eV-Technologies

RF-Optics Hybrid GaN-FDSOI Technology Solutions for 5G & 6 G

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September 2022

Think Energy !

Outline Overview

1 ▶ Challenges, Motivation & Technology Solutions

2 ▶ Main Results, Analysis & Discussions

Energy-Efficient Multi-Beam Systems

Toward Hybrid GaN -FDSOI FEMs

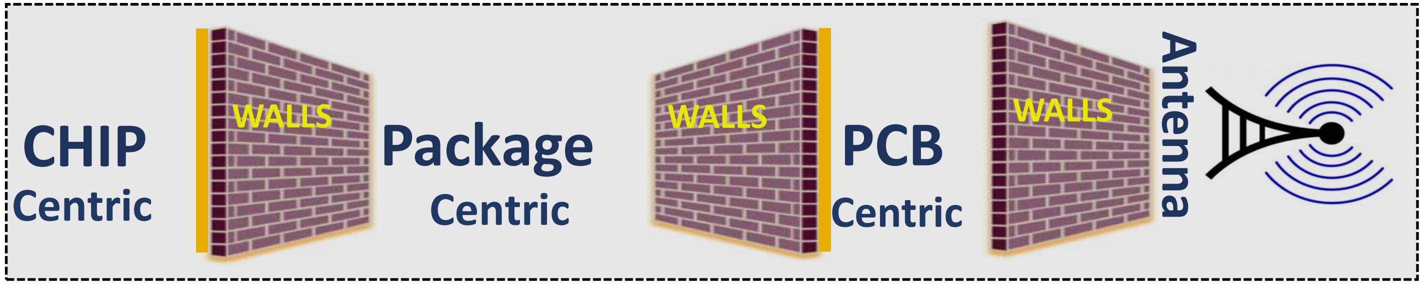
3 ▶ Concluding Remarks & Look-Ahead

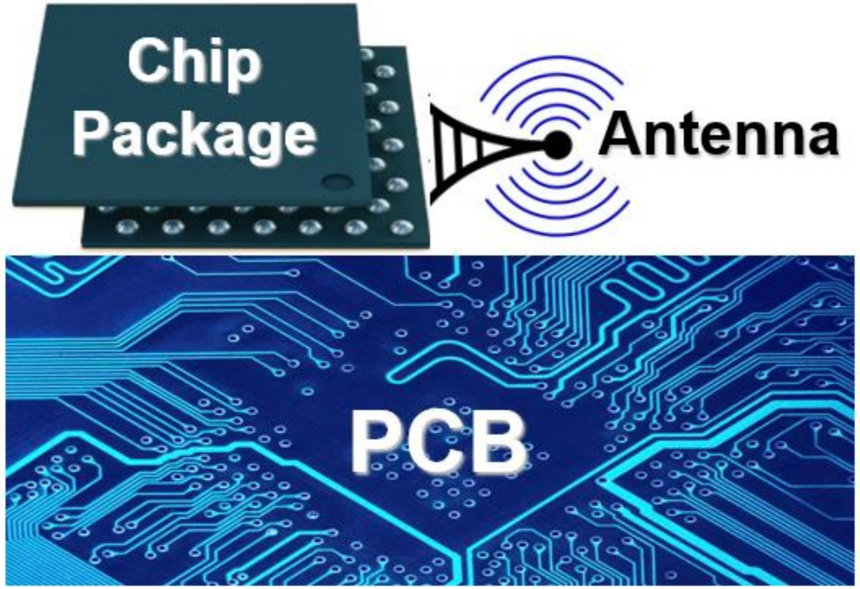
+ Backup Slides in Case of Questions

1 Challenges, Motivation & Technology Solutions

Business Motivation

The market expects a GLOBAL IC-Package-PCB-Antenna solution to meet the challenges of emerging IoT and RF/mmWave products.





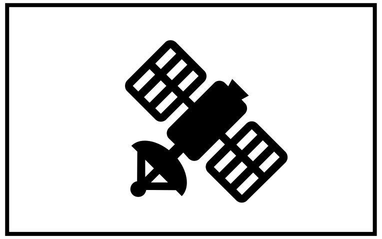
MISSING 20% of success
@Chip, @Package, @PCB,
@Antenna
will result in:
80%x80%x80%x80%~41% of final Product success.

Need for HOLISTIC Chip-Package-PCB Co-Design & Co-Verification accounting for Antennas !

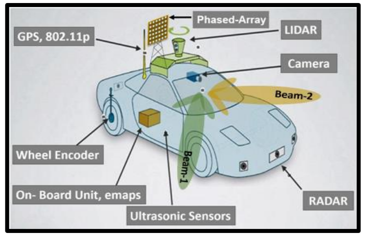
NOBODY Centric Vision for Emerging IoT & RF/mmWave Technologies !

RF/mmWave 5G

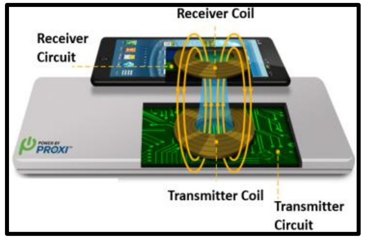
SATCOM & IoT



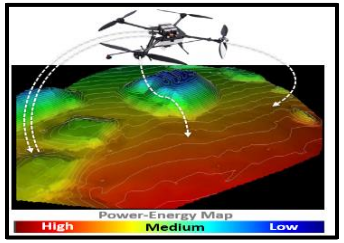
Automotive



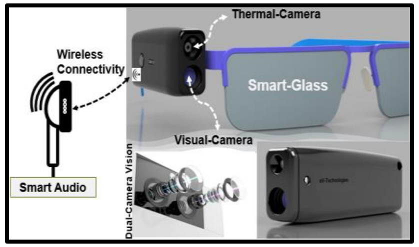
NFC



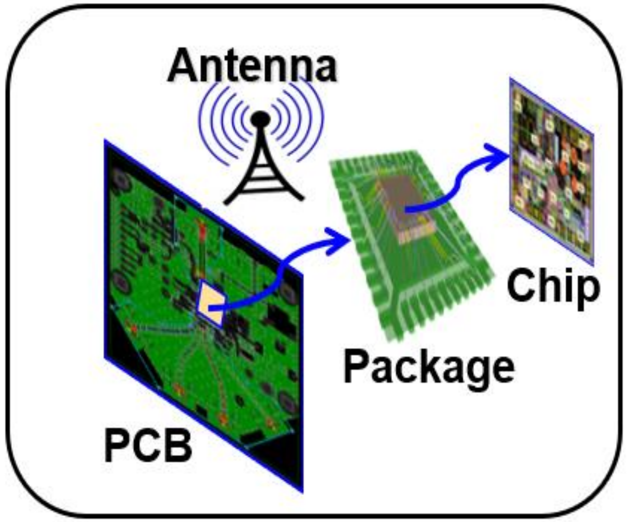
Mission Critical



Smart Wearables



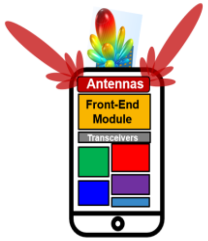
NOBODY Centric Vision for Emerging IoT & RF/mmWave



Enabling GLOBAL IC-Package-PCB-Antenna Co-Design:

Unique BROADBAND EXTRACTION SOLUTION accounting for Radiations

Opening doors in the WALLS separating Chip, Package, PCB & Antenna domains for Unleashing Global Performances



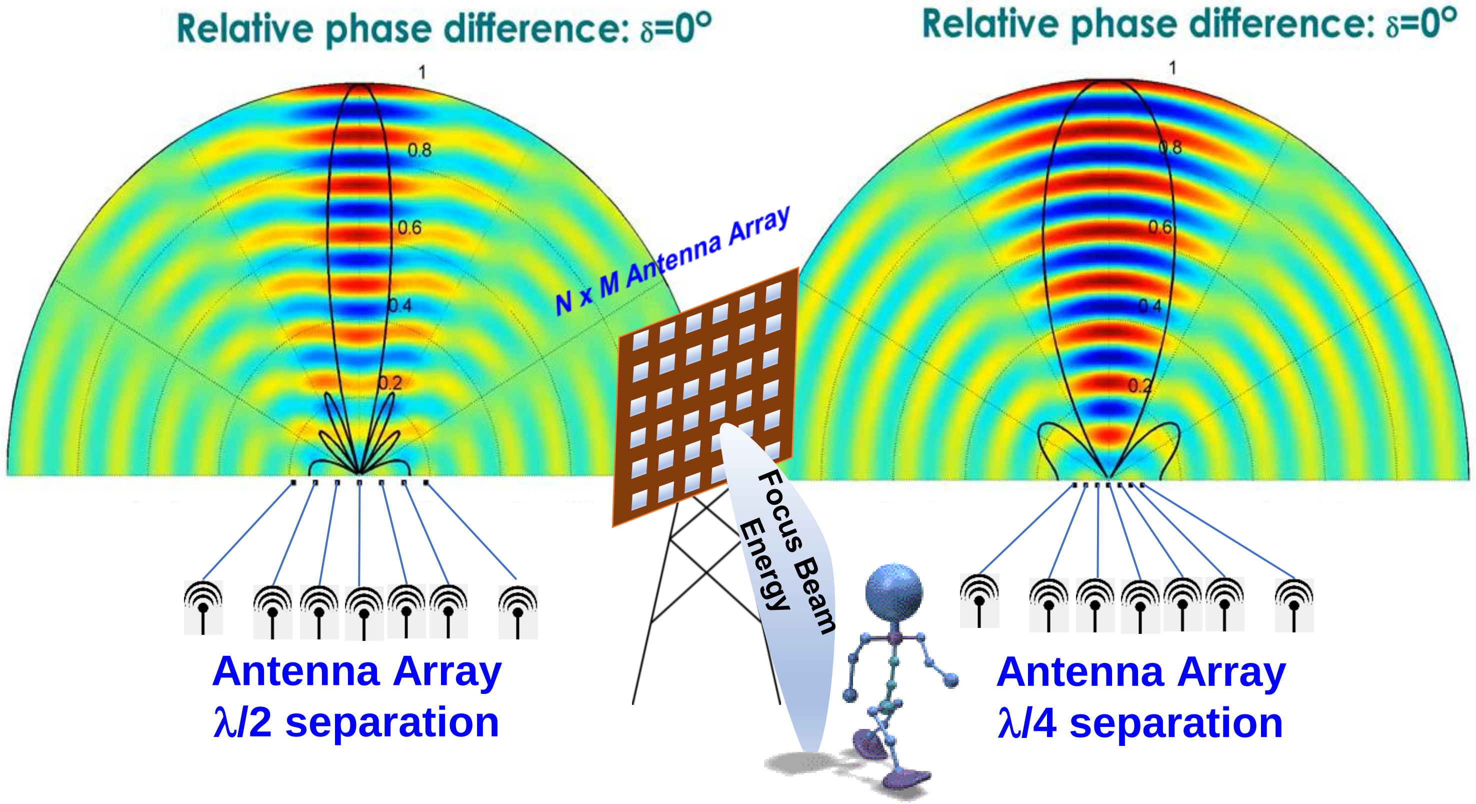
Bridging the gap between SPICE Models & Antenna Radiations for FEM Co-Design

Technology Incidence:

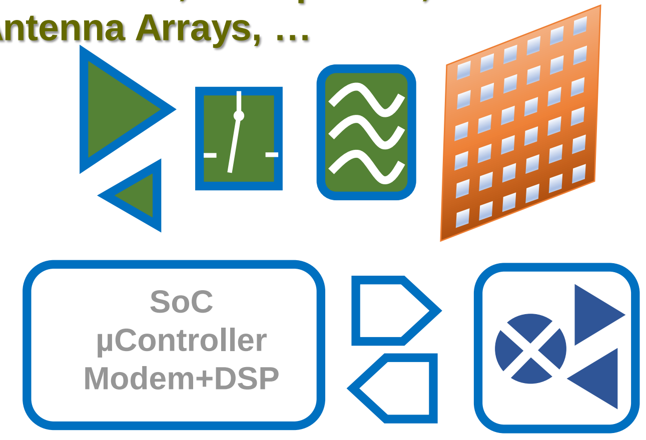
- @Packaging-Level: WLCSP Solutions will create new paradigms: AiP & Tuning Solutions
  [Partnership with Synergie-CAD PSC]
- @PCB Level: New Flexible/Conformal Connectivity & Transition Solutions
  [Partnership with Orange/Thales/LEAT/Eurecom on new Lens-based Beamformers]
- @Chip-Level: Bringing Cognition to RF/mmWave including Technology Hybridization
  [Partnership with Dolphin-Design on Digital-Processing/Control in FDSOI]
  [Partnership with UMS-RF on Hybrid GaN-FDSOI Technology Solutions]

5G mm-Wave MIMO & Phased-Arrays

Control of Energy localization and spatial distribution identified as one of the main critical challenges for emerging applications (e.g., 5G, IoT).



Basic Building blocks for Beamforming: PA, LNA, Filters, Mixers, Modulators, Splitters, Switches, Antenna Arrays, …



Need for Agile Technology solutions

Innovative solutions will open new Business Opportunities for effective implementation of MIMO & Phased-Array functionalities towards higher data rate with improved energy efficiency.

Reference in S. Wane, «MIMO and Phased-Array Systems embedding Cognition» internal report, 2018.

Energy Efficient Beamforming & MIMO Solutions

Hybrid Analog-Digital Beamforming provides effective solution in controlling Energy localization & spatial distribution for MIMO/Phased-Array applications.

MIMO Performances

Shannon Channel Capacity (w/o Diversity)

$$\text{Channel Capacity} = \text{Nopt} \times \text{B}\,\text{log2}[1 + \text{SNR}]$$

Number of antennas (independant channels)

Bandwidth

Signal-to-Noise Ratio

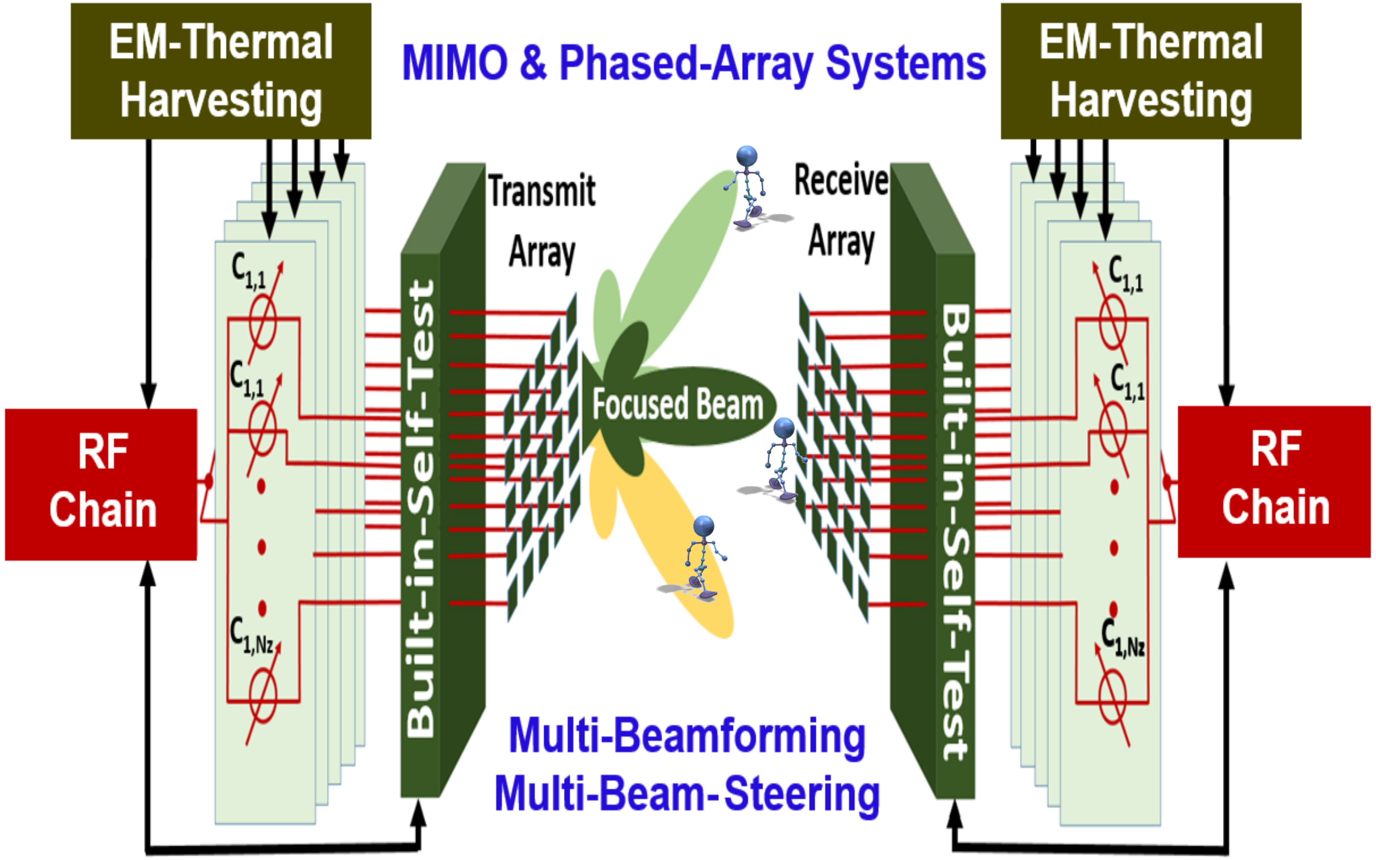
Correlation Matrix $R_X = E[XX^H]$

Channel Transfer Matrix

$$I(X,Y) = \log_2 \det\left[I + \frac{1}{\sigma_v^2} H R_v^{-1} H^H R_X\right]$$

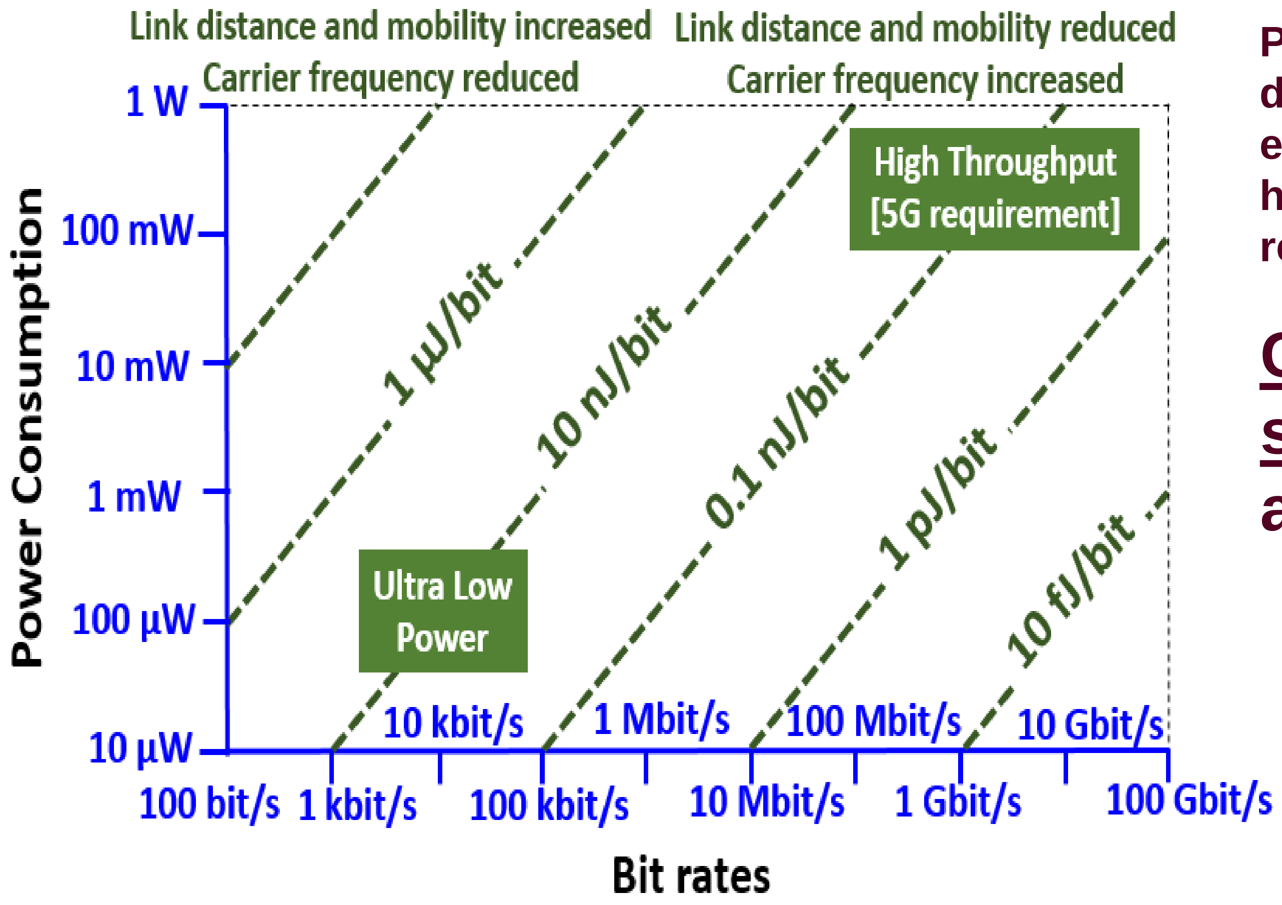
Related to Differential Entropy (Maximisation)

Correlation Matrix $R_v = \frac{1}{\sigma_v^2} E[vv^H]$



Need for Energy-Efficient Multi-Beamforming Solutions with Embodied Cognition

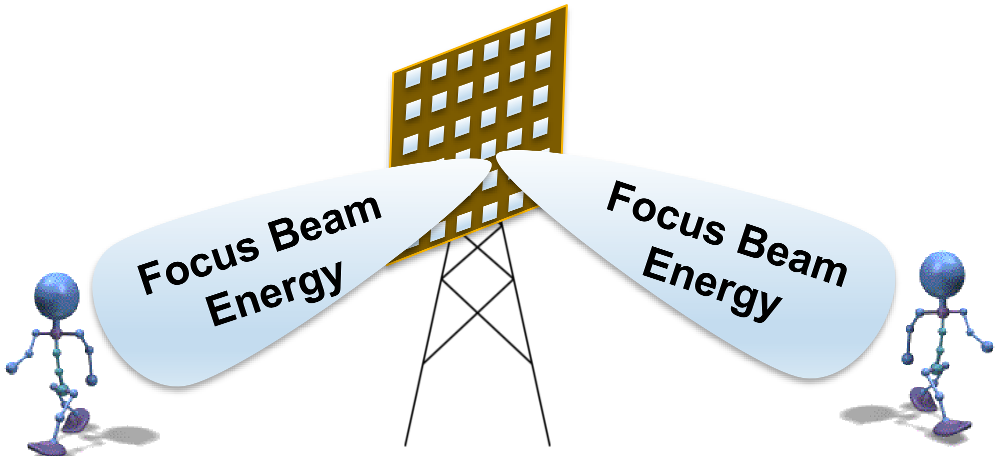
Technology Trends of Power Consumption versus Bit Rates



S. Wane et al., "**Energy-Geometry-Entropy Bounds aware Analysis of Stochastic Field-Field Correlations for Emerging Wireless Communication Technologies**", URSI General Assembly Commission, session on "**New Concepts in Wireless Communications**".

Power consumption as function of bit rates versus dissipated energy in J/bit: In the perspectives of emerging technologies including 5G applications where high throughput and low latency are important requirements.

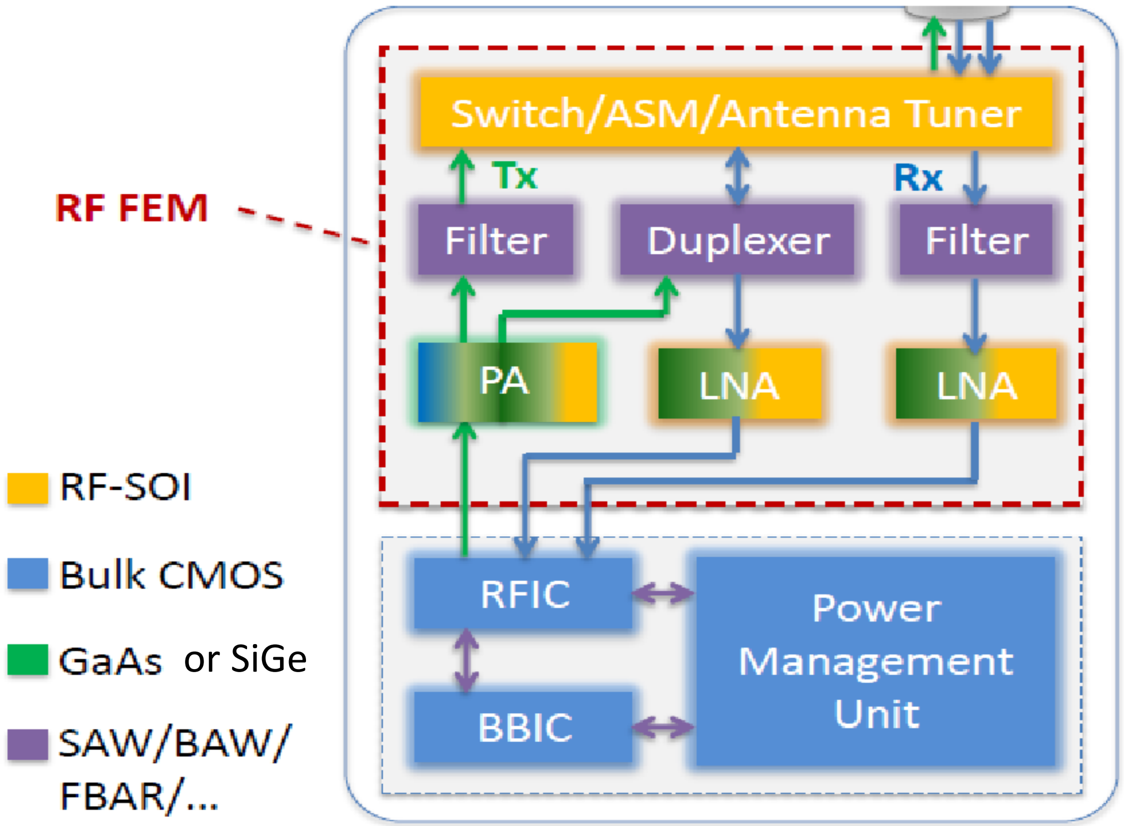
Control of Energy localization and spatial distribution key for emerging applications (e.g., 5G, IoT).



