TEST VISION SYMPOSIUM

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

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TEST VISION SYMPOSIUM

Overview

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

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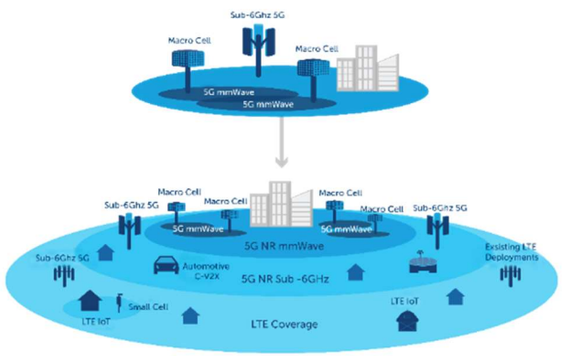
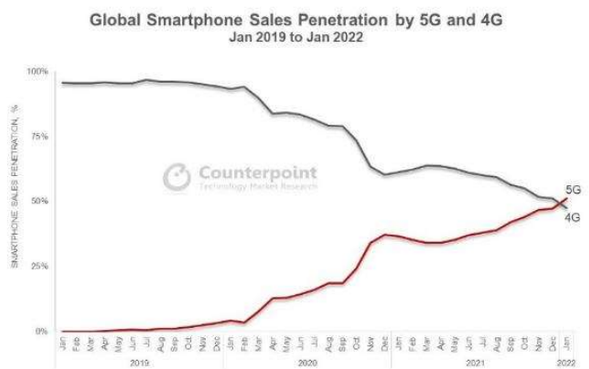
5G is Ramping…

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



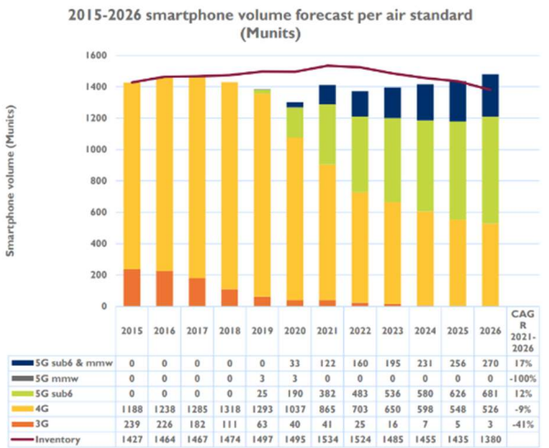
Source: CTS Corporation

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



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

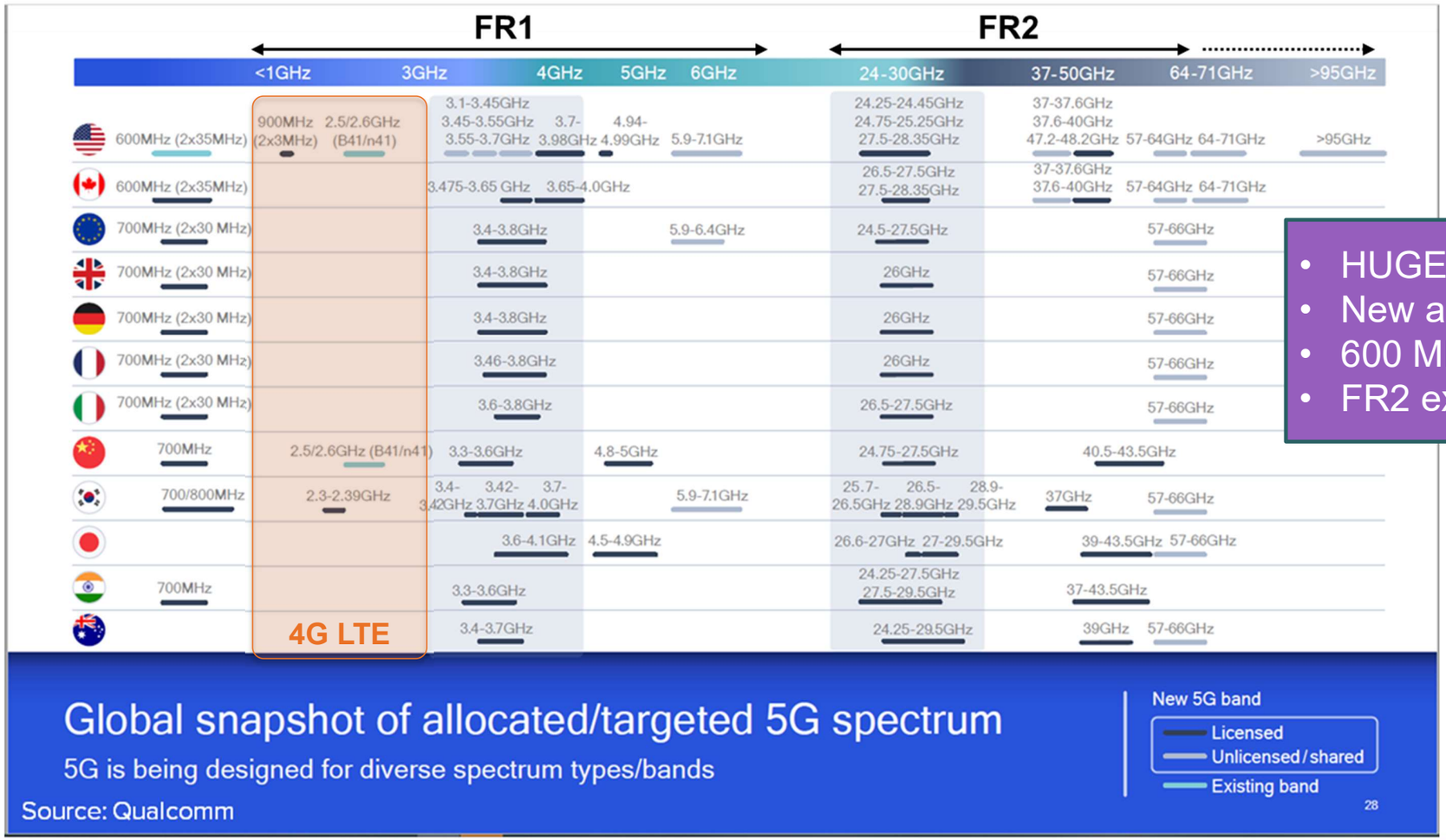
Demand ramp is soaring and will continue



