Integrated Millimeter-Wave Power Amplifiers and Analog Linearization

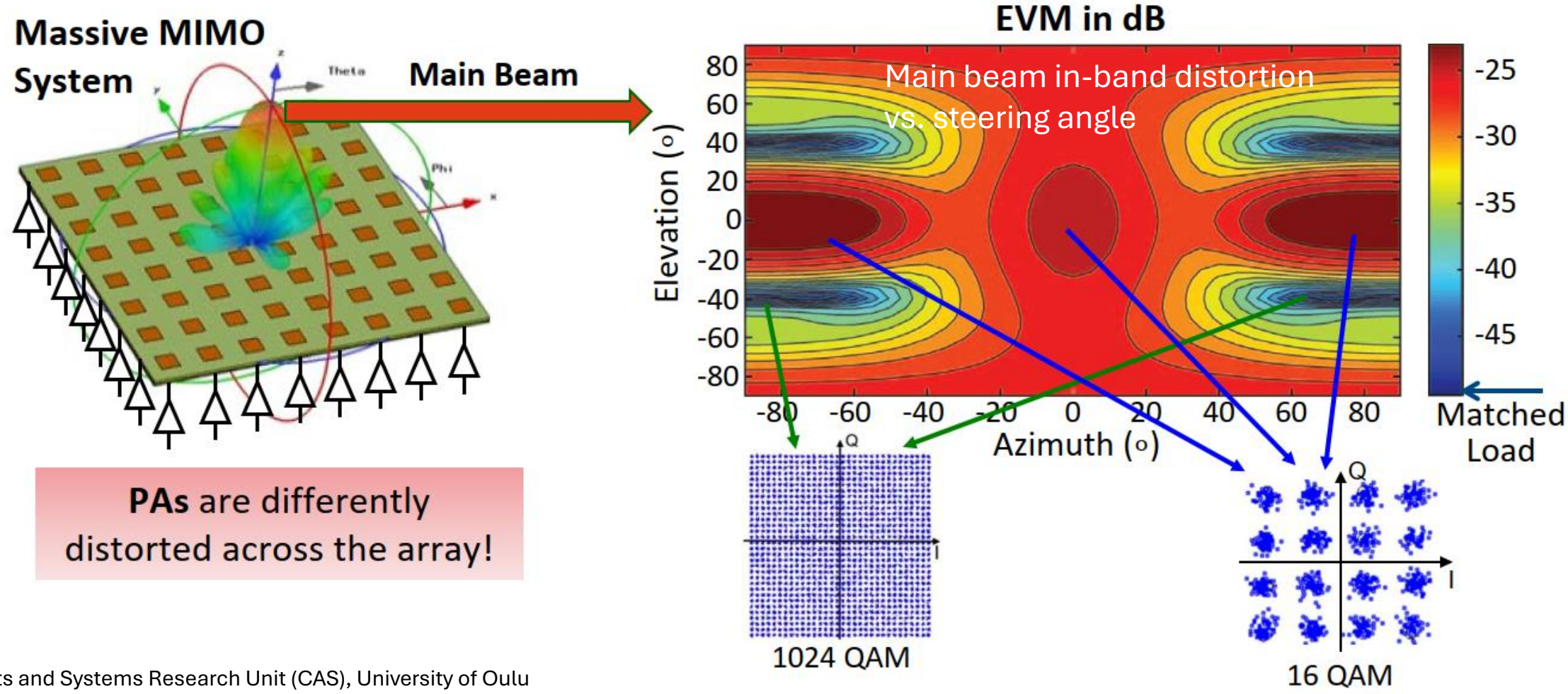
Janne Aikio, Timo Rahkonen, Jere Rusanen, Sauli Haukka

10.3.2025

© Circuits and Systems Research Unit (CAS), University of Oulu

Introduction

- In mmW phased arrays PAs preferred before each antenna to reduce losses
- No space for isolators => each PA has different load due to mutual coupling

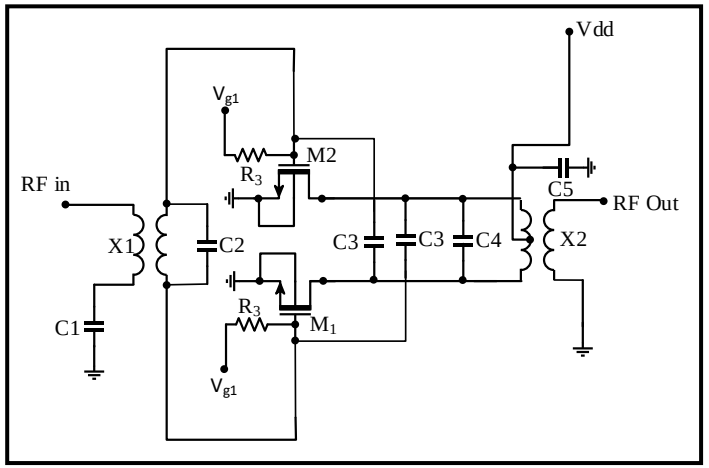


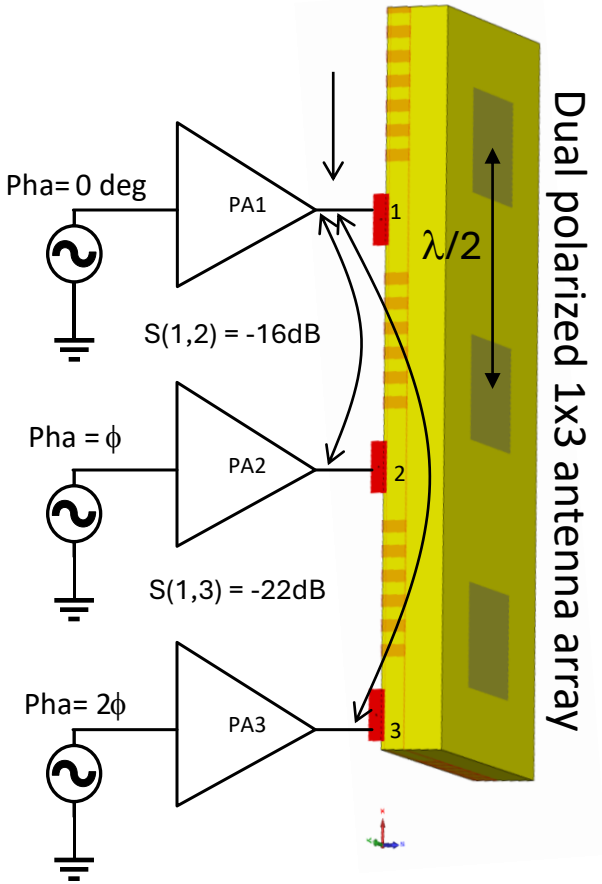
© Circuits and Systems Research Unit (CAS), University of Oulu

Introduction

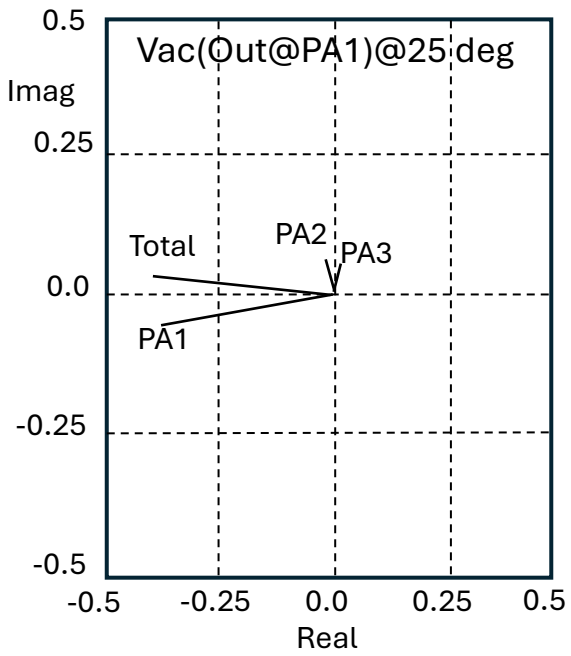
- Simple 3-element array case study to simulate the effects of mutual coupling
- Parallel PAs are pulling the load and causing AM-AM and AM-PM
- Nonlinear analysis difficult without distortion contribution analysis

