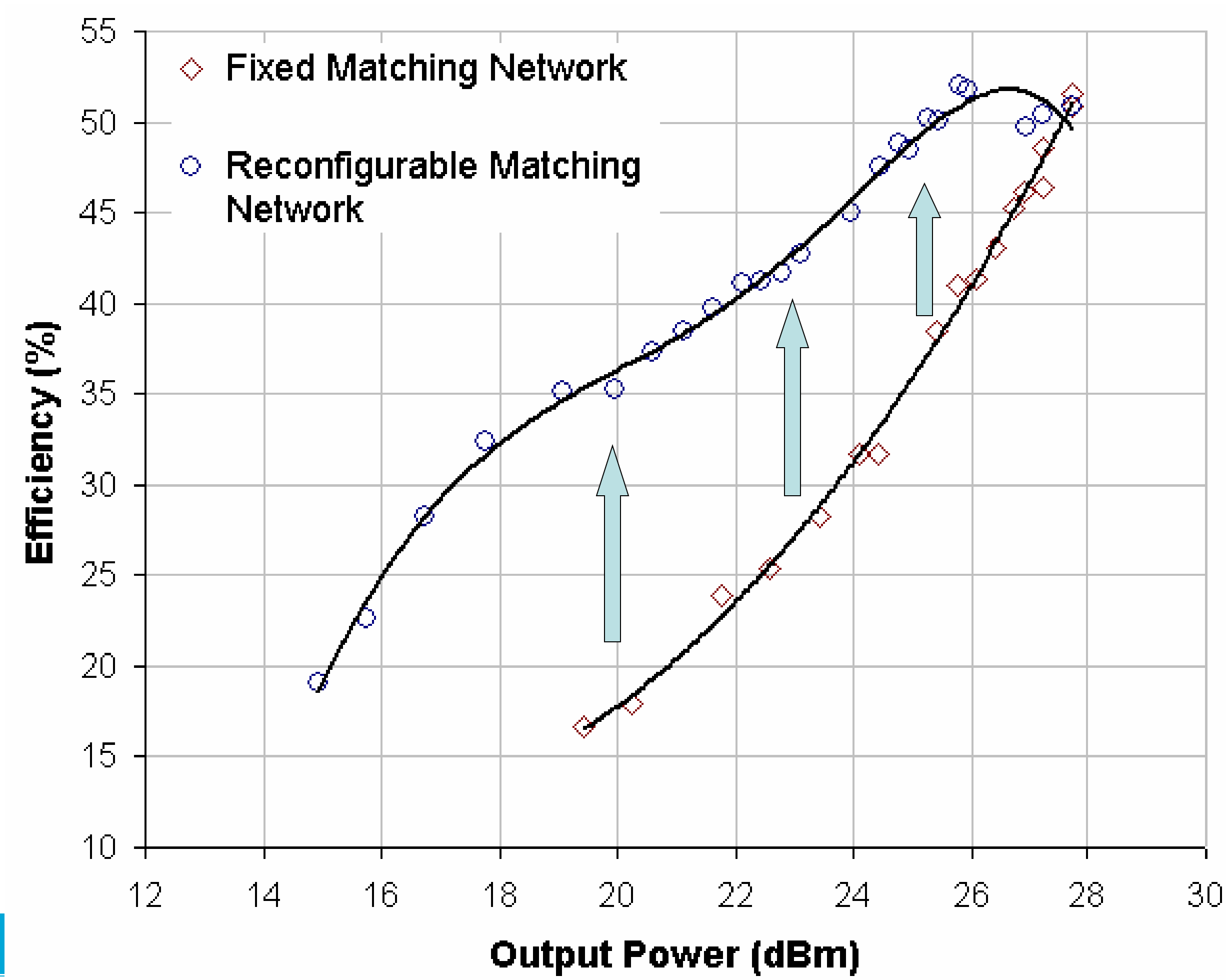
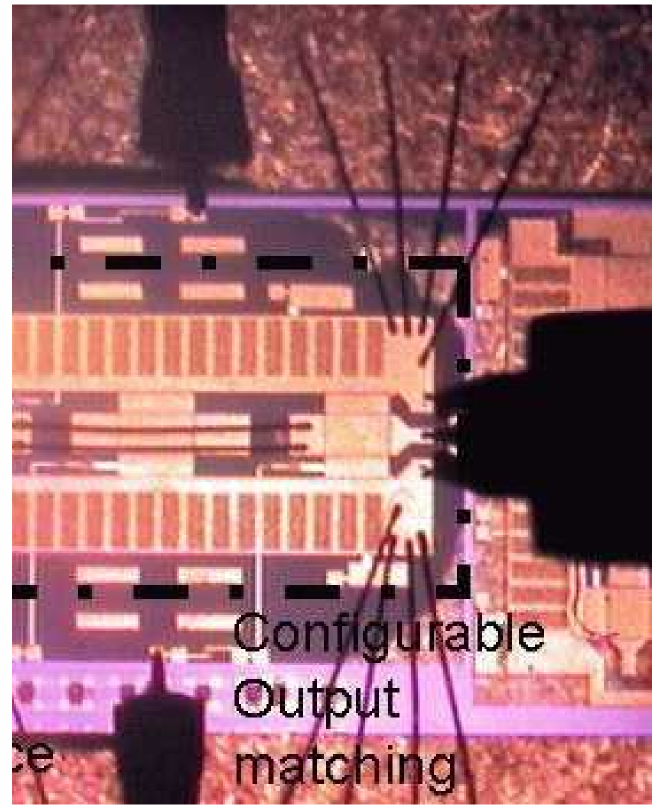
# Outlook: Multi-mode, Multi band PA's

## High performance varactors for RF adaptivity




***Band-switching & Collector efficiency improvement with adaptive matching networks***



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# Acknowledgement


- Philips Semiconductors: R. Jos, P. Lok, F. van Straten P. Hammes, F. v. Rijs, J. Gajadharshing. A. de Graauw, S. Theeuwen
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- Infineon: J.E. Muller
- Skyworks: P. Zampardi
- Many people of Agilent, BSW, Maury etc.
- UCSD L. Larson & P. Asbeck

In special (in alphabetic order):

V. Cuoco, M. v.d. Heijden, E. Neo, M. Pelk,
and M. Spirito of the TUDelft.