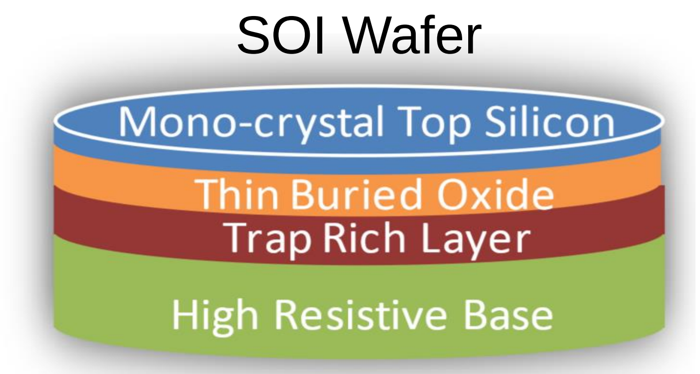
MIMO+Beamforming+5G

FDSOI seen as a unifying Analog-Digital Technology solutions

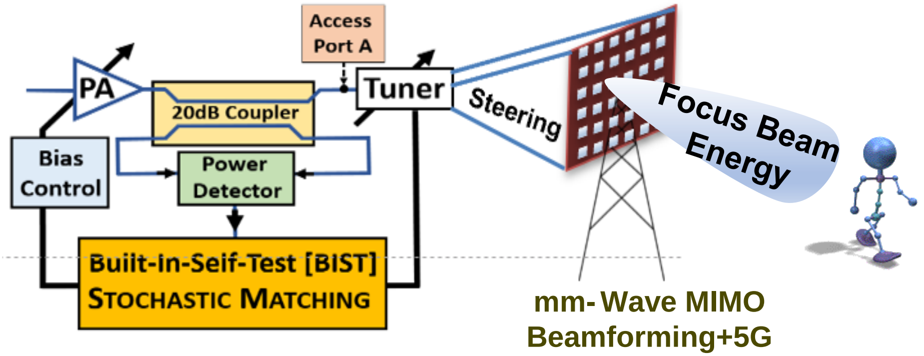
Design & Integration Constraints



Need for Agile Technology solutions
Perspectives for SOI-based Technologies
[e.g., FD-SOI]



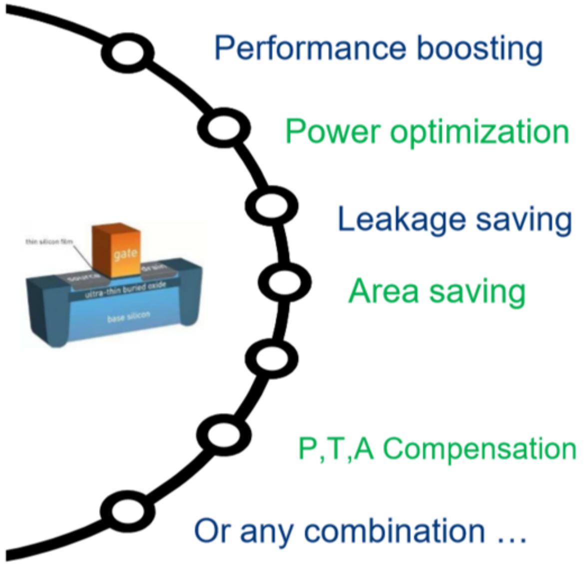
- Adaptive Body Biasing
- Energy-Efficiency
- Reconfigurability, Regulation and Control
- Reliability & optimization of RF performances
- Energy Harvesting/Storage management



Challenges of Power-Combining

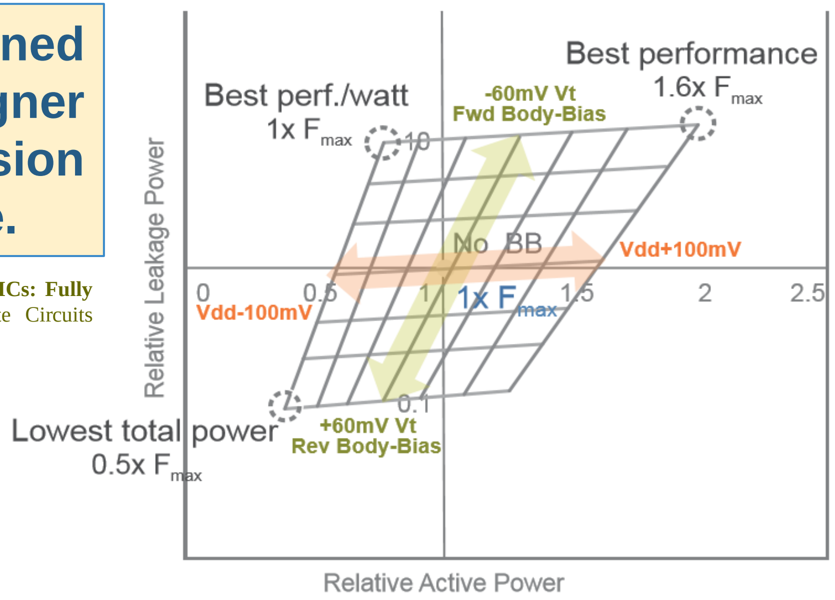
Path to Hybrid SOI+GaN

Importance of FDSOI Technology Solutions



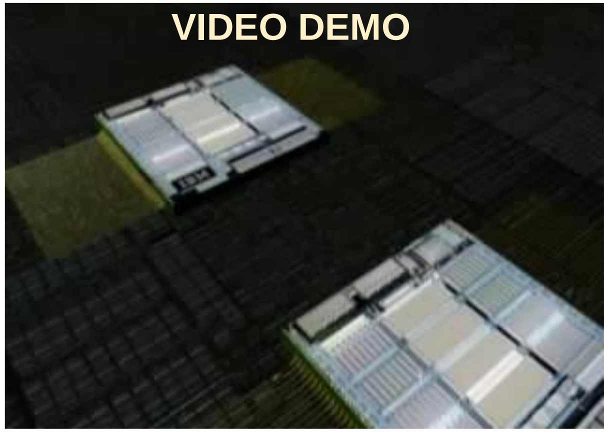
When body-biasing corners are combined with traditional PVT corners, the designer has access to an entirely new dimension to optimize for power and performance.

Bich-Yen Nguyen, Philippe Flatresse, et al., "A Path to Energy Efficiency and Reliability for ICs: Fully Depleted Silicon-on-Insulator (FD-SOI) Devices Offer Many Advantages", IEEE Solid-State Circuits Magazine (Volume: 10 , Issue: 4 , Fall 2018).



Capabilities for RFIC-Photonics using SOI Technology Solutions:

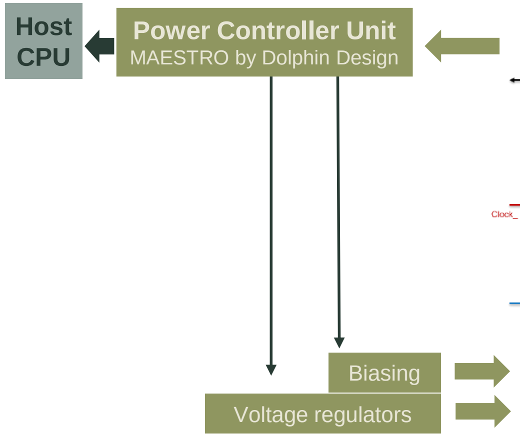
- **Compatibility to CMOS technology & packaging/assembly**
- **Co-Integration of optical waveguiding with large selection of photonic components with heterogeneous integration Si/GaAs/InP/GaN.**
- **3D Chip-Package-PCB-Antenna EM-Thermal-Mechanical Co-Design accounting for energy efficiency backed-up by unified EDA and Instrumentation solutions.**



Making Robust AMBIENT COMPUTING by Design and in the Field

ASIL-D ABB IP

Automotive certified ABB IP
For field reliability compensation
And thermal runaway control



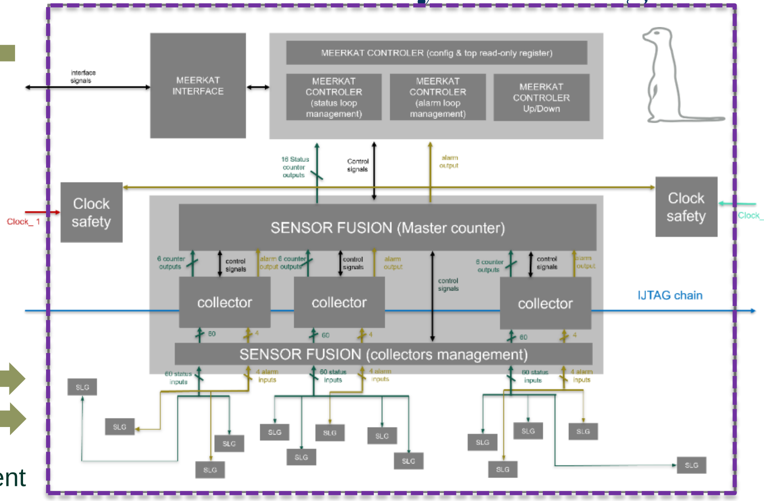
Biasing & Voltage Scaling Management

On-Chip

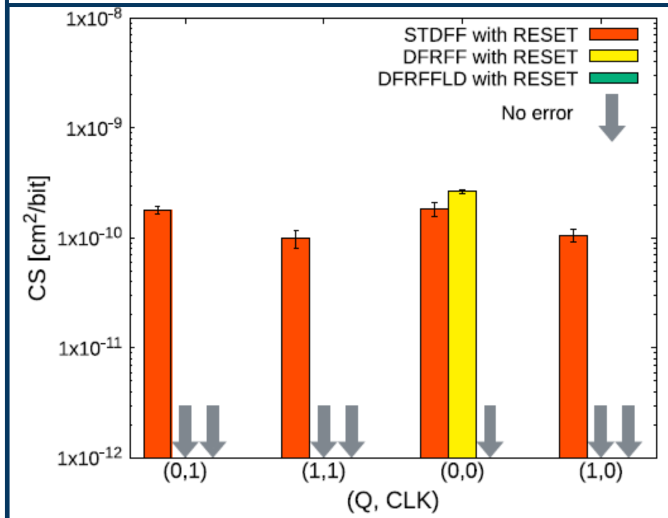
Unique patented monitoring solution
Enables fail operational safety and silicon lifecycle management

SIEMENS

MEERKAT



Space RadHard



Best-in Class patented Space RadHard FF

Heavy Ions qualification done
Neutron qualification Oct'22

2

Main Results, Analysis & Discussions

Energy-Efficient Multi-Beam Systems
Toward Hybrid GaN -FDSOI FEMs

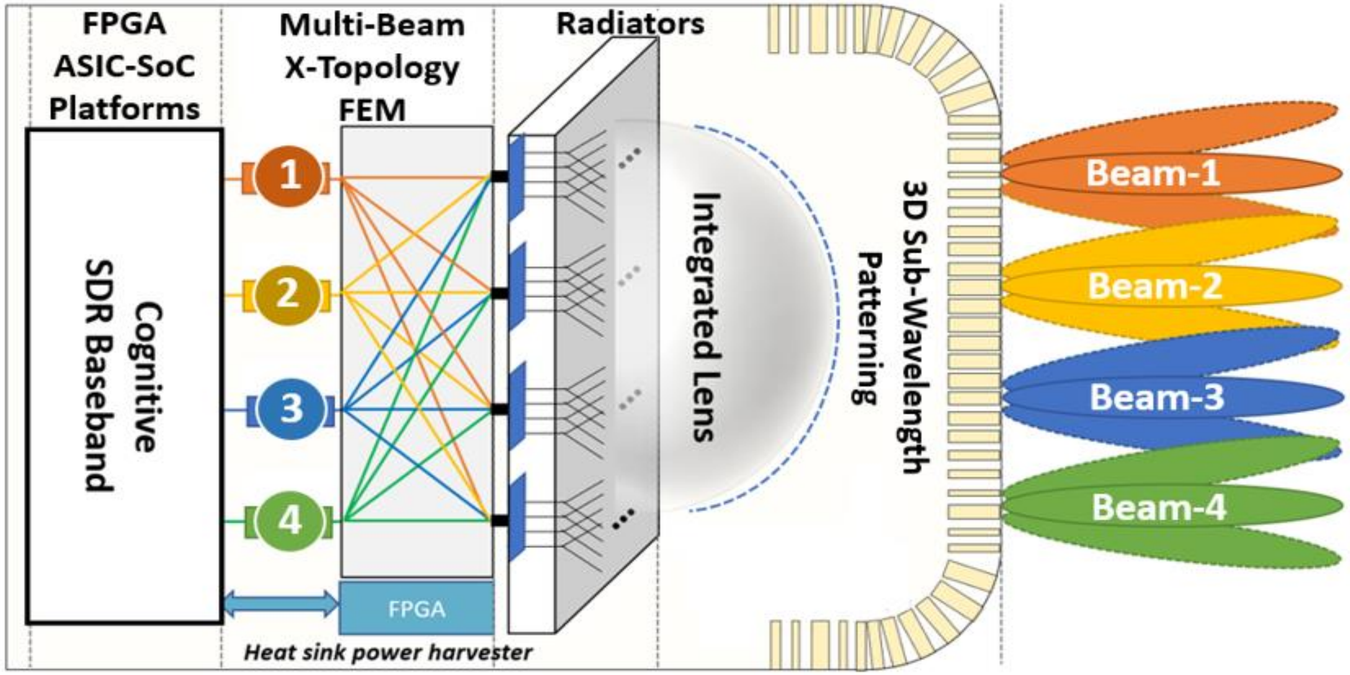
Scope & Context

Energy Efficient Millimeter Wave FIXed access (EEMW4FIX)

[Government Funded Project (ANR)]

- *More than one billion homes worldwide still find themselves without a regular broadband connection.*
- *Fixed Wireless Access (FWA) can provide a broadband service to homes, business and factories, when there is no infrastructure to deliver wired broadband via copper, fiber or hybrid solutions.*

Next-generation FWA such as beam-switching at millimeter waves (mmW) will require robust, reliable and cost-efficient solutions on a massive scale



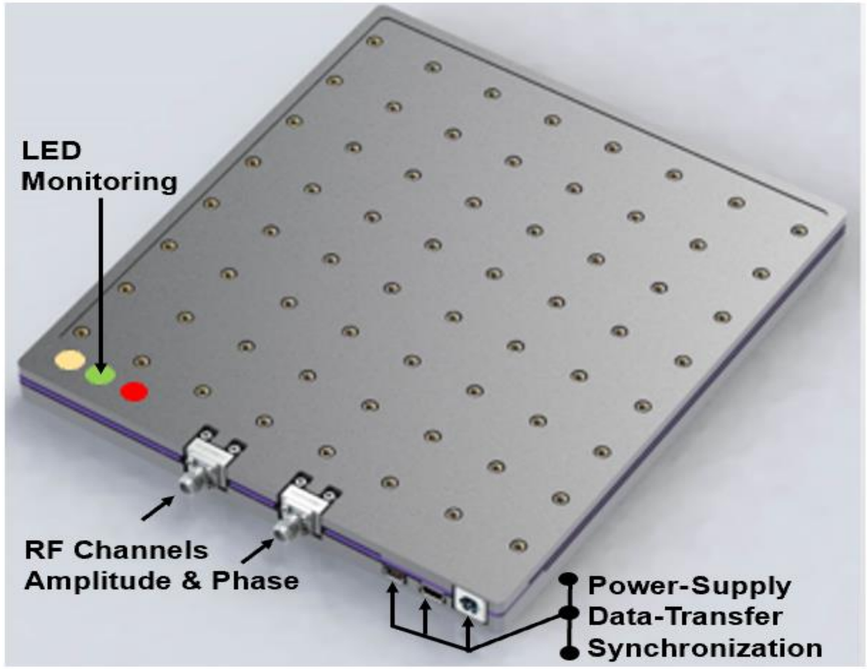
To make mmW FWA a reality, *highly-directive beam-steerable antennas* are required to ease UE set-up and to mitigate environment effect (e.g., *wind, vibration on urban furniture, temperature, etc.*).

These smart antennas must also exhibit **low power consumption**, **multi-band and multi-beam** capabilities to offer a wide range of services over the frequency bands allocated by ITU.

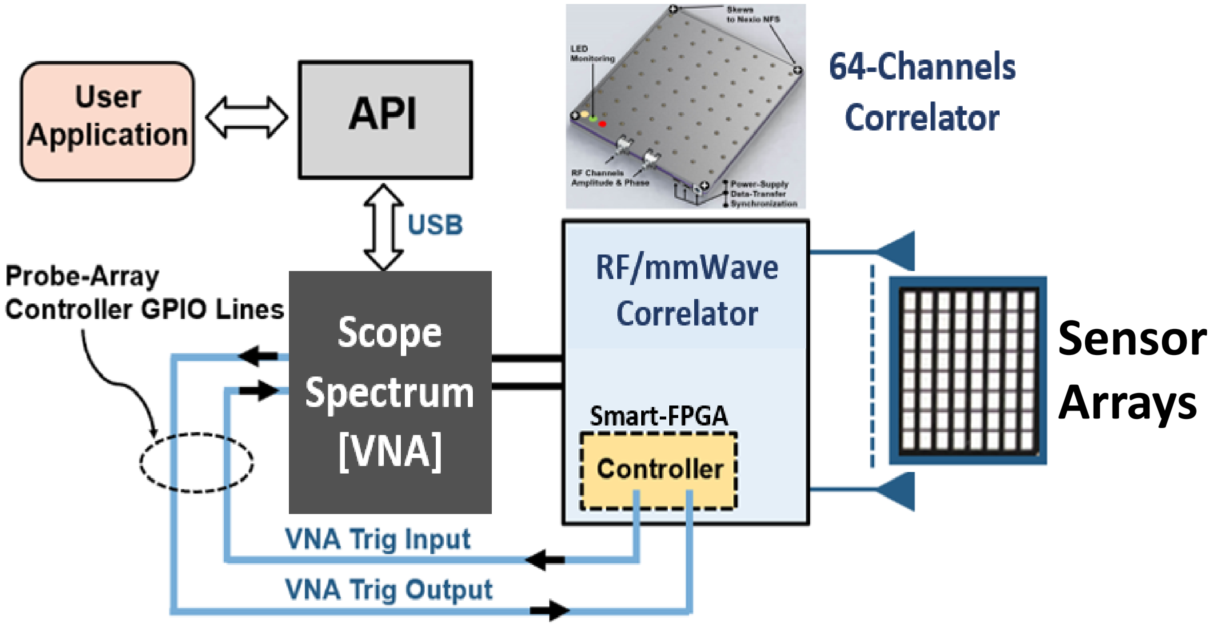
RF & mmWave Technology Solutions

The Art of Correlating Signals & Energies

64-Channels DC-10GHz, DC-30GHz or DC-44GHz Amplitude & Phase Correlator Modules



Real-Time Frequency-Domain and Time-Domain Auto & Cross-Correlation Measurements



ASIC-based RF & mmWave Correlators with Embedded FPGA for advanced AUTO-CORRELATION and CROSS-CORRELATION Measurements

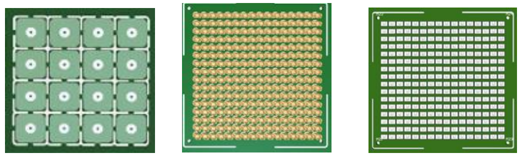
Wane, S. "**ASIC-Correlators with Embedded Cognition for Smart OTA Test**", EMC and OTA Tests of Wireless Devices in Reverberation Chambers, EMC-Europe 2021, online workshop: https://www.emc2021.emcss.org/assets/images.

RF & mmWave Technology Solutions

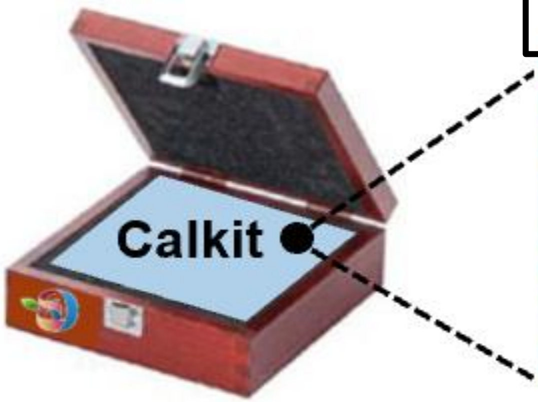
Mosaic-Based Architecture Solutions

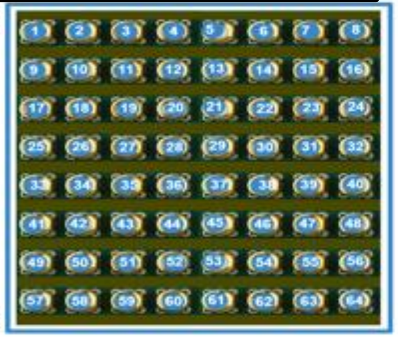
64-CHANNELS CORRELATOR

- 100dB Channel Isolation
- Integrated Signal-Processing & Control Module
- Stable Temperature Regulation
- Wireless Signal Control

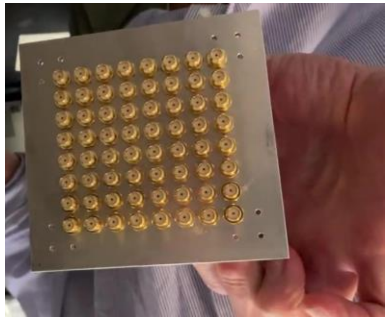


64-Channels Traceable Calibration-Kit





64-CHANNELS Calibration-Kit

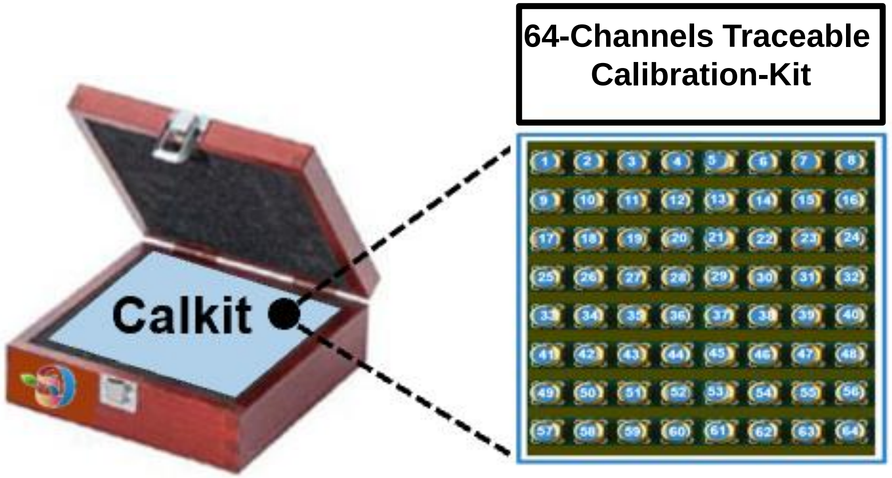


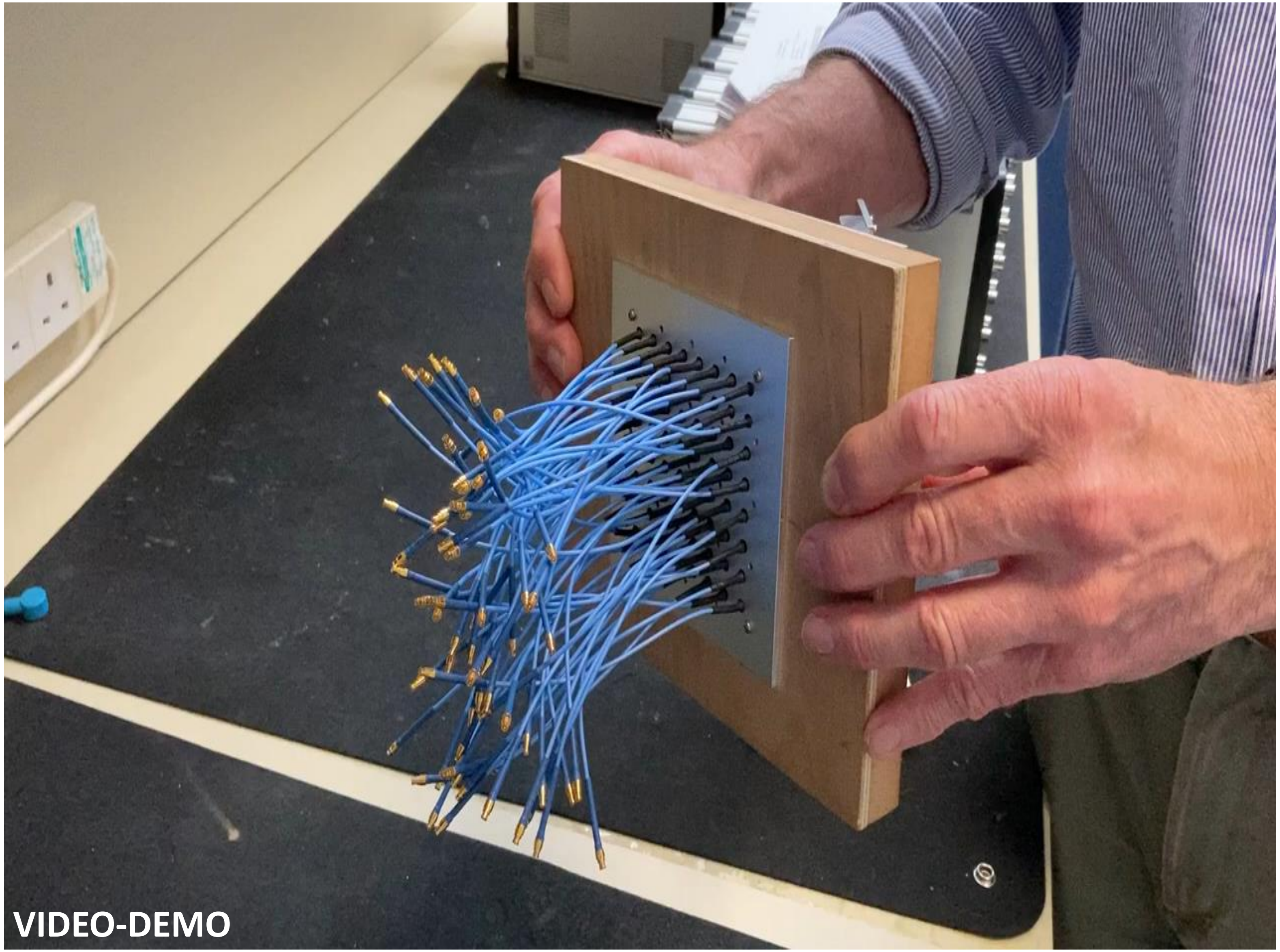
Compliant with State of The Art Time-Domain & Frequency-Domain Instruments

Wane, S. "**ASIC-Correlators with Embedded Cognition for Smart OTA Test**", EMC and OTA Tests of Wireless Devices in Reverberation Chambers, EMC-Europe 2021, online workshop: https://www.emc2021.emcss.org/assets/images.

