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Three Very Low-Cost Technology Solutions for SI Applications

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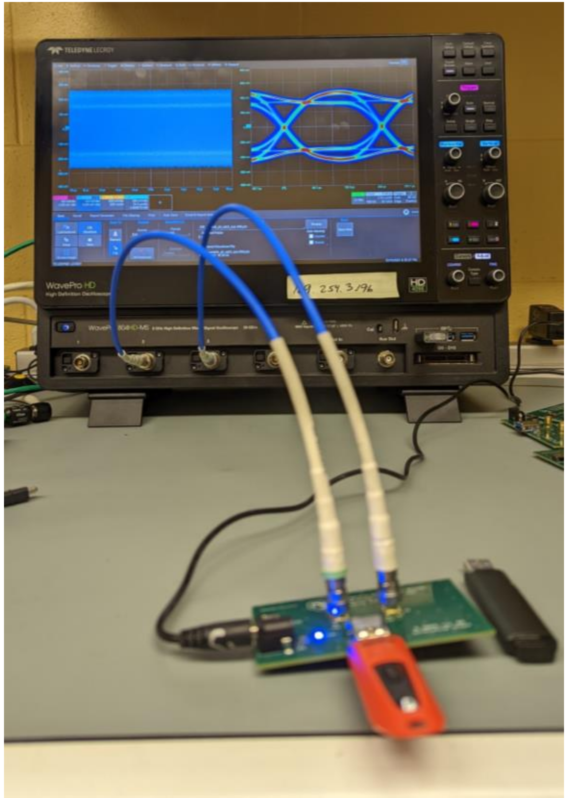
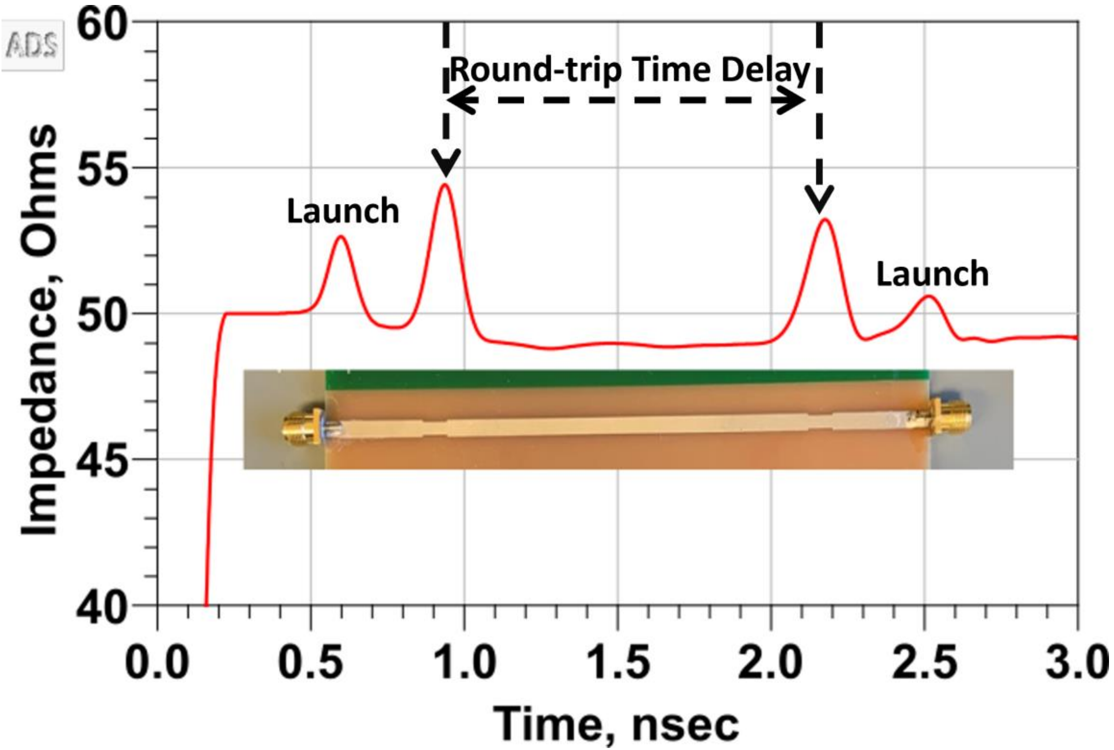
Eric Bogatin is currently a Professor at the University of Colorado, Boulder, a Fellow at Teledyne LeCroy and the technical editor for the Signal Integrity Journal.

