5G mmWave: Enabling Higher Parallelism Wafer Test

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Introduction

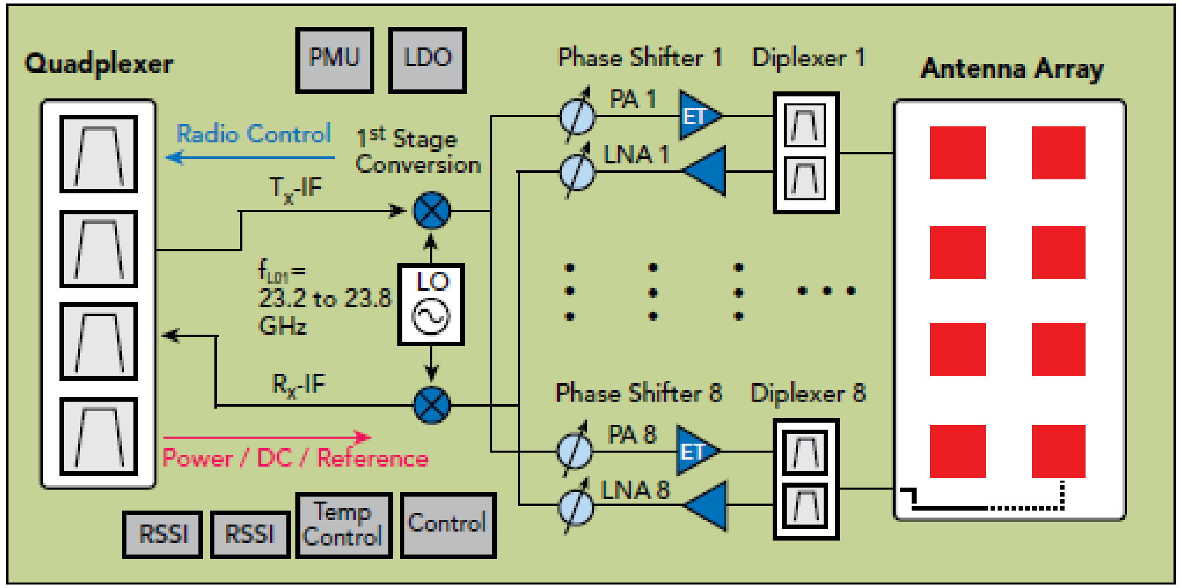
- 5G mmWave systems are no longer in the future. 5G is actively being deployed, with more cell phones with integrated the mmWave radios.
  - 5G mmWave chips have moved out of engineering/development labs and into mass production, and therefore need to meet the ramp demands of the market
  - This change also means a required reduction in cost of test which is a large part of what is driving parallelism increases
- FormFactor will go over our solutions to meet the demanding requirements for 5G

Agenda

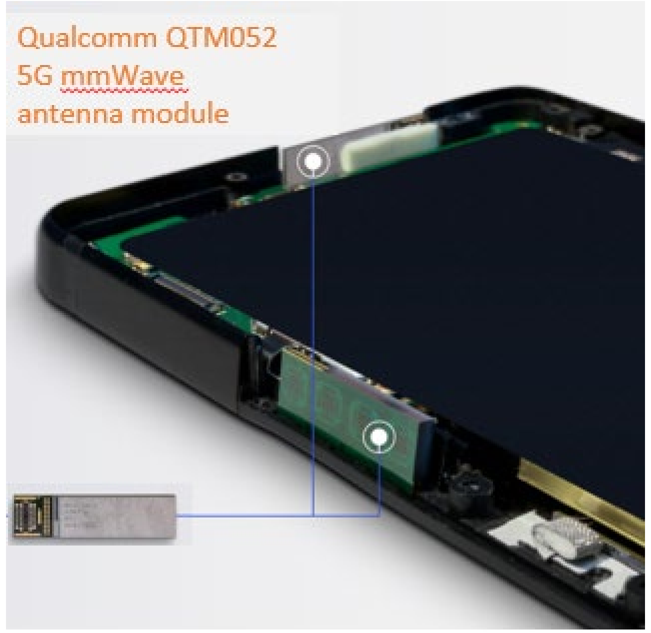
- Discussion of 5G deployment
- Probe Head Technology Parallelism Expansion
- Test Cells
  - ATE Resource limitations
  - How to Expand Parallelism
- Summary

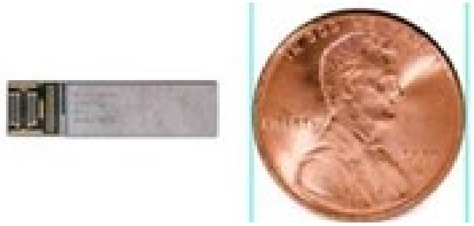
What is the 5G mmWave?

- The 5G mmWave is the radio inside of the cellphone that operates at bands greater than 6 GHz, with ultra-fast data speeds
  - The mmWave chips are using more RF channels with multiple patch antennas in order to maximize performance when compared to 4G systems



