SWTEST

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2023 CONFERENCE

On Membrane Attenuators for 60 GHz Loopback Transceiver Testing

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FormFactor™

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Agenda

- Background
- Problem Discussion
- Analysis
- Solution
- Design
- Validation
- Conclusions

Problem Statement

STMicroelectronics has observed variable attenuation across sites in their Receiver Signal Strength Indicator (RSSI) signal causing test failures and delays in their production test.

Technology Background

STMicroelectronics ST60A3

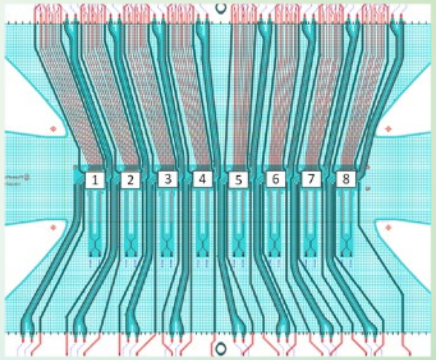
60 GHz V-Band transceiver for contactless connectivity up to 480 Mbps

“wireless connector”

- Up to 480 Mbps (eUSB2)
- Small footprint with integrated antenna
- Ultra low power
- -20°C to 85°C

FormFactor Pyramid Probe P800s

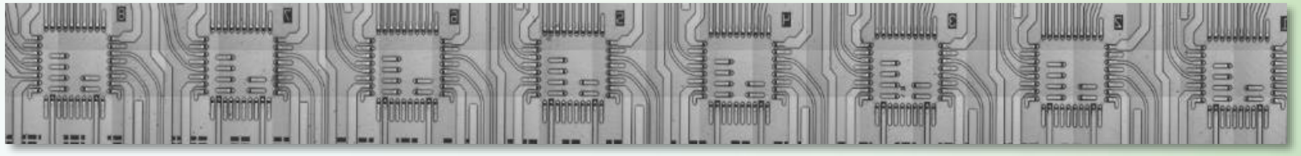
Most widely qualified wafer test solution for production test



- Frequency range to 67 GHz with better than -10 dB Return Loss (RL) to maximize test accuracy out to specified frequency
- Multi-site 5G antenna and RFFE die testing
- Probe geometries engineered for low contact resistance on pads and solder

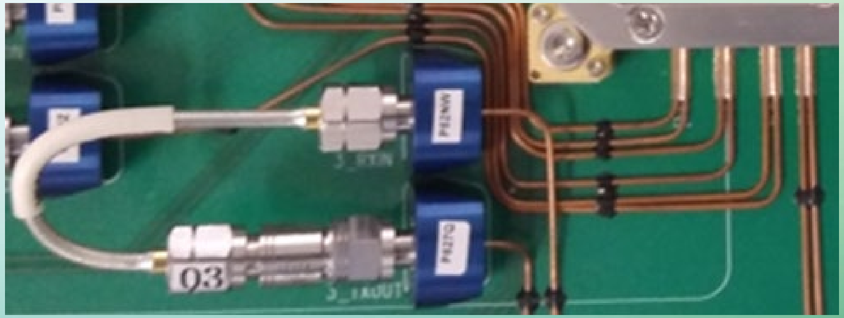
Test Strategy

Measurement Challenge: To test the ST60A3 requires expensive equipment. This results in high cost of test. To reduce cost, a test technique called loopback testing was employed.



Implantation Requirements:

- Loopback path needs a high level of attenuation to ensure the transmitter (Tx) doesn't saturate the receiver (Rx).
- Wafer on bump testing
- Use x8 parallelism

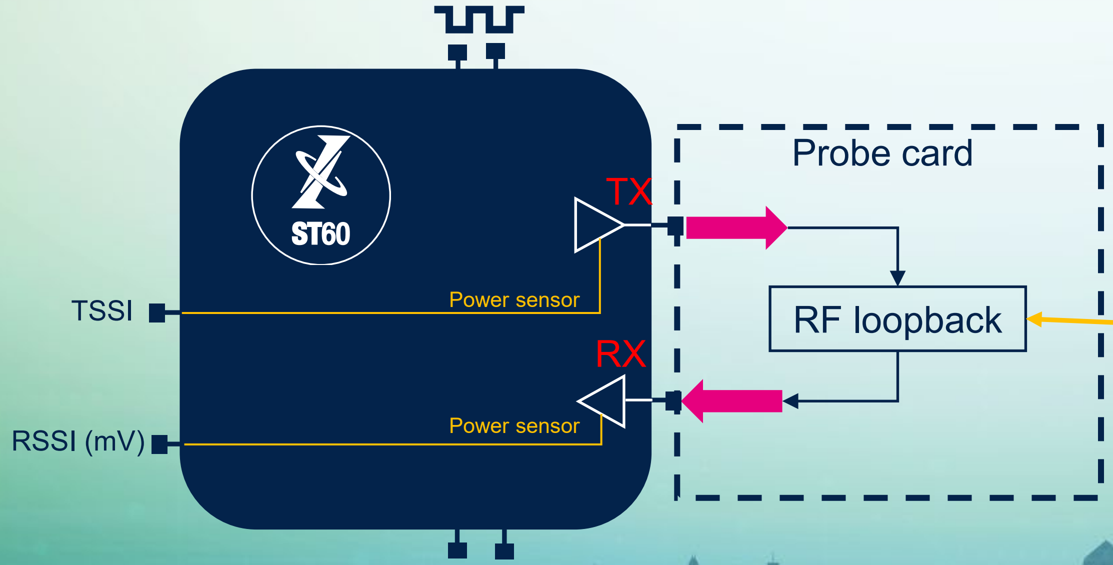


Tx and Rx blocks are tested by looping one to the other:

Loopback Testing

- **Output power at TX**
  - P_{OUT} calibrated at fixed level and verified through TSSI (Transmitter signal strength indicator)
- **Input power at RX**
  - P_{IN} at RX is evaluated from RSSI (Receiver signal strength indicator) measurement on ATE (in mV)

This presentation focuses on RSSI data collection



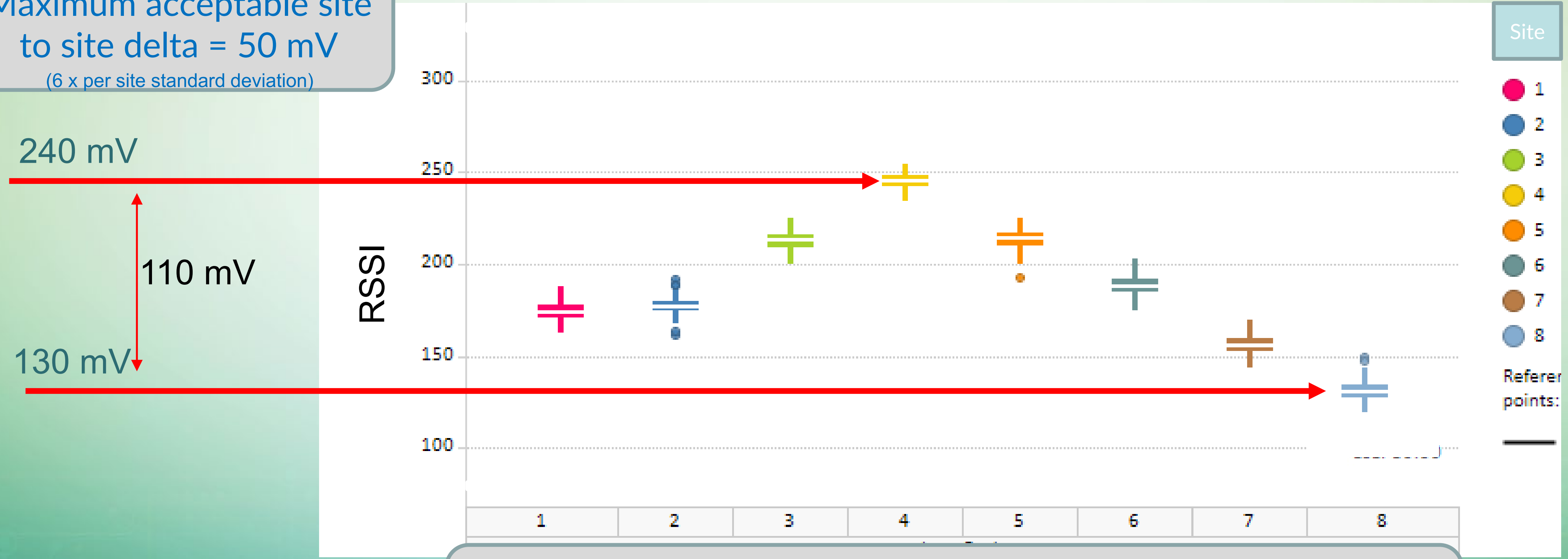
Problem Discussion

Observed:

There is more than 3 dB (110 mV) difference between site 1 and site 8.