	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	

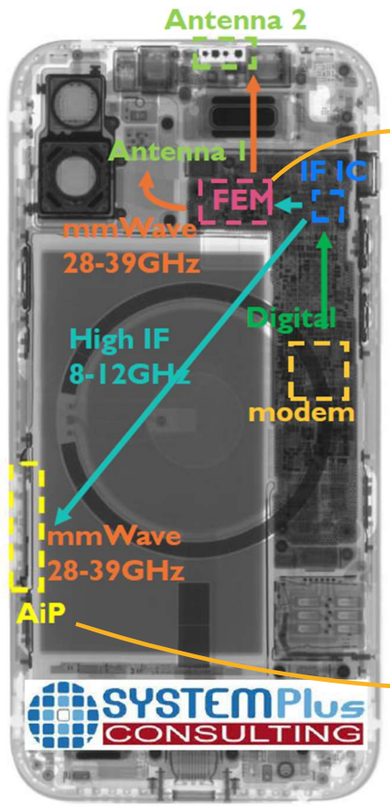
Cellular RF Front-End Technologies for Mobile Handsets 2021 | Report | www.yole.fr | ©2021

5G Frequency Spectrum Landscape

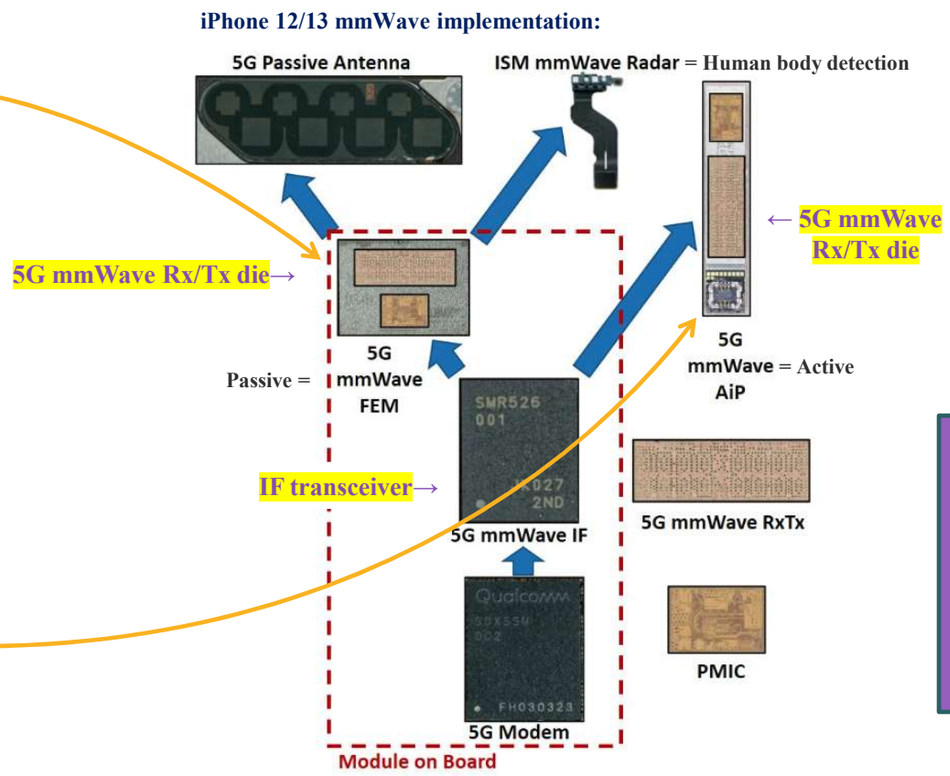


- HUGE increase in spectrum usage
- New allocations in all regions
- 600 MHz to >**71 GHz**
- FR2 extends 5G into mmWave