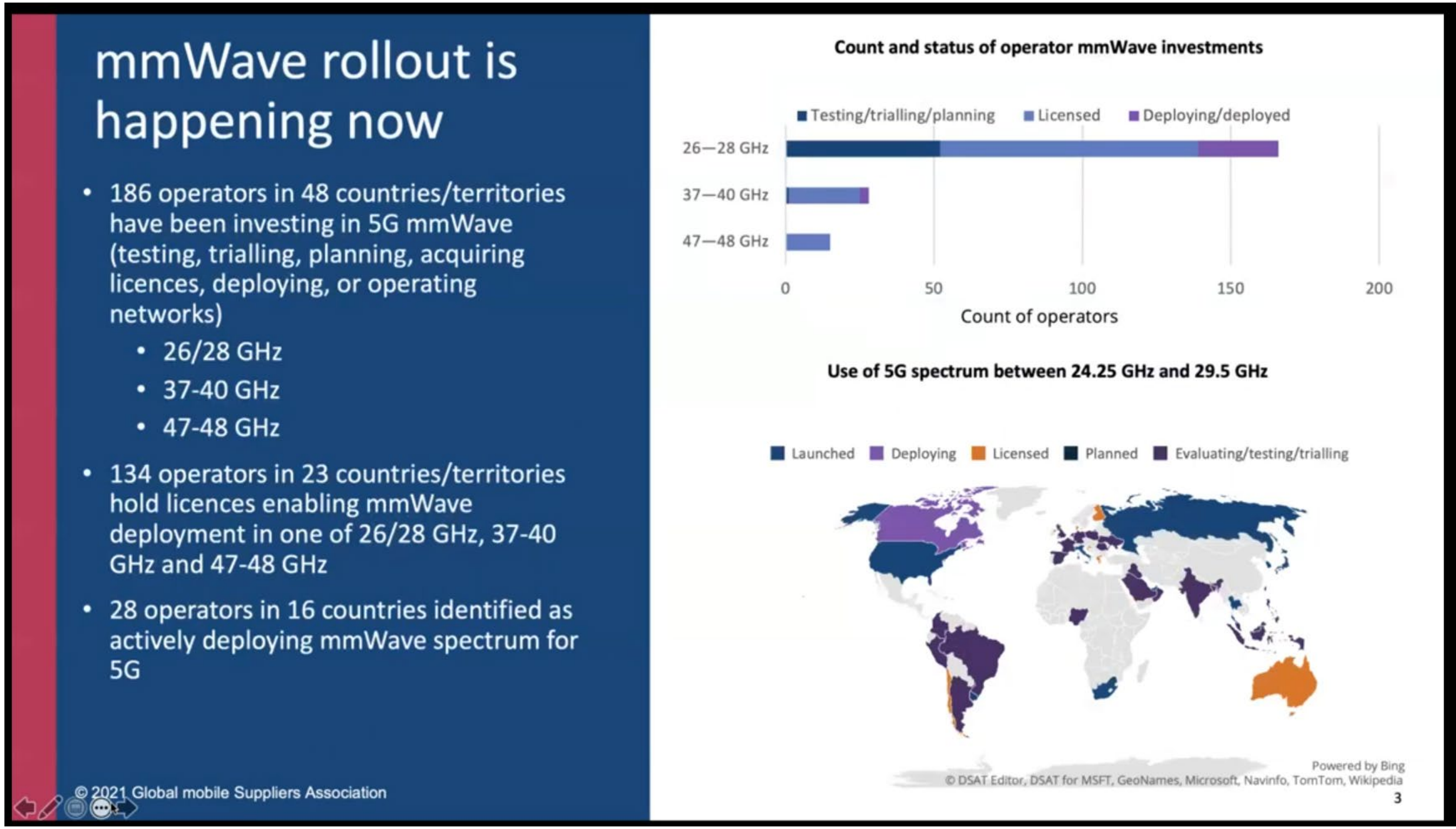
▲ Fig. 5 5G FDD beamforming module architecture. Source: arXiv:1704.02540v3 [cs.IT].





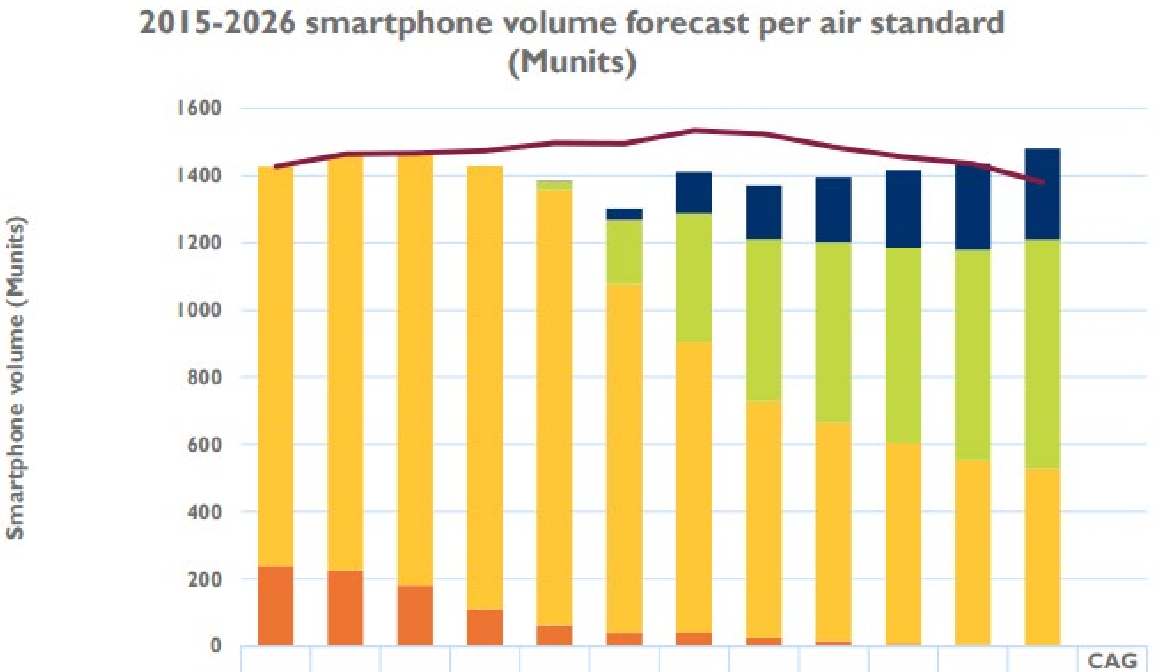
Status of 5G mmWave Deployment

- 5G is rolling out today in increasing speed and volume
- This deployment is leading to a ramp in the number of chips being tested



Growth in 5G

- With the 5G mmWave network deployment, there is rapid growth in the number of phones providing mmWave capability
- Since each phone requires about 3 AiP chips, it is estimated that by 2026, more than 750M 5G mmWave chips will need to be tested per year



	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	

Ref: Cellular RF Front-End Technologies for Mobile Handsets 2021. Market and Technology Report 2021, Yole Development

Model of Volume – How many test cells vs Parallelism to meet Ramp?

