SCIENCE
PASSION
TECHNOLOGY

Technological Innovations in MW Front-Ends

The future is wireless !

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Microwaves Today vs. Yesterday

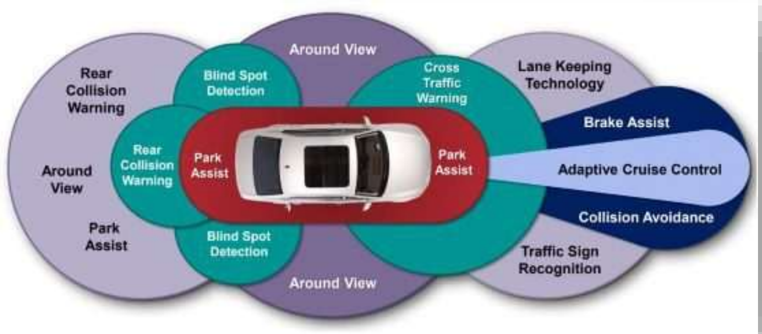
1980

- FM- Radio
- TV
- Radio amateur
- Police radio

Quellen:
[amateur radio magazine]
https://www.deutschlandfunk.de
http://bs.cyty.com/menschen/e-etzold/archiv/TV/philips
http://www.hifi-forum.de/themen/produkte/grundig

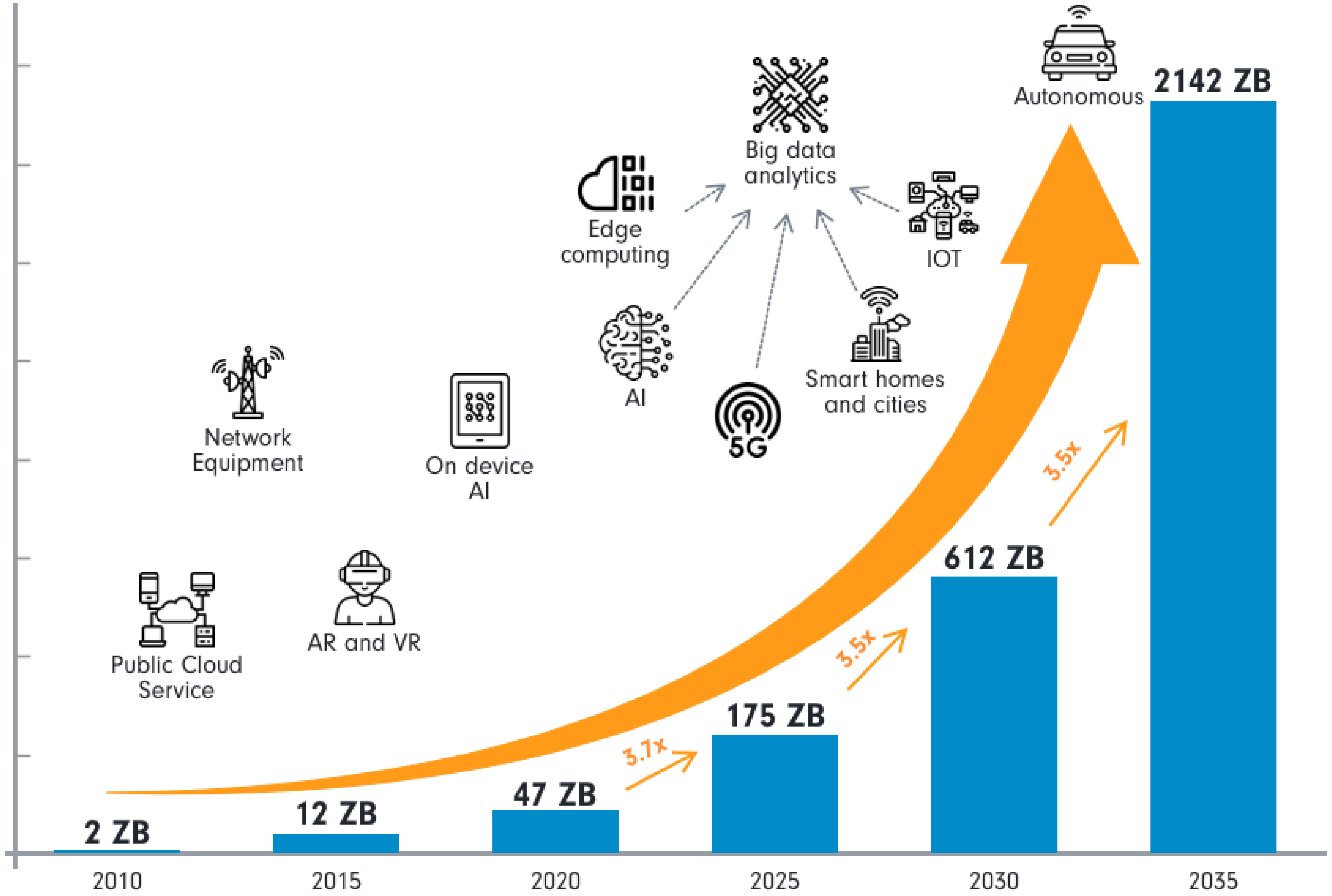
2025

- GPS
- Weather radar
- Earth observation
- WiFi
- ADAS automated driving
- Internet – Last Mile
- Mobile handsets
- Smart-Watch
- Industry 4.0
- Avionics / maritime radar
- Sensor networks
- Smart City
- Smart Home
- etc.....



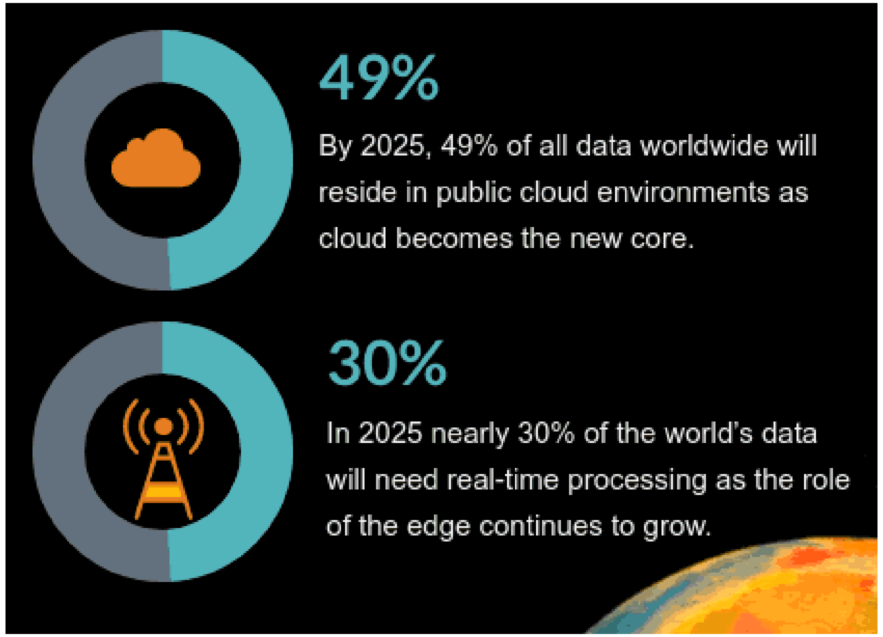
Quellen:
https://science.orf.at
https://www.tinymdm.net/en-sg/
https://www.autoserviceprofessional.com/articles/8793-dealing-with-advanced-driver-assist-systems

Exponential growth of data volume



Source: Statista Digital Economy Compass 2019

1 ZB = 10^{21} Bytes
1 ZB = trillion GB



Source: IDC & Seagate Data Age 2025

Increased centralized and decentralized data volumes need to be
Stored, processed and transmitted

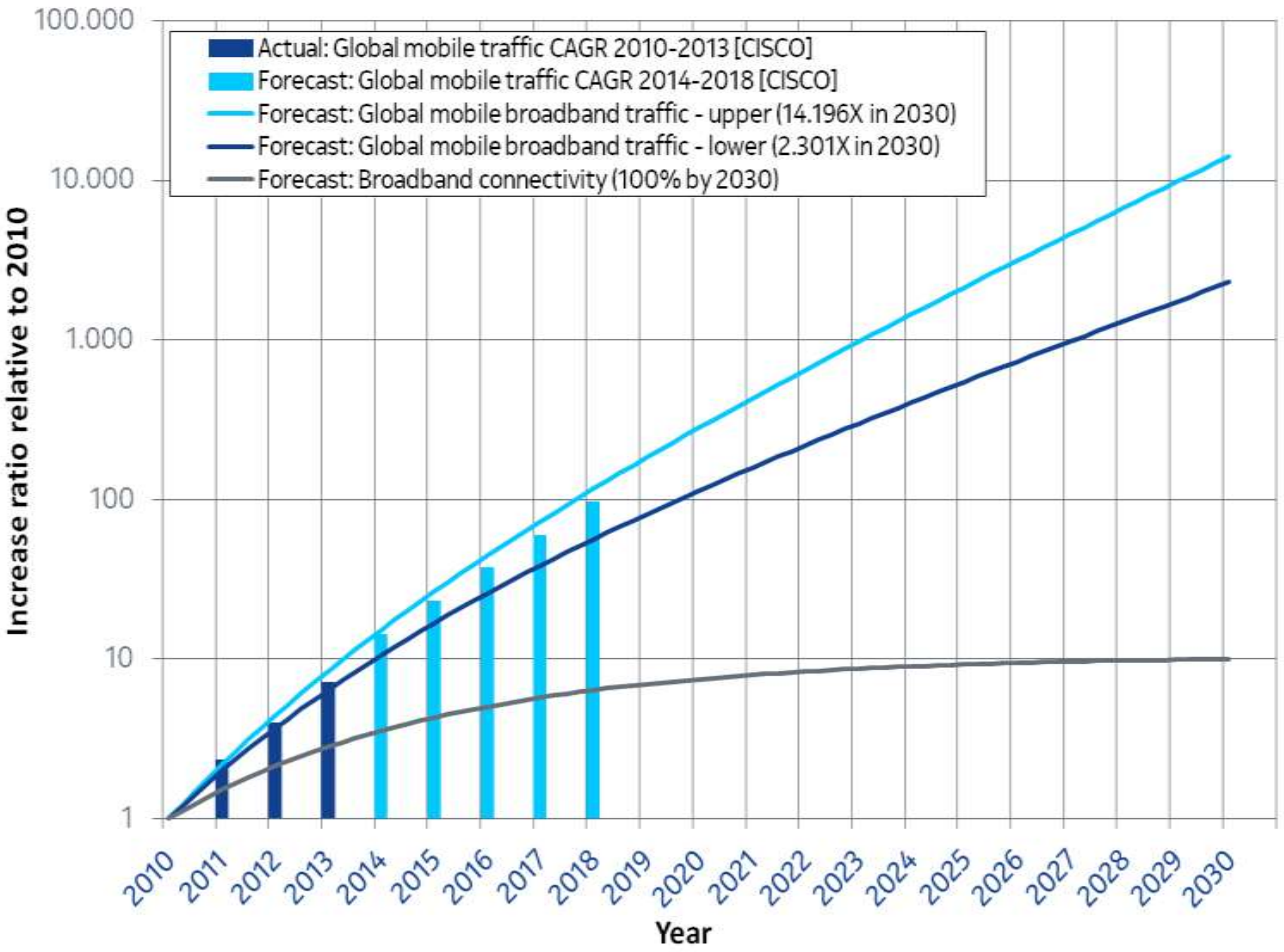
Courtesy of AT&S

Global mobile broadband traffic growth

Year	Global Internet Traffic
1992	100 GB per day => 15 Netflix Videos
1997	100 GB per hour
2002	100 GB per second
2007	2,000 GB per second
2017	46,600 GB per second
2022	150,700 GB per second

Cisco, “**500 billion devices** are expected to be **connected** to the **Internet** by 2030. Each device includes sensors that collect data, interact with the environment, and communicate over a network. These smart, connected devices generate data …..”

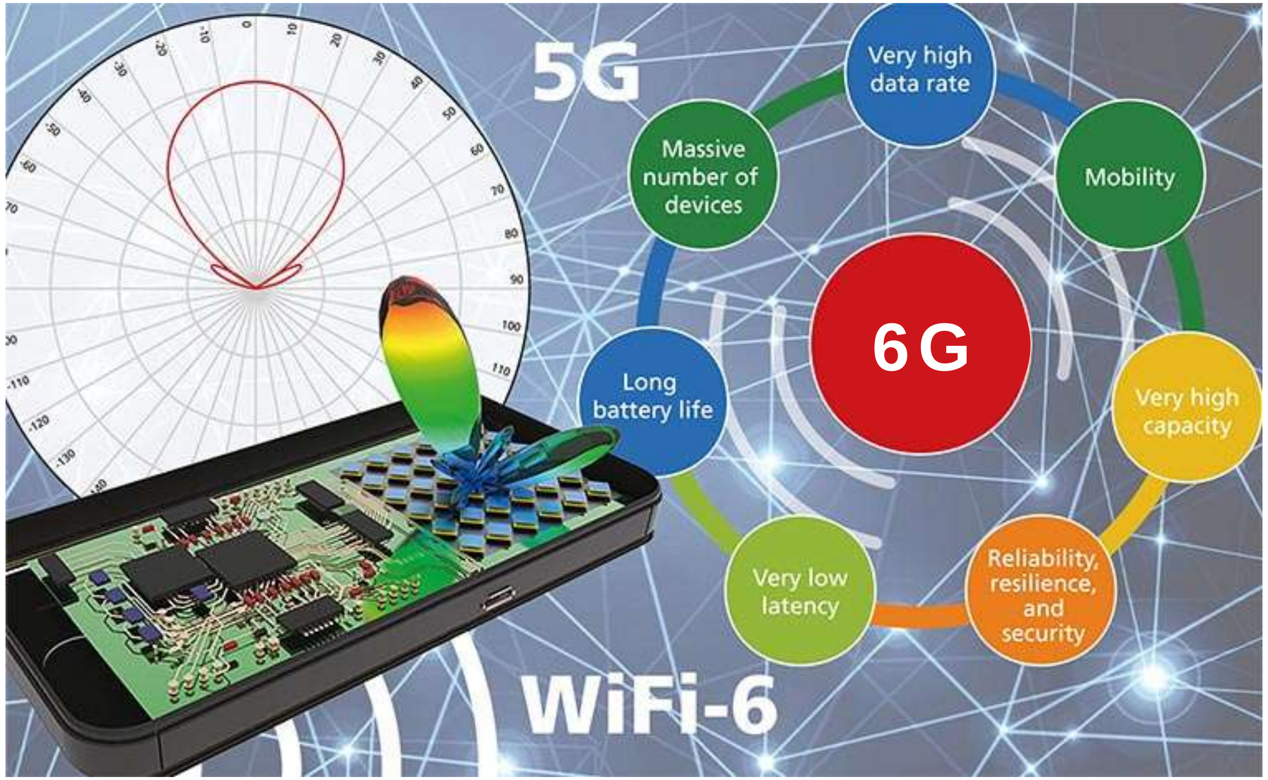
Source: CISCO



Source: International Telecommunication Union, “IMT traffic estimates for the years 2020 to 2030,” Report No. ITU-R M.2370-0

5G/6G Application area &Trends

- **Most of the billions** of interconnected devices are **low-power & wireless !**
- **Strong trend towards higher frequencies**



