DesignCon® 2014

De-Mystifying the 28 Gb/s PCB Channel: Design to Measurement

Heidi Barnes
Robert Sleigh
Mike Resso

Agilent Technologies

Jack Carrel
Hoss Hakimi

XILINX ALL PROGRAMMABLE.

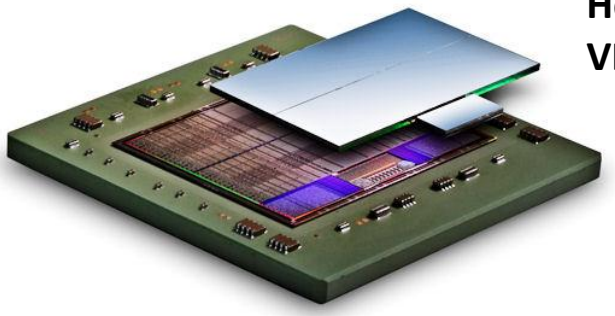
January 28-31, 2014 | Santa Clara Convention Center | Santa Clara, CA

UBM Tech

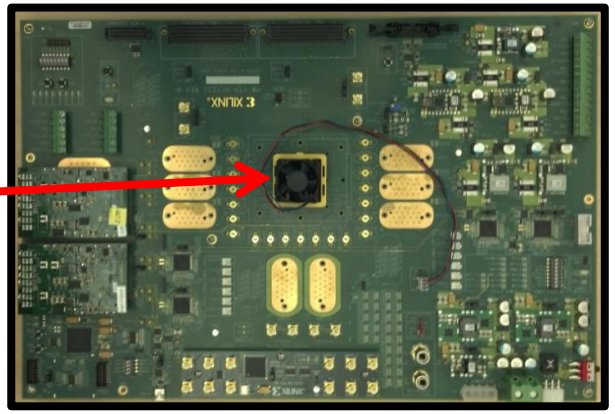
Outline

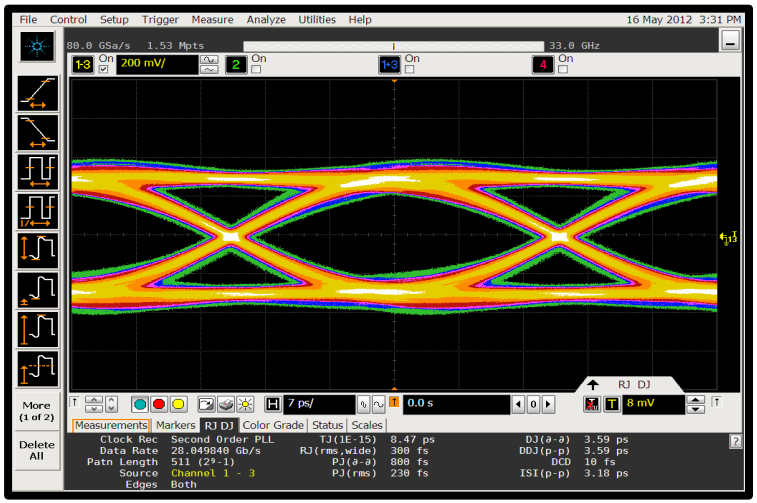
- 28 Gb/s SERDES Channel Overview
- Design Analysis for Band Limited Fixture Removal
- Fixture Removal Methods
- 28 Gb/s SERDES Measurements at the DUT

28nm FPGA with GTZ XCVR 7H580T



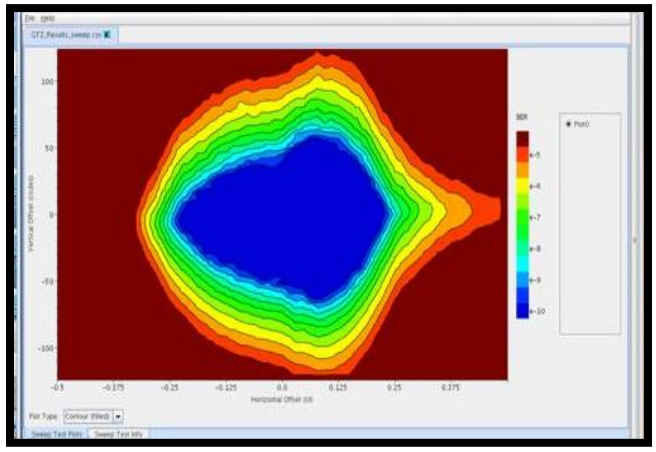
Heterogeneous
VH580T





VH580T GTZ TX

Eye Diagram: 28.05Gb/s

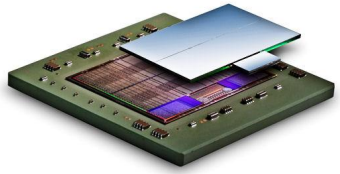


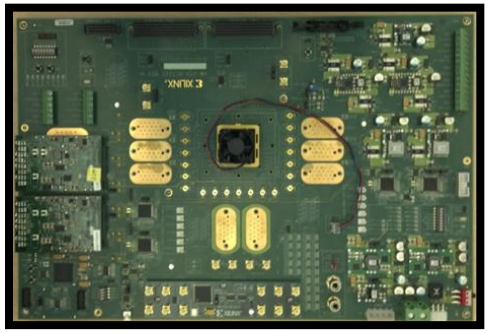
VH580T GTZ

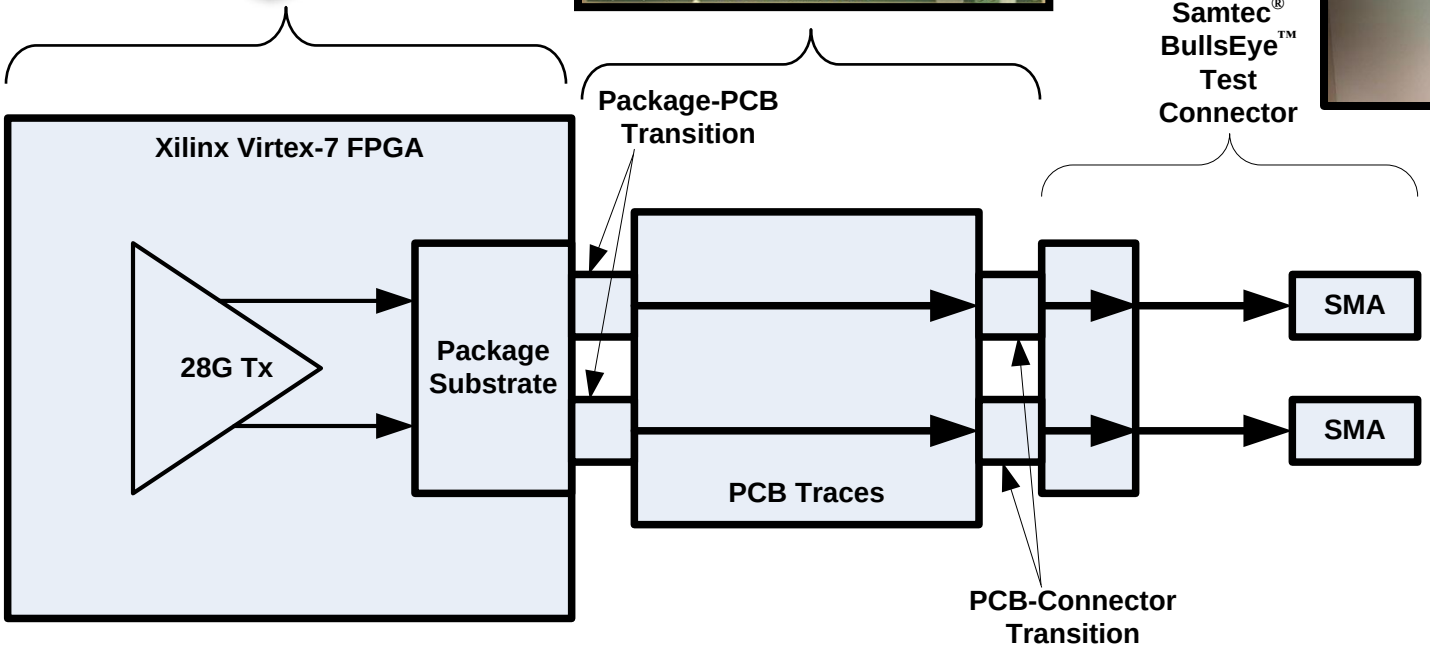
RX Eye Scan: 28.05Gb/s

Through a 12.5 dB Lossy Trace

28 Gb/s Channel





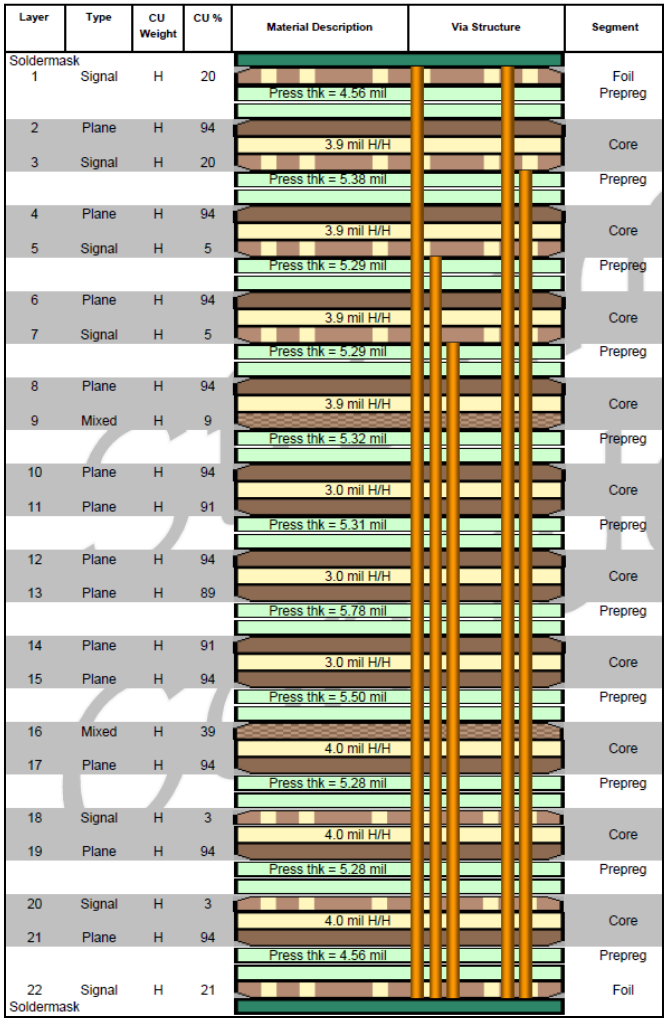


Physical Description PCB Stackup

PCB Stackup

- 22 Layers
- HS signal layers: Panasonic Megtron6
- Other layers: ISOLA 370HR - FR4
- For Megtron6 and 370HR interleaved in lower layers for mechanical stability