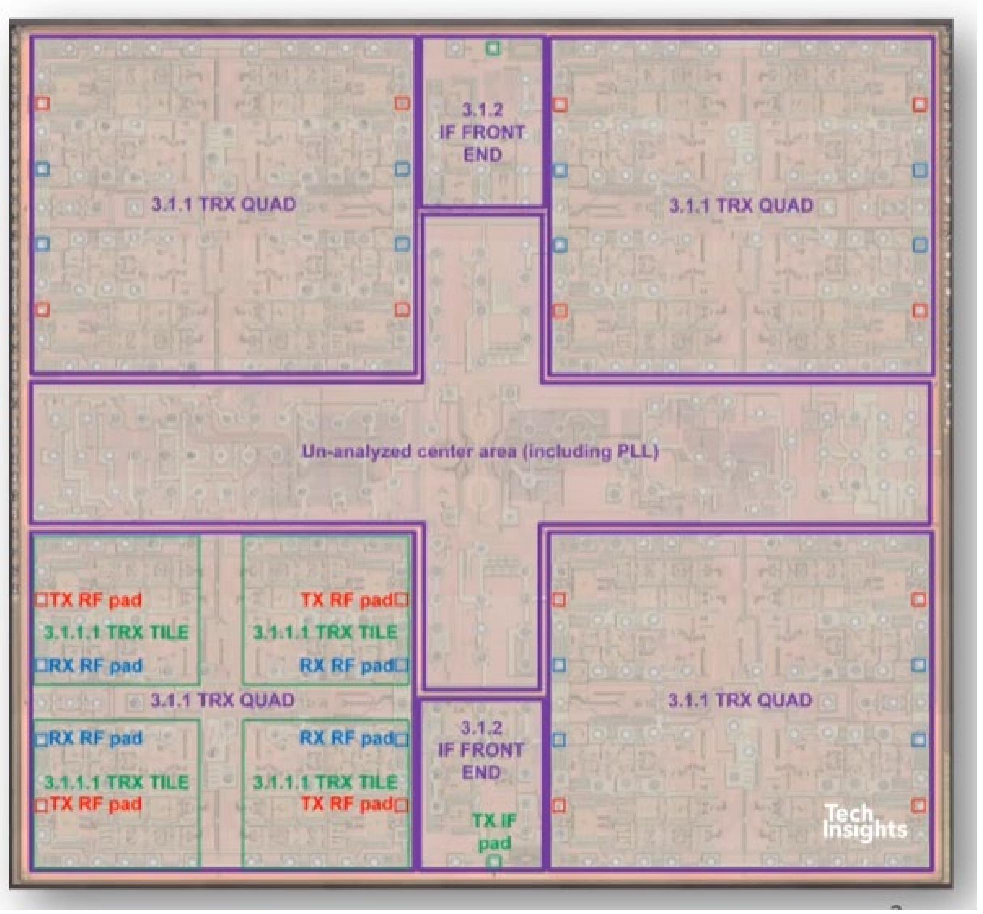
- Using current market forecasts, the cost of test depends highly on the parallelism
- The table below shows that as the parallelism increases, the cost savings in the reduction in the number of test cells is substantial, up to $500M in 2025 for the semiconductor manufacturers

# of 5G Test Cells Needed							
Parallelism	x1	x2		x4		x8	
Year	#	#	Est. Savings ($M)	#	Est. Savings ($M)	#	Est. Savings ($M)
2020	83	41	$41	21	$62	10	$72
2021	306	153	$153	77	$229	38	$268
2022	402	201	$201	101	$301	50	$351
2023	489	245	$244	123	$367	61	$428
2024	580	290	$290	145	$434	73	$507
2025	642	322	$321	161	$482	81	$562

Parallelism effect on Number of test cells. For estimates, 1 test cell costs about $1M

How Many RF Channels are needed for 5G FR2?

- Each mmWave chip for 5G requires a large number of RF channels due to the phased array design
- For example, in TechInsights[1], an X-ray analysis of the QTM052 and show that it has a total of 24 RF ports, 8 in each quadrant
- Therefore, in x8 testing, one would need 192 RF ports



QTM052 from TechInsights

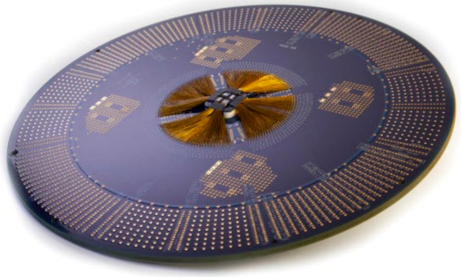
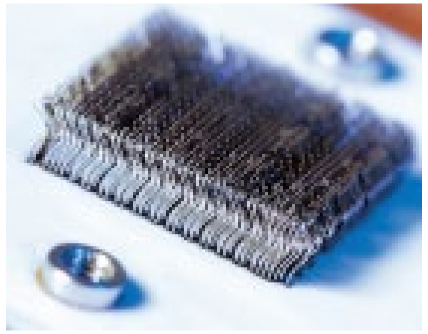
- [1]https://www.techinsights.com/webinars/webinar-space-power-beams-shorten-trek-gain-edge-5g-chip-design-and-manufacturing

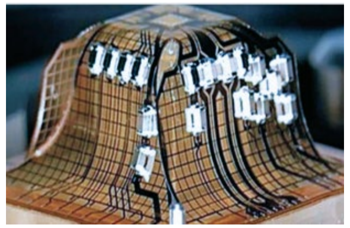
Test Capabilities Higher Parallelism Checklist

- In order to provide the wafer test solution for high parallelism, the test cell needs to:
  - ❑ Wafer Contactor capable to operate > 55 GHz
  - ❑ Accommodate large RF test heads to support the mmWave frequencies
  - ❑ Have enough mmWave tester channels (~192) to cover the RF ports required
  - ❑ Provide sufficient space on the board for components/connectors.