Transformer matched
Differential CMOS PA @28 GHz

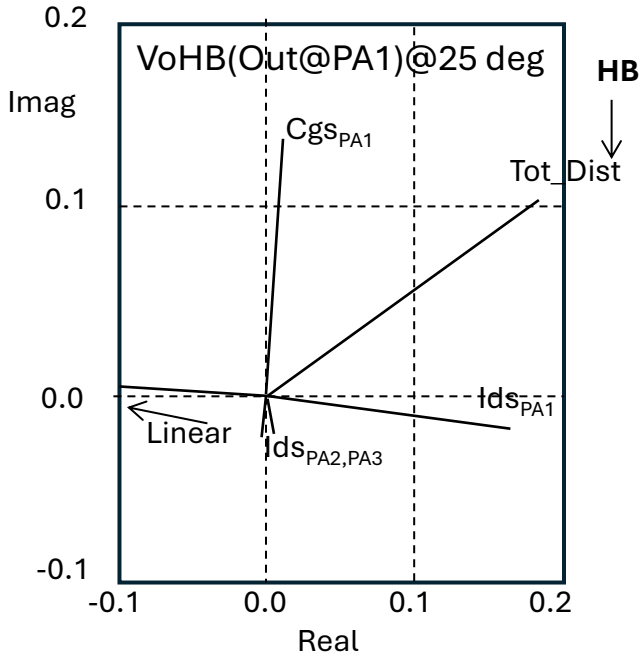




AC superposition



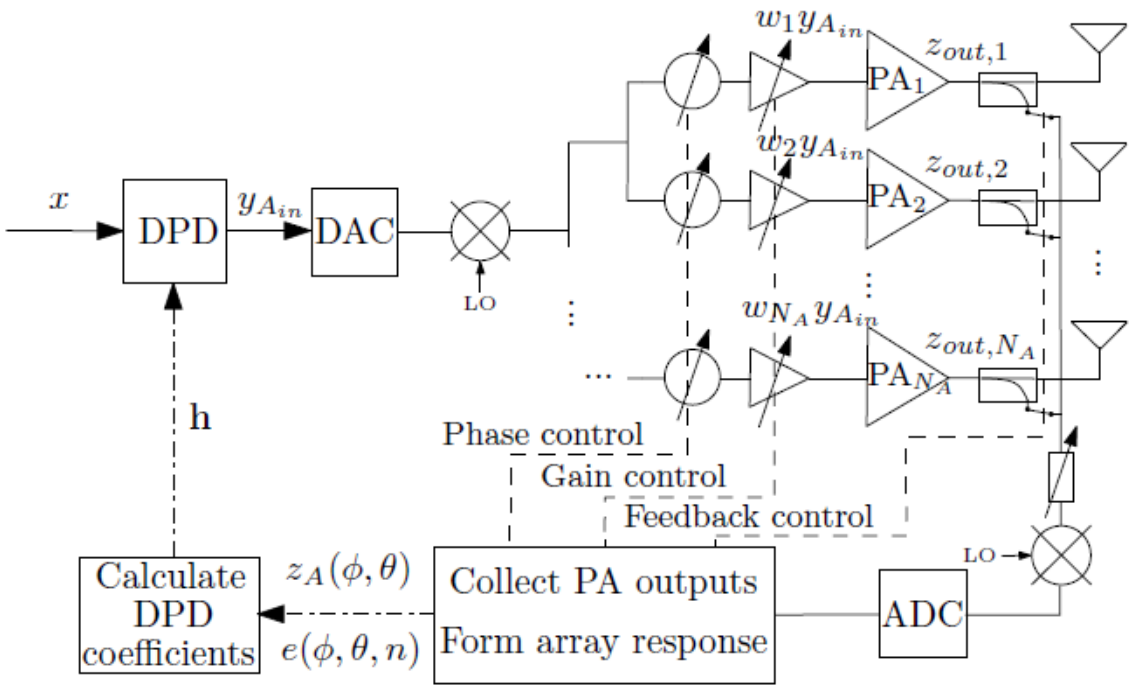
Distortion Contribution Analysis

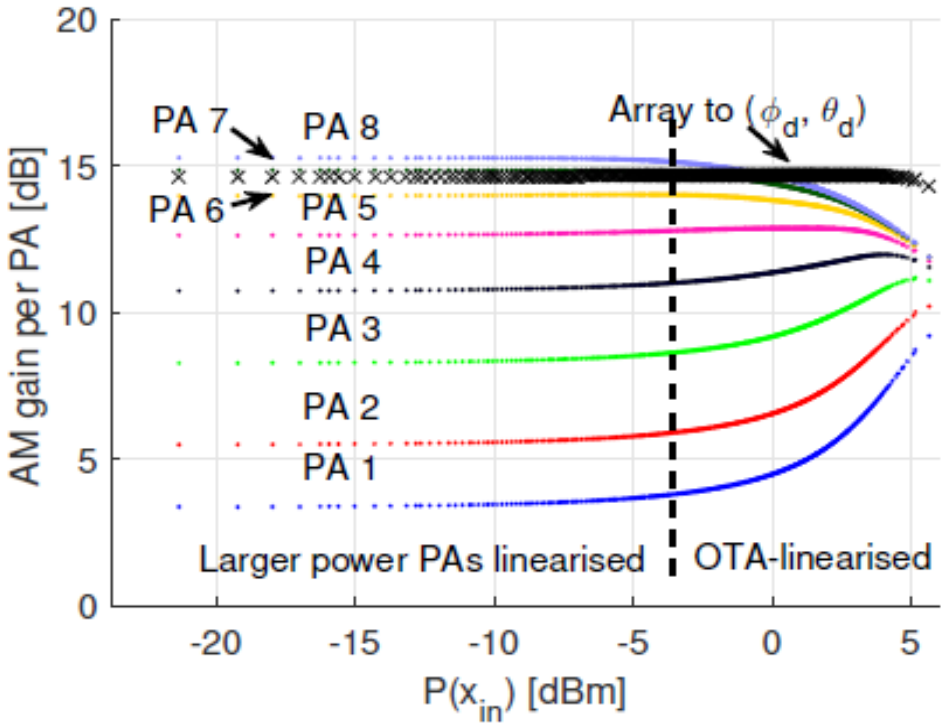


© Circuits and Systems Research Unit (CAS), University of Oulu

Introduction

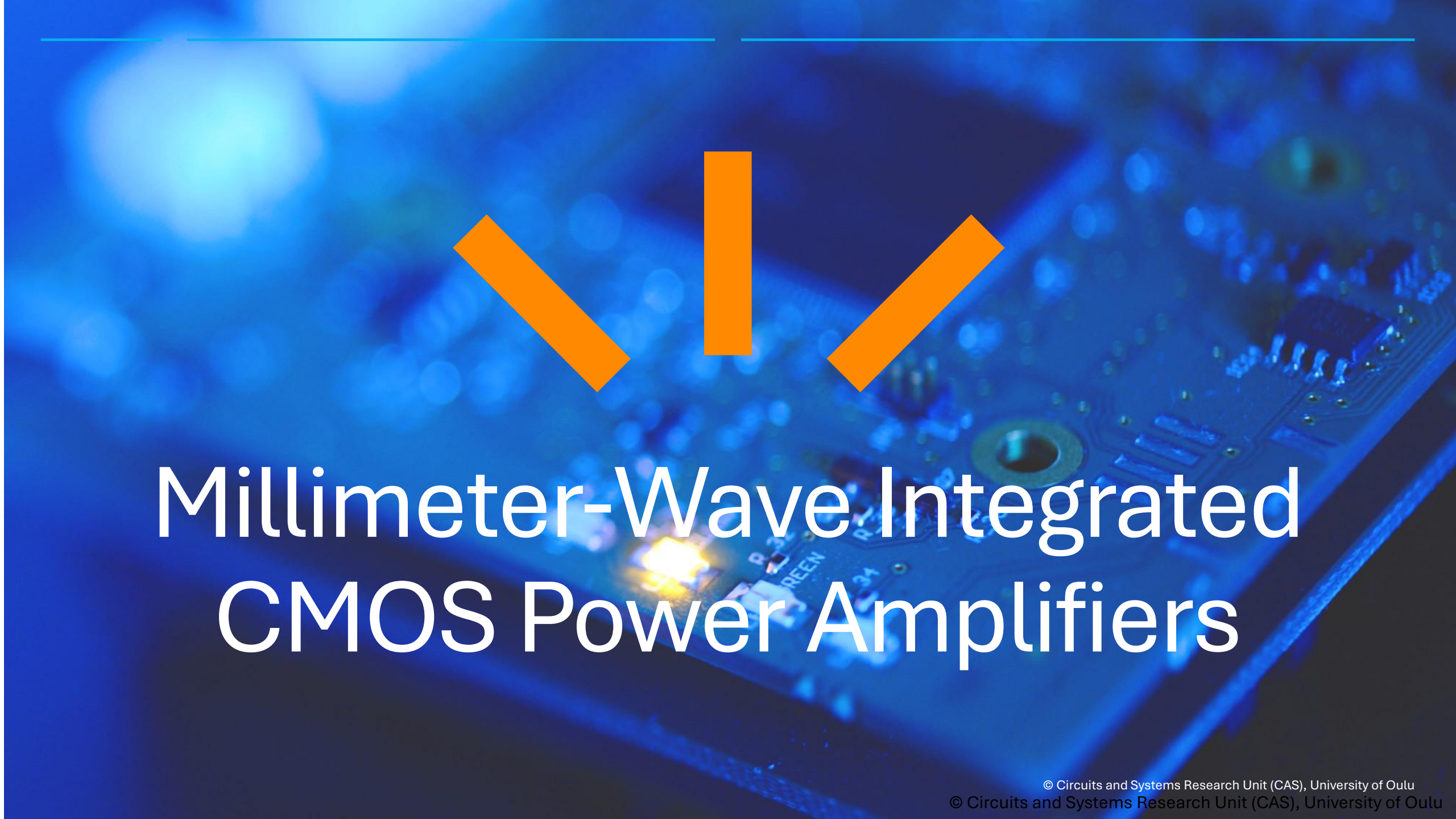
- With a single DPD some PAs are expanding and others compressing
- Linearization is spatially narrow and limits the degree of freedom of the DPD
