DESIGN TRICKS FOR mmW/RF CHIPS

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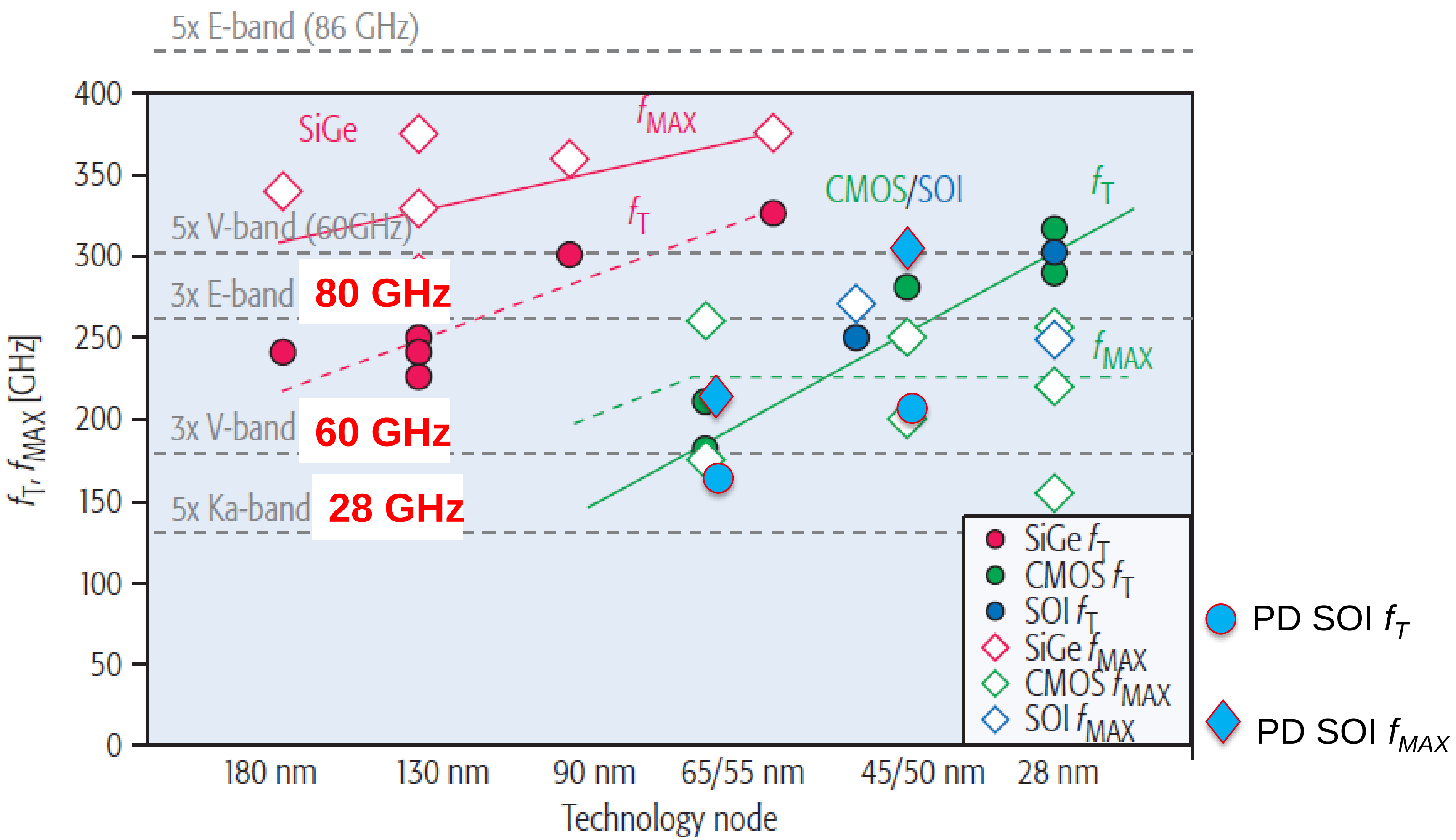
INCREASE OF CHANNEL BANDWIDTH

- Increase of data-rate
  - Exploiting more bandwidth at higher frequencies: i.e. 2.16 x 4 = 8.64 GHz on IEEE 802.11.ay → Technology for mmW? DBB BW? Channel bonding?
  - Increasing modulation order: 64 QAM/256 QAM and beyond? → Hard requirement of LO phase noise
- Going to mmW frequencies at medium/long range:
  - Requirement to attain an acceptable link budget: high antenna gain → Antenna array systems for high gain

Source: Industry perspectives, Making 5G Millimeter-Wave Communications a Reality, IEEE Wireless Communications, August 2017

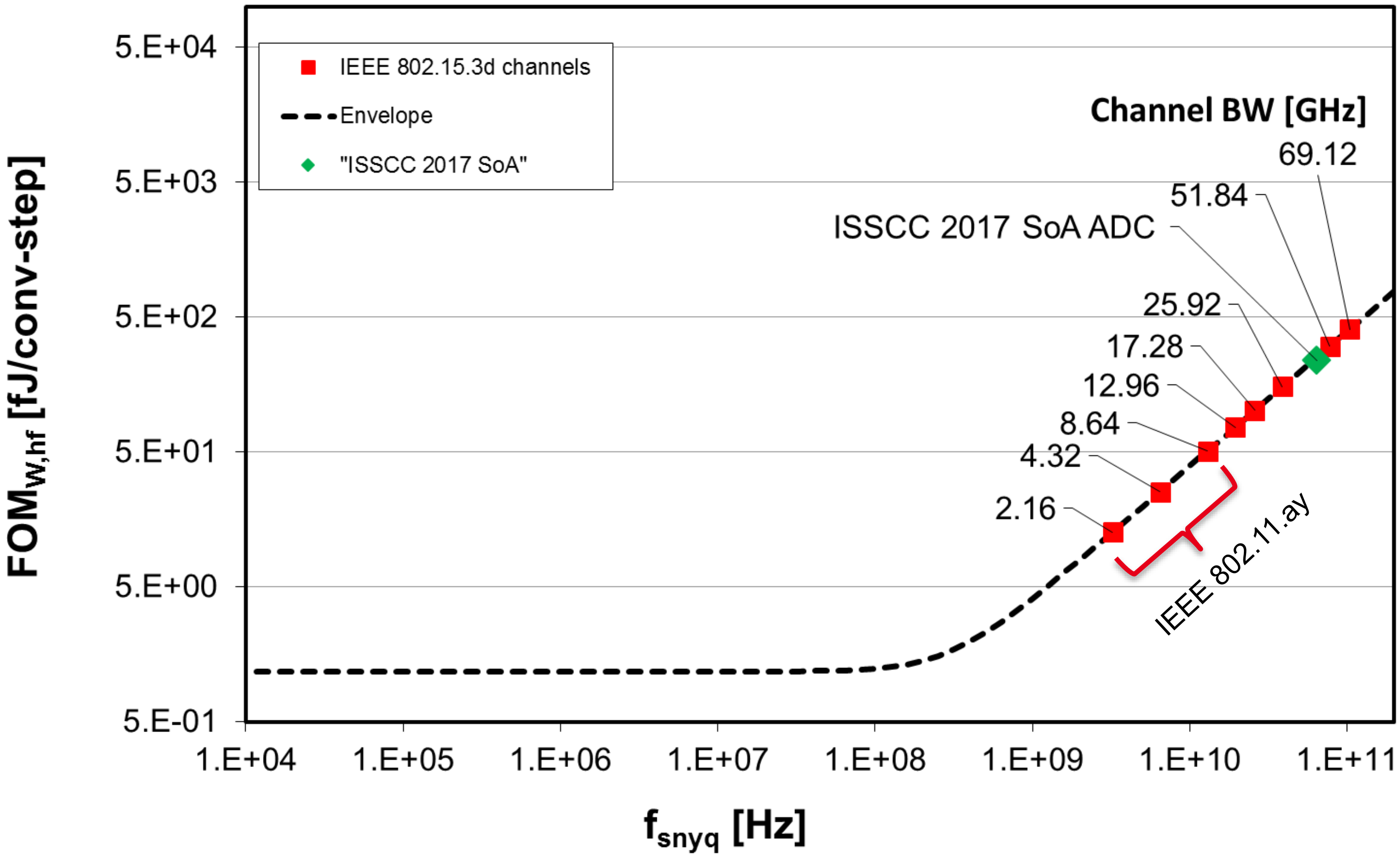
HIGHER BW, HIGHER FREQUENCY: THE CHOICE OF TECHNOLOGY



Source: Industry perspectives, Making 5G Millimeter-Wave Communications a Reality, IEEE Wireless Communications, August 2017

HIGHER BW, HIGHER FREQUENCY: BASEBAND BW

The data converters bottle neck



Source: B. Murmann, "ADC Performance Survey 1997-2017," [Online]. Available: http://web.stanford.edu/~murmann/adcsurvey.html.