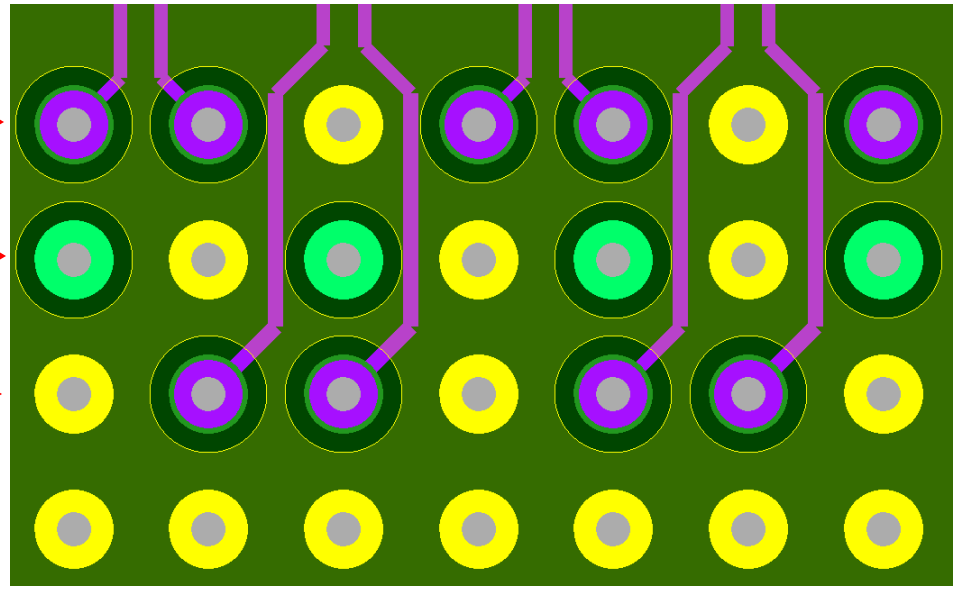
Note: For economic reasons other layers are standard FR4 (ISOLA 370HR)



Physical Description Pin/Via Breakout

BGA Pin Via Field

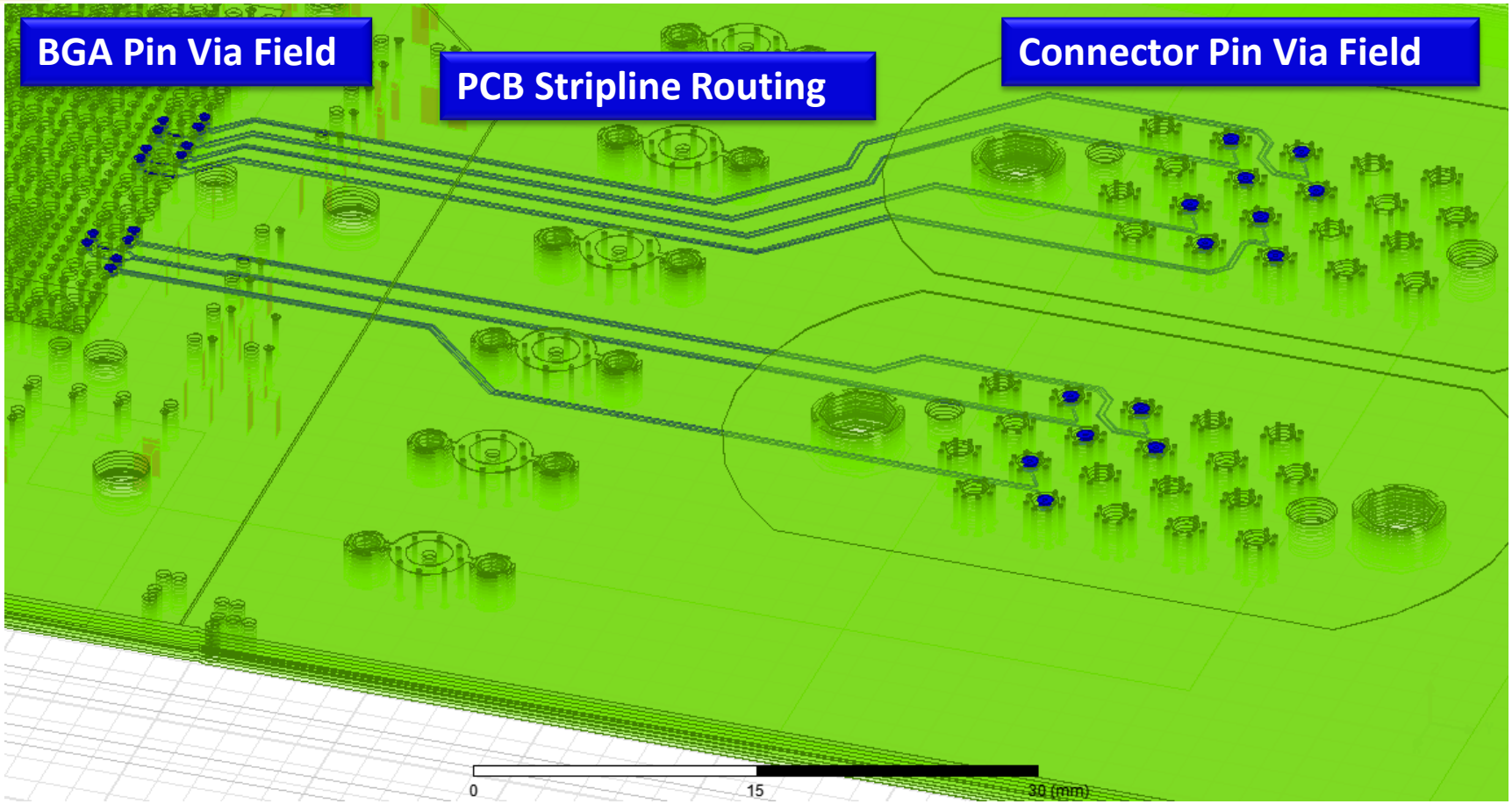
- High-speed Signal Via (Backdrilled)
- Standard Signal Via (Not Backdrilled)
- Ground Via (Not Backdrilled)



Via Topology

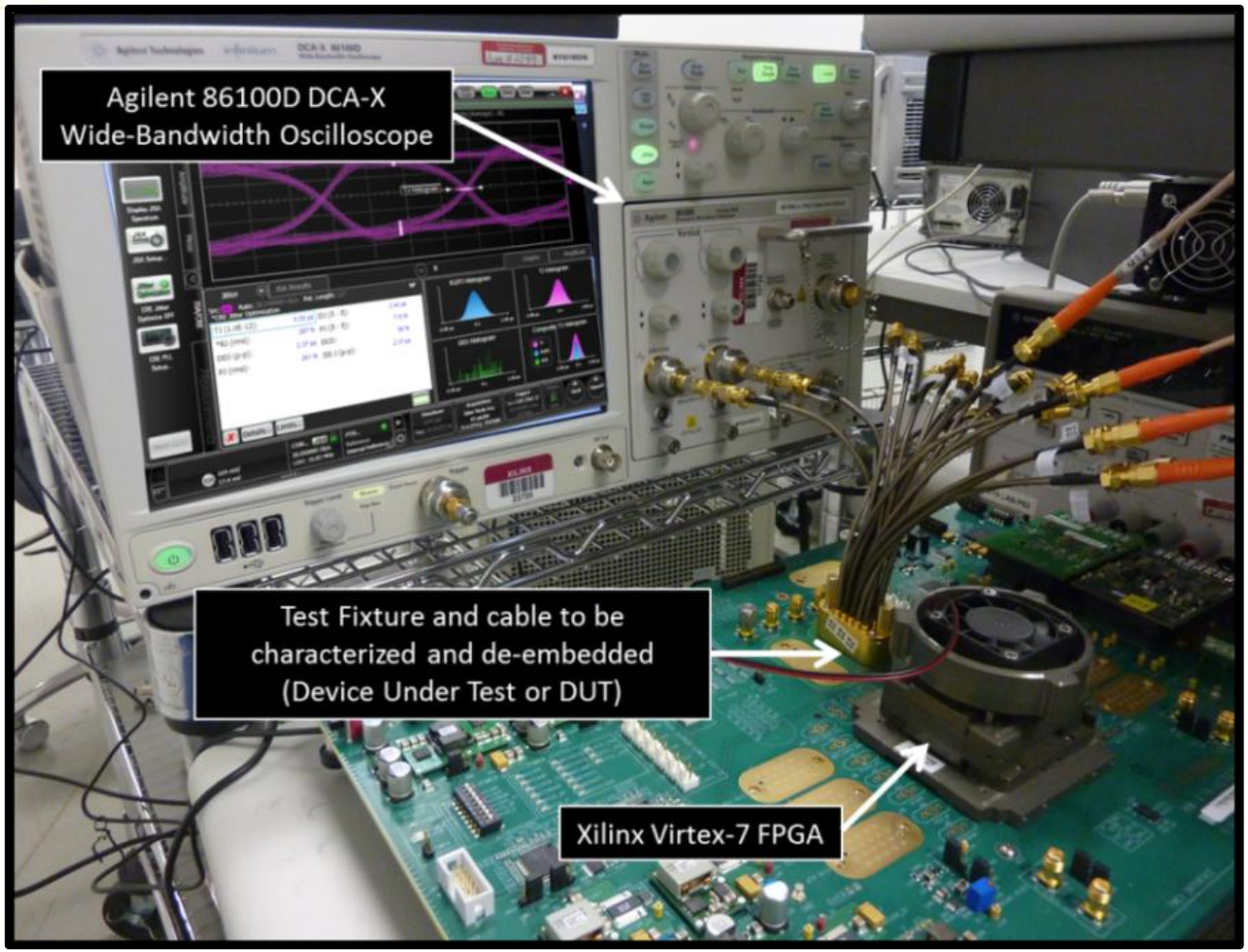
- 10 mil Drill
- 20 mil pad
- 28 mil anti-pad
- Backdrill – 8 mils from target layer +/- 3mils