Smart factory

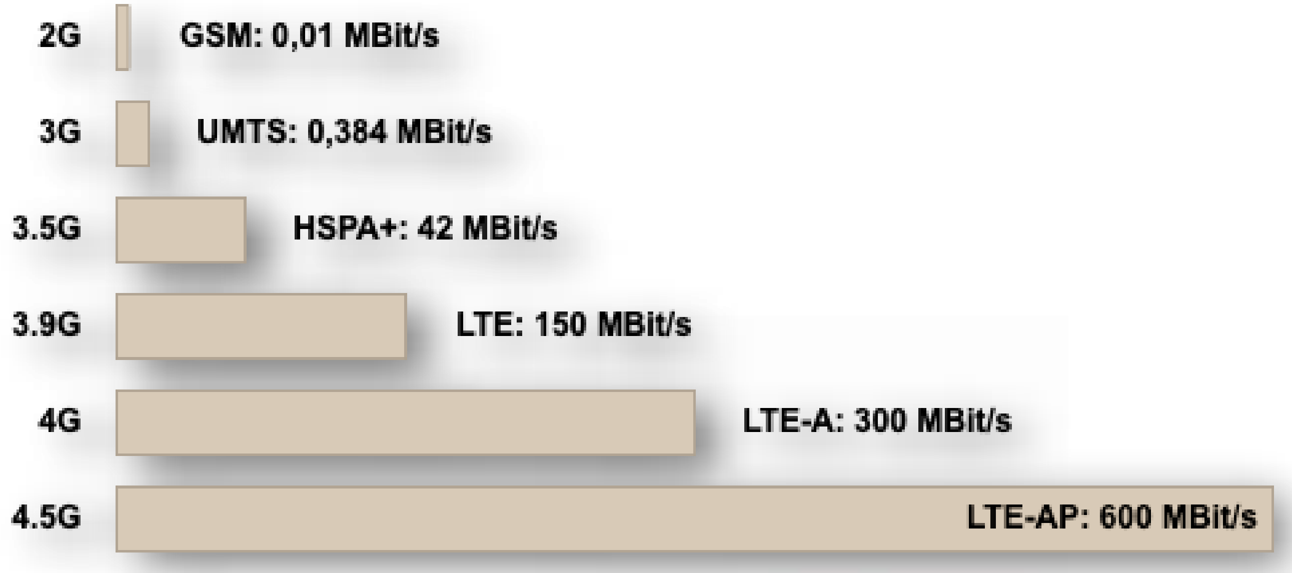
Smart home

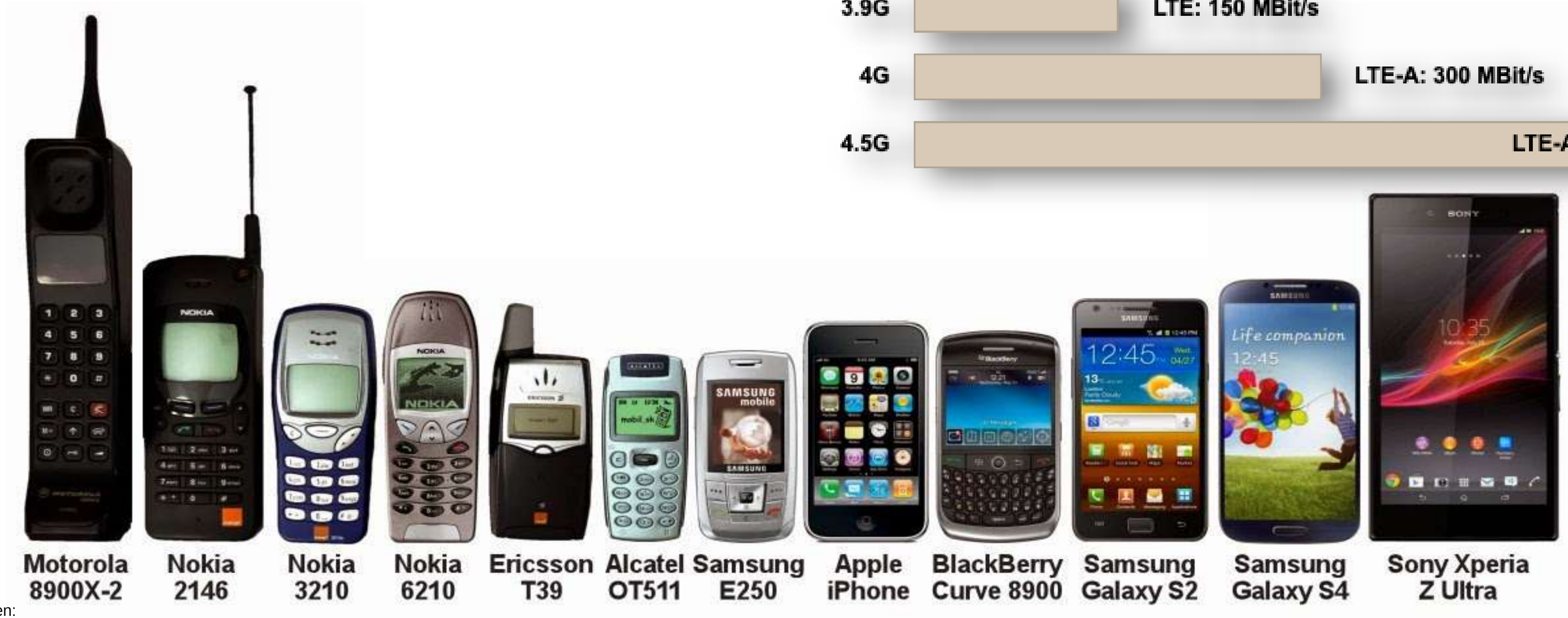
E-Mobility

Smart cities

Evolution of the Mobile Phone

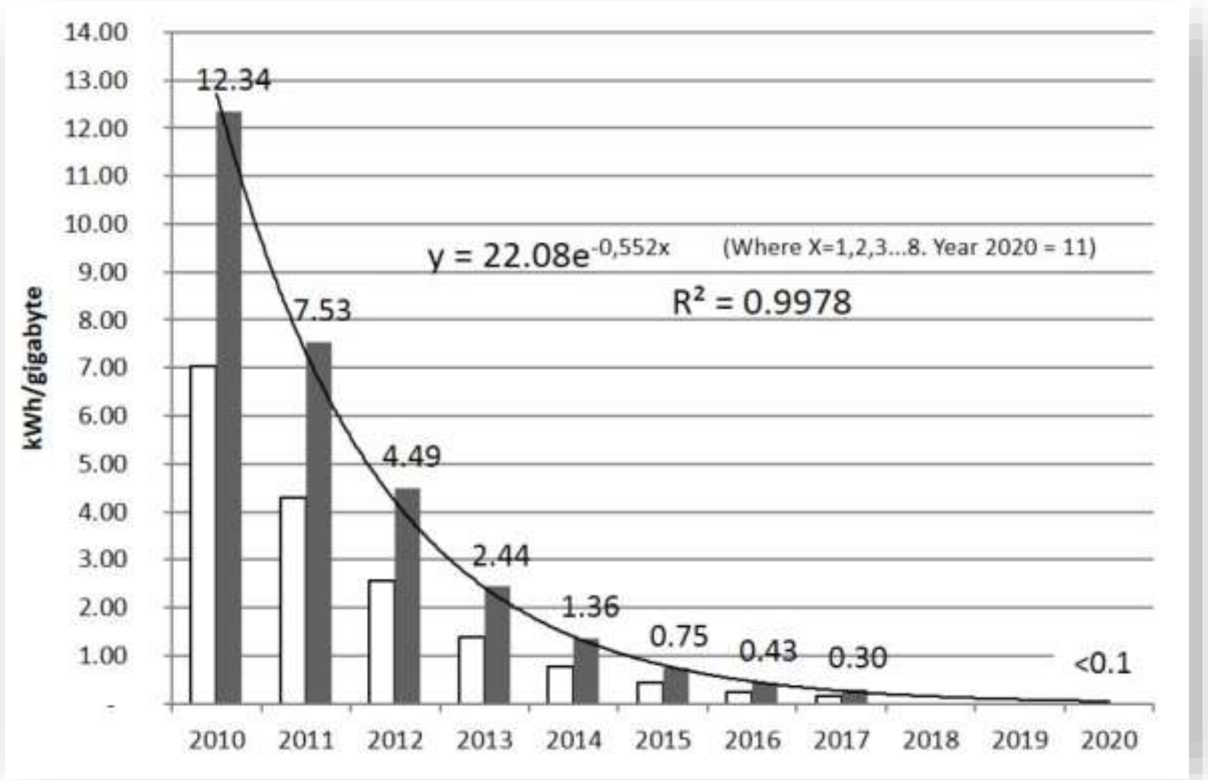
Exponential increase in the data rate however roughly **same energy consumtion** and significantly higher complexity
(smart phone, multiple radios, etc.)





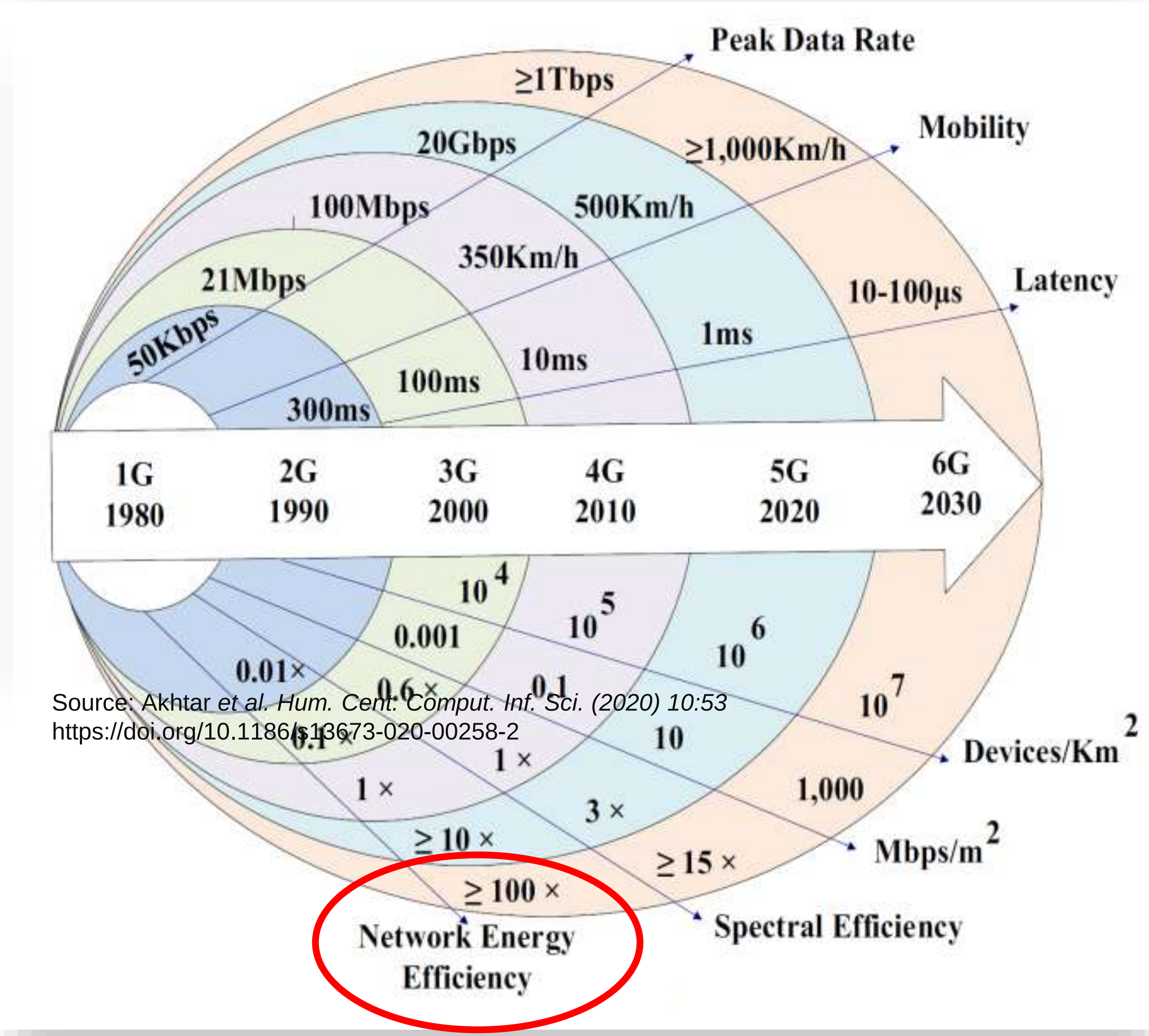
Quellen:
https://www.searchabledesign.com/blog/post/cell-phone-interesting-facts & https://www.elektronik-kompendium.de/sites/kom/0910141.htm

Key Performance Indicators 6G - Efficiency development



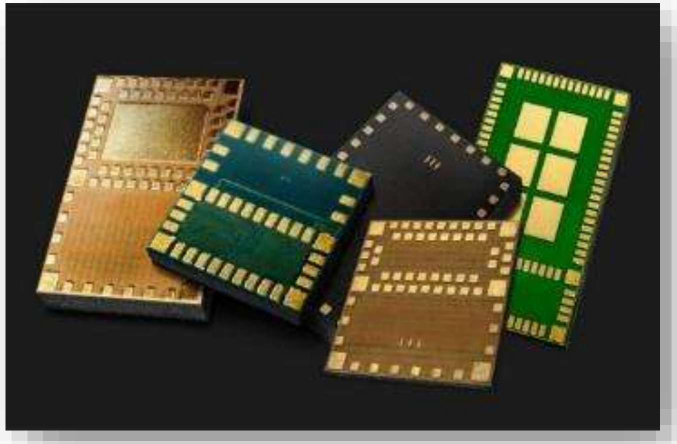
Development of **energy efficiency of transmitted mobile data** (kWh/gigabyte) in Finland during 2010–2017. Grey bars represent estimated consumption for production networks and white bars for base stations only

Pihkola, H.; Hongisto, M.; Apilo, O.; Lasanen, M. Evaluating the Energy Consumption of Mobile Data Transfer—From Technology Development to Consumer Behaviour and Life Cycle Thinking. *Sustainability* **2018**, *10*, 2494. https://doi.org/10.3390/su10072494

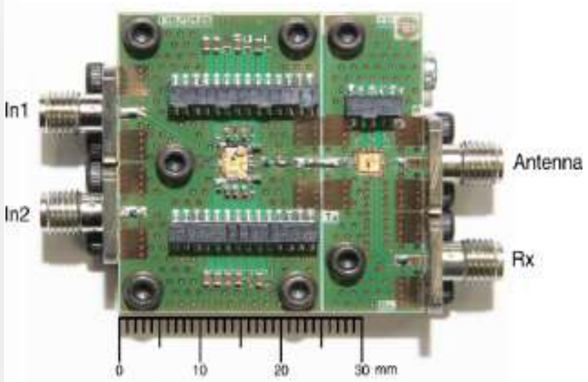


Source: Akhtar *et al. Hum. Cent. Comput. Inf. Sci.* (2020) 10:53
https://doi.org/10.1186/s13673-020-00258-2

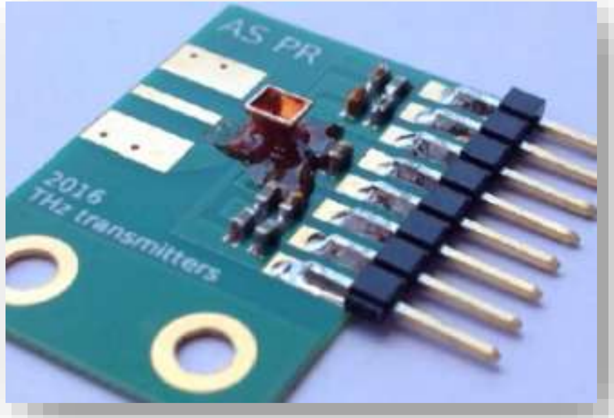
Challenges future communication and sensor systems



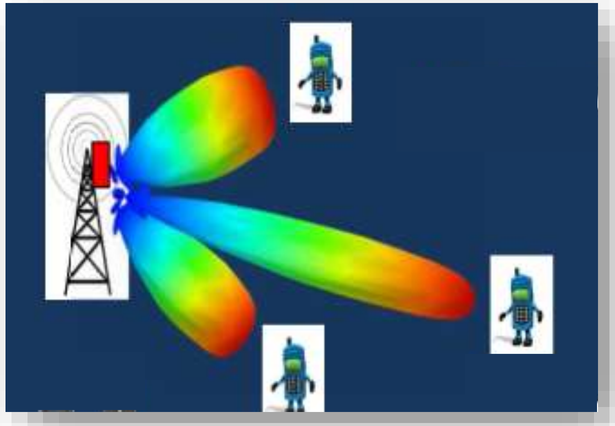
https://www.5gtechnologyworld.com



All digital front-end



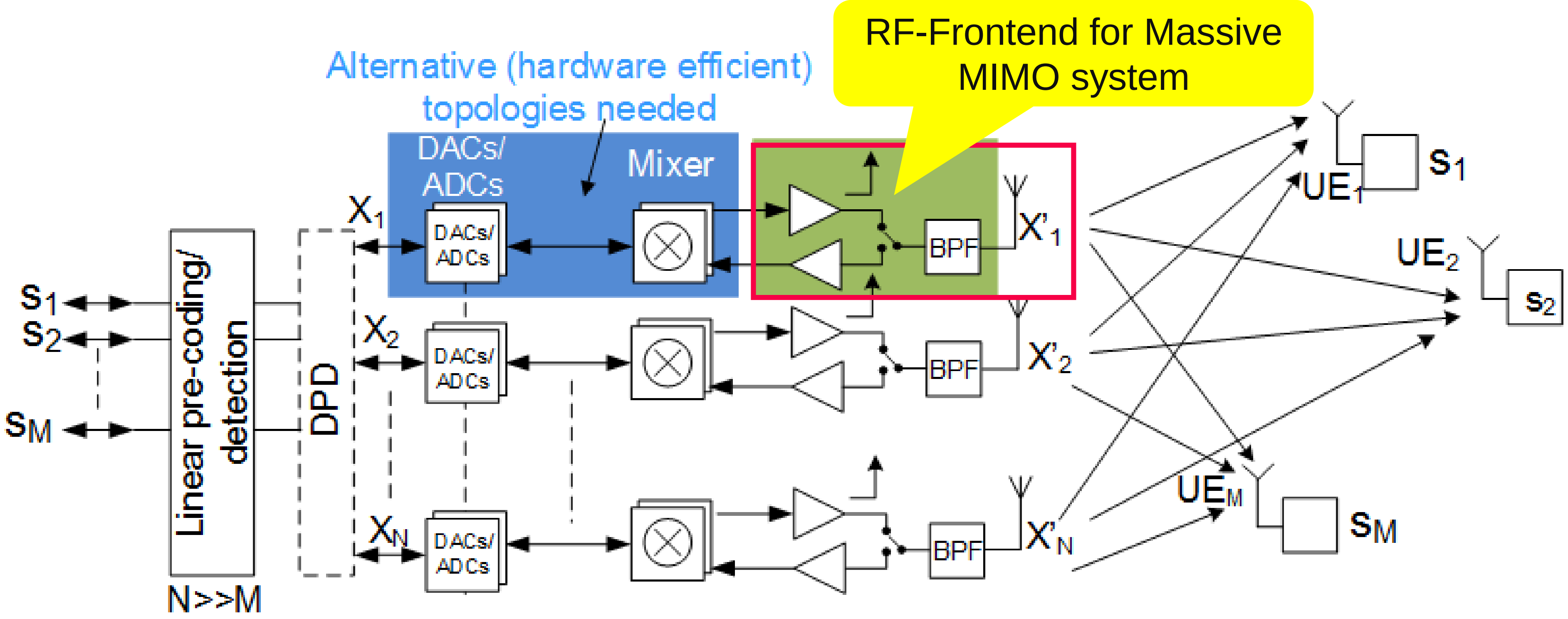
mmW transceiver with horn antenna

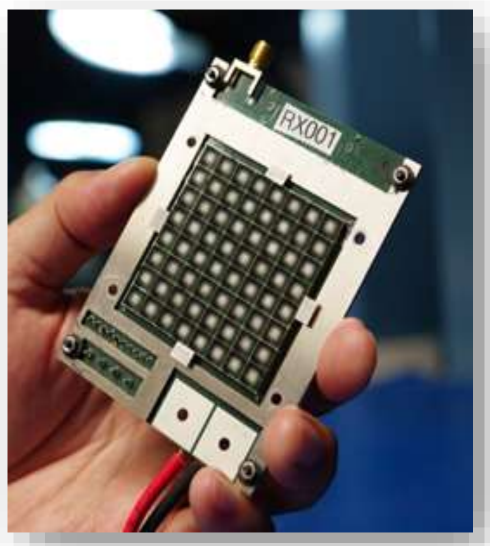


Beam forming and beam stearing

- **Low power consumption**
- Higher data rates - **higher frequencies**
- **Beam-steering** for fixed and mobile devices
- **Heterogeneous integration** technologies
- **Low-loss** interconnect **feeding concepts**
- Adaptive **integrated filters** and **antennas**
- **Interoperability,** robustness and electromagnetic compatibility (EMC) **dependable systems**

