TEST VISION SYMPOSIUM

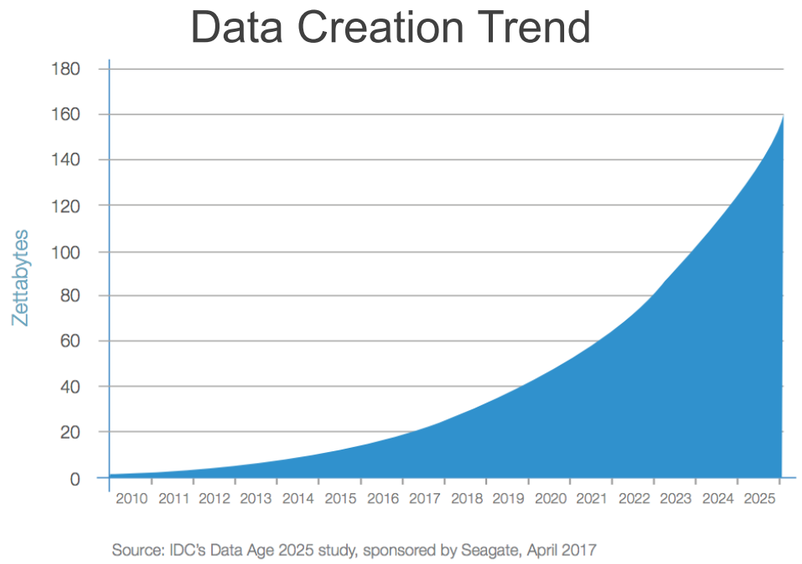
The Digital Revolution: PAM4 Wafer Test

David Raschko

semi

Introduction

- The demand for data is increasing exponentially over time
  - With this increased demand comes a need to move data faster
    - Novel approaches for increasing data rate will need to be introduced to keep up with demand
      - How do these new approaches impact semiconductor test?
- FormFactor has investigated the impact of the upcoming changes in digital test and has developed new capability to meet the new, increased requirements



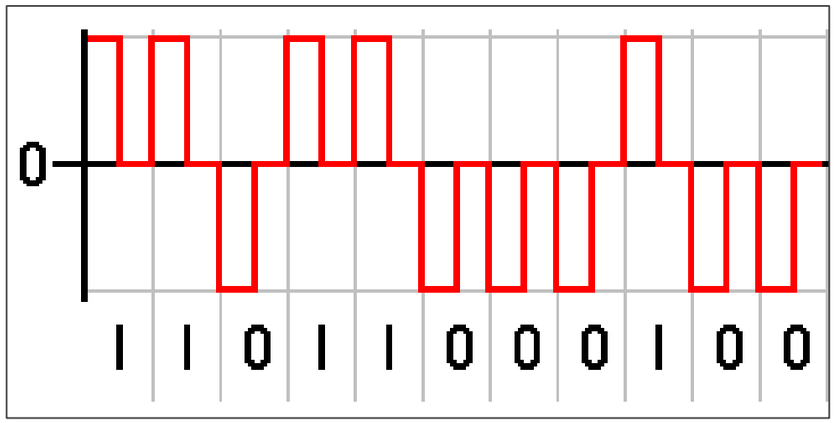
Agenda

- Introduction of Digital Test and PAM4
- What is the Status Quo for Digital Test?
- What changes with PAM4 for Test?
- How is Digital Test Managed?
- Future Solutions and Summary

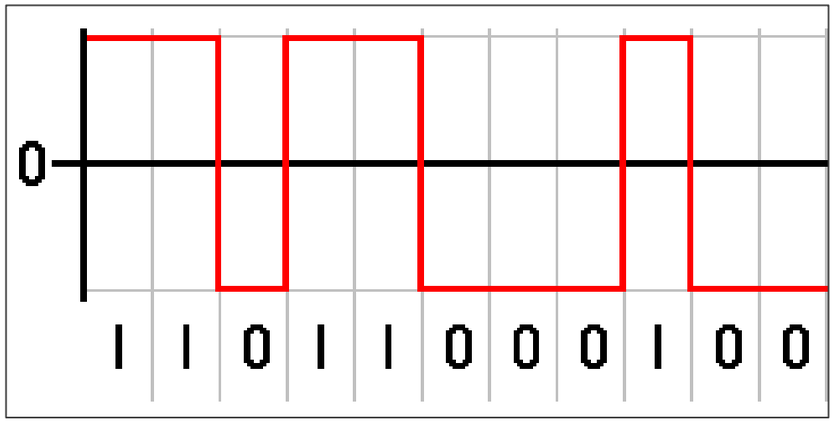
What is Digital Communication?