Maximum acceptable site to site delta = 50 mV
(6 x per site standard deviation)

RSSI (P_{IN}) Measured for Complete Wafer Using x8 P800s

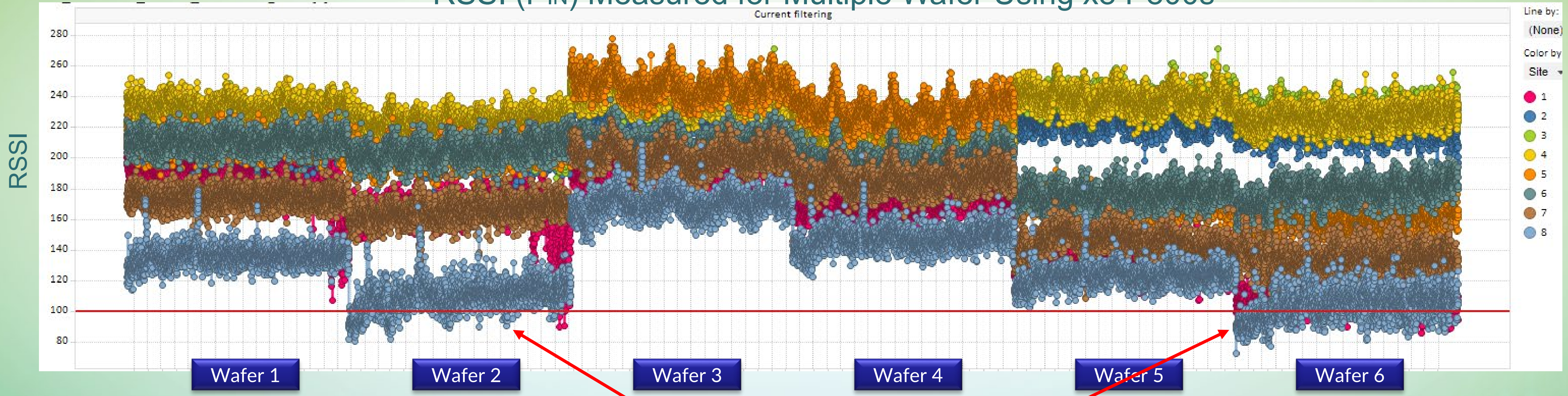


The problem is due to more than 3 dB of variation
Next let's look at what we did to solve it.

Problem Discussion

- **Observed variability in measurement data for site to site (8 sites), wafer to wafer, probe card to probe card and tester to tester.**

RSSI (P_{IN}) Measured for Multiple Wafer Using x8 P800s



Note:

- Each plot is 1 tested die on a wafer
- Data comes from different test setup conditions (different testers, different probe cards & cores)
- Data below red line resulted in a test failure.

!! Yield loss impact !! And CpK below 1

Model and Hypothesis (Analysis)

- Model 1: Core + PCB ✗
- Model 3: Semi Rigid Cable ✗
- Model 2: Core to Board Interface ✗
- Model 4: Bridge Beam + Shim + PC interaction ✓

Analysis

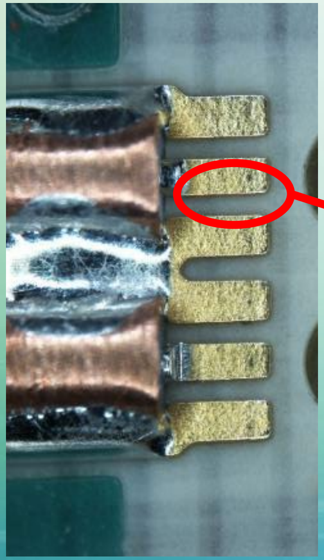
Core + PCB Testing

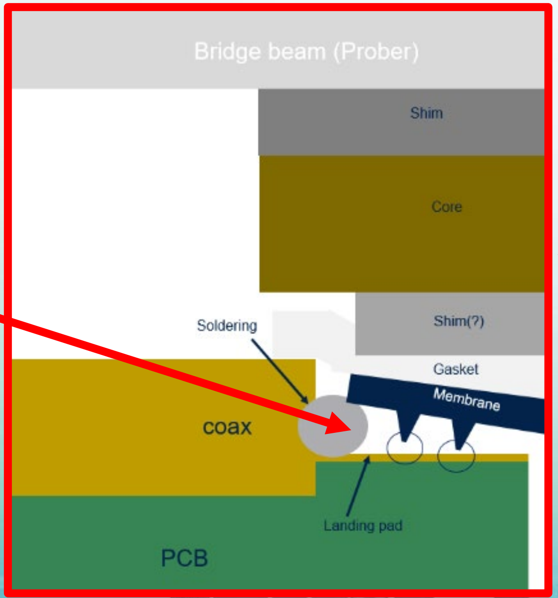
Observation: Not all bumps at the CBI make contact with the PCB pad.

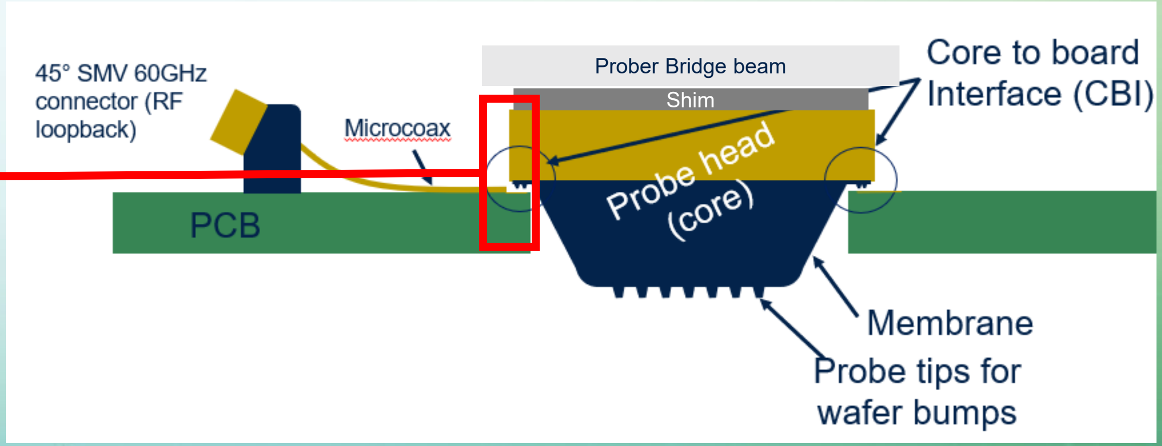
Hypothesis: Interference between membrane & coax makes only 1 contact/imprint at CBI.

- Built a model to study bump & pad.
- Model shows no significant difference with 1 or both bumps touching down on PCB
- Kapton tape is 30 um thick and produced a 3 dB effect. (similar difference in RSSI)