Physical Description - PCB Layout



Differential Pair Routing: 3.5 mil Traces with 10 mil gap

28 Gb/s Tx Measurement Challenge

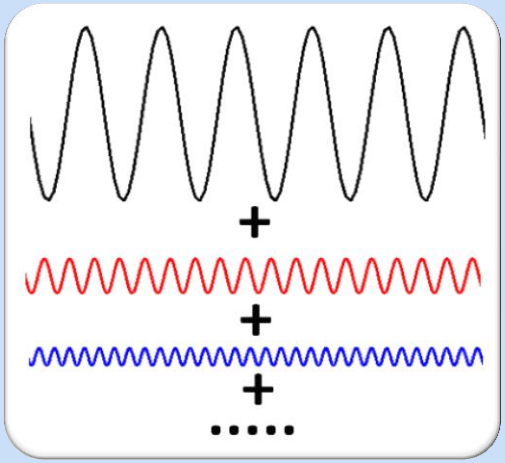


Measurement Fixture

- Coaxial Adapters
- Cable Assembly
- PCB Routing
- BGA Via Field

Band-Limited S-Parameters for De-Embedding

Frequency to Time Domain Inverse Fourier Transform



Summation of Sine Waves

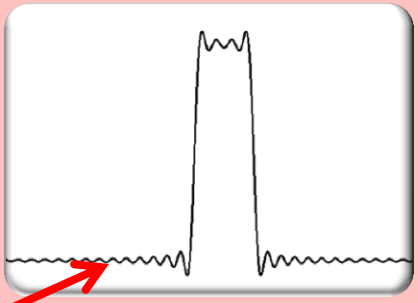
=

Case 1

Infinite Sum of Sine Waves

Case 2

Finite Sum of Sine Waves

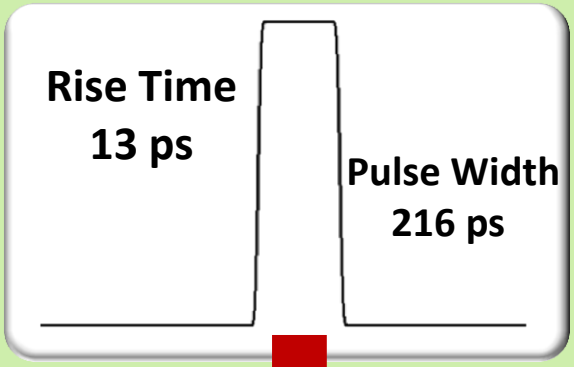


Non-Causal Ripple - Gibbs Phenomena

28 Gb/s Tx	Bandwidth Rule-of-Thumb
Rise Time 13 ps 3 dB B.W.	17 GHz
Rise Time 5 ps 3 dB B.W.	44 GHz
3rd Harmonic	42 GHz
5th Harmonic	70 GHz

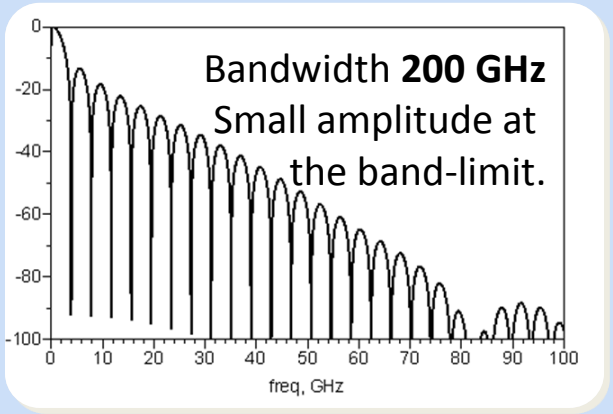
Error Due to Gibbs Phenomena

Time Domain Simulated Pulse



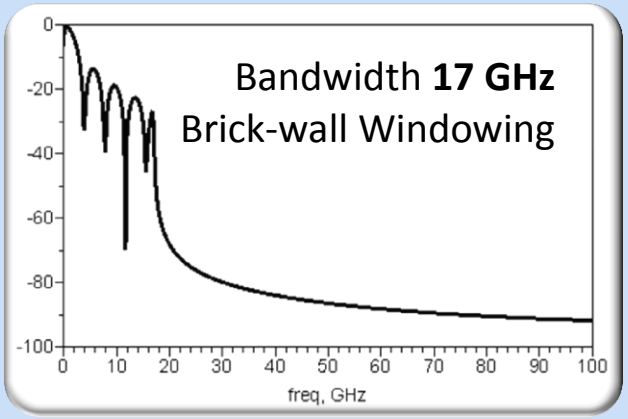
1

Frequency Domain (FFT of Pulse)



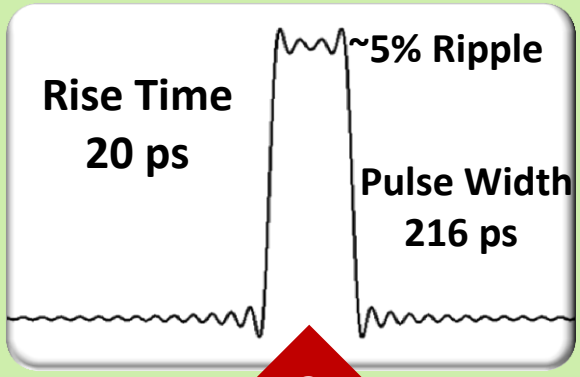
2

Frequency Domain (FFT of Pulse)