- "Morse Code"
  - Communicating in Binary (Sending 1's and 0's)
    - Direct translation from 1's and 0's to information

Return to Zero

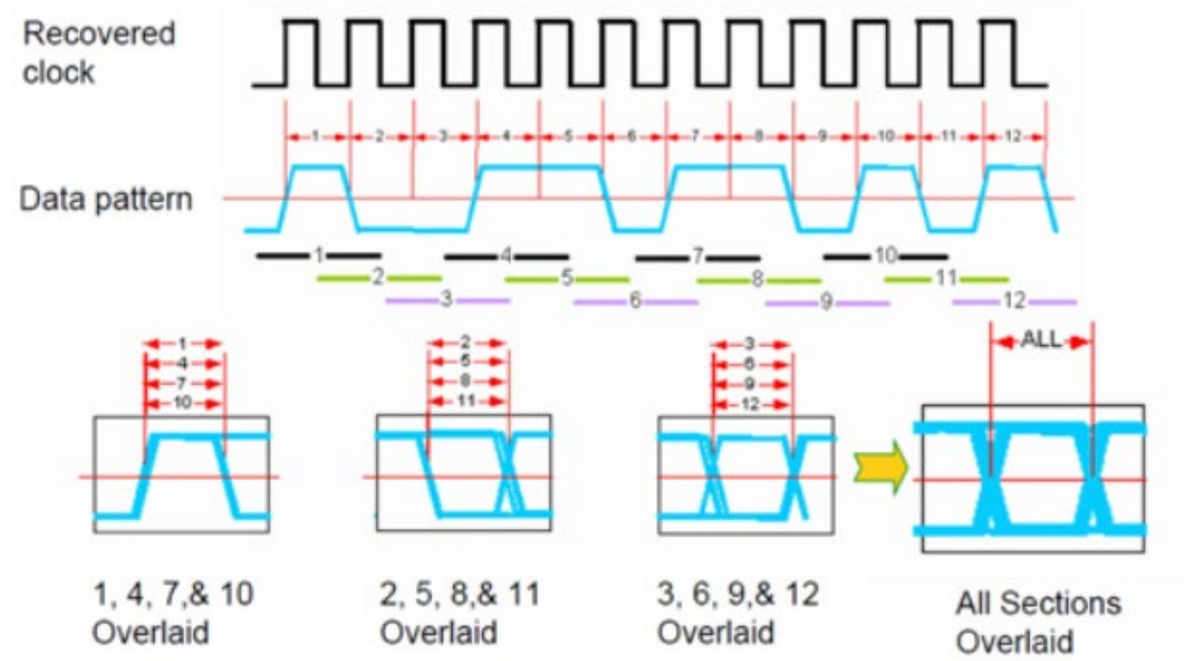


Non-Return to Zero



How are Digital Signals Tested?

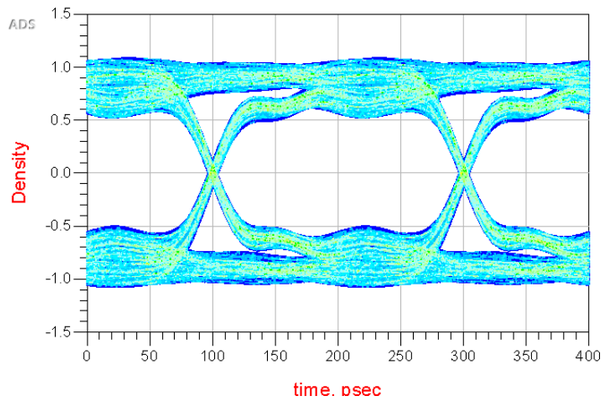
- 2 Common Methods of test:
  - BER (Bit-Error-Rate)
    - Send a known psudo-random bit stream through a device and see if the device can output the same bit-stream
      - Device performance measured as the number of bits that are not correct
  - Eye Diagram
    - Repeated Sampling of a digital signal overlayed onto the same plot
      - Depicts ability to distinguish between voltage levels

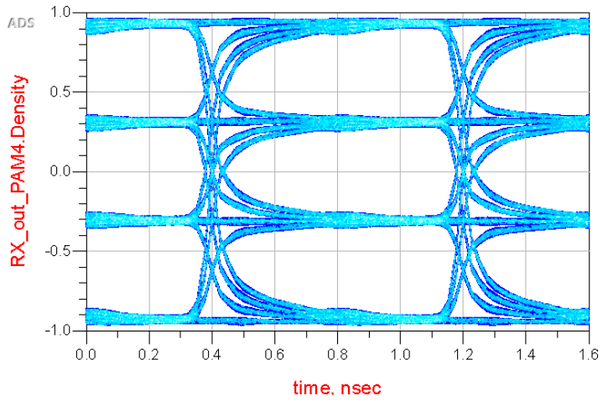


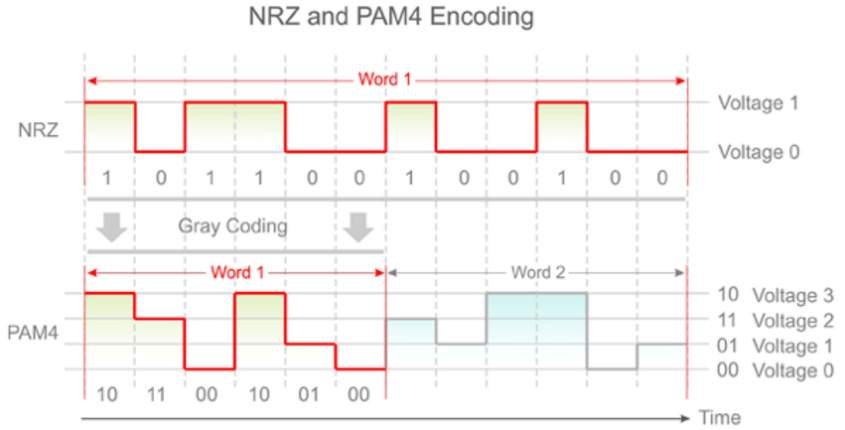
https://www.signalintegrityjournal.com/articles/432-s-parameters-signal-integrity-analysis-in-the-blink-of-an-eye

What is PAM4?