Not the Problem







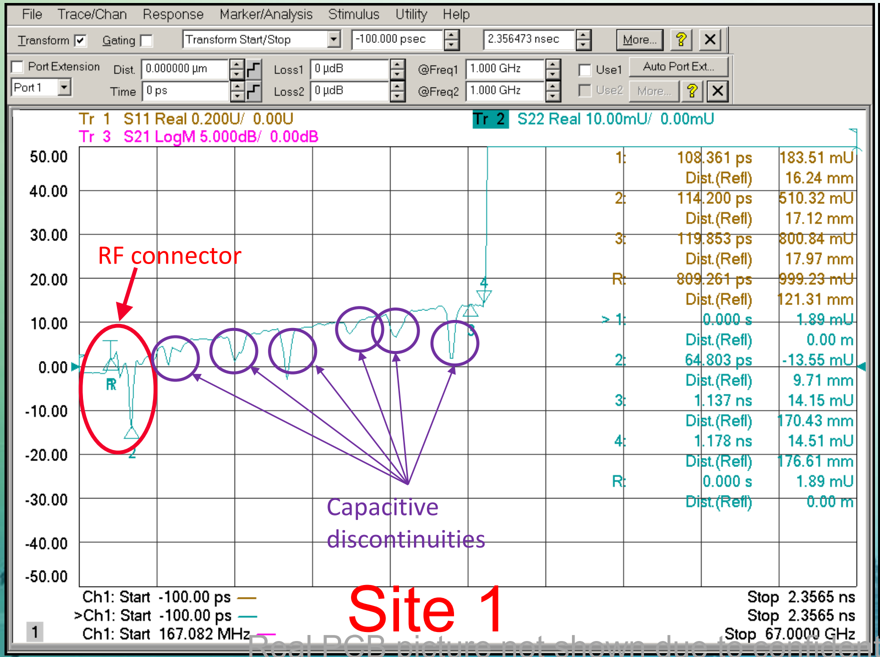
Semi Rigid Cable

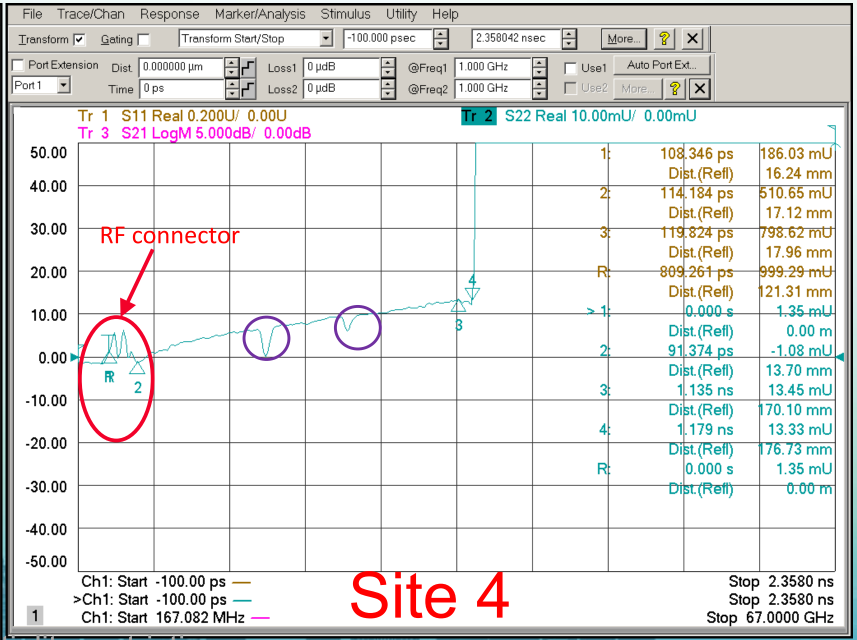
Observation: Semi rigid cable was length matched (600 ps +/- 2.5 ps) but some had more bends than others.

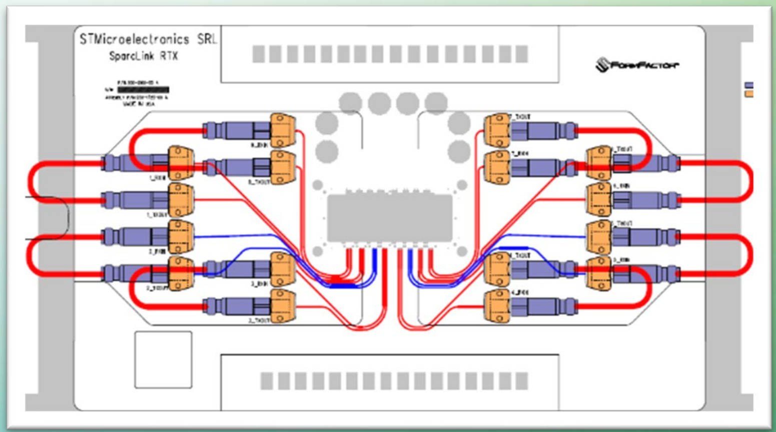
Hypothesis: Bends in cable causing discontinuities that are leading to attenuation issues.

- Minimum on sites 4 & 5 and most on 1 & 8. (also max number of cable bends)
- It's known that there is about 3 dB difference between site 1 and site 4.
- IL measurements of site 1 & 4 show < 0.2 dB difference.

Not the Problem







Real PCB picture not shown due to confidentiality restrictions

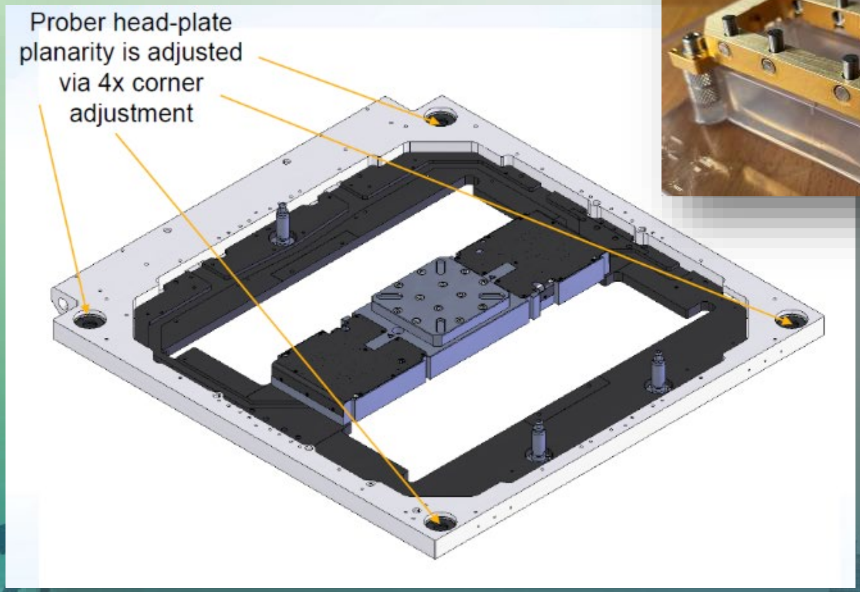
Bridge Beam vs Core Interference

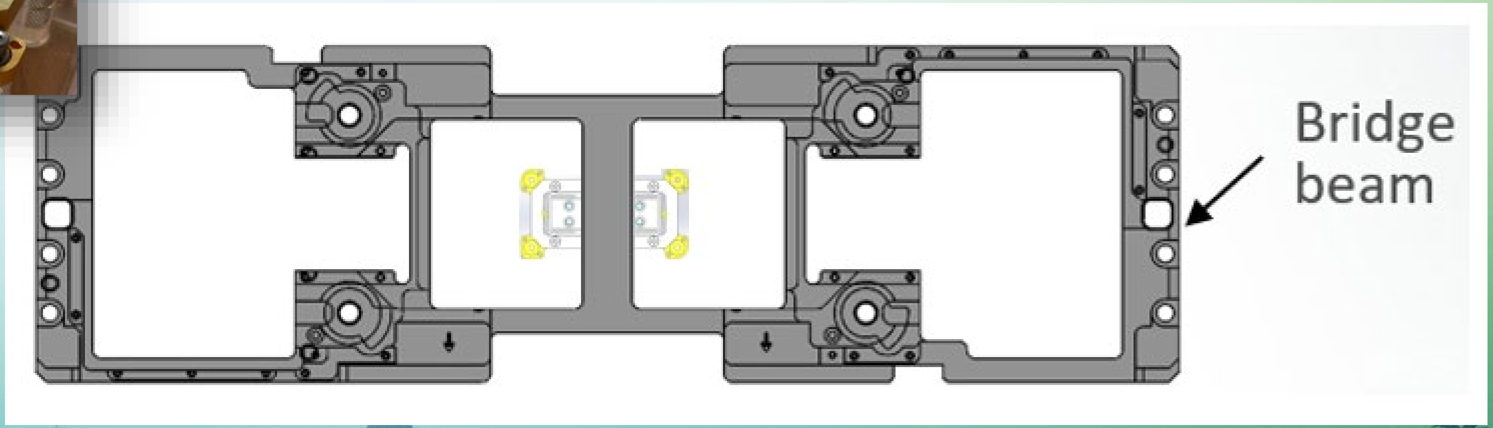
Observation: Different test cells were producing different results for the same Probe Card (PC)

Hypothesis: Lack of planarity and uniform pressure of the bridge beam and core was causing attenuation issues.

- Special fixture was designed and manufactured to measure the interference
- It was found that the planarity and interference was within spec for the test setup