Comparison of 4 Primary Probe Head Technologies

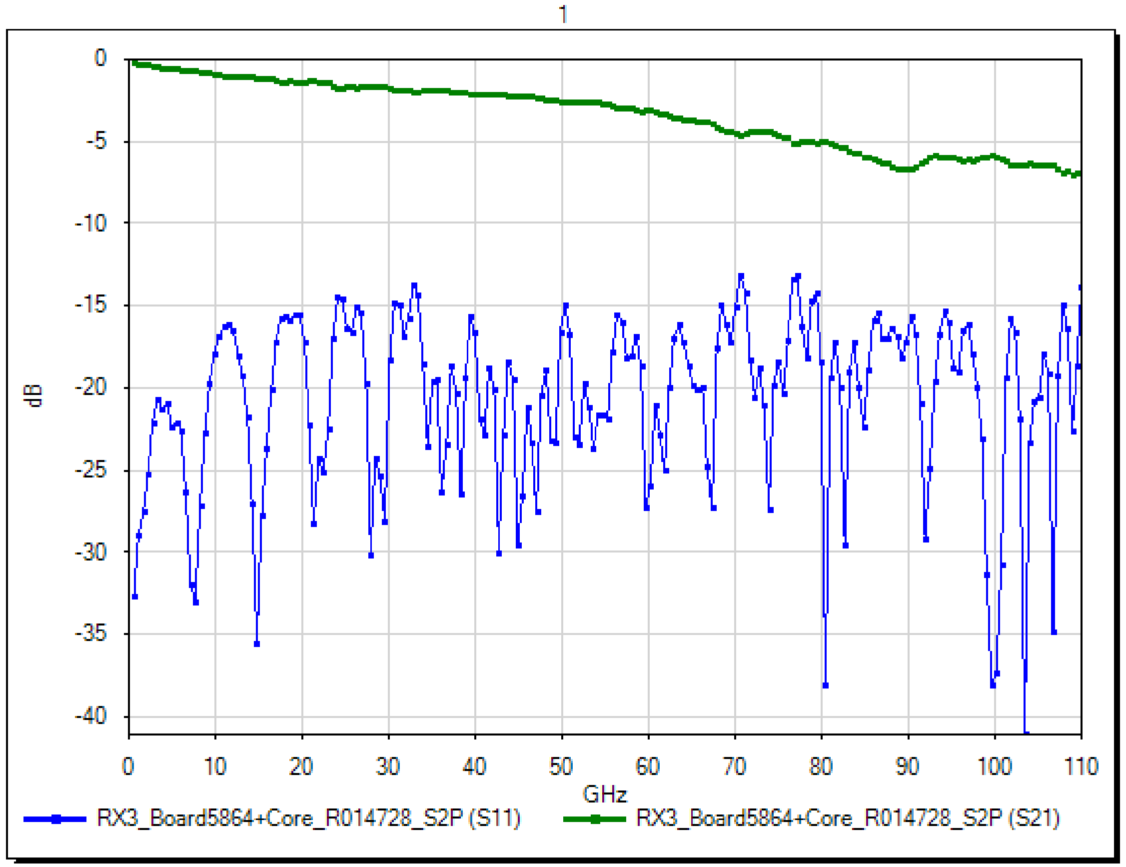
	Cantilever	Vertical MEMS	Spring Pin	Membrane
RF Performance	< 3 GHz	< 40 GHz	< 55 GHz	> 80 GHz
Array Capable?	No	Yes	Yes	Yes
Pitch	40 µm, peripheral	90 µm	>150 µm	100 µm
Max Size	90x20mm	100 x 100mm	90x20 mm	10x80 mm
Power Integrity (bypass cap distance from tip)	5mm	5mm	10mm	3mm

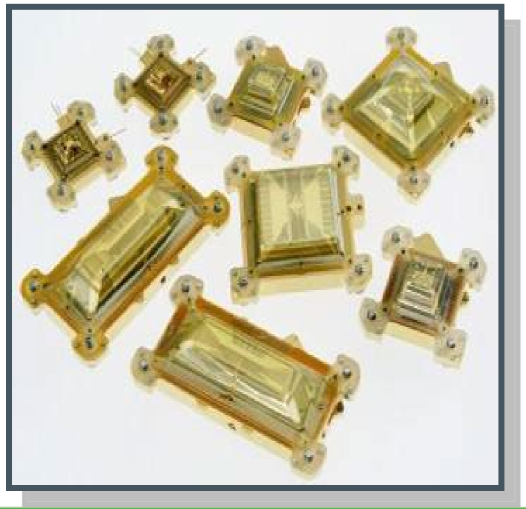



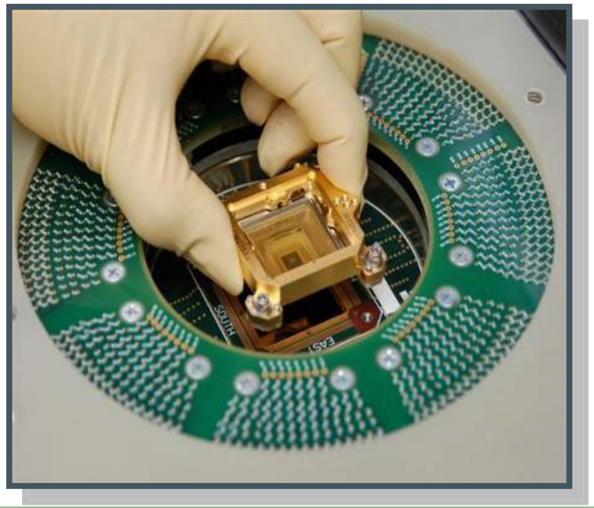


Pyramid Probe Family of Wafer Probe

- Pyramid Probe has proven RF performance out to 80 GHz
  - Maintains the better than -10 dB RL out to > 80 GHz with good margin
  - Better than 6 dB IL out to 80 GHz