- Analog domain linearization is tempting in mmWave phased arrays as APD can be integrated on the same RFIC with the PA to provide local linearization





N. Tervo, J. Aikio, T. Tuovinen, T. Rahkonen, and A. Parssinen, "Digital predistortion of amplitude varying phased array utilising over-the-air combining," in 2017 IEEE MTT-S International Microwave Symposium (IMS), 2017, pp. 1165–1168

© Circuits and Systems Research Unit (CAS), University of Oulu

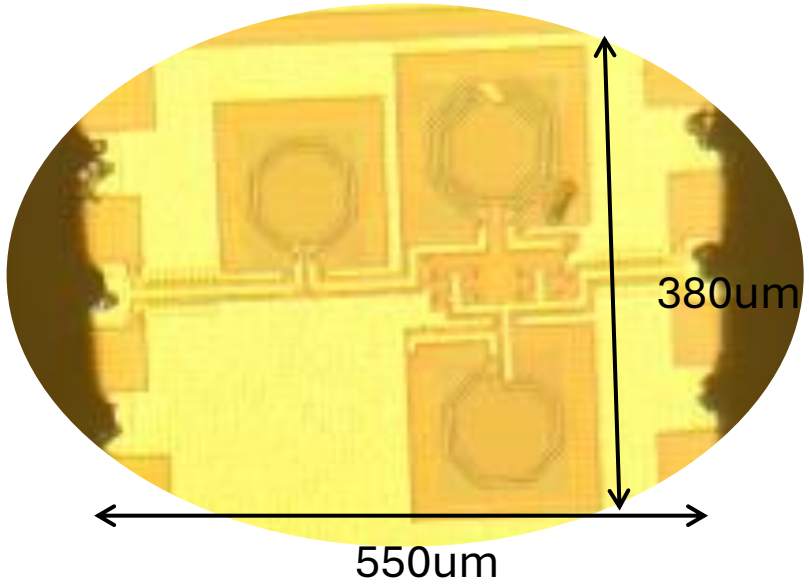


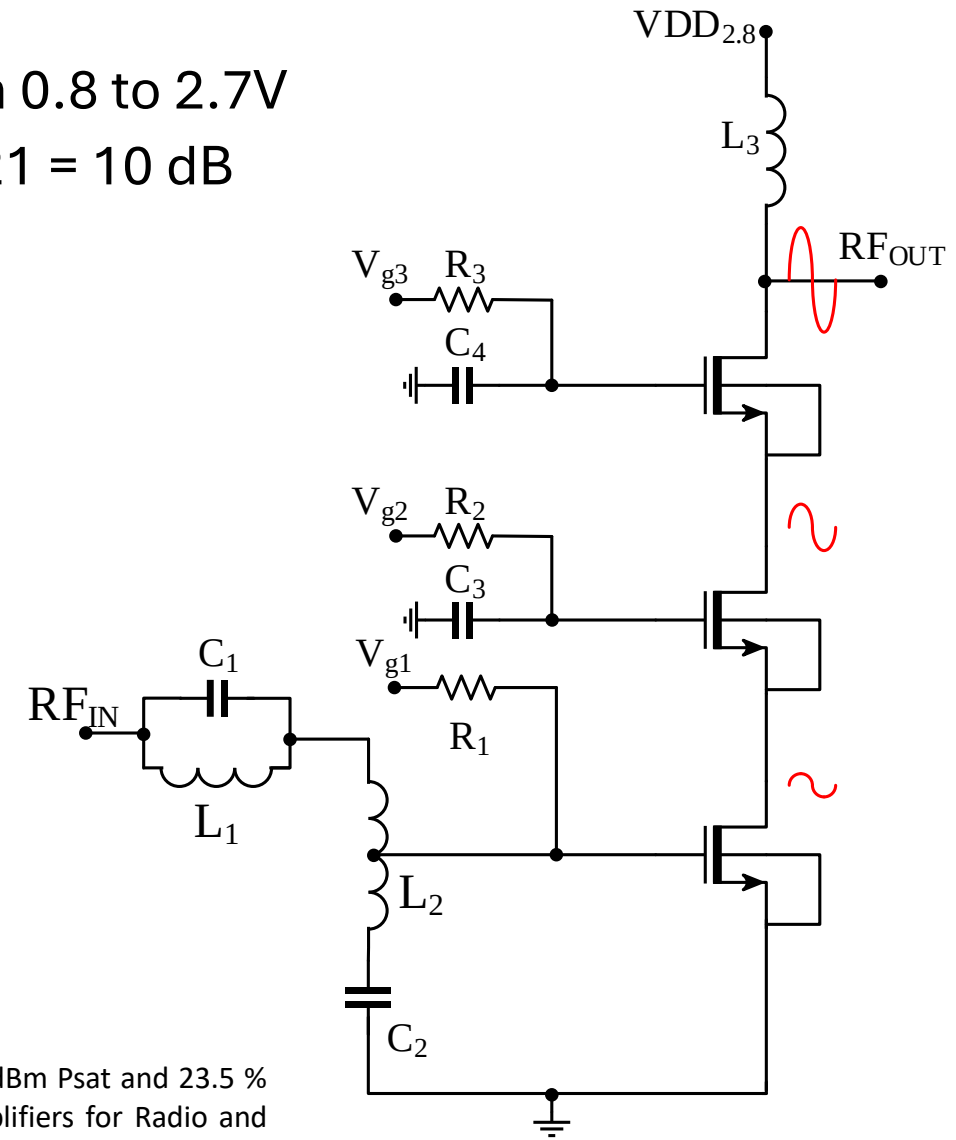
Millimeter-Wave Integrated CMOS Power Amplifiers