- Pulse Amplitude Modulation
  - Next generation digital signal modulation
- Uses 4 Amplitude Levels to send 2 bits per Unit Interval
  - Effectively doubles the data rate without a change in clock speed

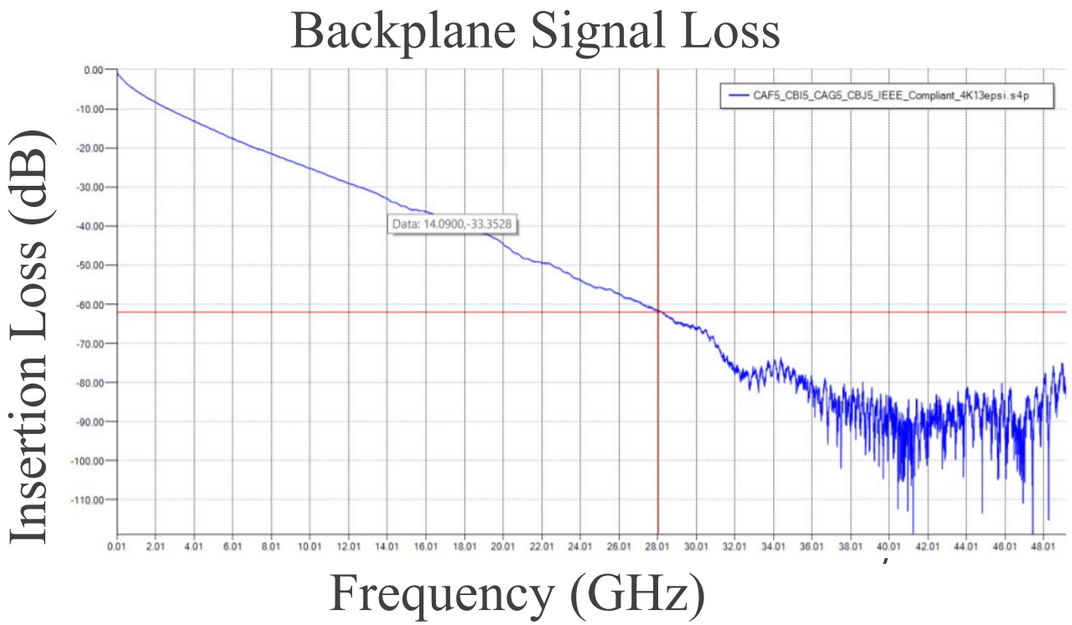






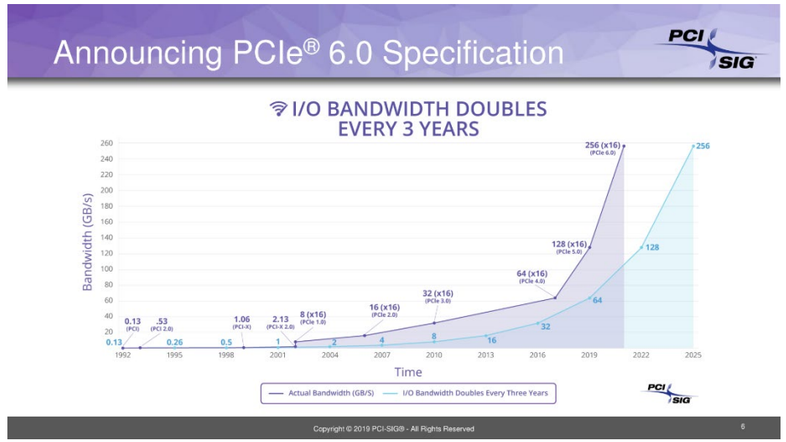
Why Move to PAM4?

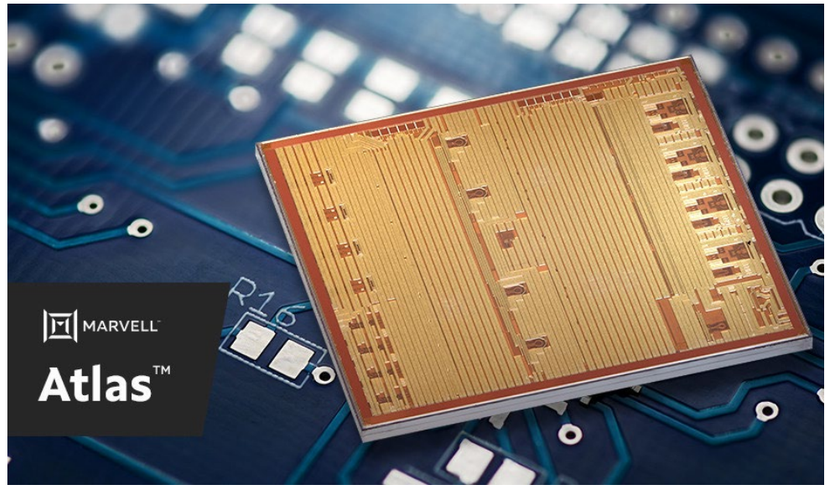
- As speeds increase loss also increases
- PAM4 2x the data rate without increasing frequency
- PCIe as an example:
  - Data rates double with each new standard
  - PCIe 4.0 =16Gbps
    - 8GHz (NRZ)
  - PCIe 5.0 = 32Gbps
    - 16GHz (NRZ)
  - PCIe 6.0 = 64Gbps
    - 16GHz (PAM4)