HIGHER BW, HIGHER FREQUENCY: BASEBAND BW

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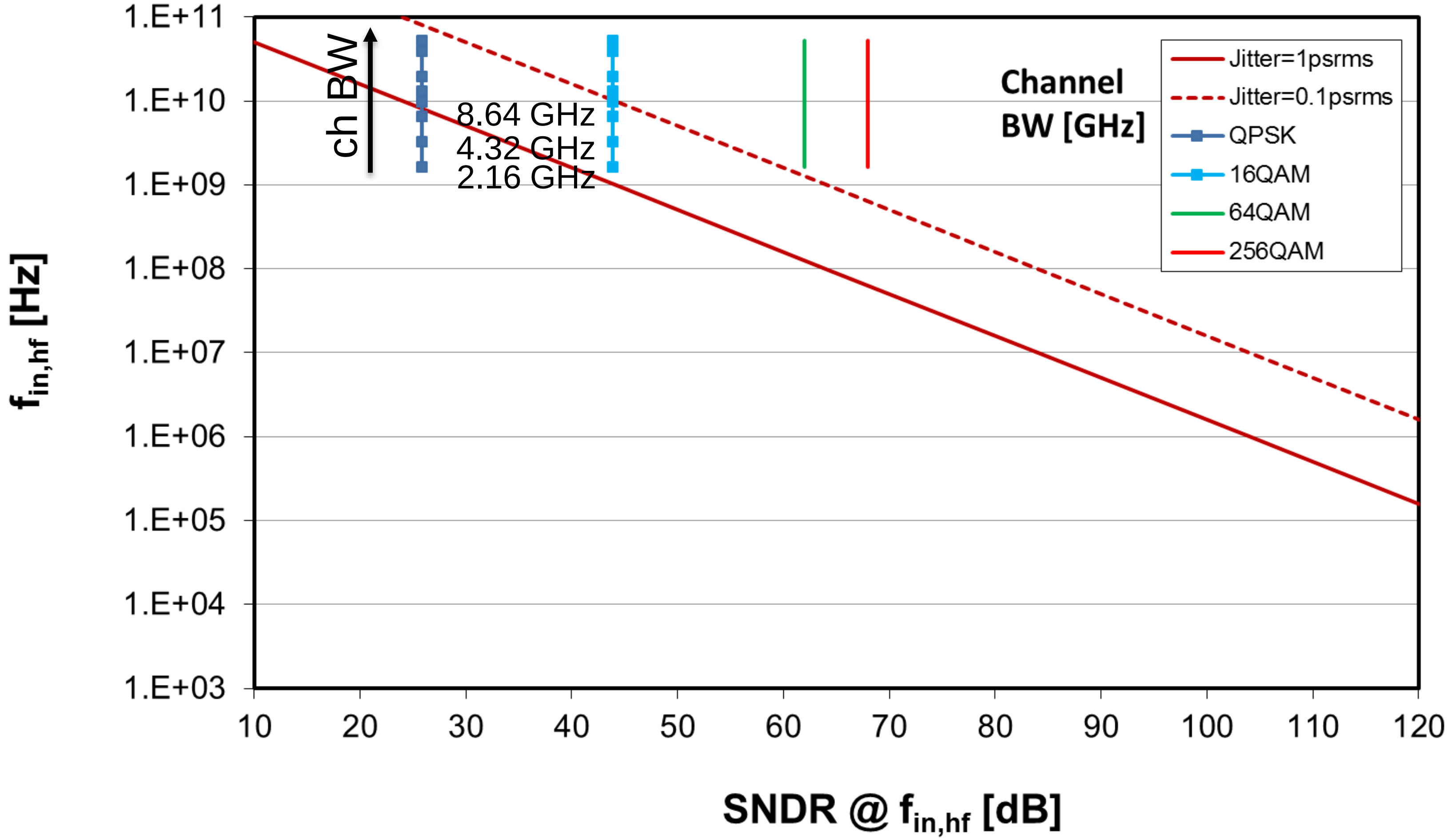
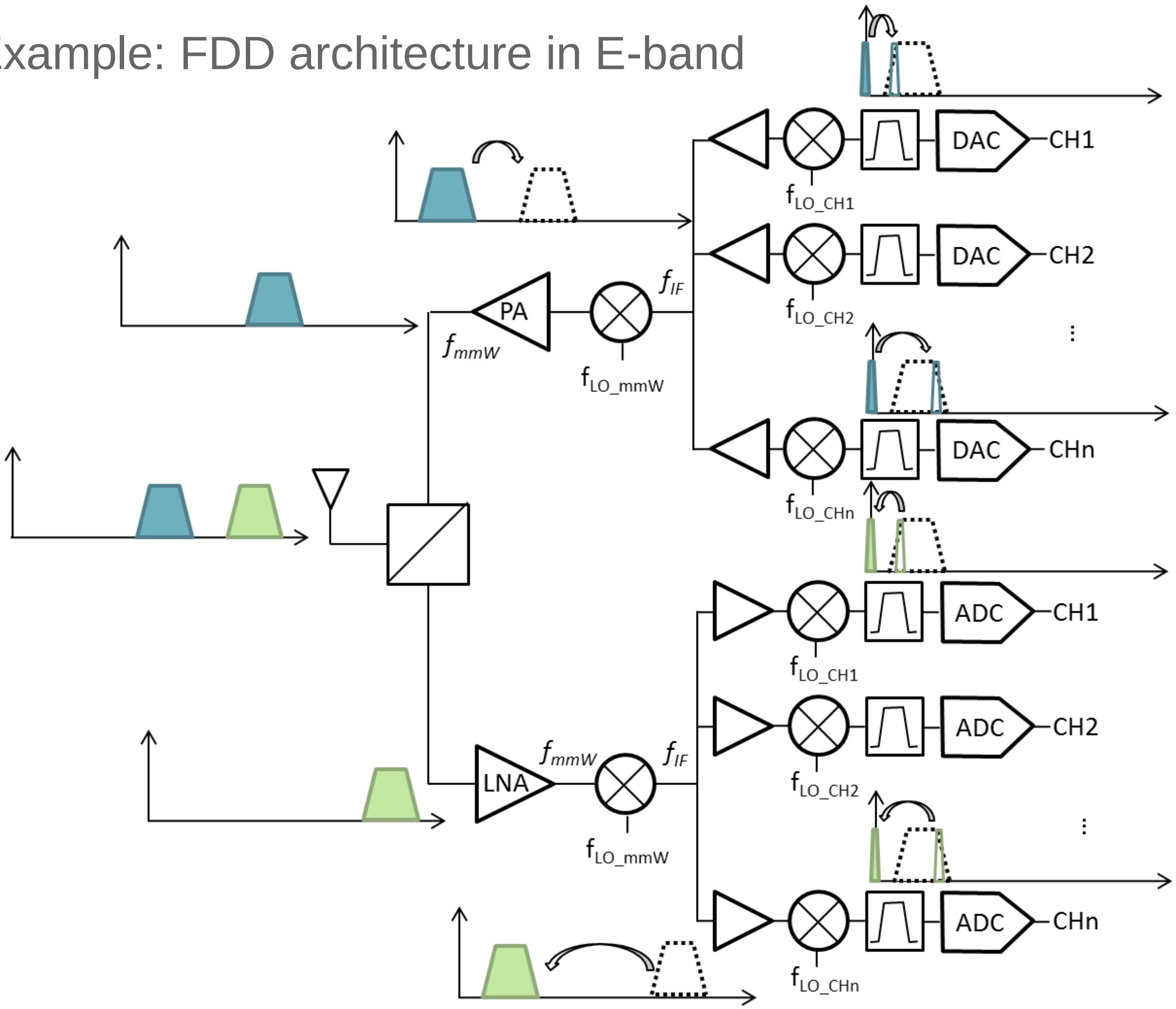


Source: B. Murmann, "ADC Performance Survey 1997-2017," [Online]. Available: http://web.stanford.edu/~murmann/adcsurvey.html.

HIGHER BW, HIGHER FREQUENCY: BASEBAND BW

The solution: channel bonding architectures

Example: FDD architecture in E-band



Drawback: several LOs are required simultaneously

Source: E3Networks FP7 project, available on-line http://ict-e3network.eu

HIGHER MODULATION RATE: LO PHASE NOISE REQUIREMENT

- Phase noise for 2% differentiator angle error (60 GHz SC, No DBB compensation)

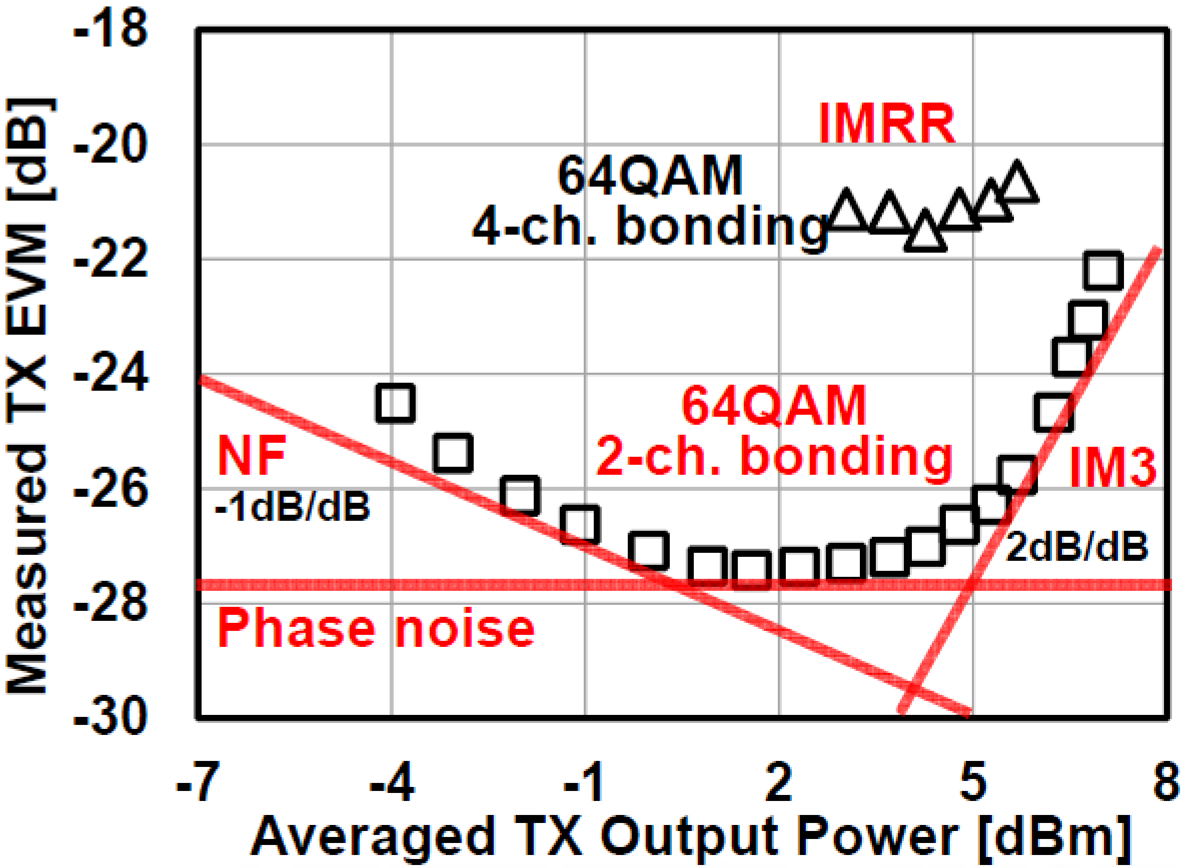
Modulations	Phase Noise in dBc @ 1MHz
QPSK	-100
16 QAM	-105
64 QAM	-114
128 QAM	-123
256 QAM	-132
512 QAM	-139

