A 24–31GHz 28nm FD-SOI CMOS 3:1 VSWR Resilient Inductive Hybrid Coupler-Based Doherty Power Amplifier

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Outline

- ❑ Motivations & Challenges
- ❑ Proposed Inductive Hybrid Coupler-based Doherty PA
- ❑ Measurements results
- ❑ Conclusion

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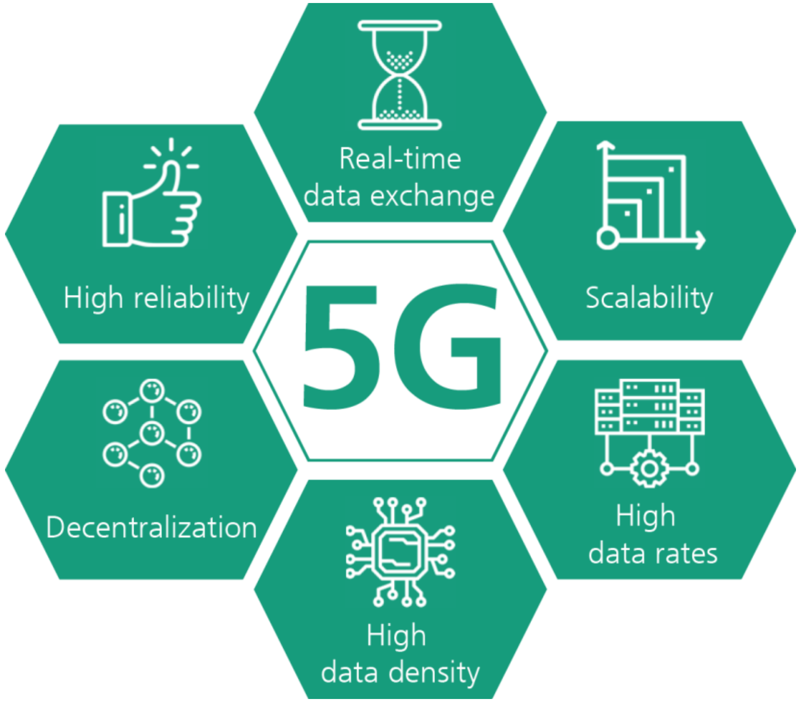
Development of the 5G New Radio

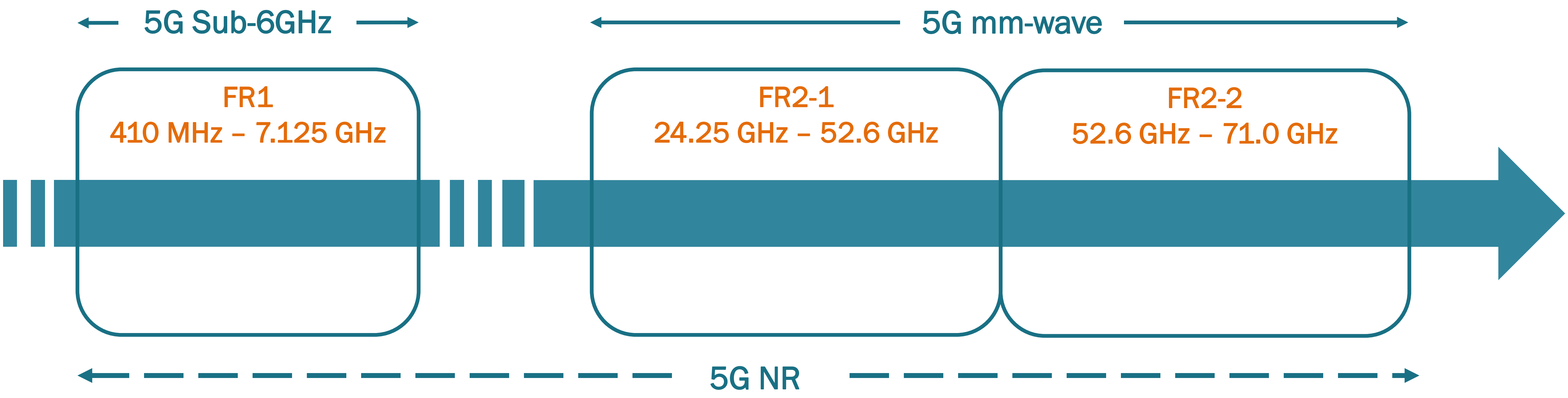


- Demand for modern wireless communications
  - High data rates
  - High reliability
  - Long battery life
- Requirement for RF transmitters (64QAM signals)
  - High linearity
  - Wideband behavior
  - High efficiency up to deep PBO
  - VSWR Robustness

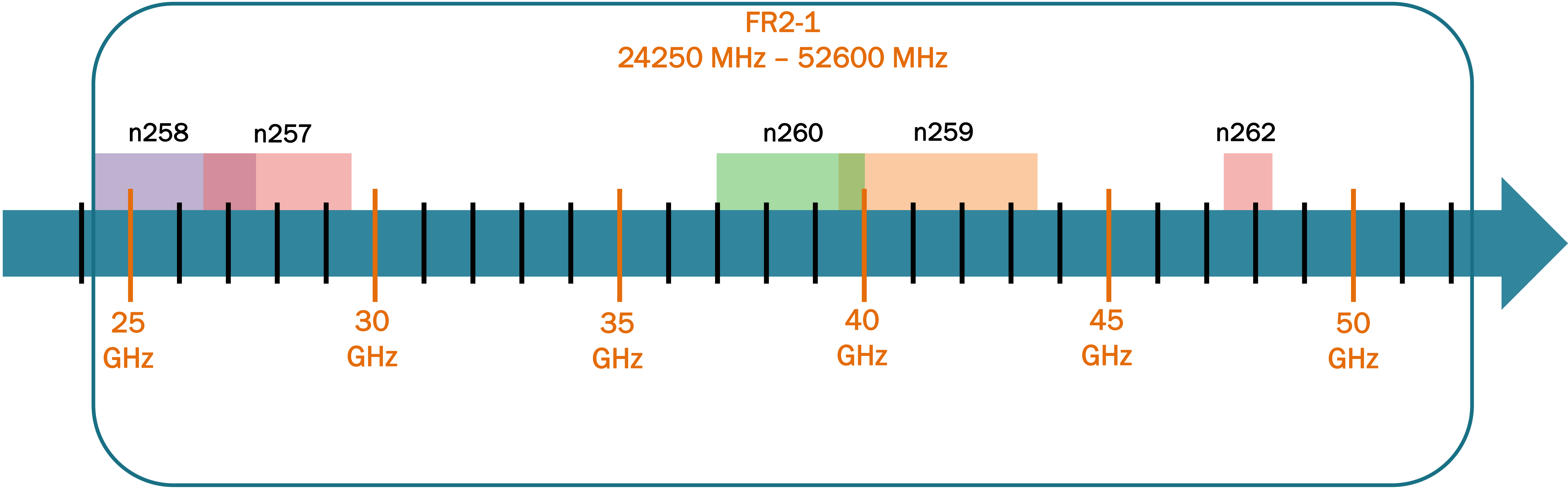
➢ **KEY WORDS : Linearity, Efficiency, VSWR Robustness, Wideband**

5G NR spectrum

- 5G NR spectrum is composed of two frequency ranges :
  - 5G Sub-6 GHz
  - 5G mm-wave



5G NR spectrum



- **Band of interest : 24.25 – 29.5 GHz, i.e. 20% relative bandwidth**

From Beamforming…

- 5G relies on beamforming antenna arrays that require for PA :
  - moderate output power
  - high efficiency

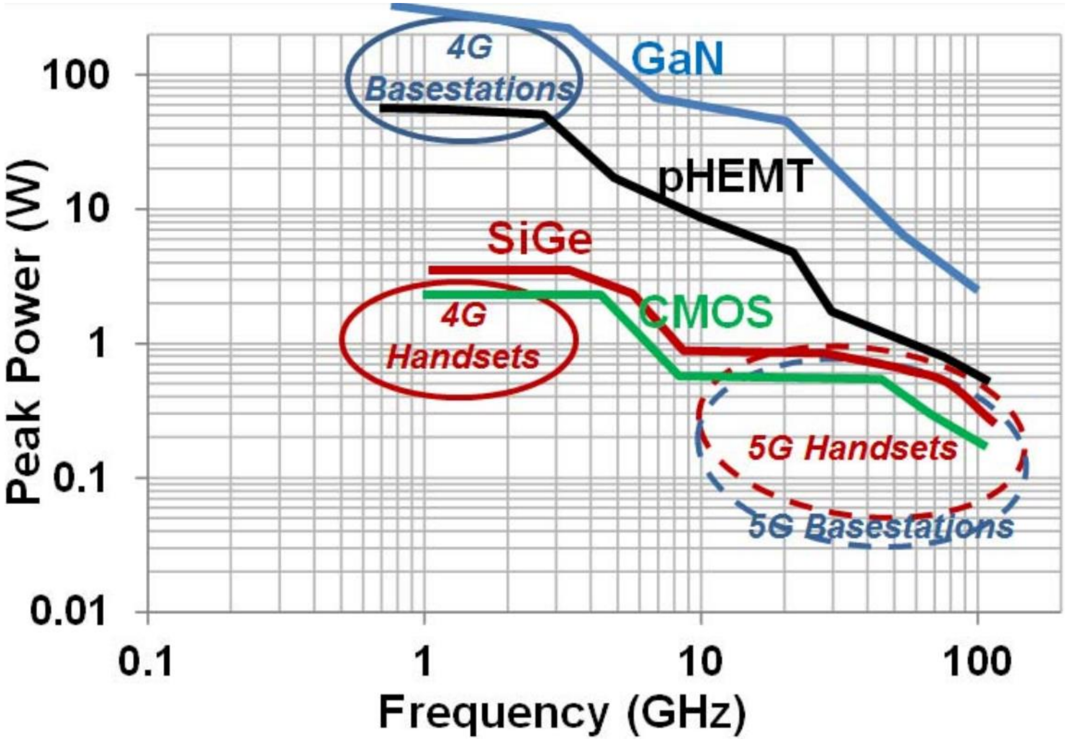
	Handset	Access Point	Base Station	Backhaul
EIRP (avg)	30 dBm	45 dBm	55 dBm	60 dBm
N_{ant}	4-6	32	64	256
P_{avg} / PA	11-15 dBm	12 dBm	16 dBm	9 dBm
P_{max} / PA	20-24 dBm	21 dBm	25 dBm	18 dBm
$Efficiency_{avg}$	20 %	20 %	20 %	20 %
DC Power	0,4-0,6 W	2,5 W	12 W	10 W