Three Solutions

- **TDR based Dk Measurement**
  - A simple structure with two distinct discontinuities to extract the speed of a signal using a TDR.
- **Low-Cost 2-Layer SMA Connector**
  - Using a $0.35 through hole connector as an edge launched connector for GHz applications.
- **5 Gigabit for $5**
  - Low-cost USB devices as signal generators.



TDR Method to Measure Dielectric Constant



$$\varepsilon_{eff} = \left(\frac{c_0 \times RTD_{Meas}}{2 \times L}\right)^2$$

Effective Dielectric Constant?

- A property of any microstrip trace.
- Fields in air faster than fields in the dielectric.
- Approximation to obtain the "effective" value.

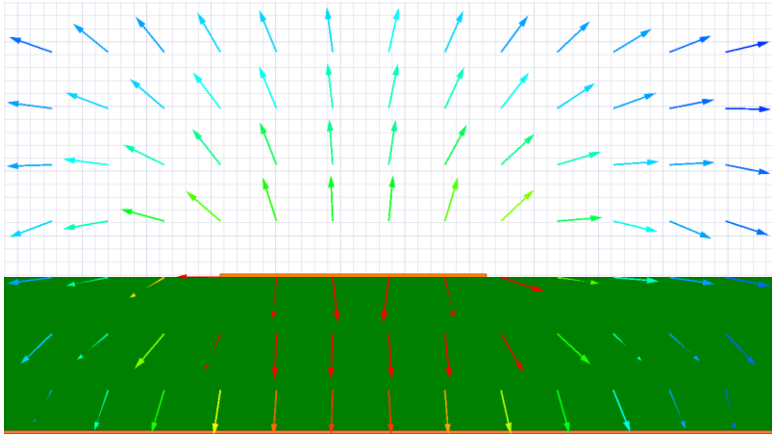
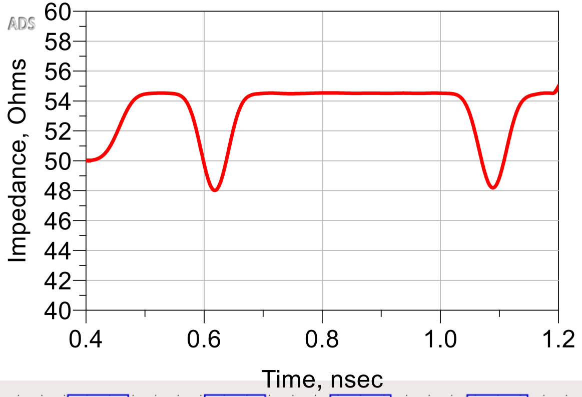


Fig. Field distribution for a microstrip line

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1 + 12H}{W}\right)^{-1/2} \quad (2)$$

Virtual Simulation Environment

- Study structures with no measurement limitations
- Analyze each artifact individually:
  - Time resolution
  - Anomalous Dispersion
  - Losses
  - Non-TEM behavior