Beam Steering & Massive-MIMO Systems

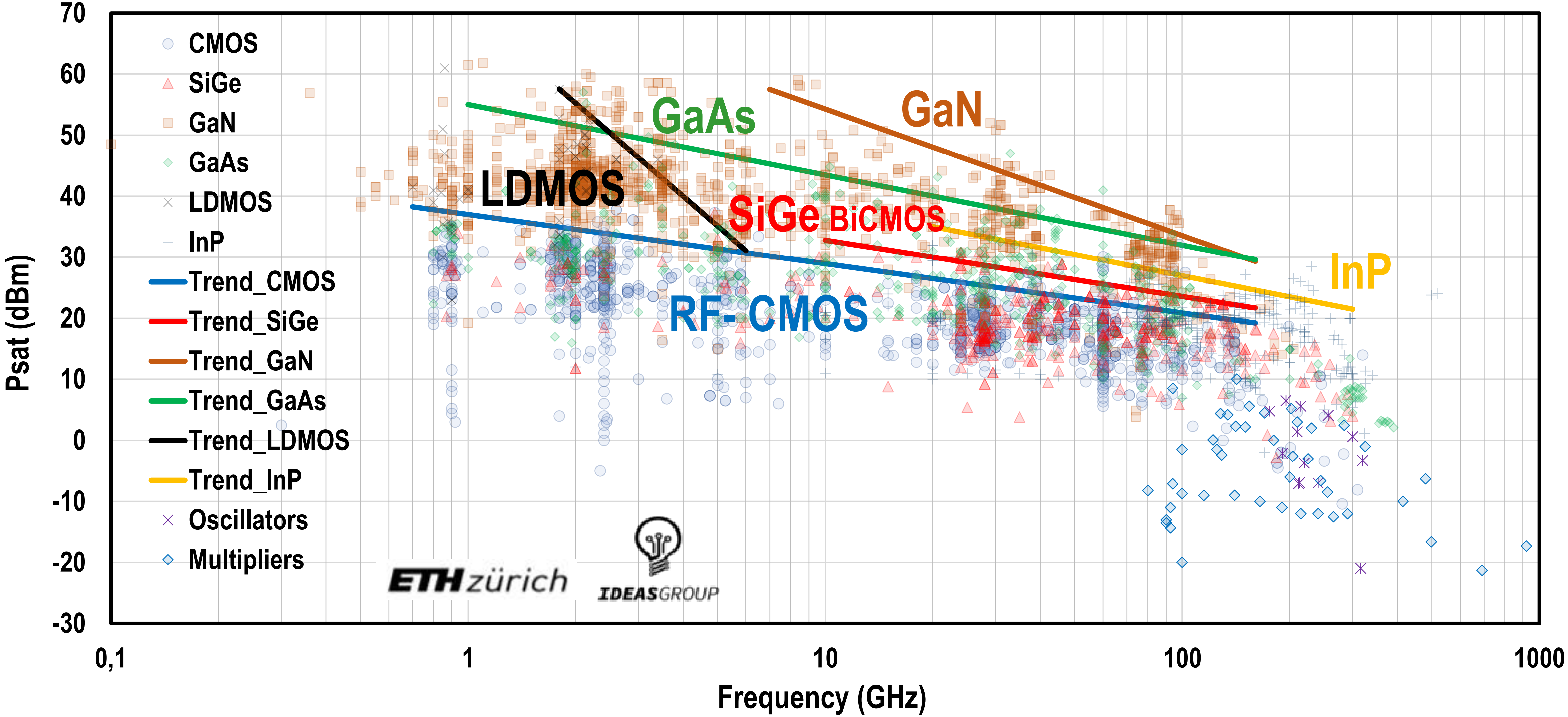




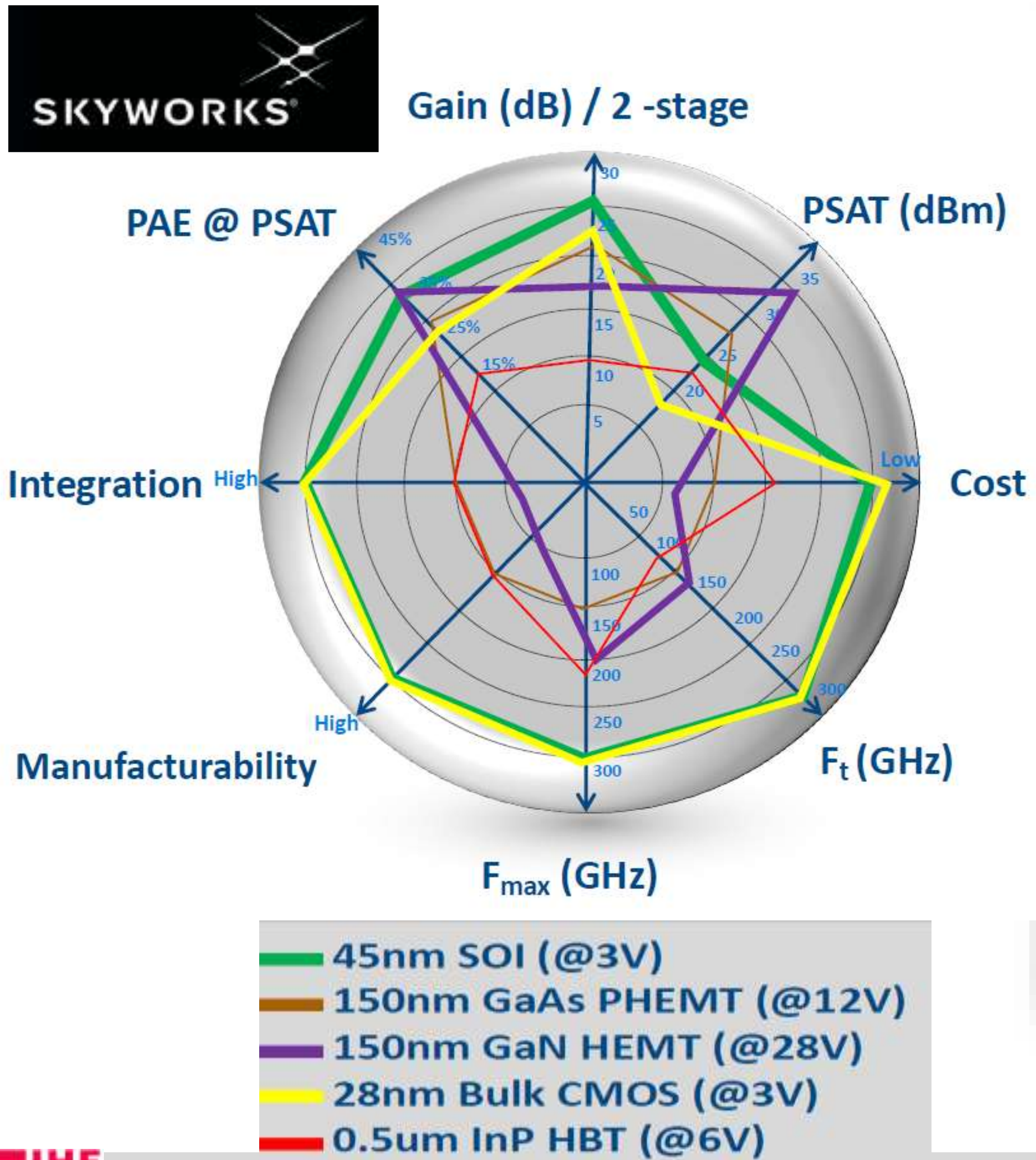
Source: Movandi integrated 5G RF front-end (analogictips.com)

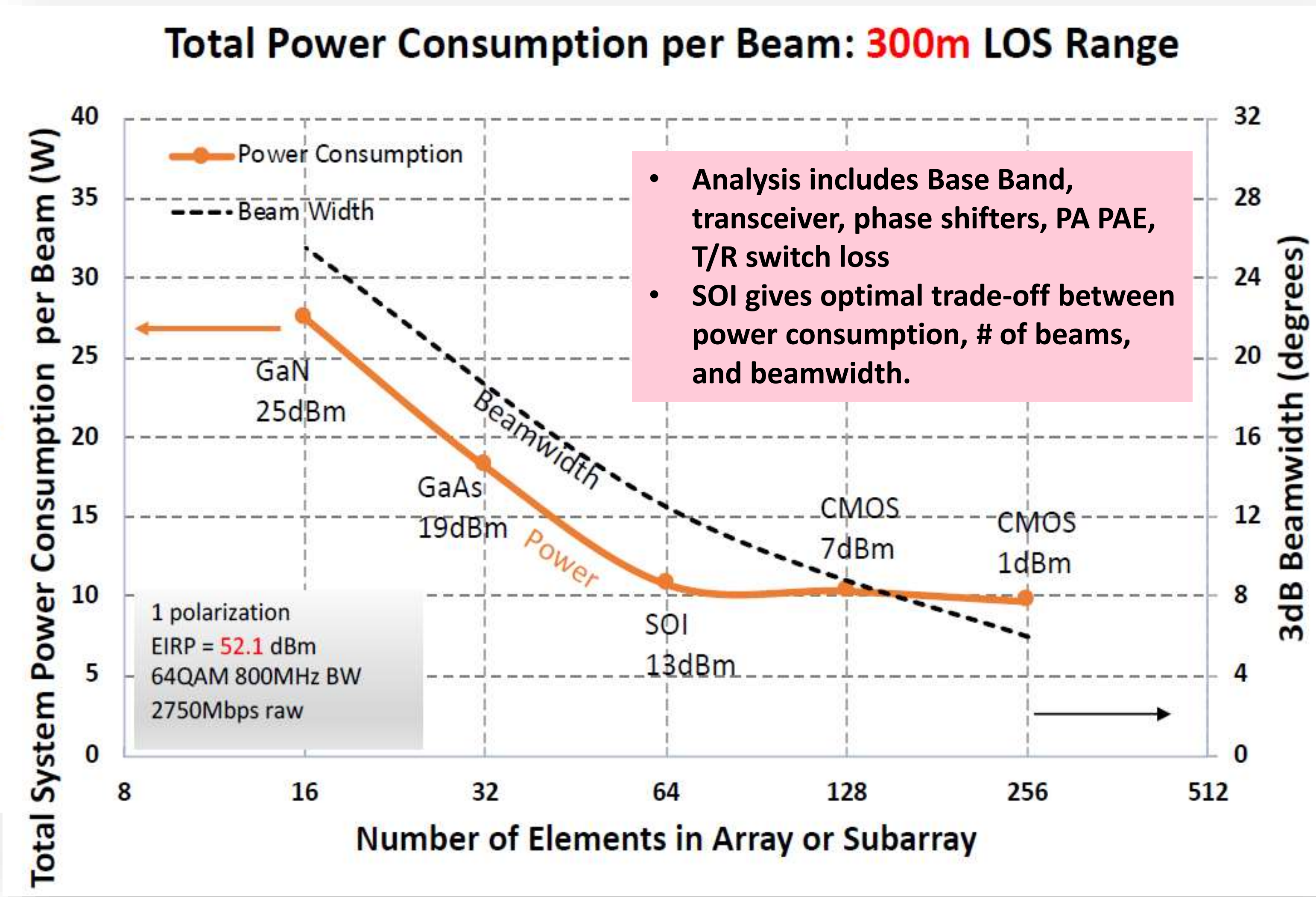
- Near linear increase of area and **power consumption** with array size => **low power & efficiency**
- Traditional analog/RF approach becomes inefficient => **more digital components** in the system
- Efficient System in Package - **SiP solution: PA+LNA+Switch+Filter+Antenna =>** **Integration**

PA Survey 2024: Saturated Output Power vs. Frequency (All Technologies)



Technology selection for 5G **mmW applications**



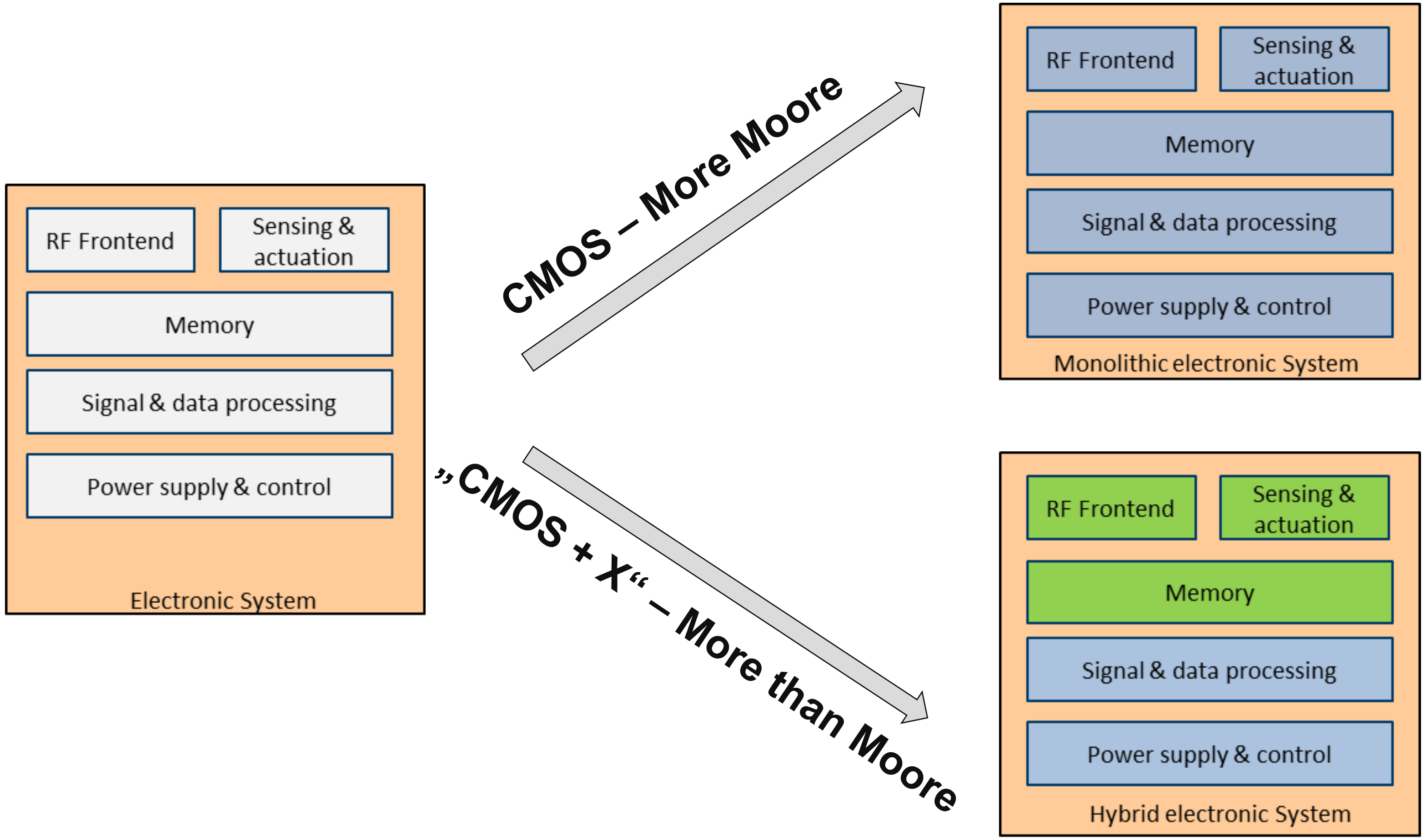


Source: Skyworks IWPC Workshop 2019

More than Moore or "CMOS +X"