Automated x64 Channels Calibration Solution

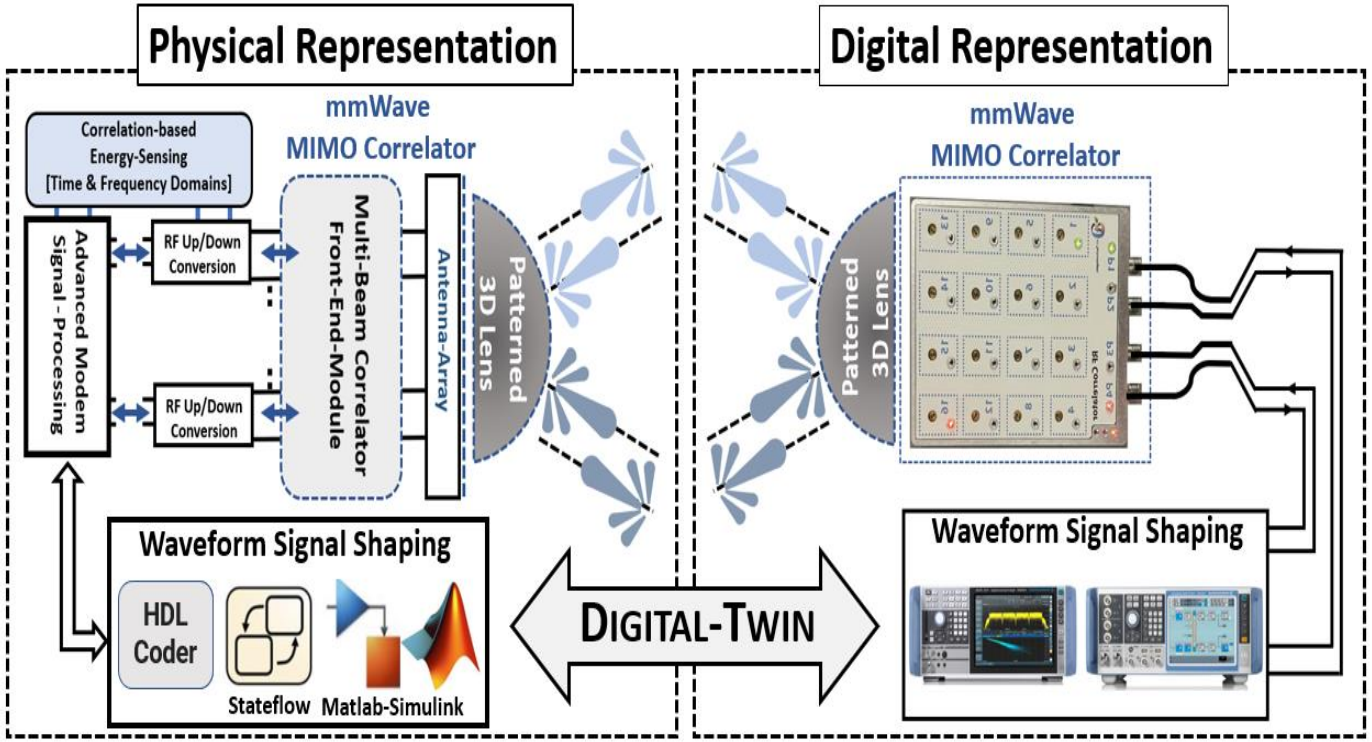
- **5G FR1 & FR2 Support**
- **DC Extrapolation for IoT**
- **Time-Domain FFT**
- **Custom Drivers**





Wane, S. "**ASIC-Correlators with Embedded Cognition for Smart OTA Test**", EMC and OTA Tests of Wireless Devices in Reverberation Chambers, EMC-Europe 2021, online workshop: https://www.emc2021.emcss.org/assets/images.

Digital-Twin Using RFSoC & SDR Platforms



EVM-based Correlation Measurement

The NIST (USA) and NPL (UK), supported by many institutions and corporations have been working on a new standard and method to **measure the Error Vector Magnitude (EVM) of radio systems**, requiring correlation techniques. eV-Technologies solutions can enable compliance of measurement platforms.

➔ For the resulting IEEE P1765 standard, the industry will look for compliance.

J. Sombrin, "On the formal identity of EVM and NPR measurement methods: Conditions for identity of error vector magnitude and noise power ratio," in EuMC Proc. ,Manchester, UK, 2011, pp. 337-340.

- **EVM** can be applied **over the air (OTA)** to each beam of a multibeam antenna and to each channel or the combination of channels of a MIMO transmission.
- **FPGA-based reconfigurable platform** is proposed for OTA testing of **multi-beamforming systems using *correlation-based EVM metrics***.
- The experimental setup uses **automated MATLAB-based toolbox control modules** combined with **Rohde & Schwarz's mmWave signal generation and analysis** for remote testing in time and frequency domains of stochastic signals.

https://fr.mathworks.com/products.html

Towards compact lens antenna

Height gradient

Fresnel lens

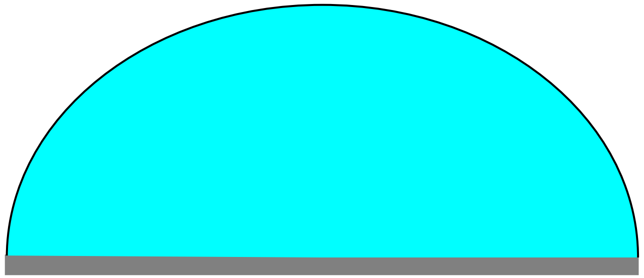
Compact but less efficient

Index gradient

Diffractive RF lens by index gradient

Artificial material approach

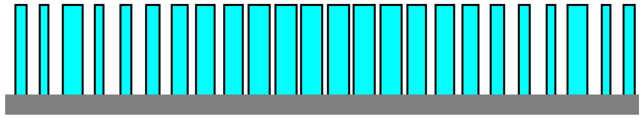
THALES



Bulk dielectric RF lens

∅180mm – 42GHz
Lens antenna

Effective index gradient



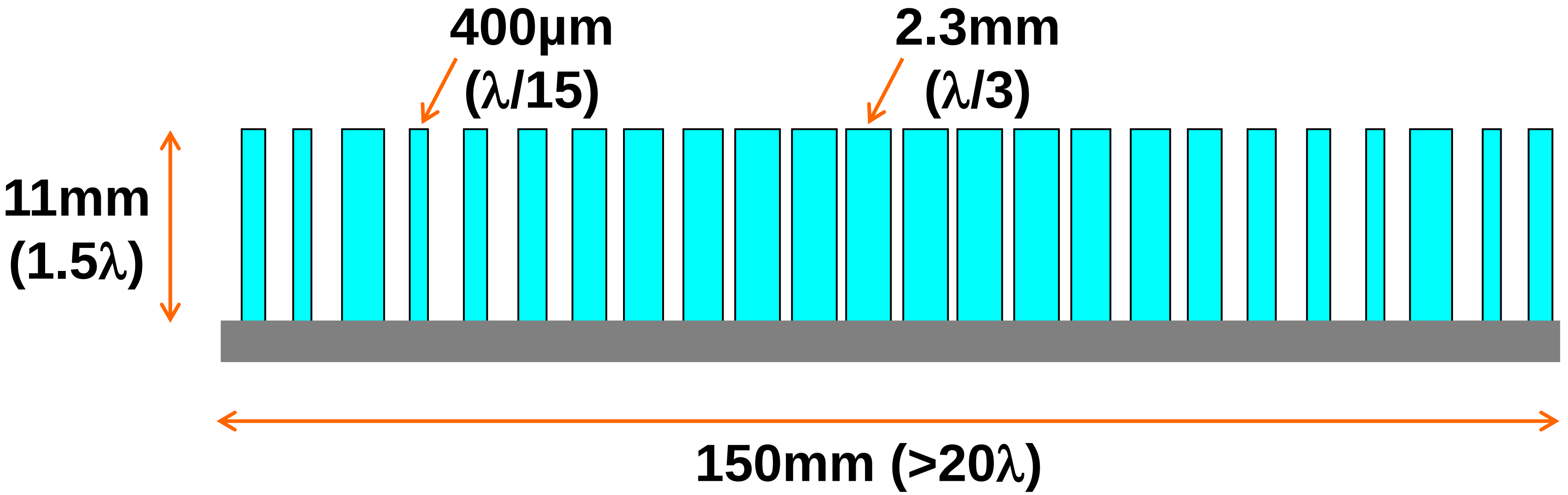
Sub-λ diffractive RF lens

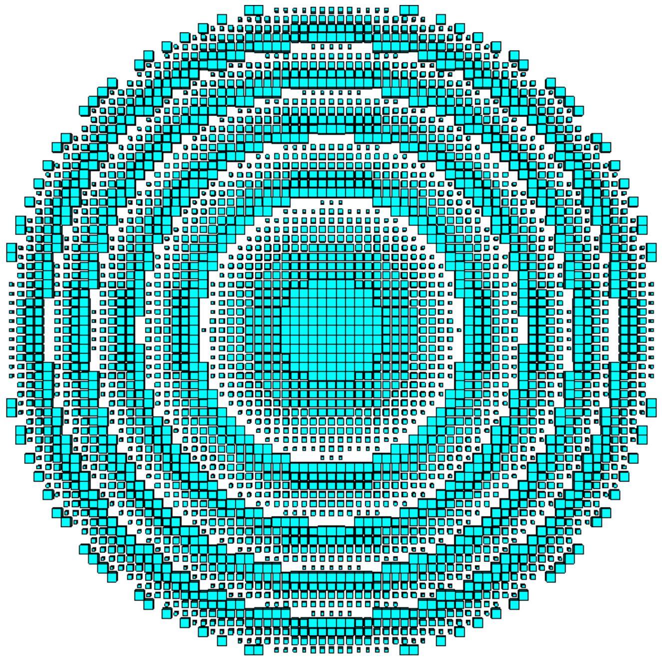
Low profile and efficient

R. Czarny, et al., “**High permittivity, low loss, and printable thermoplastic composite material for RF and microwave applications**”, 2018 IEEE Conference on Antenna Measurements & Applications (CAMA), held in Västerås, Sweden, 3-6 Sep. 2018.
X. Lleshi, R. Grelot, T. Q. Van Hoang, B. Loiseaux and D. Lippens, "**Wideband Metal-Dielectric Multilayer Microwave Absorber based on a Single Step FDM Process**," 2019 49th EuMC, pp. 678-681.

Towards compact lens antenna

- Example of a sub-wavelength dielectric lens antenna @ 42GHz
  - **ε_R = 2.6 and $\tan\delta = 7.10^{-3}$**
  - **Thousands of pillars**





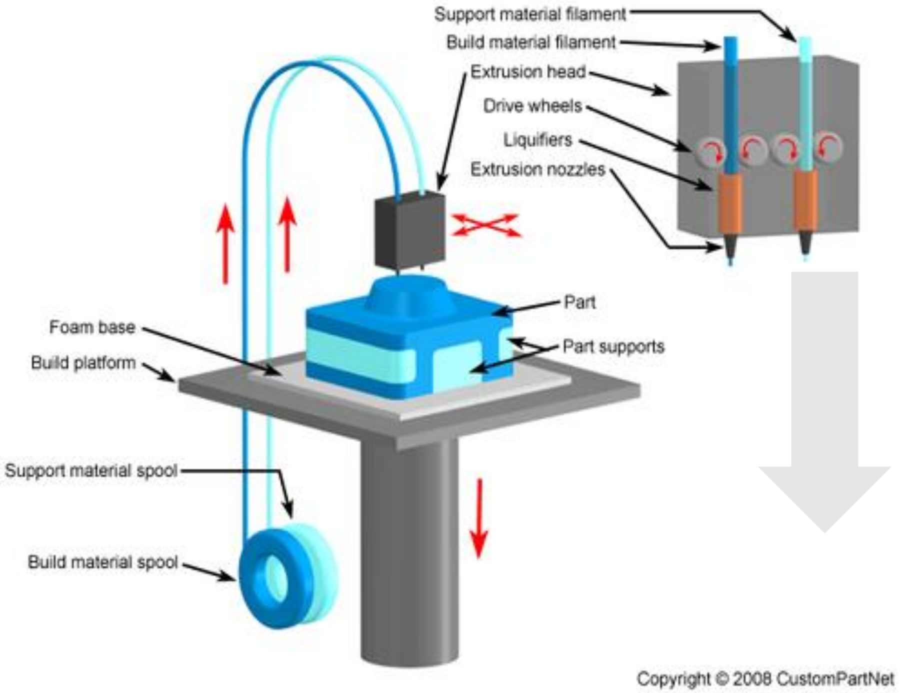
How to fabricate this kind of structure?

THALES

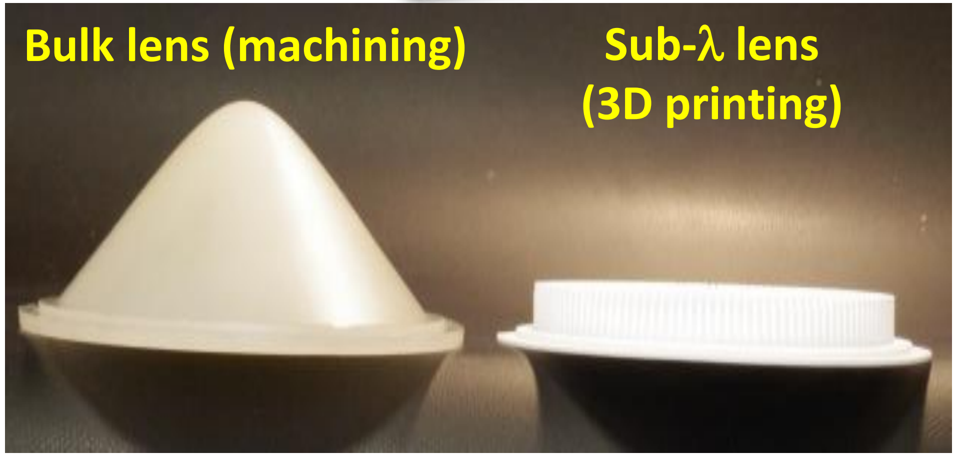
R. Czarny, et al., "**High permittivity, low loss, and printable thermoplastic composite material for RF and microwave applications**", 2018 IEEE Conference on Antenna Measurements & Applications (CAMA), held in Västerås, Sweden, 3-6 Sep. 2018.

X. Lleshi, R. Grelot, T. Q. Van Hoang, B. Loiseaux and D. Lippens, "**Wideband Metal-Dielectric Multilayer Microwave Absorber based on a Single Step FDM Process**," 2019 49th EuMC, pp. 678-681.

How to manufacture ?



Toward Compact Lens Antenna

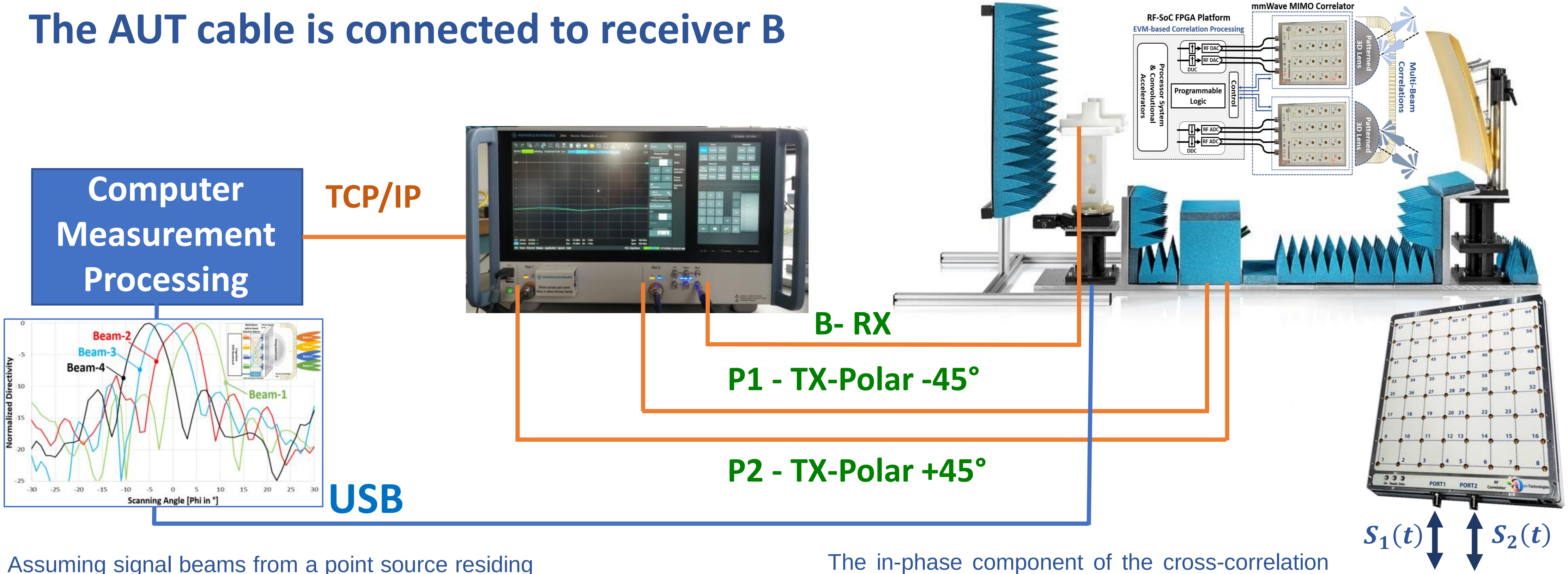


Artificial material + 3D printing
= Functional RF parts with better performance

- Gain improvement up to 1.5 dB
- Thickness reduction by 4 (13mm vs. 53mm)
- Weight reduction by 3 (160g vs. 445g)
- Cost reduction by 10 (100€ vs. 1000€)

Rx Mode: Dual-Beam Correlation Measurement

- **The two ports of the reflector source are connected to VNA port 1 et 2**
- **The AUT cable is connected to receiver B**



Assuming signal beams from a point source residing at angle θ and received on two antennas $S_1(t)$ and $S_2(t)$ separated by a baseline D:

$$S_1(t) = cos\left[2\pi\left(F_0 t + \frac{K}{2}t^2\right)\right] + n_1(t)$$

$$S_2(t) = cos\left[2\pi\left(F_0(t-\tau_g) + \frac{K}{2}(t-\tau_g)^2\right)\right] + n_2(t)$$

F_0 is the carrier frequency, K (Hz/s) is the chirp rate, and $\tau_g = (D/c)\sin(\theta)$ is the geometrical time delay of the wavefront between the two antenna elements.

The in-phase component of the cross-correlation of the two received signals $S_1(t)$ and $S_2(t)$ can be expressed as:

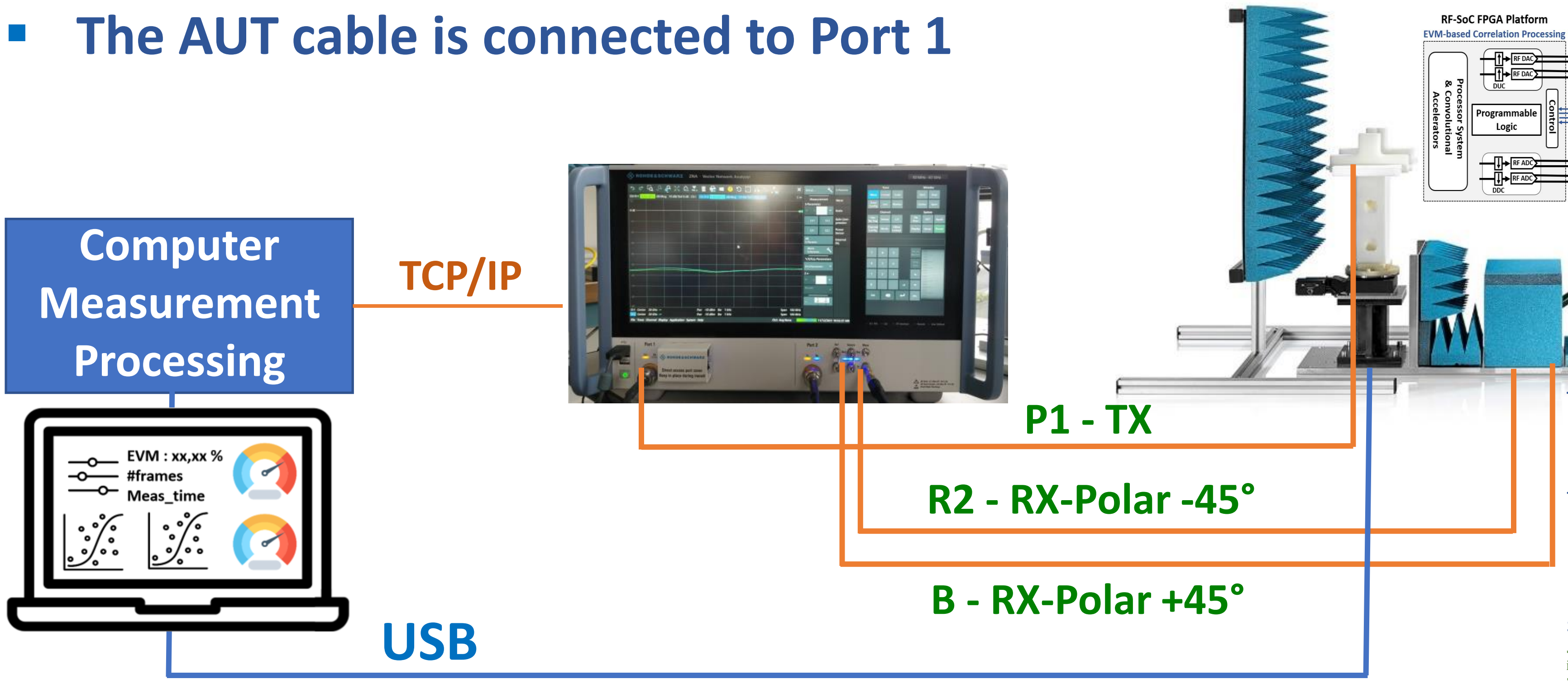
$$C_{S_1S_2}(\tau_g) = \left\langle cos\left[2\pi\left(F_0 t + \frac{K}{2}t^2\right)\right] \middle| cos\left[2\pi\left(F_0(t-\tau_g) + \frac{K}{2}(t-\tau_g)^2\right)\right]\right\rangle = cos\left[2\pi\left(F_0 + Kt - \frac{K}{2}\tau_g\right)\tau_g\right]$$

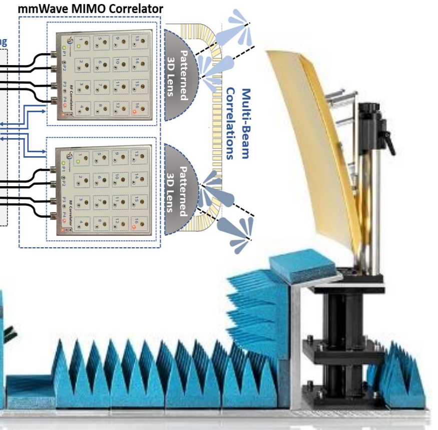
The noise terms are suppressed as they are assumed uncorrelated with each other and with the received signals.

https://www.rohde-schwarz.com/fr/produit/ats800b-page-de-demarrage-produits_63493-642314.html

Tx mode: Correlation-based EVM Measurement

- **The two ports of the reflector source are connected to receiver R2 and B**
- **The AUT cable is connected to Port 1**





The classical method for EVM (Error Vector Magnitude) computation is to compute vector errors between received (y_n) and ideal (x_n) symbols and then to compute a root-mean-square of the magnitude of these vectors for all symbols in a frame. For this, it is necessary to extract an optimum gain γ (amplitude and phase) between received and ideal symbols that minimizes the EVM.

