SWTEST

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2022 CONFERENCE

# 5G mmWave: Multi-site RF Probe Cards Enable Lower Cost-of-Test in Mass Production

FormFactor™

Ryan Garrison

Sr. Product Business Manager

FormFactor, Inc.

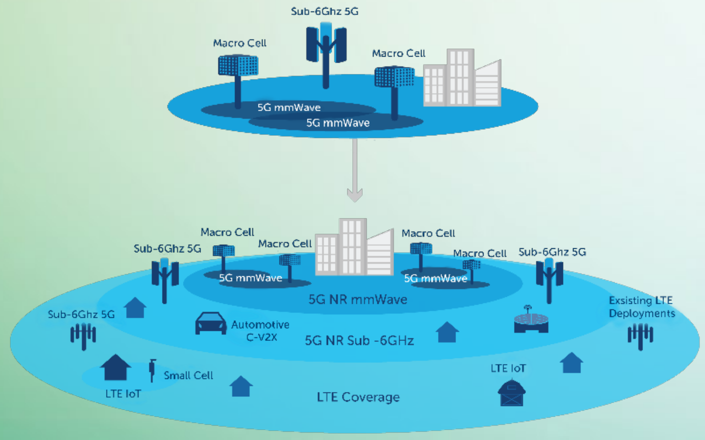
June 5 - 8, 2022

# Overview

- 5G Rollout Update
- mmWave in the Handset
- 5G Test Metrics and Strategies in Characterization and Production
- Key Challenges Overcome
- Summary

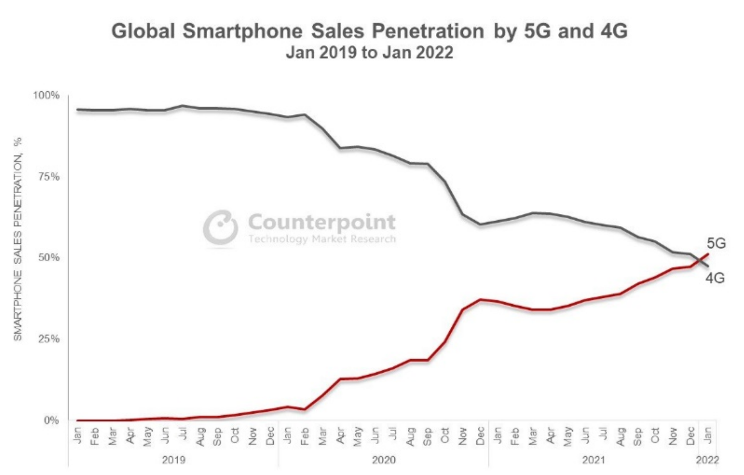
# 5G is Ramping...

## The world's leading economies are actively deploying 5G coverage



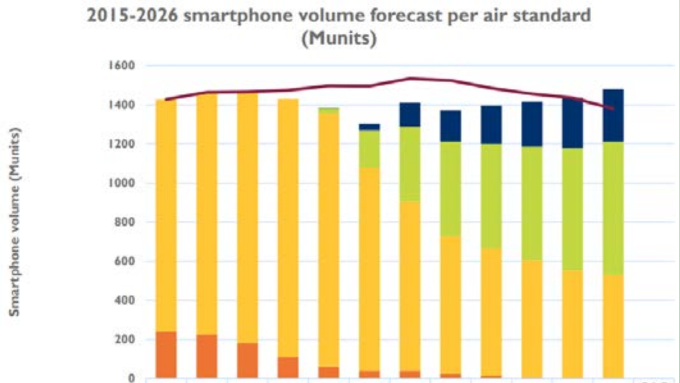

Source: CTS Corporation

## Over half of Smartphones shipped in 2022 will include 5G functionality




Source: Counterpoint's Global Monthly Handset Model Sales (Sell-through) Tracker, Jan 2022

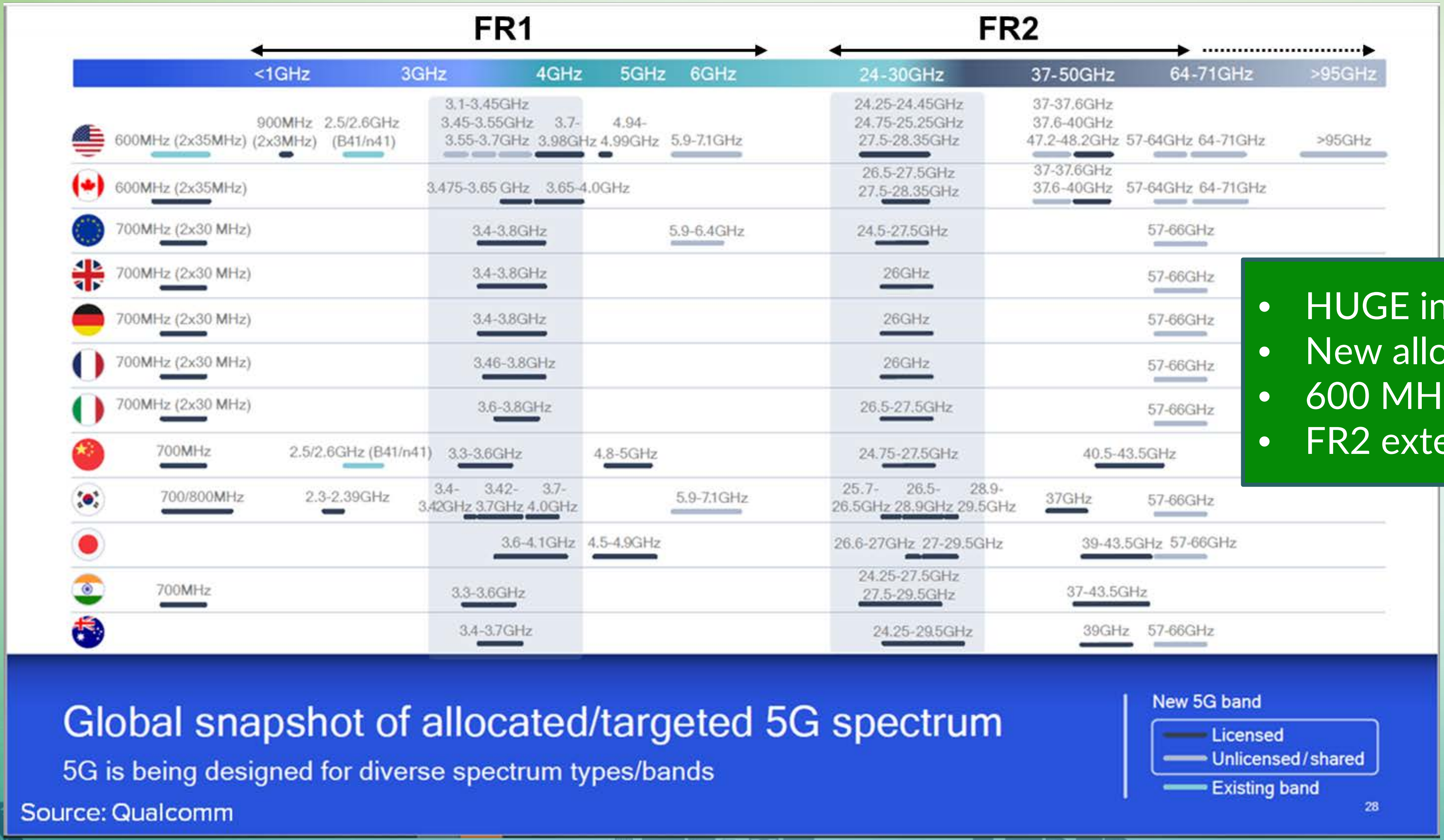
## Demand ramp is soaring and will continue non-linearly




| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | CAGR 2021-2026 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5G sub6 & mmw | 0 | 0 | 0 | 0 | 0 | 33 | 122 | 160 | 195 | 231 | 256 | 270 | 17% |
| 5G mmw | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | -100% |
| 5G sub6 | 0 | 0 | 0 | 0 | 25 | 190 | 382 | 483 | 536 | 580 | 626 | 681 | 12% |
| 4G | 1188 | 1238 | 1285 | 1318 | 1293 | 1037 | 865 | 703 | 650 | 598 | 548 | 526 | -9% |
| 3G | 239 | 226 | 182 | 111 | 63 | 40 | 41 | 25 | 16 | 7 | 5 | 3 | -41% |
| Inventory | 1427 | 1464 | 1467 | 1474 | 1497 | 1495 | 1534 | 1524 | 1485 | 1455 | 1435 | 1380 | |