[1] P. M. Asbeck, N. Rostomyan, M. Ozen, B. Rabet, and J. A. Jayamon, “Power amplifiers for mm-wave 5g applications : Technology comparisons and cmos-soi demonstration circuits,” IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 7, pp. 3099–3109, 2019.

… to CMOS technologies choice

❑ CMOS technologies are favored for :

- their production low cost
- their integration high capacity



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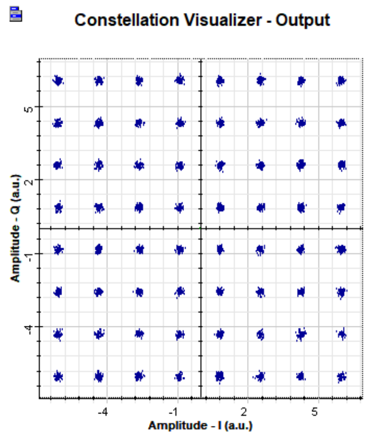
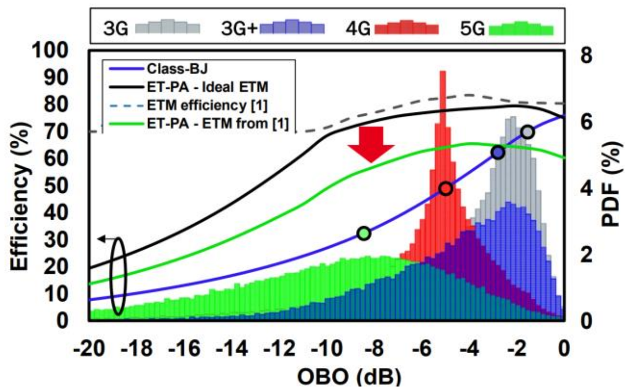
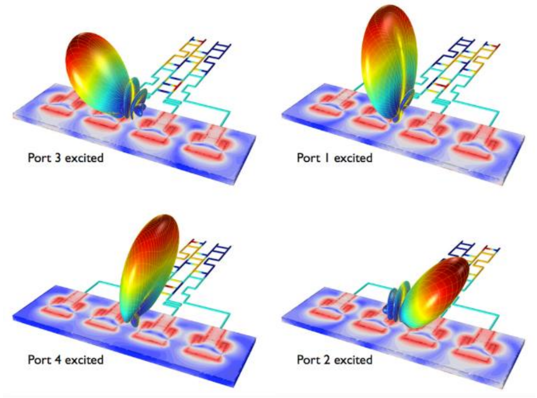
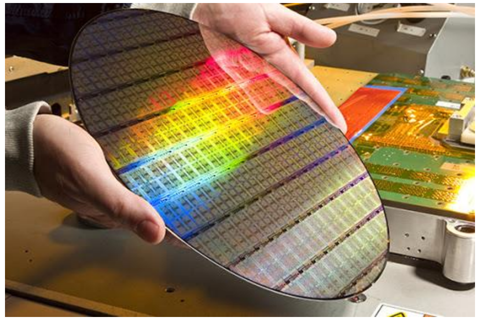
Requirements for 5G PA

High linearity over 100 MHz bandwidth	High efficiency up to deep power back-off	1.5:1 VSWR Immunity	Compactness
5G signals use spectrally efficient modulation schemes (high order QAM) over large bandwidths	5G high-order QAM signals result in high peak-to-average power ratio (PAPR)	Beamforming antenna arrays exhibit large impedance variations which induce VSWR variations	A high level of integration for power amplifiers is needed due to their large size









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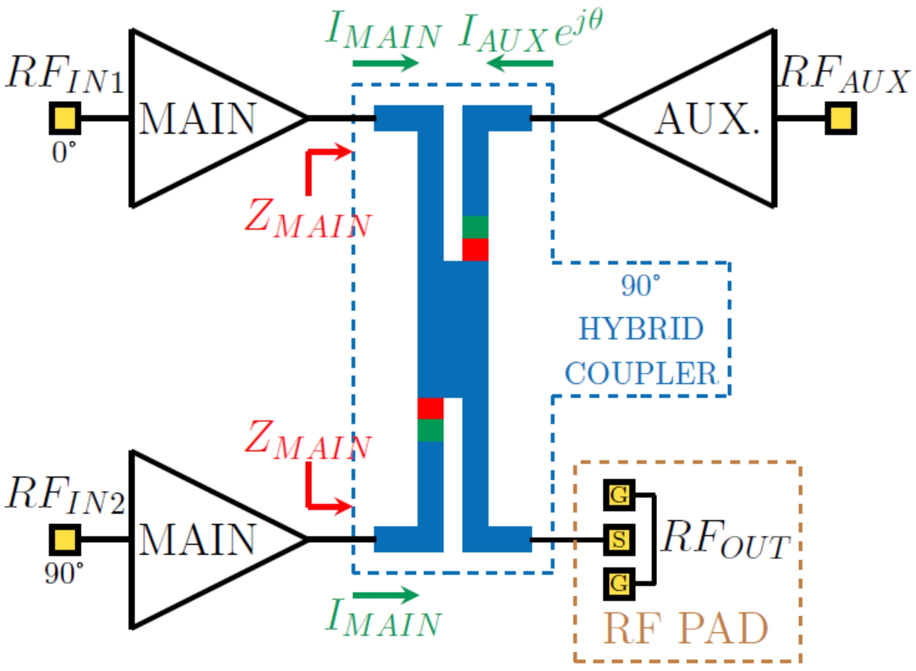
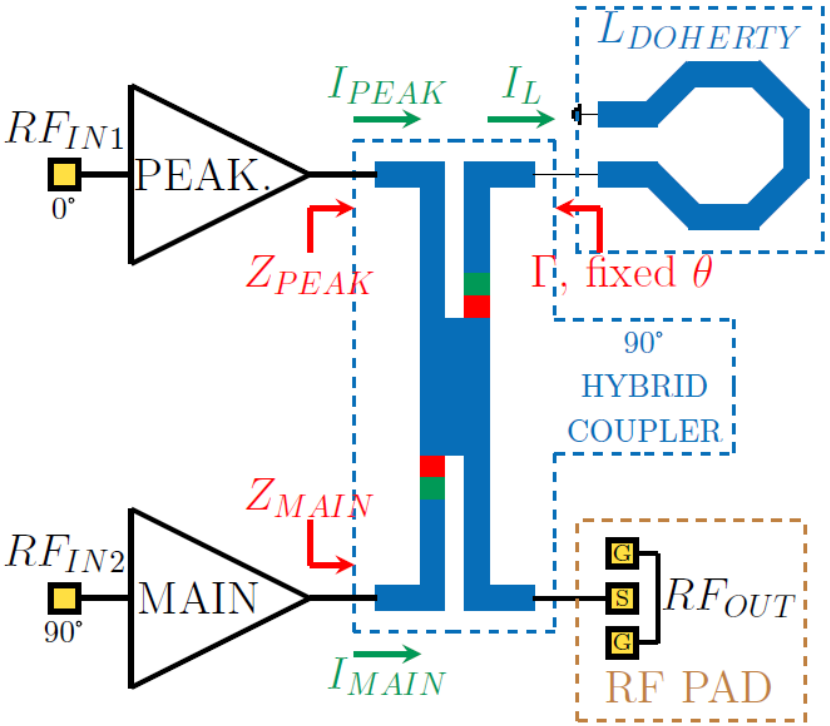
From LMBA to Doherty Principle

Conventional LMBA



$$Z_{MAIN_{(LMBA)}} = Z_0.(1+\sqrt{2}\frac{I_{AUX}}{I_{MAIN}}e^{j\theta})$$

Proposed solution



$$Z_{MAIN_{(DOHERTY)}} = Z_0.(1+\sqrt{2}\frac{\Gamma.I_L}{I_{MAIN}}e^{j\theta})$$

From LMBA to Doherty Principle

- Since the load is purely reactive, the signal is reflect :
  - with a phase shift $\theta_L = tan^{-1}\left(\frac{X_L}{Z0}\right)$
  - without attenuation ($|\Gamma| = 1$)
- The load impedance at the main amplifier output becomes :