- The constraint is higher at higher frequencies ~20log(*f*)
- Other degrees of freedom (Tx power, etc), are limited by phase noise effect

Source: NEREID, available on-line http://ict-e3network.eu

HIGHER MODULATION RATE: LO PHASE NOISE REQUIREMENT

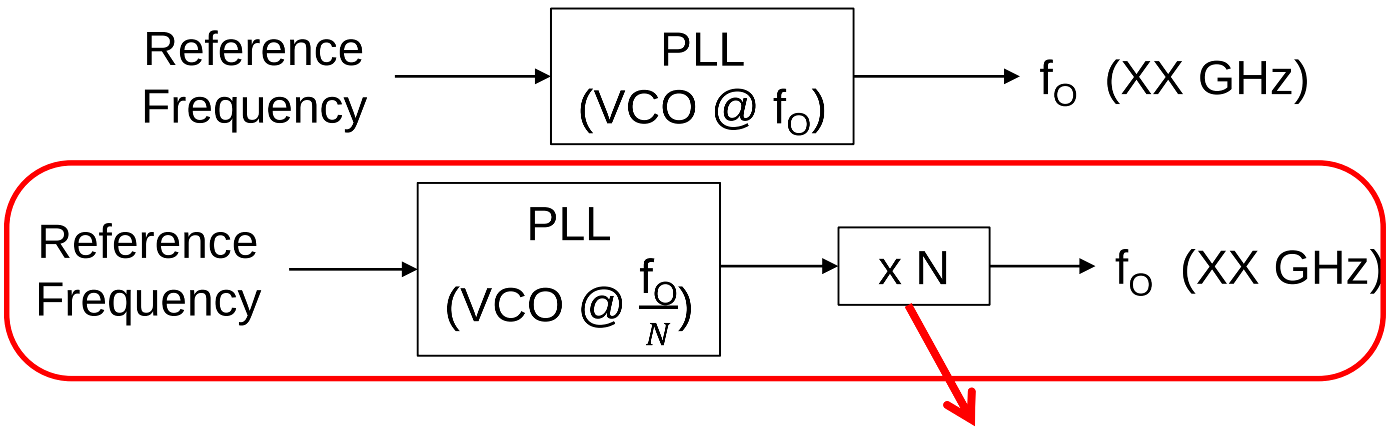
- EVM as a function of Tx power



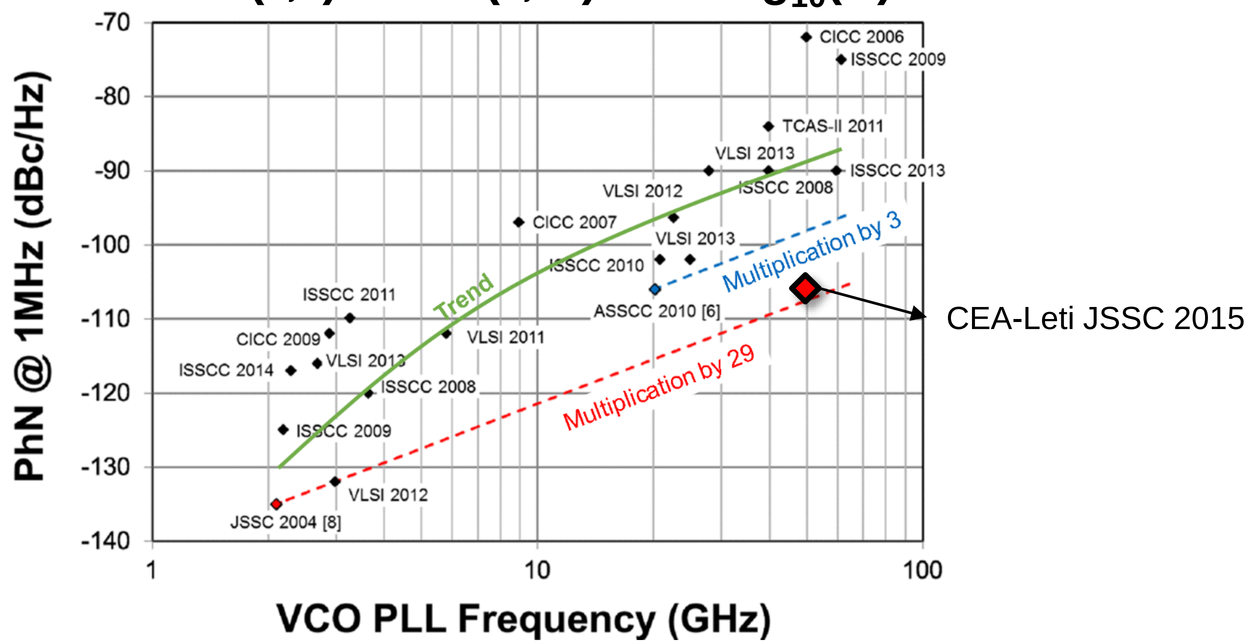
Source: R.Wu et al, ISSCC 2016

HIGHER MODULATION RATE: LO PHASE NOISE REQUIREMENT

The solution: High order frequency multiplication



$$PhN(S_{f_0}) = PhN(S_{f_0/N}) + 20\log_{10}(N)$$

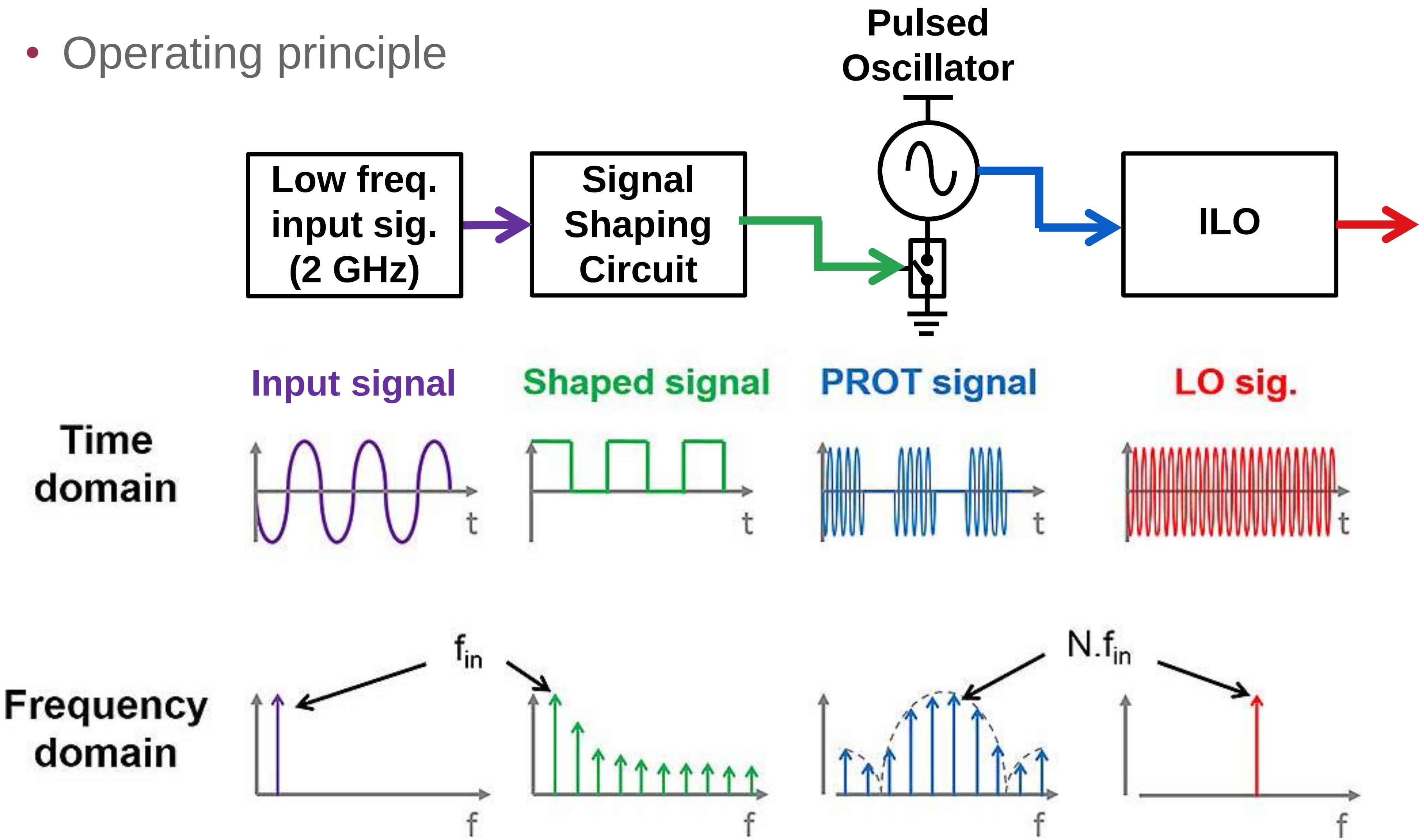


C. Jany, *et al*, "A Programmable Frequency Multiplier-by-29 Architecture for Millimeter Wave Applications," in IEEE JSSC, vol. 50, no.