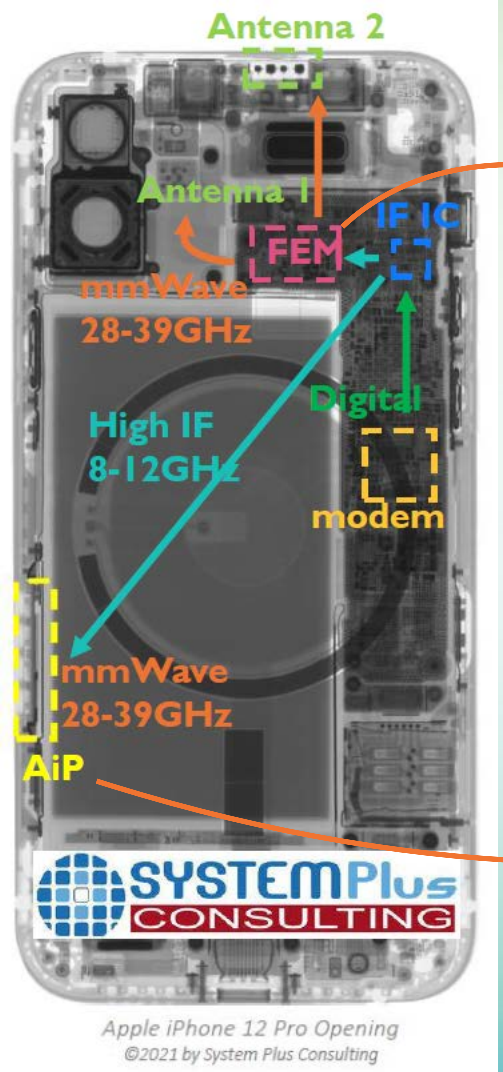
Cellular RF Front-End Technologies for Mobile Handsets 2021 | Report | www.yole.fr | ©2021

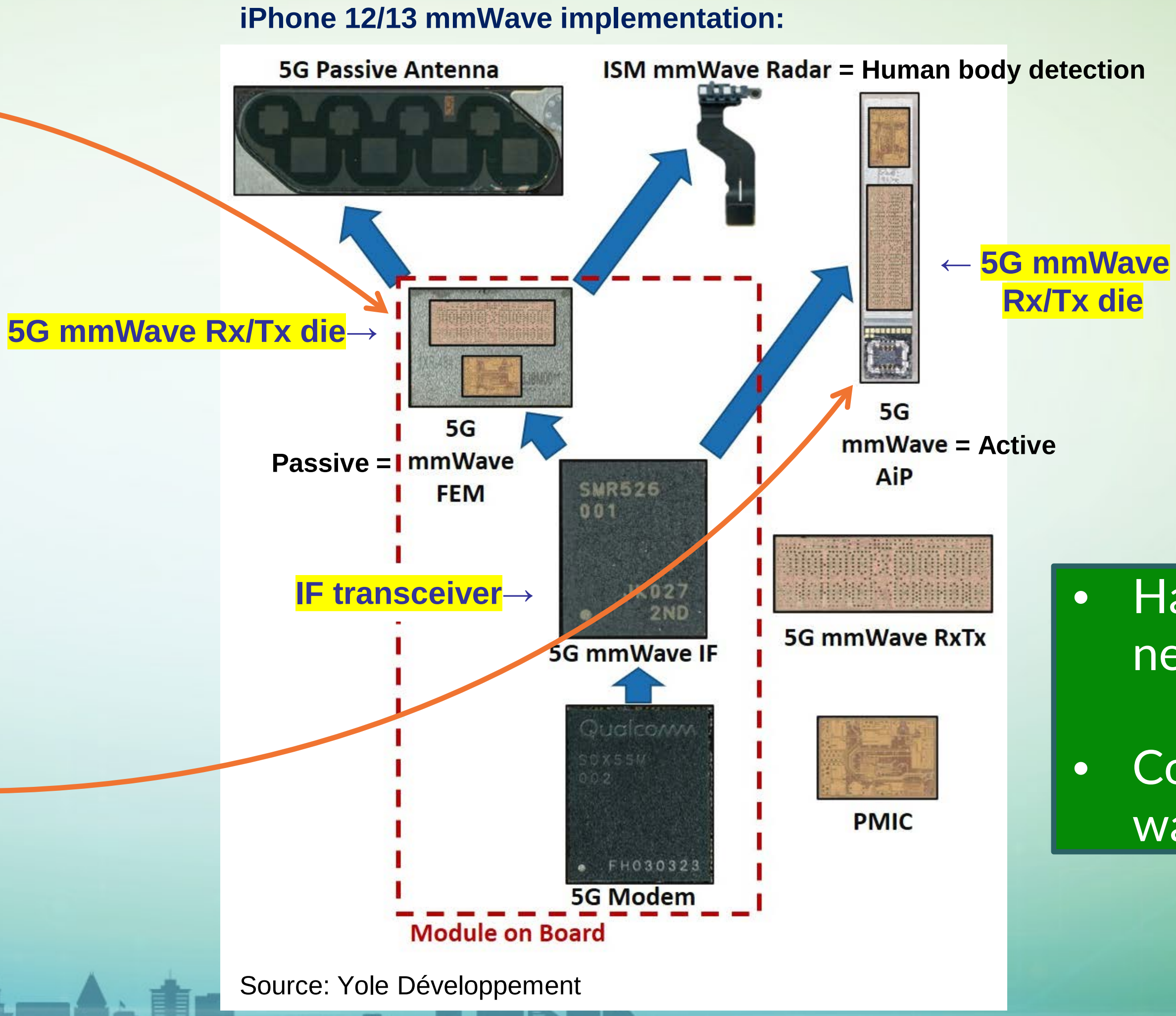
# 5G Frequency Spectrum Landscape




- HUGE increase in spectrum usage
- New allocations in all regions
- 600 MHz to >**71 GHz**
- FR2 extends 5G into mmWave

# 5G mmWave in the Handset

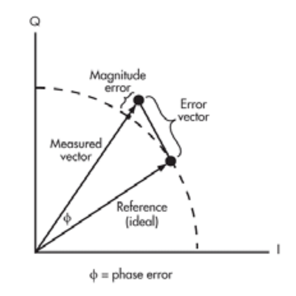


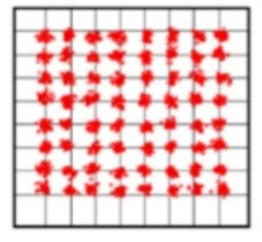

- Handsets have 2+ new mmWave dies
- Cost/yield drives on-wafer test for KGD

# 5G mmWave RxTx Test Metrics

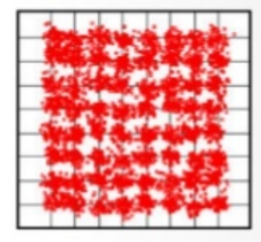
- **5G mmW Rx/Tx die encode data by varying phase and amplitude of RF carrier**
- **Error Vector Magnitude (EVM) is key performance metric for RF transceivers, including 5G mmW Rx/Tx die**
- **Incredibly tight phase modulation is used to steer the transmission beam**