5G mmWave in the Handset



Apple iPhone 12 Pro Opening
©2021 by System Plus Consulting

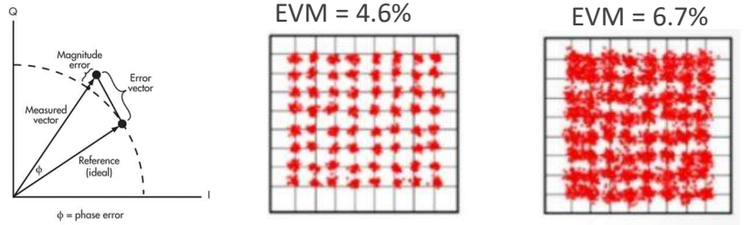


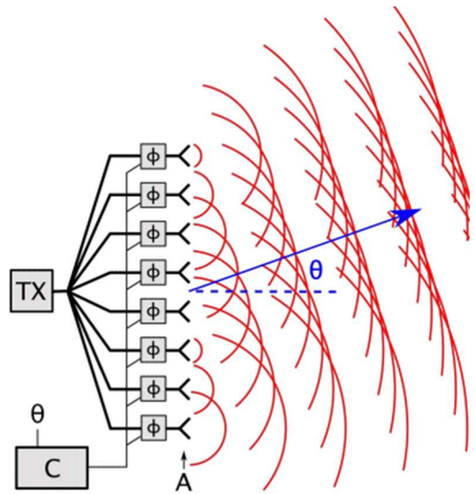
Source: Yole Développement

- 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**

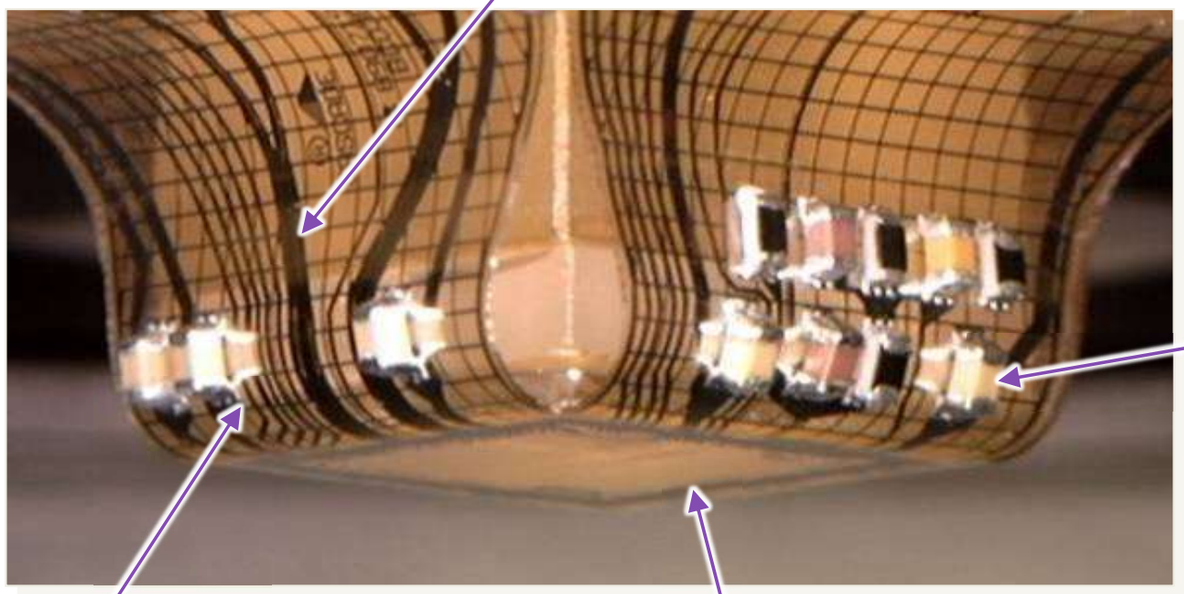




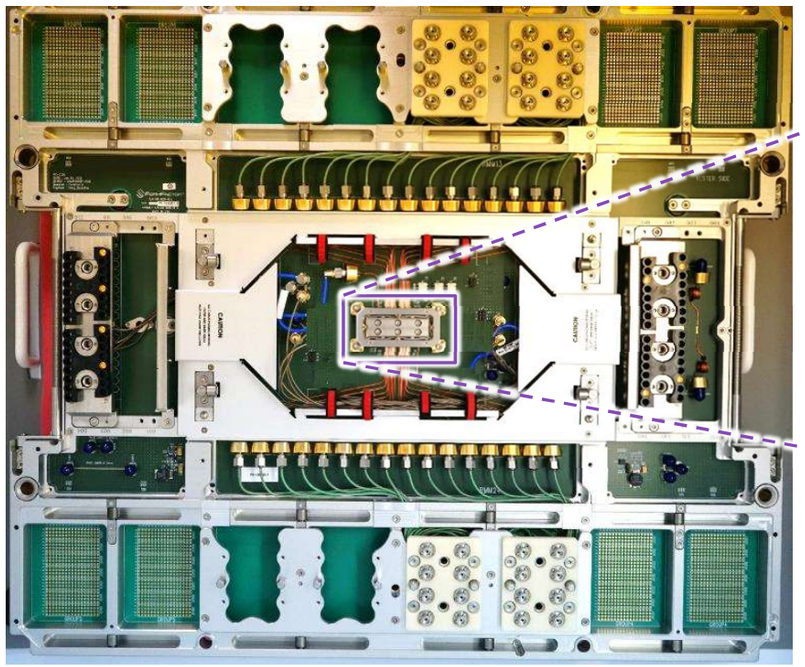
- 5G mmW Transceiver module is the antenna which has unique test requirements