HIGHER MODULATION RATE: LO PHASE NOISE REQUIREMENT

High order frequency multiplication: the PROT technique

- Operating principle

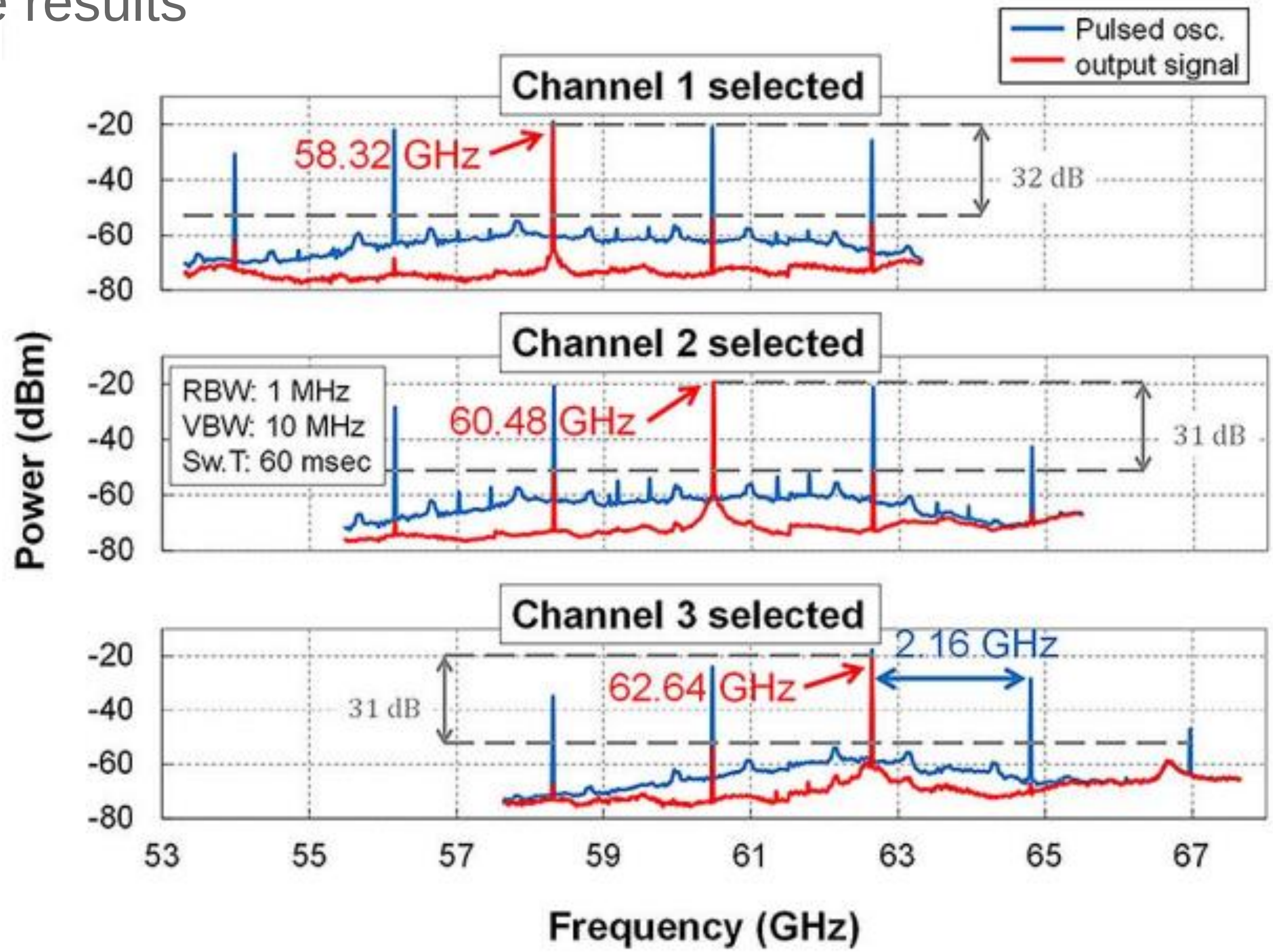


C. Jany, *et al*, "A Programmable Frequency Multiplier-by-29 Architecture for Millimeter Wave Applications," in IEEE JSCC, vol. 50, no. 7, July 2015.

HIGHER MODULATION RATE: LO PHASE NOISE REQUIREMENT

High order frequency multiplication: the PROT technique

- Some results



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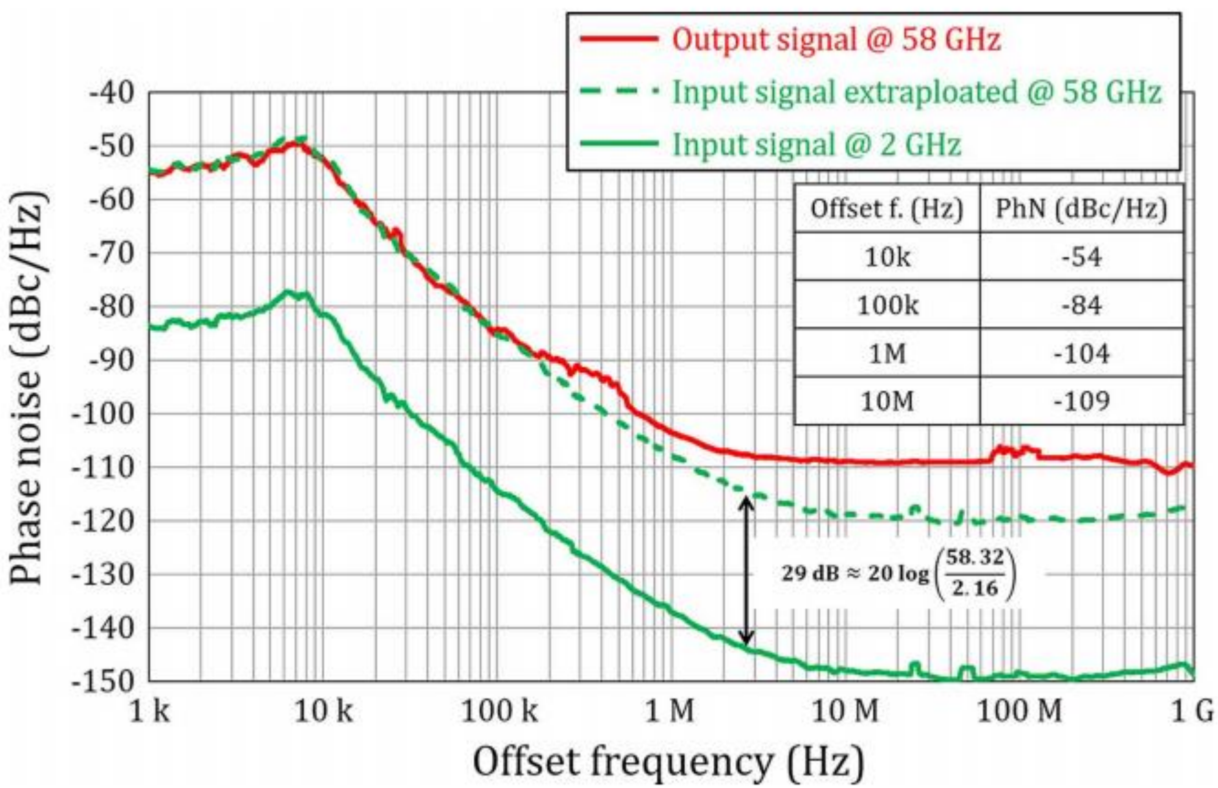

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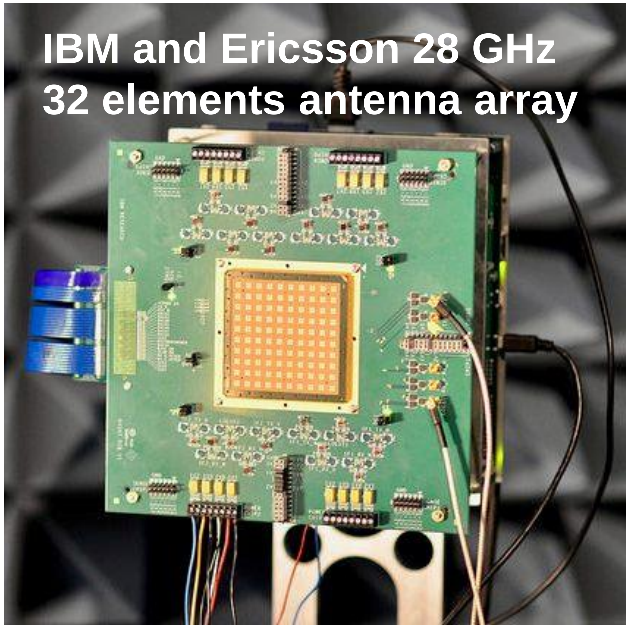
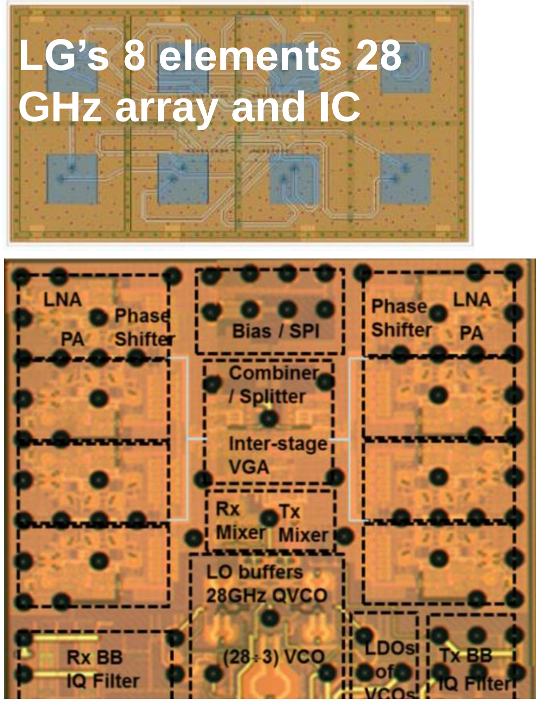
ANTENNA ARRAYS AT mmW

Testing issues





The challenge of testing/calibrating phase-array systems:

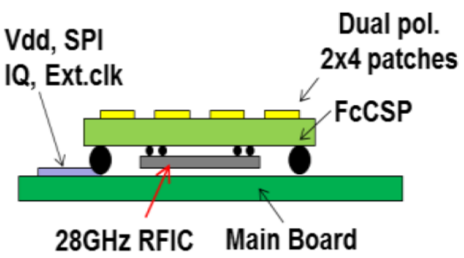
- Output RF nodes of Tx/Rx not available once antenna-array is build.
- Even if transceivers are previously tested, the assembly with the antennas has to be verified.

Source: J.L. Gonzalez "NON-INVASIVE CALIBRATION AND BIST FOR PHASED-ARRAY SYSTEMS," ISSCC 2018 Forum.