64 QAM
EVM = 4.6%

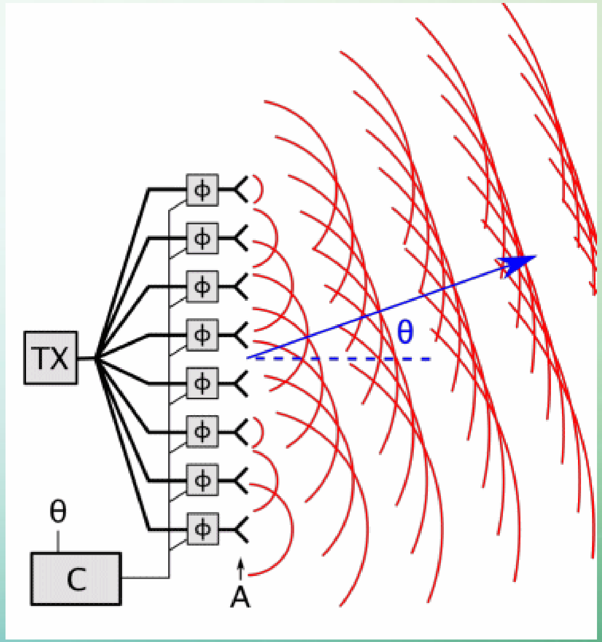


64 QAM
EVM = 6.7%



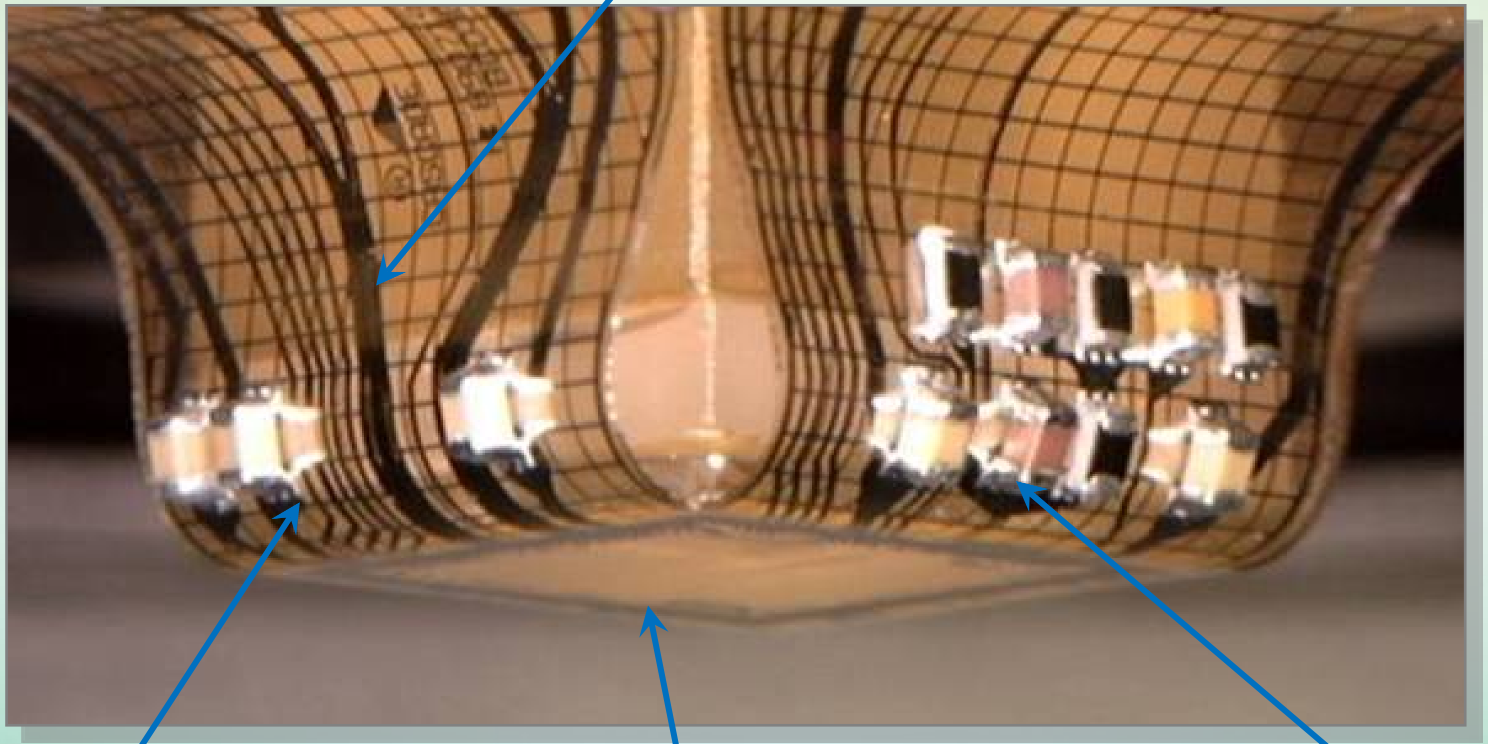
5G mmW Transceiver module is the antenna

➔ Die characterization must happen at wafer sort and requires full mmWave connectivity



# Pyramid Probe: Best Production On-wafer Signal Integrity

Controlled impedance transmission lines

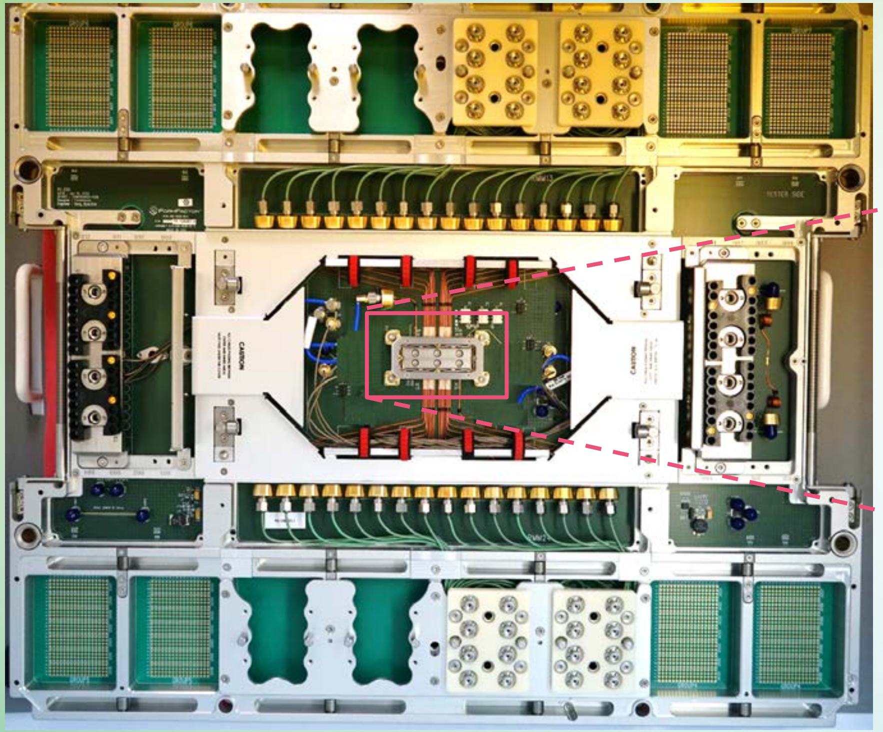


Low inductance power and ground to the probe tips

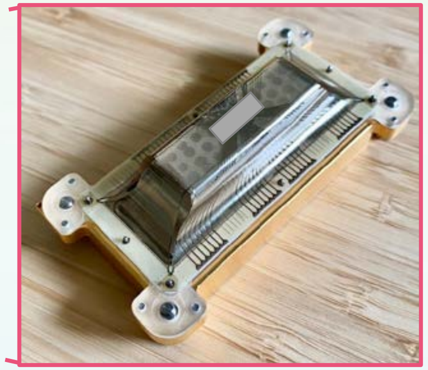
Low contact resistance <200 milliohm on different metals