➔ RF measurements need lab-grade for characterization and repeatability for production

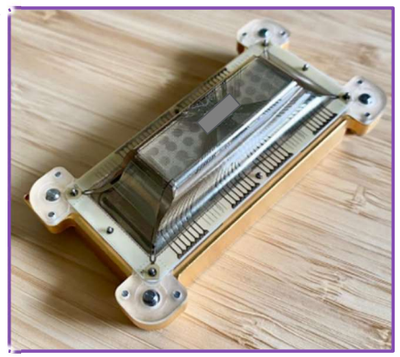
Pyramid Probe: Best Production On-wafer Signal Integrity



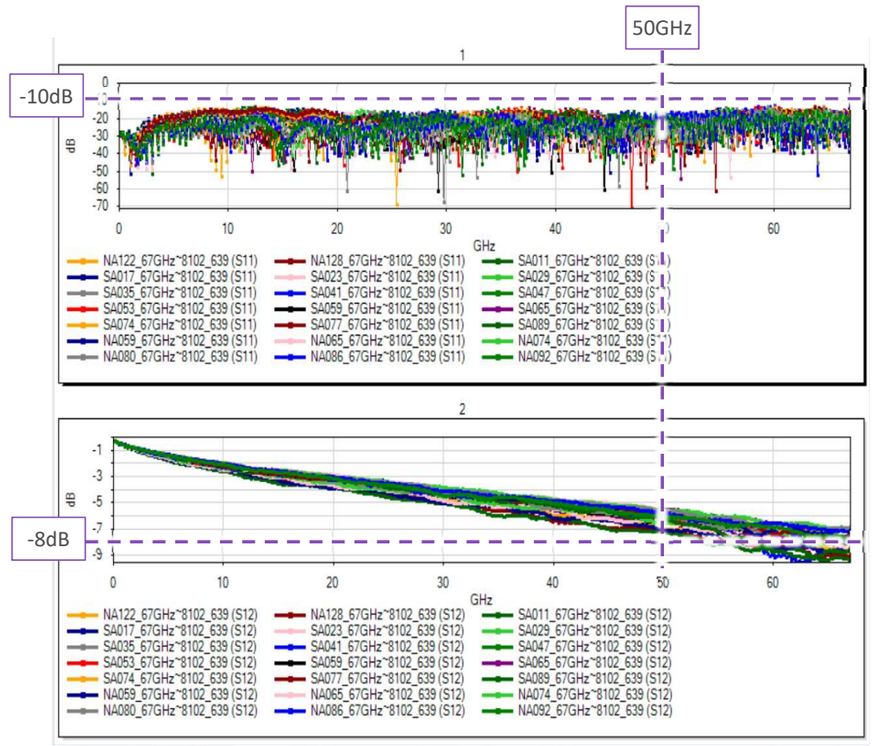
FormFactor x1 Card for RF Characterization



1X ATE Probe Card – V93000: full mmWave routing



1X Contact Engine (core)



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

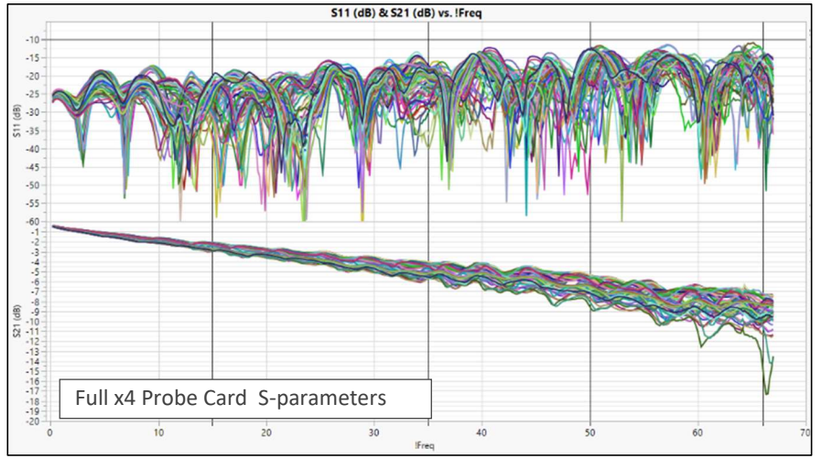
Pyramid probe cards have low RF loss and phase stability for accurate characterization of mmWave RxTx