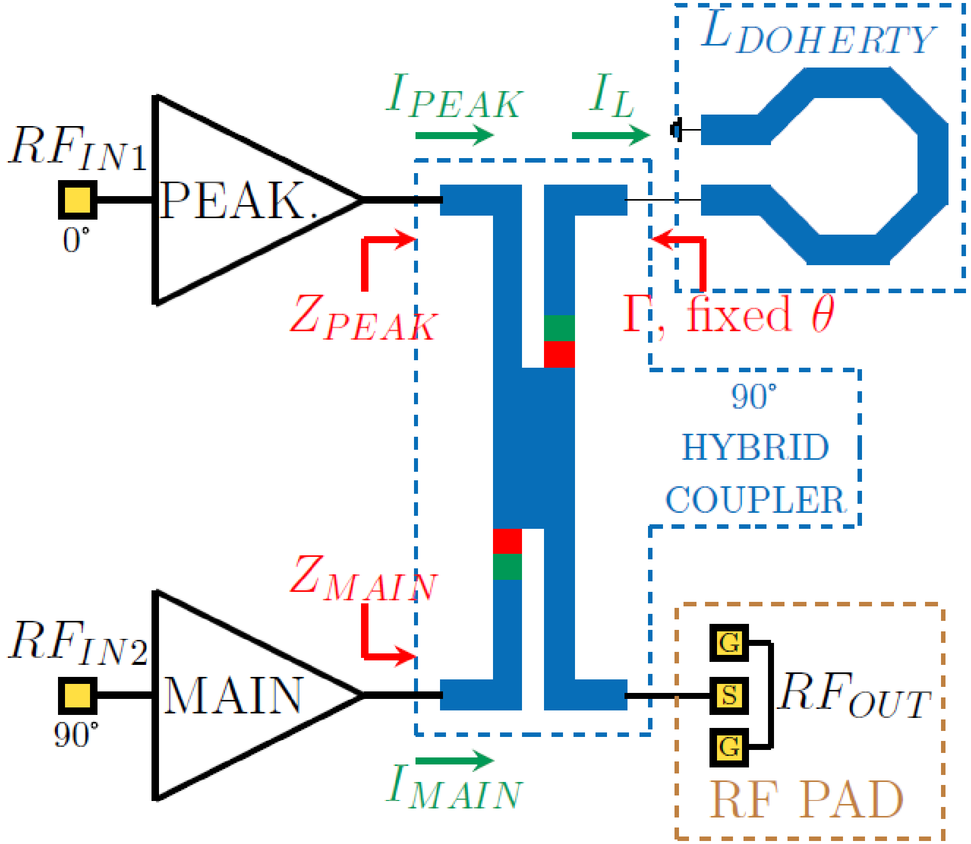
$$Z_{MAIN} = Z_0.(1 + e^{j\theta})$$

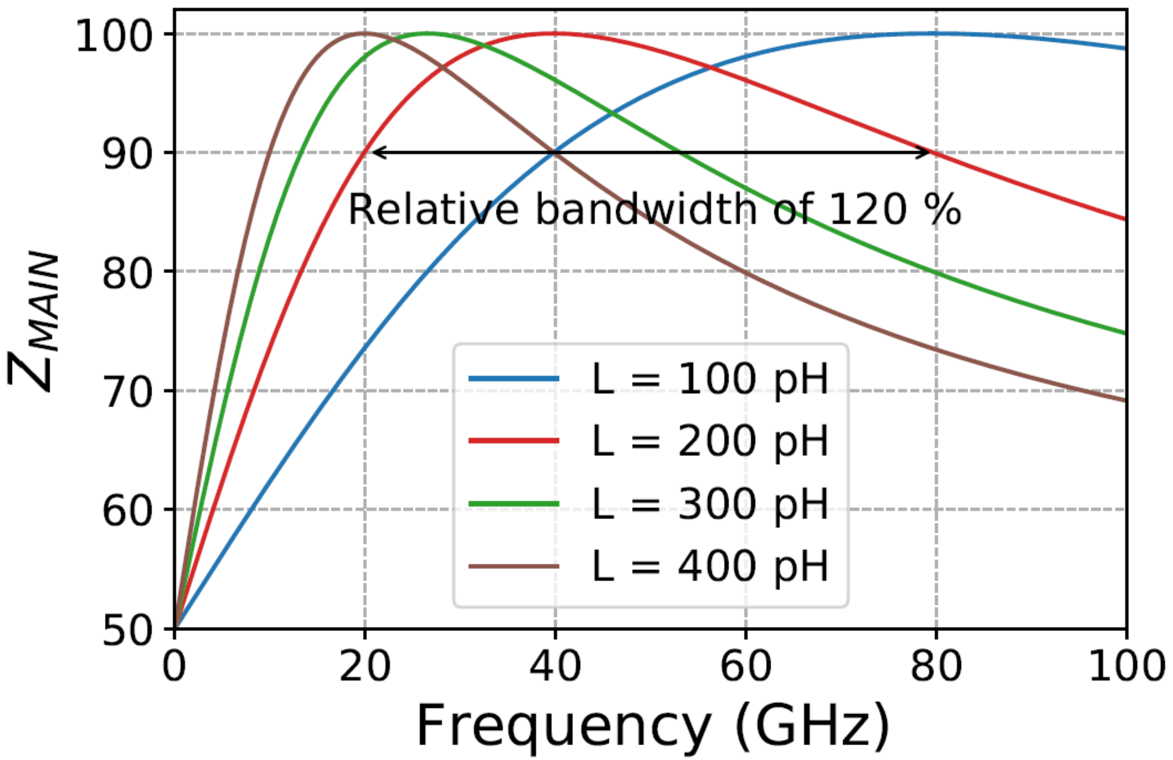
- A load of 2 Z_0 is thus presented at the main amplifier output if :