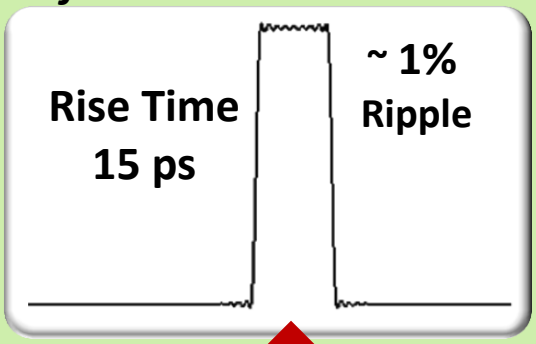
3

Time Domain i-FFT of Bandlimited Frequency Domain Data



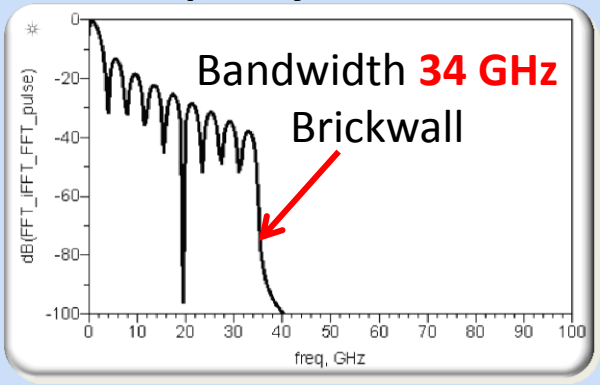
Required Channel Bandwidth

Time Domain
i-FFT of 34 GHz Bandlimited Data

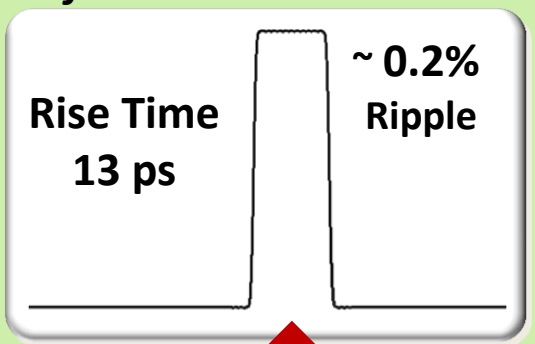


Inverse-FFT

Frequency Domain

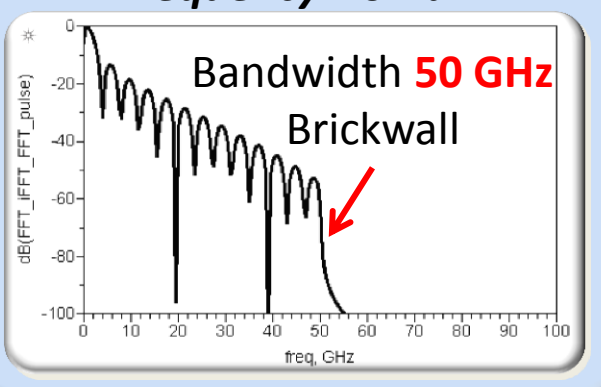


Time Domain
i-FFT of 50 GHz Bandlimited Data



Inverse-FFT

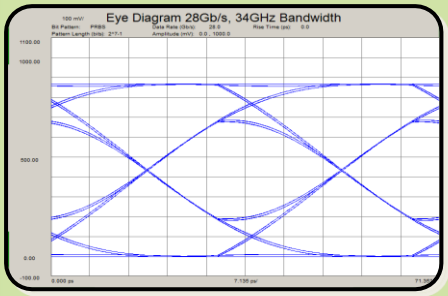
Frequency Domain

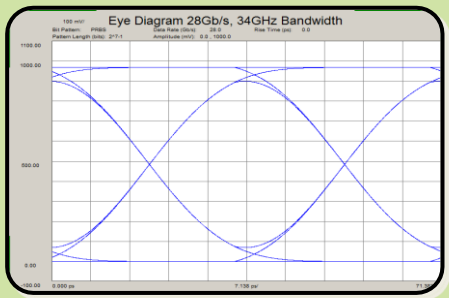


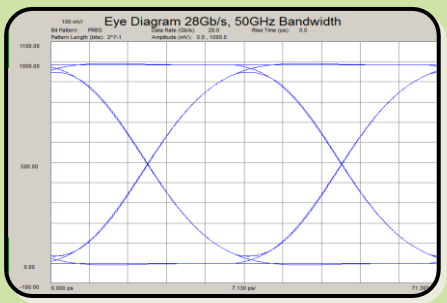
Eye Diagrams with Band-Limited S-Parameters

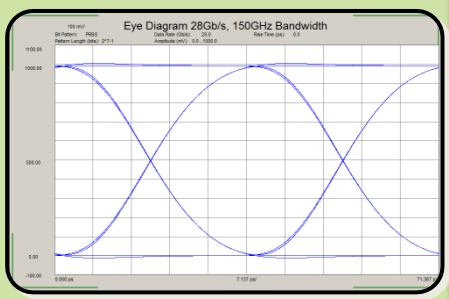
28 Gb/s , PRBS 7 Eye Diagrams

Inverse Fourier Transform with 4th Order Bessel Windowing

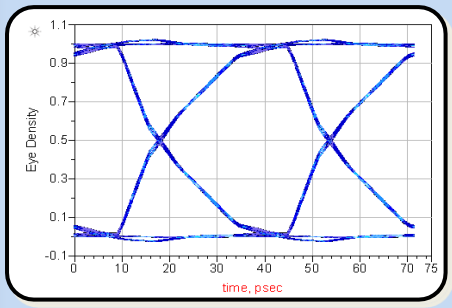


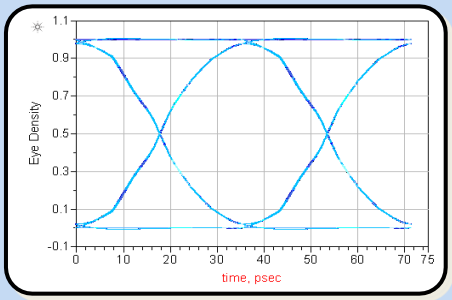


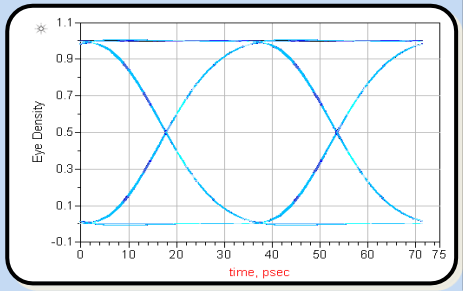


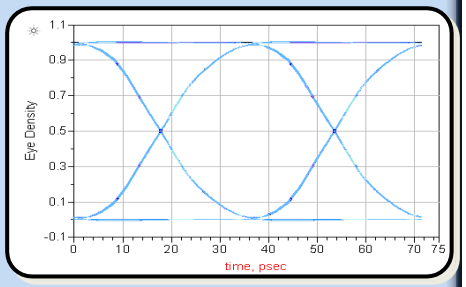


Bandlimited 17 GHz S-Parameters	Bandlimited 34 GHz S-Parameters	Bandlimited 50 GHz S-Parameters	Bandlimited 100 GHz S-Parameters







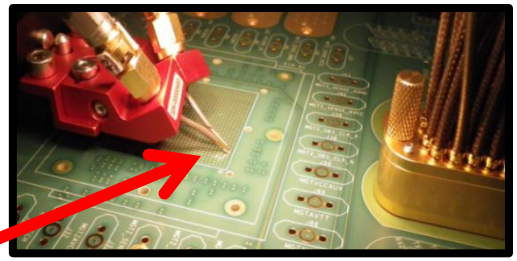


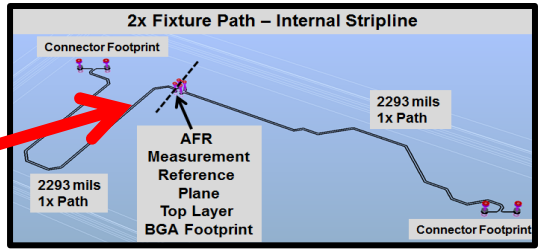
Hilbert Transform with Causality Enforcement

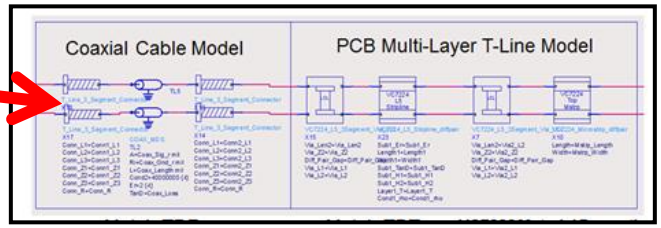
Fixture De-Embedding Methods

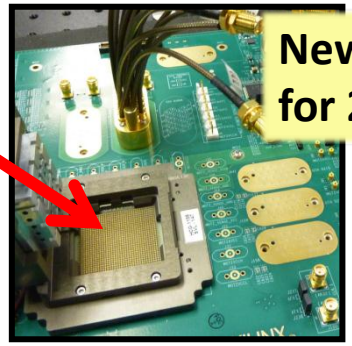
Channel Model De-Embedding Options

1) **Direct Probe** Measurement
2) **Test Coupon** Structure with AFR
3) **Hybrid** Multi-Path Simulation with Minimal Test Structures
4) **Direct Reflect** Measurement with AFR algorithm.