Bypass capacitors or components as little as 20 ps from the DUT

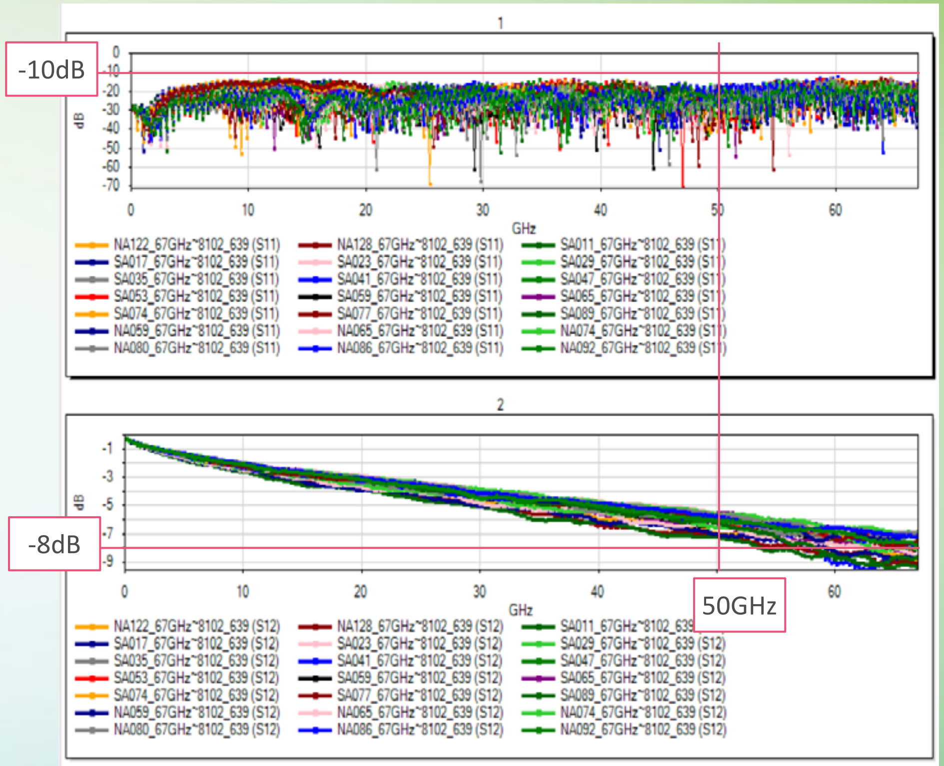
# FormFactor x1 Card for RF Characterization



1X ATE Probe Card – V93000: full mmWave routing



1X Contact Engine (core)




Full probe card RL/IL graphs. Low loss. Repeatable.

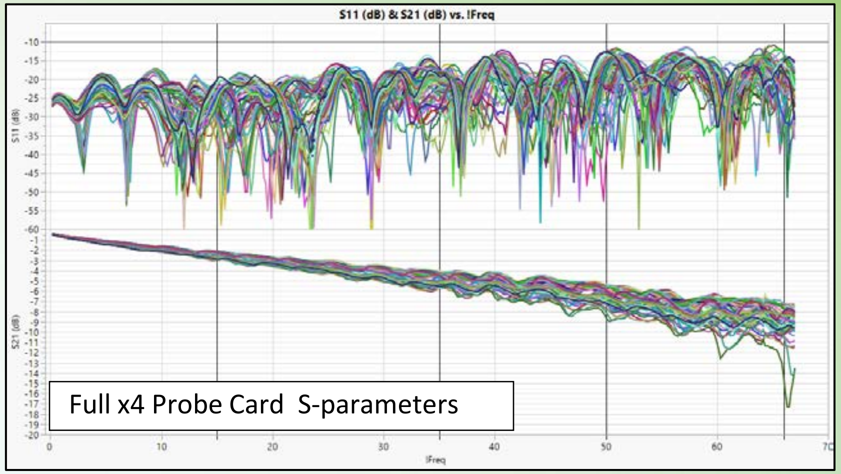
Pyramid probe cards have low RF loss and phase stability allow for accurate characterization of mmWave RxTx EVM and Beam Steering performance

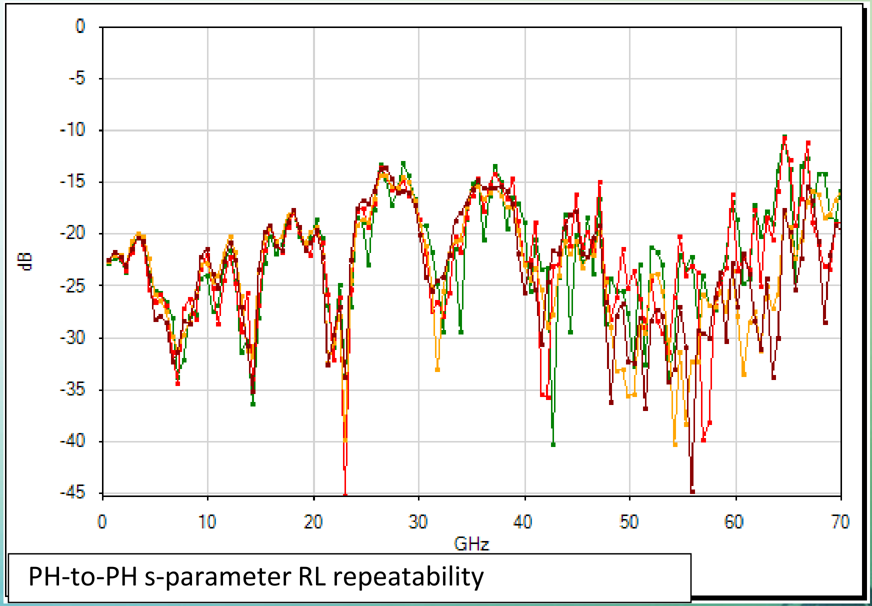
# Consistent RF Performance

- **Membrane fabrication tolerances = tight distribution of RF performance**
  - Low site-to-site variation
  - Low card-to-card variation
  - Low touchdown to touchdown variation
  - Low loss by design

- **Customers successfully use statistical techniques like NNR and Multivariate PAT to avoid rejecting good dies**