Not the Problem



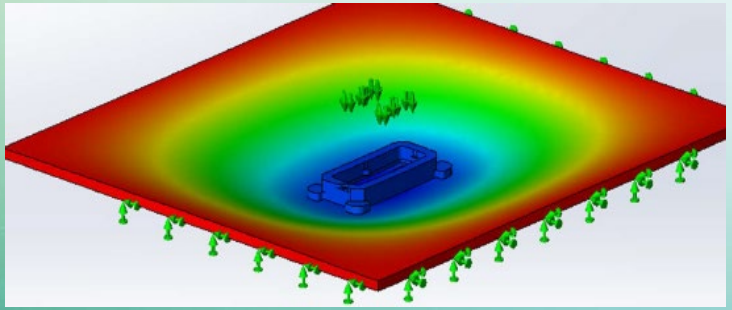


Bridge Beam Interaction

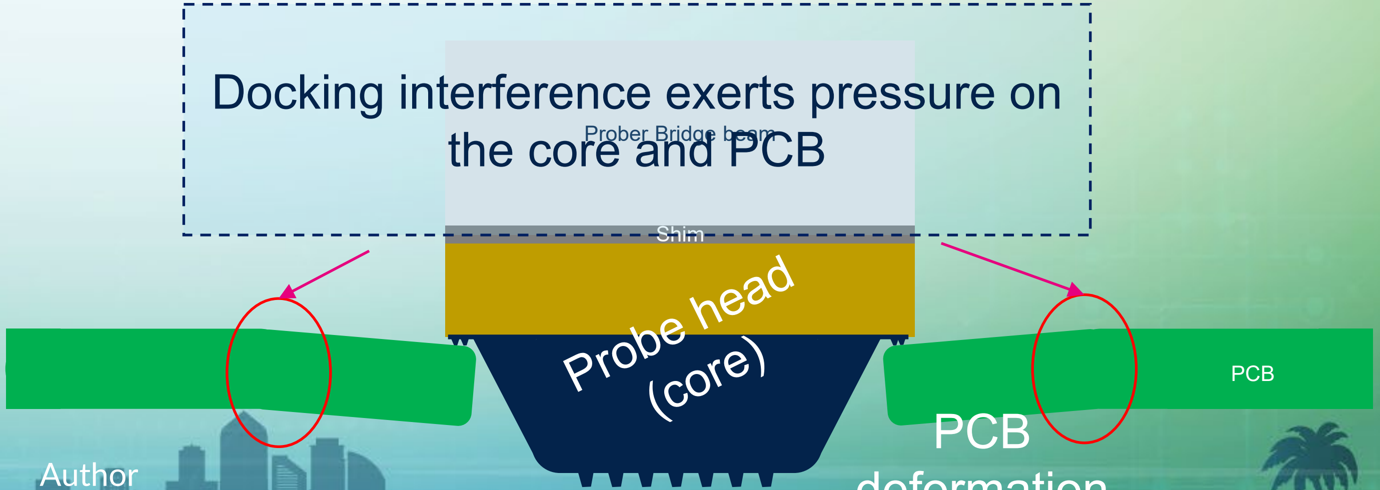
Observation: Numerous configurations have shown that mechanical forces negatively impact the RSSI.

Hypothesis: There is a PCB + Core interaction that affects the RSSI measurements

- Using combinations of shims, docking and undocking, tape and Over Drive (OD) it was possible to affect the RSSI level measured.
- This effect was not seen on any other application. Was unique to this design.
- Bridge beam interaction effects were eliminated by moving all attenuators from the PCB to the membrane.

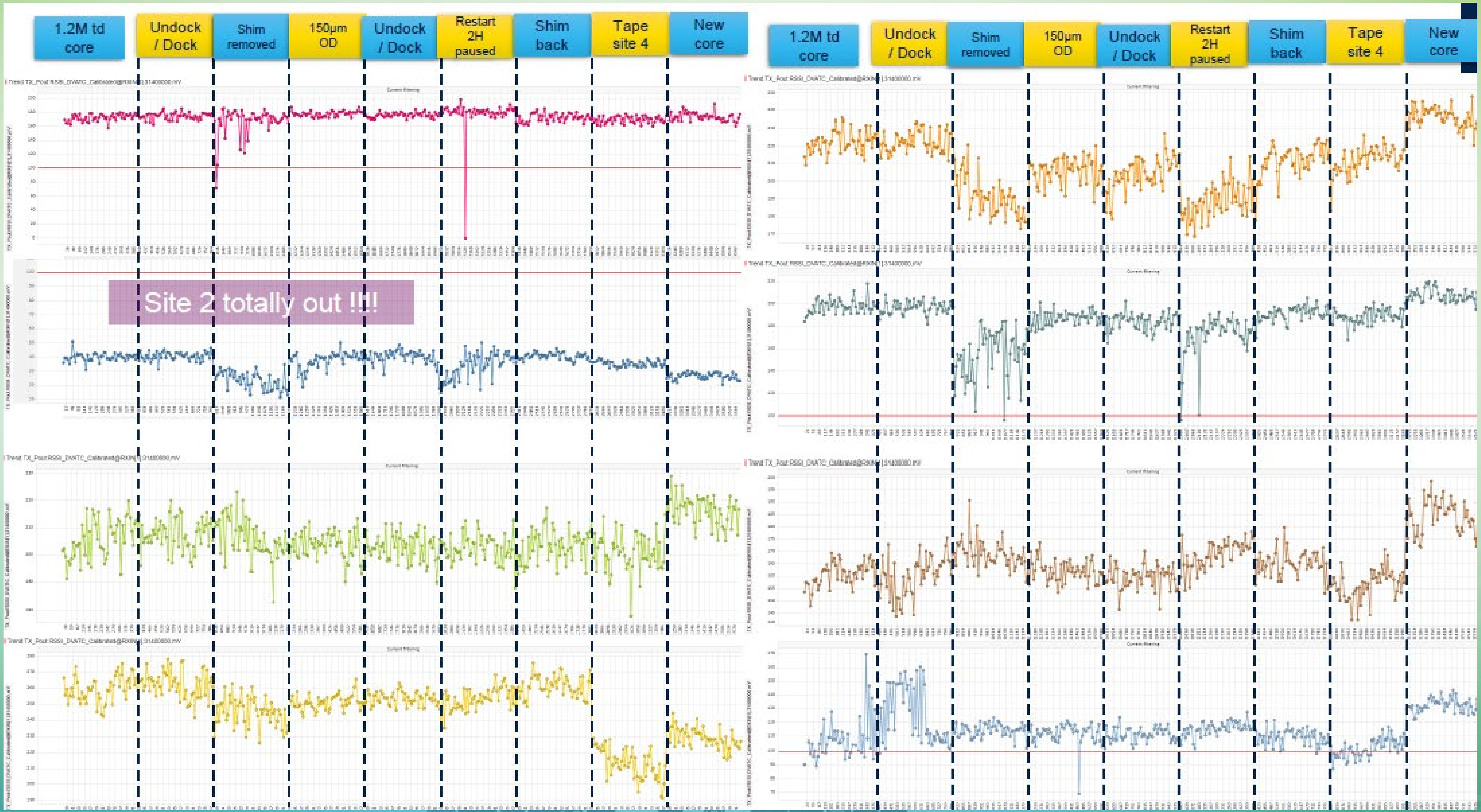


Force applied by prober docking stack



Author

RSSI Manipulation



Solution

- Attenuator Trade Off Analysis
- Coupler Theory
- Design Considerations
- 50 Ω Trick
- Simulation
- Measurements (Validation)
- Results (Summary)

Using "on membrane attenuators" solves our problem. Let's look at how this is implemented…

Solution

Attenuator Trade Off Analysis

Design Consideration	Resistive	Coupler	TX Line
60 GHz Operation	🔴	🟢	🟢
RL Performance	🔴	🟢	🟡
Crosstalk/Coupling	N/A	N/A	🔴
Area (minimum)	🟢	🟡	🔴
Design Complexity	🟡	🟢	🟡
Routing Considerations	🟢	🟢	🔴
Assembly Error	🔴	🟡	🟢
SMT Quantity	🔴	🟡	🟢

🔴 = bad 🟡 = neutral 🟢 = good

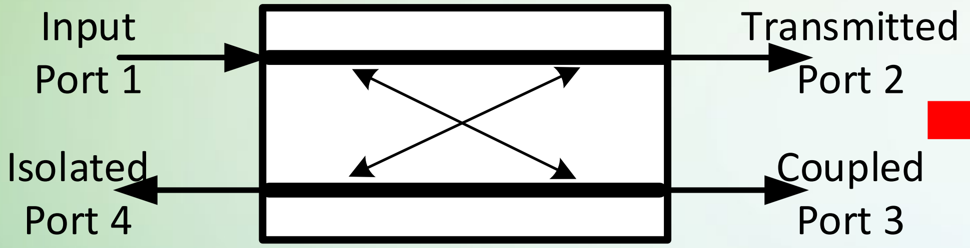
Next let's look at what a coupler attenuator is!

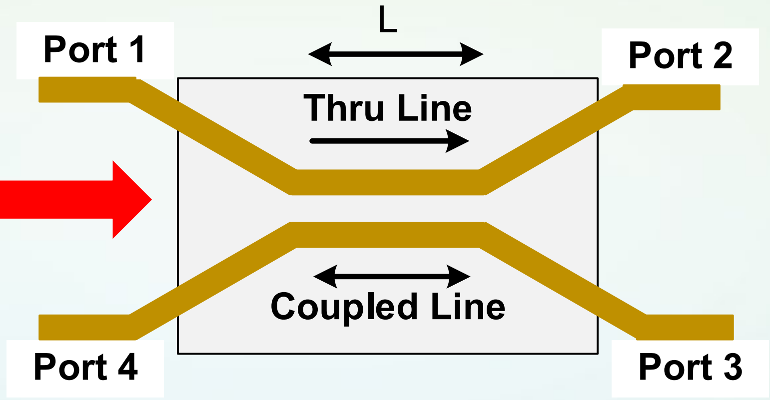
Note:
Ranked highest to lowest importance.
Resistive and TX line attenuator is least suitable. It will not be considered any further in this presentation…

Solution

Coupler Theory

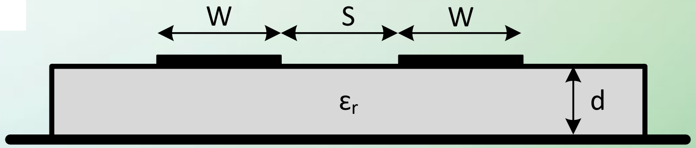
Coupler Definition (Ideal): Directional device where power suppled to port 1 (input) is coupled to port 3 (coupled port) while the remaining power is delivered to port 2 (transmitted port). There is no power at port 4 (isolated port).