$$\theta = 2\theta_{CPL} + \theta_L = -\frac{\pi}{2} + \theta_L = 0$$

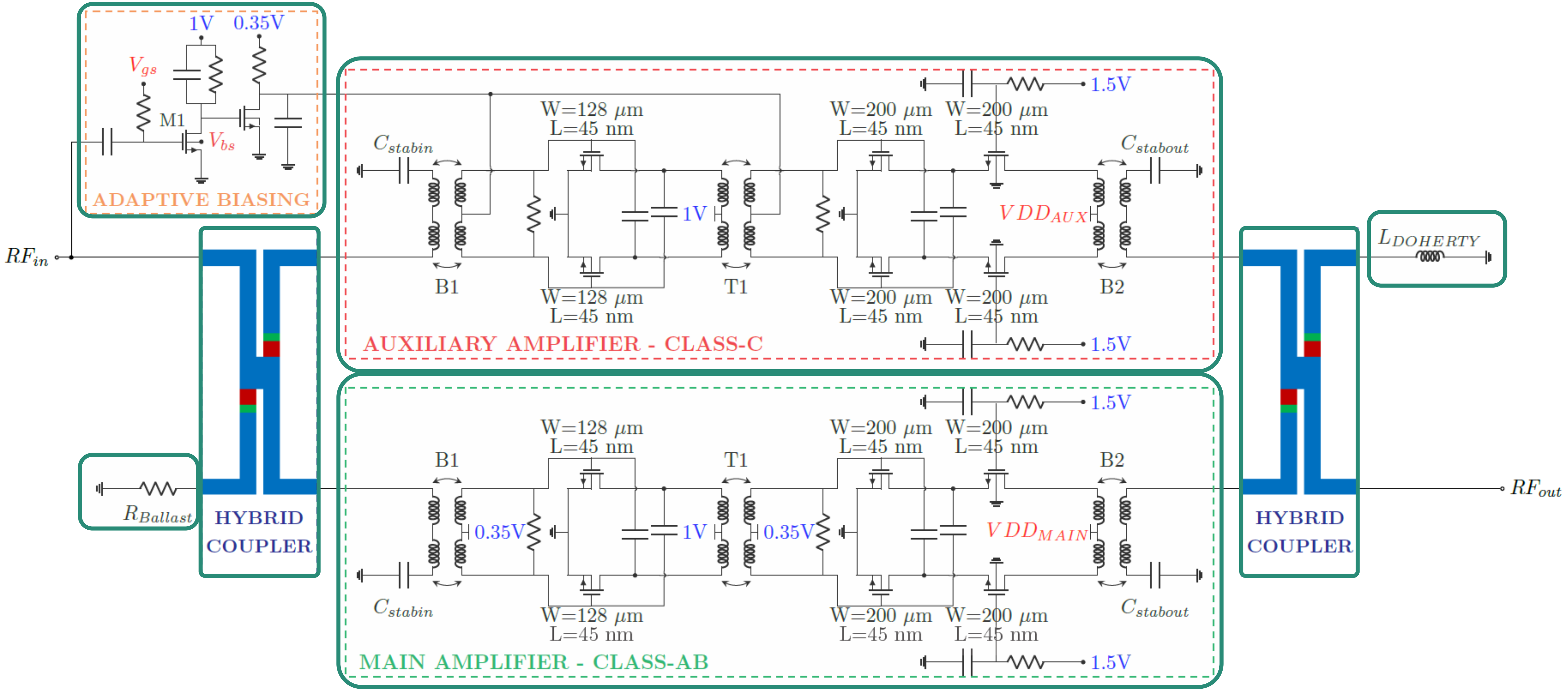
From LMBA to Doherty Principle

- The architecture achieves 120 % relative bandwidth



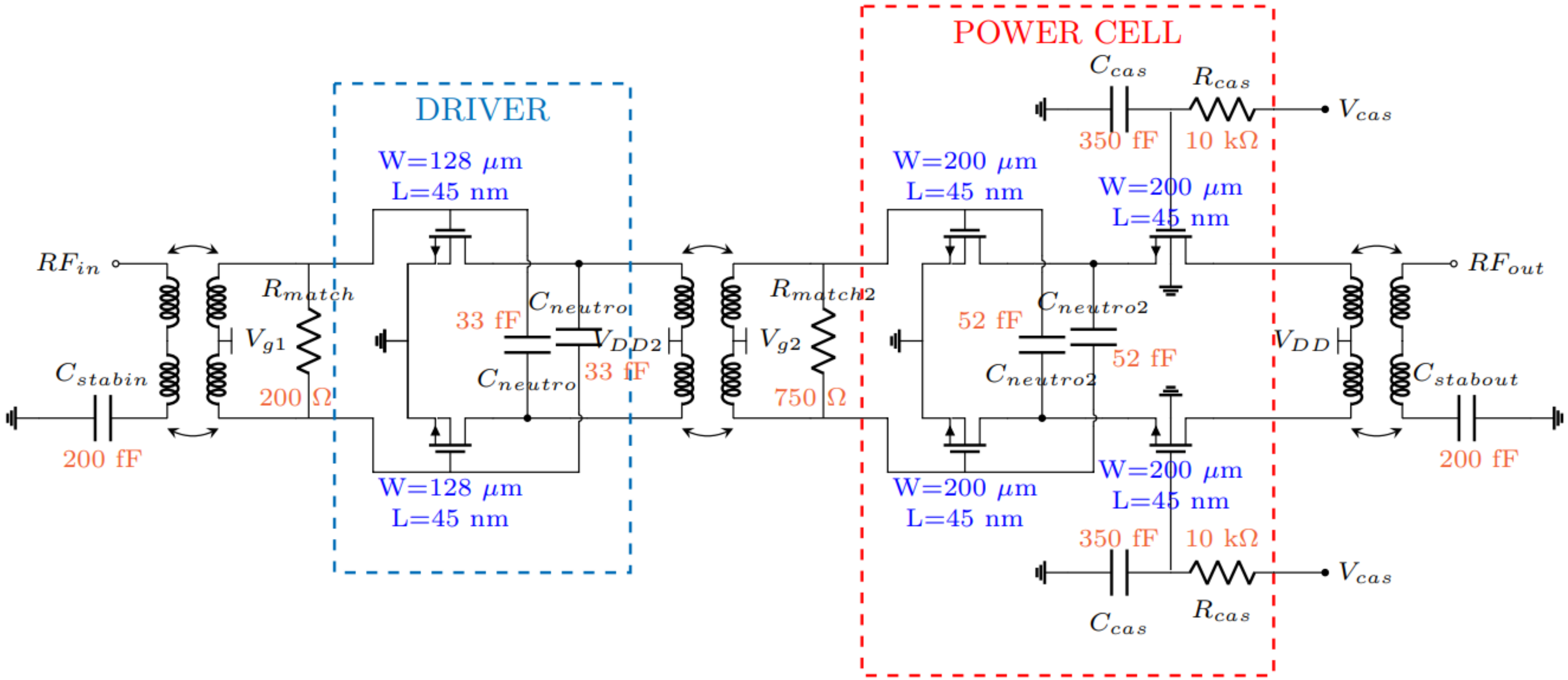


Chosen Architecture



Class-AB Elementary Power Unit

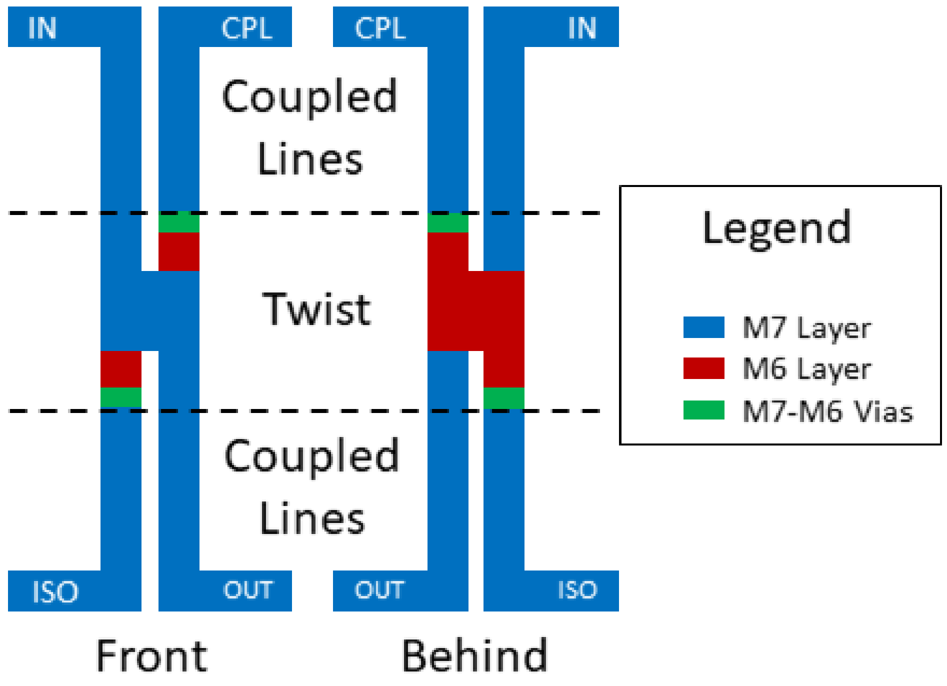
- **The elementary power cell is composed of :**
  - A differential two-stacked power cell
  - A differential common source driver

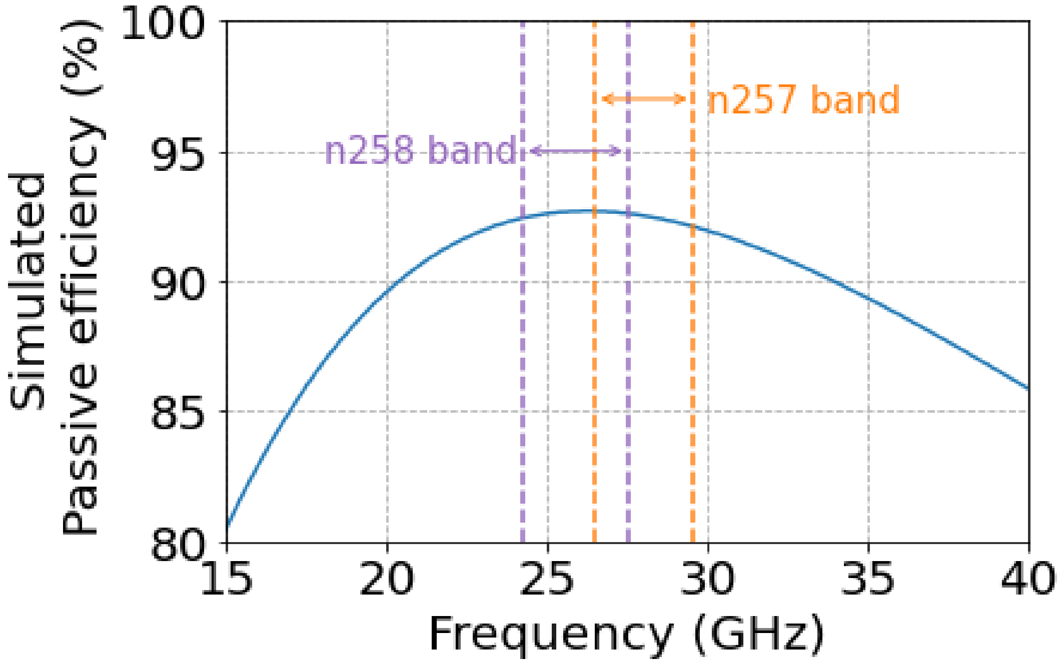


90° Twisted Hybrid Couplers

Twisted hybrid couplers are chosen for :