When will PAM4 Arrive?

- PCIe 6.0
  - Next generation PCIe communication protocol
  - Standard released in Q4 2020
- GDDR6X DRAM
  - Memory interface that uses PAM4 in conjunction with high-end graphics cards
  - Q4 2020
  - https://www.edn.com/pam4-makes-it-to-memory-interfaces/
- PAM4 DSP
  - Integration of TIAs and Laser Drivers (fiber optics)
  - https://www.prnewswire.com/news-releases/marvell-extends-pam4-dsp-cloud-data-center-leadership-with-industrys-first-integrated-solution-301306389.html





How do Specifications Change with PAM4?

- Probe Card specs traditionally derived through the Nyquist frequency
  - The Nyquist frequency is the maximum frequency f_{max} that can be measured with a system sampling at frequency f_{sample}
    - $f_{sample} = 2\ f_{max}$
    - 15dB Return Loss
    - 3dB Insertion Loss
    - 20dB Crosstalk
  - For a 16 Gbps NRZ signal, the 3 dB point is 8 GHz using this short-hand
- Do these specs work for PAM4?

Why Will Specifications be Different?

- The specifications for PAM4 require better performance than a NRZ signal operating at the same symbol rate
- That is due to:
  - Higher number of transitions
  - Smaller change in voltage levels

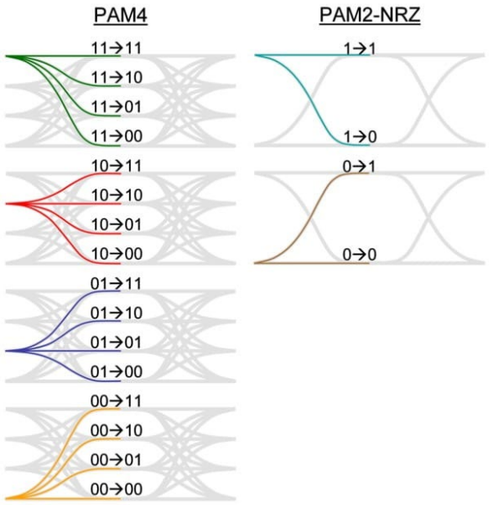
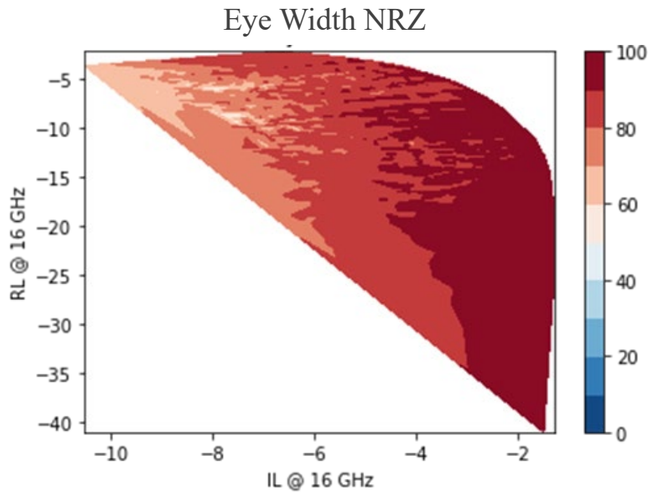


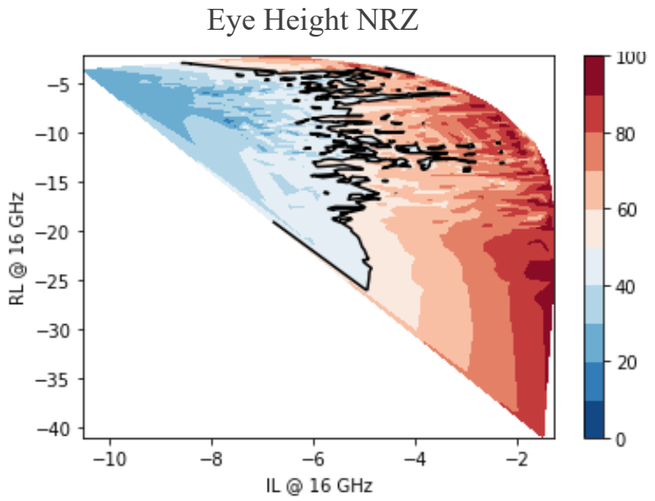
TABLE 1		
	NRZ	PAM4
Bits Per Symbol	1	2
Symbols	2	4
Eye Diagrams Per UI	1	3
Relative SNR Electrical	0 dB	9.5+ dB
Relative SNR Optical	0 dB	4.7+ dB
Distinct Transitions	2	12
Rising/Falling Edges	2	6
Average Transition Density	50%	75%
Skew and Compression	Absent	Present