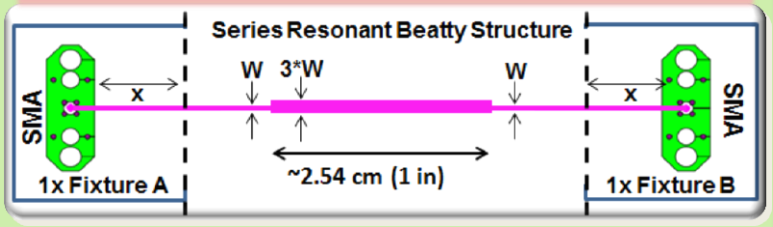


New Technique for 2014

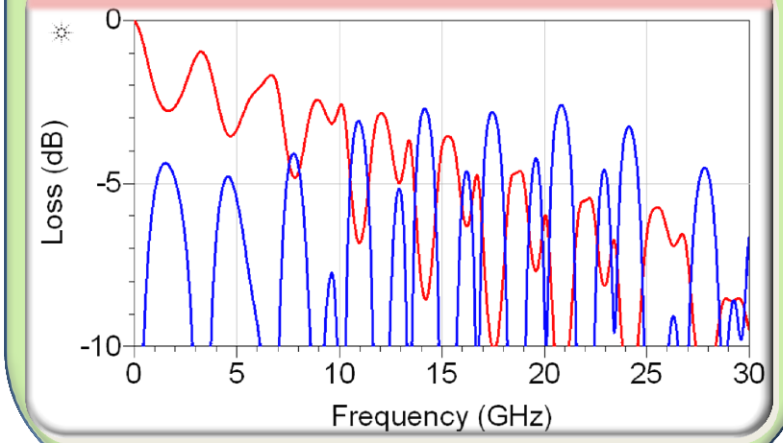
Fixture Removal Review

BEFORE

FIXTURE + Resonant Beatty Structure



S-Parameters before Fixture De-Embed

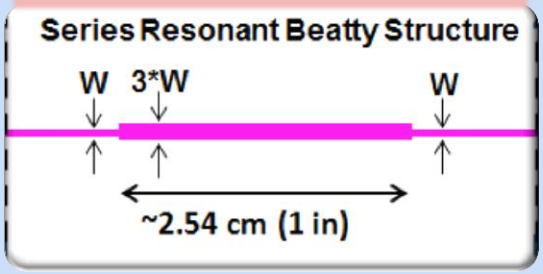


FIXTURE DE-EMBED

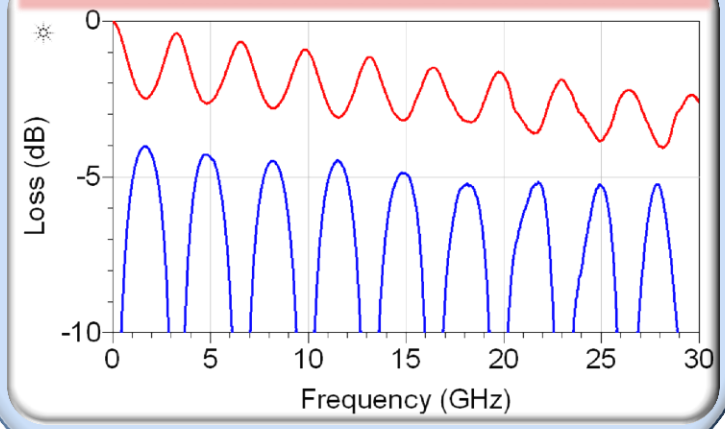
T-Matrix

AFTER

DUT with Fixture Removed



S-Parameters after Fixture De-Embed

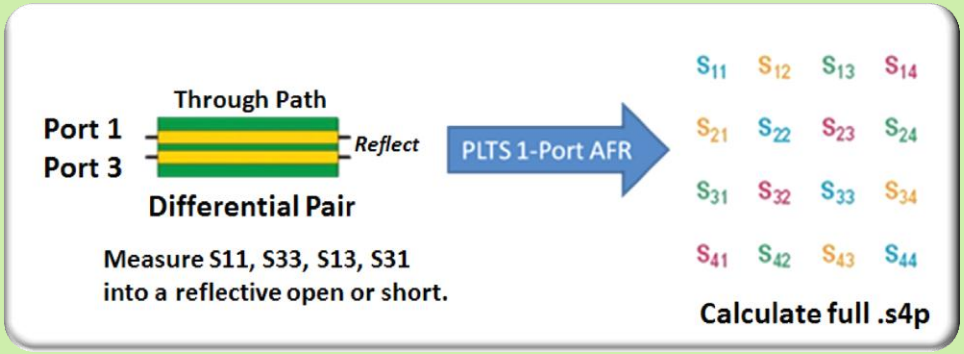


New 1-Port Automatic Fixture Removal

1-Port AFR

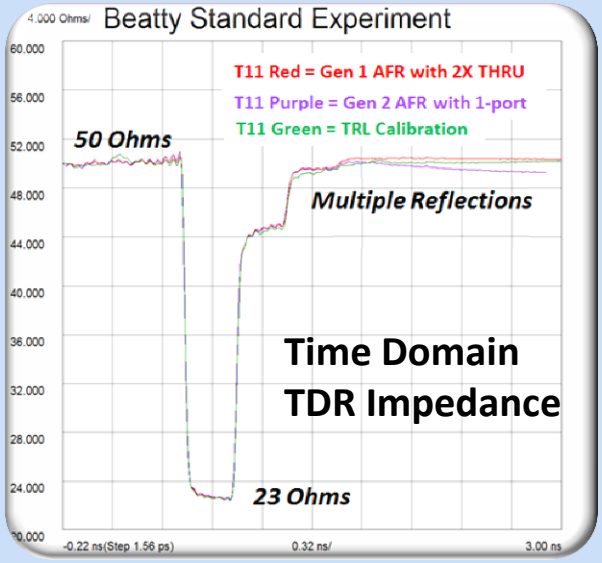
1-Port, Open at DUT
In-Situ Path Measurement

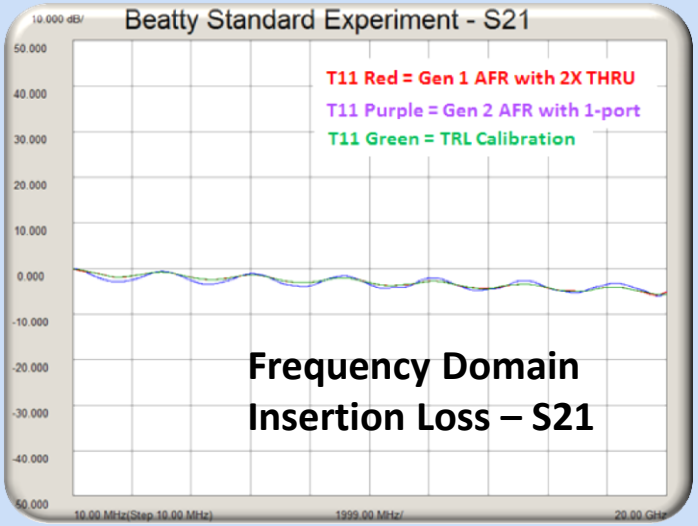
Note: Only 4 S-Parameters are used to calculate the differential .s4p fixture behavioral model.



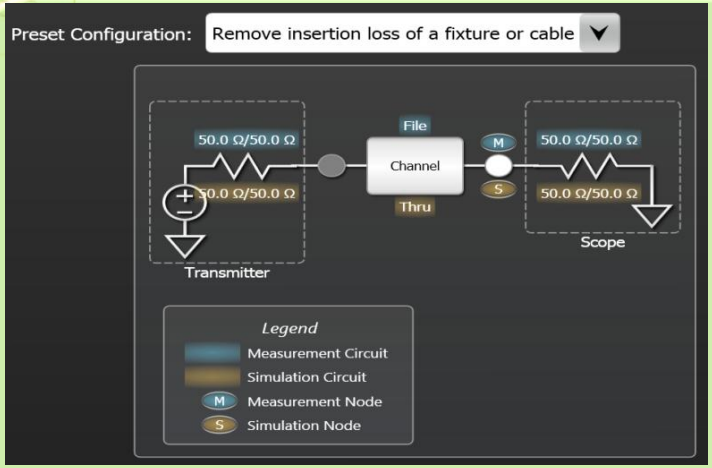
Compare

2x Thru AFR
1-Port AFR
TRL Multiple Stds





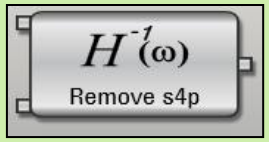
Partial vs. Full De-Embedding

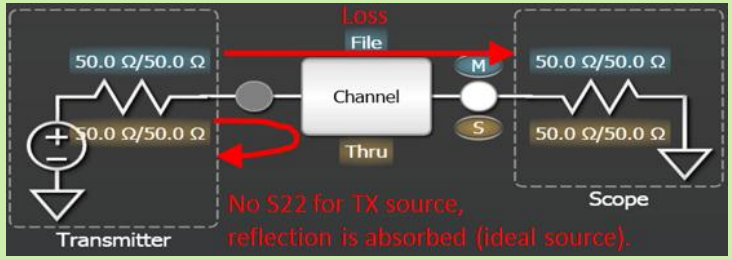


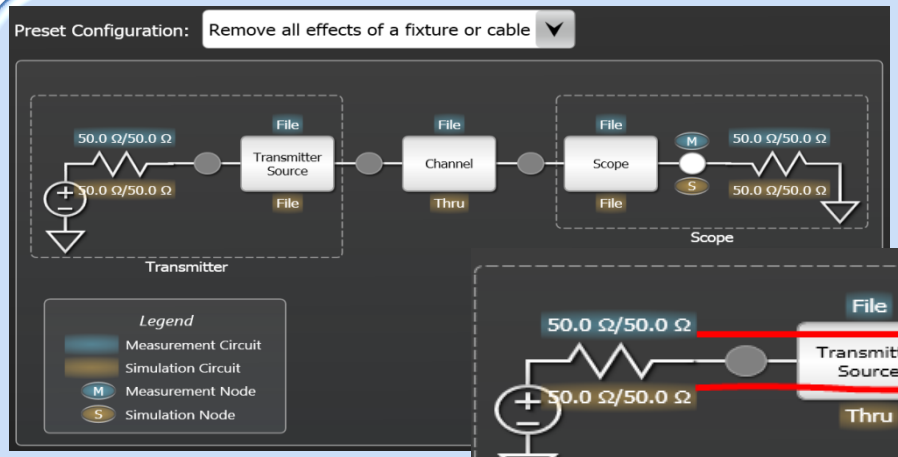
Partial De-embedding:

This paper's focus.