- their wideband behavior
- their low insertion losses





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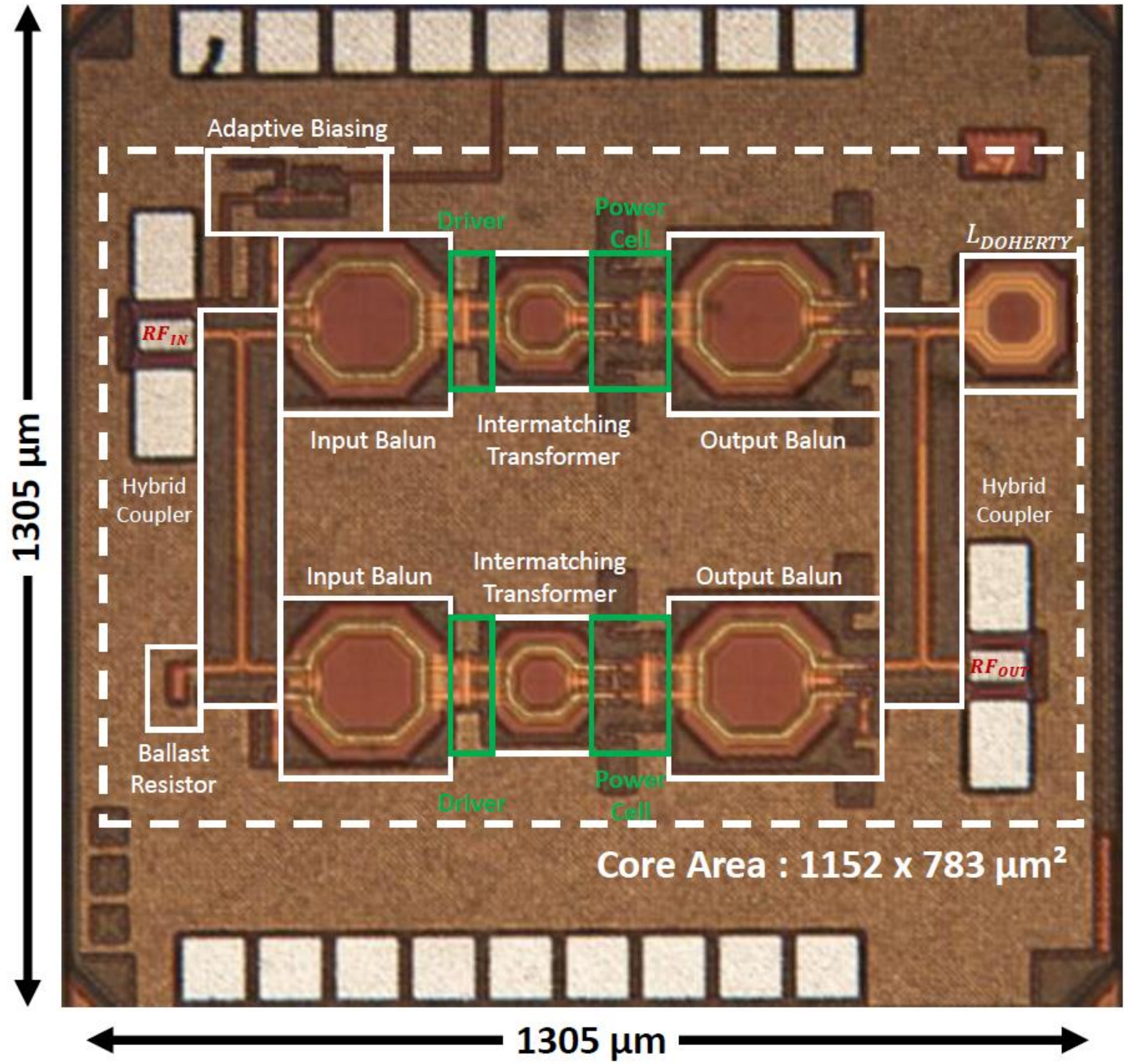
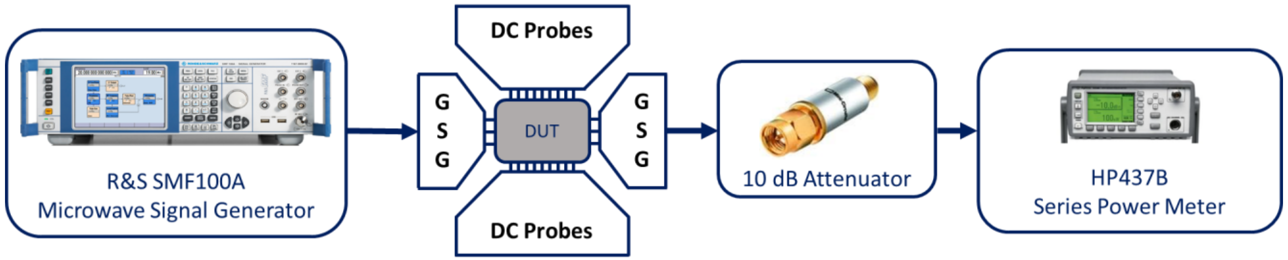
Die Micrograph



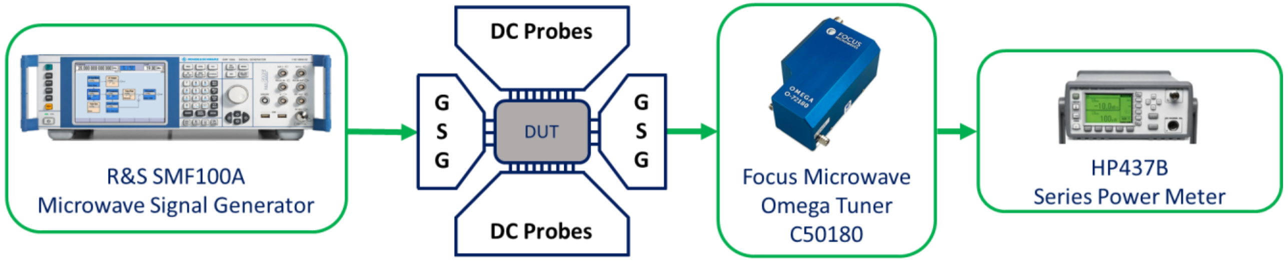
- ST Microelectronics CMOS 28nm FD-SOI
- Total Area : 1305 x 1305 µm²
- Core Area : 1152 x 783 µm²