https://www.signalintegrityjournal.com/articles/1151-pam4-for-better-and-worse

NRZ Sensitivity to Loss

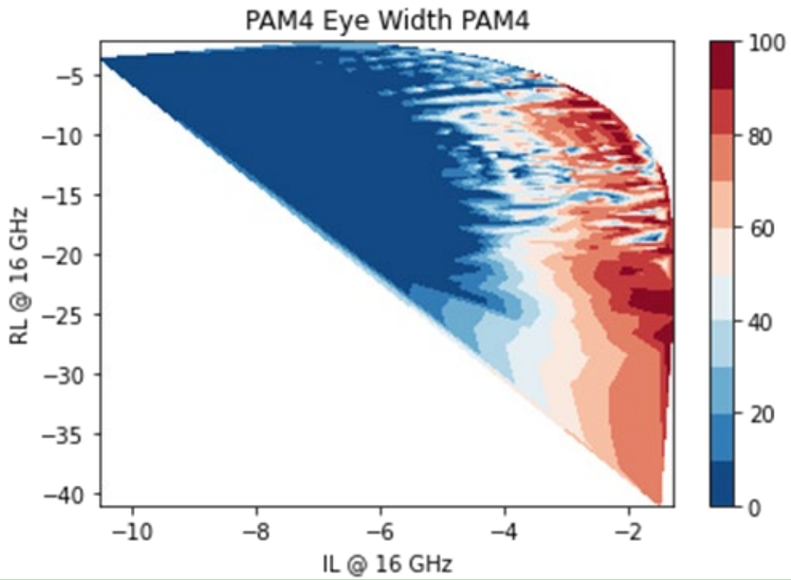
- Sensitivity analysis exploring eye opening vs. Insertion Loss and Return Loss
  - NRZ overall performance appears to be dominated by the height, NOT WIDTH
  - At 16 GHz, if IL is < 5 dB, then the eye is larger than 50%

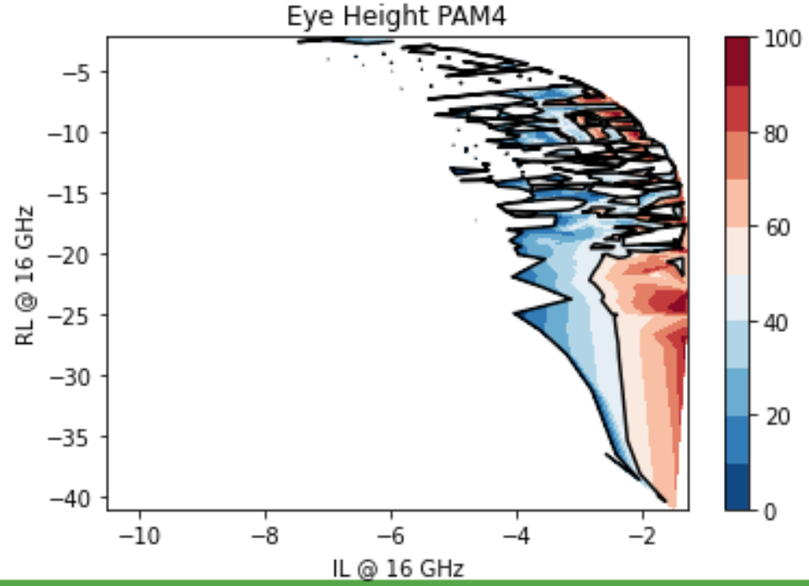




PAM4 Sensitivity to Loss

- Sensitivity analysis exploring eye Width vs. Insertion Loss and Return Loss
  - To maintain a 50% eye opening Insertion loss must be better than -3dB and Return Loss must be better than -10 dB at the Nyquist Frequency
    - Represents a ~2x increase in Probe card performance compared to NRZ





Observations on PAM4 Eye Height and Width

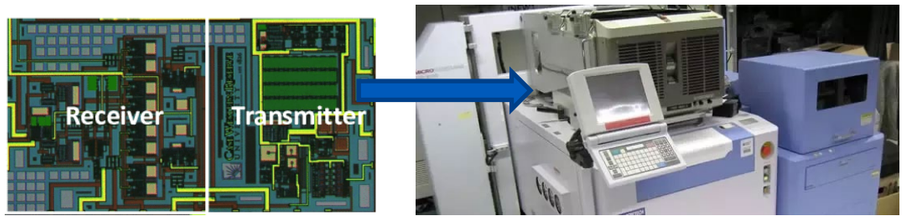
- PAM4 and NRZ Probe Card Spec:

Digital Protocol Type	Insertion Loss Spec	Return Loss Spec
NRZ	-5 dB	-10 dB
PAM4	-3 dB	-10 dB

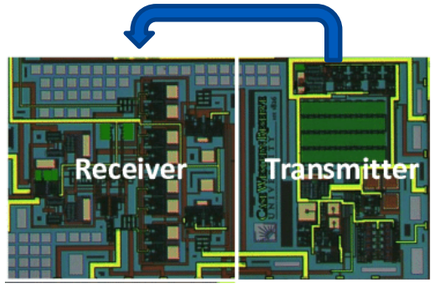
- It appears that the eye height is more sensitive to performance than the width
  - Most likely since Insertion Loss is known to be more important to the performance than Return Loss due to its impact on overall system loss
  - IL affects the height more than the width, and RL affects the width more than the height

How is Digital Test Managed?