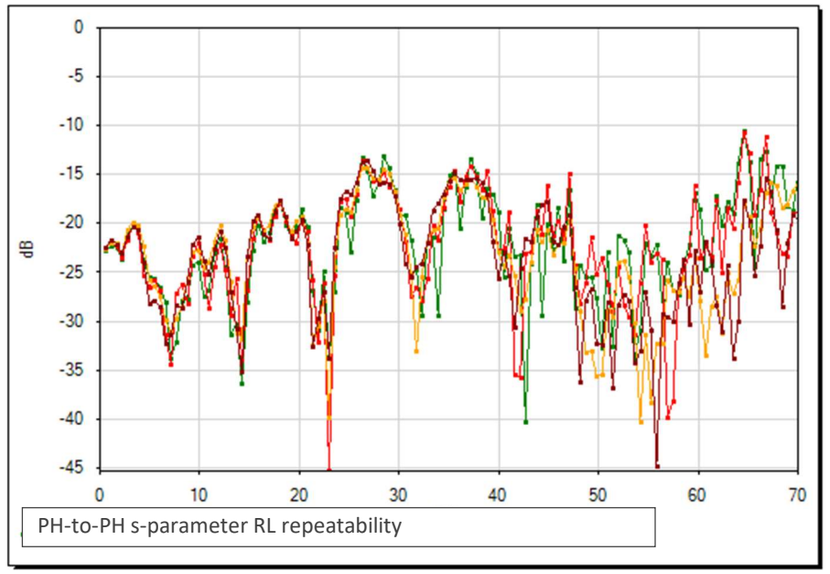
Consistent RF Performance

- 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

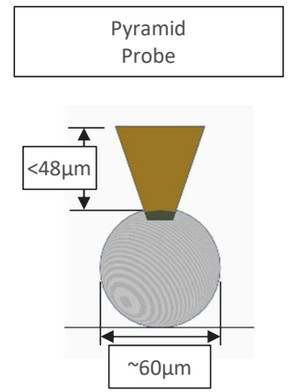
Predictable RF performance = improved die yields

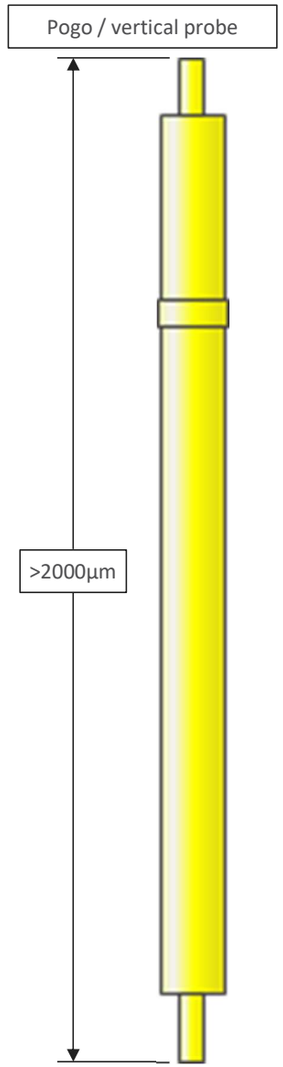




Wavelength Matters

- At 55 GHz, 1 wavelength = 5.545mm
- Structures **<u>below</u> 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 **<u>above</u> 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

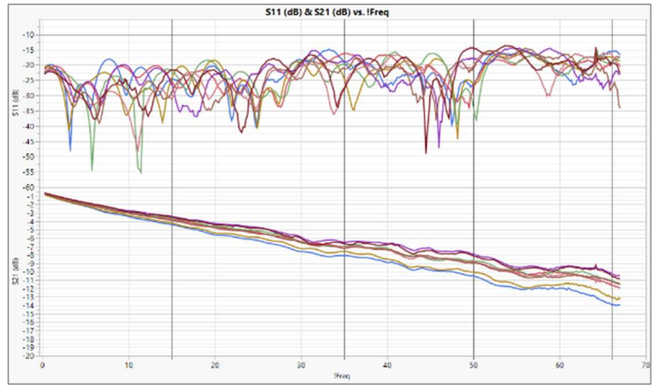




Short probes are best for RF to achieve best performance

Consistency Leads to Effective De-embedding

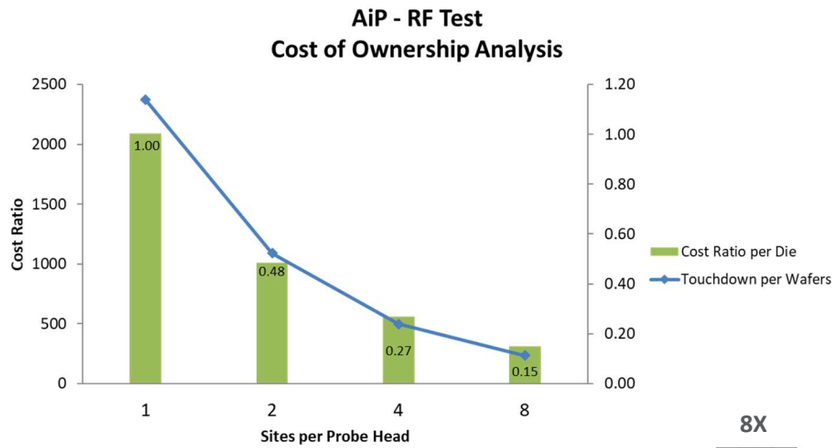
- **De-embedding** defined:
  - Technique used to remove the effects of the probe card and test cell from the measured s-parameters leaving behind transmission qualities of the DUT
- Calibrated connector-to-probe-tip s-parameters measured in-factory, then de-embedded from any measurement taken anywhere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