Measurement Setup

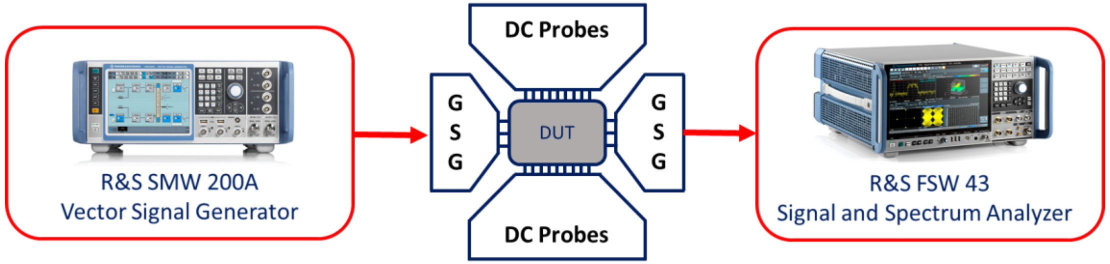
CW Measurements

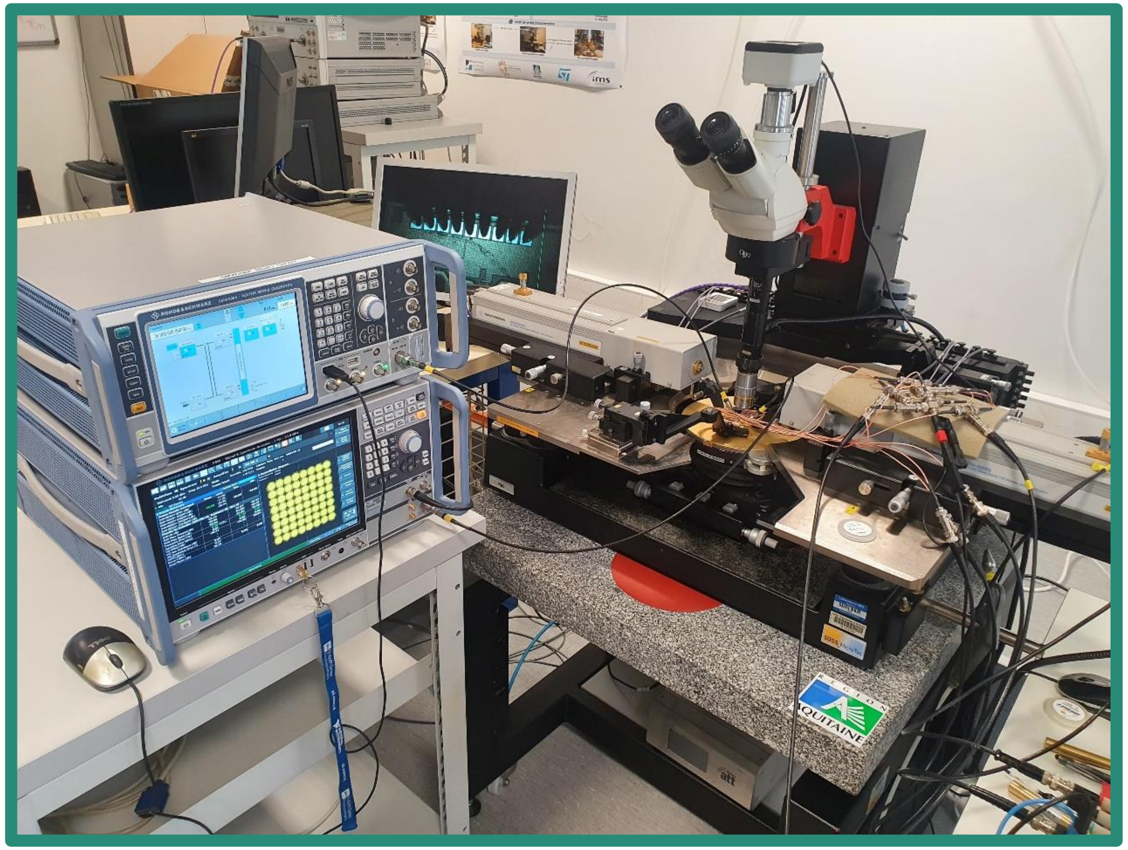


CW Measurements with load pull tuner



Modulation Signal Measurements





Symmetrical configuration

S Parameters

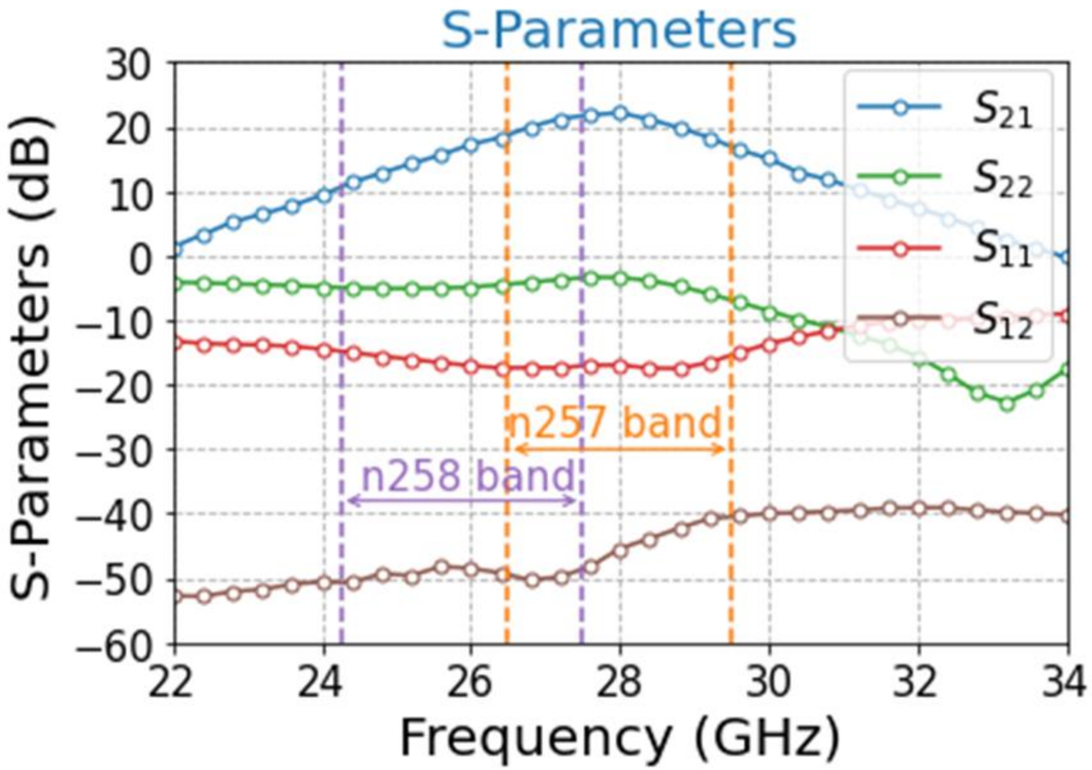
- The input is well matched (S_{11} < -15dB)
- Maximum S_{21} gain of 21dB at 28GHz
- S_{21} > 10dB is maintained

CW Measurement at 26 GHz

- PAE_{max} = 37 % - PAE_{6dBPBO} = 25 %
- P_{sat} = 20.6 dBm

CW Measurement over frequency bands

- PAE_{max} > 29 % (max. 37% at 27GHz)
- PAE_{6dBPBO} > 21 % (max. 25% at 26GHz)
- P_{sat} > 18.5 dBm (max. 20.6 dBm at 26GHz)



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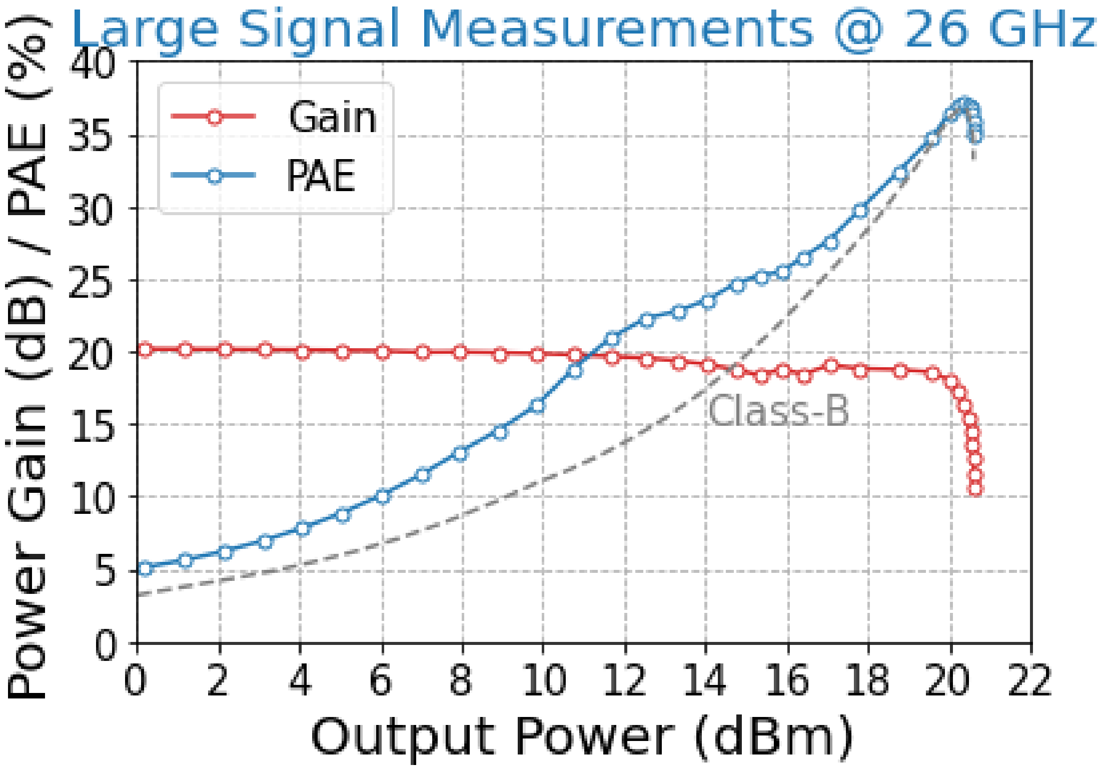

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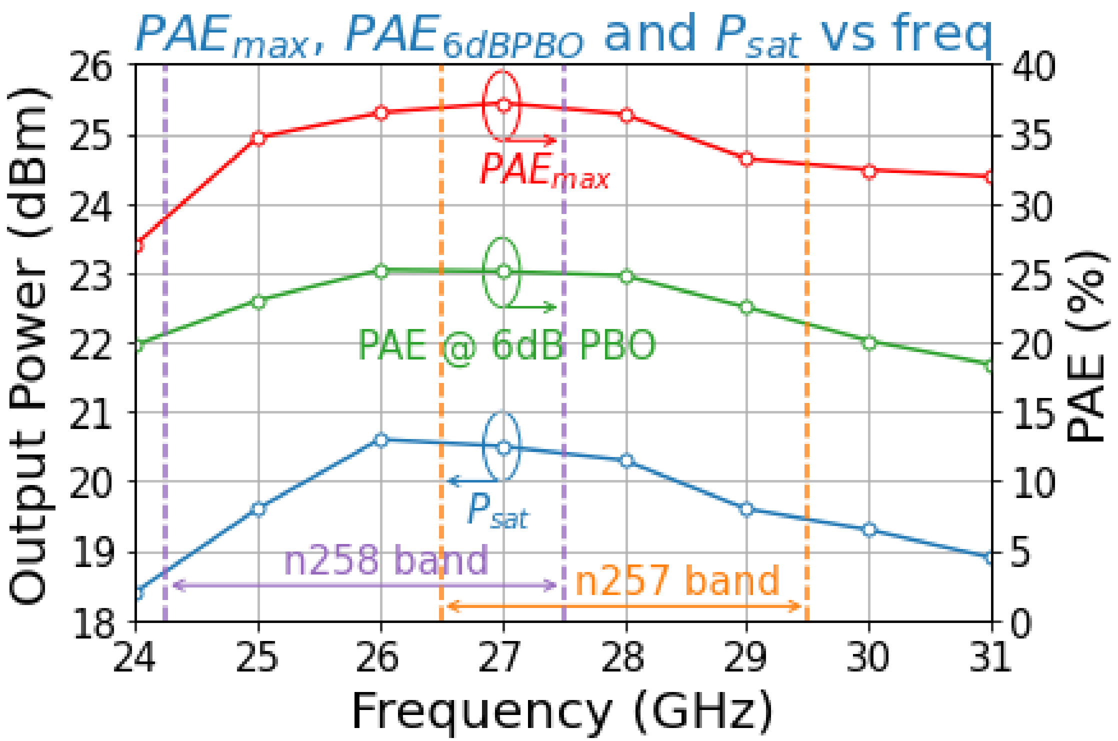