J. Sombrin, "On the formal identity of EVM and NPR measurement methods: Conditions for identity of error vector magnitude and noise power ratio," in EuMC Proc. ,Manchester, UK, 2011, pp. 337-340.

We introduce Correlation-based EVM measurement: The optimum gain is computed by using autocorrelation and cross-correlation of ideal and received symbols. All these computations can be done in the following steps by replacing the optimum gain by its value and using the covariance between ideal x and received y symbols vectors.

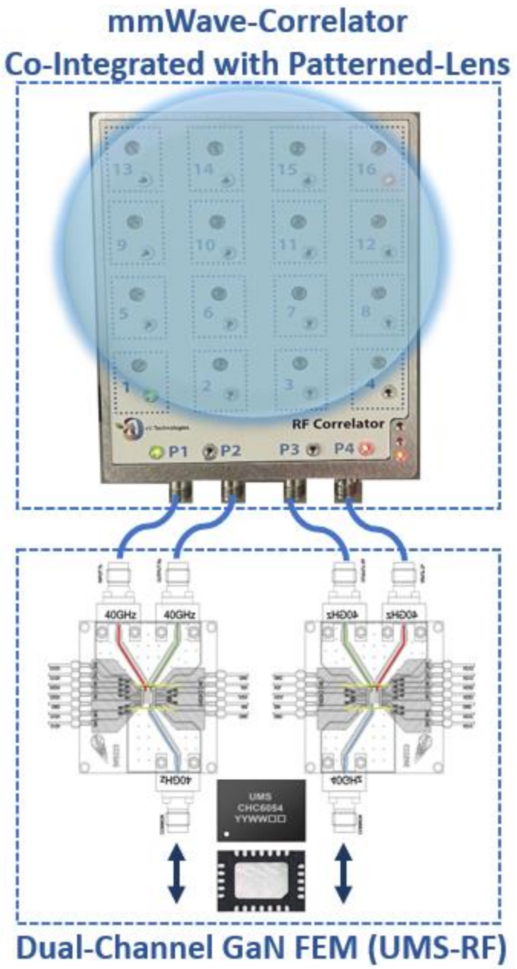
$$\cos\theta = \frac{\left|\sum_{n=1}^{N} y_n x_n^*\right|}{\sqrt{\sum_{n=1}^{N} y_n y_n^* \sum_{n=1}^{N} x_n x_n^*}} = \frac{|\langle y, x\rangle|}{\|y\|\|x\|}$$

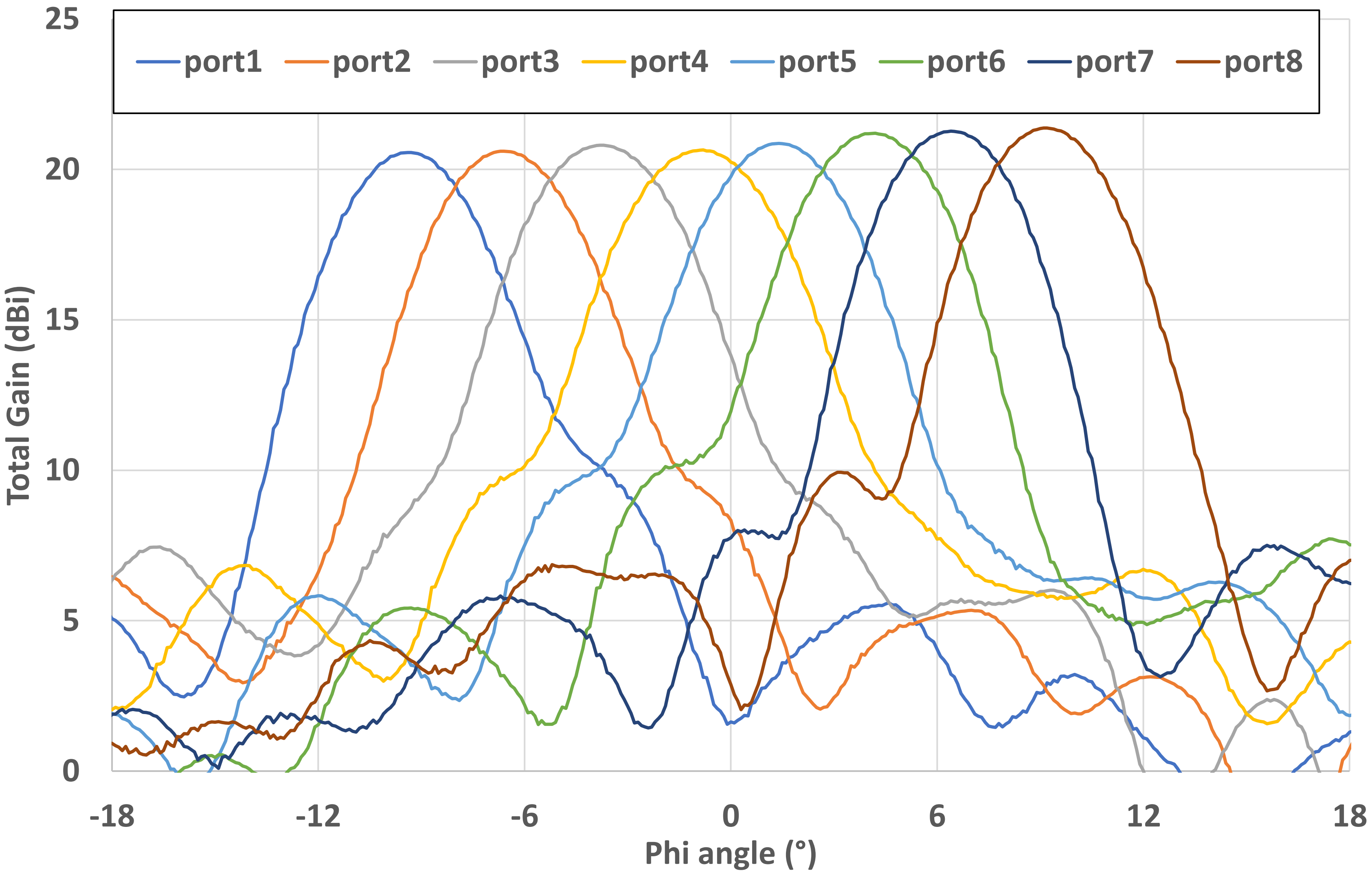
⇒

$$EVM = \sqrt{\frac{1}{\cos^2\theta} - 1} = \tan(\theta)$$

https://www.rohde-schwarz.com/fr/produit/ats800b-page-de-demarrage-produits_63493-642314.html

Multi-Beam Measurements



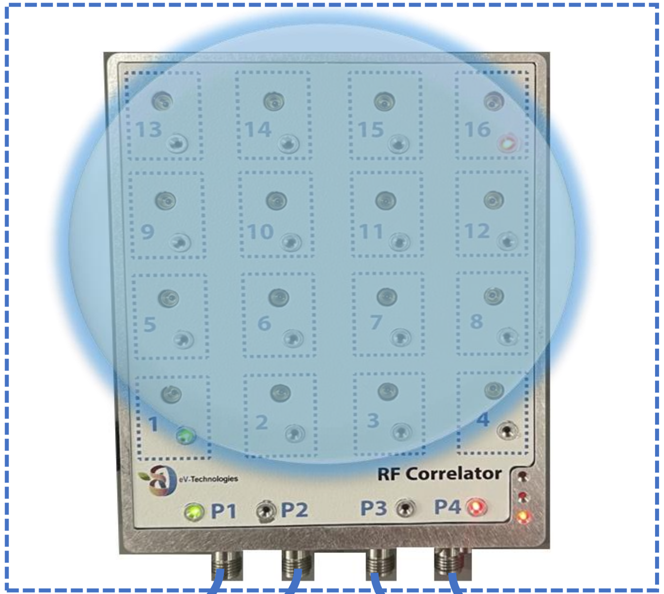


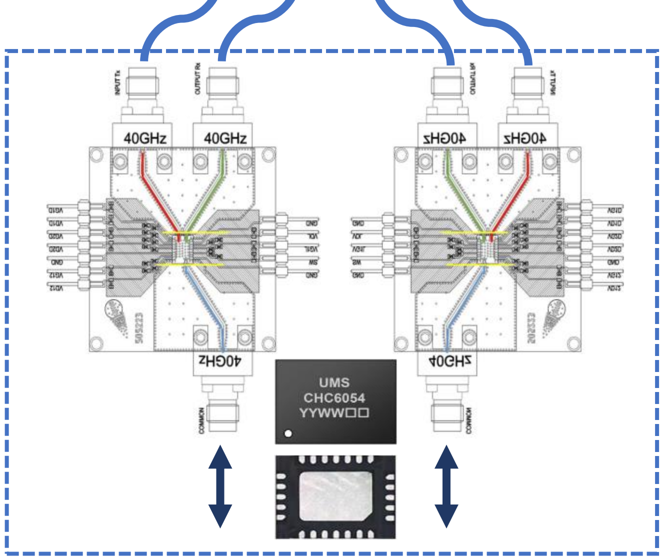
Energy Efficiency [without Harvesting]

Baseline Metrics	Classical mmW Phased-Array	Proposed Solution for 1 RF Path	Proposed Solution for 4 RF Path
Dimensions	5*5*5 cm	10*10*~10cm	10*10*~10cm
Antenna Elements	64	64	64
Tx EIRP Without GaN	54 dBm	48 dBm	48 dBm per path
Tx EIRP with GaN	59 dBm	53 dBm	53 dBm per path
Rx gain	23dB	29dB	29dB
Total Tx+Rx without GaN	78dB	77dB	77dB
Total Tx+Rx with GaN	83dB	82dB	82dB per path
Activated Elements	64	4	16
RF Power Consumption	**10W**	**0.6W**	**2.4W**
Scan-Angle	+/- 60°	+/- $\kappa \times 15°$	+/- $\kappa \times 15°$
Number of Beams	1	1	4

the parameter κ=1 for the scanning angle. Ongoing developments are expected to significantly increase this value.

mmWave-Correlator Co-Integrated with Patterned-Lens



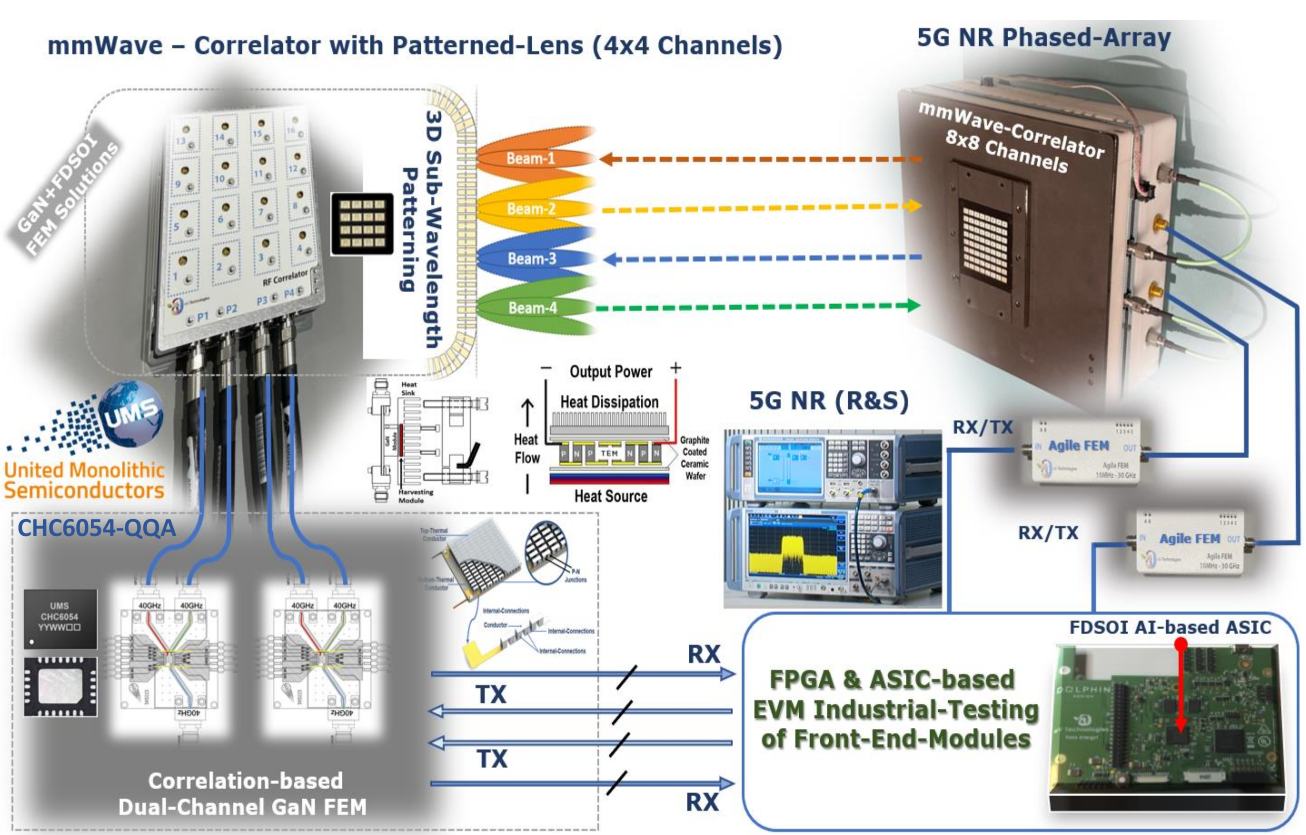


Dual-Channel GaN FEM (UMS-RF)

https://www.ums-rf.com

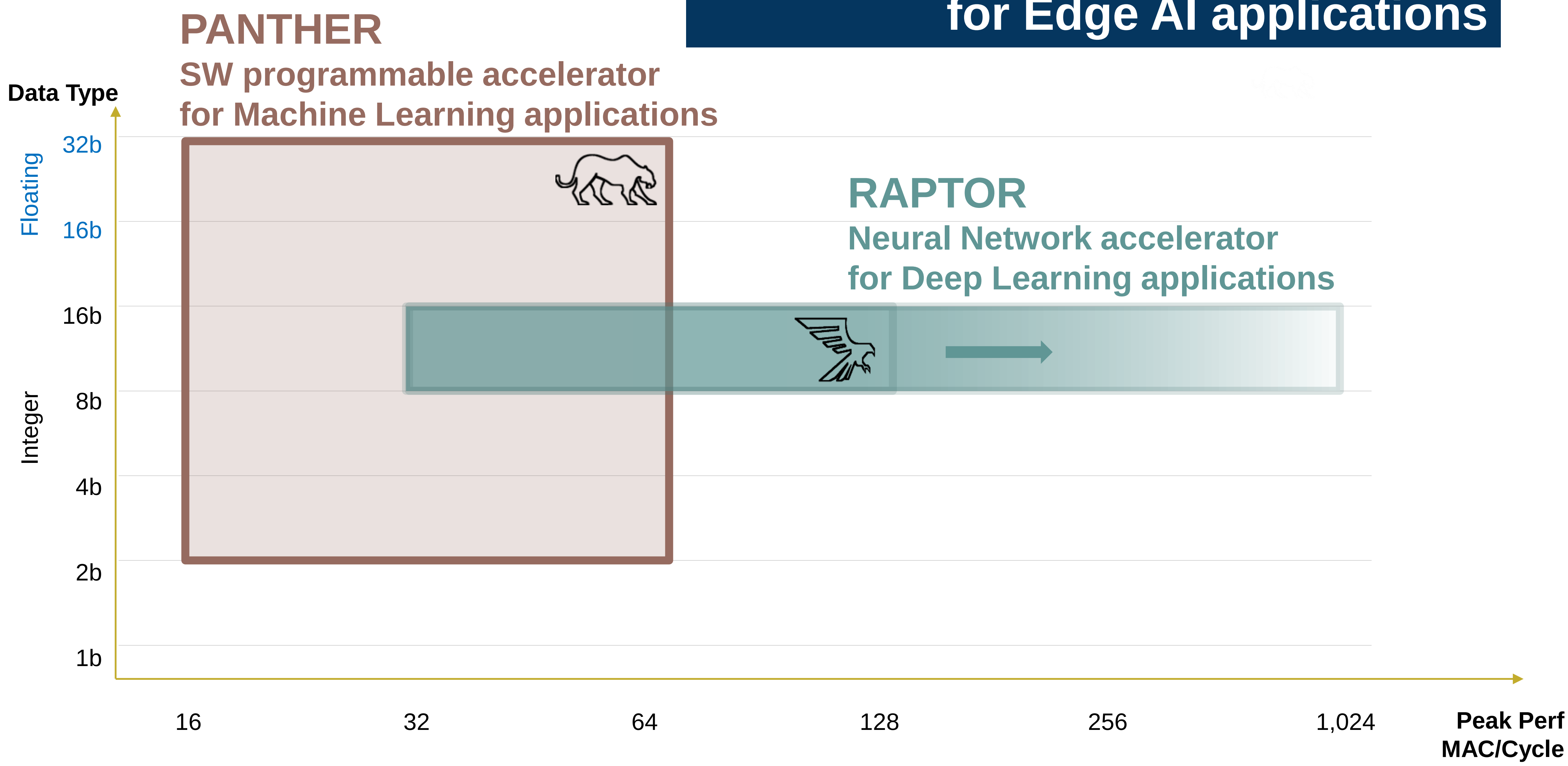
Energy-Efficient Hybrid GaN-FDSOI Technology Solutions for 5G mmWave Multi-Beam Systems

- **Energy-Efficient** Correlation-Technologies based **Multi-Beam Systems:**
  - → Lower complexity: Lower power consumption: **improvement by at least a factor of 10**
  - → **Energy-Harvesting (Thermal-EM) Solutions:** perspectives of "Zero-Carbon" target.
- **Correlation-based security:** immune to blocking and jamming (Auto/Cross-Correlation of MIMO receivers with sensitivities below -145dBm@28GHz).
- **Lens-based Beamformers** for single-beam and multi-beam systems.
- Digital-Twin platforms with DSP-based accelerators at FPGA & ASIC levels using **Correlation-based EVM metrics : Toward Hybrid GaN-FDSOI with Embodied Cognition.**



VIDEO-DEMO

Accelerating AI/ML algorithms for Edge AI applications



RAPTOR NPU accelerator IP
Awarded HW&SW co-design approach

Near-Memory Computing

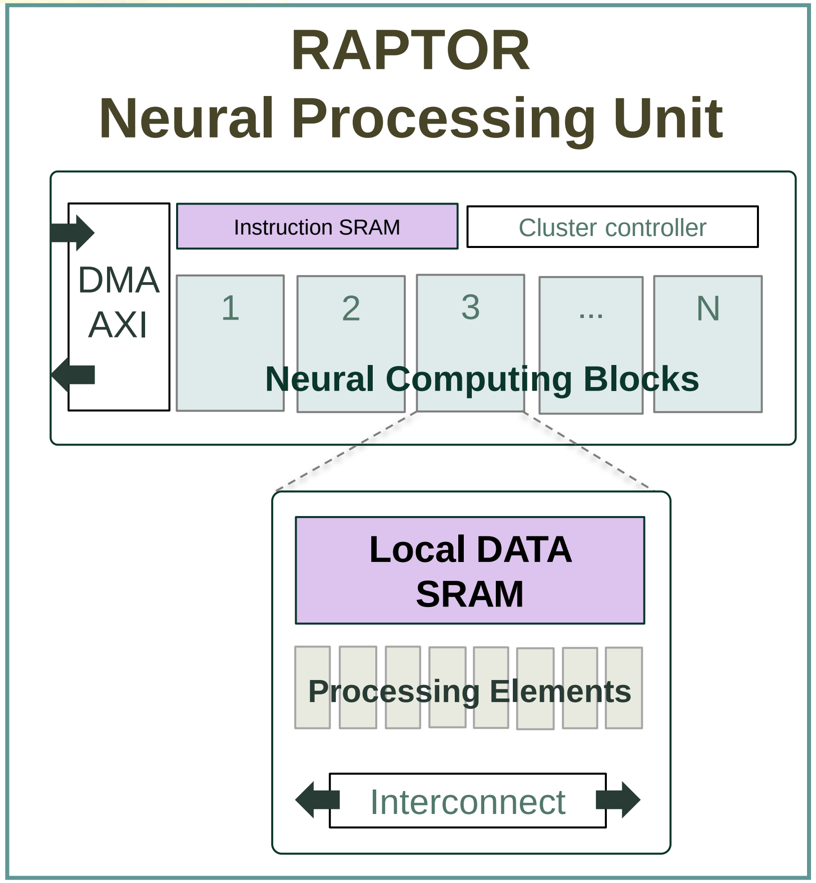
Reinventing the concept to save
energy with very low data movement

High MAC usage

RAPTOR architecture maximizes MAC
Achieving over 60% for common NN

Ease of integration

Standard AMBA interface
AXI with 64b and 32b support
APB 32b support
Low Area *(<1MGates for 128MAC/cy)*



Performance Comparison

Image classification
Using Mobilenet v1 0.25
On 128x128 RBG inputs

Per inference	Latency (Mcycles)	Energy (uJ)
RAPTOR	0.275	30
ARM A53	21.23	16131
Ratio	80x	540x

PANTHER accelerator IP
SW programmable with accelerator energy

High bandwidth TCDM

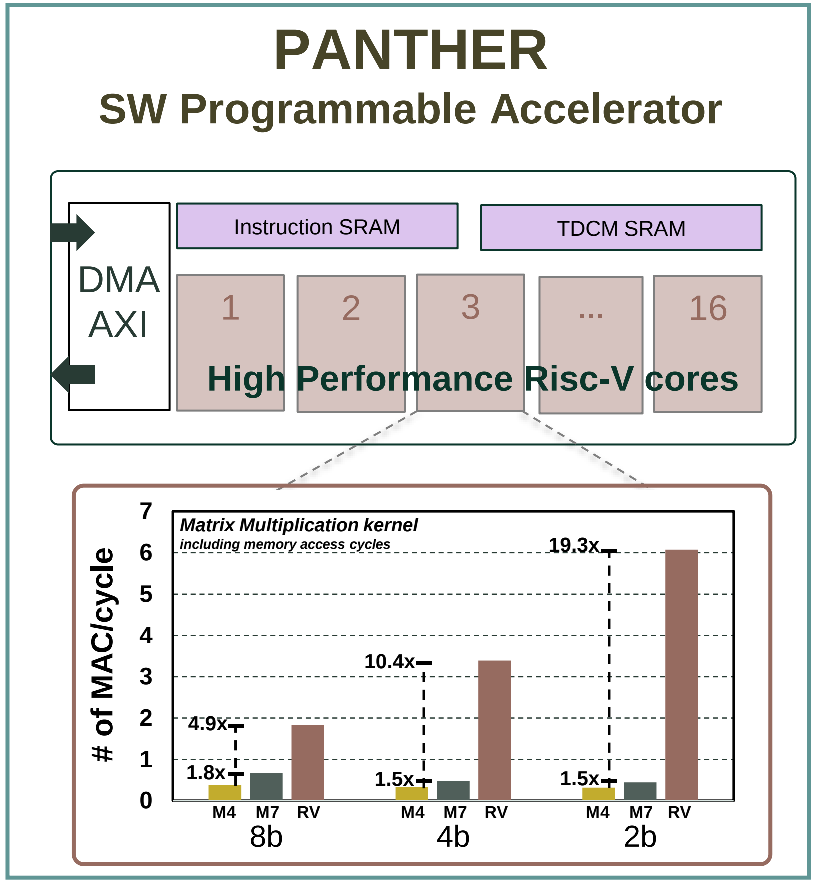
Reinventing TCDM approach with contention-free interconnect topology enabling up to 16 cores altogether

Energy Efficient MAC usage

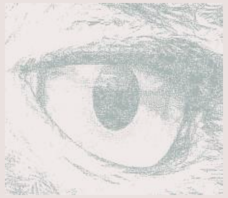
High MAC/core thanks to specialized Risc-V cores instructions
Dedicated event-based architecture for Ultra-low power results

Ease of integration/SW

Standard AMBA interface
AXI with 64b and 32b support
Program it like a single core thanks to GCC/CMSIS-like approach
Low Area *(<2MGates for 16 cores)*