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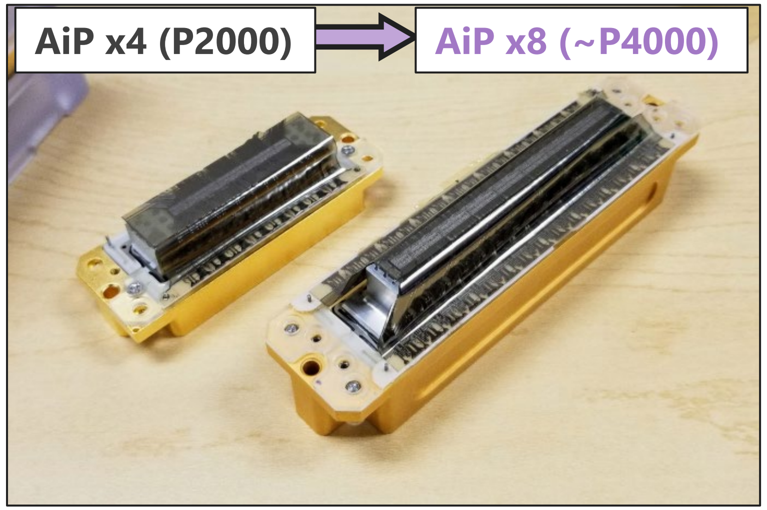
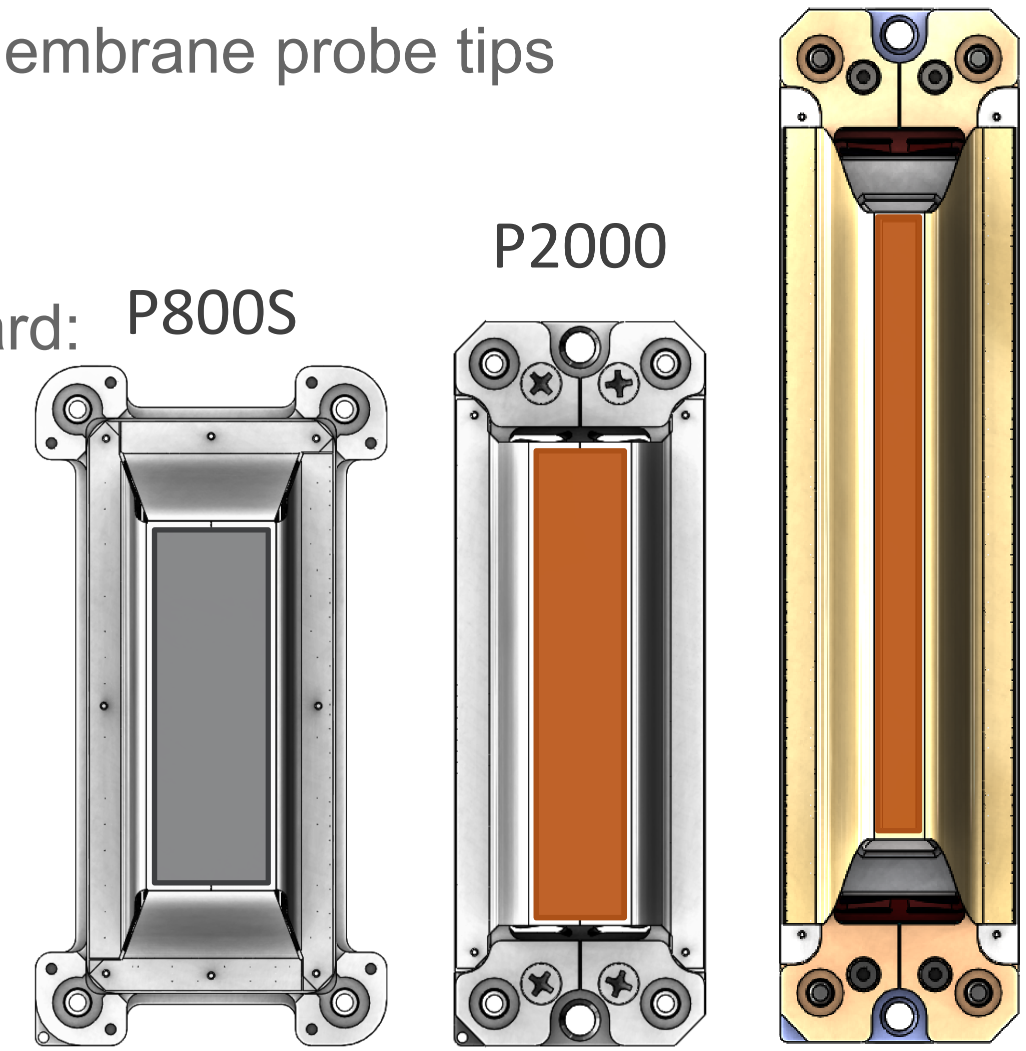
  - ❑ Provide sufficient space on the board for components/connectors.

Pyramid Probe Area Expansion

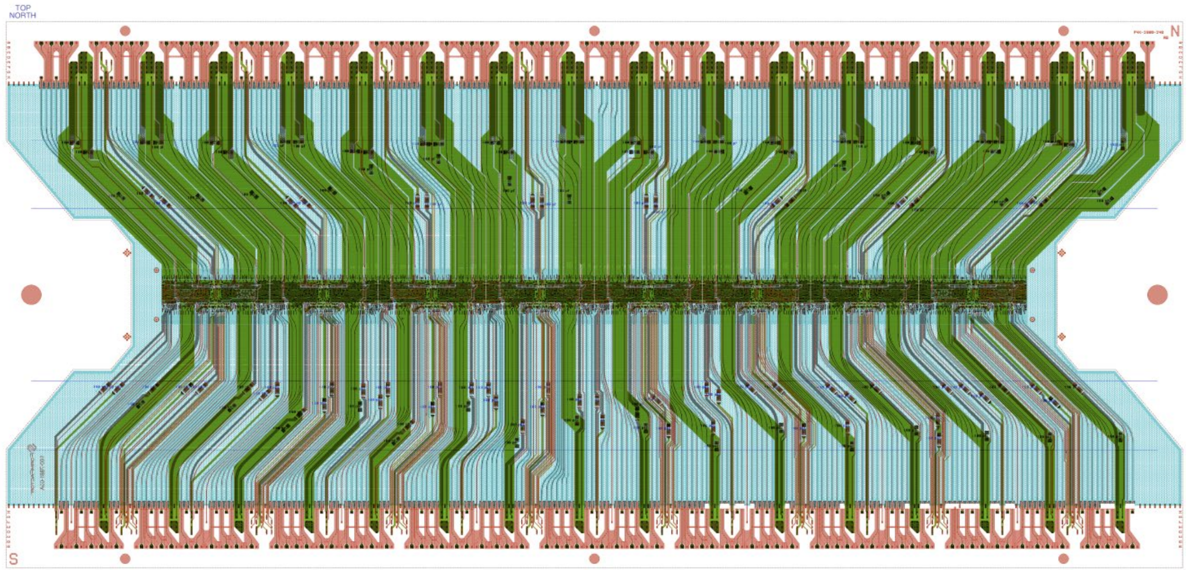
- Expand active probing area using traditional membrane probe tips
  - P2000 supports a **4x AiP** in a linear array today
  - P4000 will support an **8x AiP** in 2022
- Pyramid membrane performance carries forward:
  - Excellent RF measurements
  - Stable CRES with consistent probe marks
  - Replaceable cores from tester side