- Removes insertion loss
- Does NOT remove reflections (assumes an ideal source, receiver)
- Easier to implement

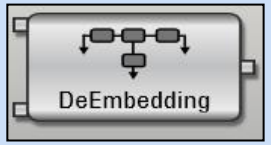


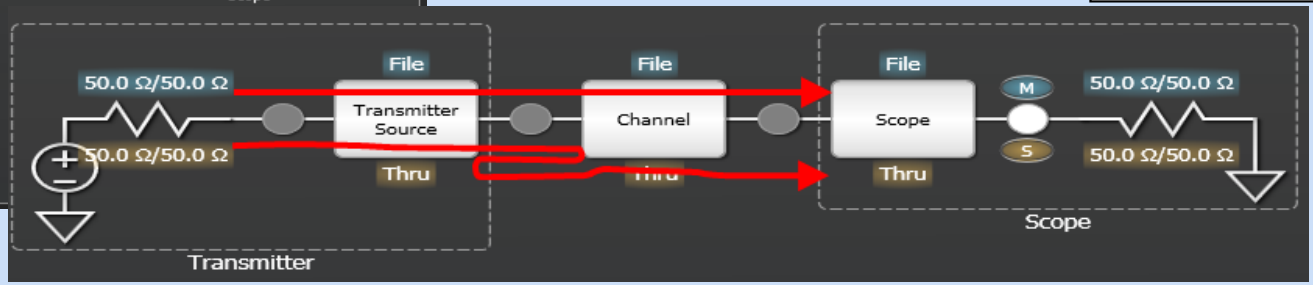




Full De-embedding:

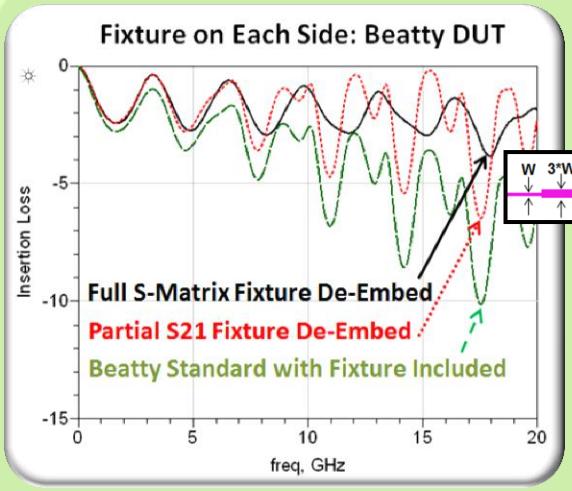
- Removes insertion loss and reflections between circuit elements
- More accurate (but less forgiving if models/delays are not correct)

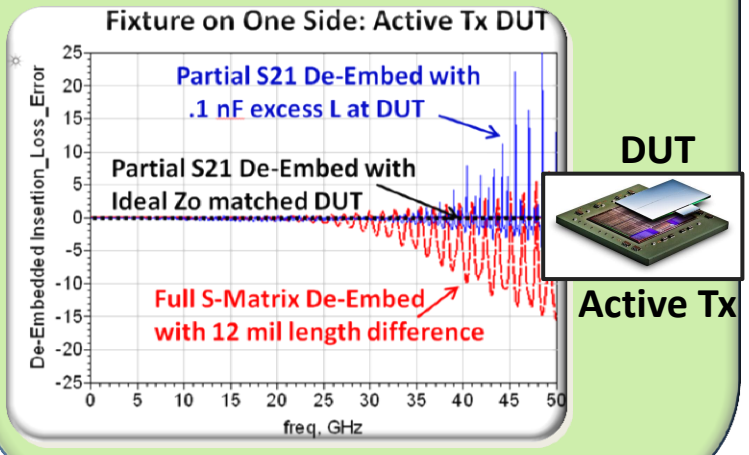




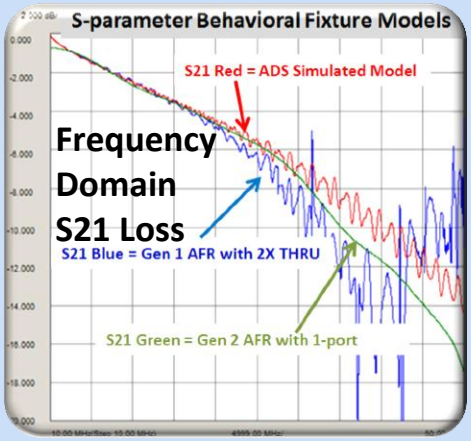
Partial S21 De-Embedding for 28 Gb/s Fixture

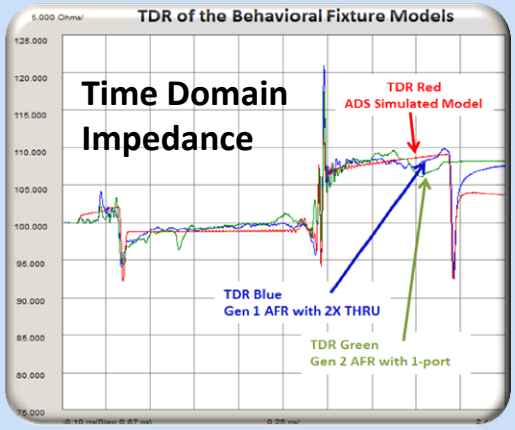
Partial vs. Full De-Embedding



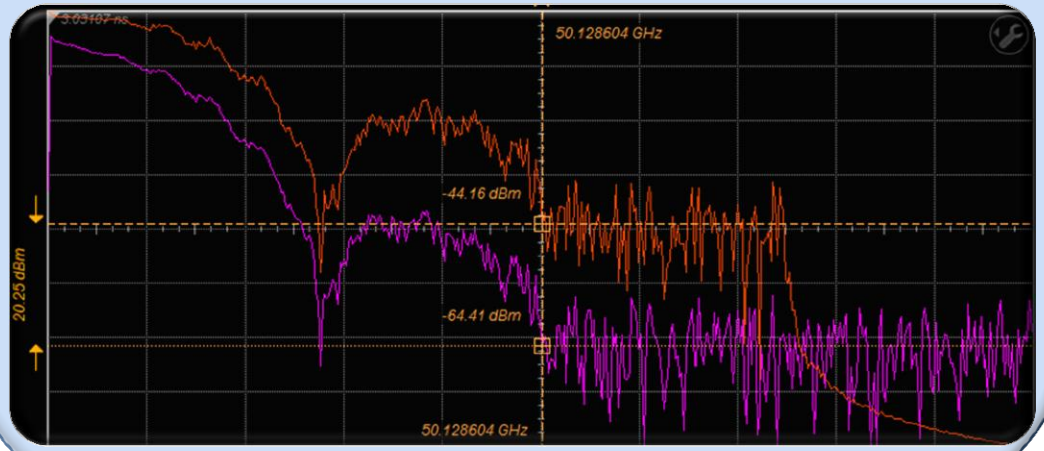


Fixture Behavioral Models





Tx PRBS7 Spectrum Before and After Partial De-Embedding

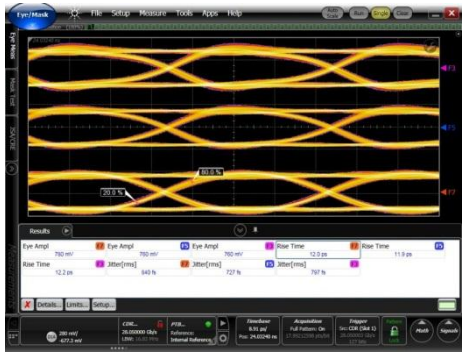


Device Characterization

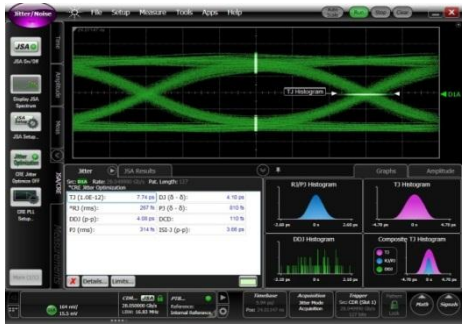
Measurements used to compare de-embed models

- Waveform
  - Compare specific bit sequences (bits onscreen)
  - Rise/Fall Time
  - Amplitude

- Eye Diagram
  - Fast and efficient, examine all bits in a pattern
  - Rise/Fall Time
  - Eye Amplitude
  - Eye Height

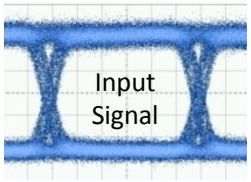


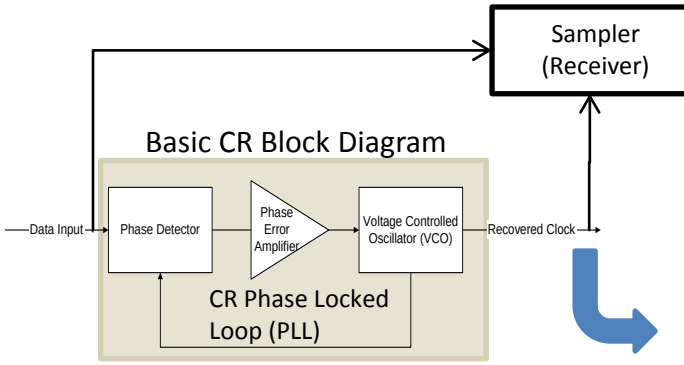
- Jitter and Amplitude Analysis
  - Isolate random and deterministic components
  - Focus on inter-symbol interference (ISI)
    (check efficacy of S-parameter models used for de-embedding)

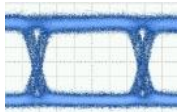


Clock Recovery (CR) Basics

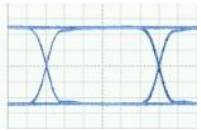
Clock Recovery is <u>required</u> for compliant jitter measurements.