Courtesy of the Leibniz Institute for high performance micro electronics

Combining technologies to get the overall best performance



CMOS – More Moore

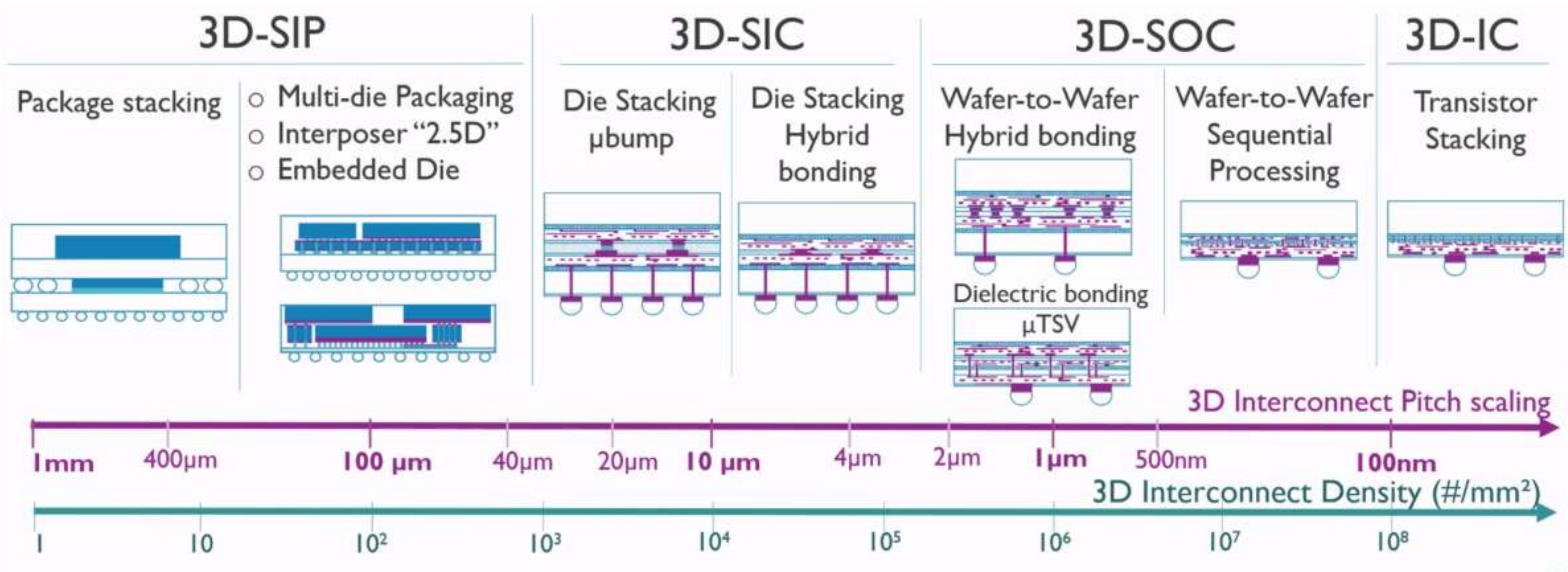
- Highest possible integration level
- Minimum fabrication cost
- Limited functionality & performance

"CMOS + X" – More than Moore

- Medium integration level
- Medium fabrication cost & complexity
- Best functionality & performance

Advanced Heterogeneous Integration

Trend: Advanced heterogeneous integration rather than pure monolithic integration



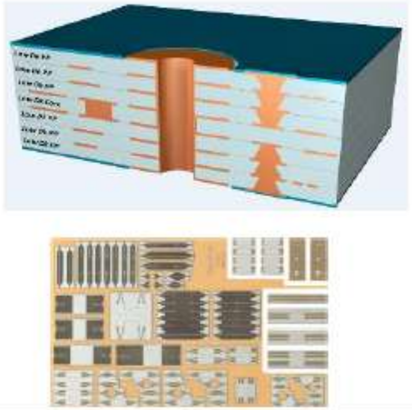
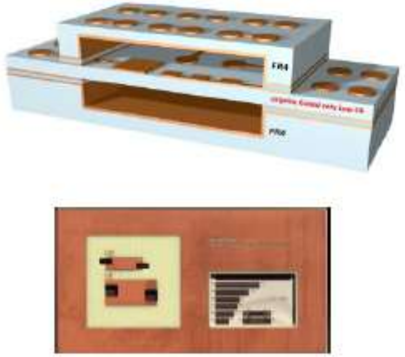
3D interconnect landscape (source: IMEC)

Courtesy of the Leibniz Institute for high performance micro electronics

Advanced PCB Technologies

Enabler for miniaturization and **enhanced functionality**

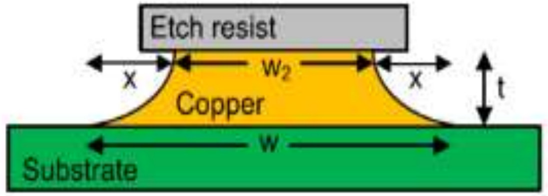
Courtesy of AT&S

Asymmetric Build up with embedded dies	Antenna & Main Board in one	Substrate Integrated Waveguide	Air Cavities
			
Feature ▪ Signal Path beyond Chip ▪ Antenna on top ▪ Thermal Path on bottom ▪ Excellent Thermal Pad in Z-axis ▪ Embedded GaN PA component ▪ Scaleable concept	**Feature** ▪ Seperate Manufacturing of Antenna Board and Main Board ▪ No compromize of different requirements needed ▪ Asymmetric Build up without non used layers	**Feature** ▪ Via structures are used to replace conventional microstriplines to form a **waveguide** ▪ Loss reduction due to a **changed transmission mode**	**Feature** ▪ Air cavity beyond & below the antenna or feeding line for **reduced dielectric losses** ▪ Suspended microstripline incl. shielding

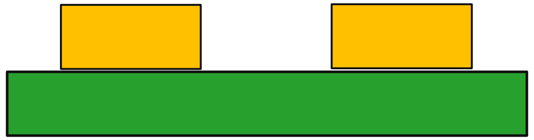
Loss reduction is key

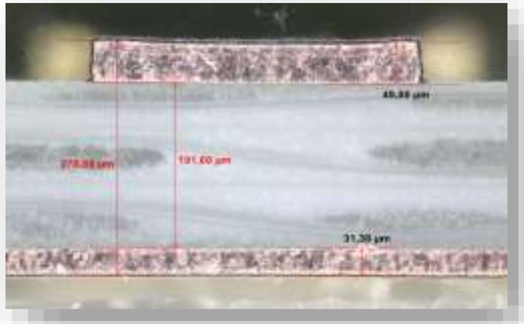
Modified semi additive process (mSAP)

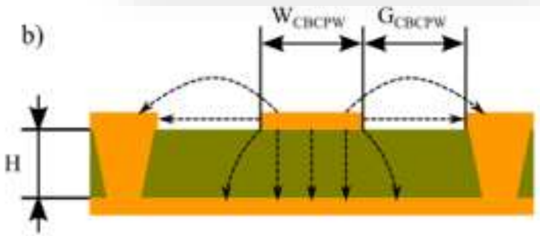
Subtractive



mSAP



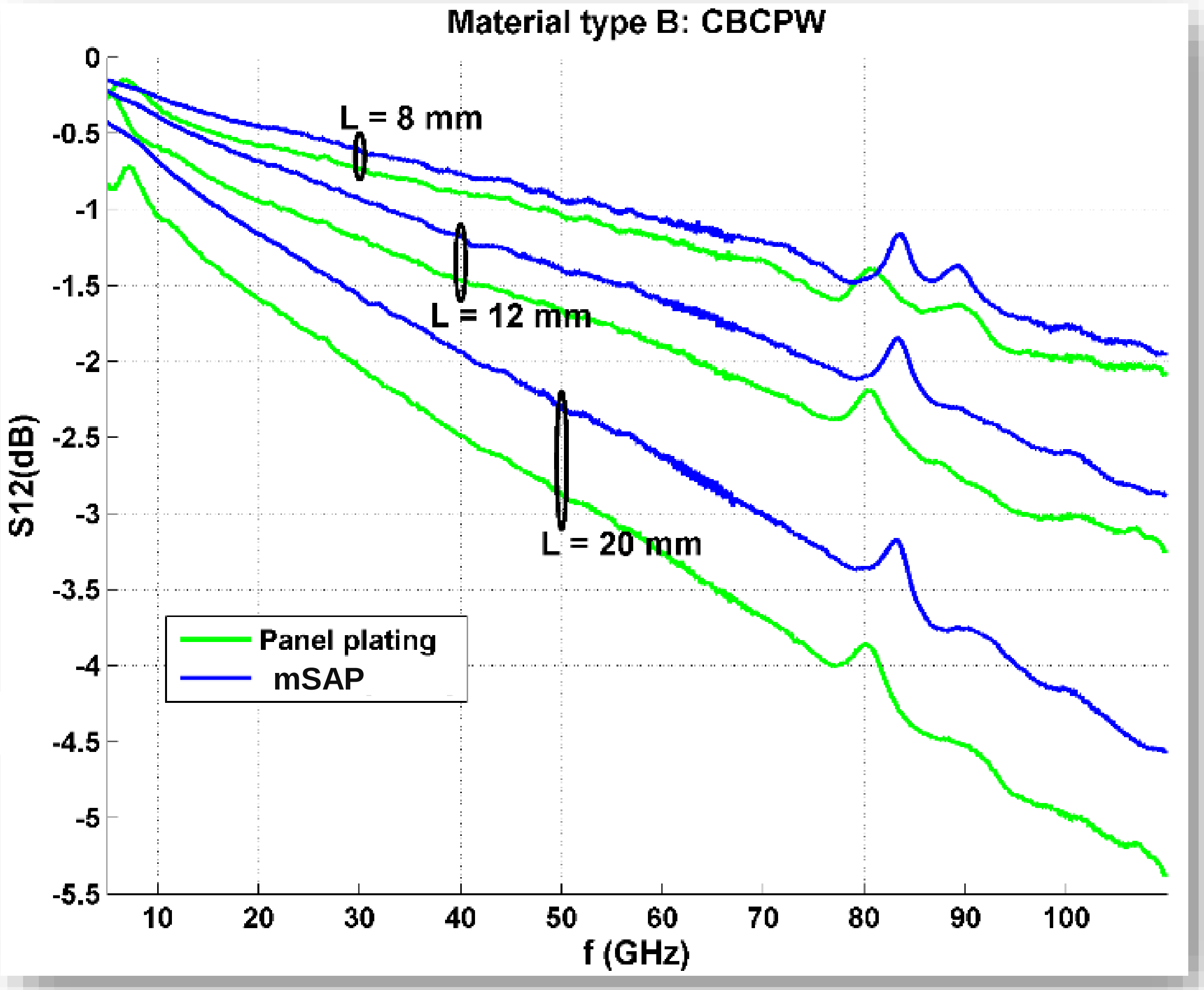




Line width mSAP: **250µm +/ 4%**
Line width Panel Plating: 250µm +/- 20%

Losses: Conductor-backed Coplanar Waveguide

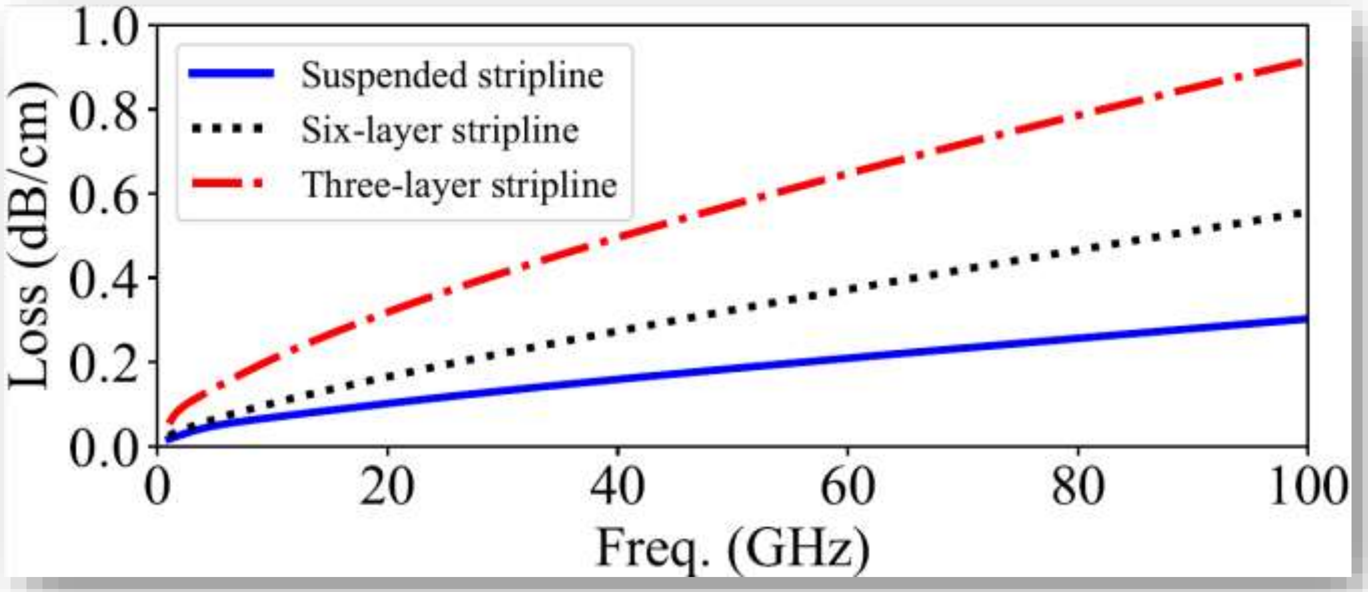
Courtesy of AT&S

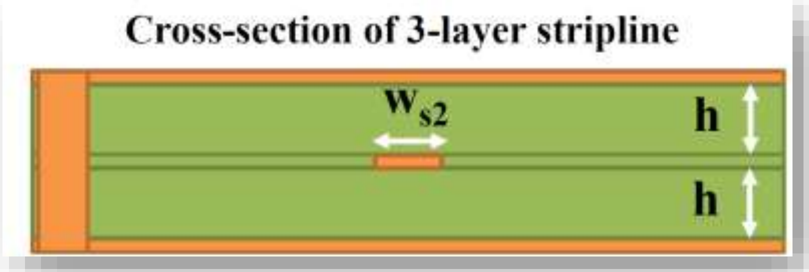


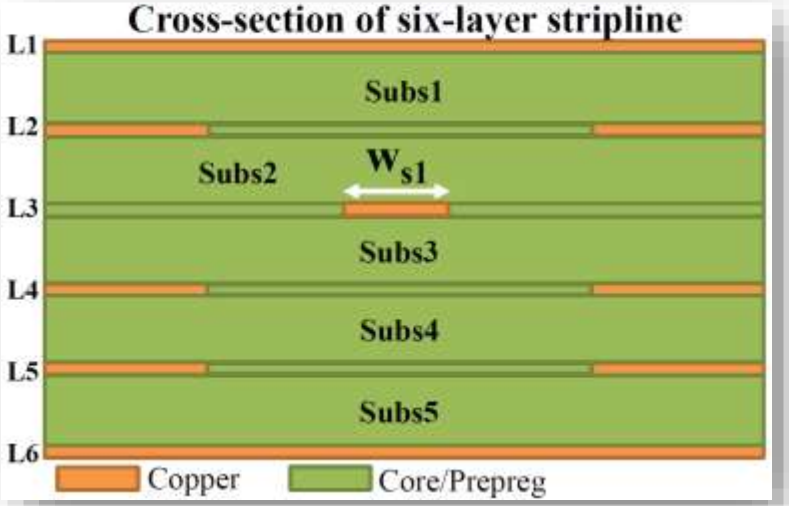
PCB embedding technology: Stripline loss comparison

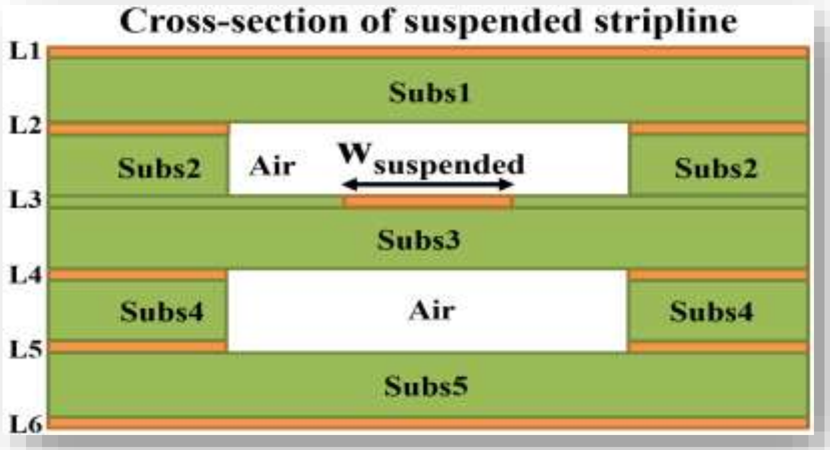
Air-filled transmission lines:

- Lowest losses
- Higher power handling capabilities
  appropriate for PA feeding lines

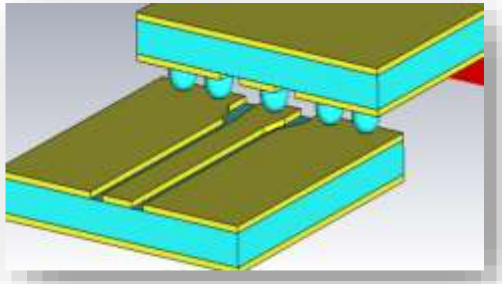


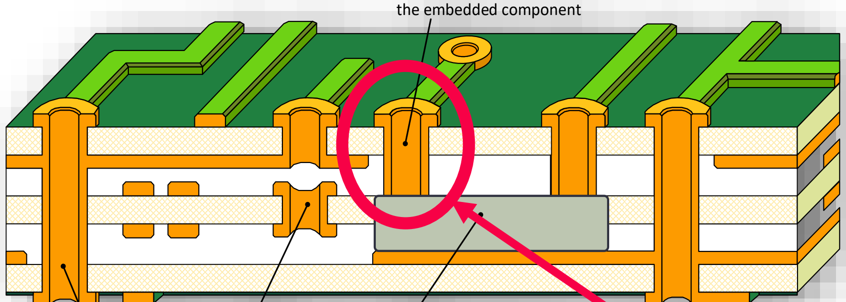




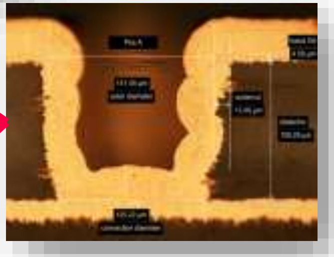


Losses - BGA vs microVIA (embedding)