Enabling Higher Density with FFI Thin Film Technology

- Dense die breakout and routing with higher number of I/O
  - Cross of RF lines with ground in-between
  - Larger power nets
  - World-class impedance control (+/- 80 mrho over entire signal path)
  - Impedances other than 50 Ω available within the same probe head possible.



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  - ❑ Have enough mmW tester channels (~192) to cover the RF ports required
  - ❑ Provide sufficient space on the board for components/connectors.

ATE Comparison Table – x8 Parallelism Challenge

- In order to meet the channel count, the testers from the major wafer test manufacturers have increased their mmWave capability
  - However, the complexity in mmWave test channels has limited the maximum number of channels in an ATE possible

	RF Bandwidth	Max Channel Count
Teradyne UltraFlex[2]	44 GHz	128[1]
Advantest WaveScale[2]	70 GHz	64
NI STS[2]	44 GHz	~50

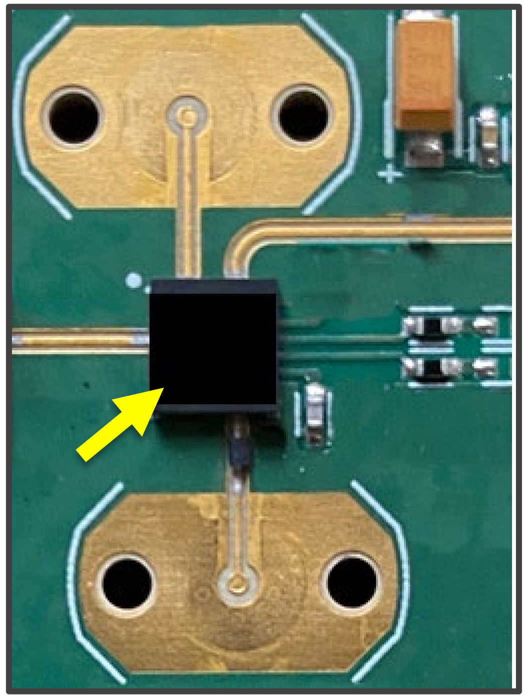
[1] The max is 128 (https://www.teradyne.com/products/mmwave/)
[2] The information here is based on the associated datasheets/documentation on each manufacturer's website (Nov 1, 2021)

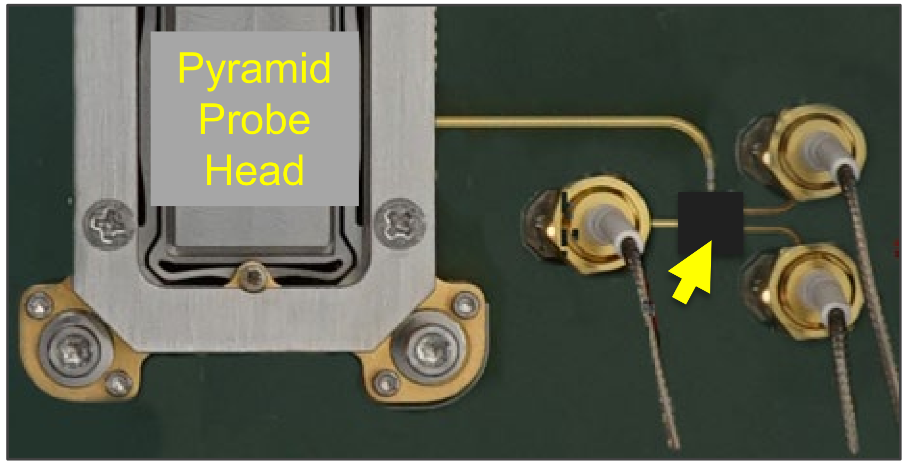
How to Increase Parallelism Outside of the Tester?

- There are multiple ways to increase the parallelism without increasing the tester channels
  - To maintain RF channel test capability, RF switches can be used
    - By switching serially through the channels, all RF paths on the DUT can still be tested with minimal test time change (switch speed <1 μs)
  - Loopback is also possible
    - This allows the device to test itself at high speeds, but it could miss a functional error in some scenarios