Predictable RF performance = improved die yields

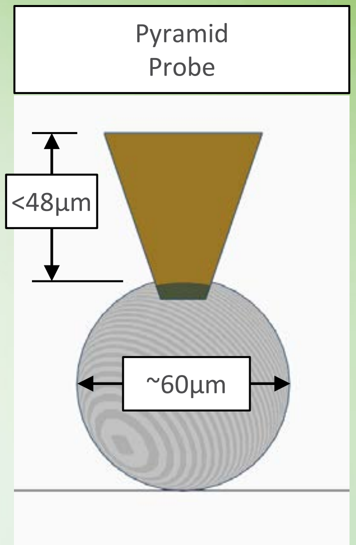


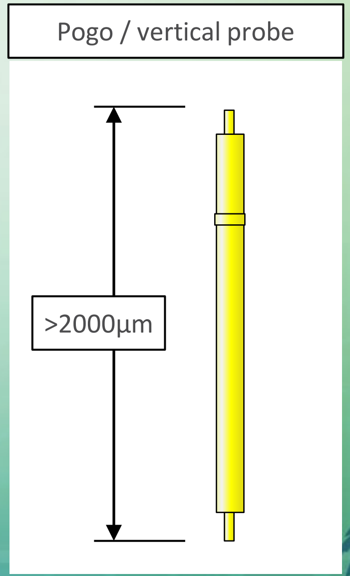



# Wavelength Matters

- **At 55 GHz, 1 wavelength = 5.545mm**
- **Structures below 1/10 wavelength act like lumped elements**
  - Pyramid tips are less than 1/100 wavelength → negligible
  - Minimal geometry changes vs. over travel and probe lifetime
- **Structures above 1/10 wavelength act as distributed components**
  - Pogo and vertical probes ~ ½ wavelength minimum (~2mm min length)
  - Phase shifts from touch-down to touch-down
- **Consistency at each touchdown enables simple de-embedding calibration methodology**

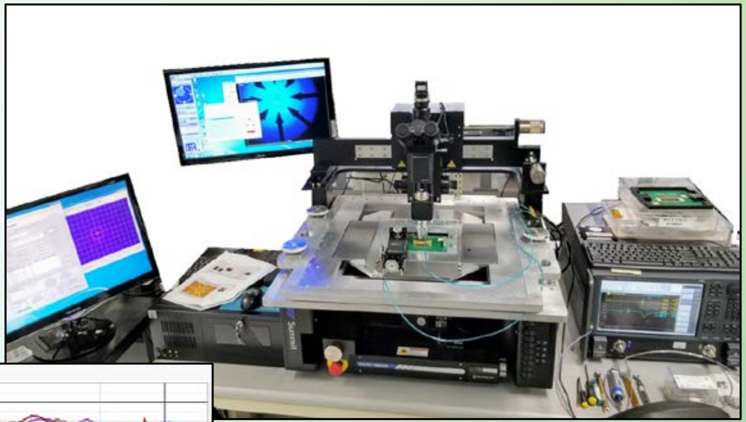

Short probes are best for RF to achieve best performance

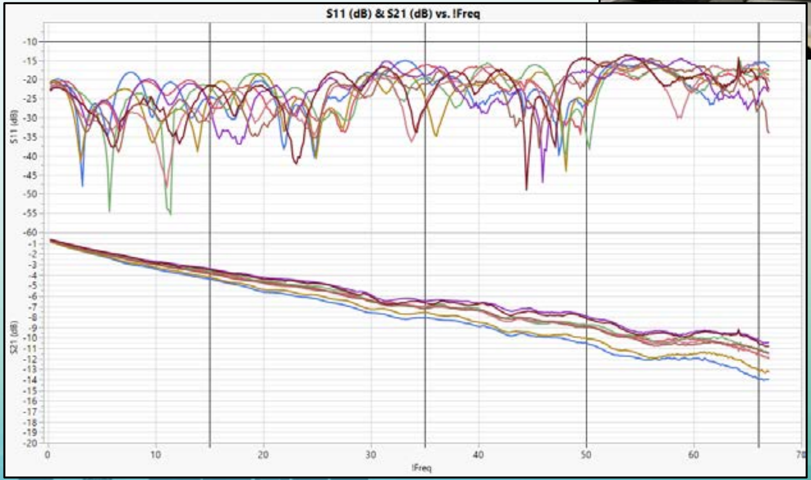


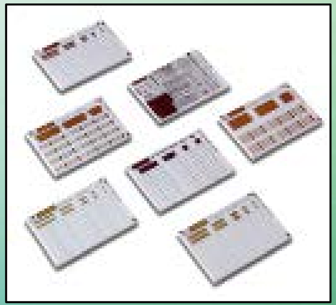



# Consistency Breeds Effective De-embedding

- **De-embedding defined:**
  - Technique used to remove the effects of the probe card and test cell from the measured s-parameters leaving behind transmission qualities of the DUT
- **Calibrated connector-to-probe-tip s-parameters measured in-factory, then de-embedded from any measurement taken anywhere**
  - Customized RF test cell
  - Multipurpose calibration standard with SOL
  - 67 GHz VNA

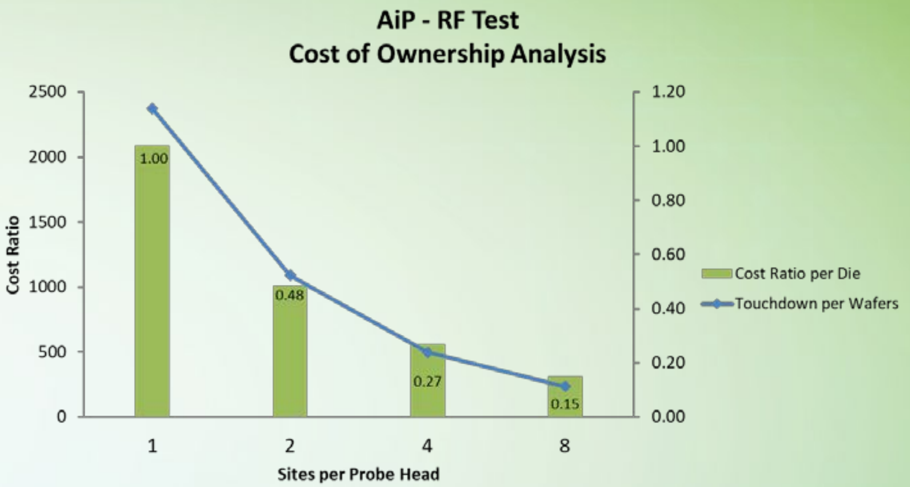


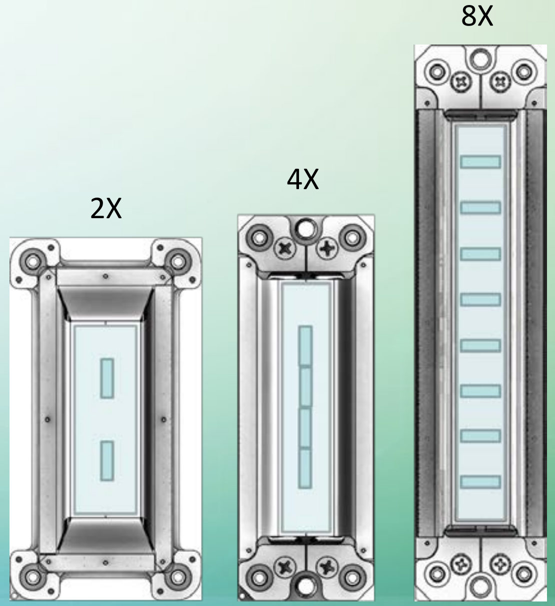


# mmWave Device Test in Mass Production

- **Production volume for 5G mmWave RxTx chips growing rapidly**
  - 2019: 10M units
  - 2020: 75M units
  - 2021: 248M units*
- **As volume goes up, cost of test must go down**
- **Probe cards with increased site parallelism enable cost reductions**
  - But capitalize on gains by not scaling up mmWave interface and tester resources
- **Cost of test is reduced by 63% using a 4X in production, and is the current state-of-the-art for mmWave Production test**