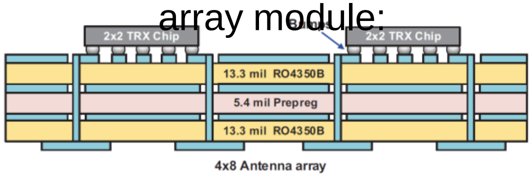
ANTENNA ARRAYS AT mmW

Testing issues

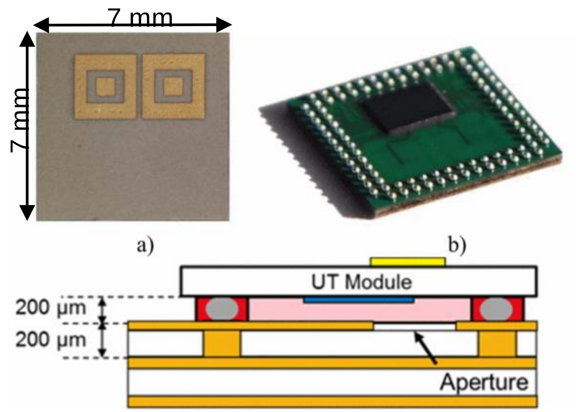
LG's 8 elements 28 GHz array module:



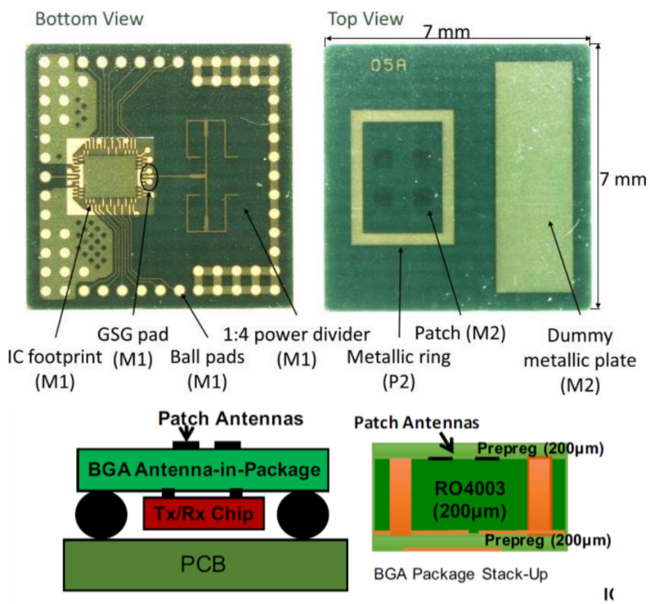
Broadcom 32 elements 28 GHz
array module:



CEA Leti
60 GHz array module:



STMicroelectronics 4 elements 130 GHz array module:



mmW array modules use advanced packaging technologies

- Very sensitive to IC to antenna feed routing.
- Compact layout, difficult to access intermediate test point.

Source: J.L. Gonzalez "NON-INVASIVE CALIBRATION AND BIST FOR PHASED-ARRAY SYSTEMS," ISSCC 2018 Forum.

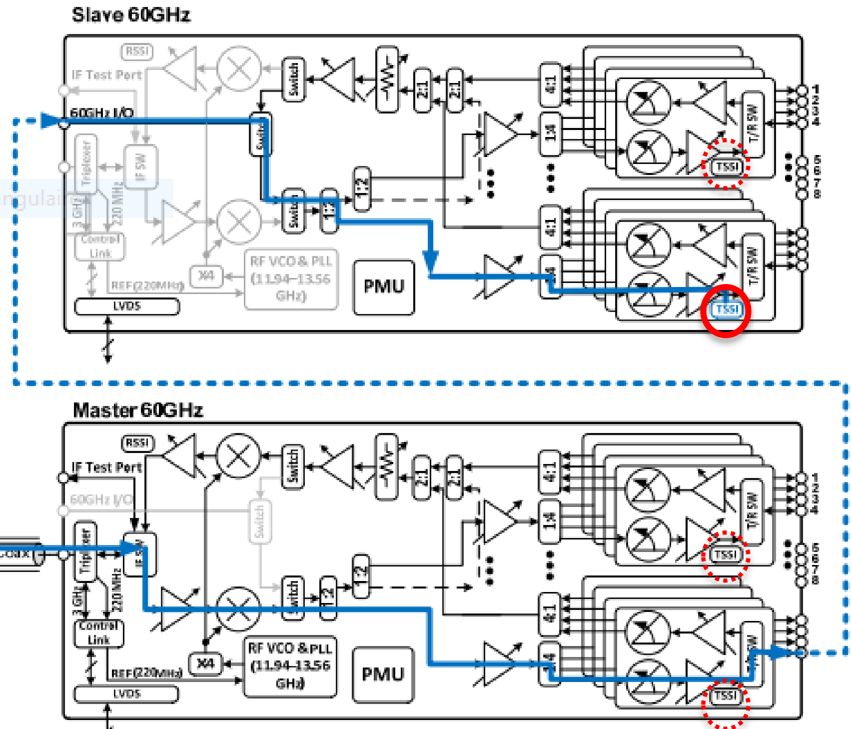
ANTENNA ARRAYS AT mmW

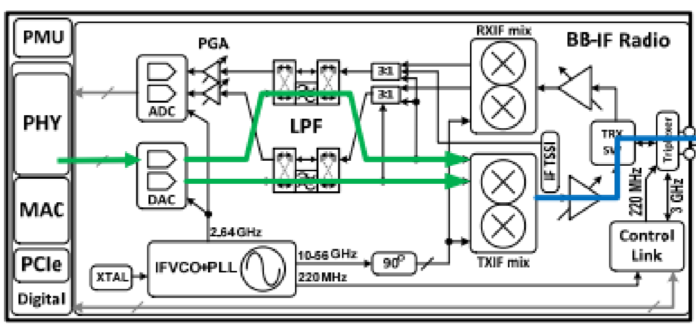
Testing issues

Example of calibration and BIST(i):

Slave 60GHz: TX Calibration and RFBIST

- **TX chain functionality:** BB to PA output in Slave. Read back TSSI.
- Sweep BB tone. Read TSSI in Slave. **Calibrate 60GHz freq response** and **TX Pout** as fixed Back-Off from PSAT.





EE International Solid-State Conference

4.2: A 60GHz 144-Element Phased-Array Transceiver with 51dBm Maximum EIRP and ±60° Beam Steering for Backhaul Application

23

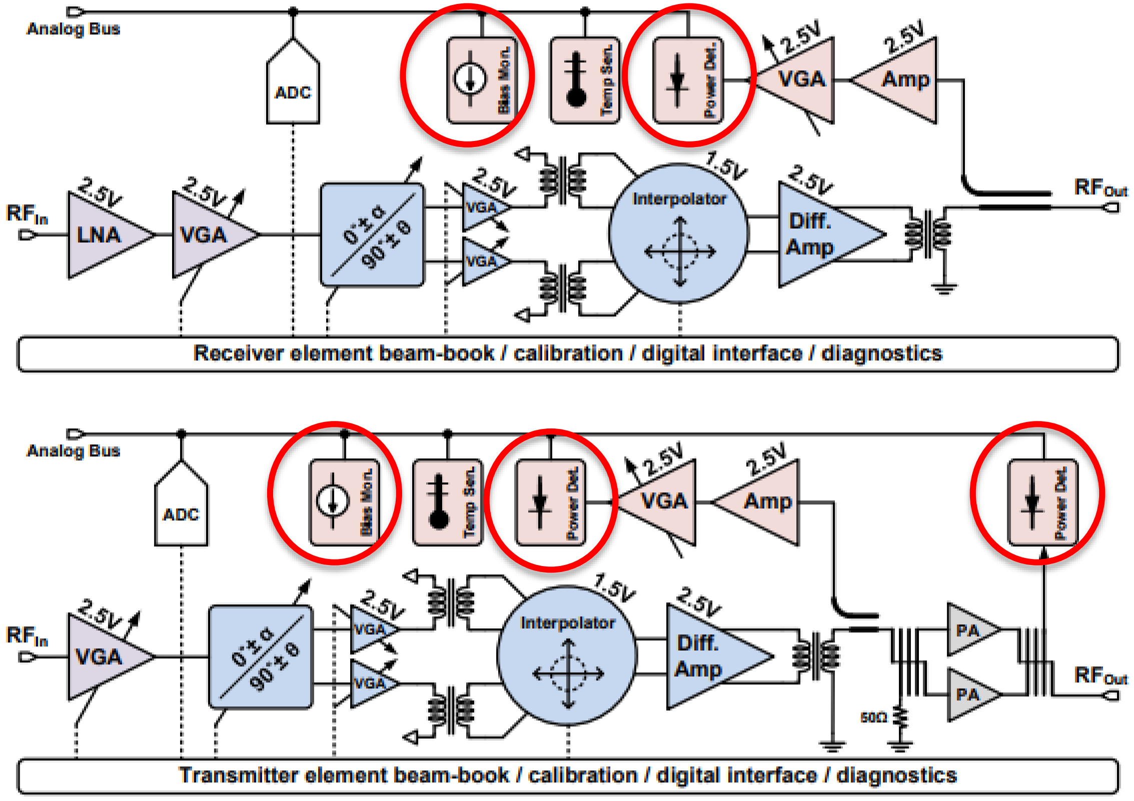
Source: ISSCC 2018 paper 4.2 by Broadcom.

ANTENNA ARRAYS AT mmW

Testing issues

Example of calibration and BIST(ii):

RX/TX Phase Shifter Architecture



- 5-bit phase shifter with < 0.5 LSB phase error
- NF < 7dB at 90GHz
- Local beam and calibration memory
- Built-in diagnostics and self test per element

- 5-bit phase shifter with < 0.5 LSB phase error
- PSAT > 8dBm at 90GHz

Source: ISSCC 2018 paper 4.6 by Nokia Bell Labs.