- Testerization – Direct Connection to Tester Channel
  - Probe -> MLO -> PCBA -> Tester Resource



- Loopback Test – Signal goes from DUT TX to RX
  - Probe -> MLO -> Probe

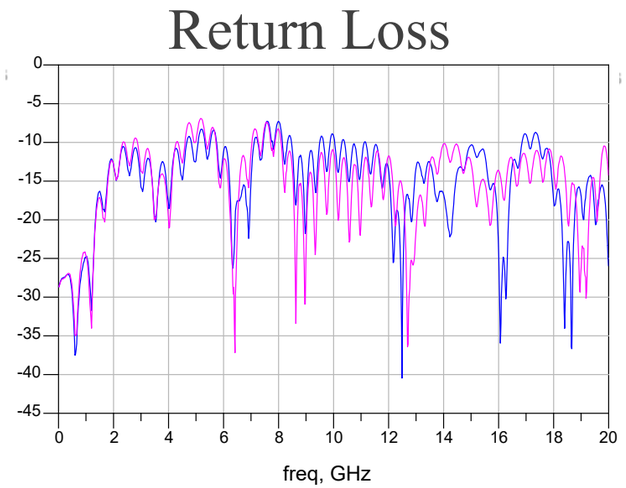


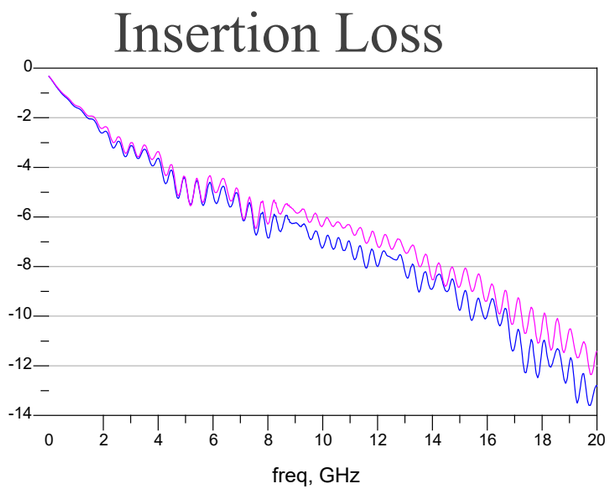
Testerization Probe Card Performance

- Testerization = Probe + MLO + PCBA to tester Resource
  - MLO and PCBA Loss dominate the performance due to long path lengths

- Max Speed:
  - PAM4 ~10Gbps
  - NRZ ~10Gbps

Pink = PCBA + MLO
Blue = PCBA + MLO + MEMS Probe

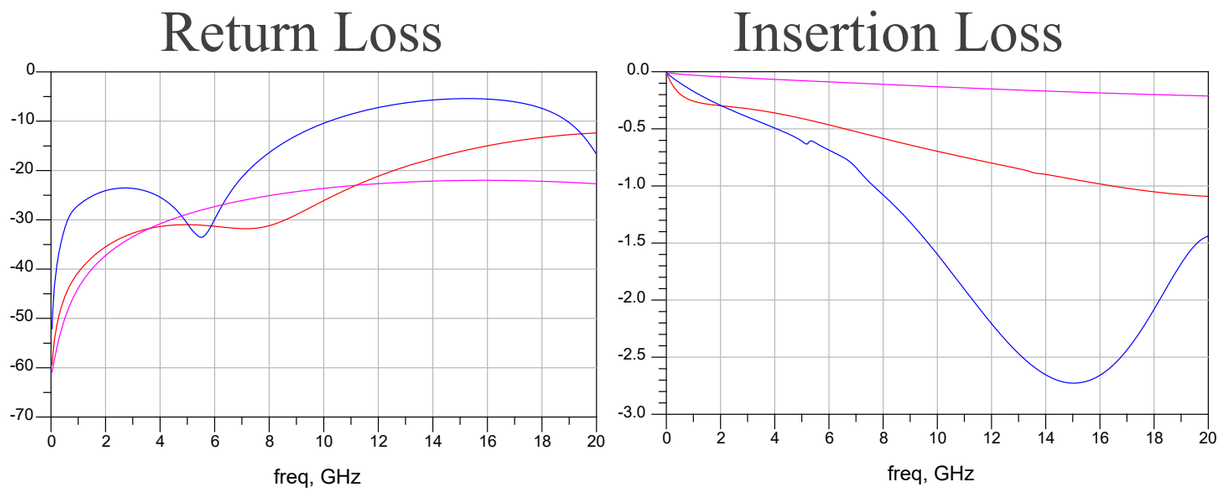




Loopback Probe Card Performance

- Loopback = Probe + MLO + Probe
  - MLO Loss ~= Probe Loss
  - Performance gated by MLO length and probe loss
- NRZ ~ 32Gbps
- PAM4 ~ 64Gbps