Performance Comparison



Matrix Multiplication
8b integer
FDSOI technology 28-22nm

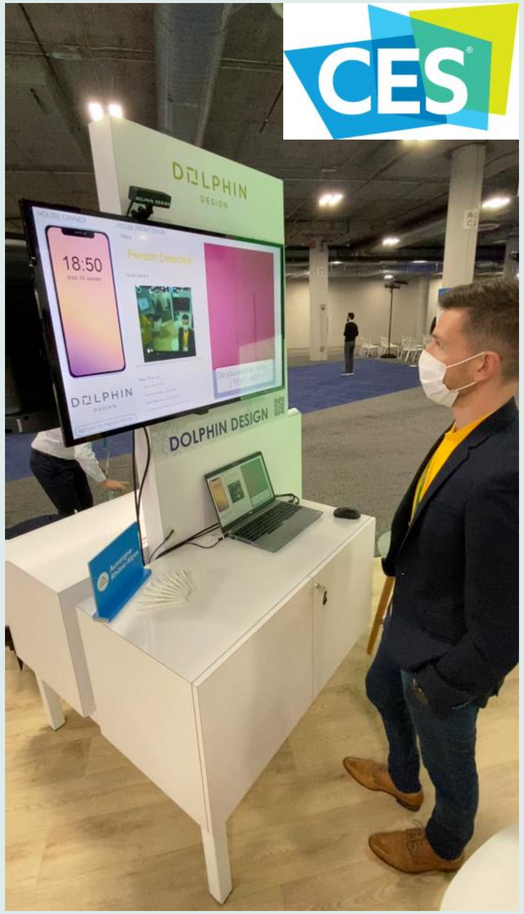
Per computation	Speed (GOPs)	Energy Efficiency (GOPs/W)
PANTHER	27	500
ARM M7	0.5	4.5
DSP	5.5	50

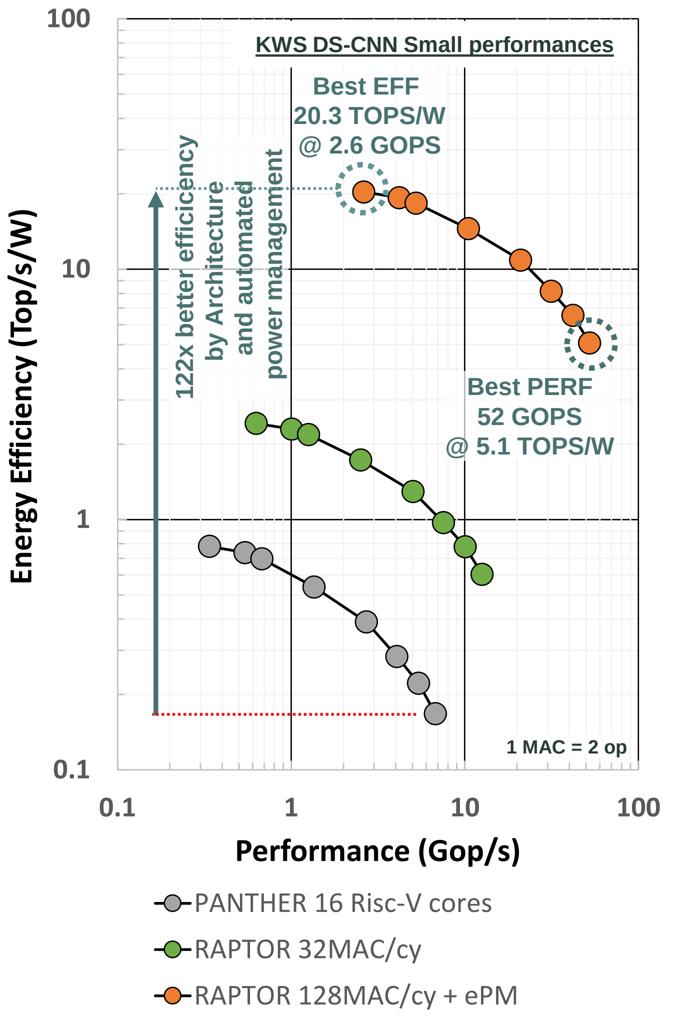
Multiple applicative demonstrations

Enabling true ambiant computing with battery lasting for months

Smart Lock

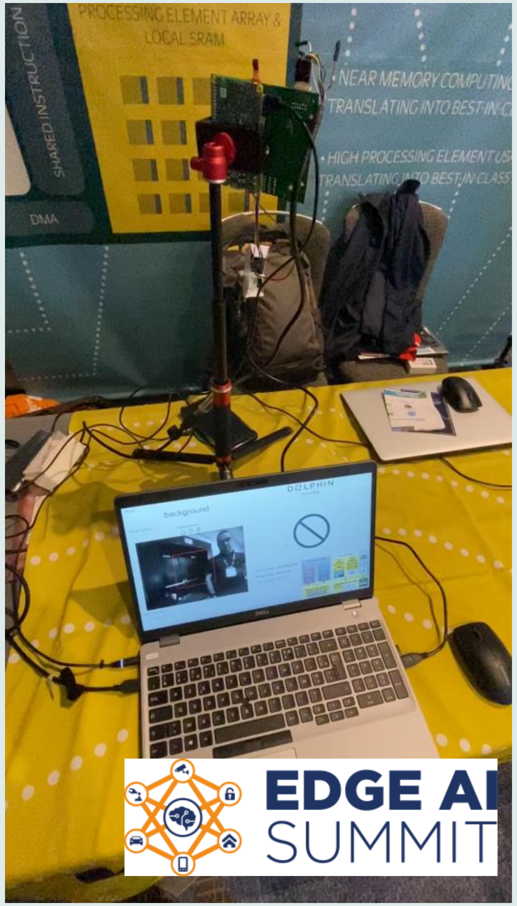
From 5 days → 6 months battery lifetime





Gesture Recognition

Sub-mW HMI based on low-res cameras



3

▶ Concluding Remarks & Look-Ahead

RF-Optics Multi-Beam Systems :
Toward Hybrid GaN -FDSOI FEMs

Concluding Remarks

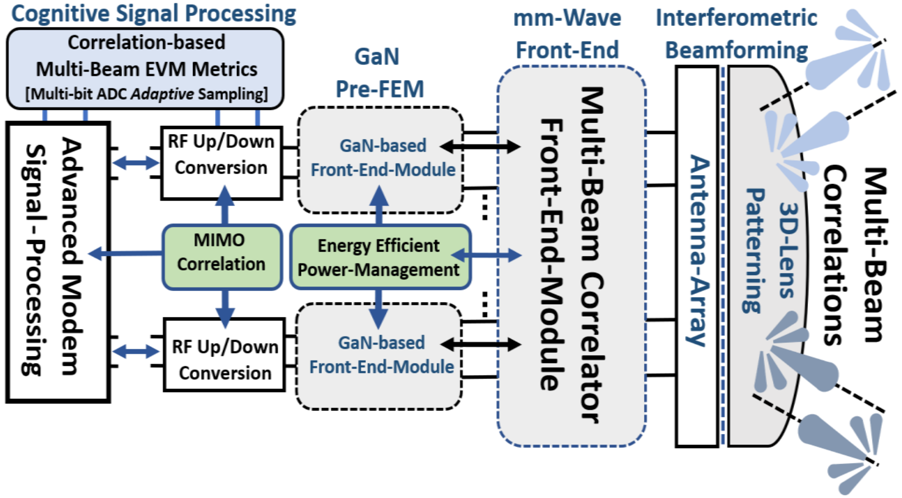
- **Hybrid GaN-FDSOI front-end-module combined with a mmWave-Correlator module and lens-based antenna-arrays:** Multi-Beam functionality with reduced complexity using scalable X-Topology Differential-Switches

  → *Lower complexity*: much fewer active electronic channels

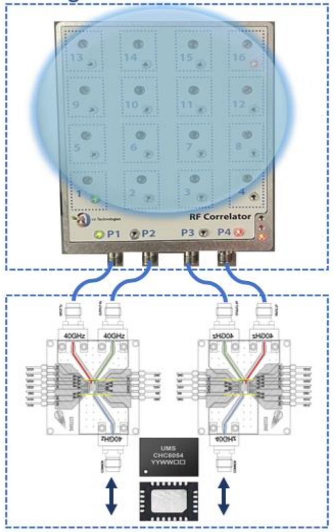
  → *Lower consumption: improvement by a factor of 10 demonstrated (vs. conventional phased-arrays)*

- **Ongoing work is relative to new DSP-based Convolutional-Accelerators for pushing Single/Multi-Beam EVM measurement to industrial-testing both in Connectorized & OTA configurations.**
- **Digital-Twin** *platforms* with DSP-based convolutional-accelerators at FPGA and ASIC levels.
- Collaboration initiated with instrumentation providers and leading academic institutions toward industrial deployment of **new standards** implementing **Correlation Technologies: e.g., IEEE P1765** [https://standards.ieee.org/ieee/1765/10560/].

Correlation Technologies
Toward Hybrid GaN-FDSOI FEMs

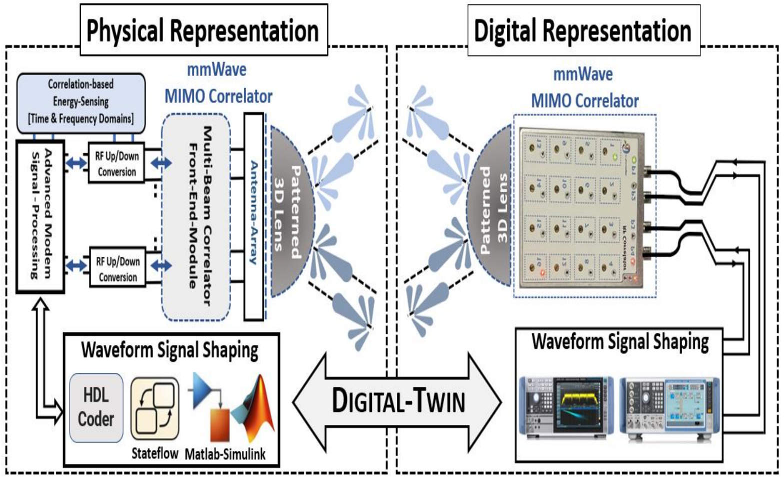


mmWave-Correlator
Co-Integrated with Patterned-Lens

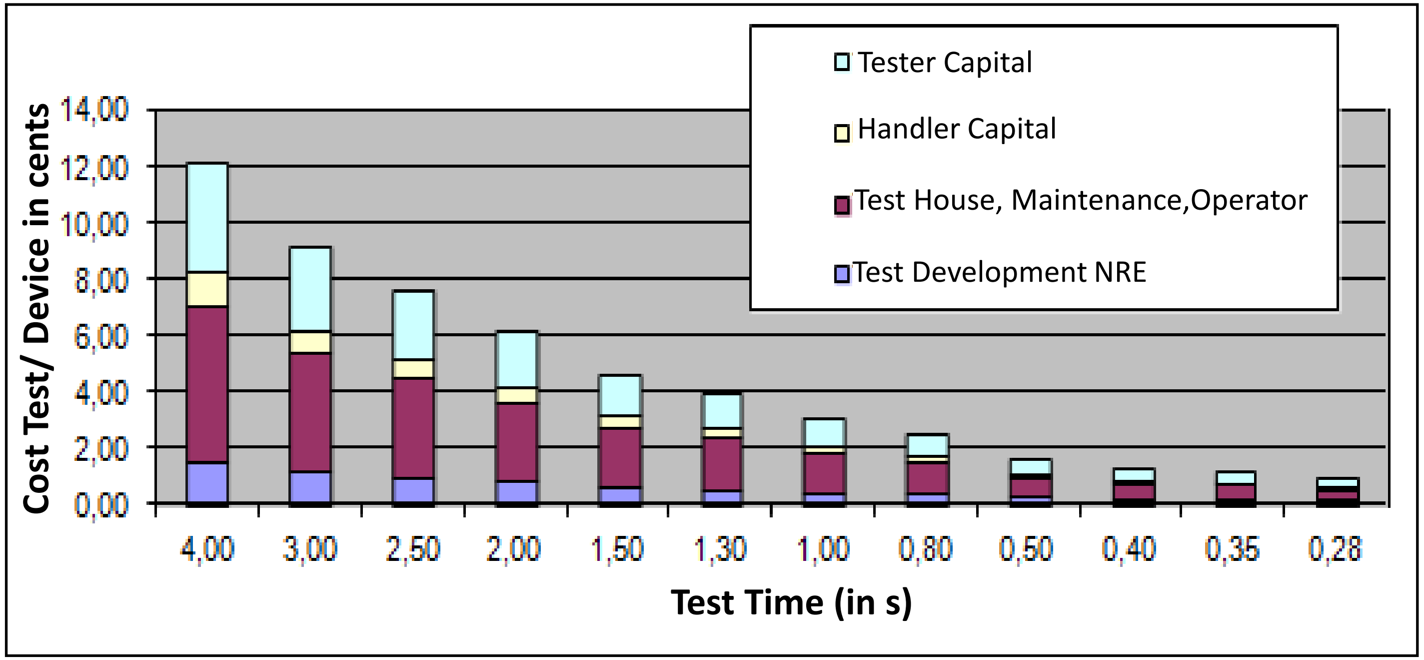


Dual-Channel GaN FEM (UMS-RF)

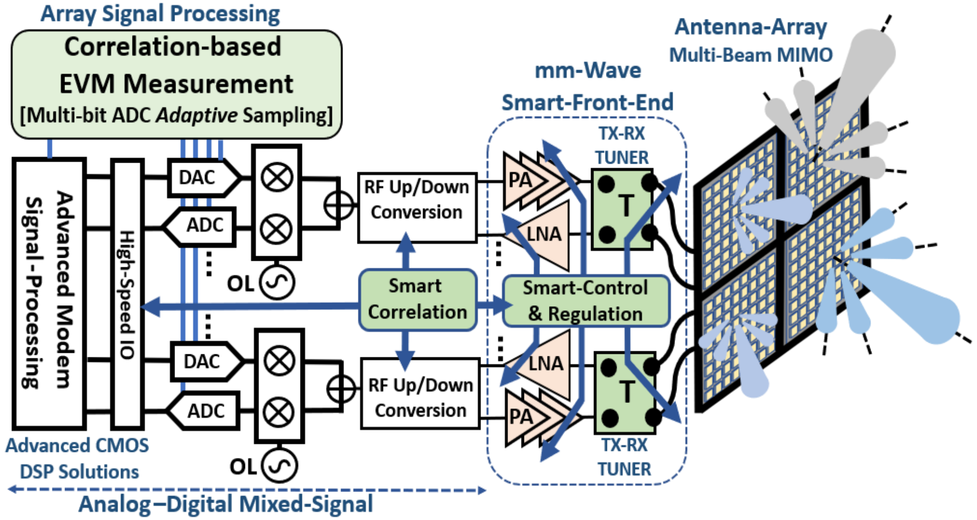
Digital-Twin Platform
for Correlation-based Multi-Beam Phased-Arrays



Need for Fast Test/Measurement



Bringing Cognition to OTA-Testing



15% to 25% of total product development cost is Test/Debug.

Main factors are:

- Test time: long test list, long test time
- Equipments cost: RF tester > 1 M$
- Operator and maintenance: qualification

We introduce ***Correlation Technologies*** both at RF/mmWave and Base-Band frequencies for **OTA testing of mobile devices** and systems. The originality of the proposed solutions resides in the following attributes:

- *At RF and mmWave frequencies*, **energy and power-density based metrics** are used for near-field and far-field sensing.
- *At Base-Band frequencies*, new ***DSP-based Convolutional-Accelerators*** are proposed for pushing **EVM measurement** solutions to industrial-testing both in connectorized and OTA configurations.
- ***ASIC-embedded Smart-Connectors*** are proposed for co-design and co-integration of adaptive Front-End-Modules with *Antenna-in-Package* (AiP) modules.

Smart RF & mmWave Test Solutions as enabler for Products Verification & Qualification

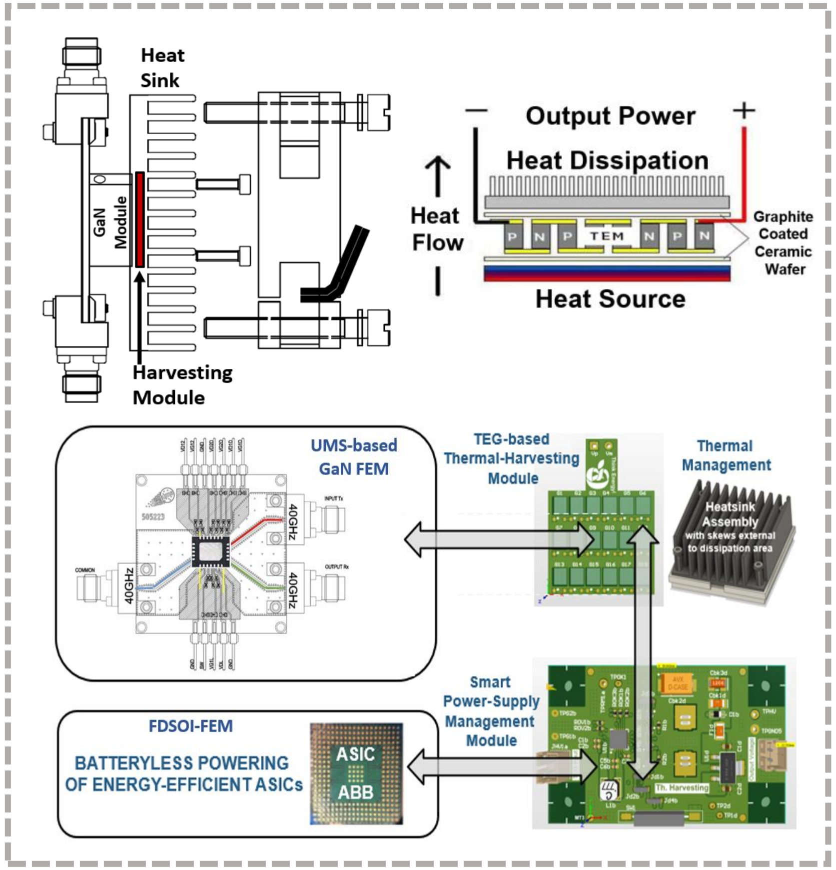
Need for FAST OTA-based Industrial Test

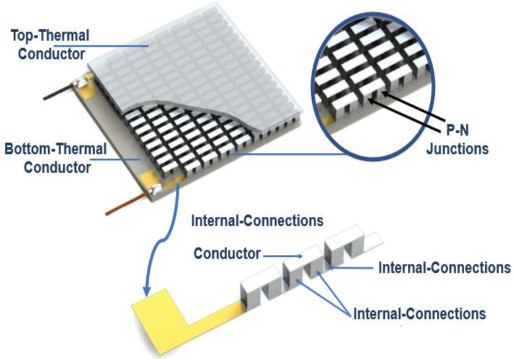
Ongoing Work & Look-Ahead

Perspectives for Multi-Physics Correlation Technologies:

- *Improved Efficiency using Energy-Harvesting Solutions*
- *Toward 3D Chip-Package-PCB-Radiator-Lens FEM Co-Design & Co-Integration*

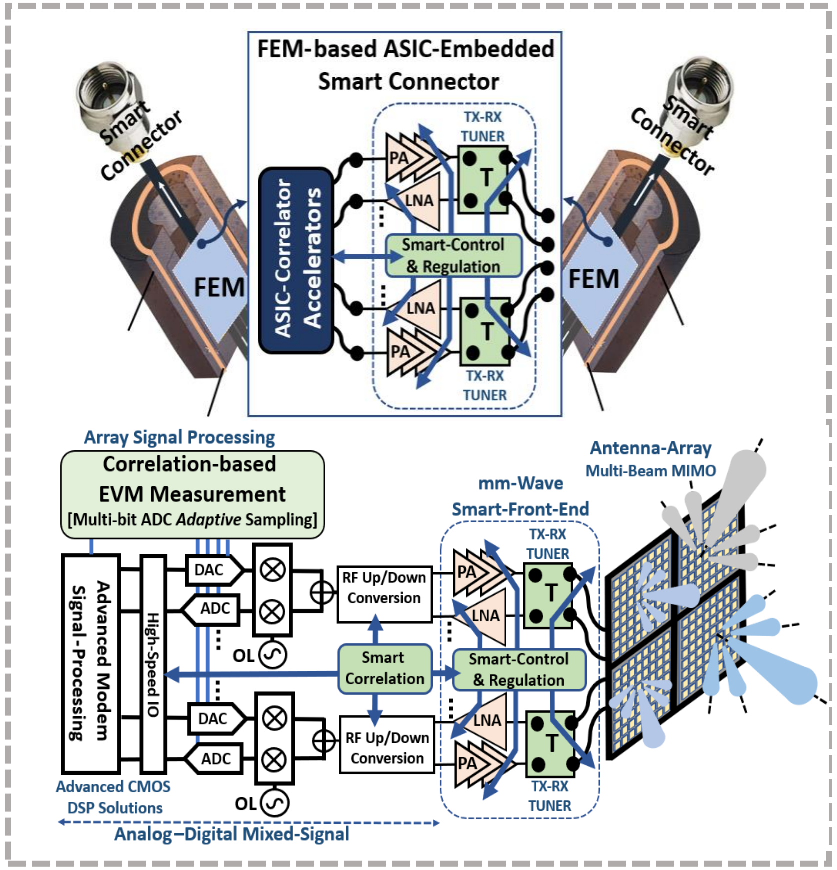
Thermal-EM Harvesting
Toward Hybrid GaN-FDSOI FEMs





Chip-Package-PCB-Radiator-Lens FEM Co-Design & Co-Integration

Smart-Connectors
with embedded Front-End-Modules



Acknowledgment

The authors thank THALES R&T and EURECOM teams for fruitful collaboration in the context of EEMW4FIX project.

Many thanks to Rohde & Schwarz for the accessibility of CATR platform and for the collaboration on EVM measurement.

The authors are very grateful to Dr. Benoît Derat for fruitful collaboration with Rohde & Schwarz teams in Munich.

Backup Slides in Case of Questions

RF/mmWave Correlator Front-End Modules

Front-End-Module-Antenna Co-Design & Co-Integration

We introduce ***Correlation Technologies*** both at RF/mmWave and Base-Band frequencies for **OTA testing of mobile devices** and systems. The originality of the proposed solutions resides in the following attributes:

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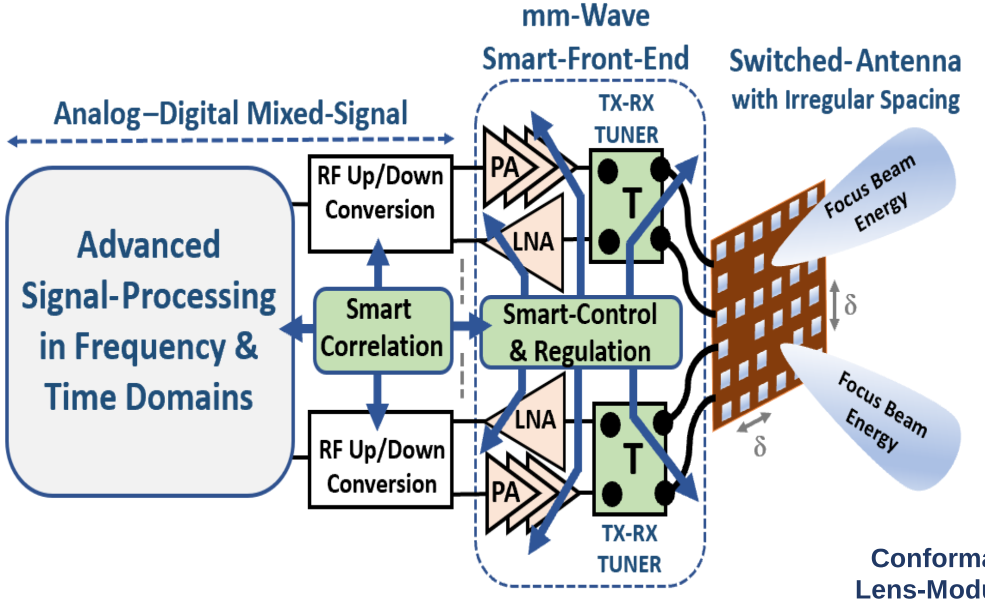
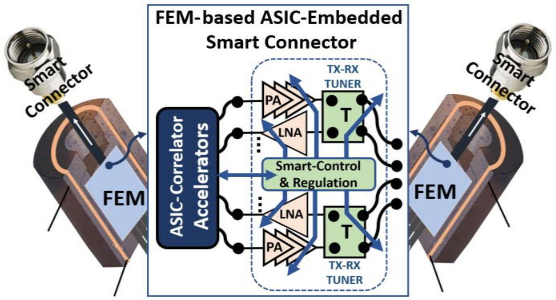
- *At Base-Band frequencies*, new ***DSP-based Convolutional-Accelerators*** are proposed for pushing **EVM measurement** solutions to industrial-testing both in connectorized and OTA configurations.
- ***ASIC-embedded Smart-Connectors*** are proposed for co-design and co-integration of adaptive Front-End-Modules with *Antenna-in-Package* (AiP) modules.