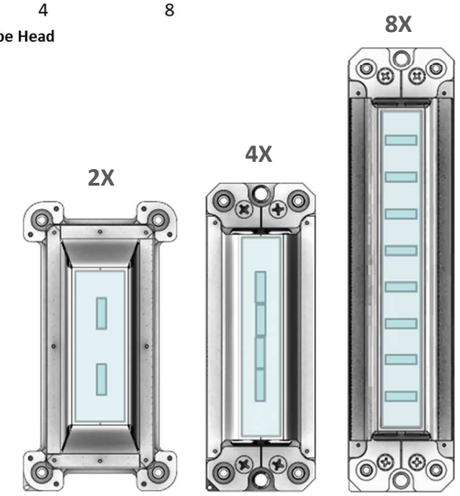


mmWave Device Test in Mass Production

- Production volume for 5G mmWave RxTx chips growing rapidly
  - 2019: 10M units
  - 2020: 75M units
  - **2021: 248M units***

  * from Yole Développement
- 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

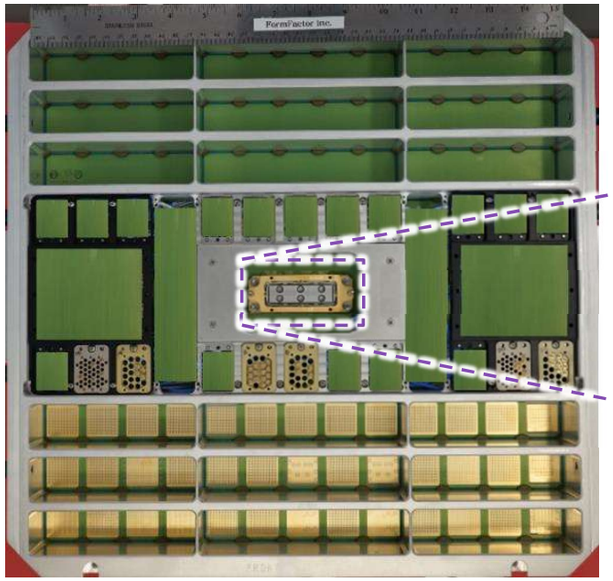




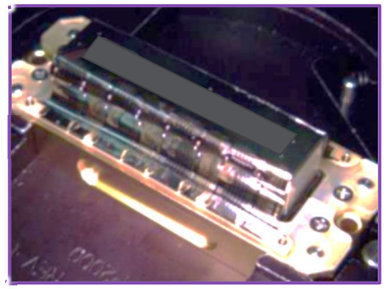
(Approx. to scale)

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

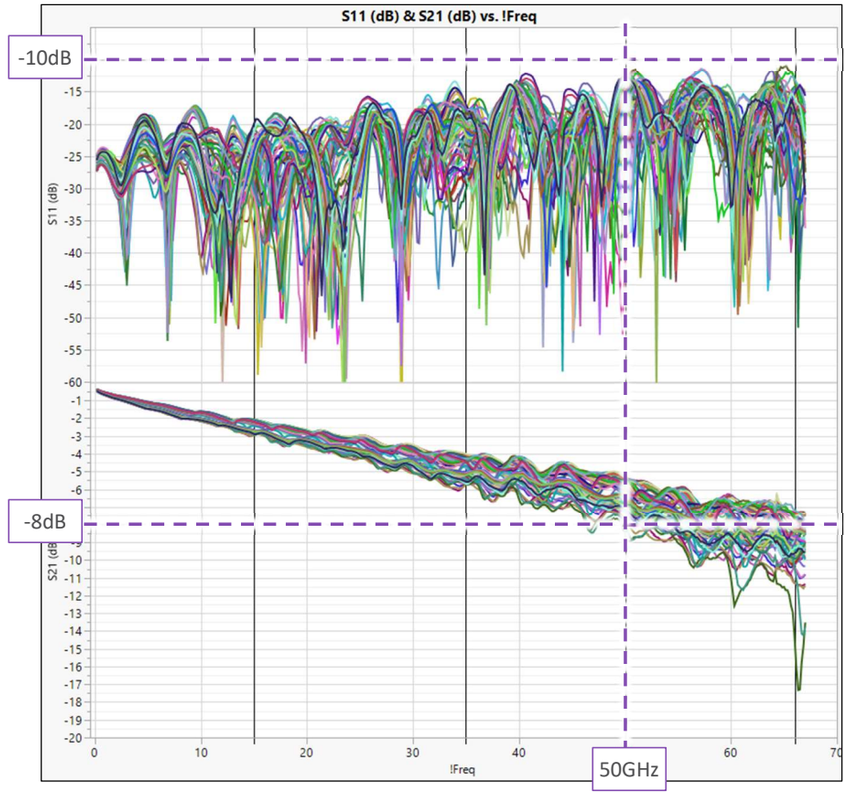
5G TxRx in HVM Production



4X Probe Card – Ultraflex DD



4X Contact Engine (core)