Symmetric coupler:

- Symmetry in x and y.
- Requires that θ = π/2 which means L=λ/4.
- λ =C/f at center frequency



Impossible to build a perfect coupler, there will be unwanted coupling:

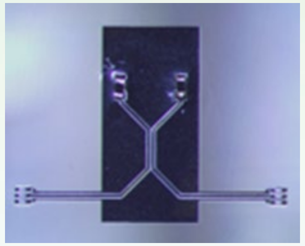
Directional holds: Sij=Sji
S21=S42=S12=S24 – TX paths are equal
S31=S42=S13=S24 – Coupled paths equal
Not perfectly matched: S11=S22=S33=S44
Limited directionality: S41=S32
Reverse coupling exists: S13=S42

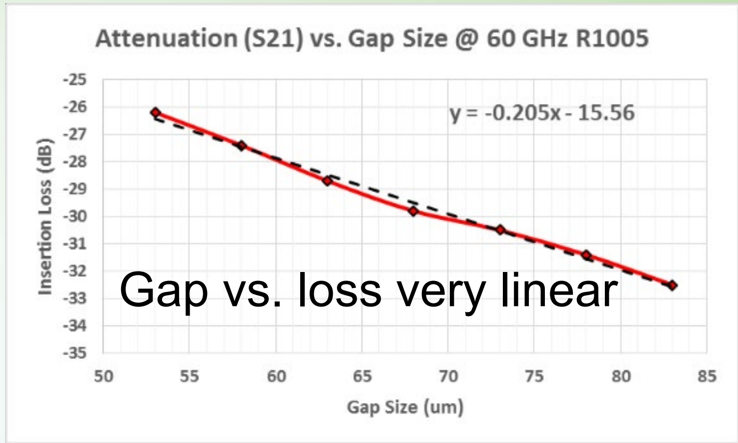
$$S = \begin{bmatrix} S_{11} & S_{21} & S_{31} & S_{41} \\ S_{21} & S_{11} & S_{41} & S_{31} \\ S_{31} & S_{41} & S_{11} & S_{21} \\ S_{41} & S_{31} & S_{21} & S_{11} \end{bmatrix}$$

S41≠0 is very important
This characteristic will be used in the design of the attenuator coupler.

Solution

Design Considerations





Design Requirements for Attenuator

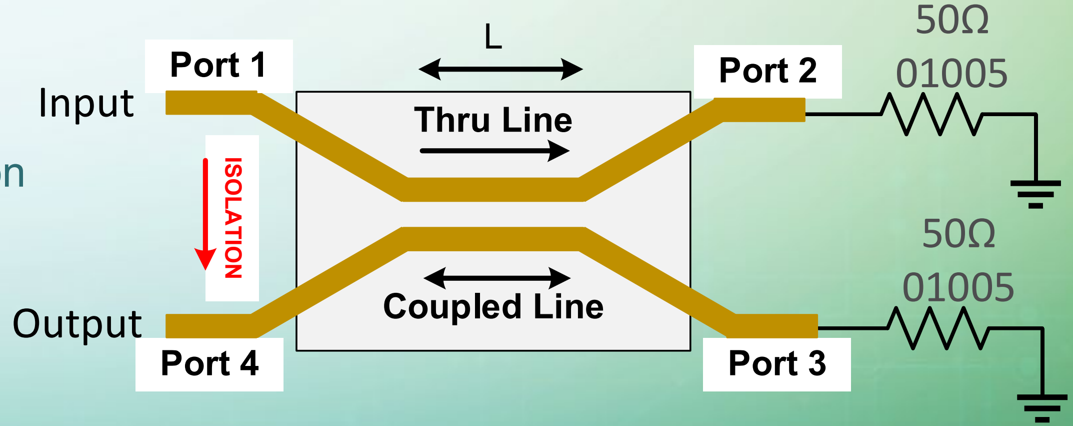
- Center Frequency (fc) = 60.5 GHz
- $P_{TX\ MAX}$ = 6 dBm ~ 4 mW -> 01005 resistors
- Attenuation = 26 dB
- Bandwidth (BW) = 500 MHz

Uses 2-ASK modulation (1 bit/symbol)Data rates for USB 2.0 (480 Mbit/s)

BW = (480 Mbit/s)/(1 bit/symbol) = 480 MHz ~= 500 MHz

Note: ASK signal requires a bandwidth equal to its baud (symbol rate)

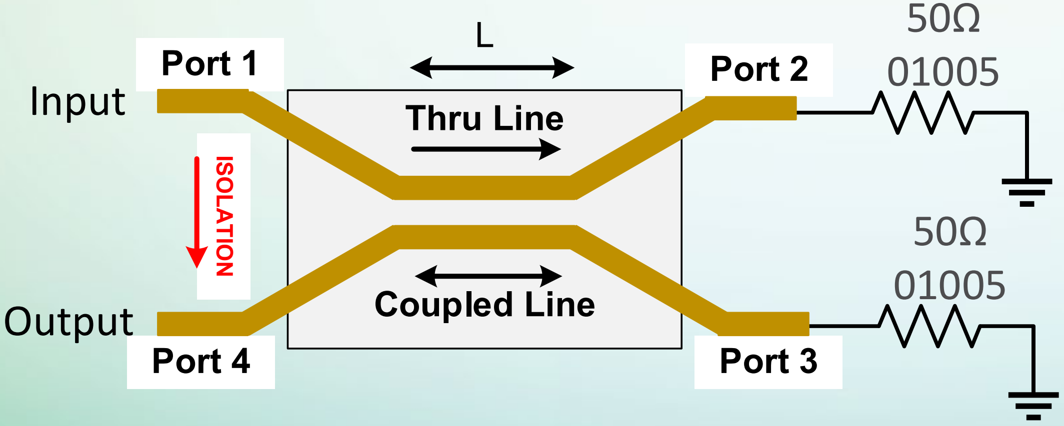
- FFI membrane design rules provide excellent line width control for microwave circuits.
- With FAB variations of +/- 2 um allows us to hold the center attenuation to +/- 0.4 dB
- Designed on 2 metal layer membrane
- Coupler attenuator technology available for new membrane design.

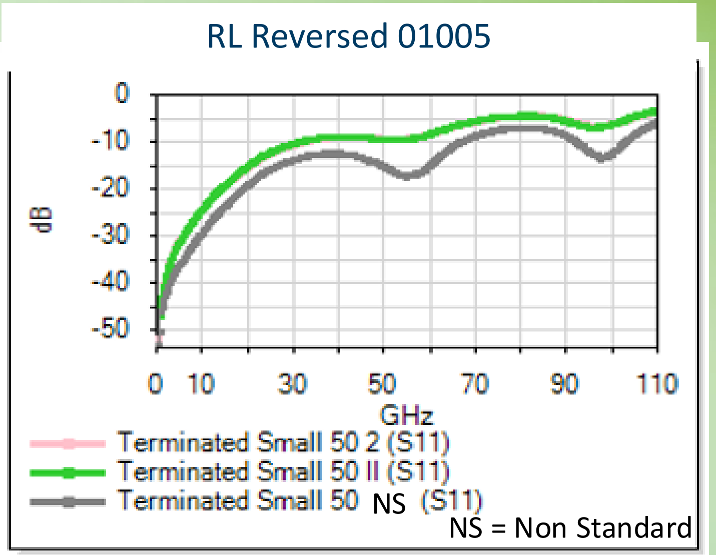


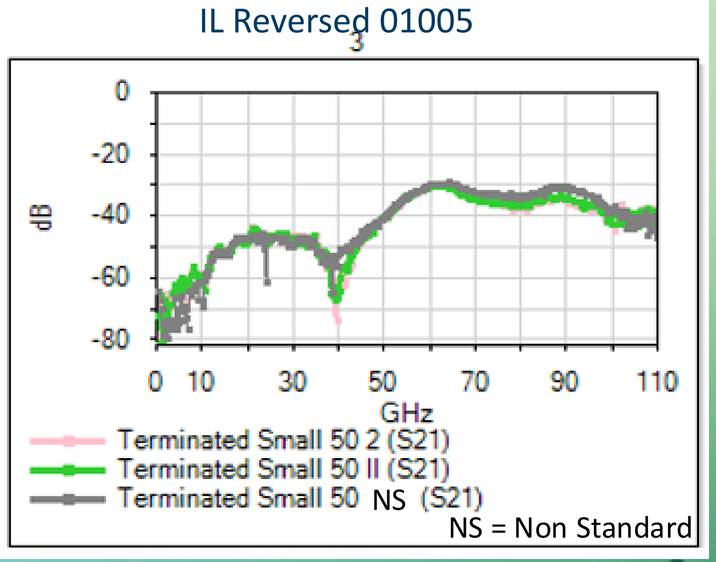
Solution

50 Ohm Trick

- Observed large improvement when the resistor is mounted in a non-standard configuration.
  - Normal: RL < -10 dB @ ~30 GHz
  - Non-standard: RL < -10 dB @ ~65 GHz
  - Best used with 60 GHz coupler