© Circuits and Systems Research Unit (CAS), University of Oulu
© Circuits and Systems Research Unit (CAS), University of Oulu

3-stack CMOS PA Using 22nm FDSOI @ 28 GHz

- In CMOS SOI processes devices can be stacked
- By stacking 3 devices VDD can be increased from 0.8 to 2.7V
- P_{sat} = 18.8 dBm, P_{1dB} = 15 dBm, PAE_{peak} = 24 %, S21 = 10 dB
- Drain connected directly to 50 ohm load
- Active area = 0.11mm^2



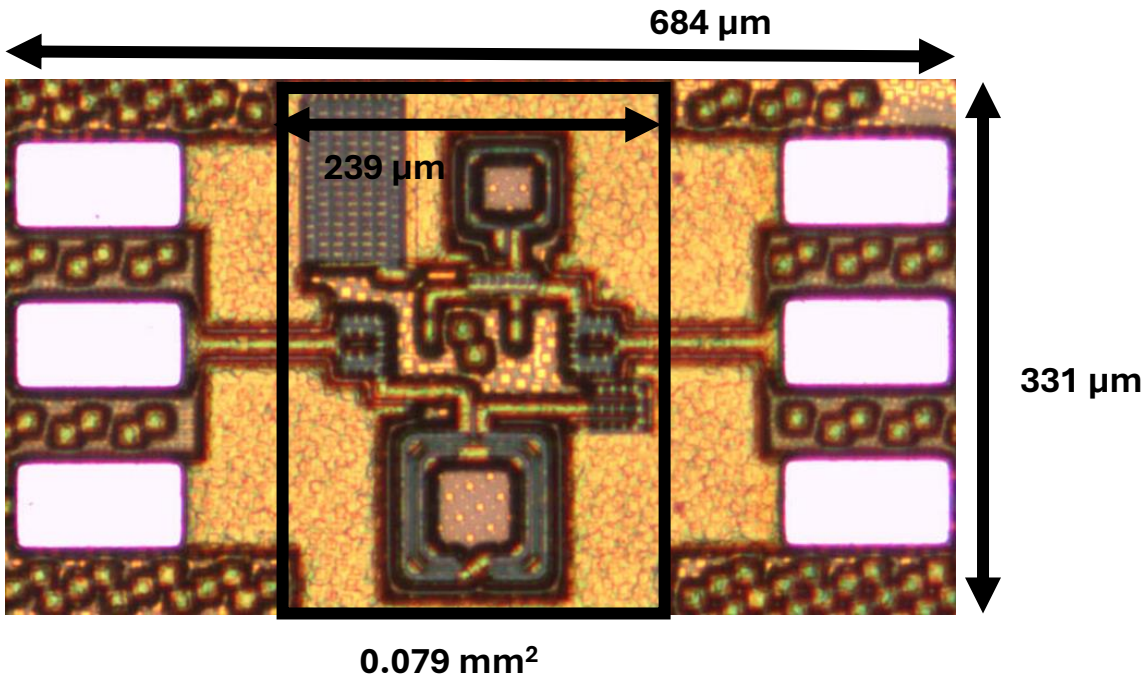


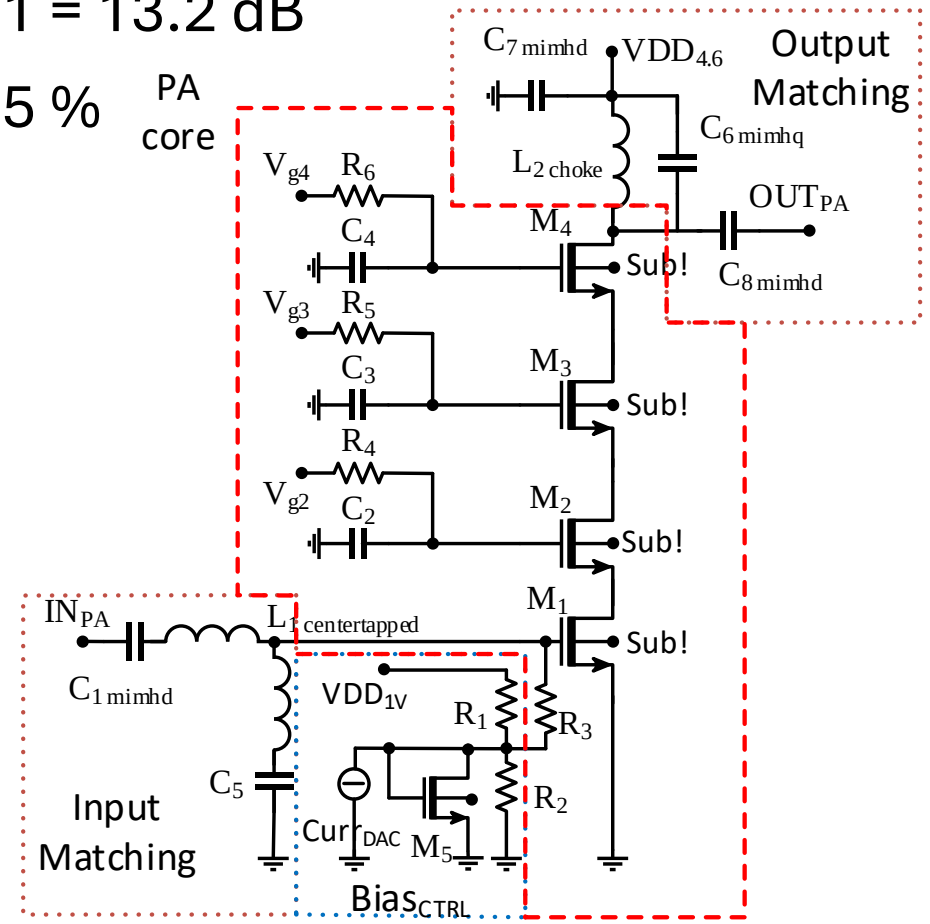
J.P. Aikio, M. Hietanen, N. Tervo, T. Rahkonen, A. Pärssinen," Ka-Band 3-Stack Power Amplifier with 18.8 dBm Psat and 23.5 % PAE Using 22nm CMOS FDSOI Technology" 2019 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR). Orlando, FL, USA, Jan 20-23 2019

© Circuits and Systems Research Unit (CAS), University of Oulu

4-stack CMOS PA using 45nm PDSOI @ 26 GHz

- BY stacking 4 devices VDD increased from 1V to 4.6V
- P_{sat} = 20.5 dBm, P_{1dB} = 18.8 dBm, PAE_{peak} = 29 %, S21 = 13.2 dB
- 100 MHz 16-QAM OFDMA: P_{avg} = 13.5 dBm, PAE = 15 %