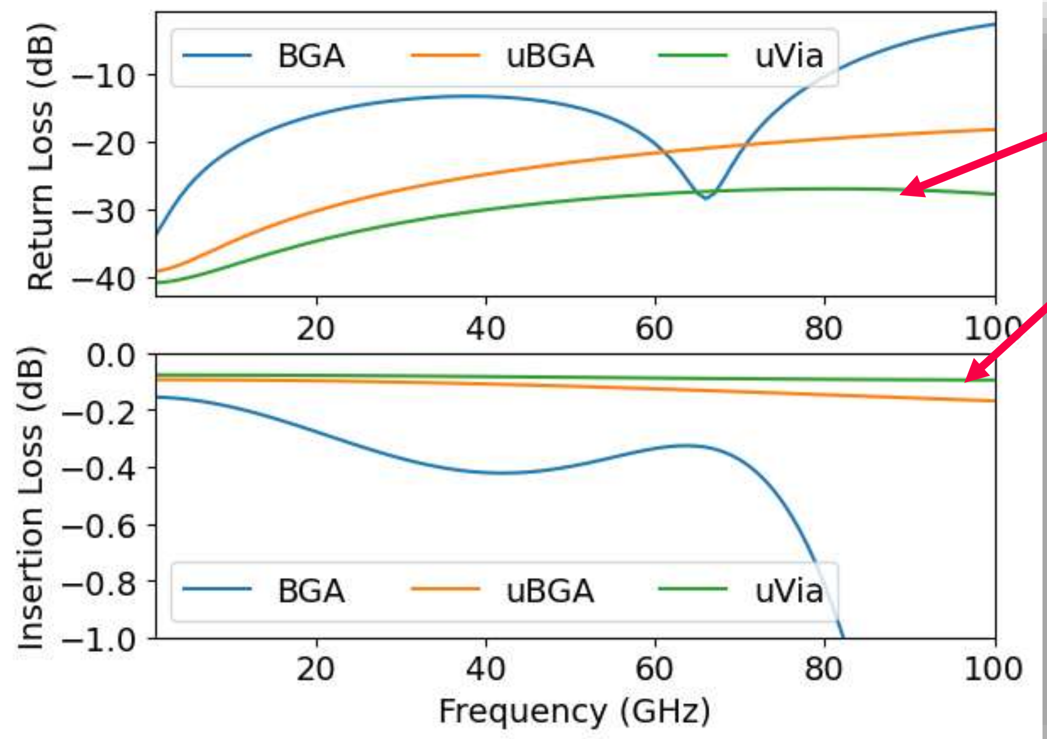




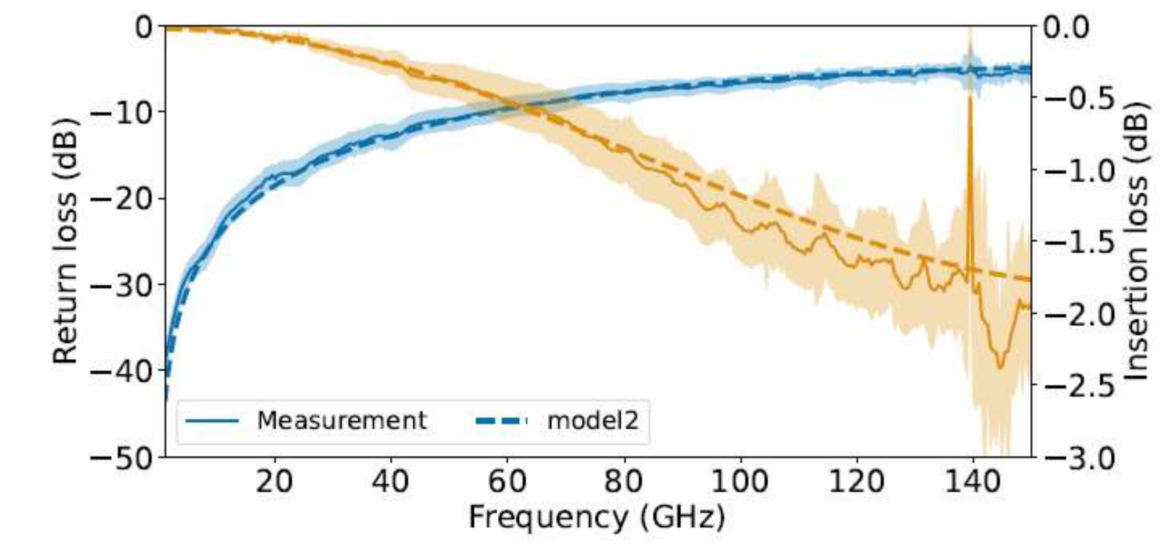
microVIA



Simulation Results



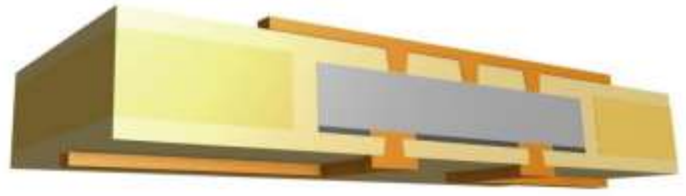
De-embedded measurement result of microVIA

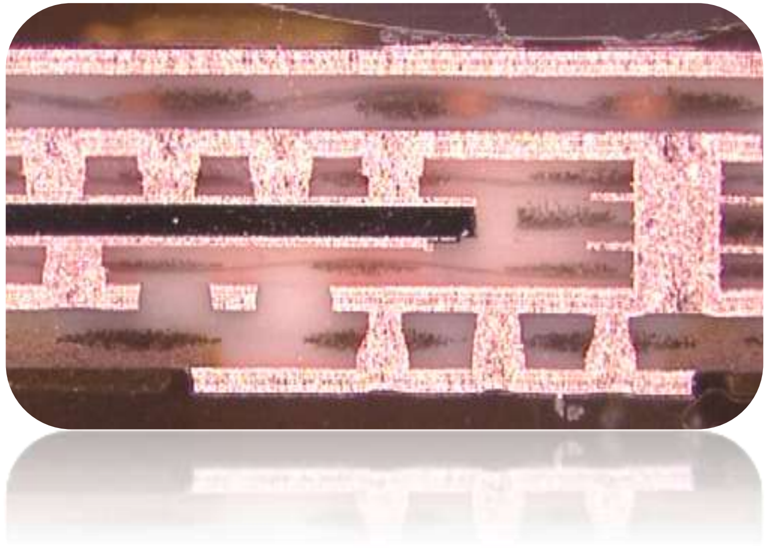


Higher integration by embedding components

ECP®
The first choice for cost-efficient packaging of passive and small-size active components

CENTER CORE EMBEDDING
The preferred packaging technology for power applications with double-sided component connection





Integrate active and passive Components

- Bare dies
- Single sided connection
- Si / GaAs / GaN …
- Pad termination: Copper, Au, Al

Performance Benefits

- Reduce Transmission losses
- Minimize Feeding Network length
- Split of Signal Path and Thermal Path
- More accurate Signal Path due Micro Via interconnection

Courtesy of AT&S

Size reduction by embedding power transistors into PCB

- **Doherty PA** design has been integrated into a **multilayer-laminate** module
- Two GaN-Si transistor dies are **embedded** inside the laminate and contacted using **laser vias**
- The **heat is dissipated** from the GaN dies using the **micro-vias** contacting the source pads at the bottom of the dies
- **Significant reduction of the footprint** of the module

ALL2GaN

KDT JU

Bare-die Doherty PA Demo

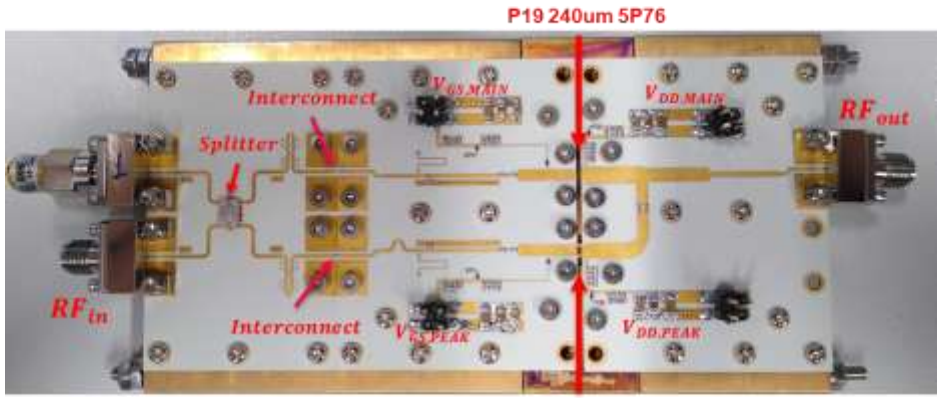
- same GaN devices, similar performance
- **Dimensions: 12 cm x 6.3 cm (area: 7560 sqmm)**

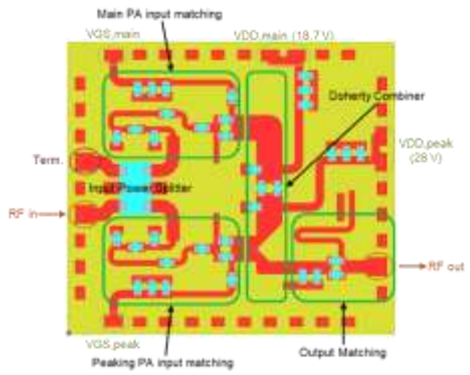
55x

CCE Doherty Module

Dimensions: 11 mm x 12.4 mm

area: 137sqmm



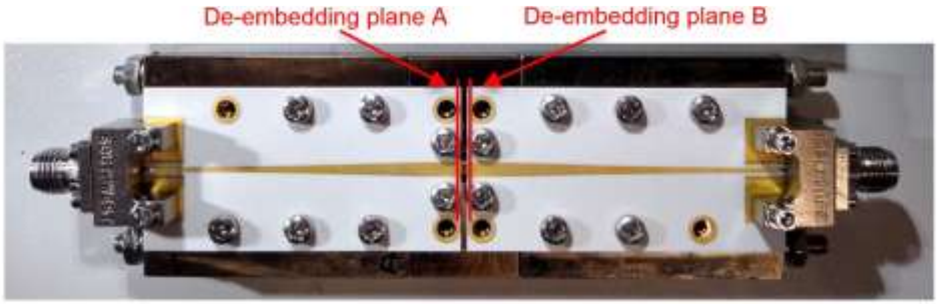


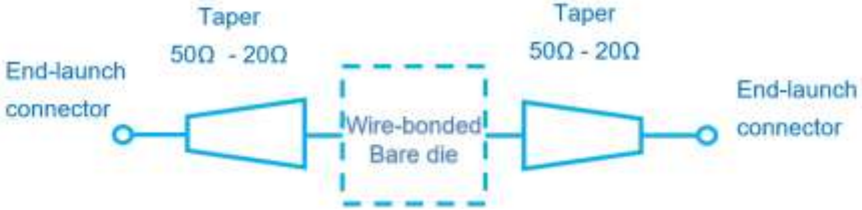
Layout of module

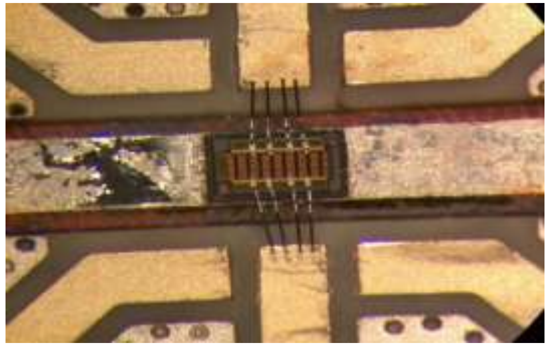
Doherty PA module in testboard

Embedding of GaN power transistors – Doherty PA

Wirebond testboard

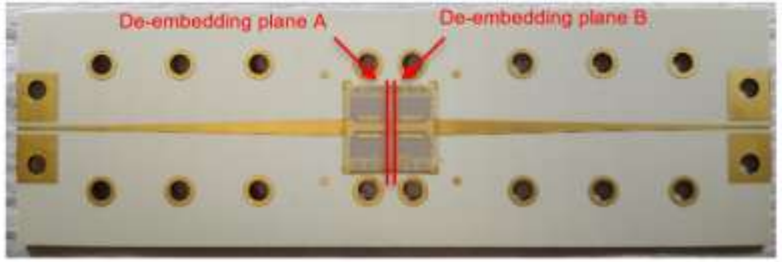


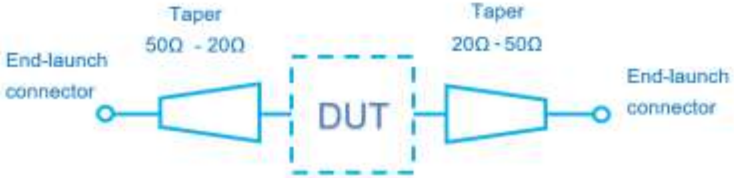


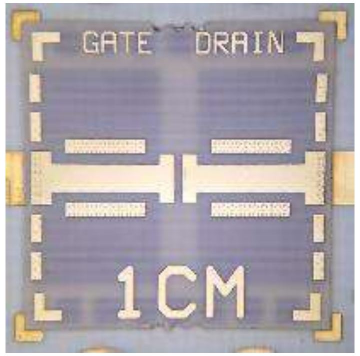


GaN-Si wirebonded

Embedded GaN testboard

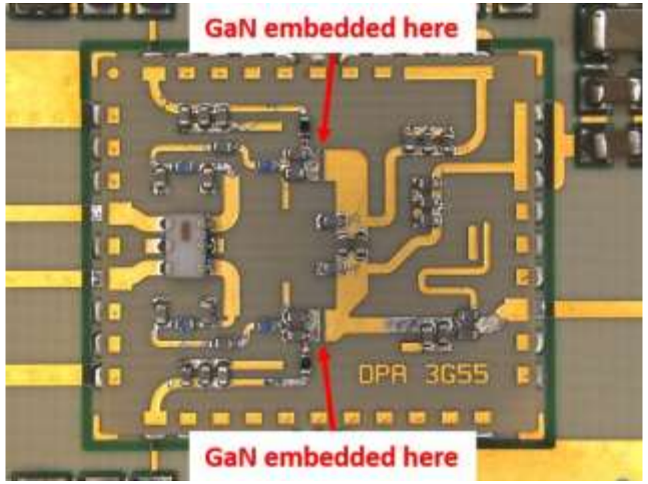




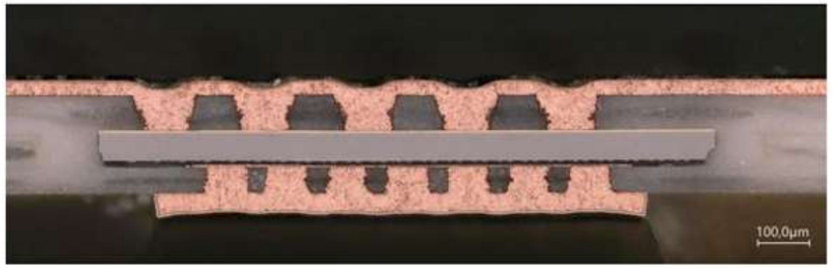


Embedded GaN device

Embedded GaN Doherty PA



Laminate cross section



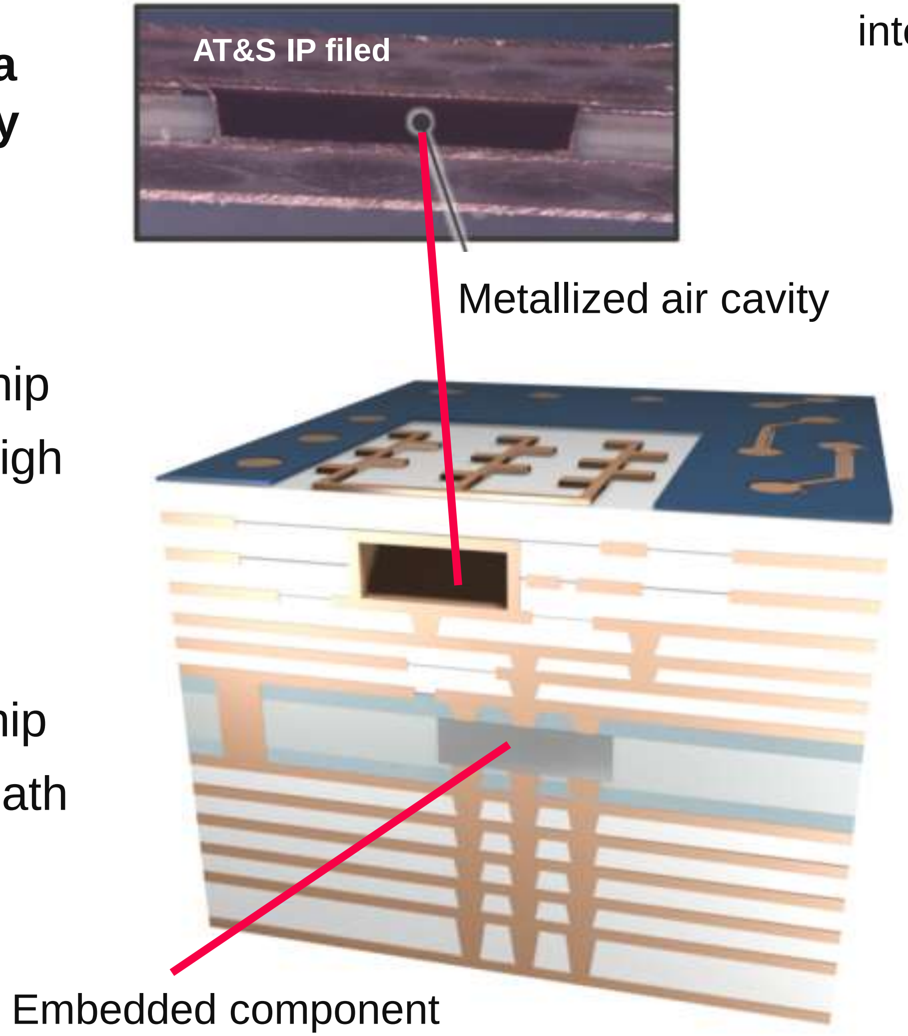
- **Contacting top & bottom pads (electrical contact + heat dissipation)**
- **Reduced interconnect inductance**