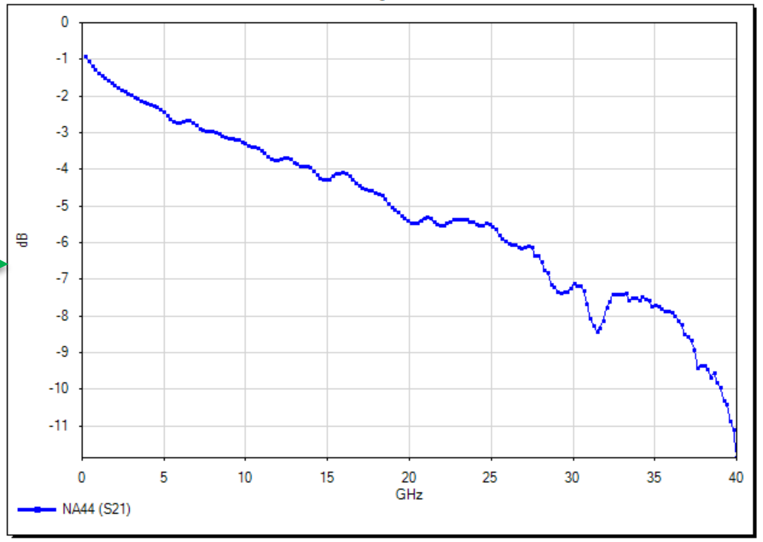
RF Switching

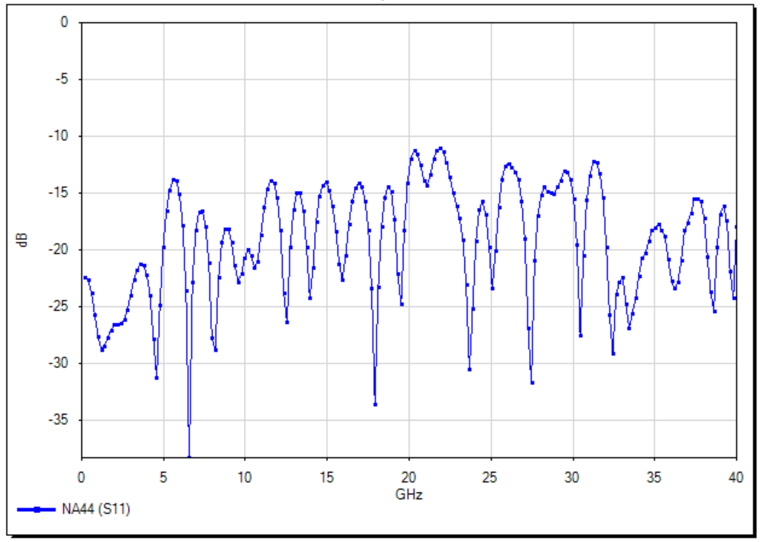
- Off the shelf options exist for switching high frequency RF paths.
- Can be used when the test cell is channel-limited or there is insufficient PCB real estate for connectors.





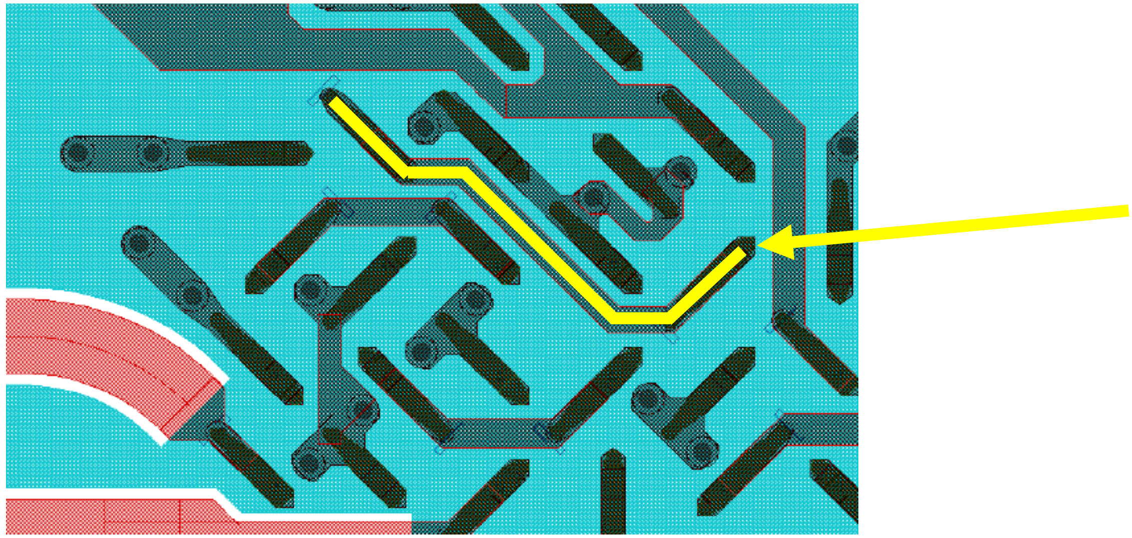
Full Path loss from Connector to probe tip including switch