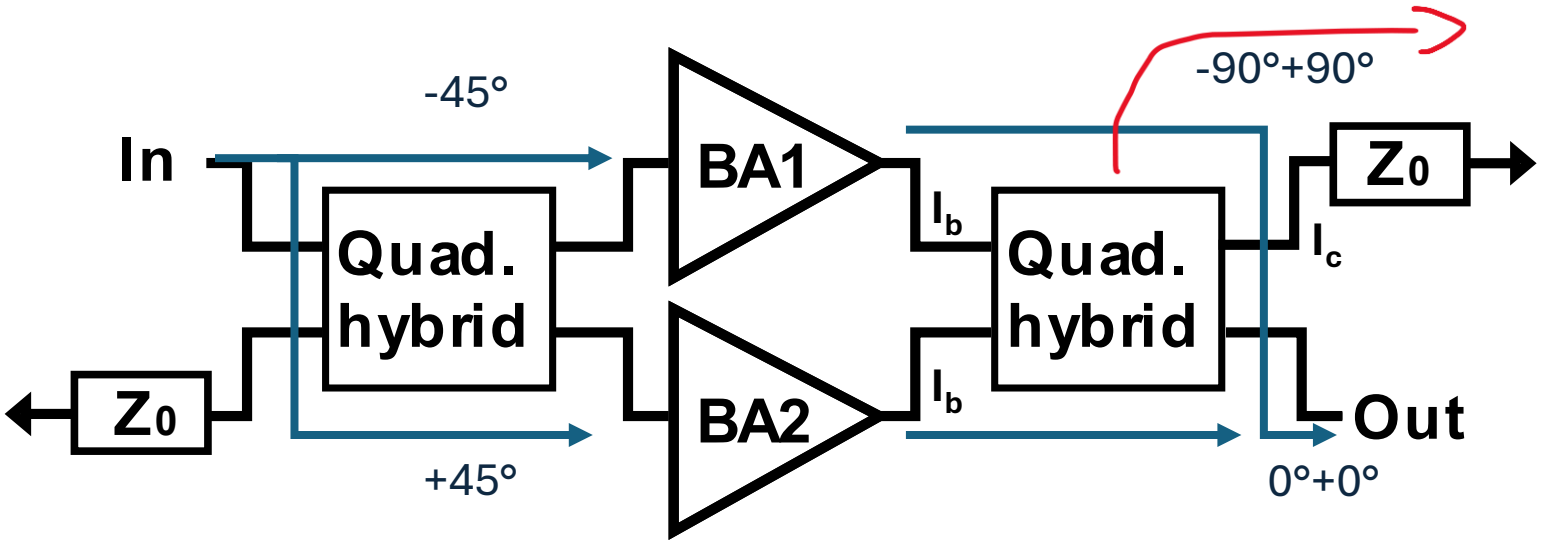


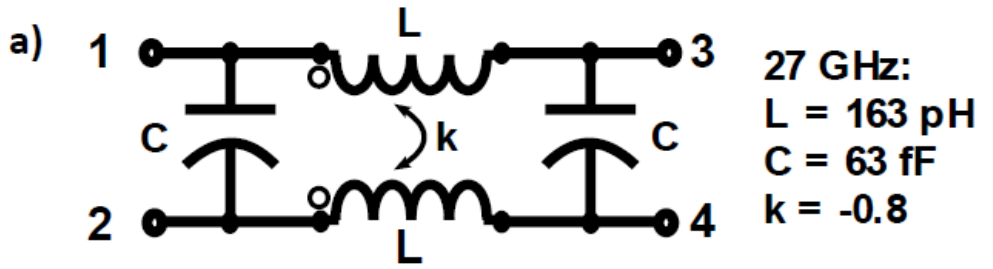
J. P. Aikio, A. Sethi, M. Hietanen, T. Rahkonen, A. Pärssinen," Ka-Band 4-Stack 45nm CMOS SOI Power Amplifier Supporting 3GPP New Radio FR2 band n258", 18th SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC), November 10-14, 2019, Aveiro, Portugal

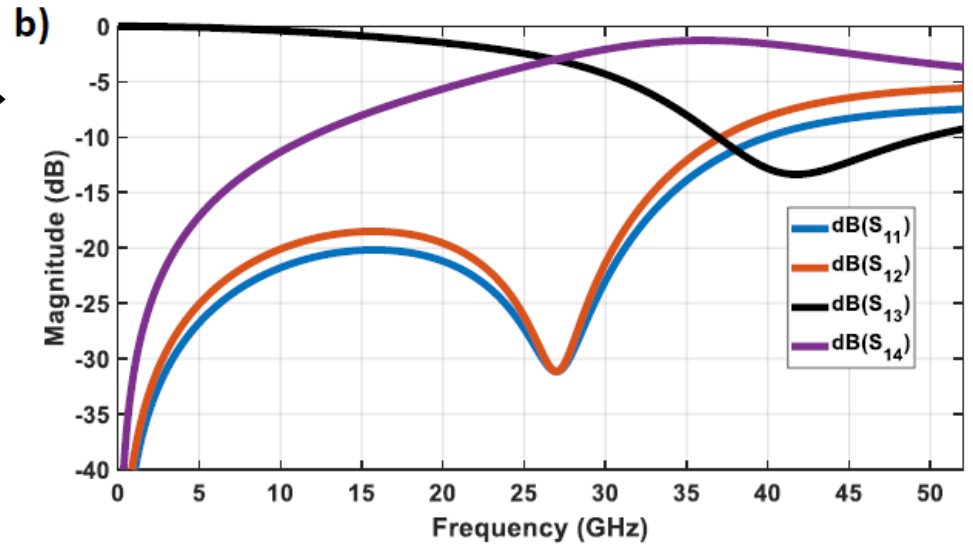
© Circuits and Systems Research Unit (CAS), University of Oulu

Quadrature Balanced Amplifier Using 22nm FDSOI

- +Good matching and stability
- +Load-pull resilient
- -Quadrature hybrid is lossy and narrow band