ANTENNA ARRAYS AT mmW

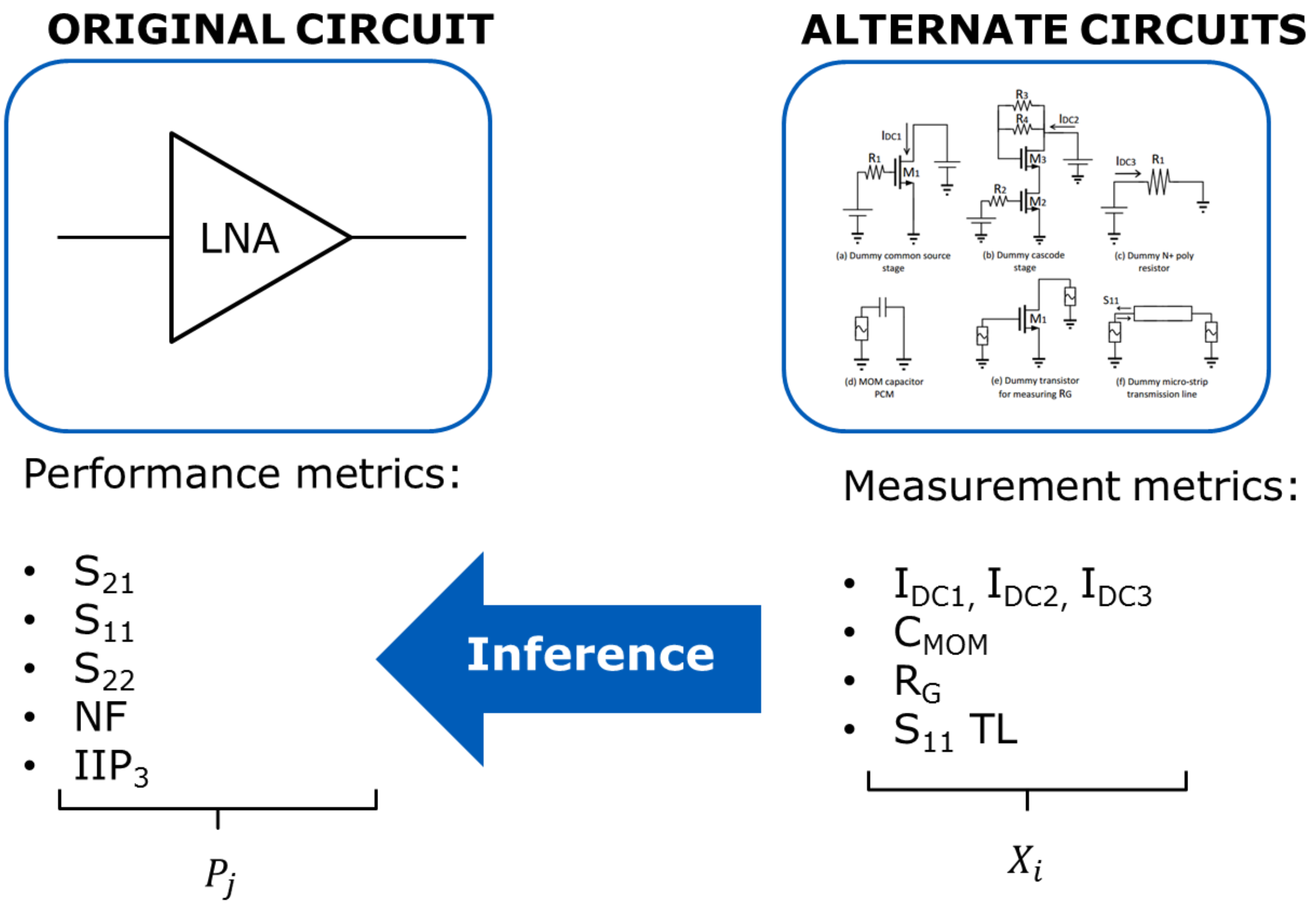
Testing issues

- **Two NON INVASIVE testing/calibration solutions:**
  - Alternate TEST
  - Using temperature as TEST OBSERVABLE

ANTENNA ARRAYS AT mmW

Testing issues

- **Alternate TEST: operating principle**

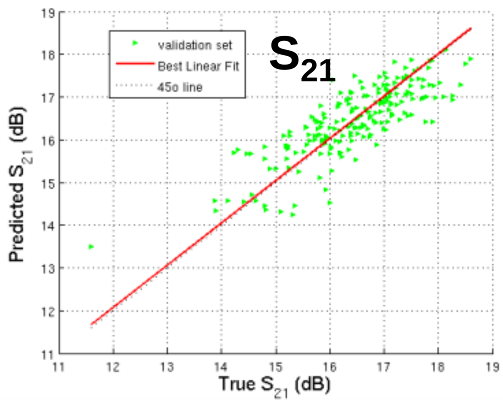


Source: From: A. Dimakos, *et al*, "Built-in test of millimetre-Wave circuits based on non-intrusive sensors," DATE 2016

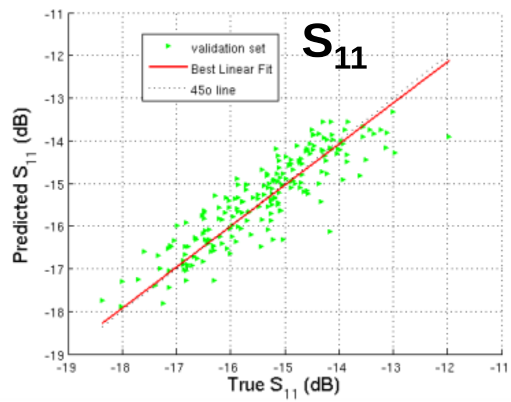
ANTENNA ARRAYS AT mmW

Testing issues

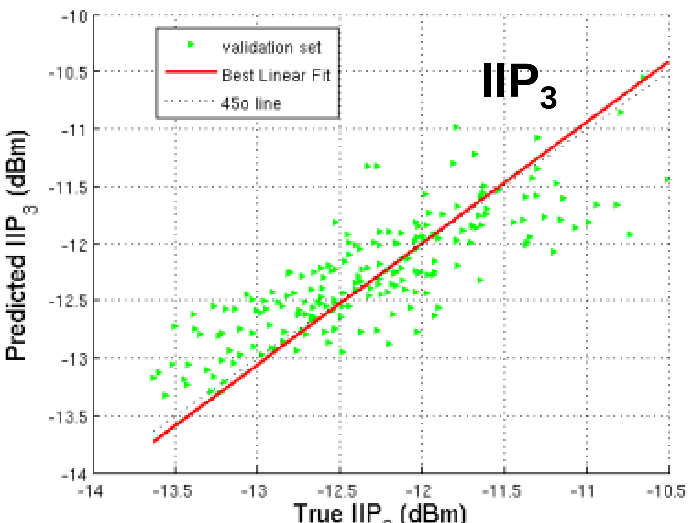
- **Alternate TEST: some results**

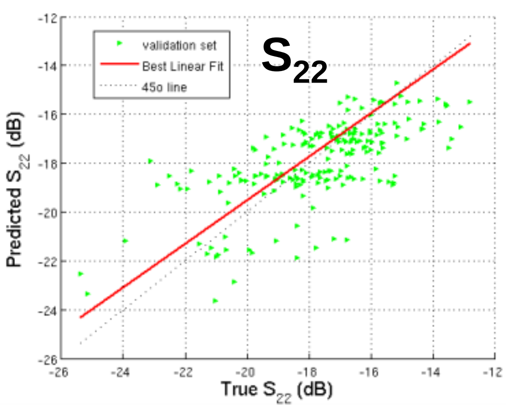


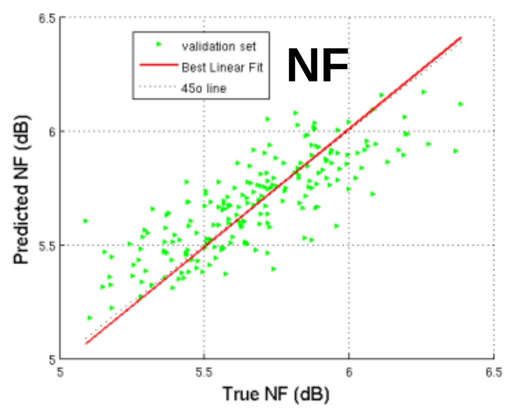
(a) S_{21}



(d) S_{11}







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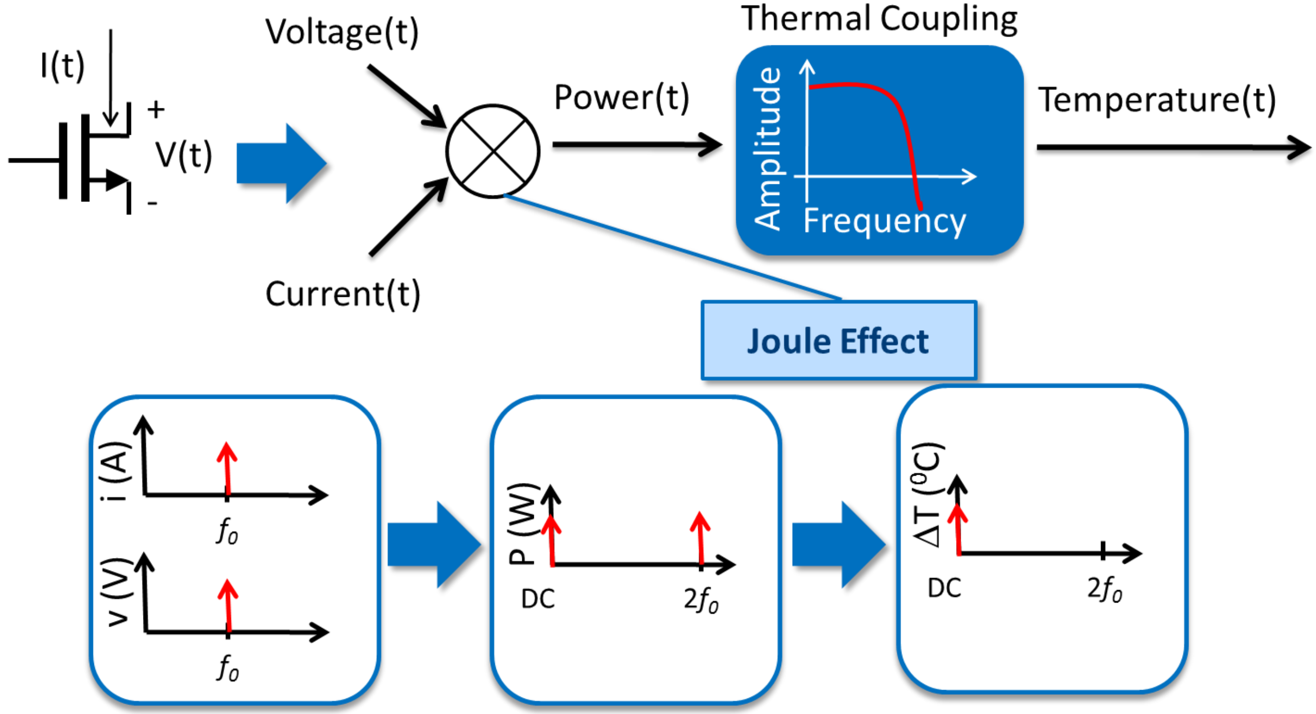
ANTENNA ARRAYS AT mmW