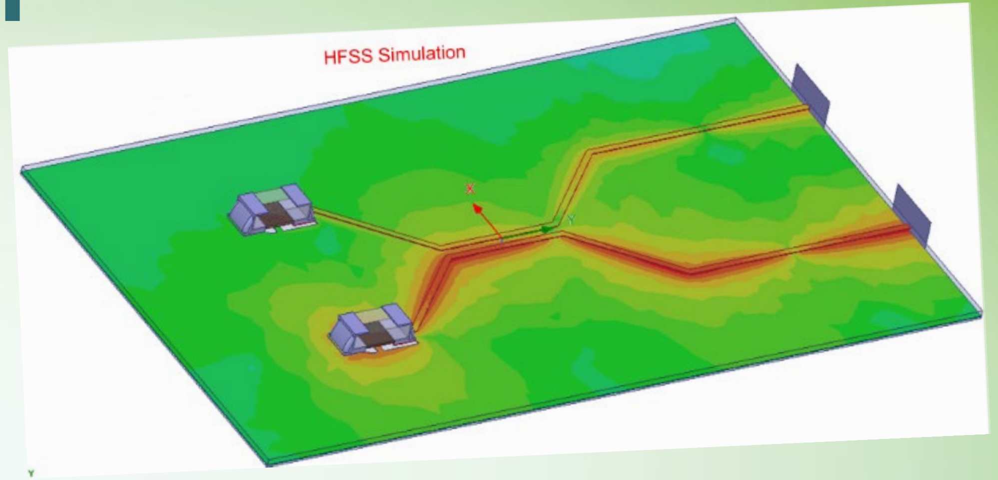


Simulation

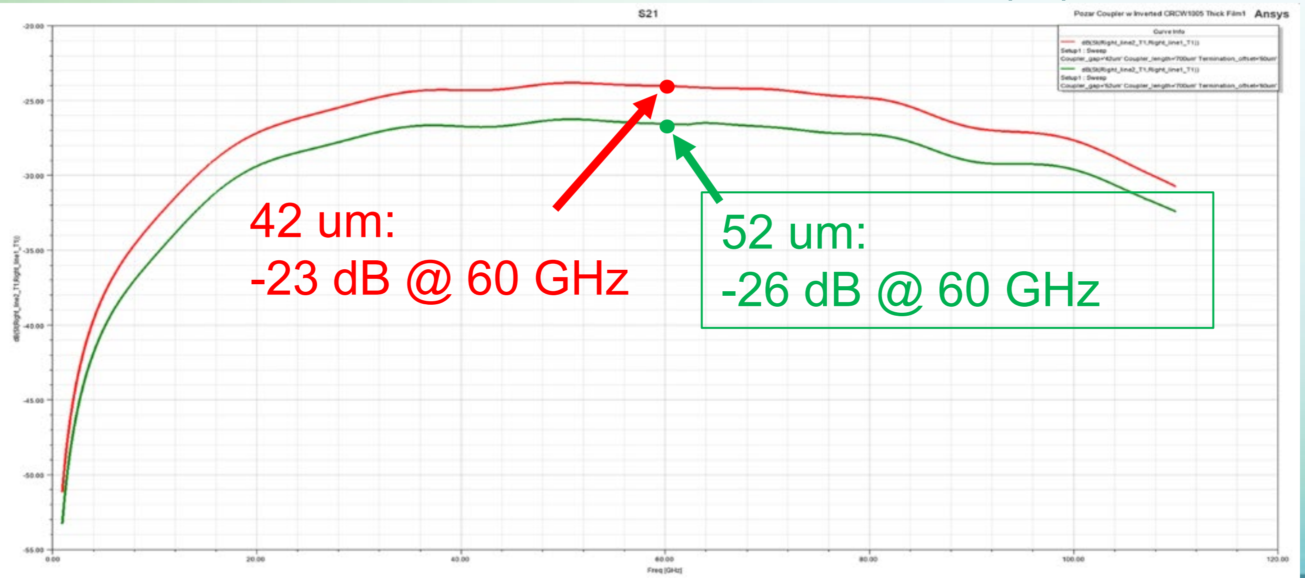
Simulation:
- The coupler design was simulated in HFSS
- The red trace is a gap of 42 um and green trace is for 52 um.

Insertion Loss (IL):
- The simulated IL at 60 GHz is reasonable.
- Model predicted 52 um achieves the required 26 dB of attenuation.

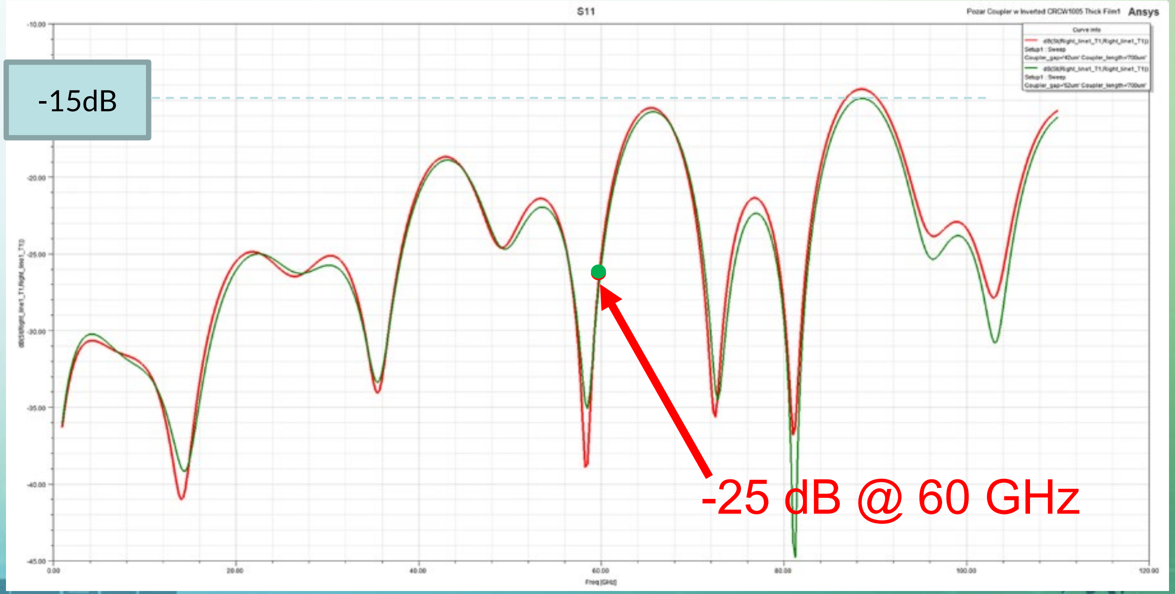
Return Loss (RL):
- RL=-25 dB at 60 GHz is acceptable.



Simulated Coupler Insertion Loss (IL)



Simulated Coupler Return Loss (RL)