I. Peppas, H. Paulitsch, W. Bösch et.al., ‘Bandwidth Extension of a Doherty Power Amplifier Through Reduction of Packaging Related Parasitic Effects’, IMS 2023, We2C-3

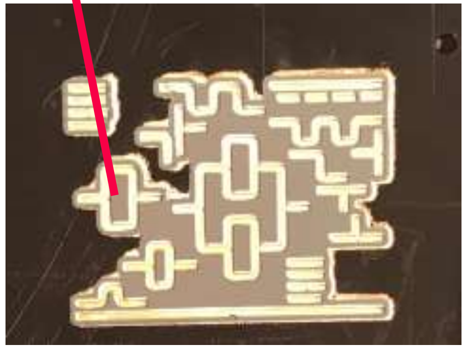
Air Cavity: Radar Sensor - 140 GHz Demonstrator

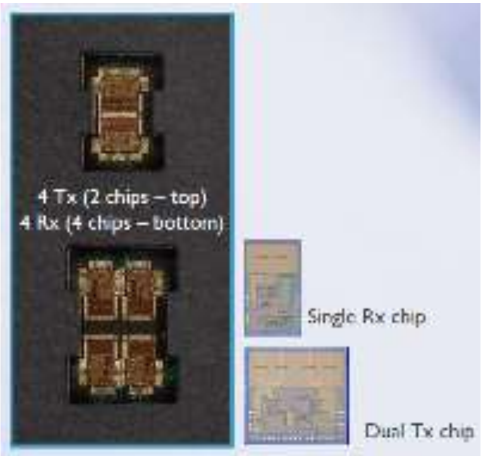
Courtesy of AT&S

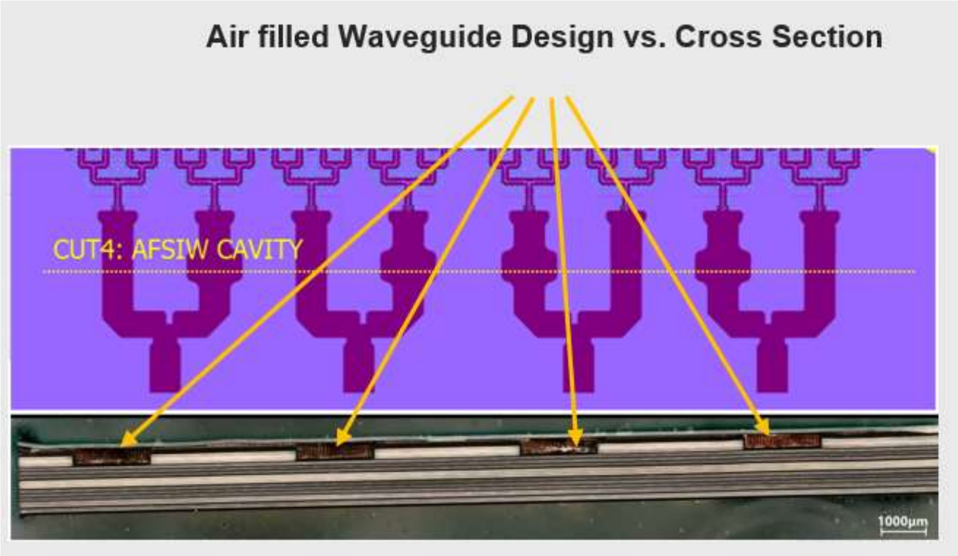
- 4 x 4 MIMO with **Antenna on Chip** & Antenna **Array on PCB** / Substrate
- **Embedded CMOS** Chip @ 140 GHz
- Al terminated Pads on Chip
- mmWave Antenna with high gain / high bandwidth
- **Air-Filled SIW as Low Loss Feeding Line**
- Signal Path above the Chip
- **Heat spreading** underneath the Chip
- Megtron 7 Material



Air filled substrate integrated waveguide

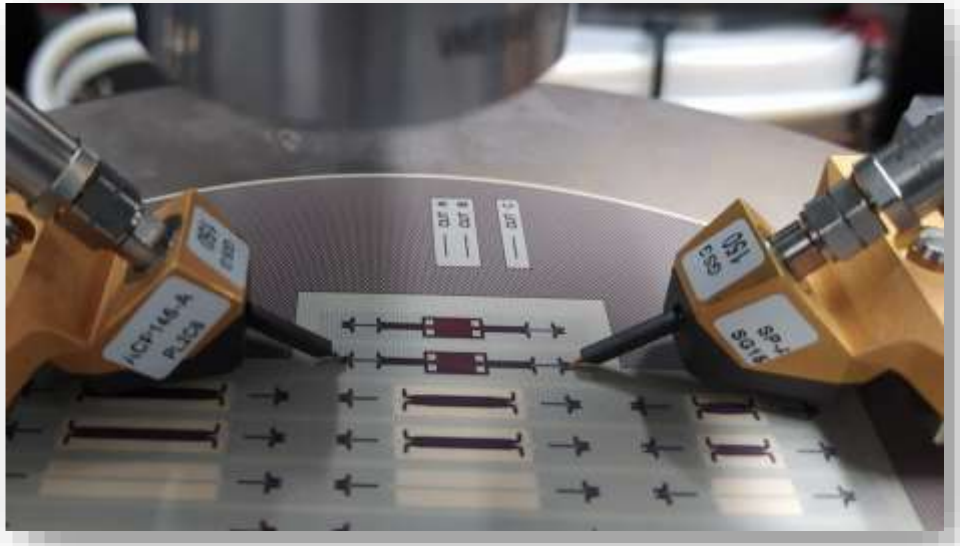


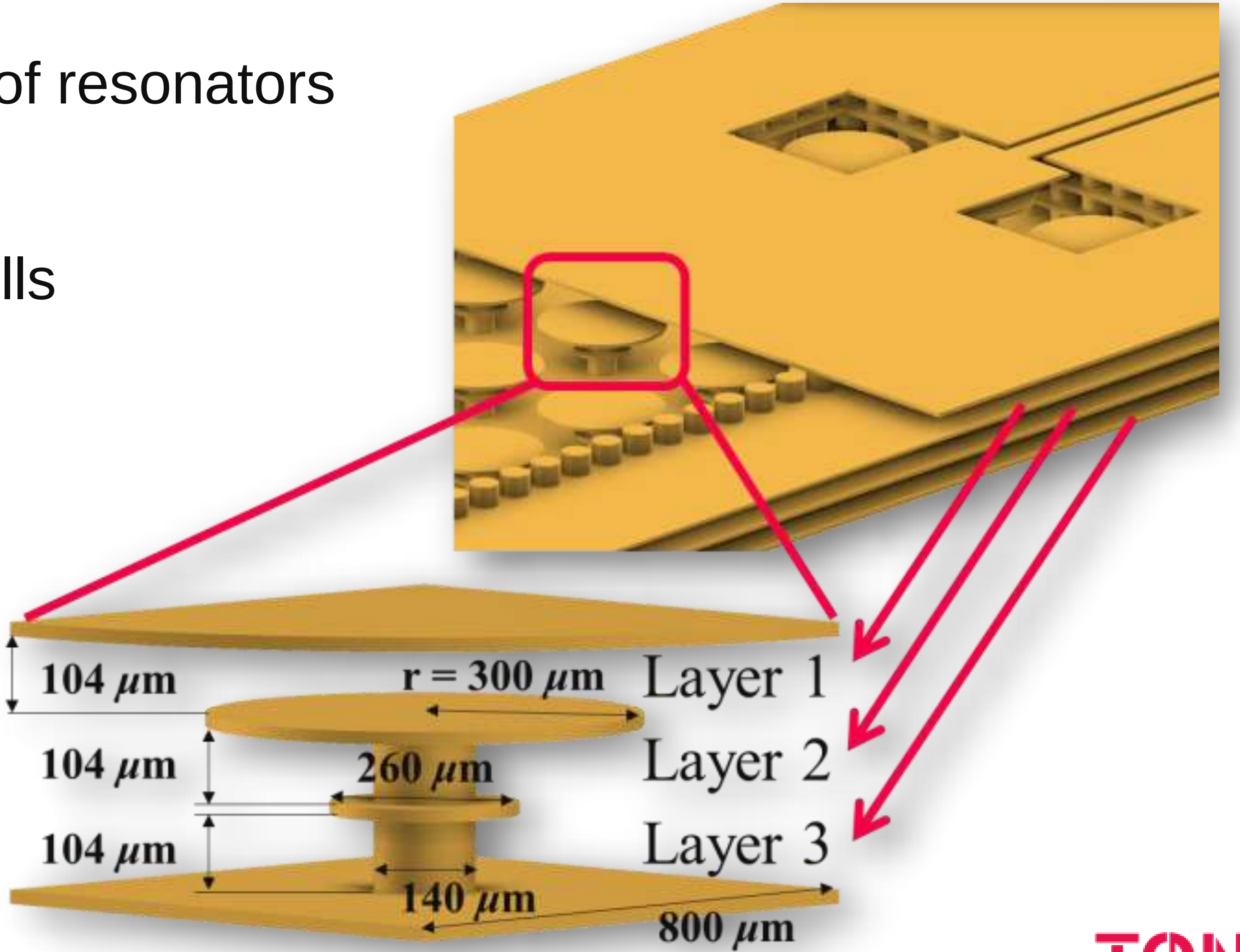




Metasurfaces in PCB technology

- **Metamaterial** => periodic structure of resonators
- mSAP PCB technology
- SIW loaded with metasurface unitcells
- Filter design with
  superior out-of-band rejection



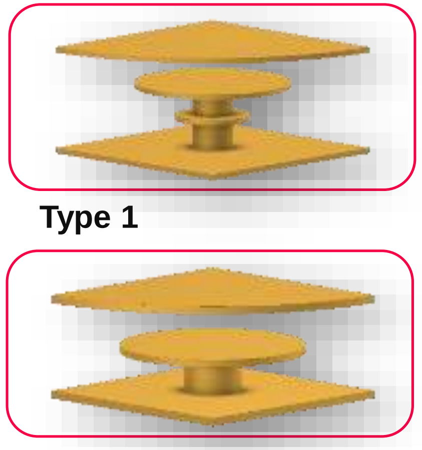


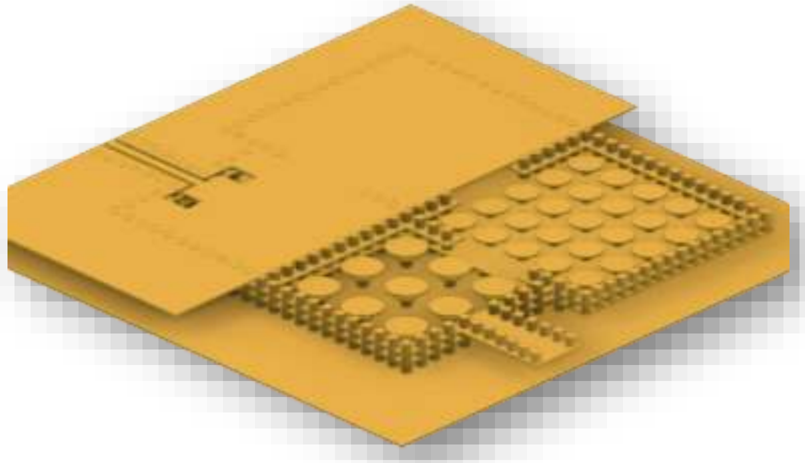
TONI

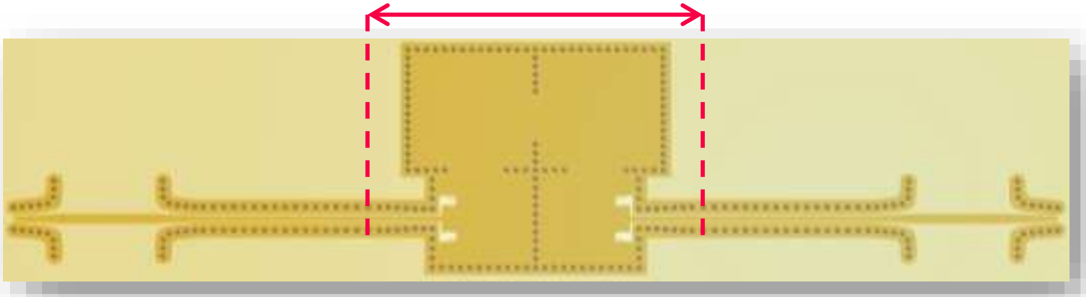
EuMW 2024 - Miniaturized Ka-Band Metasurface Filter With Wide Out-of-Band Rejection up to the 5th Harmonic – Arash Arsanjani - Session EuMC 10-4

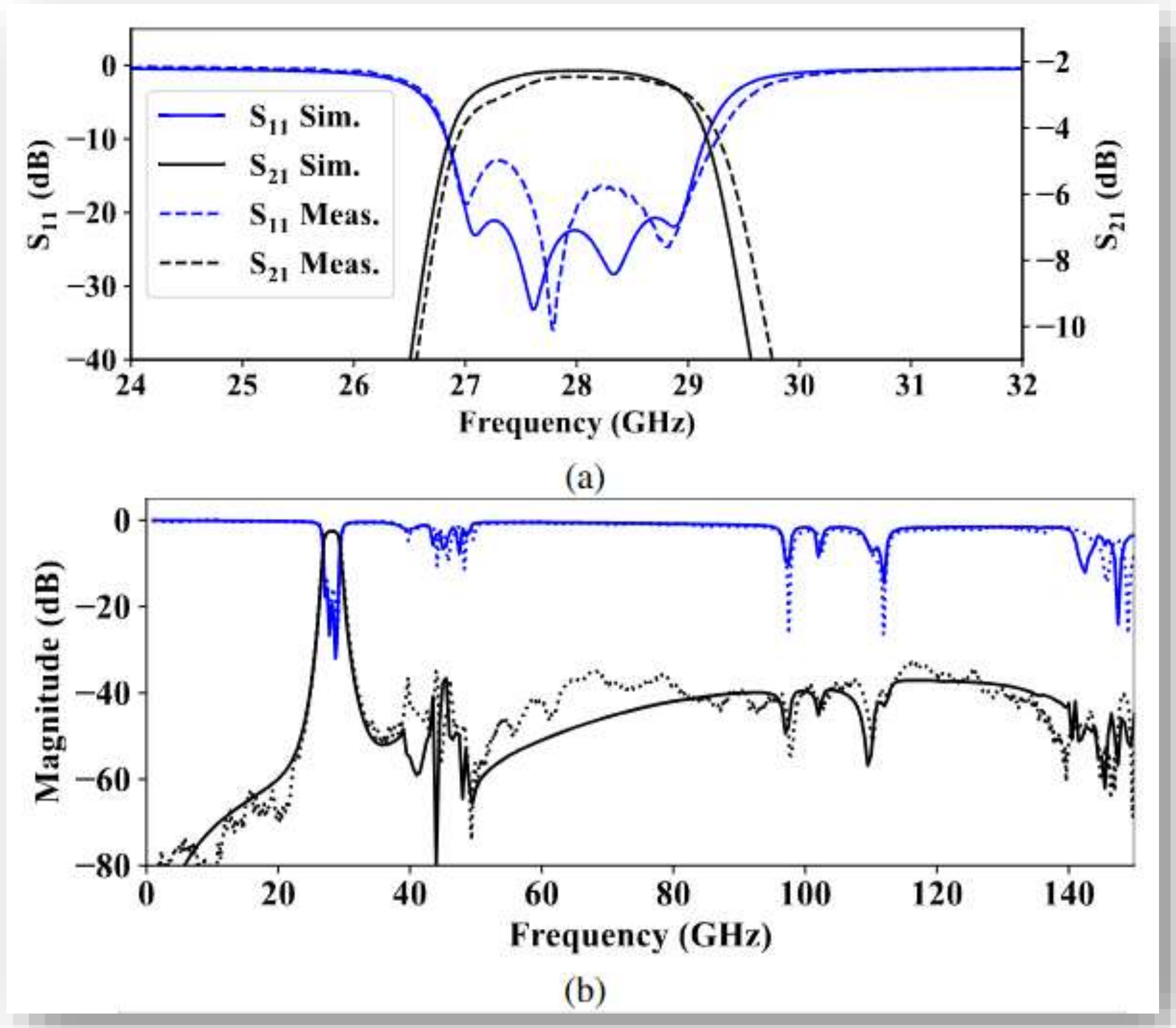
Innovative Metasurface Filter Design in PCB

- **SIW loaded with metasurface -** 2 types of resonators
- **Innovative filter design -** Out-of-Band Rejection better than 30dB from 30 to 150 GHz









A. Arsanjani, Z. Hatab, A. B. A. Alterkawi, M. E. Gadringer and W. Bösch, "Modified Semi-Additive Manufacturing of PCBs for Enabling Accurate Device Measurements at Millimeter-Wave and Sub-Terahertz Frequencies," *2024 103rd ARFTG Microwave Measurement Conference (ARFTG)*, Washington, DC, USA, 2024, pp.