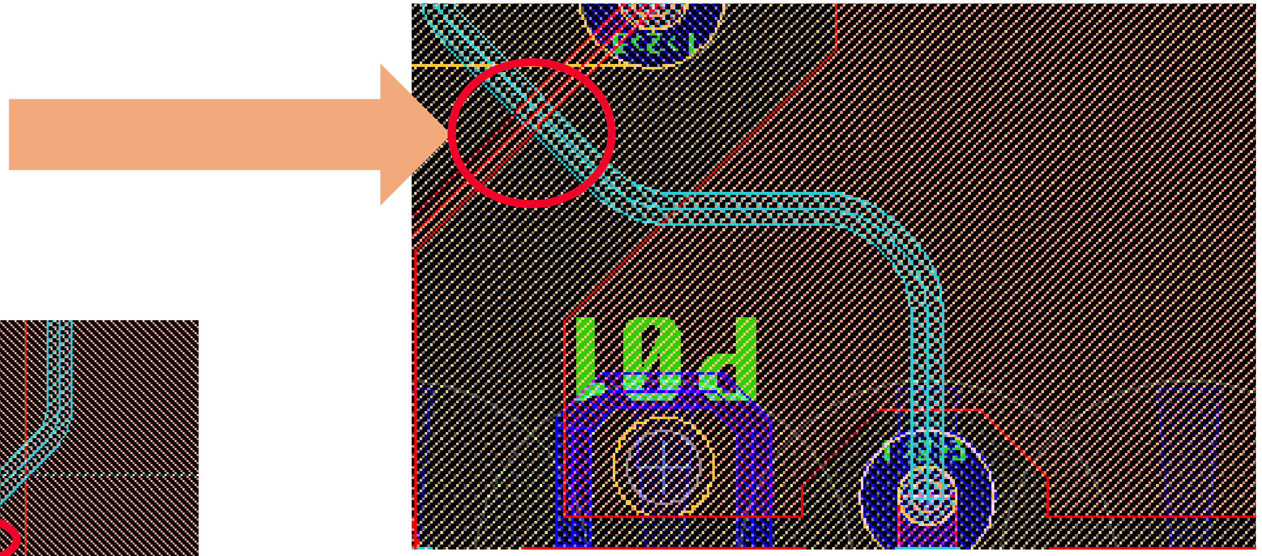


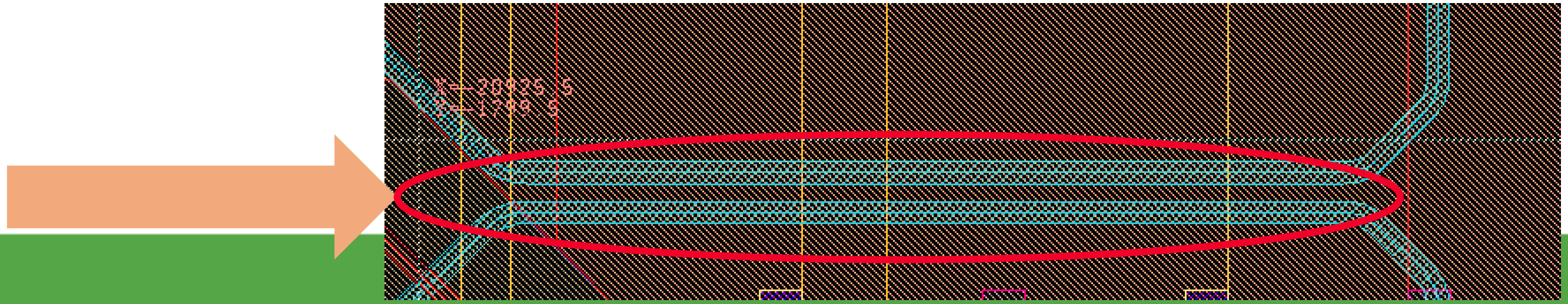


Probe Head Loopback

- FFI can also design custom loopbacks, as well as crossing lines as needed
  - Loopback lengths in the membrane can be ultrashort to minimize return loss and insertion loss
  - The Loopbacks can be crossed with a ground in between for long/complex routing in the large mmWave chips
  - Coupling structures can also be added for attenuation







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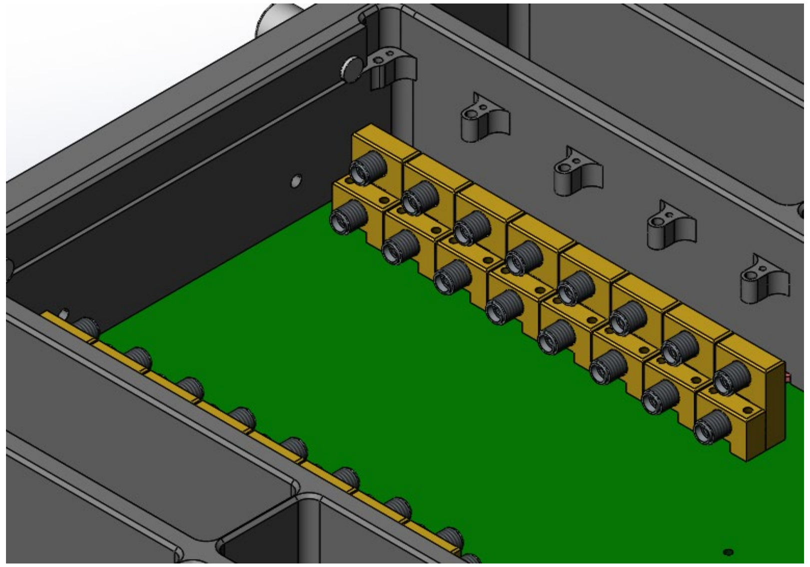
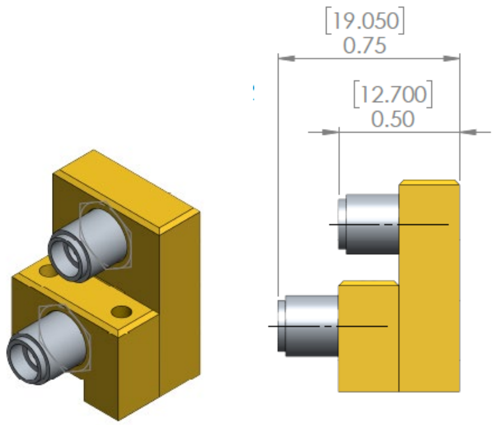
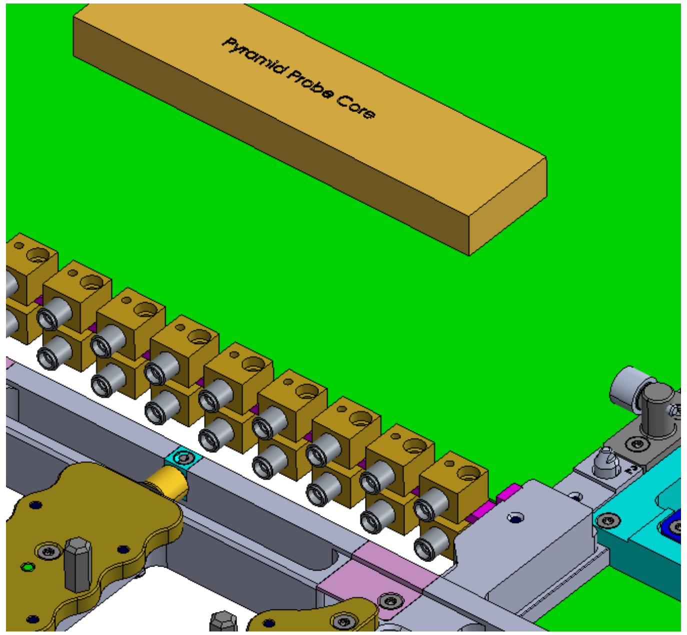
High Density Connectors

- Currently-available high density RF connector solutions cannot meet coax performance.
- Stacked connectors (with semi-rigid coax) in places where sufficient Z height is available
  - Minimizes space used for connectors to get active area back for digital content
  - When height constrained, the PCB can be cut away to allow stacking







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Summary

- Significant cost savings by going to higher parallelism
- Pyramid product is ready for the parallelism challenge
  - >55 GHz bandwidth;
  - Thin film membrane technology enables high density routing and loopbacks;
  - High RF channel count support with RF switches and compact connectors;
- FormFactor has a complete solution to provide full test capability of AiP chips to support the 5G mmWave ramp.