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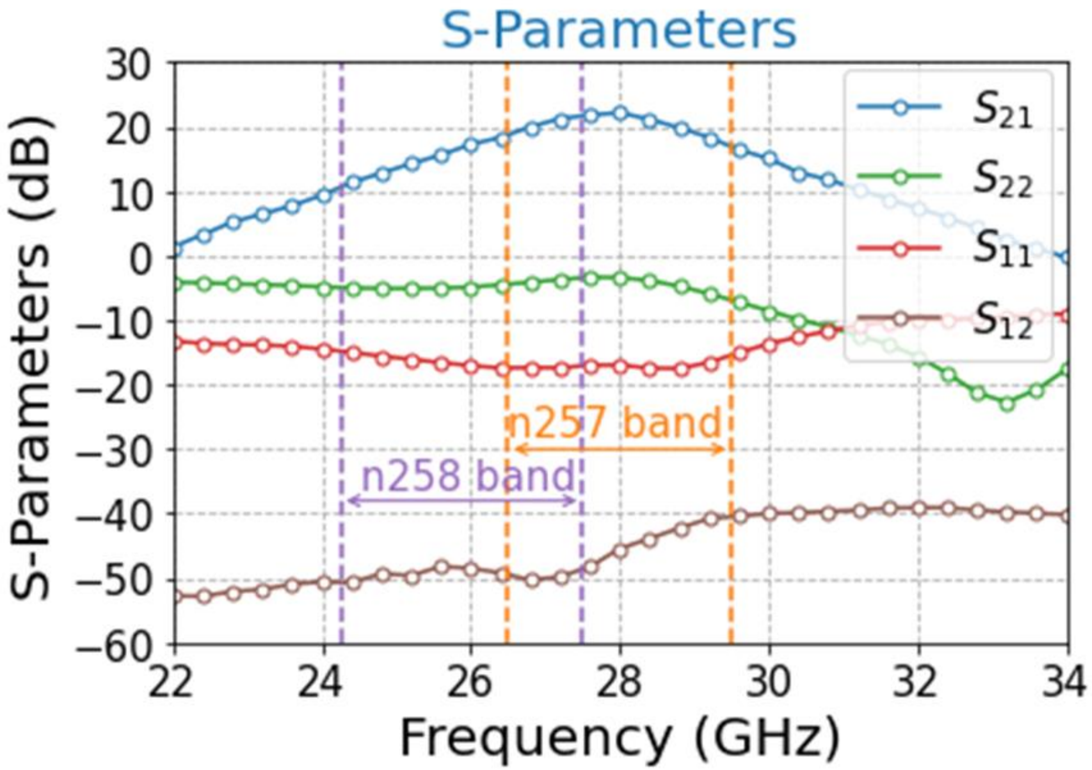

CW Measurement at 26 GHz

- PAE_{max} = 37 % - PAE_{6dBPBO} = 22 %
- P_{sat} = 18.8 dBm

CW Measurement over frequency bands

- PAE_{max} > 29 % (max. 37% at 27GHz)
- PAE_{6dBPBO} > 19 % (max. 22% at 26GHz)
- P_{sat} > 17.2 dBm (max. 19 dBm at 26GHz)

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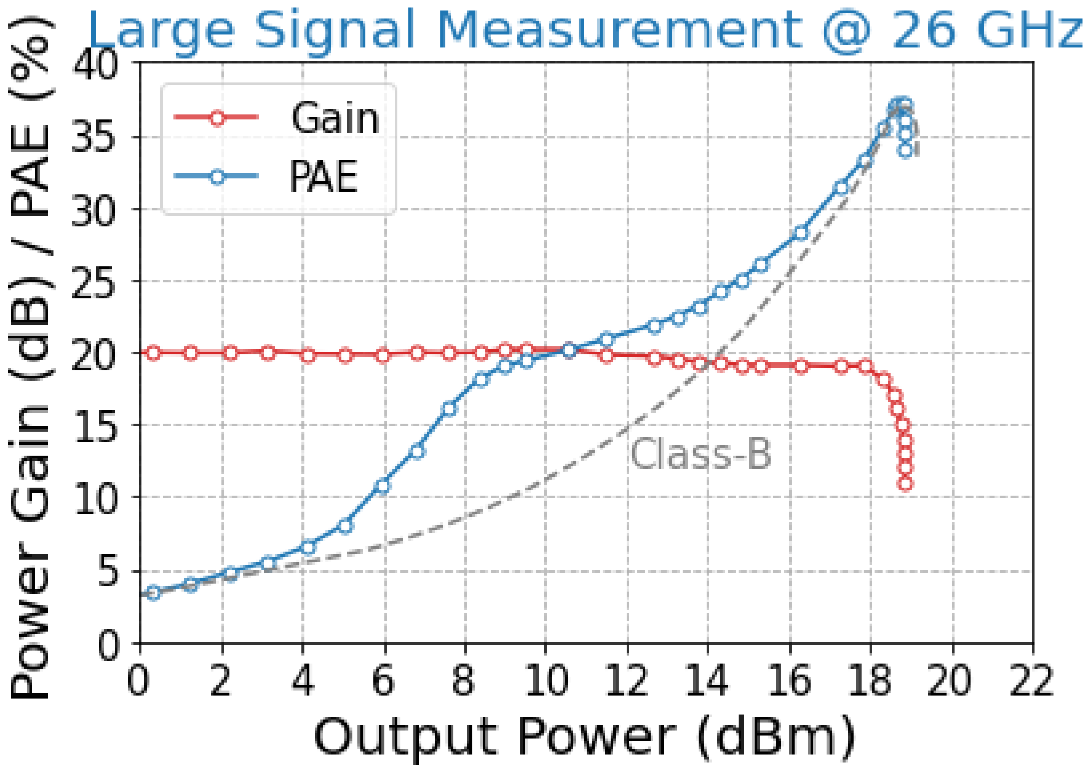

Asymmetrical configuration

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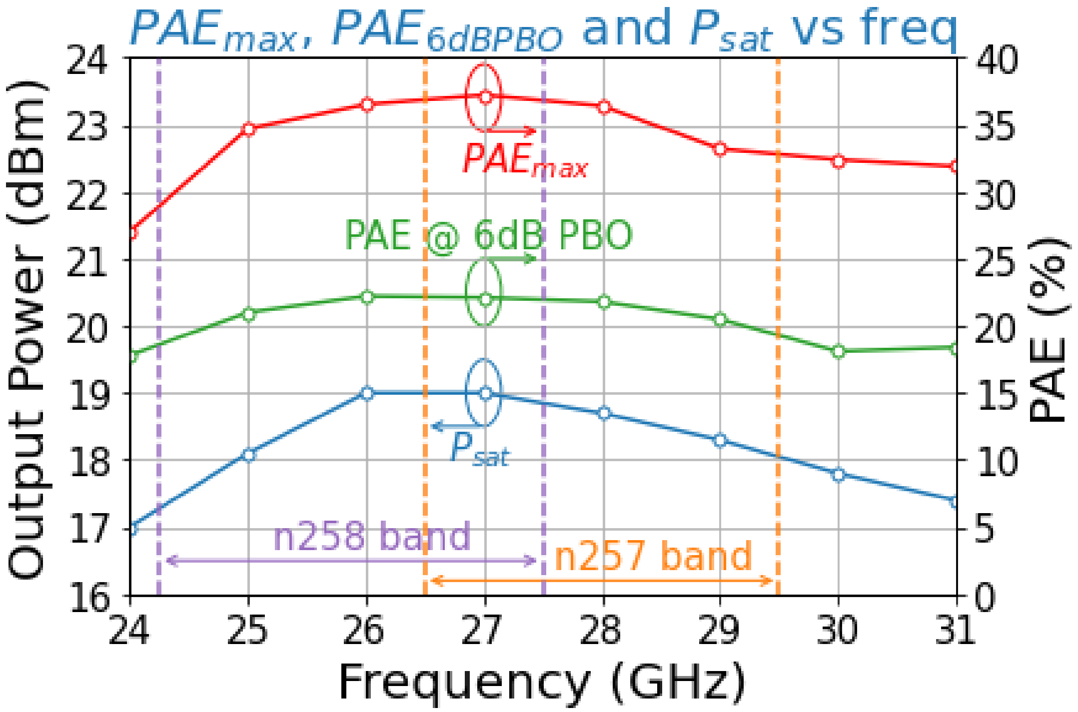
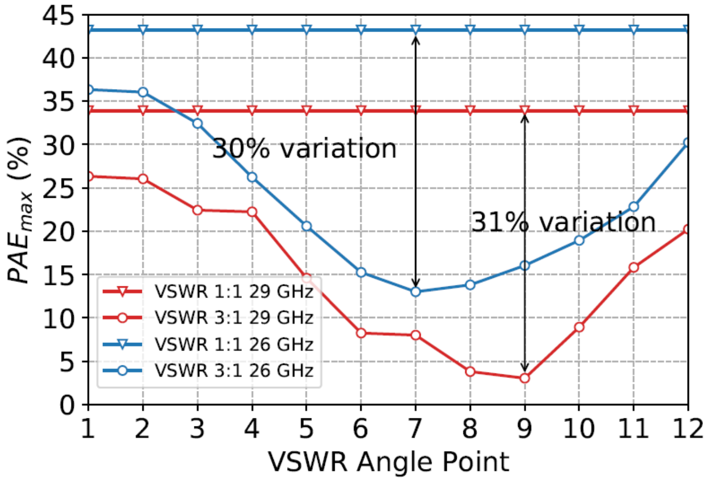
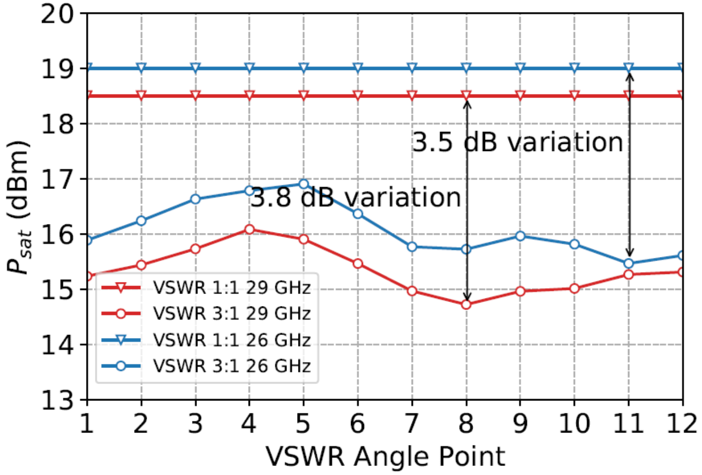