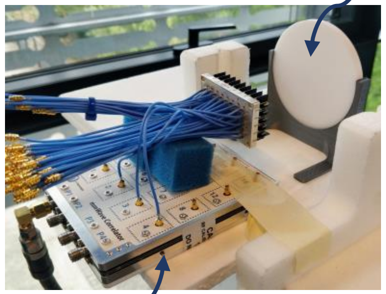
Correlation Technologies as an enabler of OTA Testing of Stochastic Signals which are intrinsically noisy, multi-harmonic and non-stationary

Chip-Package-PCB+Antenna-Tuners Co-Design





Conformal
Lens-Module



Correlator
Beamforming Module

Unified Correlation Technologies at RF/mmWave & Base-Band

ASIC-based Correlators with Embedded Cognition

Correlation Technologies & Applications

ASIC-based Correlators with Embedded Cognition

Proposed **Correlation Technologies** enable efficient combination of Information-Signal Theory (IT) & Physical Information Theory (PT) into a unified approach: **Shannon's entropy** can be directly related to **Boltzmann's entropy** for *assessing the quality of RF wireless systems: e.g., SNR, EVM, Channel-Capacity, can be accurately extracted.*

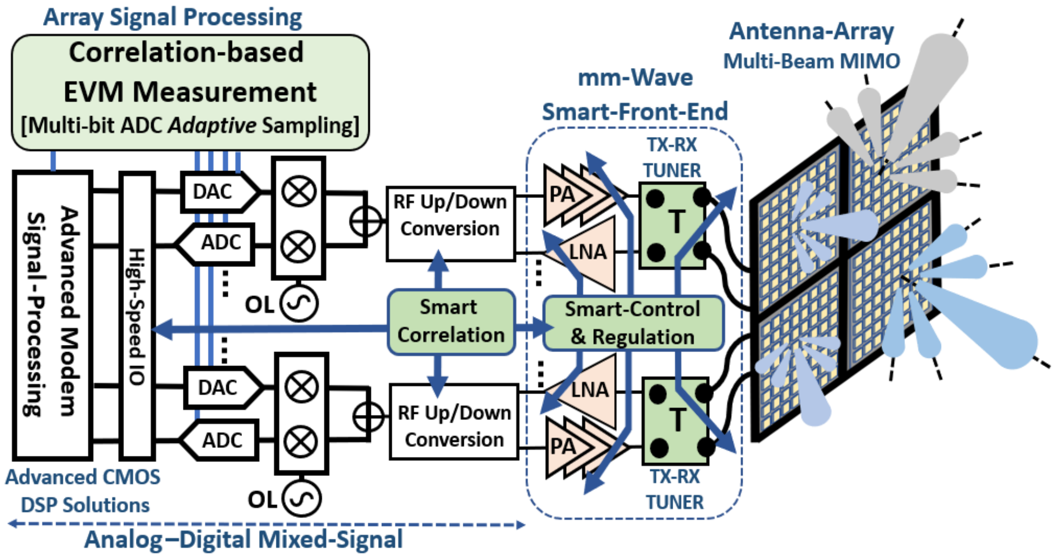
Correlation Matrix $\mathbf{R_X} = \mathbf{E[XX^H]}$

Channel Transfer Matrix

$$\mathbf{I(X,Y) = \log_2 \det\left[I + \frac{1}{\sigma_v^2} H R_v^{-1} H^H R_X\right]}$$

Related to Differential Entropy (<u>Maximisation</u>)

Correlation Matrix $\mathbf{R_v} = \frac{1}{\sigma_v^2}\mathbf{E[vv^H]}$



The Shannon–McMillan–Breiman theorem [1] provides a formal basis for such unified approach where Shannon's entropy can be directly related to Boltzmann's entropy for accurate extraction of key parameters characterizing the quality of RF wireless systems such as SNR, channel capacity, data rate and correlation between antennas in MIMO applications.

Bringing Cognition to OTA-Testing

<u>Unifying Information-Signal Theory (IT) & Physical Information Theory (PT)</u>

[1] A. Lesne, "***Shannon entropy: a rigorous notion at the crossroads between probability, information theory, dynamical systems and statistical physics***". Mathematical Structures in Computer Science 24(3) (2014).

[2] G. Gradoni, V. M. Primiani, F. Moglie, "***Reverberation Chamber as a Statistical Relaxation Process: Entropy Analysis and Fast Time Domain Simulations***", International Symposium on Electromagnetic Compatibility - EMC Europe 2012.

<u>Unifying Measurement & Modeling</u>

[3] B. Derat, et al. "**Toward Augmented OTA Testing: Bringing Full-Wave Numerical Modeling and Antenna Measurements Together**", Microwave Journal, Jan.2021.

[4] S. Wane, R. Patton, and N. Gross, "**Unification of instrumentation and EDA tooling platforms for enabling smart chip-package-PCB-probe arrays co-design solutions using advanced RFIC technologies,**" in IEEE Conf. on Ant. Measurements Applications, Sept 2018, pp. 1–4.

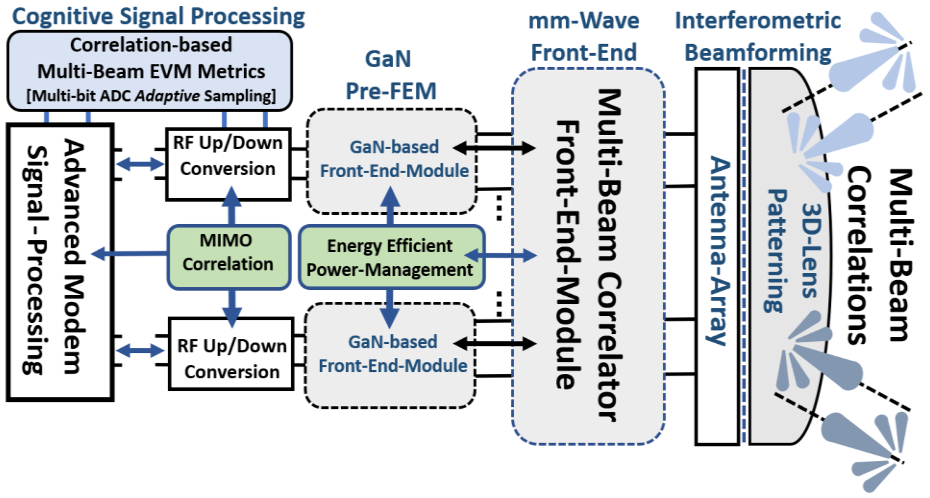
Business & Technology Motivation

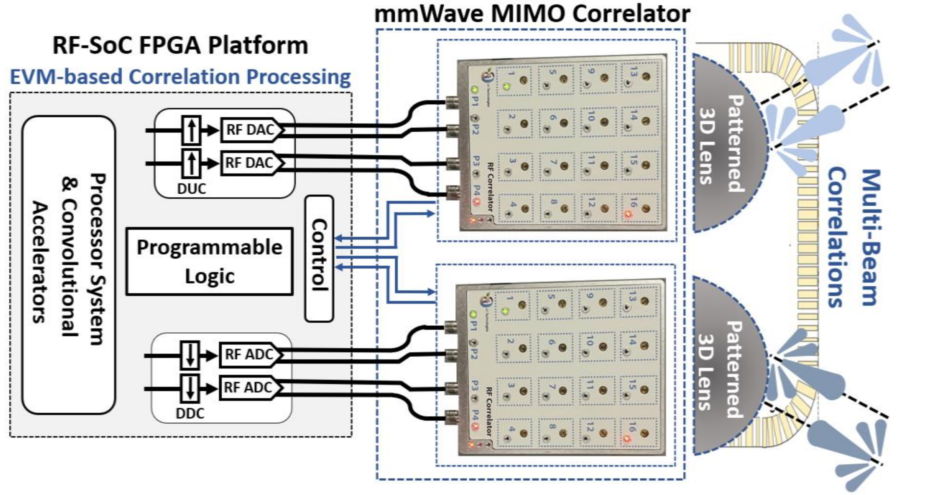
We introduce ***Correlation Technologies*** both at RF/mmWave and Base-Band frequencies for ***building Energy-Efficient Multi-Beam Phased-Array Systems***. The originality of the proposed solutions resides in the following attributes:

- *At mmWave frequencies: angle-dependent energy-density focusing capability of optical lenses*, low-consumption and low complexity beamformer front-end-module using RF-Correlators.

- *Lattice-based balanced and unbalanced switching architectures* for multi-beamforming front-end-modules: fully-differential multi-port scalable switches (in FDSOI Technologies).

- ***Correlation-based EVM metrics***, for single-beam and multi-beam systems, **compliant with ASIC and FPGA implementation**, using **advanced convolutional accelerators**.





Energy-Efficient Multi-Beam Systems Using Correlation Technologies:
Toward Hybrid GaN -FDSOI FEMs

Statistical Field-Field Auto and Cross-Correlations for MIMO Systems

The proposed concept of X-Correlation processing relies on simultaneously probing the EM Fields with the Twin Antenna Probe éléments (Channels A and B):

$$\mathbf{C}_{AB}(\tau) = \langle S_A(t) | S_B(t+\tau) \rangle = \lim_{T\to} \frac{1}{2T} \int_{-T/2}^{+T/2} S_A(t)\, S_B(t+\tau)\, dt$$

Assuming signals and noise contributions are uncorrelated, by applying the Expectation operator E[.], the following relations can be derived:

$$\mathbf{E}\left[(S_A + N_A)\overline{(S_A + N_B)}\right] = \mathbf{E}\left[|S_A|^2\right] + \mathbf{E}[S_A \overline{N_B}] + \mathbf{E}[N_A \overline{S_A}] + \mathbf{E}[N_A \overline{N_B}] = P_{S_A} + P_{Noise}$$

$$\mathbf{C}(\mathbf{t}) = \begin{pmatrix} \mathbf{C}_{11}(\mathbf{t}) & \mathbf{C}_{12}(\mathbf{t}) & \dots & \mathbf{C}_{1N}(\mathbf{t}) \\ \mathbf{C}_{21}(\mathbf{t}) & \mathbf{C}_{22}(\mathbf{t}) & \dots & \mathbf{C}_{2N}(\mathbf{t}) \\ \vdots & \vdots & \dots & \vdots \\ \mathbf{C}_{N1}(\mathbf{t}) & \mathbf{C}_{N2}(\mathbf{t}) & \dots & \mathbf{C}_{NN}(\mathbf{t}) \end{pmatrix}$$

The correlation matrix in the frequency domain can be expressed as a function of the time-windowed signal $S_T(t)$:

$$\mathbf{C}(\boldsymbol{\omega}) = \mathcal{F}\left\{\left\langle S_T(t) \middle| S_T^{\dagger}(t+\tau)\right\rangle\right\}$$

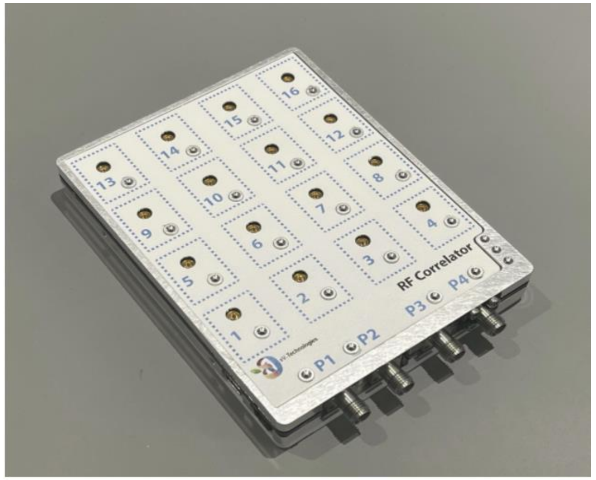
The superscript † refers to Hermitian conjugate operation.

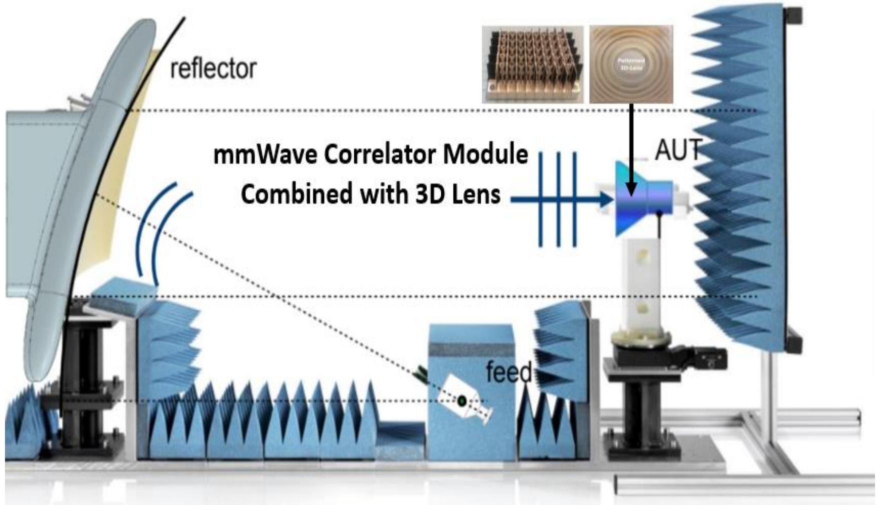
Field-Field Correlation Functions (FF-CF), in revealing unified information about the signals to which they refer and the space through which the radiation has propagated, provide solid foundations for bridging modeling and measurement into a consistently complementary framework. The extracted cross-correlation can be linked to the general theory of coherence [1-3].

- [1] B. Fourestie, J.-C. Bolomey, et al., “Spherical Near Field Facility for Characterizing Random Emissions”, IEEE Trans. On Ant. and Prop., Vol. 53, no. 8, pp. 2582-2588, August 2005.
- [2] E. Wolf, “New theory of partial coherence in the space–frequency domain. Part I: spectra and cross spectra of steady-state sources”, J. Opt. Soc. Am. 72, 343–351 (1982).
- [3] S. Wane, et al., “Correlation Technologies for Emerging Wireless Applications”. Electronics 2022, 11, 1134. https://doi.org/10.3390/ electronics11071134.

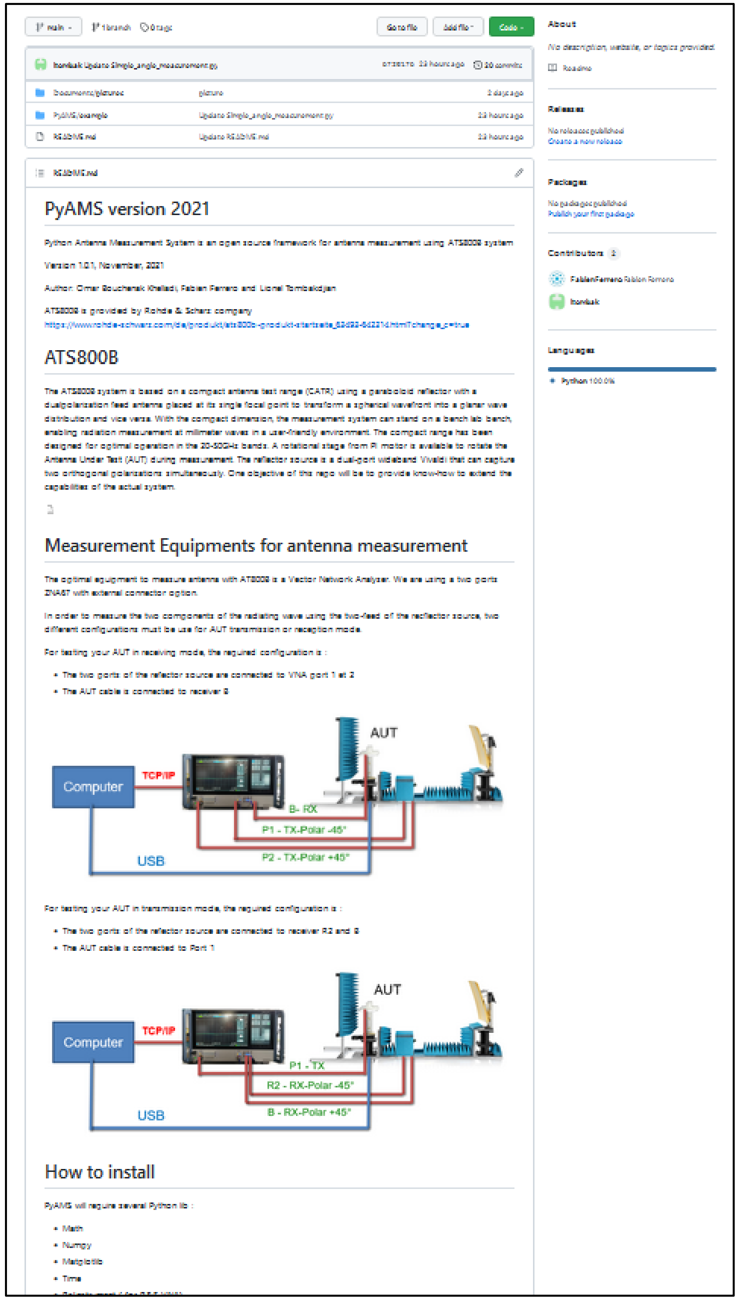
Python Library

- https://github.com/FabienFerrero/PyAMS
- Comprehensive control of rotational stage, instruments and DUT on a single platform
- Generic instrumentation framework



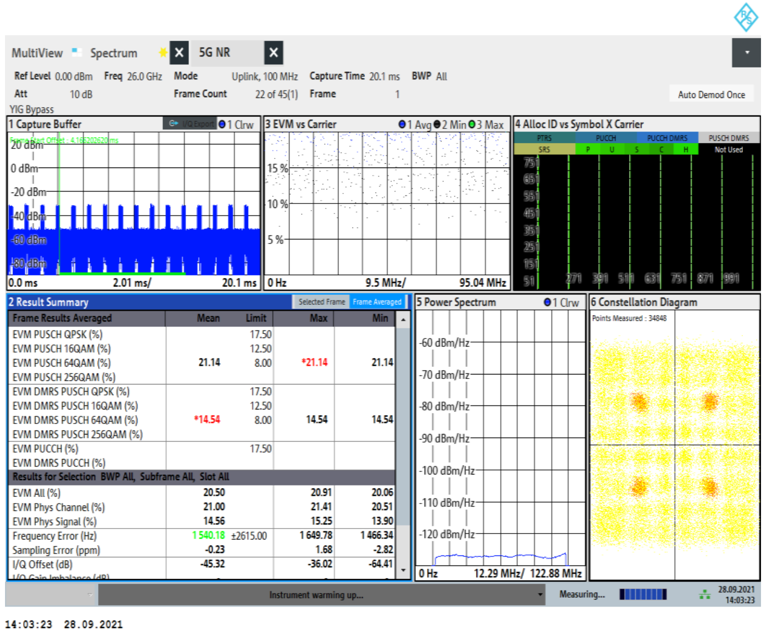


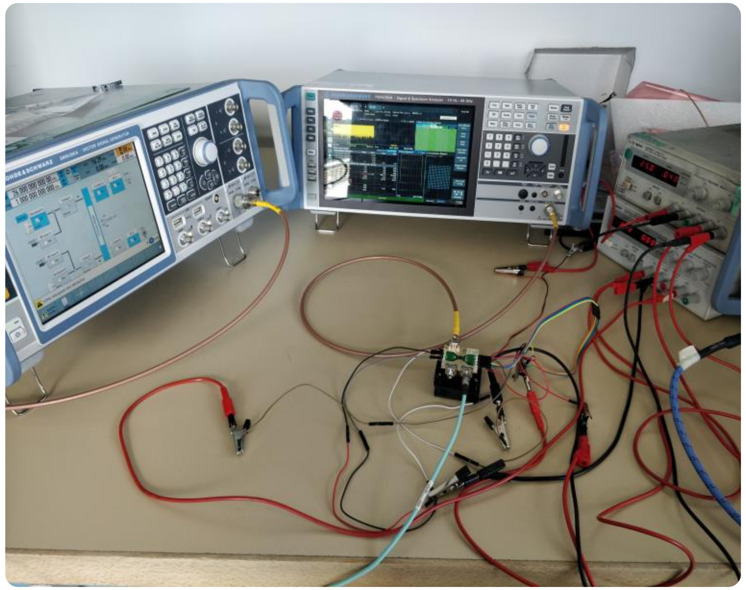
- https://github.com/eV-Technologies-Github/EVT3016_1016
- https://github.com/eV-Technologies-Github/FEM



Test & Characterization Platform

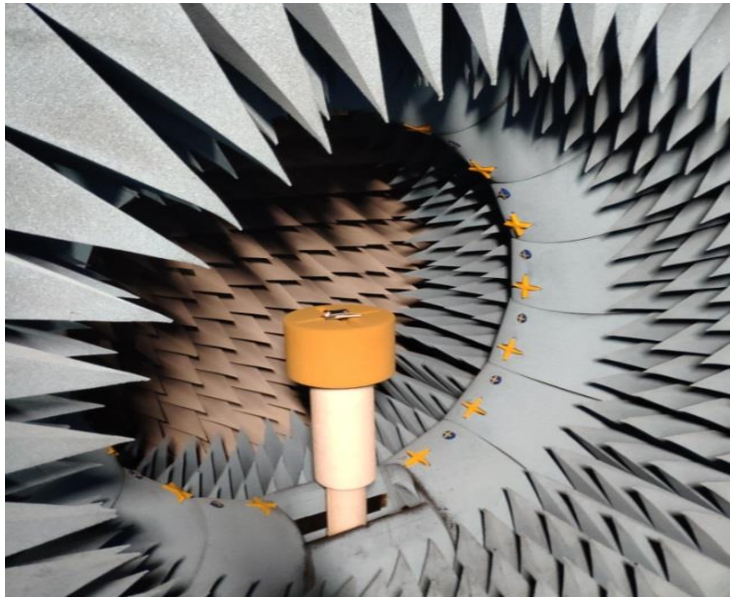
- Versatile solution to conduct prototype measurement and optimization
- Integration of various instruments and equipment is facilitated
- Ongoing work on measurement of Active metrics : EVM, TRP, TIS





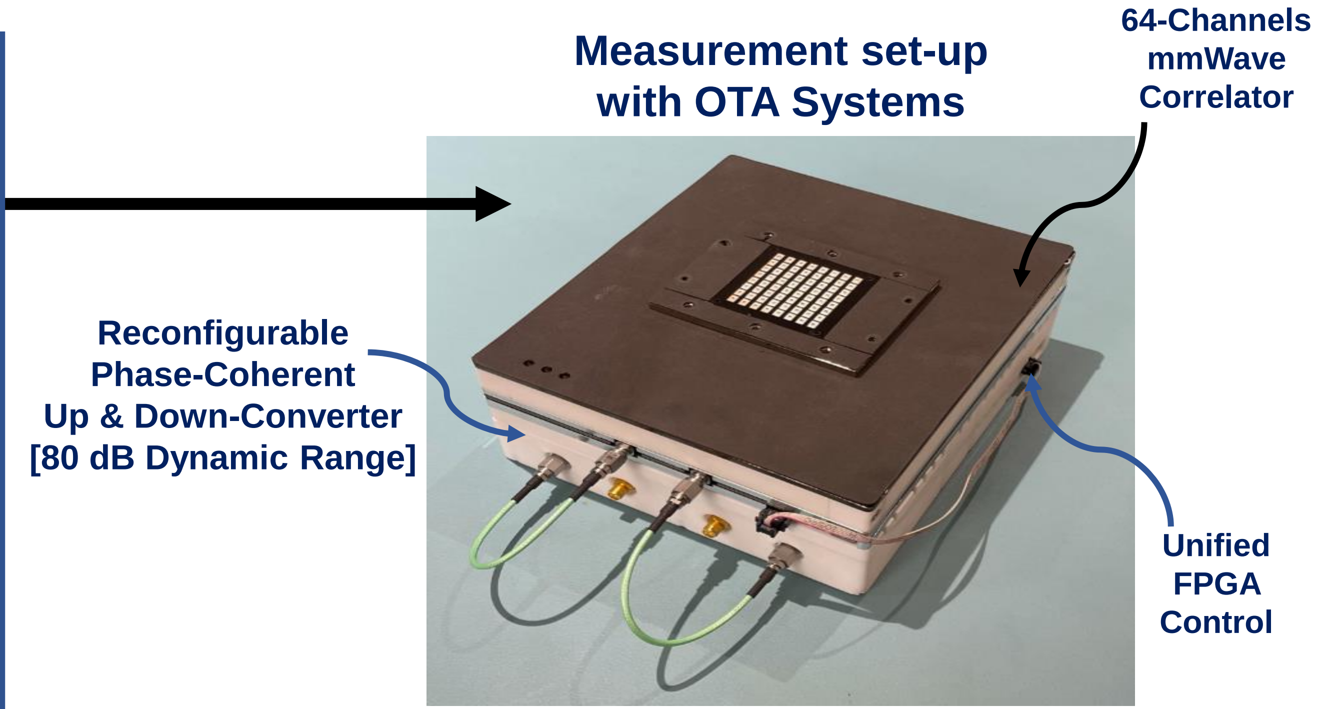
Measurement Facilities at mmWave

- Microwave measurement facilities for antenna assessments
  - S-parameter measurements up to 260 GHz
  - Anechoic chamber for radiation measurements from 600MHz to 260GHz
  - 3D Near-Field/Far Field scanner for active integrated antenna measurements



Calibration Solutions for Antenna/Probe Arrays

Use of Rohde & Schwarz CATR System



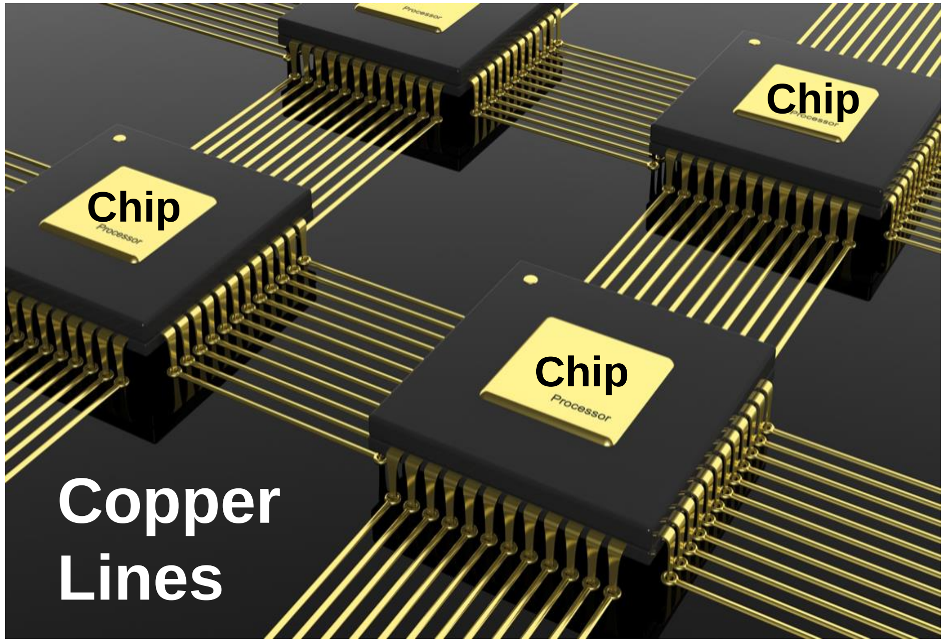
- Use a top level software application to setup the switch matrix to the setting that you want.
- Send a command over USB to the matrix to action the setting of which port goes to which output port. The module receives the command, forwards it to the switch and then send back an acknowledgment when the operation is complete. The acknowledgement is then forwarded back to the USB.
- When the computer receives the Ack character it knowns the switch action has been completed and a read of IF data can be triggered.
- The cycle can then be repeated around the switch states.