Pink = MLO Only
Blue = MLO + 60 ohm MEMS Probe
Red = MLO +50 ohm MEMS Probe



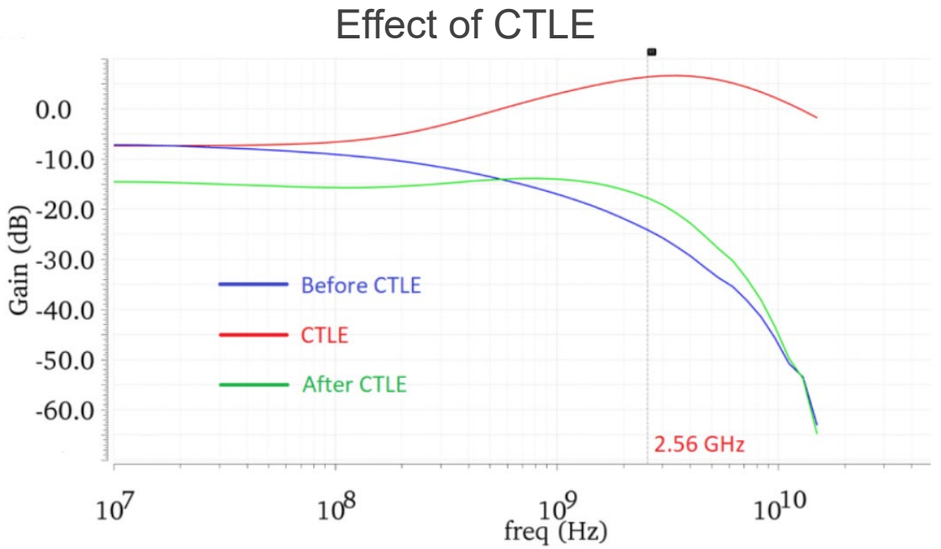
Future of Digital Test

- How do we continue to manage loss in the probe card as speeds continue to increase?

- 2 Methods:
  - Implementation of equalization at wafer test
  - Improved Probe Card Performance

Equalization: Extending Probe Card Performance

- Equalization = Frequency shaping filters that flatten the channel response up to a certain frequency
- Continuous Time Linear Equalization (CTLE)
  - boost the higher frequencies at the receiver to bring all frequency components of the signal to a similar amplitude
- Feed-Forward Equalization (FFE)
  - Creates multiple delayed versions of the input signal that are added back to the signal with the proper weights
- Decision Feedback Equalization (DFE)
  - non-linear equalization which relies on decisions about the levels of previous symbols (high/low) to correct the current symbol

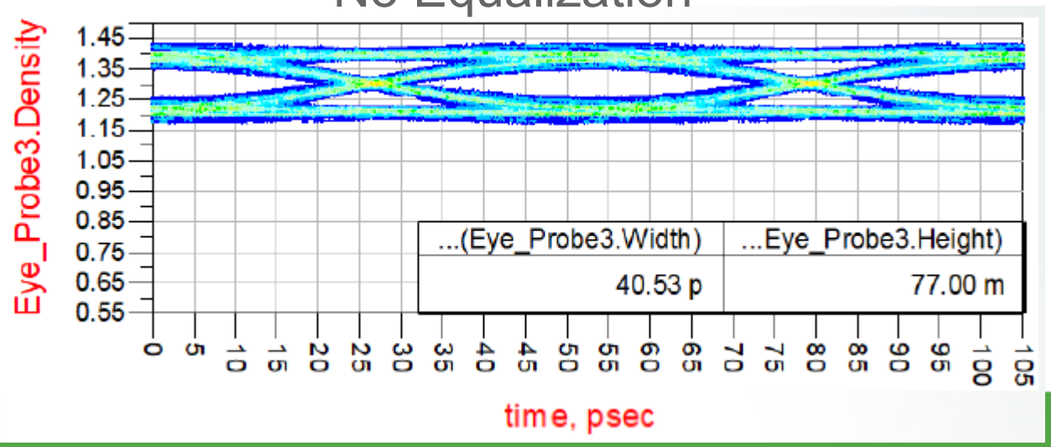


https://www.researchgate.net/figure/Schematic-of-a-CTLE-a-and-AC-response-of-the-equalizer-b_fig2_340291161