Testing issues

- **Thermal TEST: operating principle**

  - **DYNAMIC JOULE EFFECT**

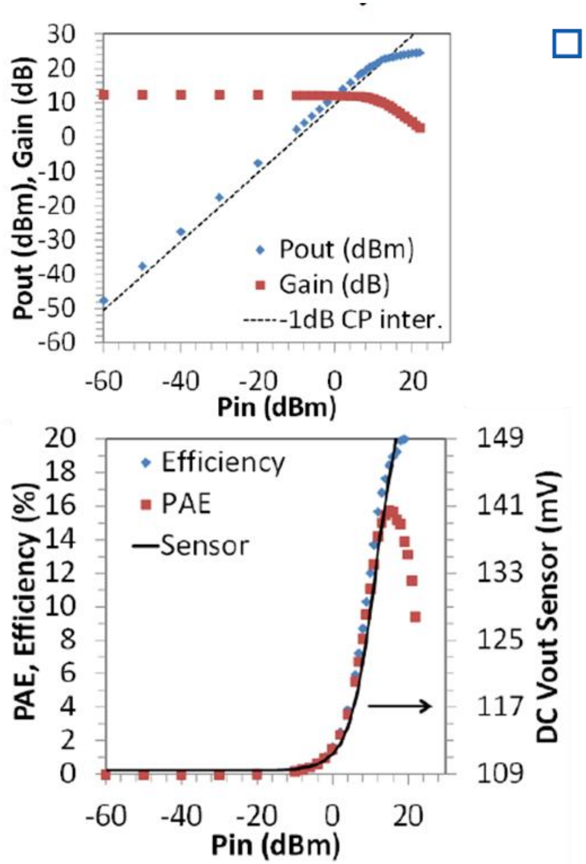


ANTENNA ARRAYS AT mmW

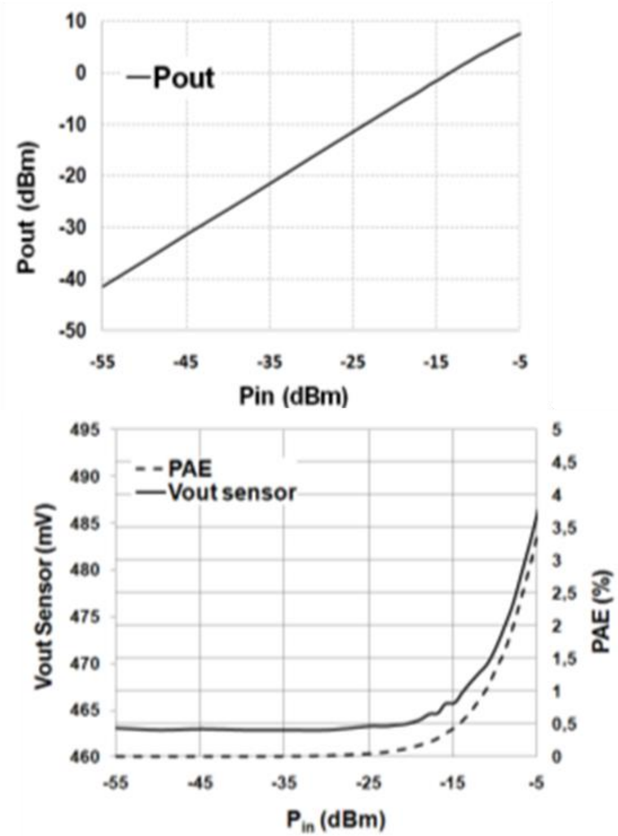
Testing issues

- **Thermal TEST: some results**

- 1.9 GHz PA



- 60 GHz PA



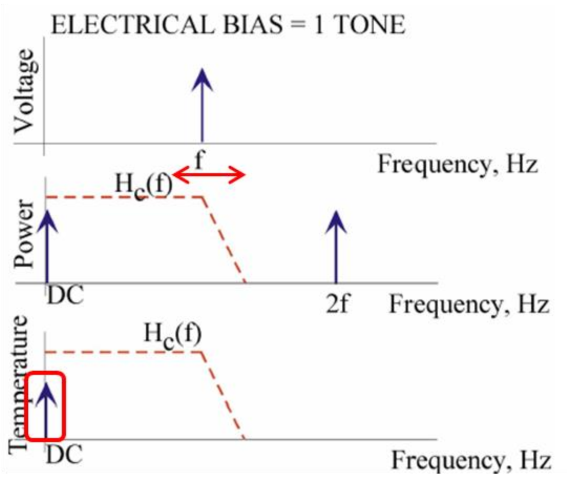
Source: J.L. Gonzalez "NON-INVASIVE CALIBRATION AND BIST FOR PHASED-ARRAY SYSTEMS," ISSCC 2018 Forum.

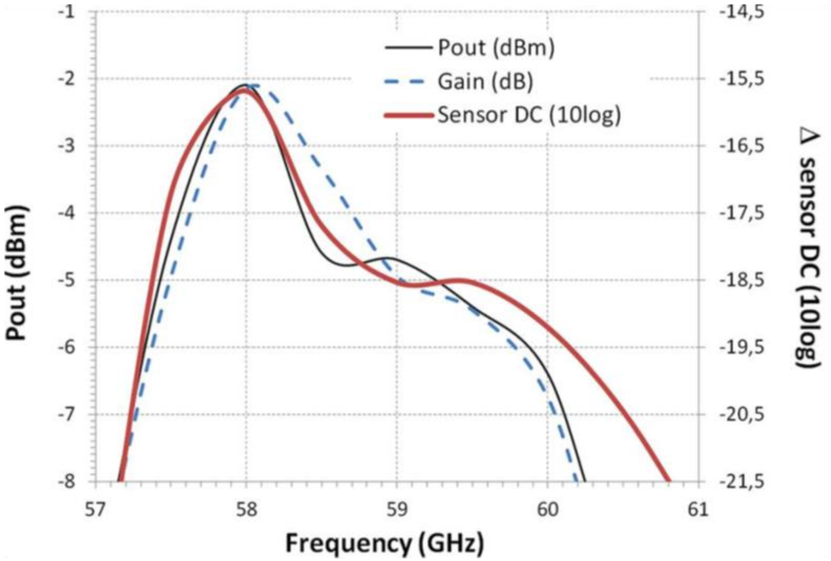
ANTENNA ARRAYS AT mmW

Testing issues

- **Thermal TEST: some results**

□ 60 GHz PA: Homodyne measurements of center frequency and BW





□ Double correlated test: sensor output is measured with no input (dissipation due to bias). Relative changes in sensor output correspond to changes in input frequency for fixed Pin= -5 dBm

Source: X. Aragones *et al*., "DC Temperature Measurements to Characterize the Central Frequency and 3 dB Bandwidth in mmW Power Amplifiers," in *IEEE Microwave and Wireless Components Letters*, vol. 25, 2015.

ANTENNA ARRAYS AT mmW

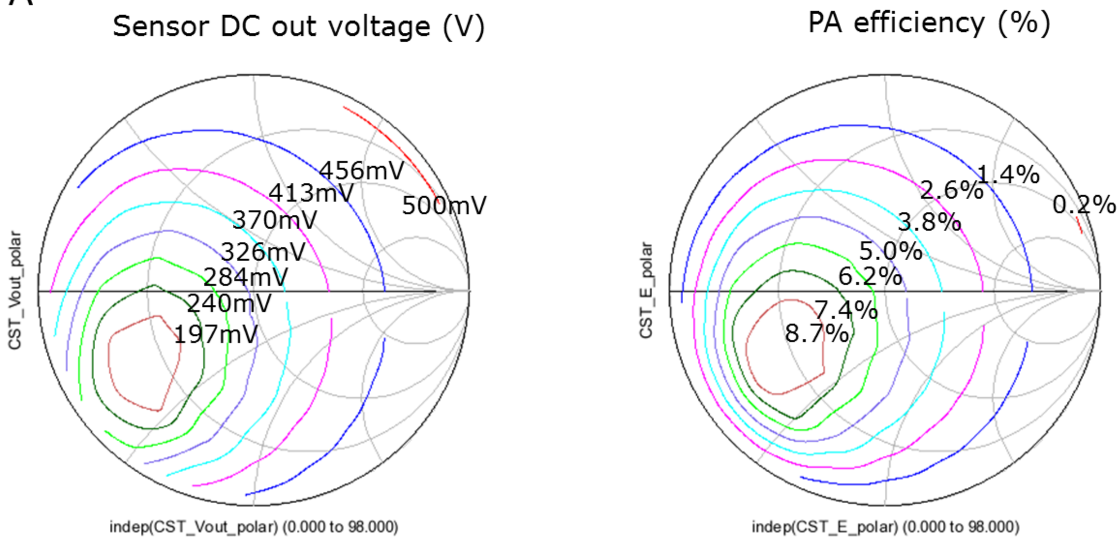
Testing issues

- **Thermal TEST: some results**

  - Results from thermal test can be used to check the IC to antenna assembly:

☐ Correlation between thermal sensor output and PA efficiency (class A-B) for load-pull test.

1.9 GHz PA



Simulation results: fixed input power, variable output load impedance.