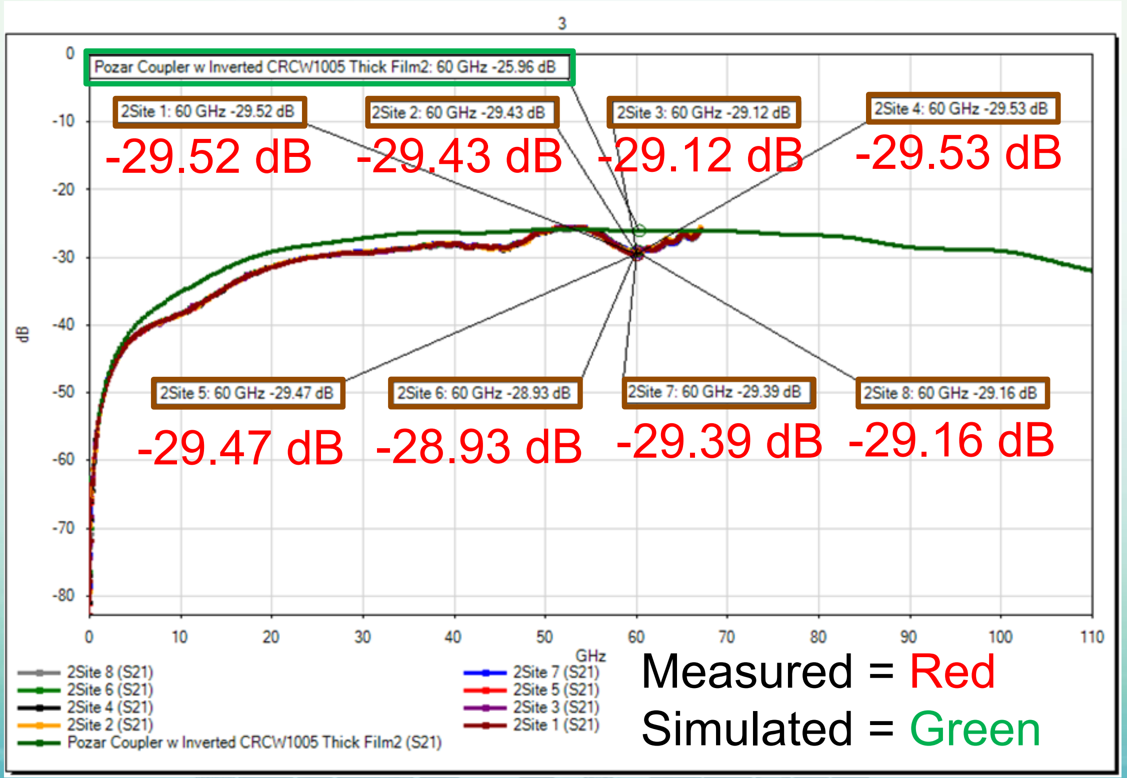
Solution

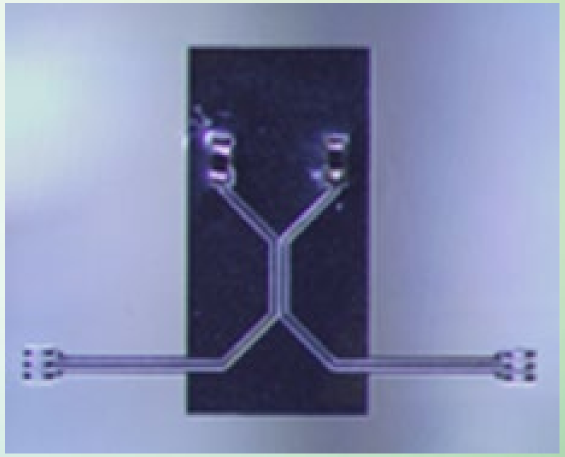
Measurements

(Validation)

- All 8 sites have an IL of approximately 29 dB. This is 3 dB below the simulated IL of 26 dB.
- Future work to perform additional work to identify why there is a 3 dB delta
- 3 dB more of IL is a benefit. It moves the receiver into a more linear region of operation.

IL For Sites 1-8 + HFSS Simulation (green)





Data is fc = 60 GHz for 8 sites on a core.

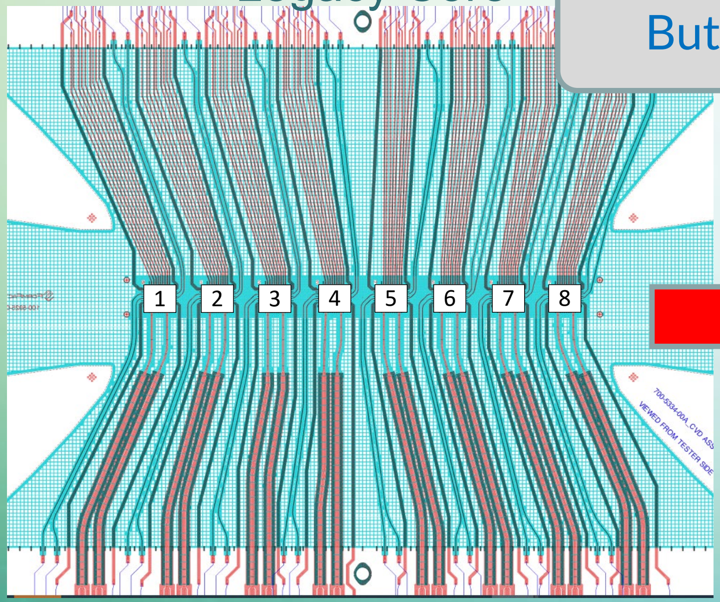
Result

(Summary)

The final membrane (Attenuator Core):

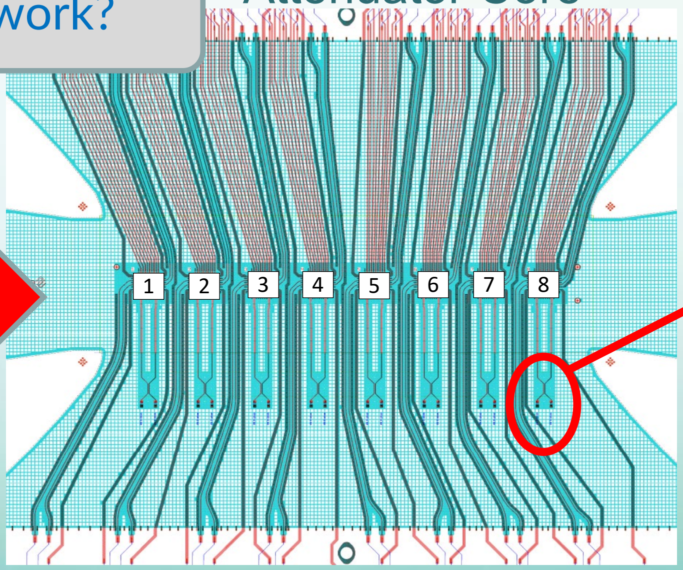
- x8 design with no RF traces routed off the membrane
- 8 couplers (attenuator) designed into the south wing of the membrane
- final attenuator design results in 29 dB of attenuation

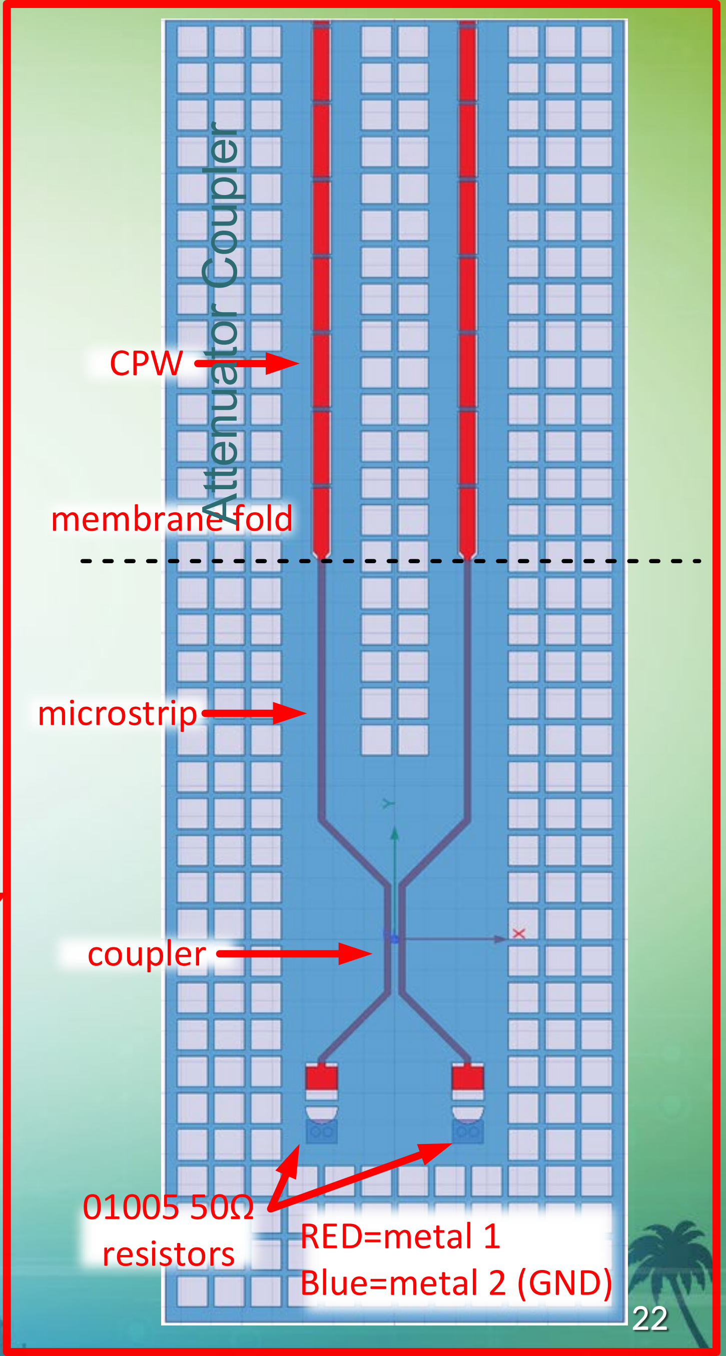
Legacy Core



But does it work?