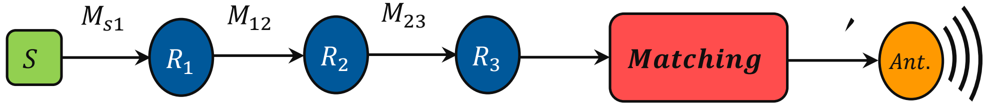
Coupled-Resonator Filter & Antenna => FILTENNA

Traditional Front-End Design:

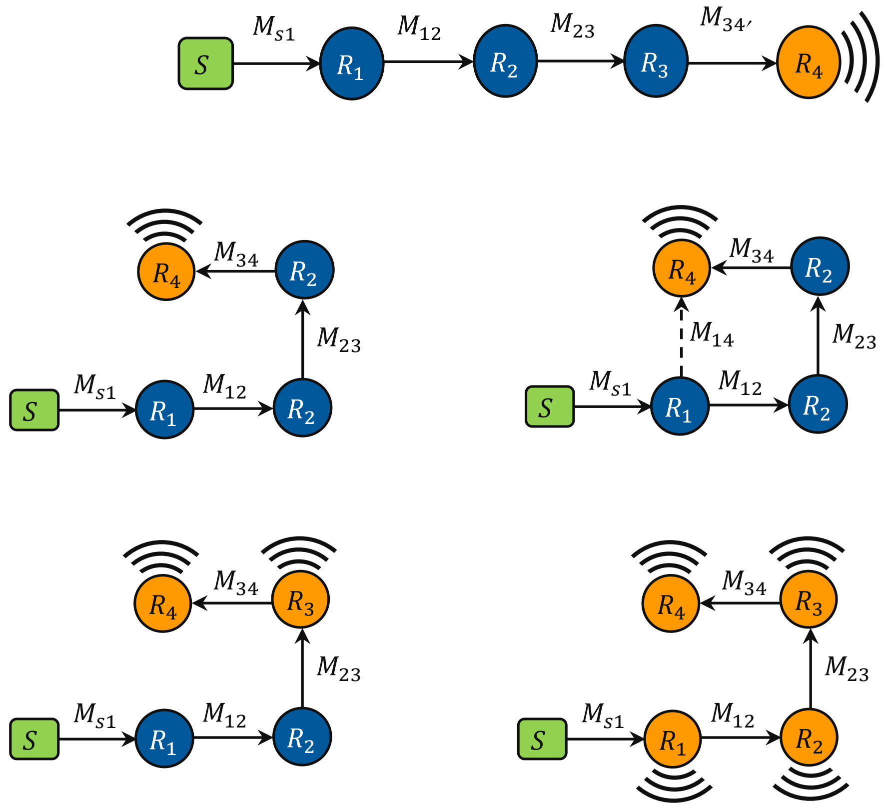
Band-pass filter and antenna are separated components and connected by a matching network

New Front-End Design:

- ➢ Simplify matching network
- ➢ Replace the last resonator of a band-pass filter with a radiating element.
  - ▪ **Size and loss reduction**
  - ▪ **Direct impedance matching**
- ➢ All radiating resonators
  - ▪ **Further size and loss reduction**

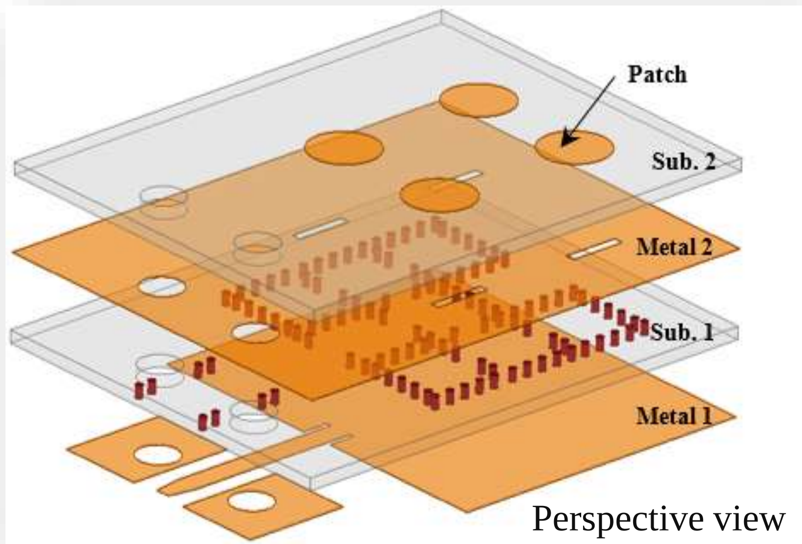


Higher loss & Large size

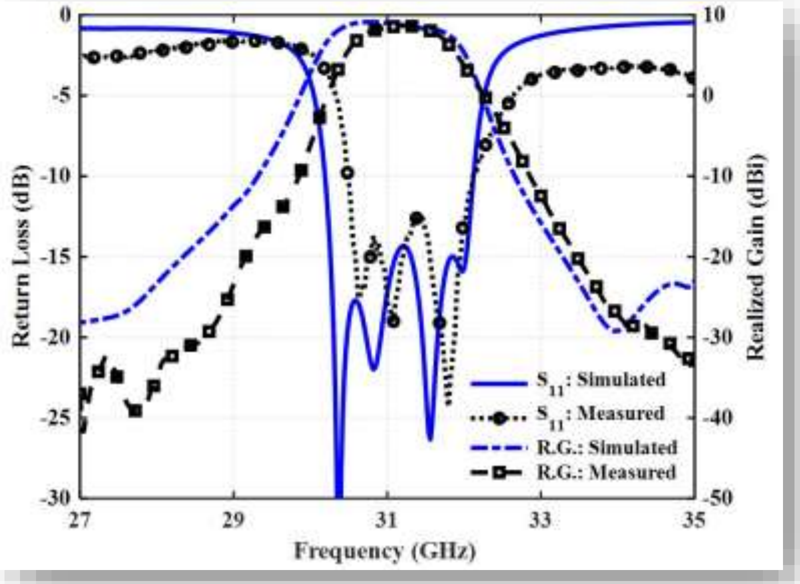


Distributed Coupled Resonator: 2 × 2 Array Filtenna at Ka-Band

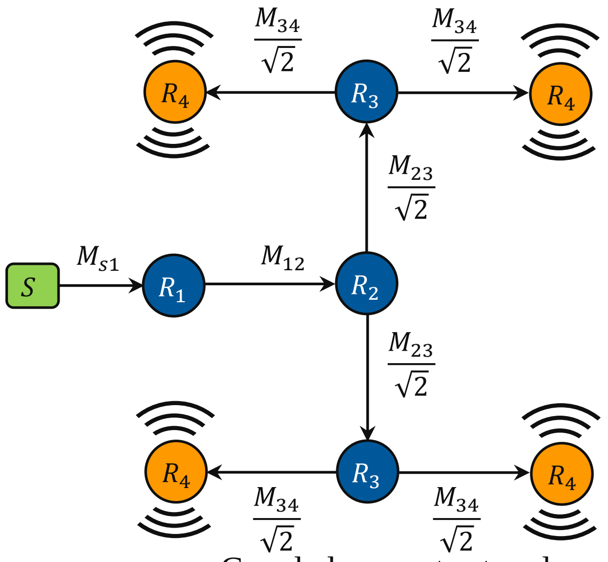
- Application: Radar
- Technology: **PCB: SIW cavity**
- Response:
  - ✓ 31 GHz, BW = 2 GHz
  - ✓ R. Gain = **8 dBi**
  - ✓ 4th degree filter
- Dimension:
  - ✓ $2.1 \times 1.7 \times 1.8 \times 0.1(\lambda_0{}^3)$



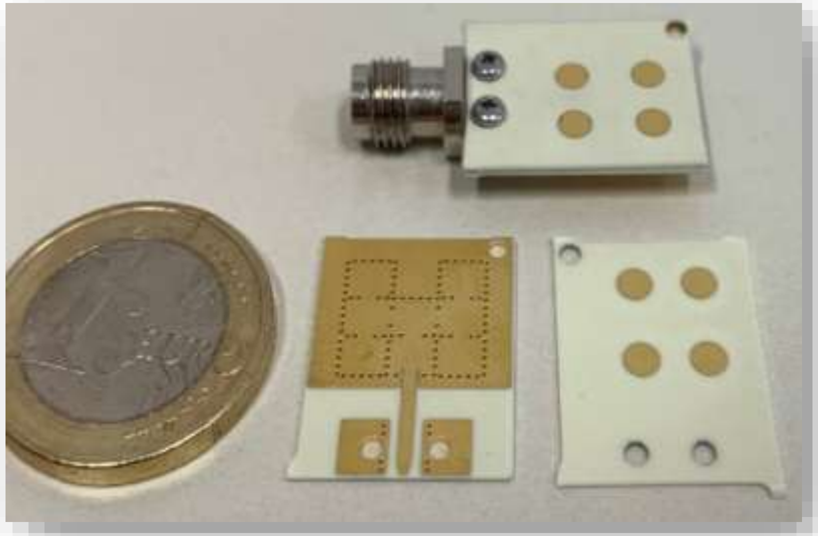
Perspective view

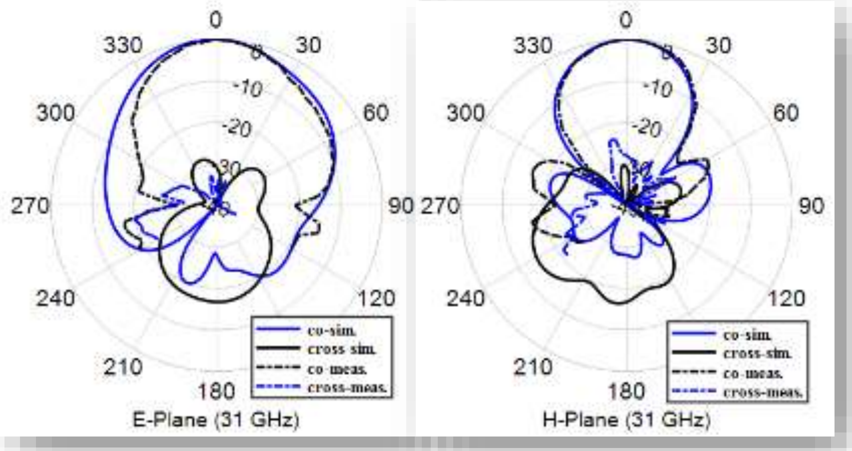


Return loss and realized gain of the Filtenna



Coupled-resonator topology

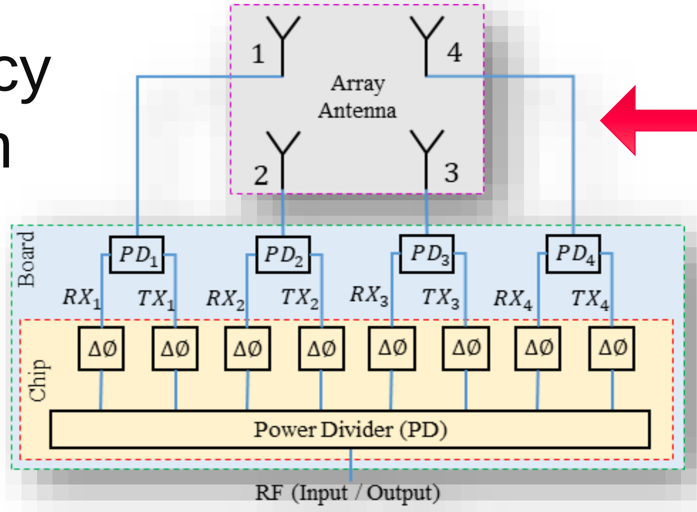

Fabricated prototype

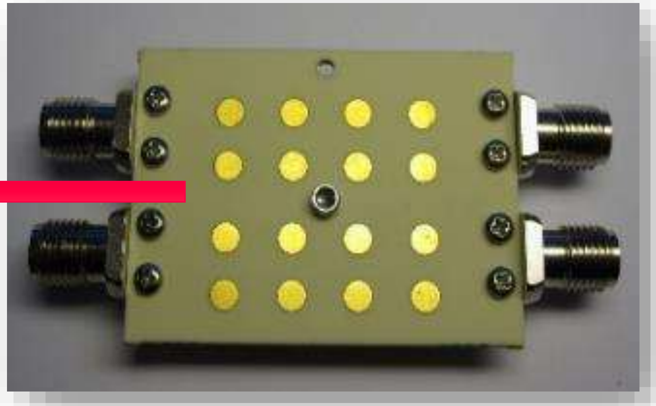


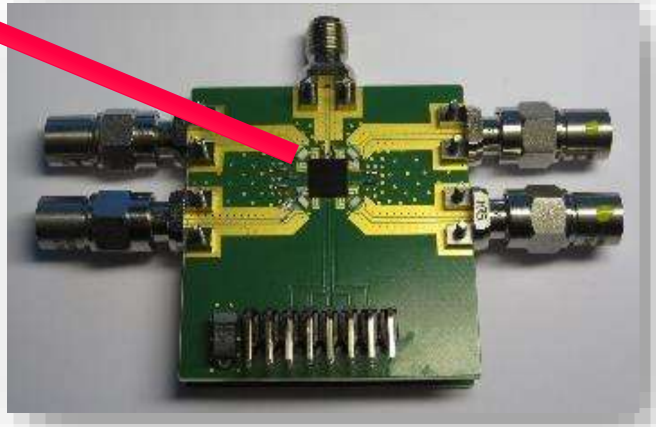
Radiation patterns at 31 GHz.

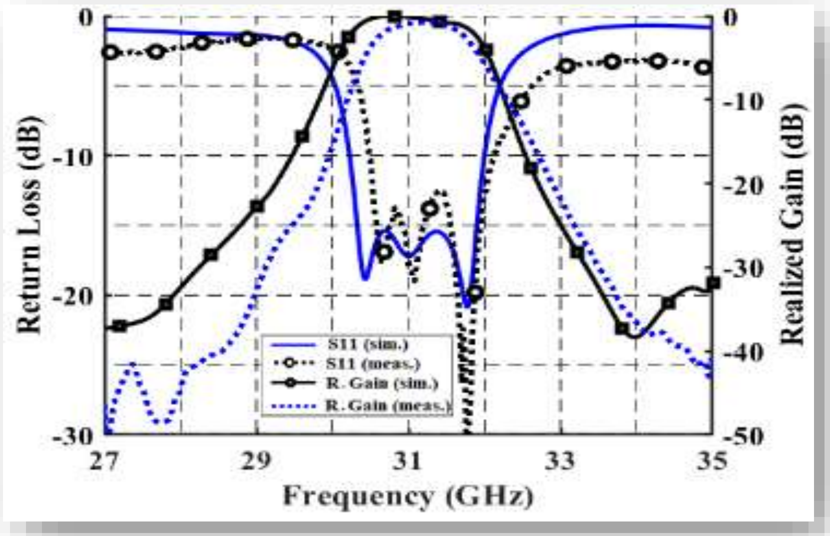
Ka-band Filtering Antenna - Stacked Phased Array

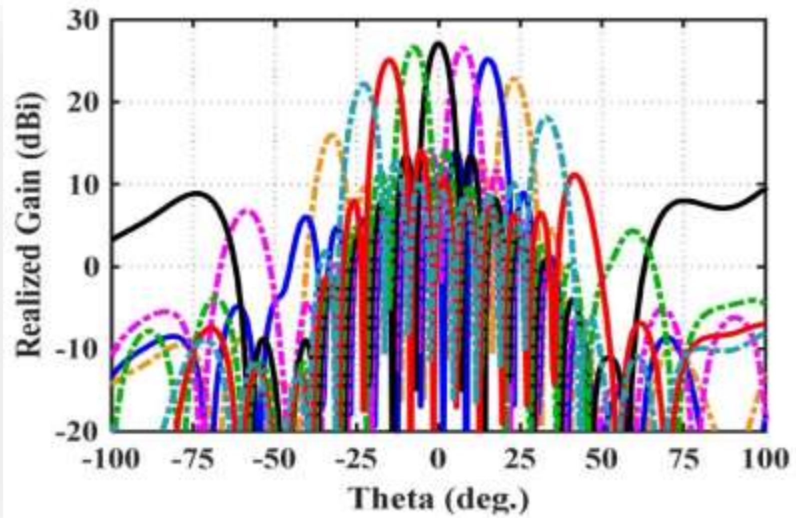
- Highly compact
- Good performance and efficiency
- Flat gain with symmetric pattern
- High frequency selectivity
  4th-degree Chebyshev
- Low-profile and scalable
  to a larger phased array