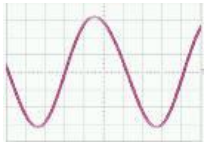
OR



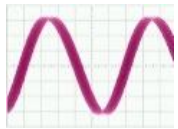
Data relative to "clean" clock (narrow loop BW)

Data relative to recovered clock (wide loop BW)

Narrow CR Loop BW



OR

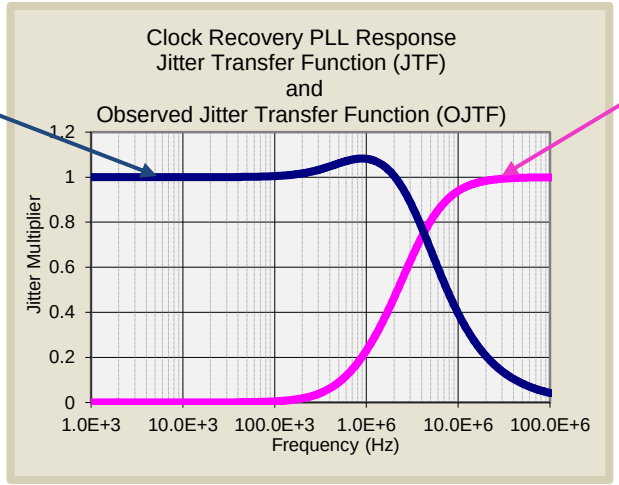


Wide CR Loop BW

PLL *"Jitter Transfer Function"* (JTF)

- indicates how much of the jitter on the input signal is "transferred" to the recovered clock (output)
- low-pass filter function (LPF)

$$JTF = \text{Closed loop gain}$$
$$= \frac{\phi_{out}}{\phi_{in}} = \frac{A(s)}{1+A(s)} = G(s) = |G(s)|e^{j\phi(s)}$$



"Observed Jitter Transfer Function" (OJTF)

- indicates the jitter that is "observed" by the receiver (scope)
- high frequency jitter on the data stream is "transferred" to the receiver (HPF)

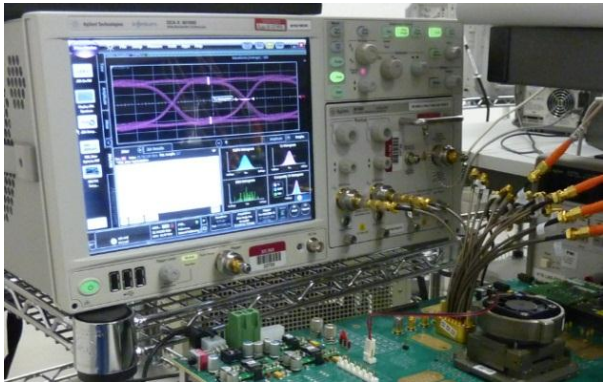
$$OJTF = 1 - JTF$$
$$= 1 - G(s) = 1 - |G(s)|e^{j\phi(s)}$$

Standards Specify:

- PLL Order/Type
- PLL Bandwidth
- Peaking (Damping Factor)

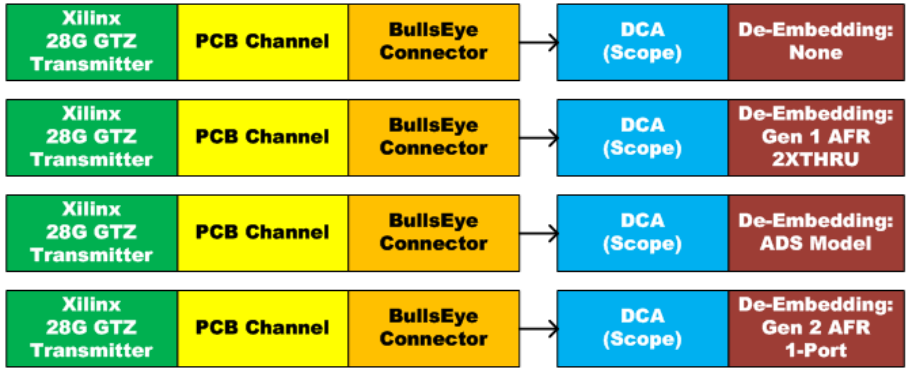
28 Gb/s Performance of Fixture Removal Methods

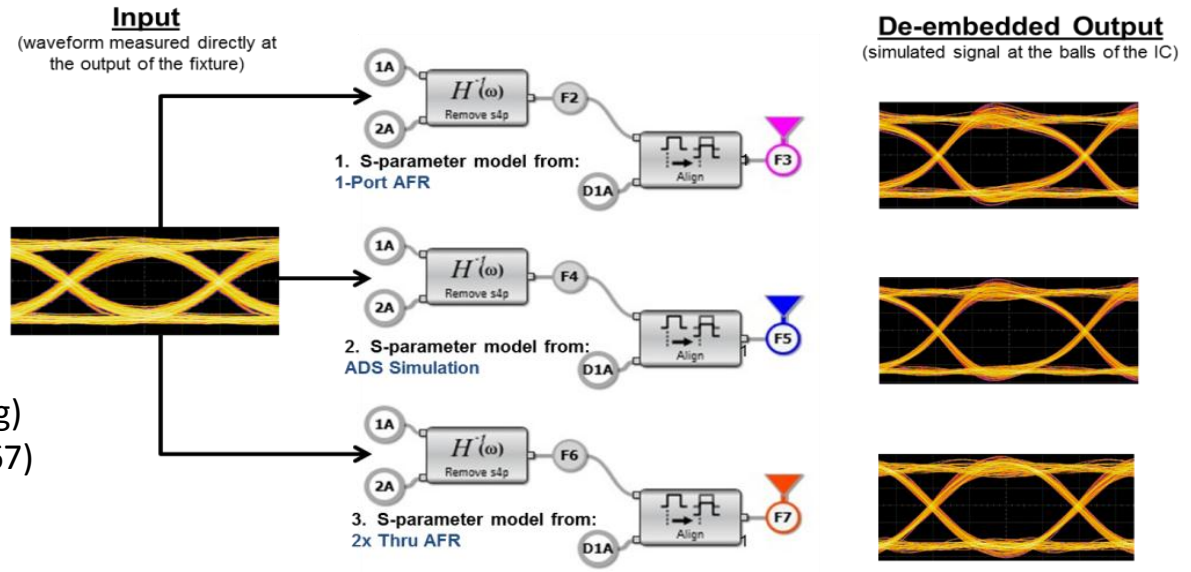
Test Equipment Setup



Agilent 86100D DCA-X with 86108B module

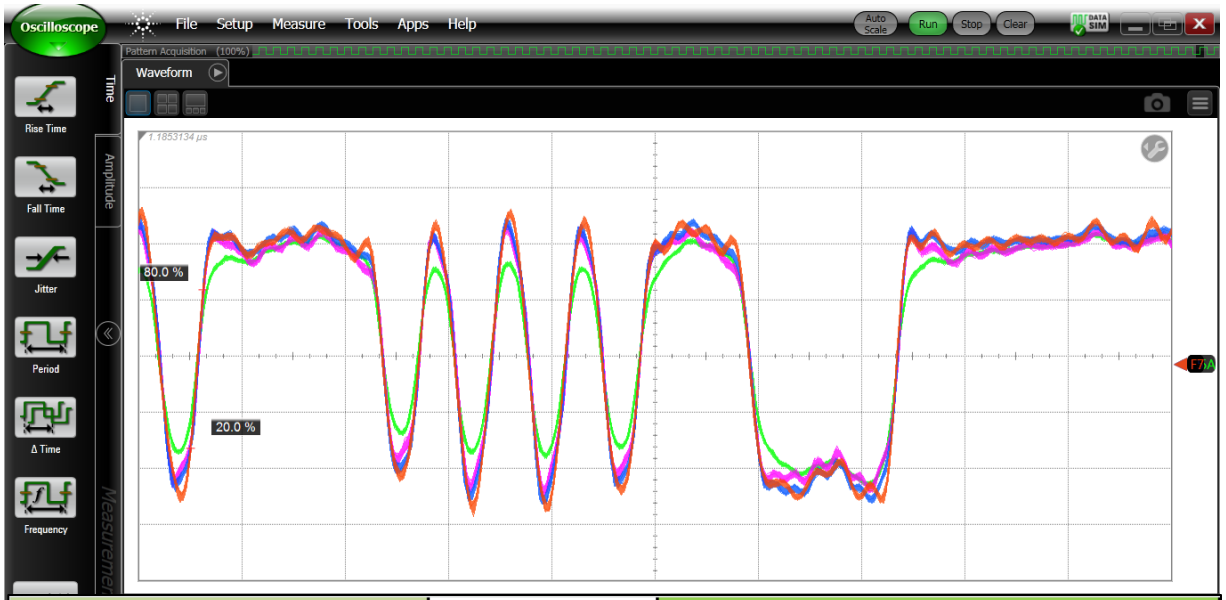
- Bandwidth: 50 GHz
- Intrinsic Random Jitter: < 50 fs rms
- Integrated Clock Recovery
  - Data Rate (DR): 28.05 Gb/s
  - Loop Order: 1st Order (0 dB Peaking)
  - PLL Bandwidth: 16.8 MHz (DR/1667)





Note 1 – the "Align" function simply removes filter delay and aligns waveforms making it easier to compare waveforms.