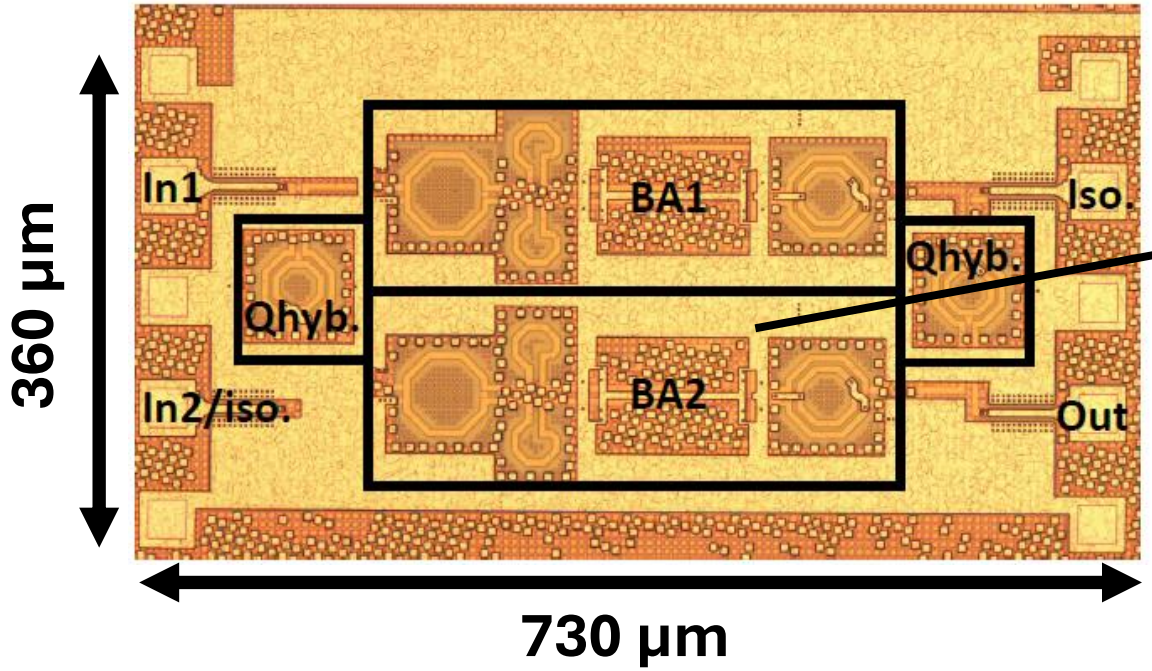


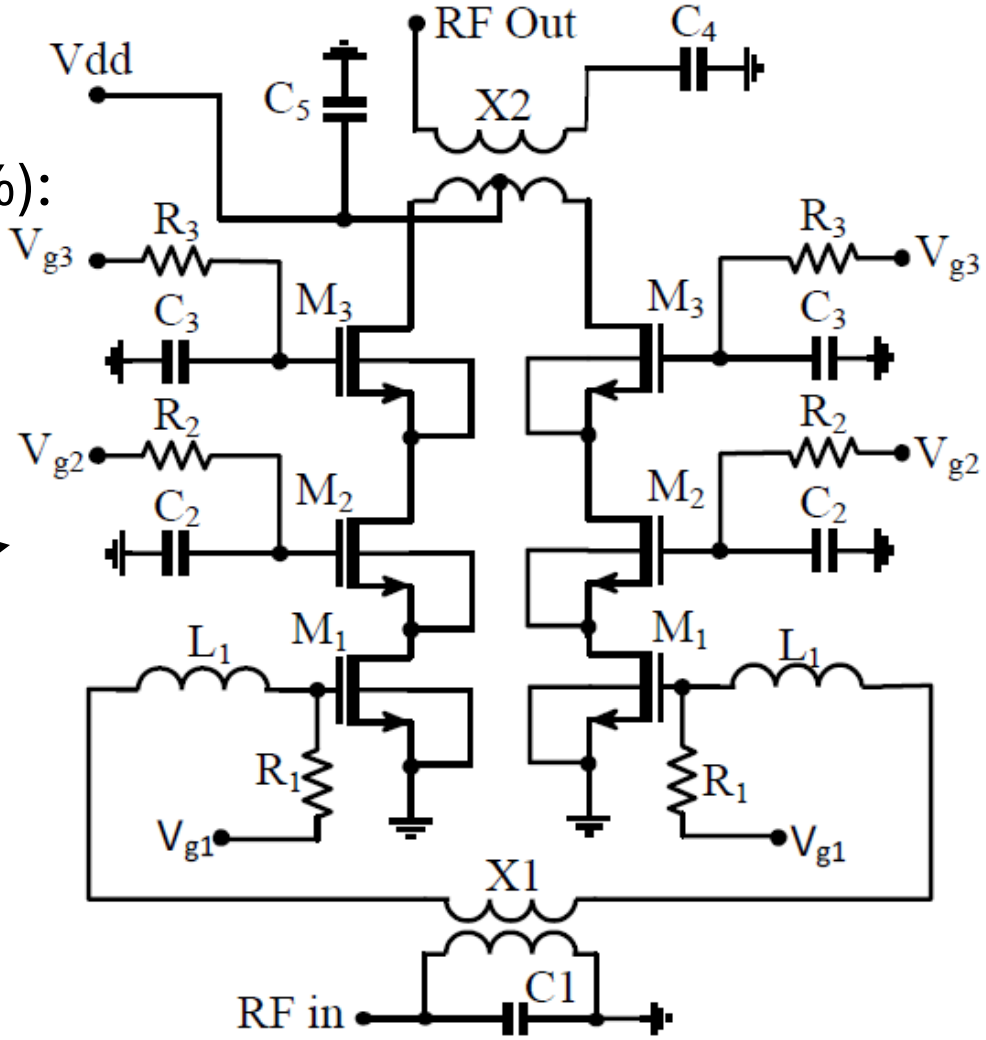
J. Rusanen, N. Shabanzadeh, A. Pärssinen, T. Rahkonen and J. P. Aikio, "Improving a Ka -Band Integrated Balanced Power Amplifier Performance by Compensating Quadrature Hybrid Mismatch Effects," in IEEE Transactions on Very Large Scale Integration (VLSI) Systems. vol. 32, no. 12, pp. 2198-2209, Dec. 2024

© Circuits and Systems Research Unit (CAS), University of Oulu

Quadrature Balanced Amplifier Using 22nm FDSOI

- CW measurements @ 26 GHz:
  P_{sat} = 18.5 dBm, P_{1db} = 15.9 dBm, PAE_{peak} = 16.5 %
- 100 MHz 64-QAM OFDMA NR @ 26 GHz (EVM = 8 %):
  P_{avg} = 13.2 dBm, PAE = 6.7 %



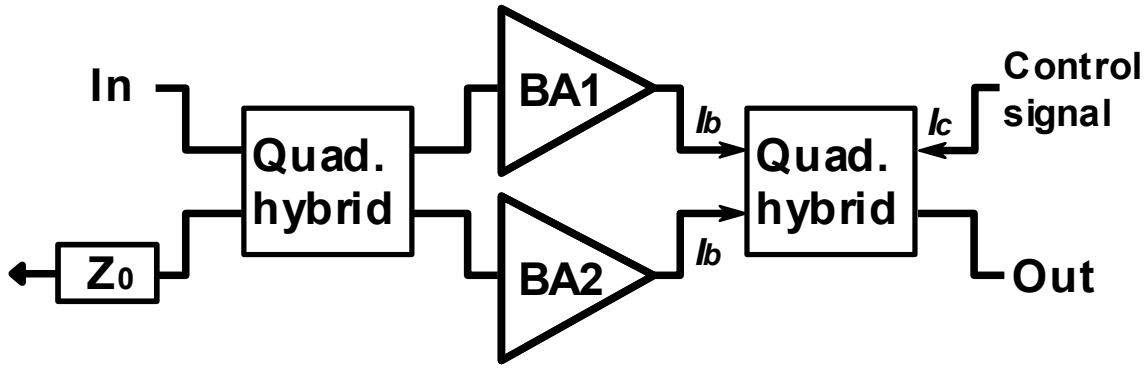


J. Rusanen, N. Shabanzadeh, A. Pärssinen, T. Rahkonen and J. P. Aikio, "Improving a Ka -Band Integrated Balanced Power Amplifier Performance by Compensating Quadrature Hybrid Mismatch Effects," in IEEE Transactions on Very Large Scale Integration (VLSI) Systems. vol. 32, no. 12, pp. 2198-2209, Dec. 2024

© Circuits and Systems Research Unit (CAS), University of Oulu

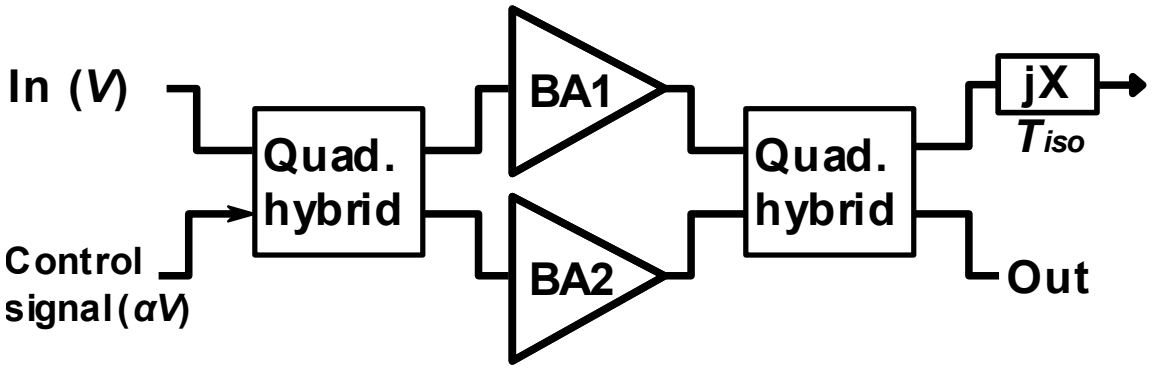
LMBA vs. OLMBA

LMBA [D. Shepphard, MWCL 2016]



$$Z_{BA1} = Z_{BA2} = (1 + \sqrt{2}\frac{I_c e^{j\varphi}}{I_b})Z_0$$

OLMBA [D. Collins, MWCL 2020]