Attenuator Core





Validation

- Validation Process With RSSI (20k Die)
- Product Improvement

Validation Process With RSSI (20k Die)

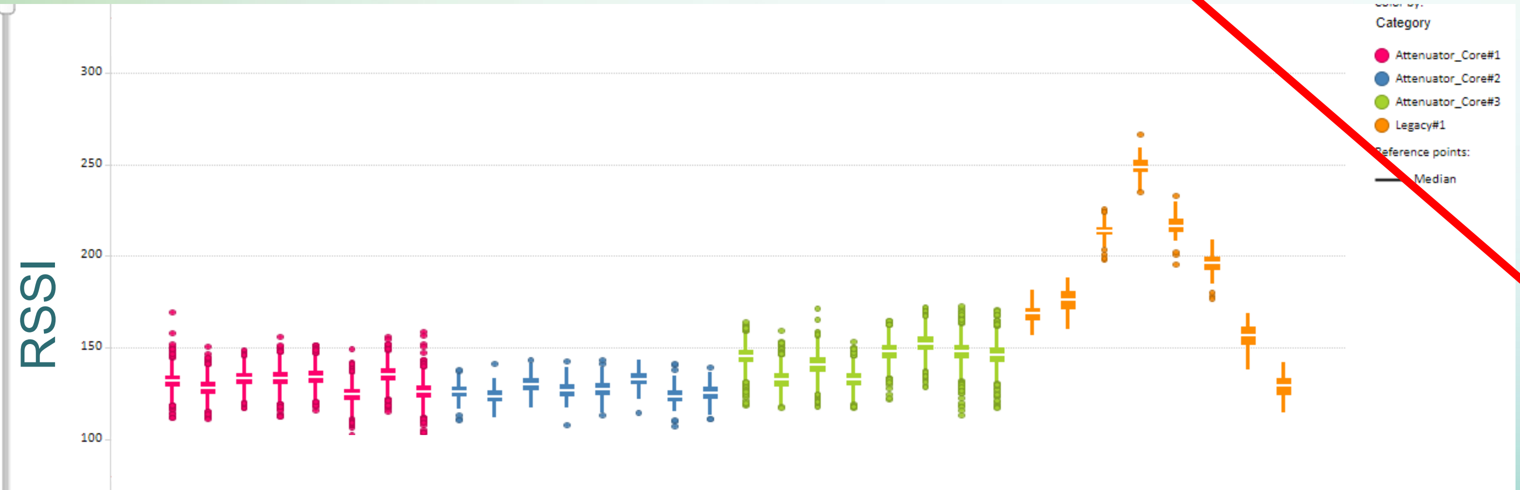
Comparing legacy and attenuator core:

- StdDev of legacy core is 5x that of attenuator core (36 mV to 6 ~ 9 mV)
- CpK of attenuator core is above 2 (now passing)
- Initially 20k die tested (small sample)
- These results are a **MAJOR** achievement

Combined RSSI (P_{IN}) Measured

	Attenuator_Core#1	Attenuator_Core#2	Attenuator_Core#3	Legacy#1
unt	19975	1110	19913	438
edian	131.124	126.901	144	185.578
tliers	137	10	18	0
Dev	6.28657	5.91876	8.93996	36.2081
kProd	2.70047	2.65309	2.35506	0.997407

RSSI (P_{IN}) Measured for Complete Wafer Using x8 P800s



	Attenuator_Core#1								Attenuator_Core#2							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Count	2647	2610	2525	2500	2479	2439	2408	2367	139	139	139	139	139	139	138	138
Median	132.034	128...	133...	133...	134...	124...	135...	125...	126...	123...	130...	127...	127...	132...	123...	125...
Outliers	31	26	30	29	26	27	31	41	5	1	1	2	3	1	6	3
StdDev	4.97776	4.8...	4.8...	5.2...	4.9...	4.8...	5.0...	5.4...	4.7...	4.8...	5.1...	5.4...	5.3...	4.6...	5.4...	5.1...
CpkProd	3.47905	3.3...	3.6...	3.4...	3.6...	3.0...	3.6...	2.8...	3.2...	2.9...	3.2...	2.8...	2.9...	3.7...	2.7...	2.9...

	Attenuator_Core#3								Legacy#1							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Count	2620	2572	2515	2494	2482	2441	2408	2381	54	55	55	55	55	55	55	54
Median	145...	132...	140...	132...	148...	152...	148...	146...	168...	176...	213...	248...	216...	196...	157...	129.608
Outliers	46	30	30	20	24	29	50	47	0	0	7	2	4	3	0	0
StdDev	5.5...	5.3...	6.0...	4.9...	5.4...	5.7...	6.2...	6.2...	4.8...	6.6...	5.5...	5.9...	6.6...	6.8...	6.6...	5.88969
CpkProd	3.9...	3.2...	3.3...	3.5...	4.1...	4.2...	3.6...	3.5...	6.0...	4.8...	6.9...	4.5...	5.6...	5.6...	3.8...	2.78037

Category » Site

Production Improvement

- On production mode after ~200 k die tested, attenuation remains stable and site variation is ok
- No more event of yield loss

RSSI (P_{IN}) Measured for Complete Wafer Using x8 P800s

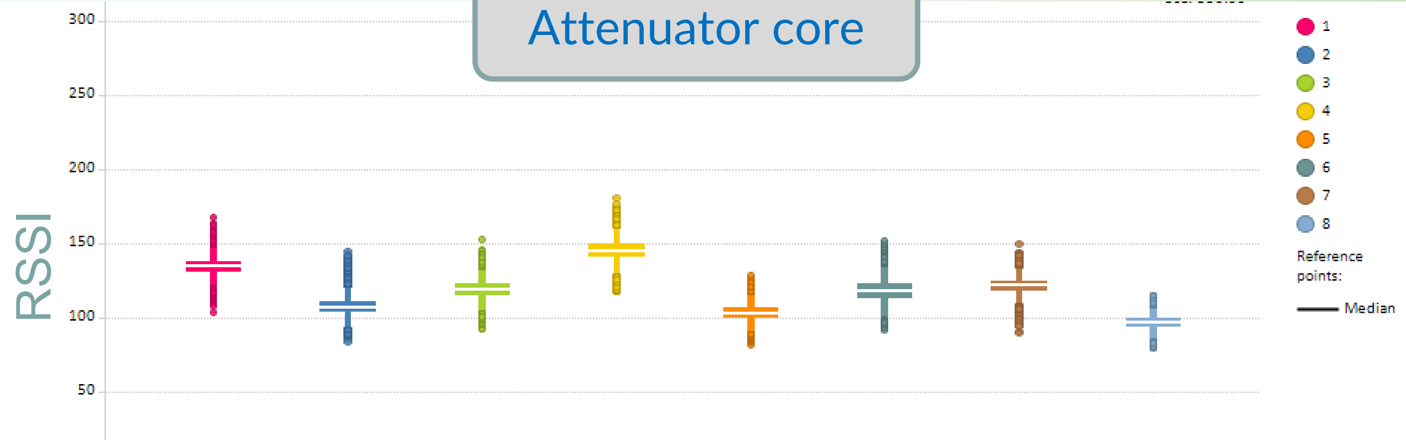
Legacy core

	1	2	3	4	5	6	7	8
	LoopBack							
Count	87	87	87	87	87	87	87	85
Median	173.928	176.9	213.31	245.478	213.961	188.096	155.553	130.895
Outliers	0	5	0	0	1	0	0	2
StdDev	5.08933	5.20672	5.01638	4.24311	5.6634	6.37692	5.31978	5.98824
CpkProd	6.17233	6.23687	7.79846	6.66759	6.87201	5.64345	4.74336	2.83585

Site » Category

115 mV of delta for median values

Attenuator core



	1	2	3	4	5	6	7	8
	k5tv9354							
Count	16469	16879	17080	17334	17472	17643	18249	18359
Median	135.079	107.779	119.563	145.732	103.748	118.195	122.37	97.1085
Outliers	215	420	196	251	156	135	268	277
StdDev	5.74464	6.23171	5.95228	6.72144	5.28731	7.03742	5.41687	4.86239
CpkProd	7.83726	5.7852	6.69751	7.21896	6.54427	5.6074	7.52841	6.66089

50 mV of delta for median values

Conclusion

- By moving attenuators to the membrane, attenuation over 8 test sites showed an improved standard deviation of 0.35 dB on two membranes, where the previous membrane version showed 1.5 dB. This amounts to a 77% standard deviation reduction.
- Additionally with the attenuator core:
  - RSSI hump has been resolved.
  - In production STMicroelectronics observed very good predictability and stability of core performance
  - STMicroelectronics considers this a great achievement on their production test

Finish