CONCLUSIONS

- **Channel bonding architectures as a solution to implemented large-overall bandwidth transceivers at mmW frequencies (mainly for back-haul/front-haul applications)**

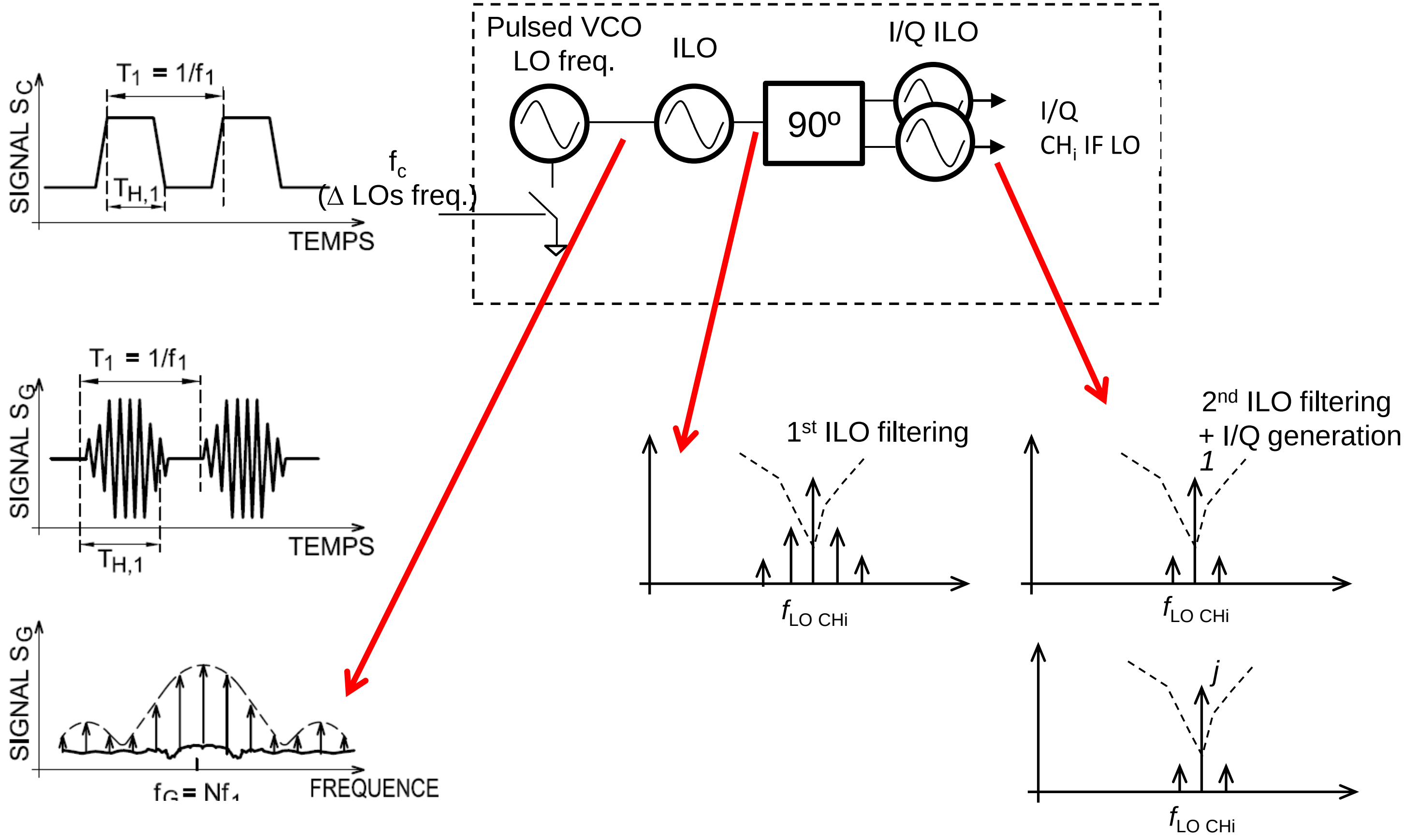
- **Innovative frequency synthesis techniques provide the required phase noise performance and flexibility required at mmW frequencies.**

- **Innovative testing and calibration techniques will be required for complex systems containing multi-antenna arrays.**

CHANNEL BONDING ARCHITECTURES

Multi-LO generation technique

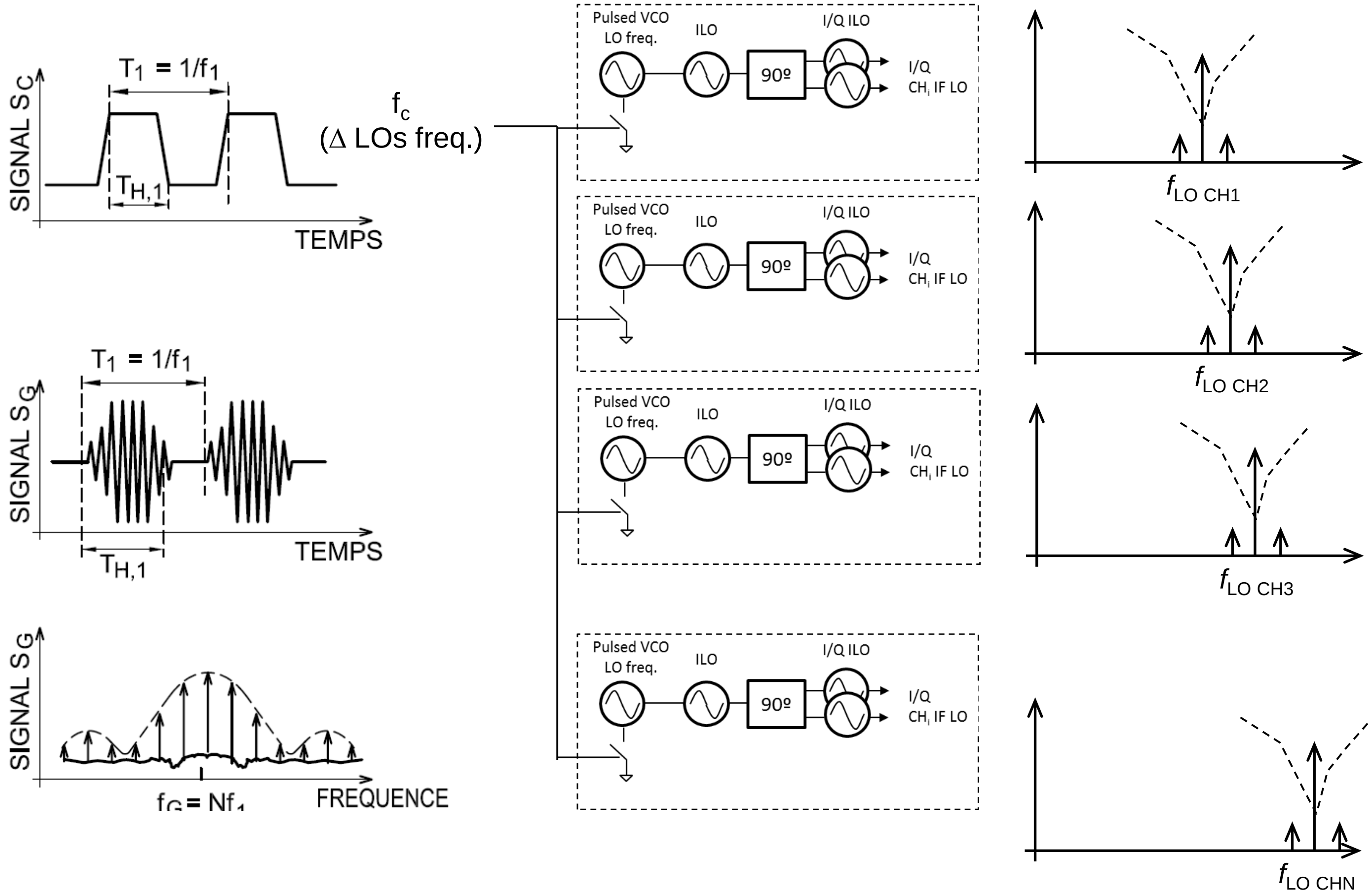
- Operating principle
  - Single channel:



CHANNEL BONDING ARCHITECTURES

Multi-LO generation technique

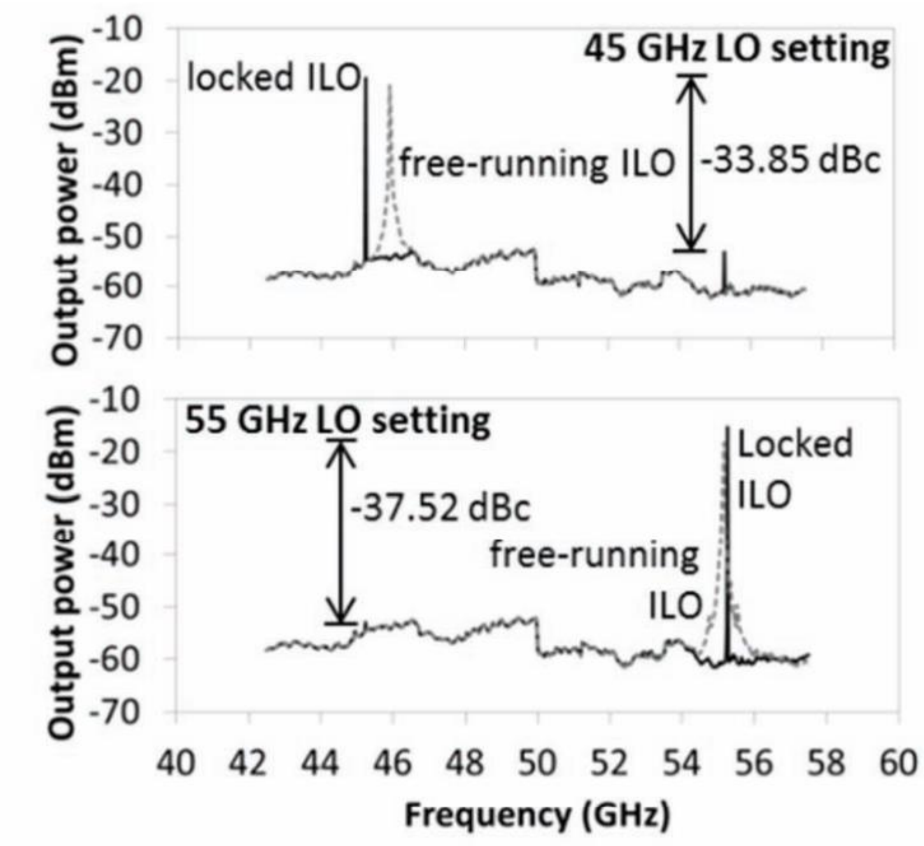
- Operating principle
  - Multiple channels



CHANNEL BONDING ARCHITECTURES

Multi-LO generation technique

- Results
  - Example for two channels



CH1: 45 GHz

CH2: 55 GHz

J.L. Gonzalez, *et al*, "A 45GHz/55GHz LO frequency selector for E-band transceivers based on switchable injection locked-oscillators in BiCMOS 55nm," in ESSCIRC 2015.