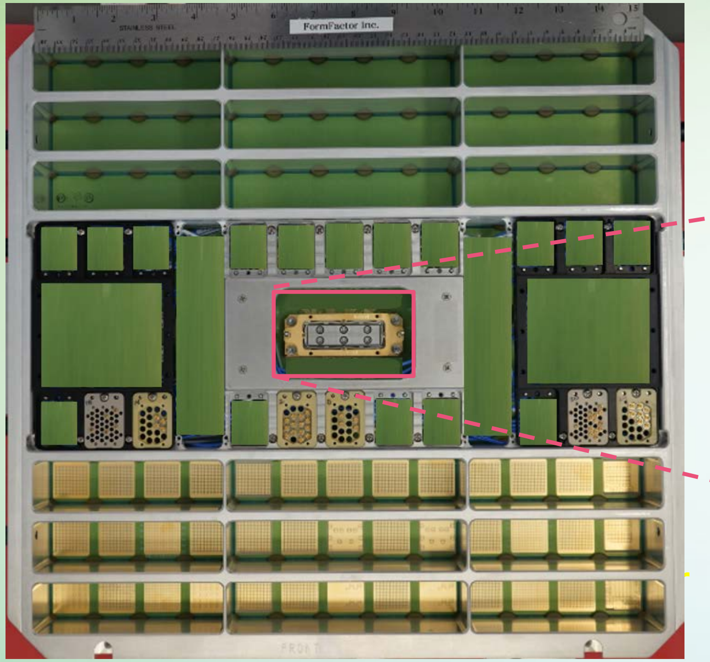




(Approx. to scale)

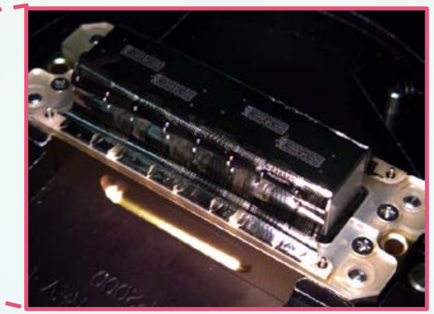
**Increased parallelism is necessary.**
**mmWave test accuracy and repeatability cannot be compromised.**

* from Yole Développemont

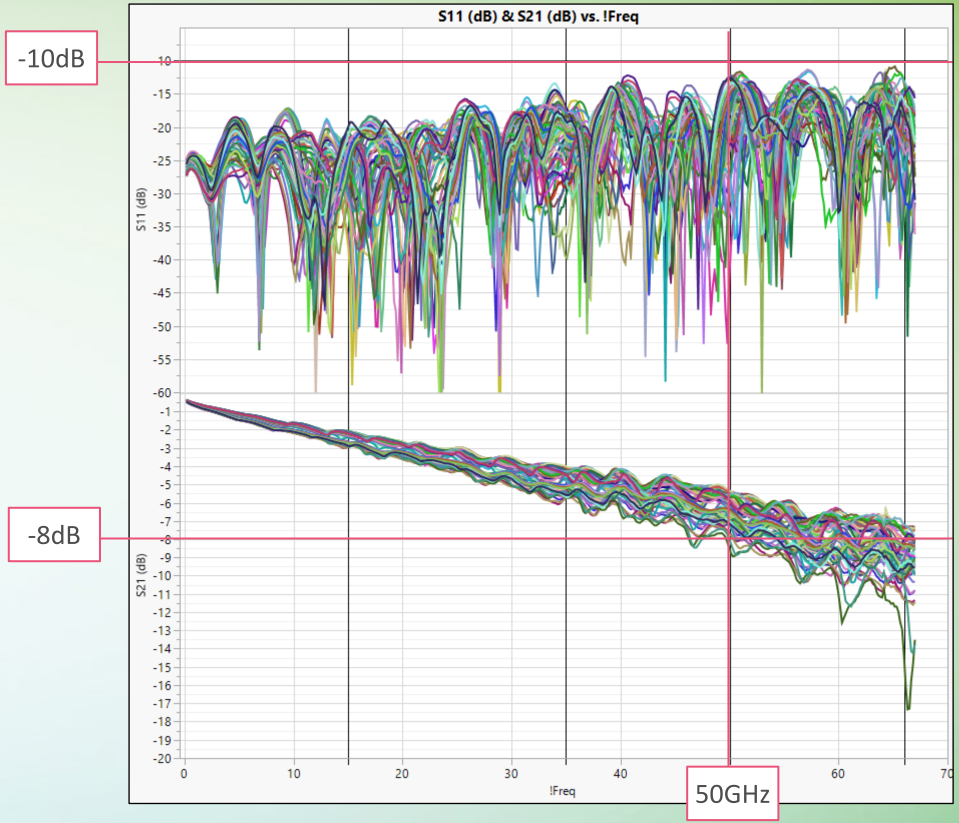
# 5G TxRx in HVM Production




4X Probe Card – Ultraflex DD



4X Contact Engine (core)

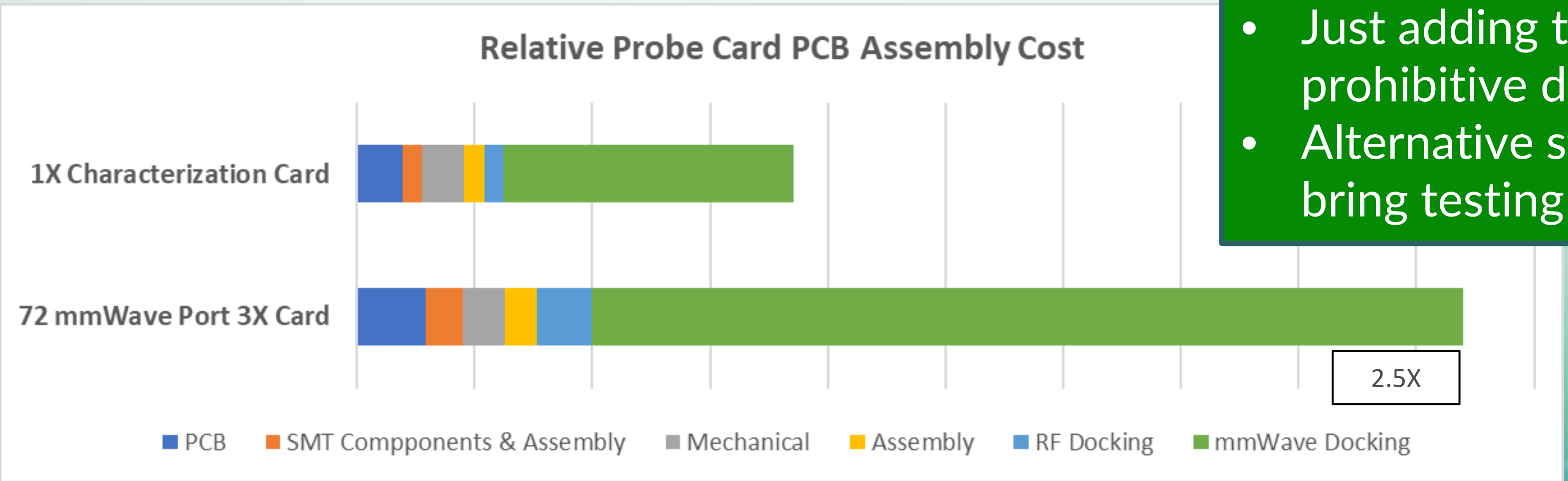



Established 4X Pyramid Production Solution

- Volume production across multiple OSAT sites
- 100s of units shipped → > 300M dies tested and counting
- 128 mmWave lines per contact engine route from DUTs to tester