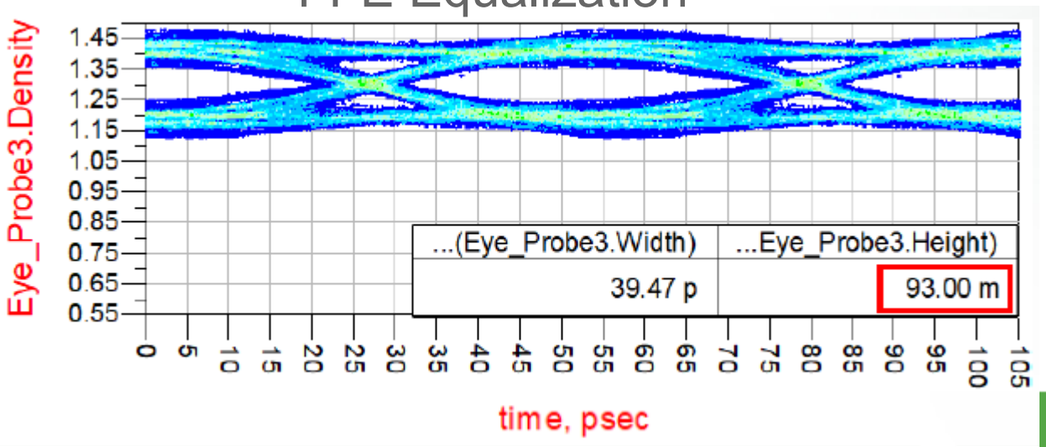
Impact of Pre-Emphasis on Probe Card Performance

- Feed-Forward Equalization used to improve probe card performance on 18Gbps channel
  - 4.1 dB FFE applied to simulation
  - Improved eye opening from 77mV to 93mV
    - **20% improvement in eye height**

No Equalization



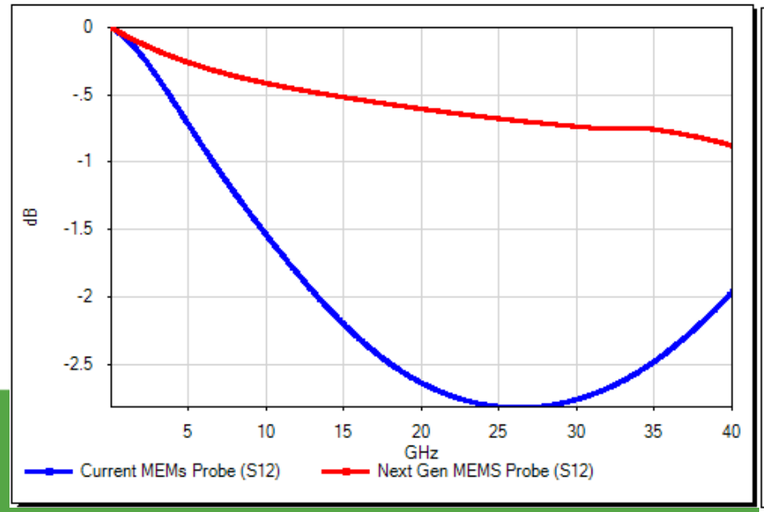
FFE Equalization



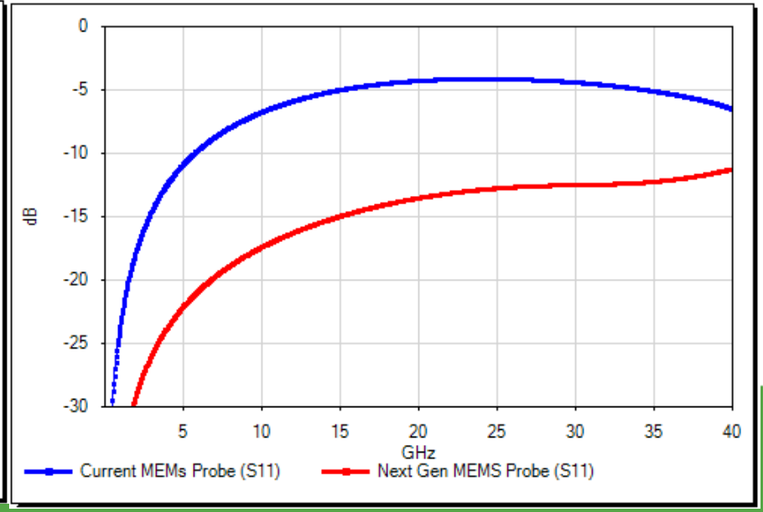
FFI Products for Digital Test

- Next Gen MT Series MEMS probe solves High-Speed Test Requirements
  - Probe is >20% shorter compared to conventional MEMS probes for reduced inductance
    - >-0.5 dB Insertion Loss at 16GHz (PCIe 5/6)
    - <-15 dB Return Loss at 16 GHz (PCIe 5/6)

Insertion Loss



Return Loss



Current MEMS Probe meets requirements for PCIe 3 and PCIe 4

Digital Test Summary

- PAM-4 specs will need to be tighter compared to NRZ:

Digital Protocol Type	Insertion Loss Spec	Return Loss Spec
NRZ	-5 dB	-10 dB
PAM4	-3 dB	-10 dB

- Testerization has problems with path length loss limiting performance to ~10Gbps
- MLO Loopbacks have significantly lower loss, but the probe begins to become the dominate loss factor
- Equalization improves probe card performance, but requires customer partnerships to understand the required inputs/outputs

Conclusion

- The requirements for PAM4 vs NRZ indicate that probe card specifications should be more stringent than that for NRZ probe cards
- As complexity of digital test increases, simulation partnerships with equalization will need to be developed
- FFI Products are ready for the challenges being presented by the move to PAM4 with custom solutions