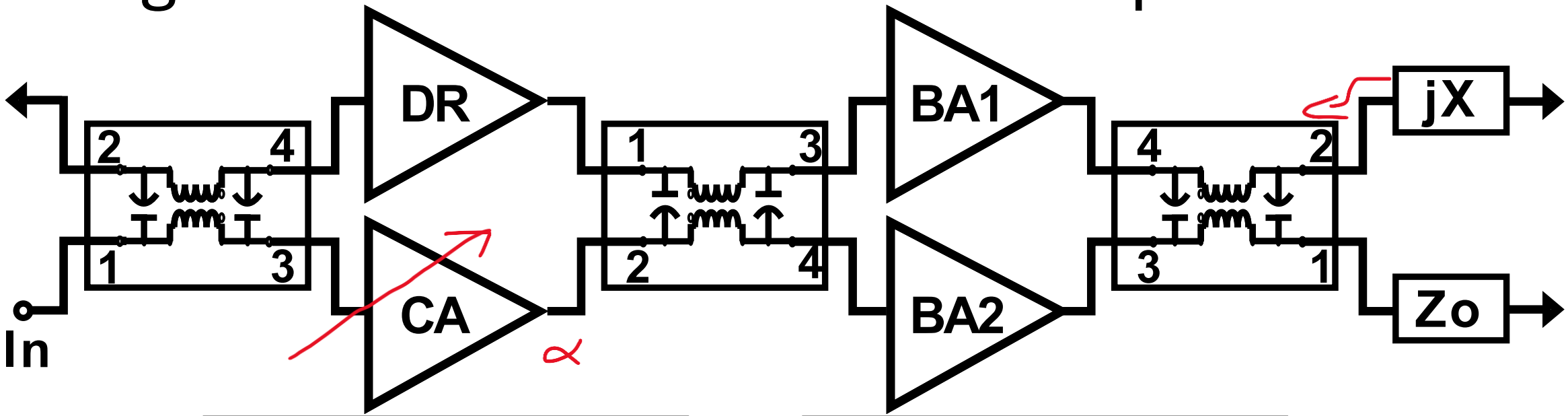


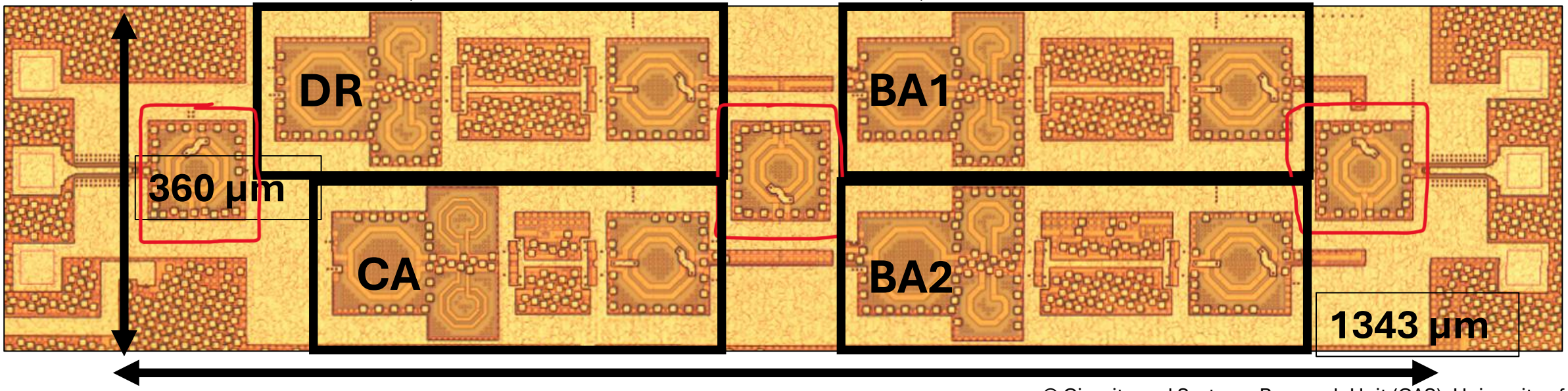
$$Z_{BA1} = \frac{(1 - 2\Gamma_{iso})j\alpha + 1}{j\alpha + 1}Z_0$$