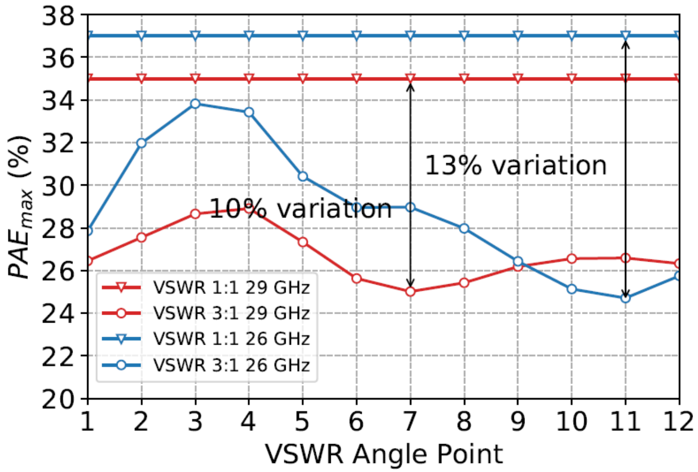
VSWR Robustness

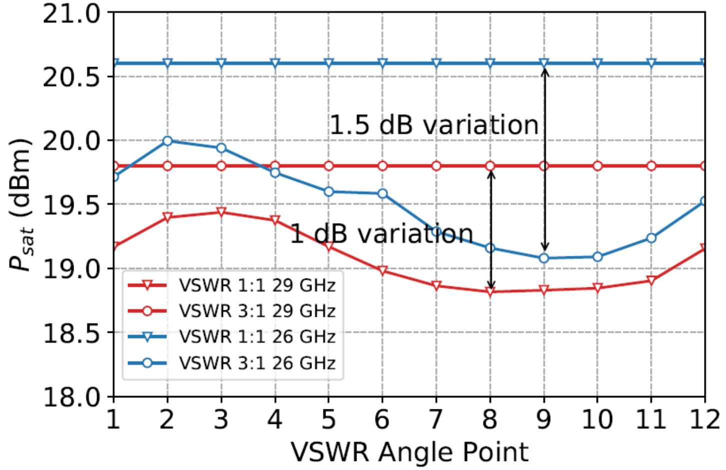
Main Amplifier : standalone implementation





Inductive Hybrid Coupler-based Doherty Power Amplifier (Symmetrical)





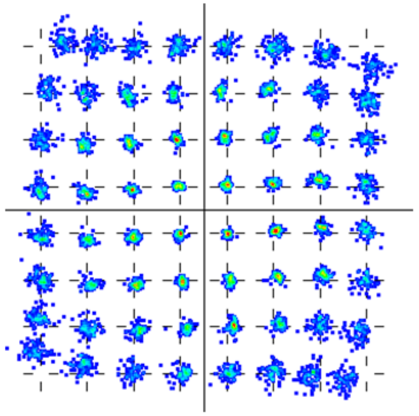
Modulation Measurements

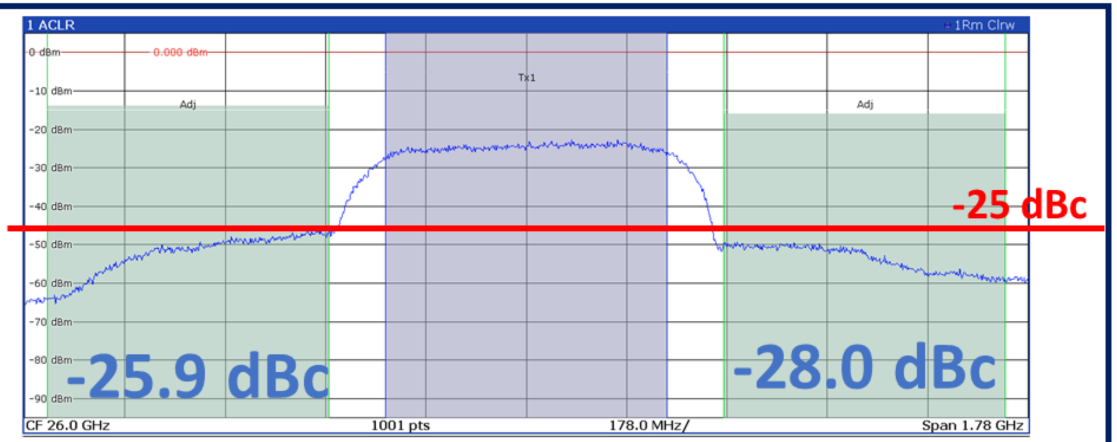
❑ Using 3 Gbits/s (500 MHz) 64-QAM signal without DPD :

- P_{avg} = 13.10 dBm
- PAE_{avg} = 23%
- EVM = -27.3 dB
- ACLR = -25.9 dBc

Symmetrical operation

Single-carrier 64-QAM
Frequency = 26 GHz
Average P_{out} = 13.10 dBm
Average PAE = 23 %
EVM_{RMS} = -27.3 dB





Comparison with the State-of-the-Art

Reference	This Work				[1] Garay ISSCC '21	[2] Li ISSCC '18	[3] Li ISSCC '20	[4] Ma ISSCC '22	[5] Qunaj ISSCC '21	[6] Mannem ISSCC '20
Technology	28nm FDSOI CMOS				45nm SOI CMOS	0.13µm SiGe	45nm SOI CMOS	55nm bulk CMOS	28nm bulk CMOS	45nm SOI CMOS
Architecture	Inductive Hybrid Coupler-Based Doherty				Dual-Drive PA Core	Continuous Mode Class F/F^{-1}	Inverse Outphasing Tx	3-way Parallel/Series Doherty	Doherty-Like LMBA	Series/Parallel Reconfigurable Doherty
Operation mode	Symmetrical		Asymmetrical							
Supply (V)	2 (Main) 2 (Aux)		2 (Main) 1.5 (Aux)		1.9	1.9	2	2.4	1.5	2
Frequency (GHz)	26		26		28	28.5	29	28	36	39
Gain (dB)	20.5		20.5		20.4	20	30	16.1	18	12.5*
P_{sat} (dBm)	20.5		18.8		20.1	17	22.7	25.5	22.6	20.8
P_{1dB} (dBm)	19.5		17.8		19.1	15.2	N.A.	24.3	19.6	20.2
PAE_{max} (%)	37		37		48.3	43.5	41.3	25.2	32	33.3
PAE_{P1dB} (%)	35		34		45.5	39.2	N.A.	24.4	30.5	32.2
PAE_{6dBPBO} (%)	25		22		23*	19*	30.6	20.4	24.2	22.4
$PAE_{12dBPBO}$ (%)	13.5		14.2		6*	6*	10*	14.2	8*	10*
PAE_{max} for 7GHz BW (%)	31		31		N.A.	27*	17*	N.A.	30*	N.A.
VSWR Immunity	3:1 VSWR		3:1 VSWR		No	No	No	No	No	3:1 VSWR
Modulation scheme	64 QAM	5G NR FR2	64 QAM	5G NR FR2	5G NR FR2	64-QAM	64-QAM	64-QAM	64-QAM	64-QAM
PAPR (dB)	6.7	9.6	6.7	9.6	9.6*	6	6	6	6	6
Data Rate (Gb/s) or BW	1.5	100 MHz	1.5	100 MHz	200 MHz	6	3	1.5	12	3
EVM_{rms} (dB)	-27.3	-21.5	-26.6	-20.94	-25	-27.6	-25.3	-25.2	-25	-22.7
P_{avg} (dBm)	13.1	9.69	10.4	8.45	10.7	10.7	16.0	17.7	16	12.2
PAE_{avg} (%)	23	17	20	18	15.5	21.4	23.8	17.5	22	16.1
ACLR (dBc)	-25.9	-25.8	-25.2	-26.2	-26.6	N.A.	-33	-27*	-25*	-25.4
Core Area (mm^2)	0.90				0.21	0.29	0.96	0.54	1.44⁺	1.18

* Graphically estimated   ⁺ Chip area   PAEmax@7GHz : minimum PAE_{max} over a 7GHz band around the PA's PAE_{max}

❑ The circuit demonstrates :

- ✓ Highest peak/PBO PAE among PAs with VSWR robustness
- ✓ Better efficiency performances than LMBA
- ✓ Best PAE_{max} / PAE_{6dBPBO} among asymmetrical Doherty PAs
- ✓ Wideband Doherty behavior over a 7GHz band
- ✓ Better efficiency performances with 5G modulated signals

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Conclusion

- ✓ A new hybrid coupler-based Doherty architecture using an inductive load on the output hybrid coupler isolation port is presented in this paper.
- ✓ A precise control of the adaptive bias triggering threshold is achieved by using the back gate feature of ST Microelectronics' 28 nm FD SOI
- ✓ The Doherty power amplifier achieves high peak and deep power back-off PAE with a 3:1 VSWR immunity while maintaining linearity, making it suitable for 5G NR FR2 wireless communication links.

Acknowledgements

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Thank you for your attention !