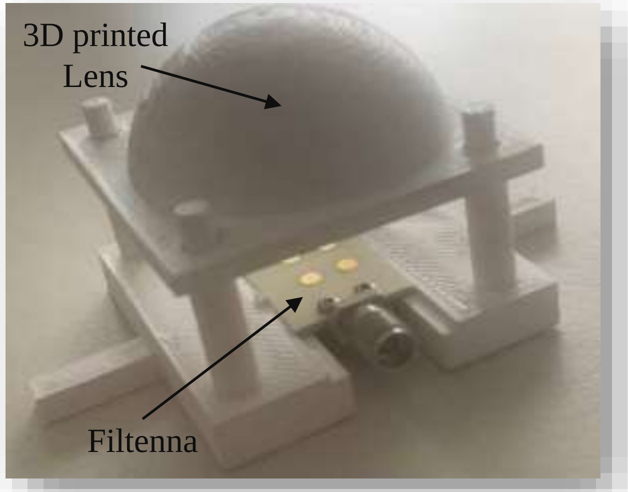


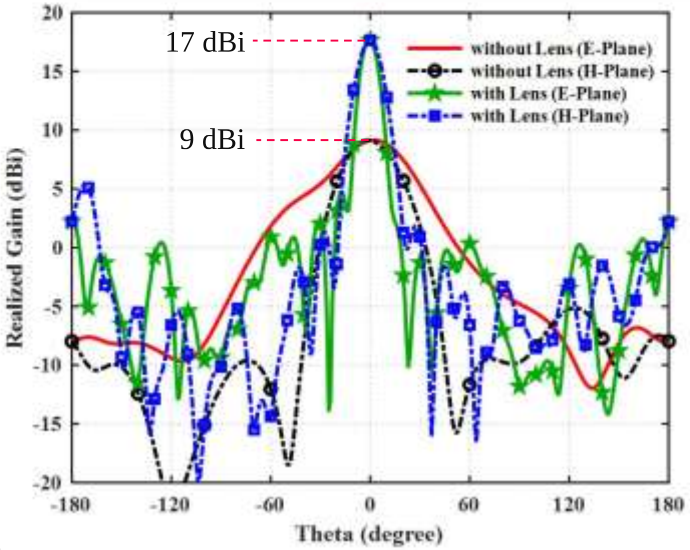
Beam steering at 31 GHz

Best Paper Award
(*iWAT* 2022)

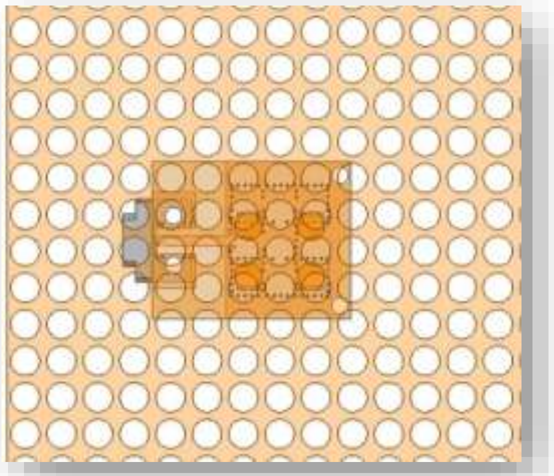
Gain improvement: Lens Antenna

3D-Printed Geodesic Lens
without lens 9dBi with lens 17dBi

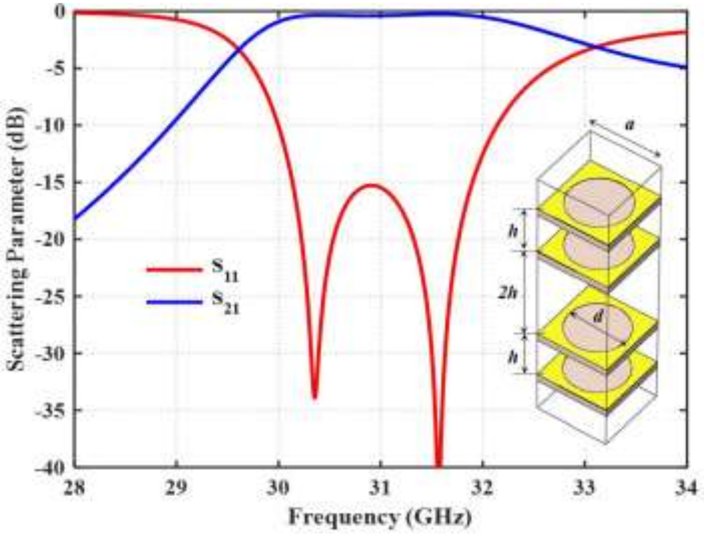




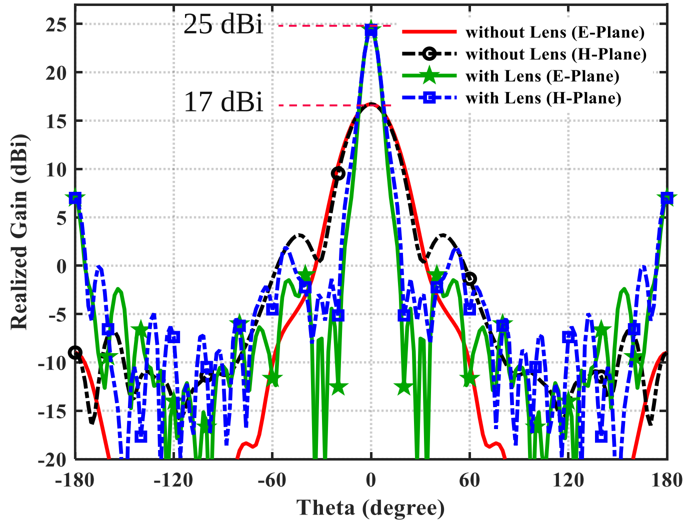
Metasurface Lens (**PCB-based**)
without lens 9dBi with lens 15dBi



Scattering parameters of the periodic unit cell

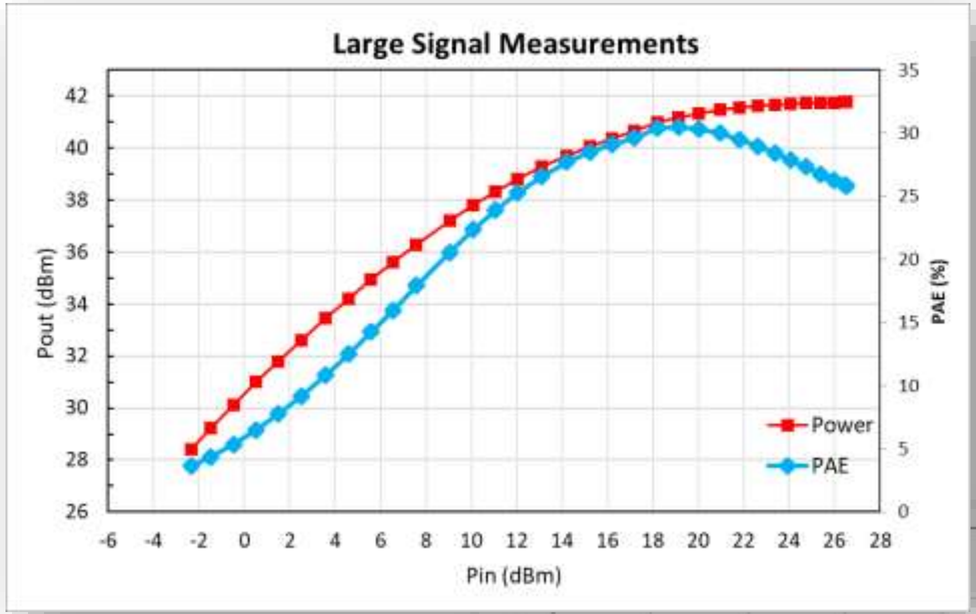


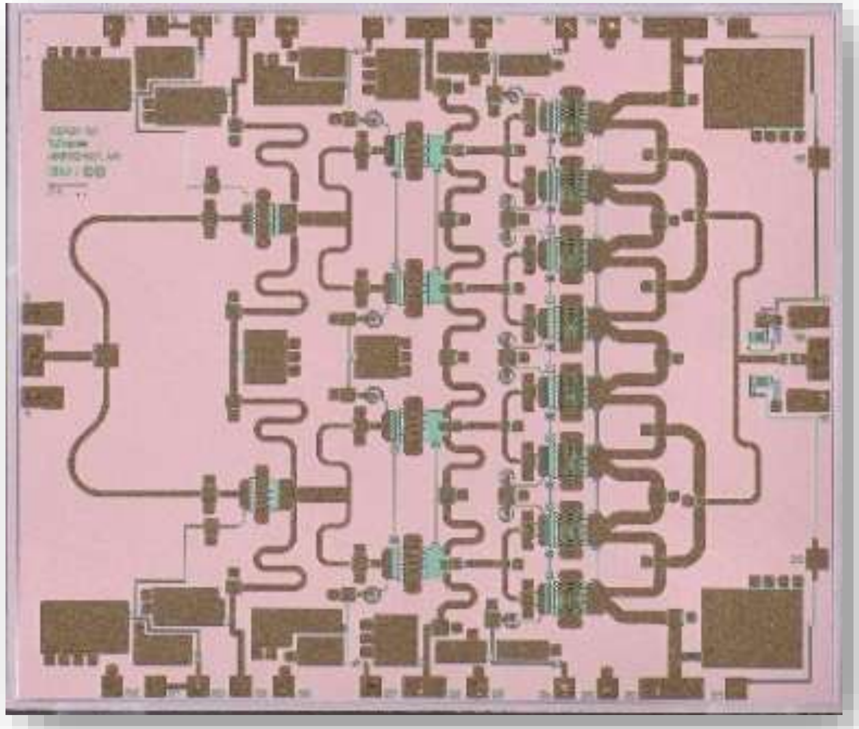
3D-Printed Graded Index Lens
without lens 17dBi with lens 25dBi

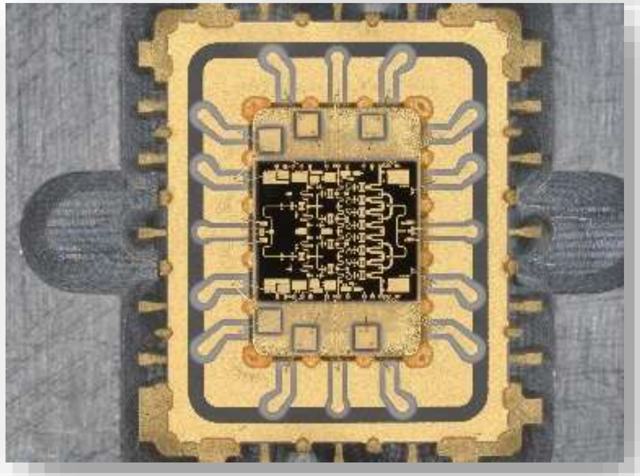


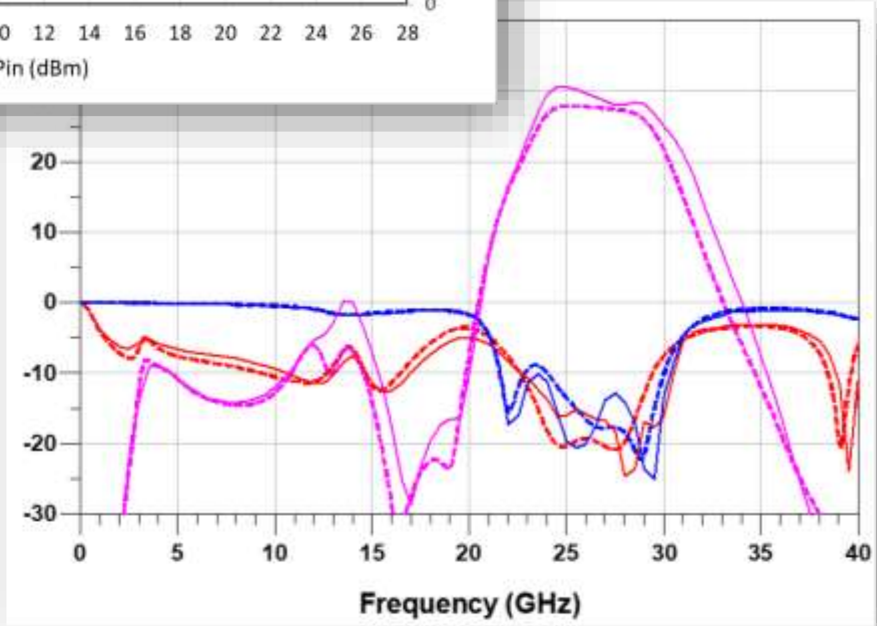
K-Band GaN HPA MMIC

- ➢ Three-stage PA design
- ➢ Integrated output power detector
- ➢ GH15 GaN technology
- ➢ Gain 24dB, Pout 41dBm, PAE 27%





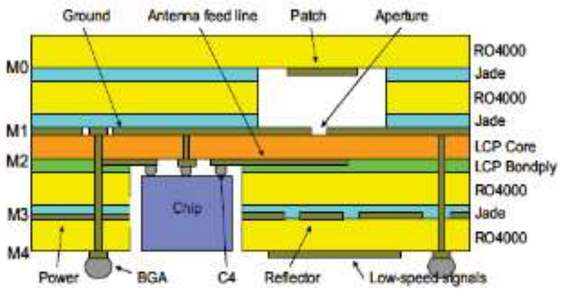




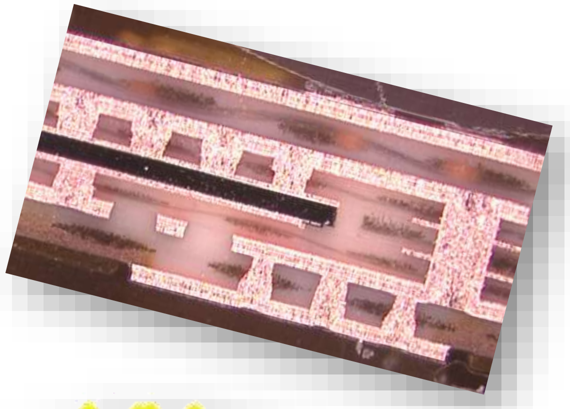
EuMW 2024 –A Compact K-Band High Data Rate Upconverter / Solid State Power Amplifier (SSPA) Downlink Engineering Model for LEO Missions – Jim Mayock

Solution

towards **cost effective** &
high performance mmW front-ends



Merging the research areas and technologies:



- Advances of SiGe / CMOS and GaN **semiconductors**
- **Quasi-Monolythic & heterogeneous integration** technologies
- Advances in the highly dense **multilayer PCB technology**
- Advances of **additive manufacturing**
- Advances in **planar antenna / filter design** / EM simulations
- Innovative **system** and **circuit design** methodologies

Multidisciplinary research effort is needed
to address future 5G / 6G and sensor / radar requirements

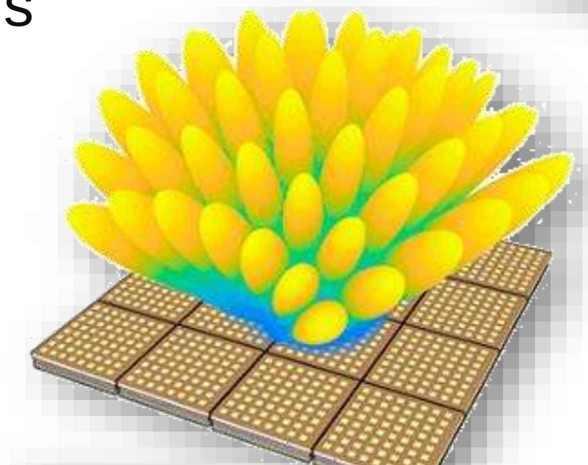
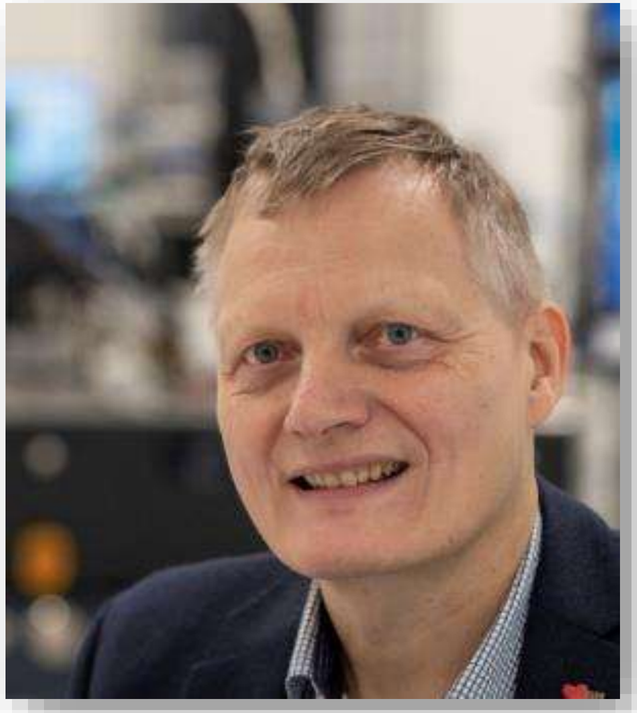


Image courtesy of DARPA

Thank you !



Christian Doppler Forschungsgesellschaft

TONI CD-Laboratory for Technology Guided Electronic Component Design And Characterization

AT&S

Fronius

Qualcomm

ihp Leibniz Institute for high performance micro electronics

FBH Leibniz Ferdinand Braun Institut

VIPER RF