RF/Optics Chip-to-Chip Communication

Chip-to-Chip Communication

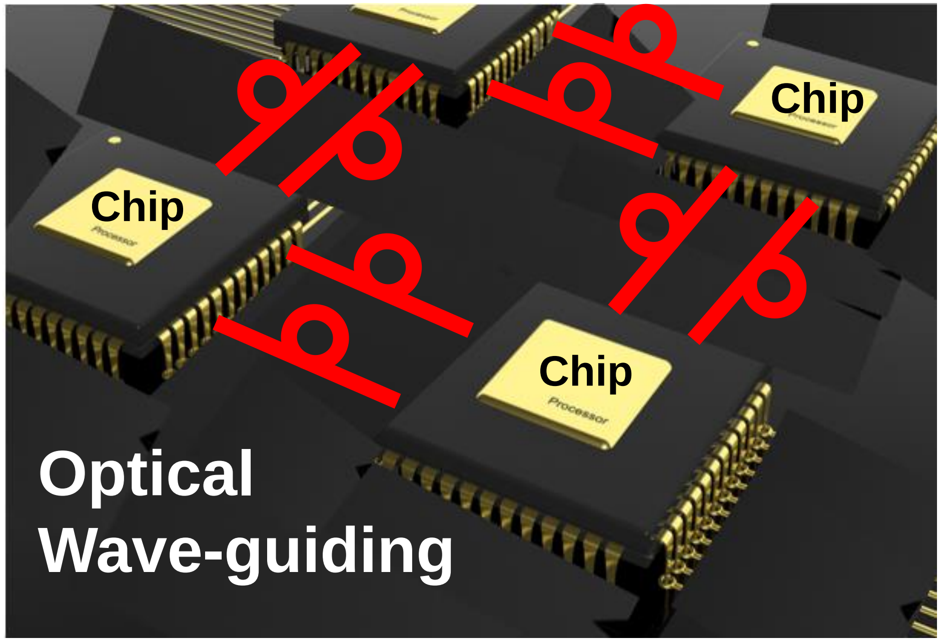
Dielectric Interconnects: Solution to the Copper Bottleneck

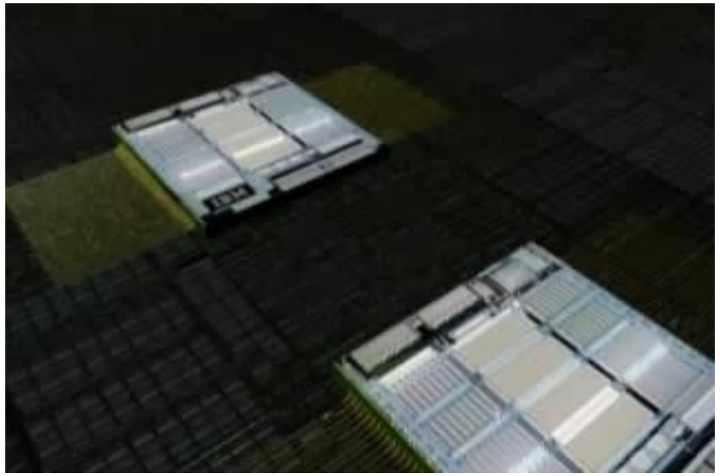
ELECTRICAL



- Copper losses
- Mutual/Proximity Couplings
- Datarate/Bandwidth

OPTICAL

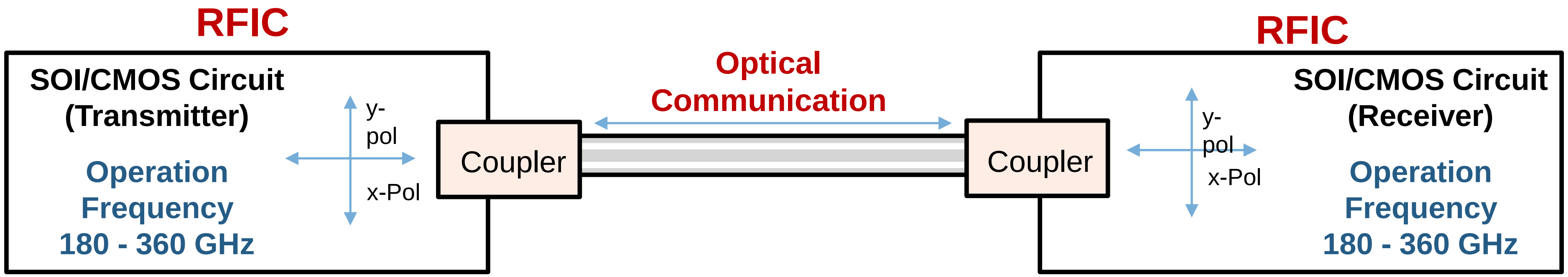




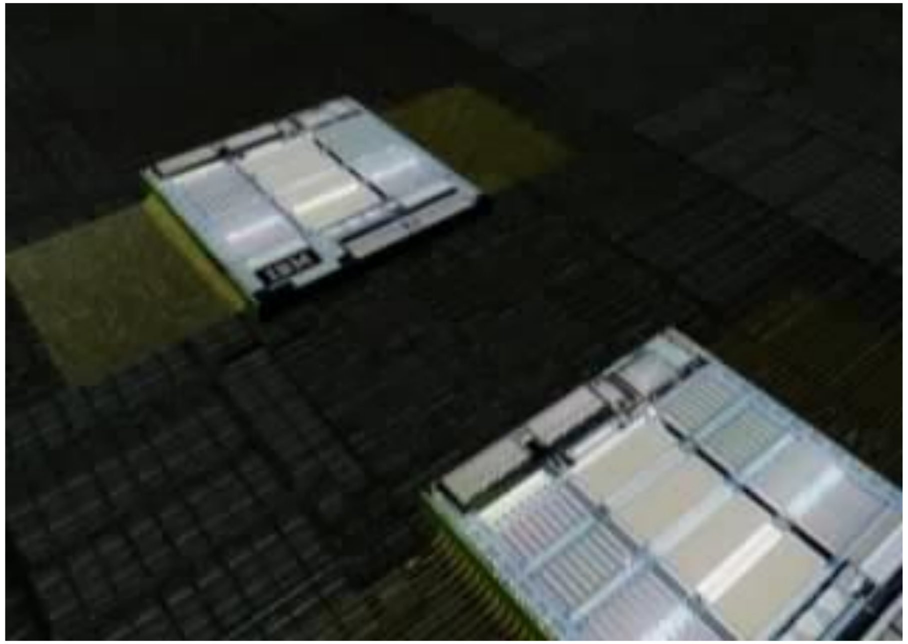
Complementary NEMF21 Near-Field Wireless C2C.

Chip-to-Chip Communication

Dielectric Interconnects



- **Full-Wave approach**
- **Multi-Physics**
- **Holistic Approach**

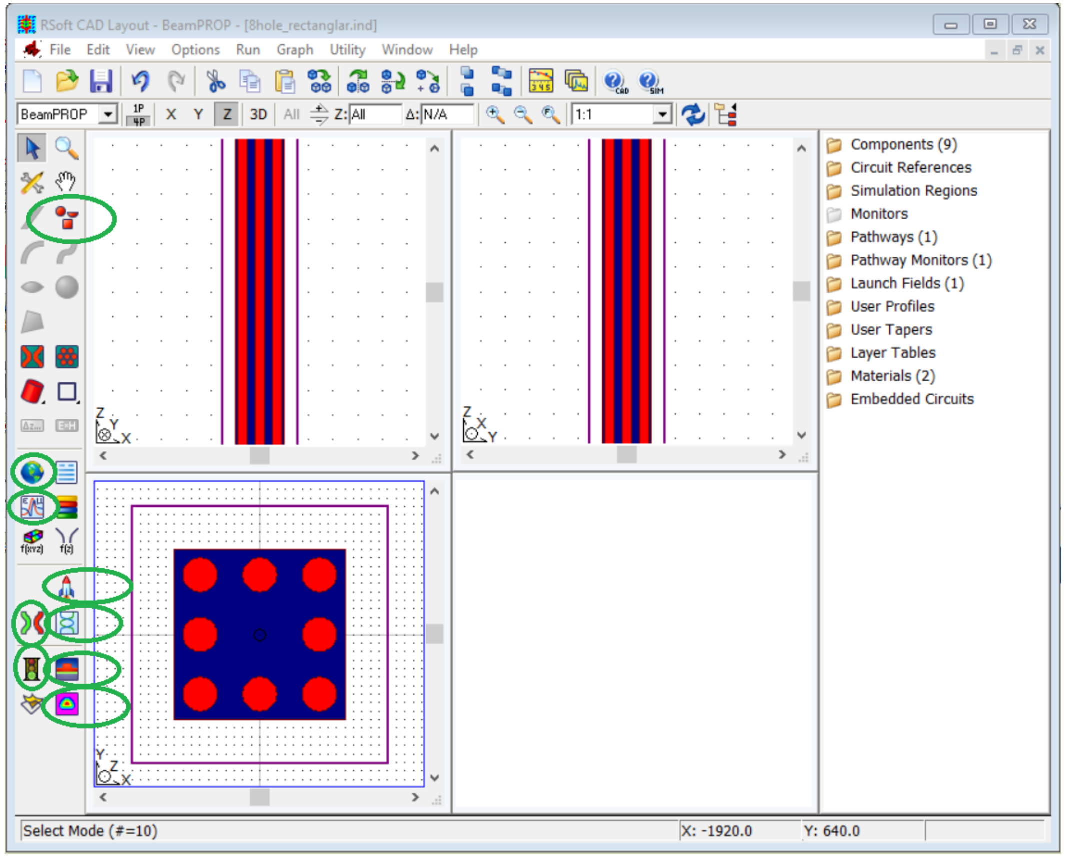


RFIC-Optics Wave-Particle Co-Design

Chip-to-Chip Communication

Dielectric Waveguiding Design

- **Holey cladding**
  - Lower loss compared to fiber core doping
  - Ease of fabrication
  - Small number of holes results in higher fabrication yield
- **Square cross section**
  - Square geometry is more resistant to polarization mode coupling between H and V which duplex the channel capacity with minimal cross-talk
  - Square geometry shows good mode confinement under breaks in symmetry
  - Maximum packing density for ribbon fiber
- **Waveguide Size**
  - Single mode across 180 GHz to 360 GHz



Chip-to-Chip Communication

Waveguide Materials | Low Loss Candidates

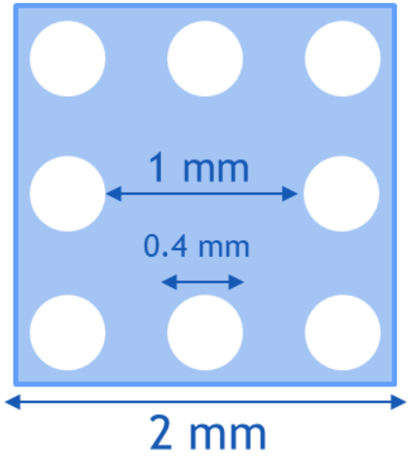
Material	*n*	Material Loss* [dB/cm]			
		200 GHz	300 GHz	500 GHz	1000 GHz
TOPAS	1.53	0.19	0.24	0.4	1.5
H-Polypropylene (h-PP)	1.53	0.26	0.35	0.39	1.43
Co-Polypropylene (c-PP)	1.50	0.10	0.17	0.26	0.74
Polyethylene (PE)	1.51	0.22	0.30	0.65	1.74
Teflon (PTFE)	1.43	0.07	0.1	0.4	2.17
PMMA	1.5	4.3	8.6	25	87
Polycarbonate (PC)	1.63	4.3	8.7	13	43
Fused Silica	1.45	0.1	0.2	0.3	1.5
Quartz	1.45	0.05	0.06	0.07	0.35

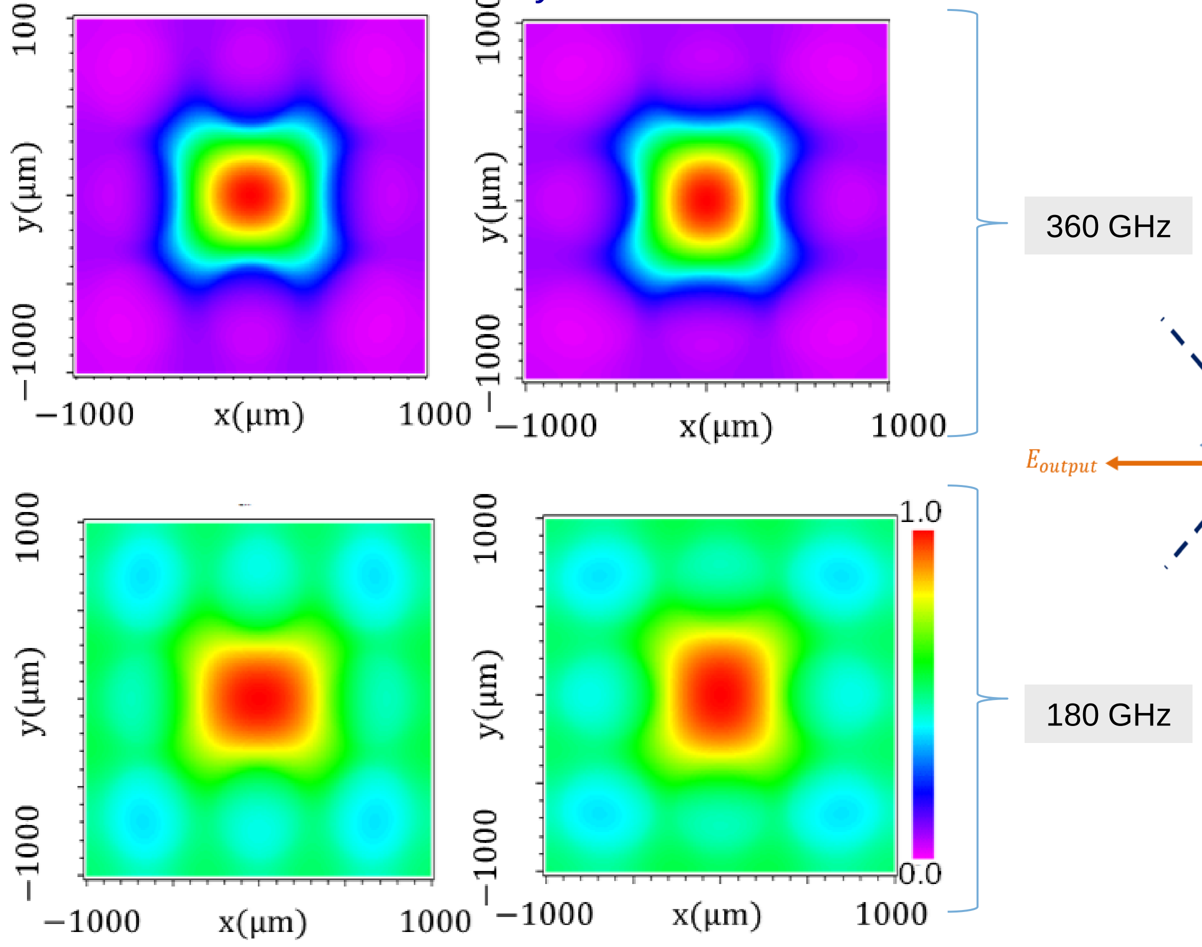
*Values depend on manufacturer and measurement method

Chip-to-Chip Communication

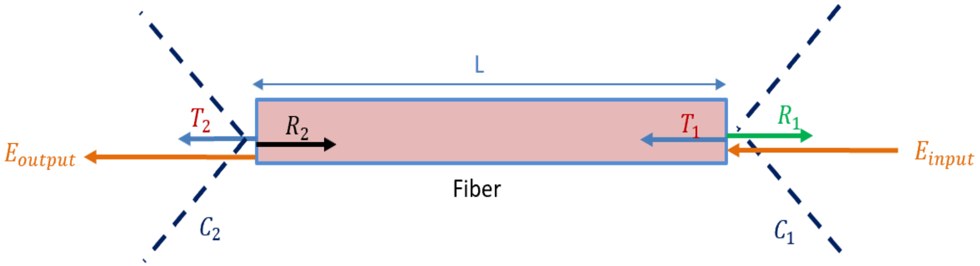
Energy Confinement

Selected Design





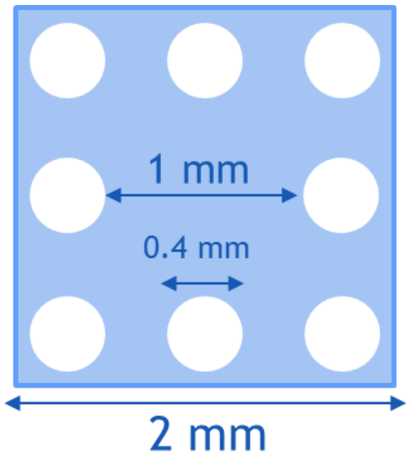
Cross sectional views



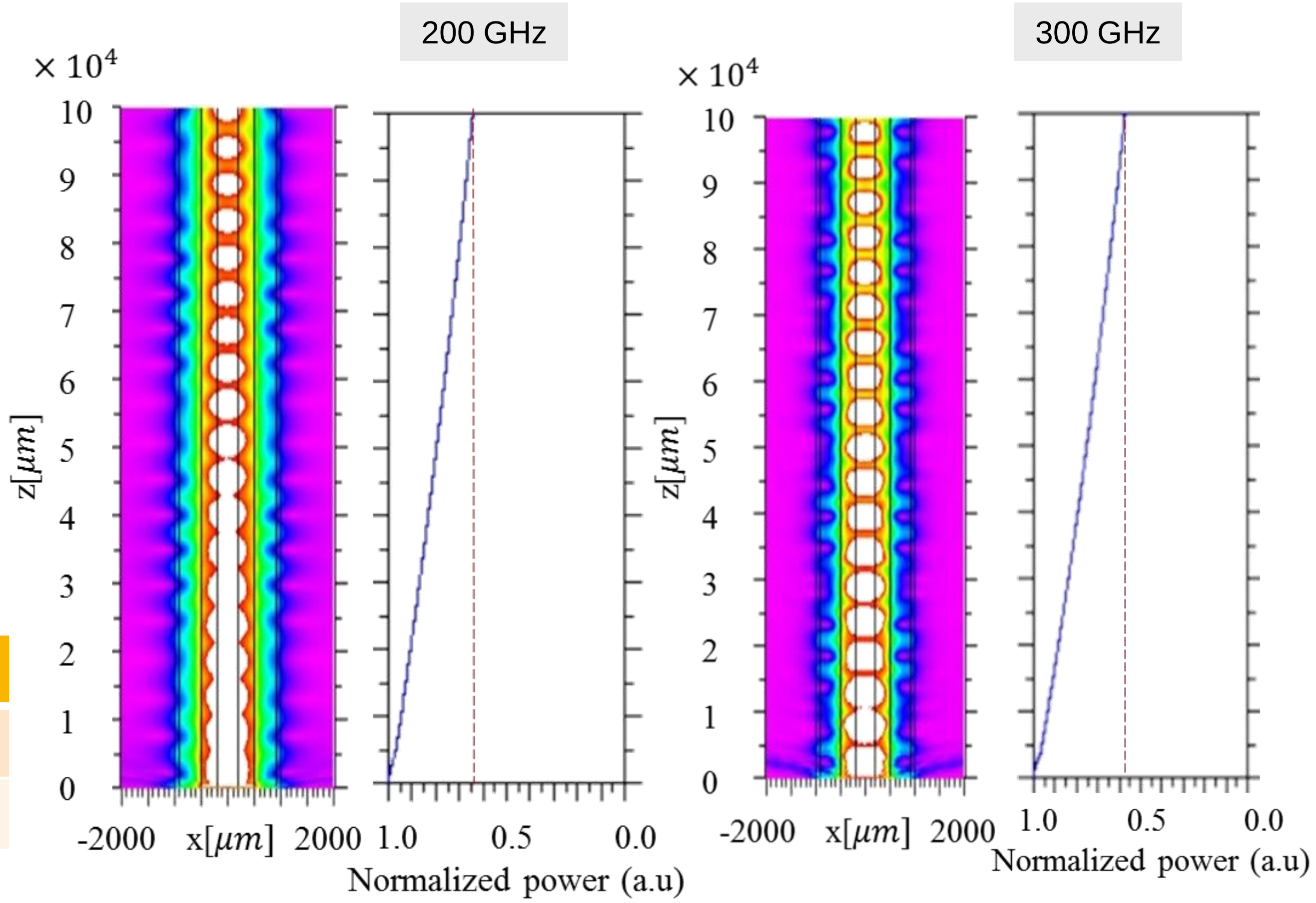
Chip-to-Chip Communication

Longitudinal Loss

Selected Design



TOPAS material loss	
0.2 THz	0.3 THz
0.19	0.24



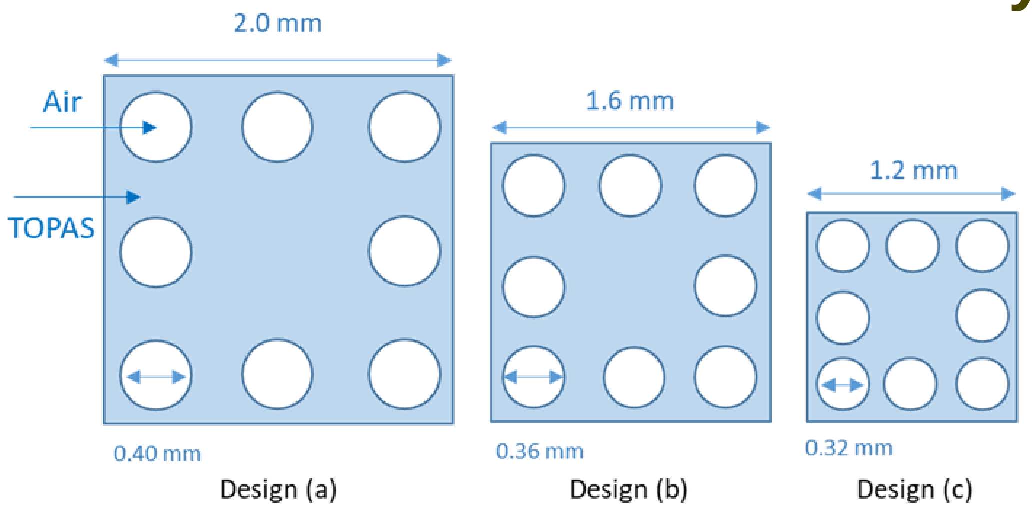
Fiber loss: 0.19 dB/cm

Fiber loss: 0.25 dB/cm

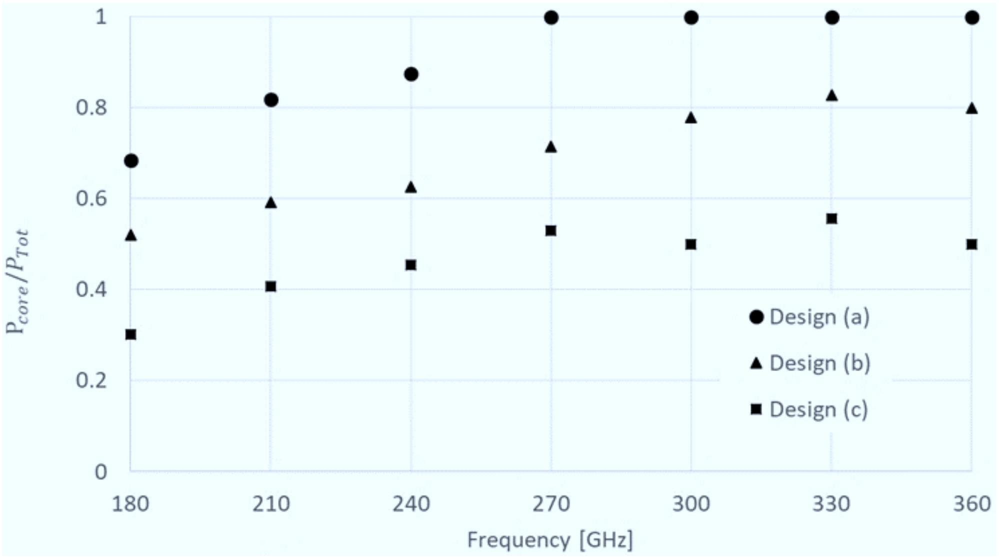
Side View

Chip-to-Chip Communication

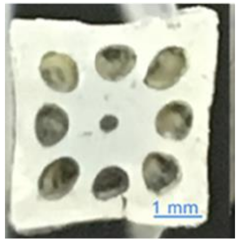
Geometry Dimensioning

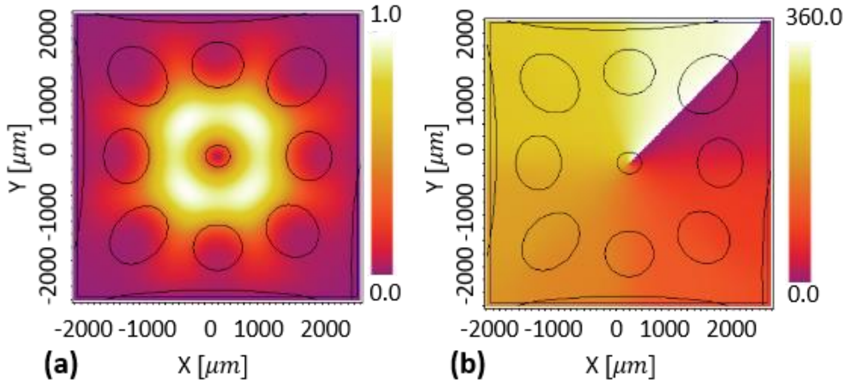


	Single Mode Frequency Range [GHz]
Design (a)	-
Design (b)	180 -190
Design (c)	180-220