Waveform Measurements



Waveform Measurements	PRBS15	S-Paramater Model Used by De-Embed Function		
FlexDCA Signal Identifier	D1A	F3	F5	F7
Description	Raw Differential Waveform	1-Port AFR	ADS	2x Thru AFR
Rise Time 20-80% (ps)	13.2 ps	10.6 ps	11.6 ps	10.2 ps
Eye Amplitude (mV)	592 mV	755 mV	752 mV	746 mV

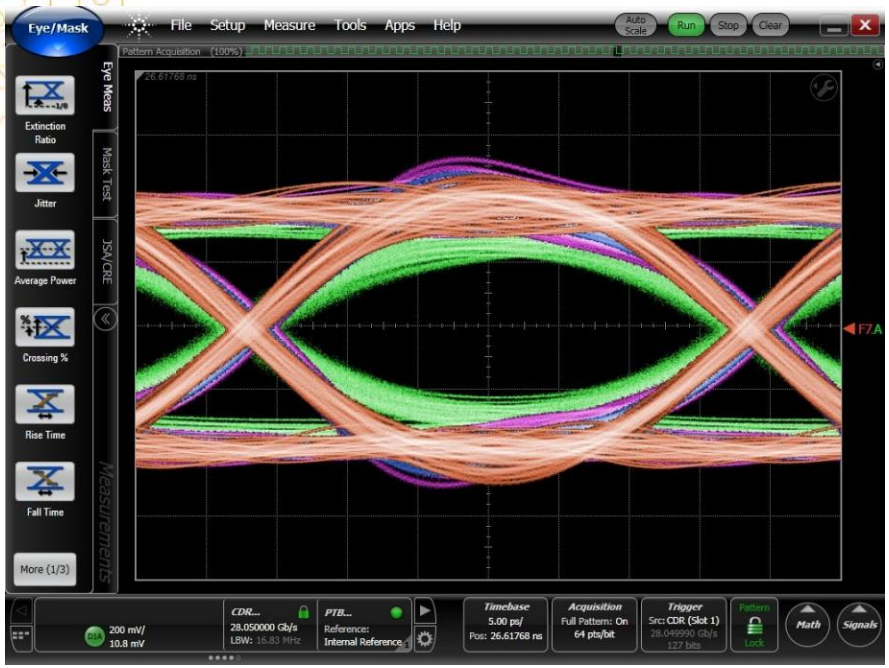
1-Port AFR Model:

- Rise time (20%-80%): 2.6 ps faster (20% improvement)
- Amplitude: 163 mV higher (27% improvement)

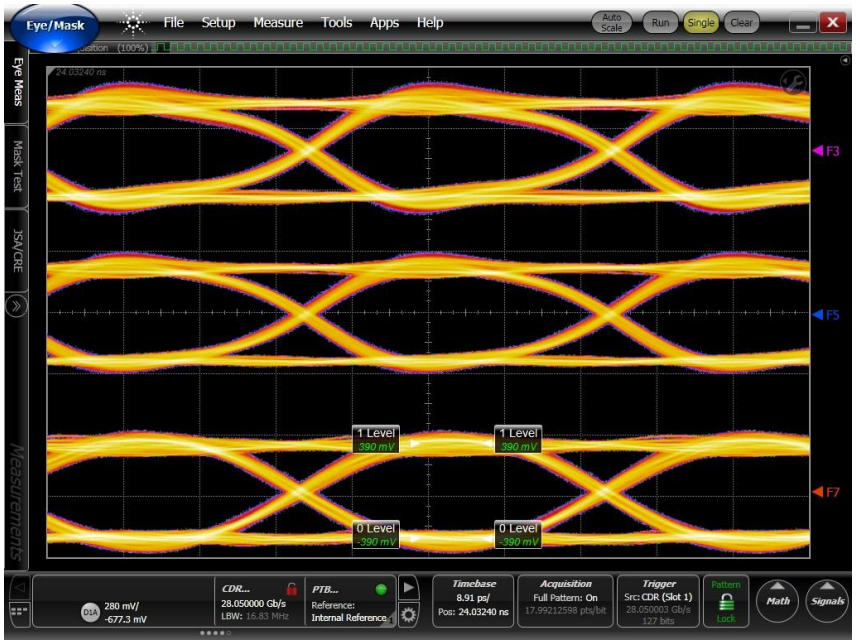
Waveform Measurements

- **Where does the ringing come from after de-embedding?**

Eye Diagram Measurements



Eye Diagram	PRBS7	S-Paramater Model Used by De-Embed Function		
FlexDCA Signal Identifier	D1A	F3	F5	F7
Description	Raw Differential Waveform	1-Port AFR	ADS	2x Thru AFR
Rise Time 20-80% (ps)	15.3	11.9	11.5	11.9
Eye Amplitude (mV)	908	1134	1134	1169.0
Eye Height (mV)	560	679	814	803.0
Jitter (rms) (fs)	934	563	510	665.0

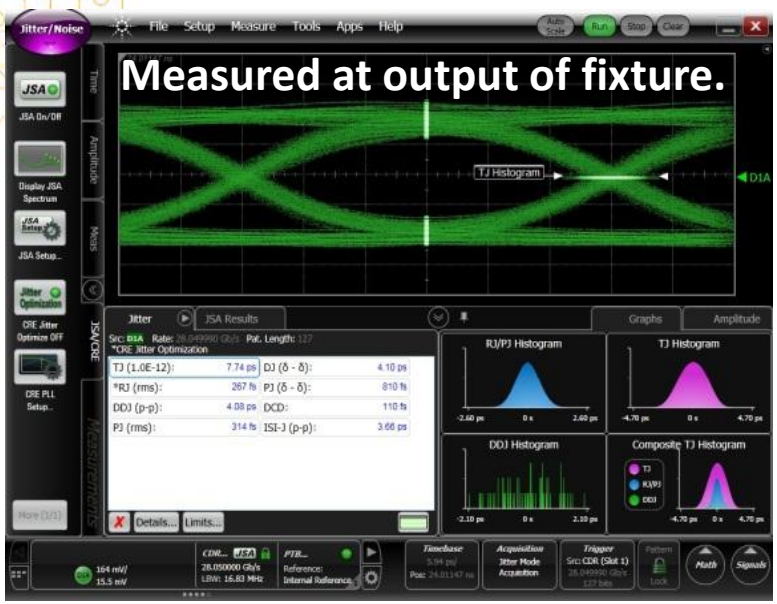


Eye Diagram	PRBS15	S-Paramater Model Used by De-Embed Function		
FlexDCA Signal Identifier	D1A	F3	F5	F7
Description	Raw Differential Waveform	1-Port AFR	ADS	2x Thru AFR
Rise Time 20-80% (ps)	15.2	12.1	11.5	11.6
Eye Amplitude (mV)	610	763	762	785.0
Eye Height (mV)	375	455	545	539.0
Jitter (rms) (fs)	993	615	537	702.0

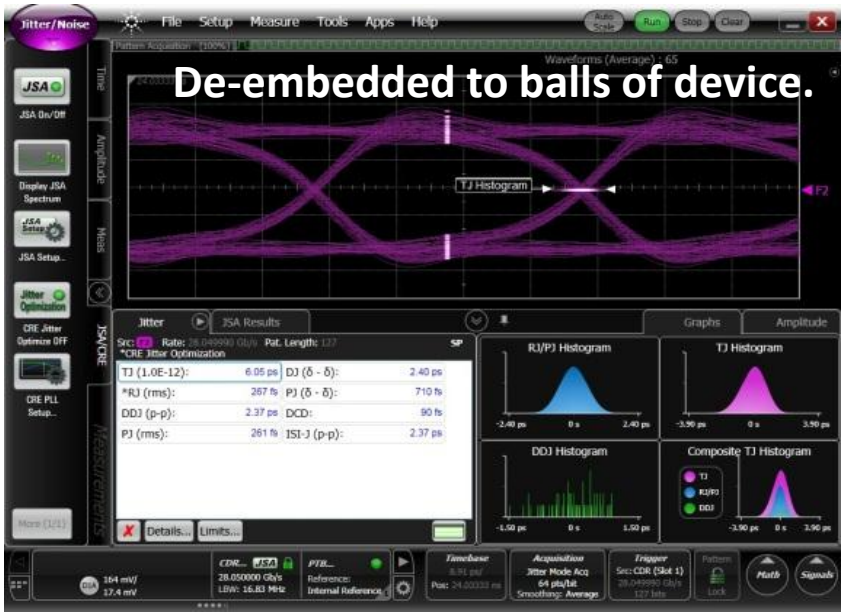
1-Port AFR Model:

- Rise time (20%-80%): 3.1 ps faster (20% improvement)
- Eye Amplitude: 204 mV higher (25% improvement)

Jitter Measurements



Jitter Analysis	PRBS7	S-Paramater Model Used by De-Embed Function		
FlexDCA Signal Identifier	D1A	F3	F5	F7
Description	Raw Differential Waveform	1-Port AFR	ADS	2x Thru AFR
Total Jitter (@ 1E-12) (p-p)	7.74	6.05	5.72	6.10
Random Jitter, RJ rms (fs)	267	267	277	256
Deterministic Jitter (δ - δ) (ps)	4.1	2.40	1.92	2.60
Inter-Symbol Interference (ISI) (p-p)	3.66	2.37	1.76	2.36



Jitter Analysis	PRBS15	S-Paramater Model Used by De-Embed Function		
FlexDCA Signal Identifier	D1A	F3	F5	F7
Description	Raw Differential Waveform	1-Port AFR	ADS	2x Thru AFR
Inter-Symbol Interference (ISI) (p-p)	6.76	4.98	4.34	5.11

1-Port AFR Model (PRBS7):

- Total Jitter (1E-12): 6.05ps (1.7ps lower)
- Random Jitter (RJ): 267 fs (~ unchanged)
- Deterministic Jitter (DJ): 2.4ps (1.7ps lower)
- Inter-Symbol Interference (ISI): 2.37ps (1.4 ps lower)

1-Port AFR Model (PRBS15):

- ISI: 4.98ps (1.8 ps lower)

Summary

- **Fixture de-embedding Lessons Learned**:
  - Test Fixture is simple to build and measure
  - Full de-embedding is sensitive to reference plane errors.
  - Partial de-embedding
    - A practical solution when Tx is impedance matched.
    - Substantially less effort than full de-embed
    - Results are sufficient in most cases
  - 1-Port AFR enables simple in-situ fixture channel measurement.

Conclusion

- This methodology is useful
  - Economical use of time and resources
  - Does not require elaborate measurement equipment and set up
  - Results are adequate without expensive effort and resources

"Accurate 28 Gb/s Tx real-time measurements at the DUT package require fixture de-embedding."

Acknowledgements

- Fangyi Rao of Agilent for his patience in explaining causal frequency to time domain transforms.

- Jim Stimple of Agilent for his explanation of the band limiting differences between real-time scopes with arbitrary data and sampling scopes with repetitive data.