$$Z_{BA2} = \frac{(2\Gamma_{iso} + 1)\alpha + j}{\alpha + j}Z_0$$

© Circuits and Systems Research Unit (CAS), University of Oulu

Integrated OLMBA with Control Amplifier

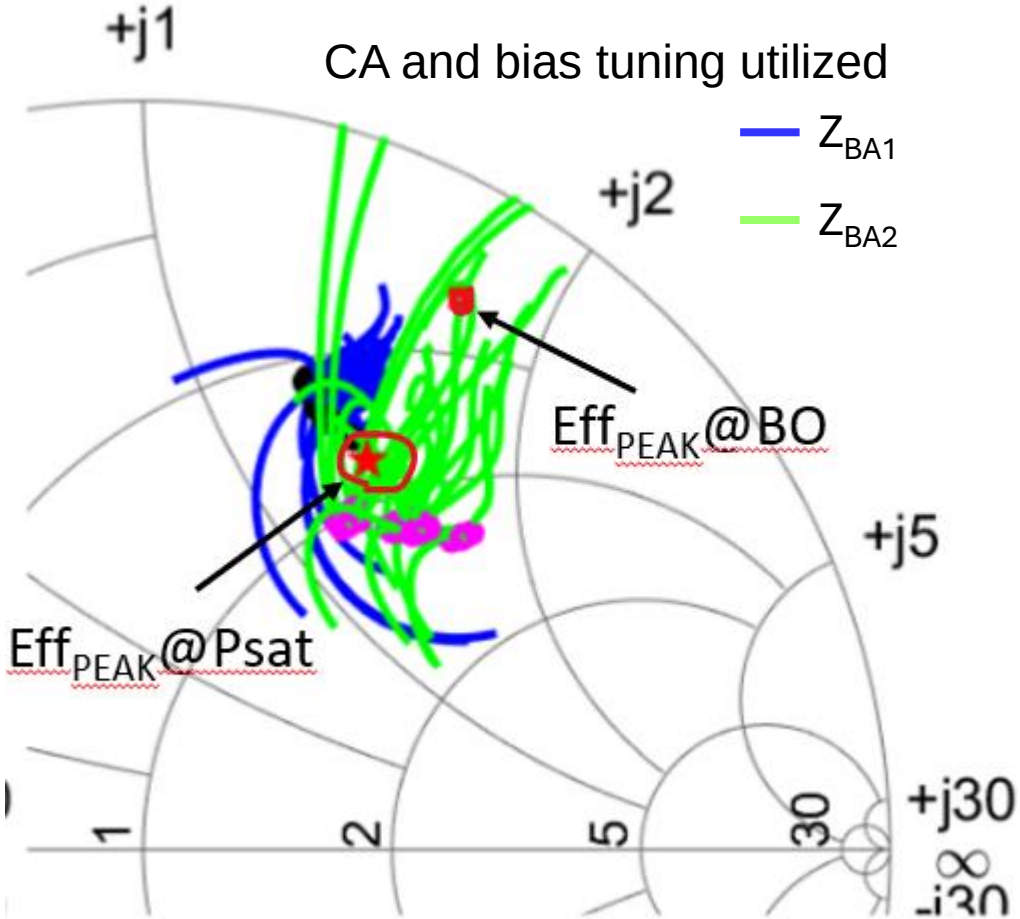


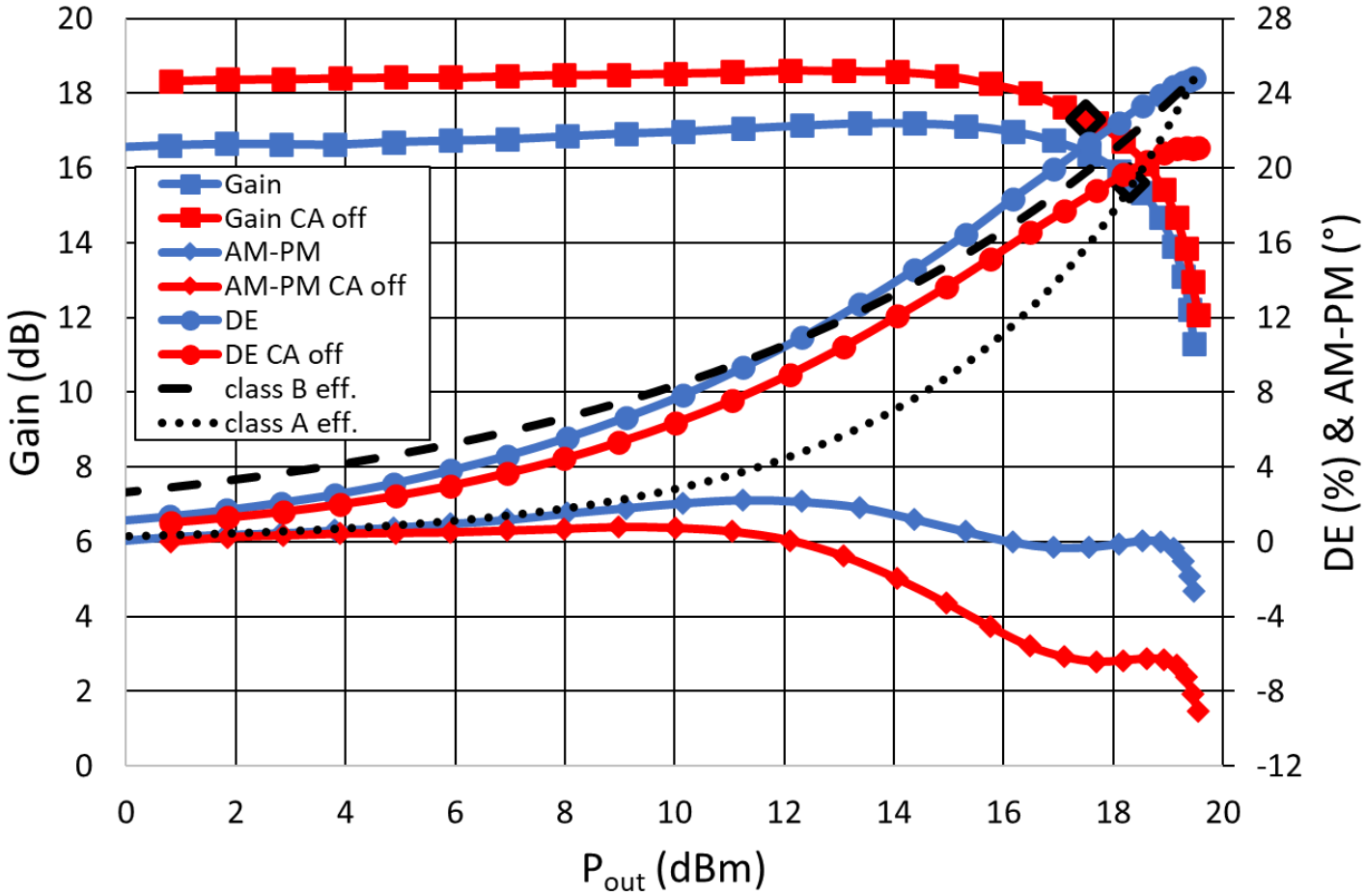


© Circuits and Systems Research Unit (CAS), University of Oulu

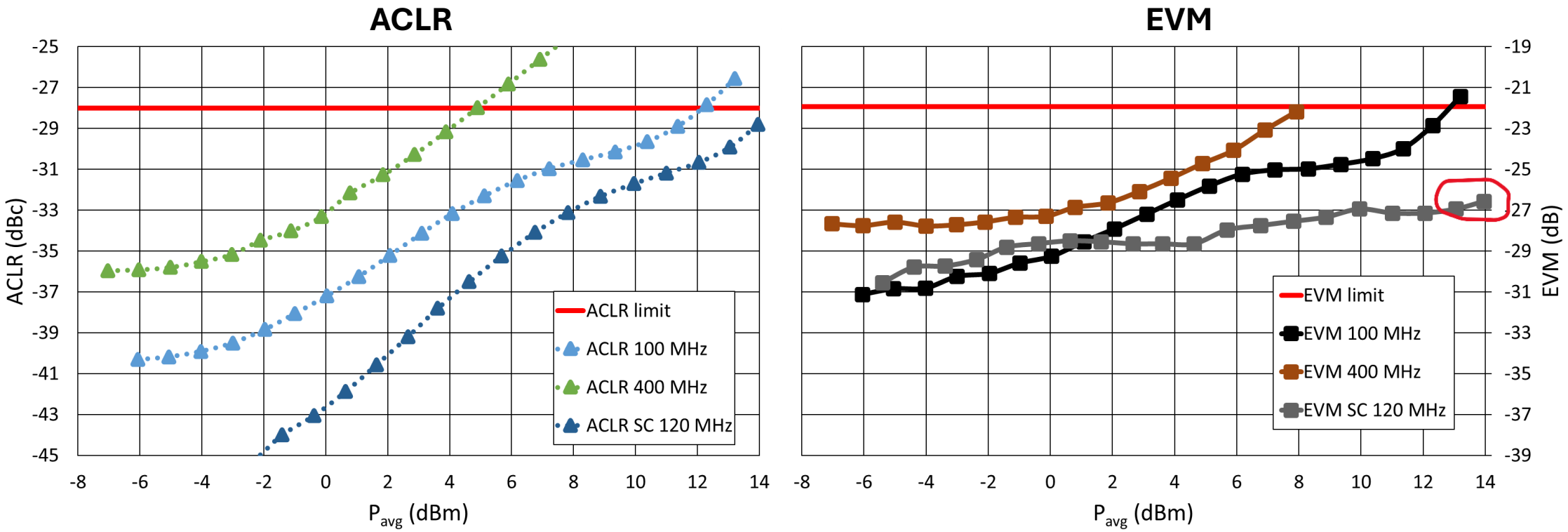
Integrated OLMBA with Control Amplifier

- Load modulation enabled by bias tuning of control amplifier (CA) and DR, BA1, BA2
- CW measurements @ 26 GHz: P_{sat} = 19.5 dBm, DE_{Max} = 25 %, S21 = 16.6 dB





OLMBA Modulated Measurements



	24 GHz	26 GHz	27 GHz	29 GHz
100 MHz 64-QAM 3GPP/NR FR2				
P_{avg} (dBm)	12.1	11.4	11.2	11.5
EVM (dB)	-23.8 (6.4 %)	-24.0 (6.3 %)	-24.3 (6.1 %)	-22.9 (7.2 %)
ACLR (dBc)	-28.1	-28.9	-28	-28.1
PAE/DE_{avg} (%)	5.7/7.8	5.6/9.3	5.6/7.7	4.3/6.7

J. Rusanen, A. Sethi, N. Tervo, T. Rahkonen, A. Pärssinen, J. P. Aikio "Ka-Band Stacked and Pseudo-differential Orthogonal Load-Modulated Balanced Power Amplifier in 22 nm CMOS FDSOI" International Journal of Microwave and Wireless Technologies, 1-8. 2023

© Circuits and Systems Research Unit (CAS), University of Oulu

Comparison Table of the CMOS PAs

PA	3 stack SE	4 Stack SE	Quad. Balanced PA	2 stage OLMBA
Technology	22FDX	45RFSOI	22FDX	22FDX
VDD (V)	2.7	4.6	2.7	2.7
P_{sat} (dBm)	18.8	20.5	18.5	19.5
P_{1dB} (dBm)	15	18.8	15.9	18.3
PAE_{PEAK} (%)	24	29	16.5	24.8 (DE)
Gain (dB)	10	13.2	13.5	16
Modulation	-	100 MHz 16-QAM OFDM	100 MHz 64-QAM OFDM	100 MHz 64-QAM OFDM
P_{avg}@ACLR28dbc	-	13.5	13.2	12.1
PAE @P_{avg} (%)	-	15	6.7	7.8 (DE)
Area (mm^2)	0.210	0.226	0.263	0.483

© Circuits and Systems Research Unit (CAS), University of Oulu

Conclusion

- To compensate path losses phased arrays are proposed for mmWave telecom
- To enable beamforming each antenna is preceded by small PA
- Due to massive parallelism single DPD not able to linearize the TX sufficiently
- PAs resilient to load variations are preferred => Quad. Balanced PAs are interesting!
- Currently P_{avg} ~ 12 dBm with NR OFDM signal is achievable with CMOS PA
- Efficiency needs to improve e.g. with the use of load modulation
- Analog predistorters preceded by each PA is tempting option to linearize small PAs
- With APD memoryless nonlinearities can be reduced significantly easing up the requirements of the DPD

© Circuits and Systems Research Unit (CAS), University of Oulu