# Cost Challenges of Increasing Test Parallelism

- **Tester channel capability supports 3X testing max**
  - V93000 Wave Scale Twinning has up to 72 ports at 67GHz (2X max //)
  - UltraFLEX UltraWave up to 96 ports at 67GHz (3X max //)
- **Tester expense**
  - mmWave ports are $$$
- **Probe card interface expense**
  - Even at 1X, mmWave docking and interconnect is > 60% of overall probe card PCB cost
  - Scales linearly with number of interconnects

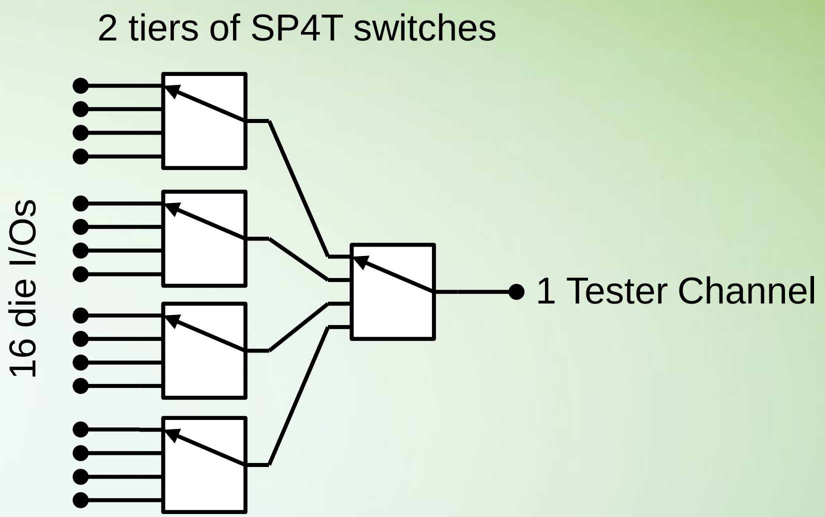


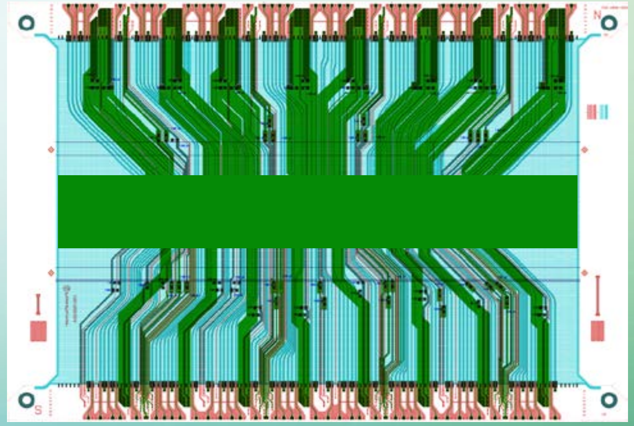

- Just adding tester resources is prohibitive due to $$$$.
- Alternative strategies needed to bring testing onto the probe card.

# MUX Strategy to Extend Tester Capability

- **RF signals onto PCB, RF Switch matrix to MUX/deMUX to one tester I/O**
- **Advantages**
  - mmWave signals routed to tester
  - Full coverage of all I/O
- **Disadvantages**
  - Serial testing
  - High loss on PCB and in switches requires high dynamic range on tester I/O
- **Challenges**
  - Cutting edge RF switches are required
  - All mmWave lines need to be fully routed to PCB

Implemented on Production 4X cards running in HVM today!

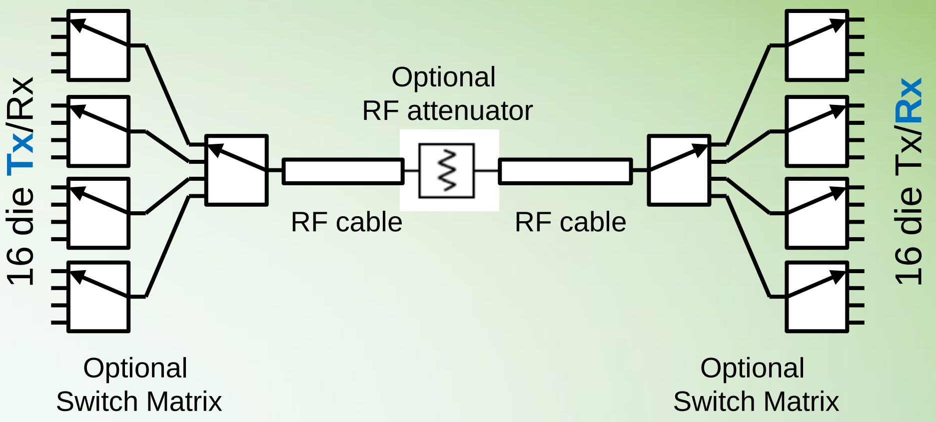


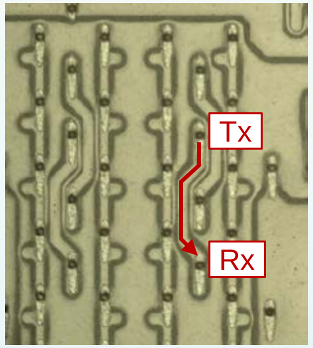
All 128 mmWave lines routed to PCB

# Loopback Approaches to Extend Tester Capability

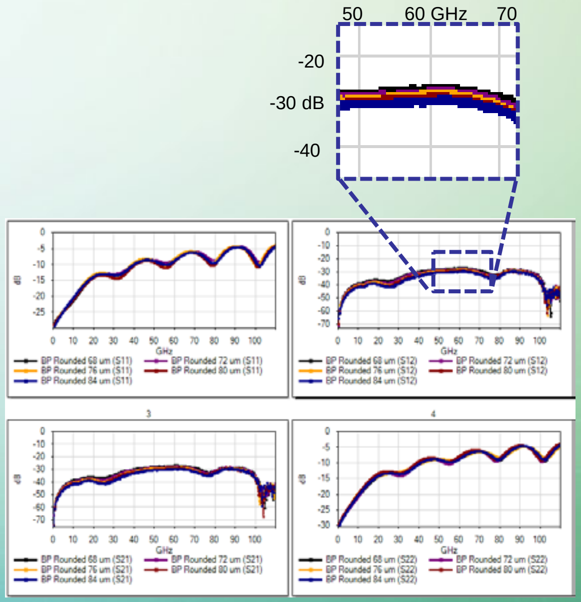
- **PCB-level loopback**
  - Connect one or more I/O together on probe card PCB
  - Can use attenuator to match power levels




- **Probe Head loopback**
  - Direct connect Tx to Rx at the die
  - No power level matching
  - Crosstalk a concern




- **Probe Head loopback with attenuation**
  - High performance microwave circuits built into the Pyramid head
  - 3D field simulation = first time right