Core-confinement of the three designs



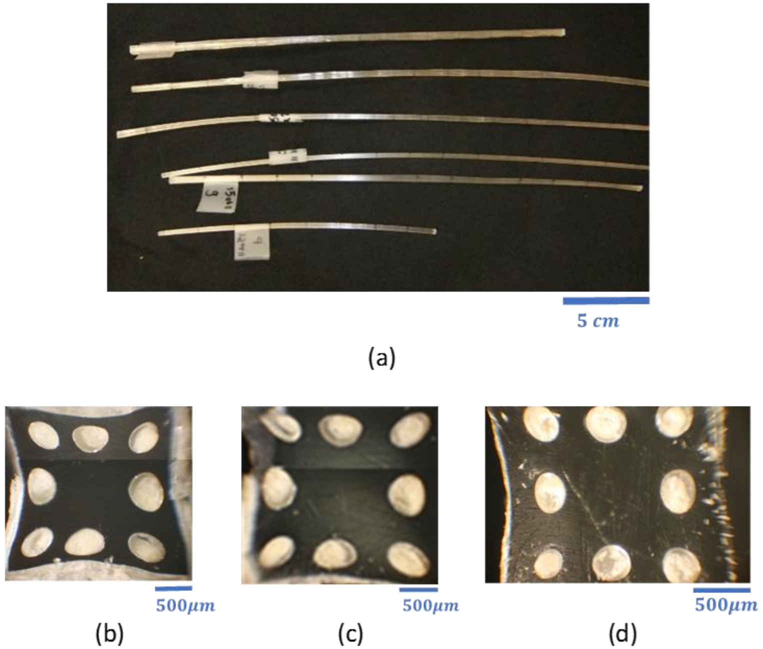


Vortex waveguide
Space+ Polarization division multiplexing

Chip-to-Chip Communication

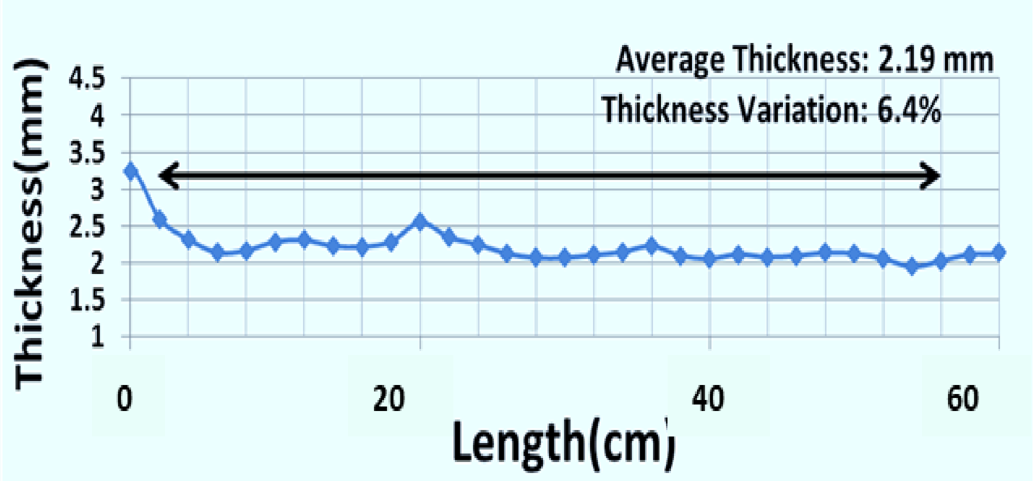
Physical Characterization | Preserved Geometry

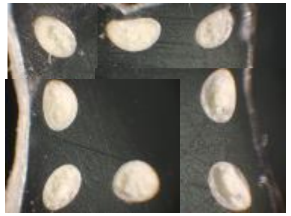
- 18 lengths of fiber have been fabricated
- Thickness variation over their lengths is $< 10\%$
- Hole patterns preserved throughout fiber lengths



(a) Fabricated waveguide samples. (b-c) Composite optical microscope images show fabricated waveguide cross sections of two different segments of fiber from the same preform. (d) Composite optical microscope image of a fabricated waveguide cross section.

Physical characterization of a sample



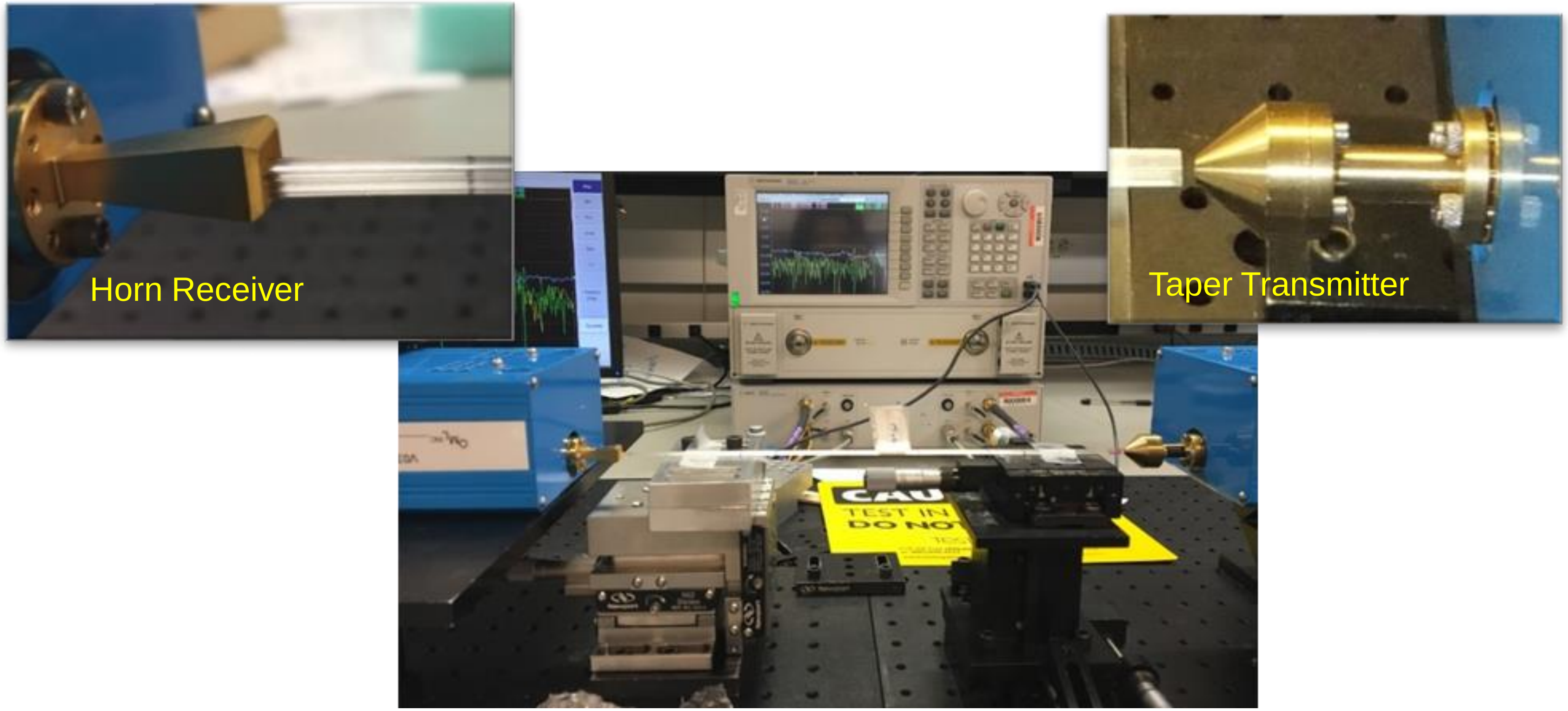


Composite image of a waveguide

Average Hole Size:	595 μm
Hole Size Variation:	4.6%
Core Size:	1359 μm
Core Shrink Factor:	11.3
Hole Shrink Factor:	9.41

Chip-to-Chip Communication

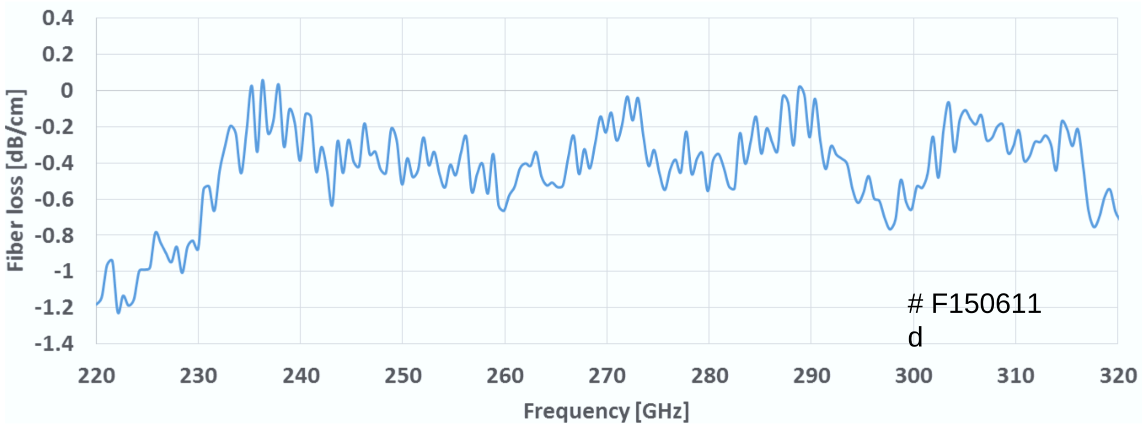
Experimental Setup



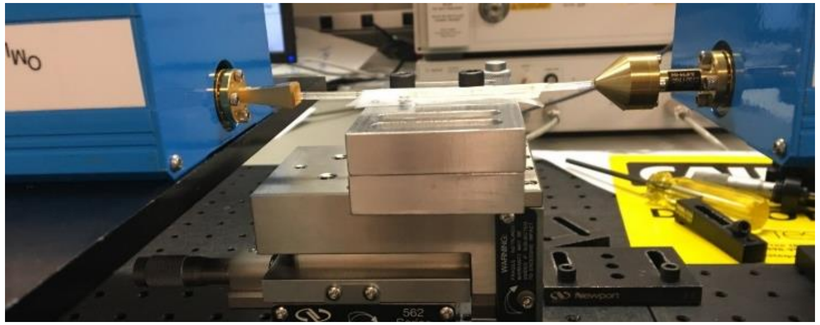
- **Waveguide is mounted on an X-Y-Z stage for better alignment**
- **Efficient coupling into waveguide using a custom taper with 1.3 mm $\times$ 1.3 mm aperture size (implies $C_1 = 1$)**
- **Efficient fiber coupling out using a WR-03 horn receiver with aperture size of 7.00 mm $\times$ 5.84 mm (implies $C_2 = 1$)**

Chip-to-Chip Communication

Functional Characterization | Fiber Loss - Sample 1



Fiber	Avg thickness (mm)	Thickness variation(%)	Length (cm)
F150611 d	2.509	5.6	12

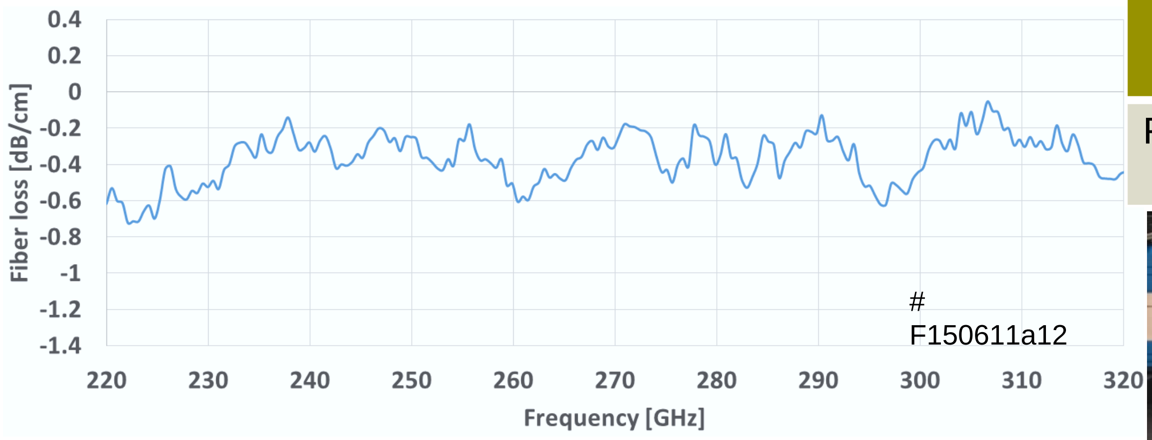


#of runs	S_{12}^2	S_{12}[dB]	R_1	R_2	T_1^2	T_2^2	C_1^2	C_2^2	Fiber loss	Fiber loss [dB]	Fiber loss/ length[dB/cm]
1	0.20	-6.94	0.21	0.25	0.96	0.94	1	1	0.222	-6.5	-0.55
2	0.14	-8.68	0.19	0.21	0.96	0.96	1	1	0.152	-8.2	-0.68
3	0.17	-7.73	0.18	0.23	0.97	0.95	1	1	0.184	-7.3	-0.61
4	0.16	-8.04	0.18	0.23	0.97	0.95	1	1	0.174	-7.6	-0.63
5	0.18	-7.43	0.19	0.18	0.96	0.97	1	1	0.193	-7.1	-0.59

$$E_{output}(\omega) = E_{input}(\omega) T_1 T_2 \, C_1 C_2 \exp\left(-\alpha \frac{L}{2}\right) \exp(-j \, \beta \, L)$$

Chip-to-Chip Communication

Functional Characterization | Fiber Loss - Sample 2

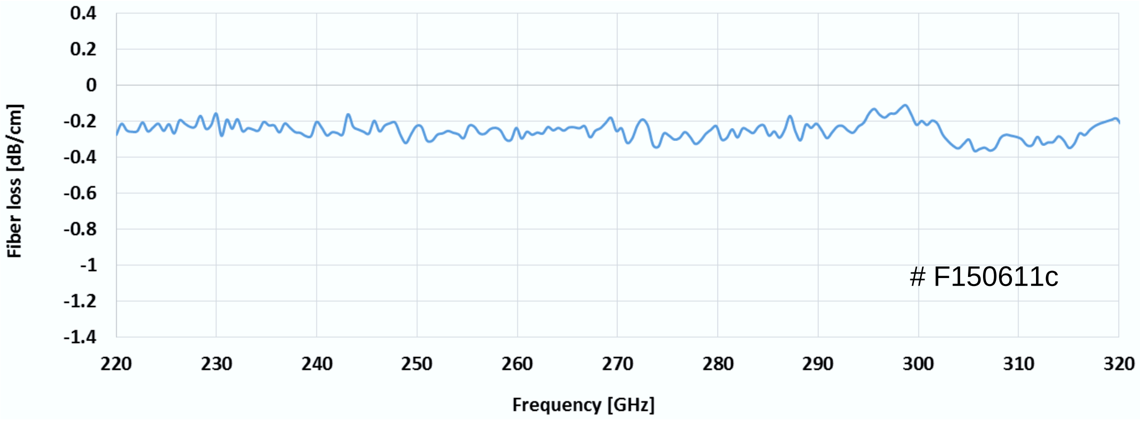


Fiber	Avg thickness (mm)	Thickness variation(%)	Length (cm)
F150611a21	2.284	6.78	19

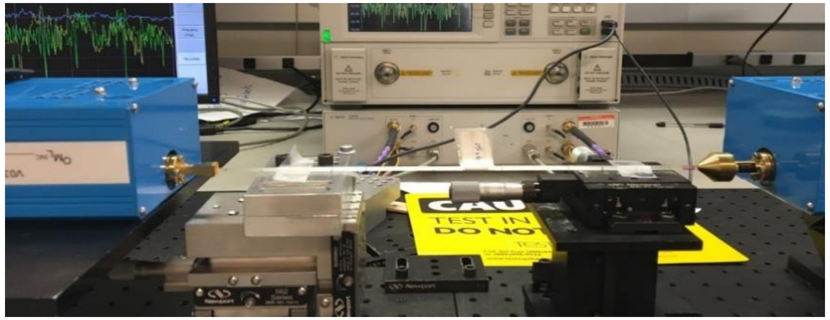
#of runs	S_{12}^2	S_{12}[dB]	R_1	R_2	T_1^2	T_2^2	C_1^2	C_2^2	Fiber loss	Fiber loss [dB]	Fiber loss/ length[dB/cm]
1	0.098	-10.1	0.15	0.17	0.98	0.97	1	1	0.103	-9.9	-0.52
2	0.098	-10.1	0.16	0.20	0.97	0.97	1	1	0.104	-9.8	-0.51
3	0.084	-10.8	0.13	0.20	0.98	0.96	1	1	0.089	-10.5	-0.55
4	0.081	-10.9	0.10	0.20	0.99	0.96	1	1	0.085	-10.7	-0.56
5	0.064	-12.0	0.17	0.18	0.97	0.97	1	1	0.068	-11.7	-0.62

Chip-to-Chip Communication

Functional Characterization | Fiber Loss - Sample 3



Fiber	Avg thickness (mm)	Thickness variation(%)	Length (cm)
F150611 c	2.303	3.8	30

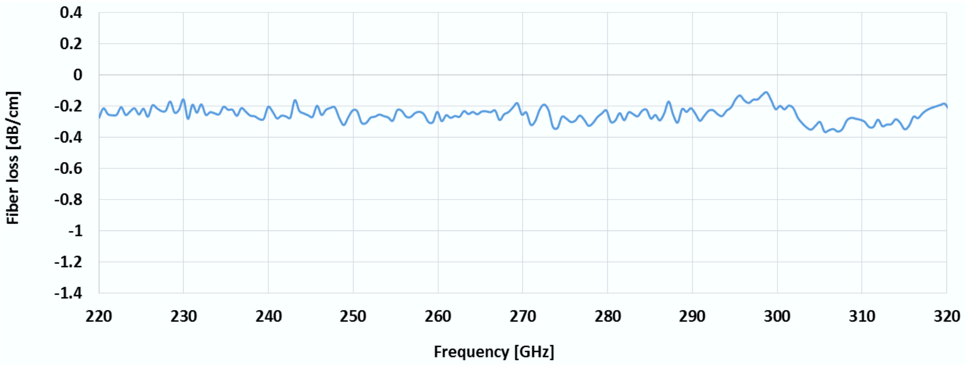


#of runs	S_{12}^2	S_{12}[dB]	R_1	R_2	T_1^2	T_2^2	C_1^2	C_2^2	Fiber loss	Fiber loss [dB]	Fiber loss/ length[dB/cm]
1	0.087	-10.6	0.18	0.17	0.77	0.80	1	1	0.14	-8.5	-0.28
2	0.11	-9.4	0.11	0.15	0.78	0.91	1	1	0.16	-7.9	-0.26
3	0.10	-9.85	0.08	0.10	0.86	0.88	1	1	0.14	-8.6	-0.29
4	0.13	-8.86	0.10	0.08	0. 08	0.84	1	1	0.19	-7.1	-0.24
5	0.11	-9.7	0.14	0.10	0.76	0.79	1	1	0.18	-7.5	-0.25

Chip-to-Chip Communication

Functional Characterization | Fiber Loss

- A range of 10 cm to 30 cm fibers were tested
- The longest fiber (30 cm) had the most reliable measurement



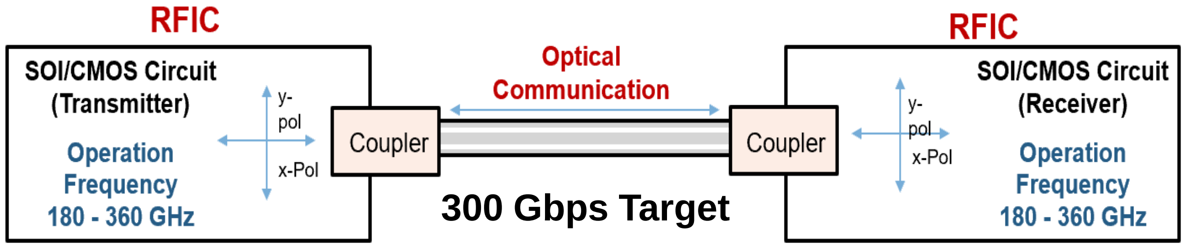
loss [dB/cm]	Source	200 GHz	300 GHz
Material loss	Literature	0.19	0.23
Waveguide loss	Simulation	0.19	0.25
	Experiment	0.22	0.26

Fiber	Average thickness (mm)	Thickness variation(%)	Length (cm)
F150611 c	2.303	3.8	30

- **A square holey cladding dielectric waveguide ready for system integration**
- **Experiments show the mode is confined to the core of the waveguide**
- **~ 24 dB fiber loss across 1 m fiber**

(typical optical link budget*)

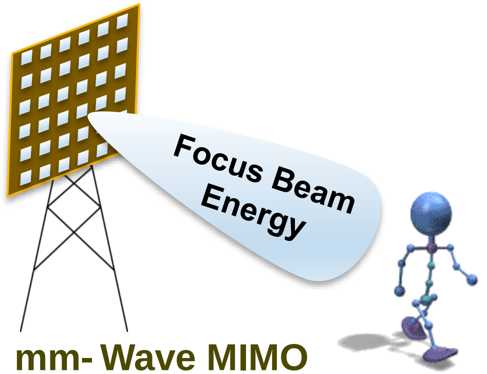
- TOPAS material loss ~ 20 dB/m
- We are limited by material loss



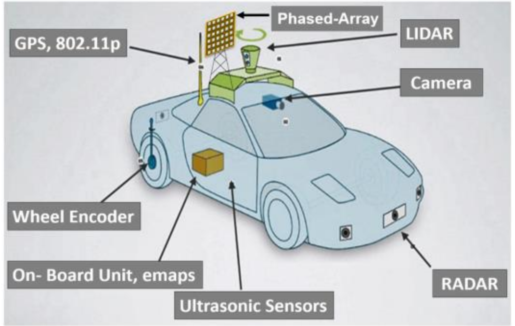
Perspectives for Hybrid RF/mmWave & Optics

Hybrid RF/mm-Wave & Optics Technology Solutions:

- Energy Control, Sensing & Localization
- Datarate/Channel Capacity
- Autonomous Systems



mm- Wave MIMO
Beamforming+5G
Toward Optical Beamforming

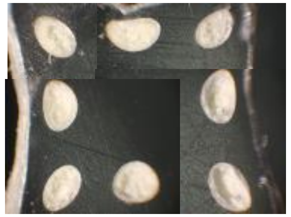


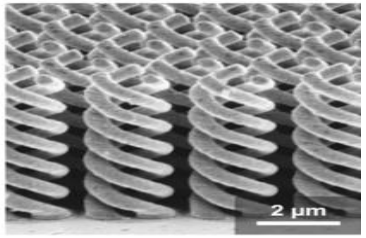
Autonomous
Systems

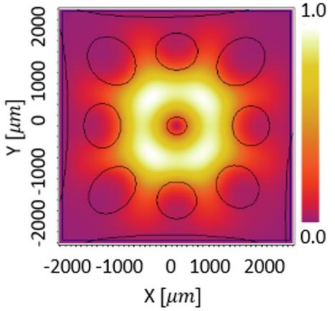
Towards RFIC-Photonics Wave-Particle Co-Design:

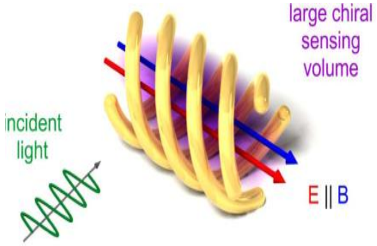
- Spin-Wave sensoring Technologies
- Photonics material patterning: *Inhomogeneity Engineering*
- Cognitive Analog-Signal Processing

  F-PGA → EH-PGA









3D ε-μ
Tailoring
Shaping