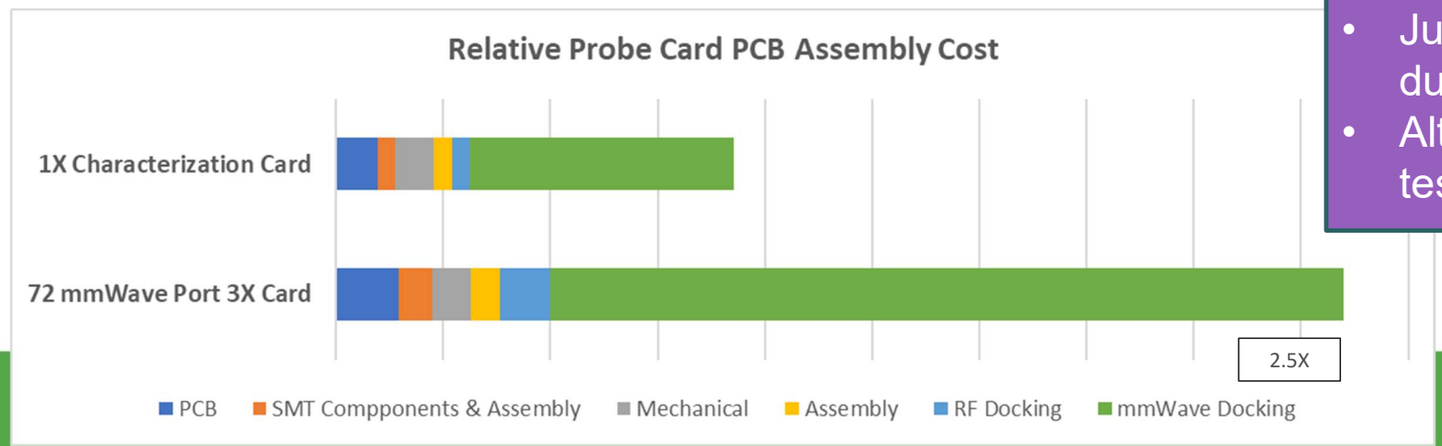


Established 4X Pyramid Production Solution

- 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

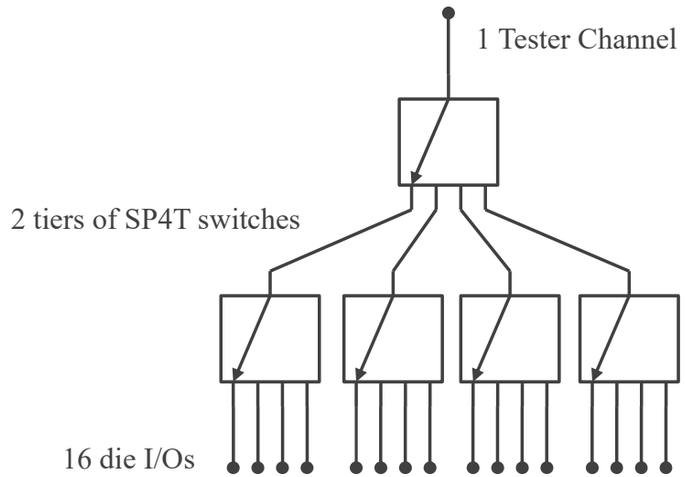
- Tester channel capability supports 3X testing max
  - V93000 Wave Scale Twinning has up to 72 ports at 67GHz (2X max //)
  - UltraFLEX UltraWave up to 96 ports at 67GHz (3X max //)
- Tester expense
  - mmWave ports are $$$
- Probe card interface expense
  - At 1X, mmWave docking and interconnect is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

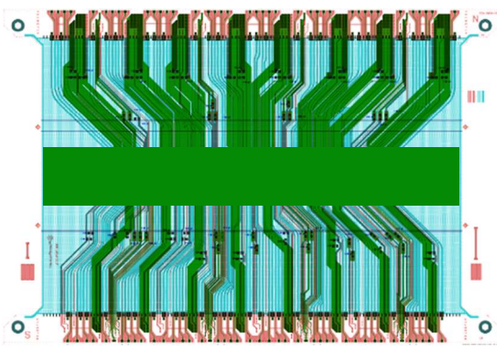


- Just adding tester resources is prohibitive due to $$$$.
- Alternative strategies needed to bring testing onto the probe card.

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



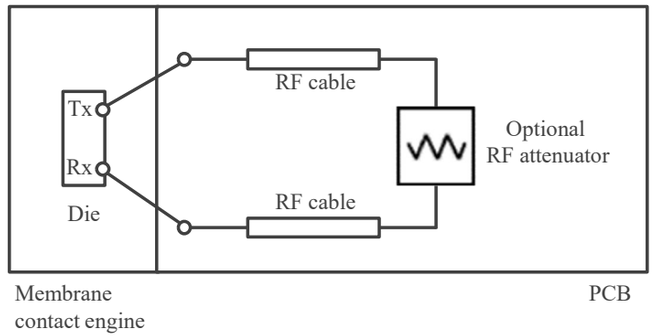


All 128 mmWave lines routed to PCB

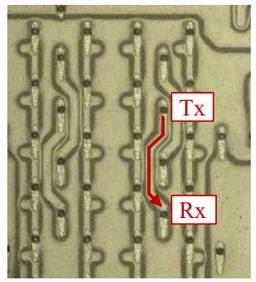
Implemented on Production 4X cards running in HVM today!