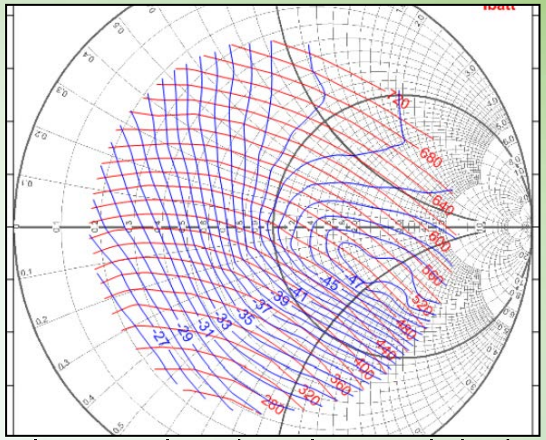



28dB attenuator at 60 GHz, measured results

**Microwave circuits in the membrane simplify the probe card**

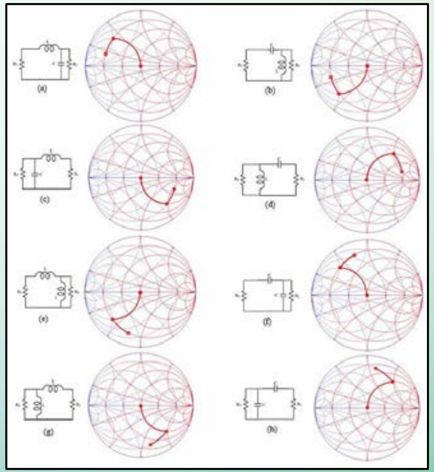
# Unique Challenges of Testing an Antenna Driver

- **Antenna input impedance is rarely 50Ω in target band**
  - Varying input parameters can result in contour lines on the Smith chart
  - Matching PA output impedance to antenna impedance minimizes reflections back into the device

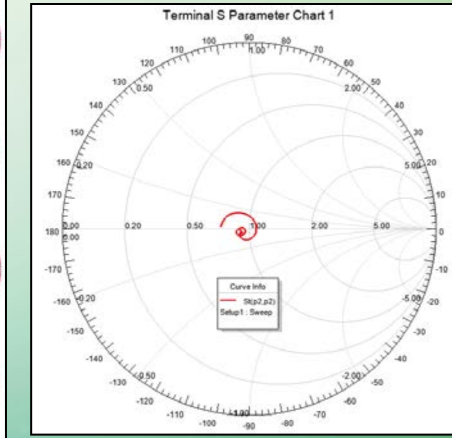


Typical Antenna input impedance optimization plot

- **Pyramid Probe transmission lines can be matched to expected input impedance**
  - Non-50Ω transmission lines
  - Complex impedance matching through discrete component networks
  - Impedance transitions in transmission lines
  - Transitions can occur very close to DUT



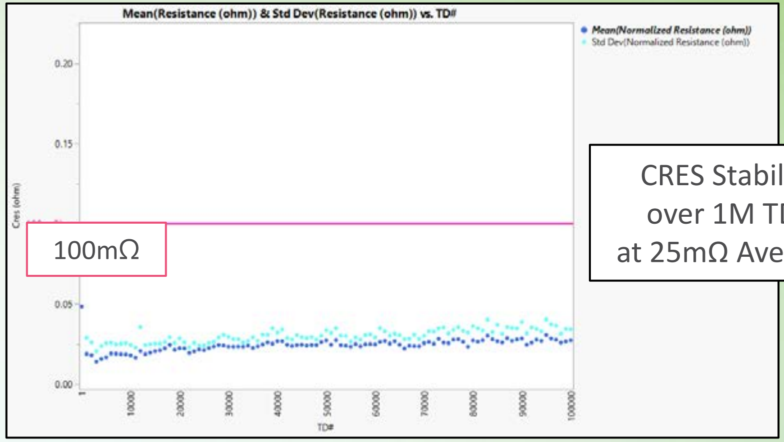
Complex impedance matching with discrete components



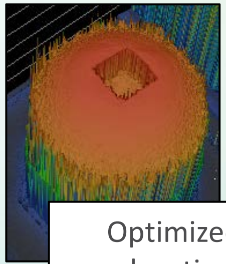

Transmission line impedance matching

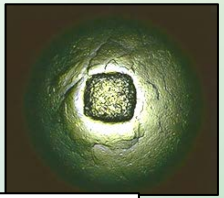
# Practical Considerations

- **CRES uniformity is the prerequisite for everything else to work**
- **Probe marks need to be consistent across all bumps**
  - Probe tip co-planarity
  - XY tip alignment
- **Cleaning optimization is needed**

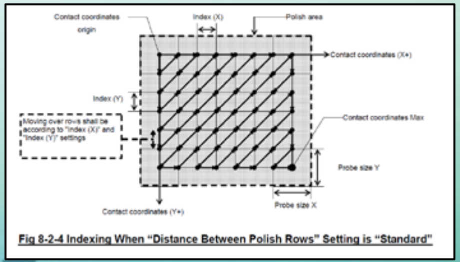


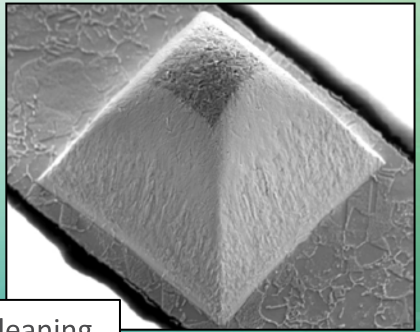

CRES Stability over 1M TDs at 25mΩ Average





Optimized probe mark location and depth



Effective probe tip cleaning

# Learnings from 4 Generations of Production Testing 5G mmWave RxTx:

- Pyramid Probe Cards enable proven, **best-in-class RF measurement through FR2 bands** — 128 RF lines @ 71 GHz
- mmWave test must be **low loss** and **consistent** across all sites, all cards, and all touchdowns — Improved die yields
- MultiDUT testing is needed to hit **cost** and **throughput** targets
- **MUX** and **off-die loopback test strategies** are used to extend tester resources in mmWave Rx/Tx production test — Reduced Cost of Test
- **50Ω** and **non-50Ω** transmission lines improve antenna testing — Improved Test Value
- **Fundamental** on-wafer probing challenges cannot be underestimated — Reliable

# Acknowledgements

- **Special thanks to:**
  - FormFactor
    - Eric Hill
    - Tim Cleary
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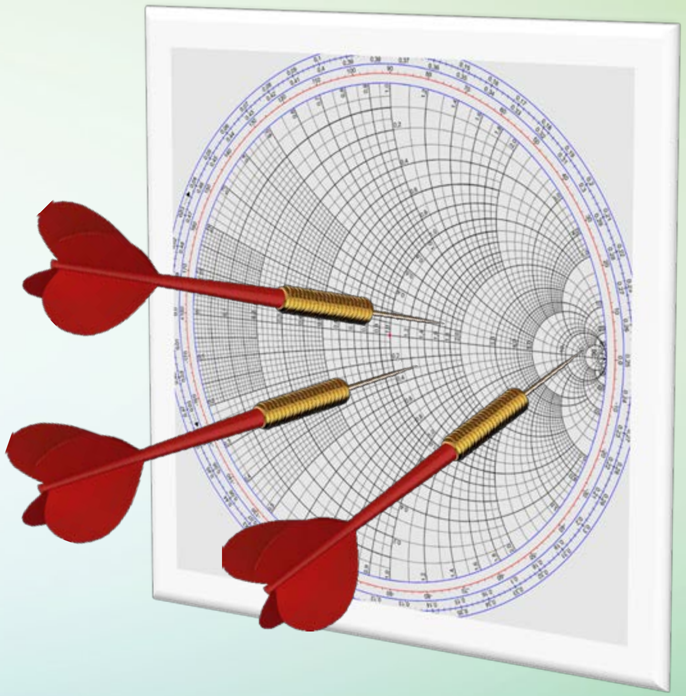
    - Dr. Daniel Bock
    - Kevin Ayers
    - Robbie Ingram-Goble
    - Jiexia Shi



Production mmWave Test Requires RF Mastery