Loopback Approaches to Extend Tester Capability

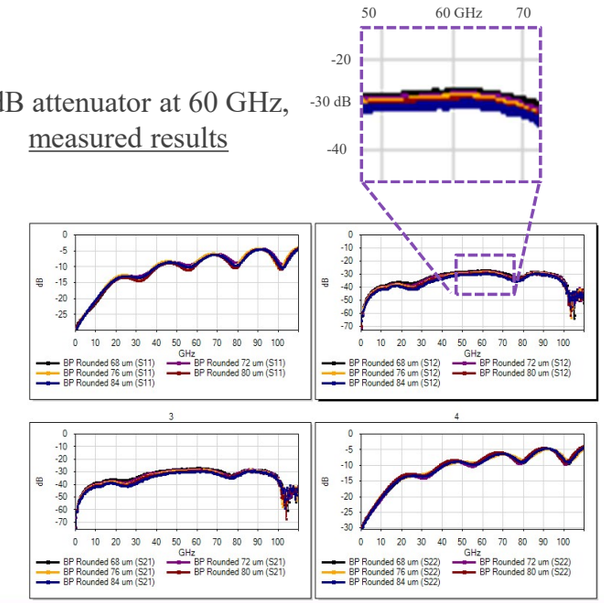
- **PCB-level loopback**
  - Connect one or more I/O together on probe card PCB
  - Can use attenuator to match power levels



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



28dB attenuator at 60 GHz, measured results

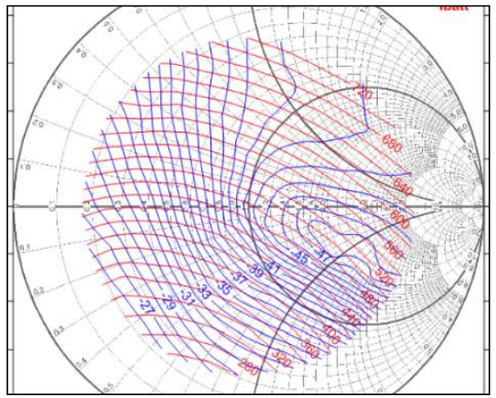


- **Probe Head loopback with attenuation**
  - High performance microwave circuits built into the Pyramid head
  - 3D field simulation = first time right

Microwave circuits in the membrane simplify the probe card

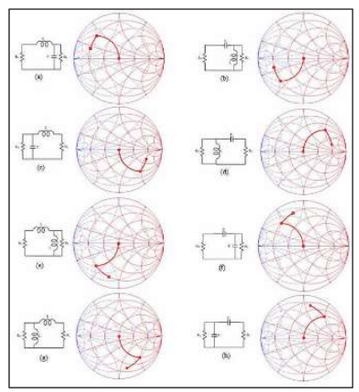
Unique Challenges of Testing an Antenna Driver

- **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

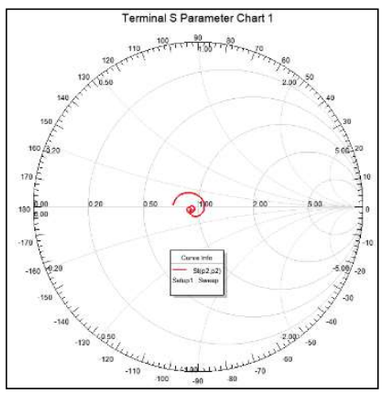


Typical Antenna input impedance optimization plot

- **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

Non-50Ω and 50Ω is predictable and well controlled with membrane

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 — Reduced Cost of Test
- MUX and off-die loopback test strategies are used to extend tester resources in mmWave Rx/Tx production 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
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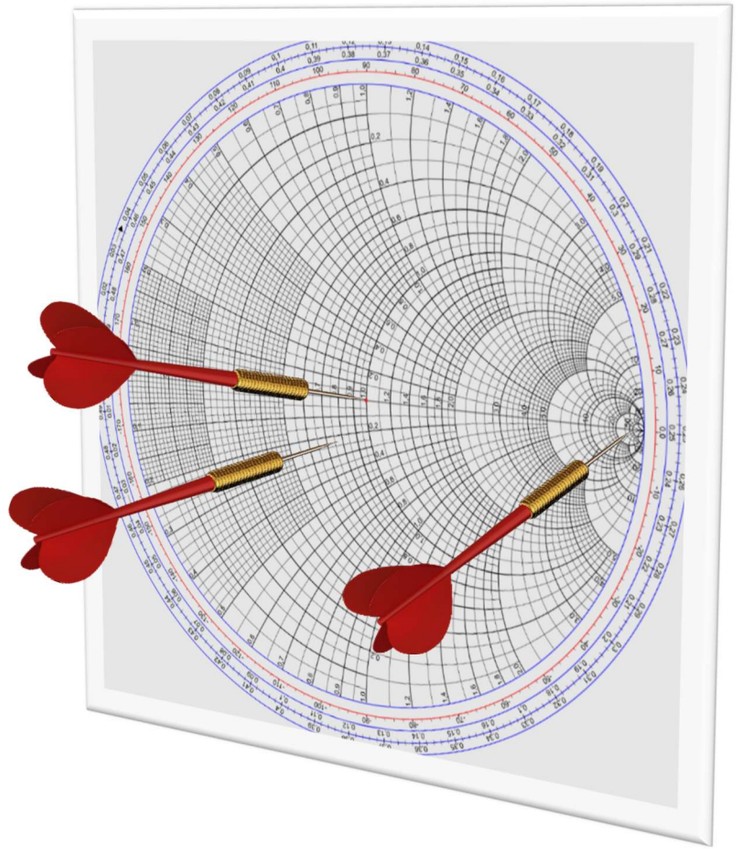
    - Dr. Daniel Bock
    - Kevin Ayers
    - Robbie Ingram-Goble
    - Jiexia Shi



Production mmWave Test Requires RF Mastery