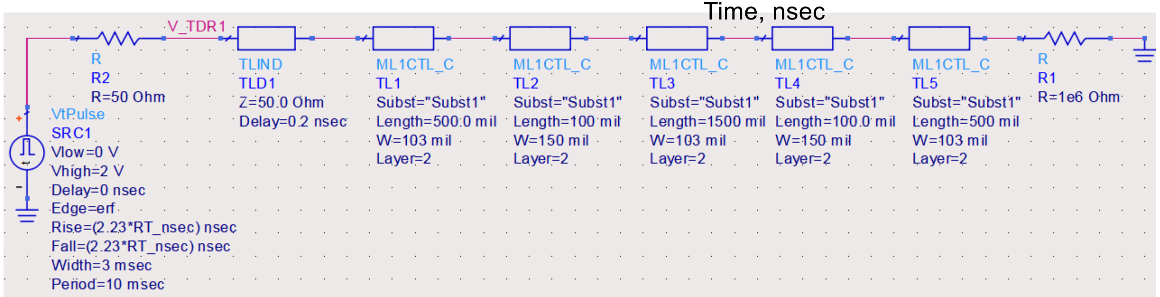


Fig 2. A TDR built in the virtual simulation environment

Artifact 1: Time Resolution Error

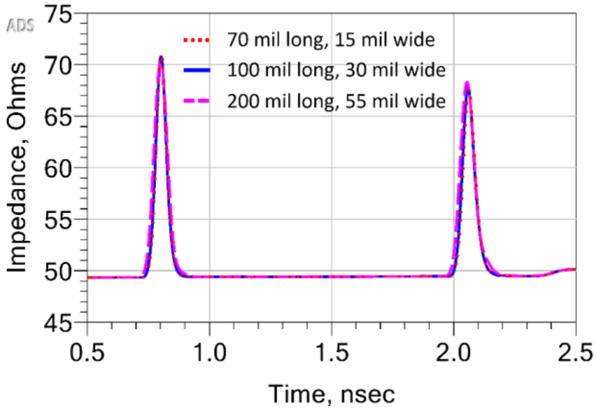
- Finite time resolution creates error: $\frac{\Delta\varepsilon_{eff}}{\varepsilon_{eff}} = 2 \times \frac{\Delta RTD}{RTD} (3)$

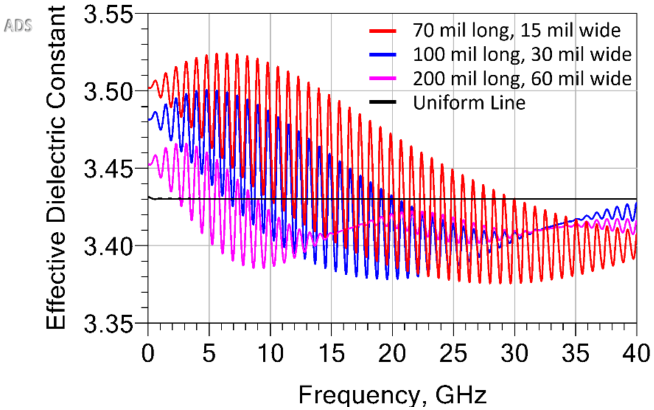
- For a measurement with a timestep of 10ps: $\frac{\Delta\varepsilon_{eff}}{\varepsilon_{eff}} = 2 \times \frac{0.02nsec}{1.33nsec} = \mathbf{3}\%(4)$

- In the Virtual Simulation Environment, with a timestep of 1ps**: 0.3%** accuracy

Artifact 2: Anomalous Dispersion

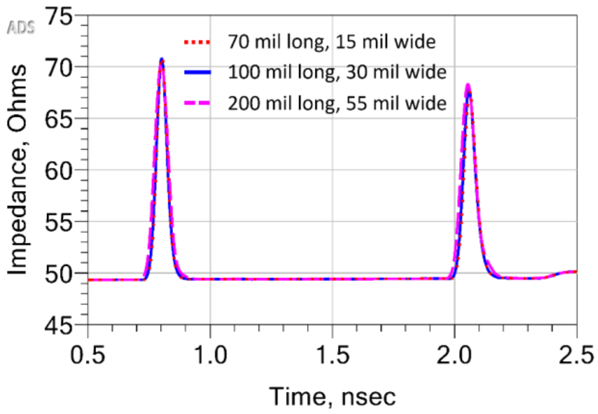
- Anomalous dispersion results in the artifact of frequency dependent dielectric constant.
- With no losses, expect no dispersion with frequency.
- Simulation of uniform line shows no dispersion.
- Simulation of line with discontinuities has dispersion.
- Three lines which look the same on a TDR because of the same excess inductance at 50ps.

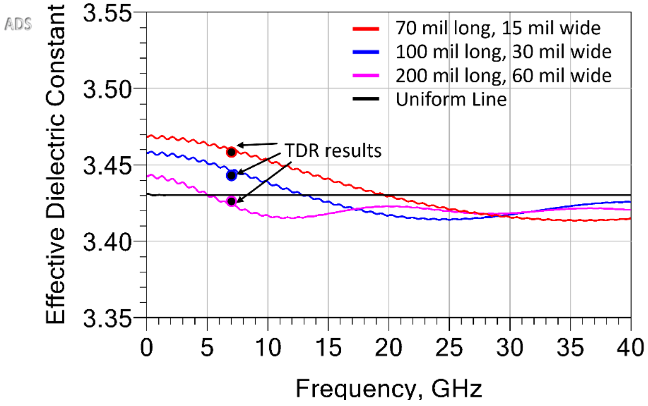




Artifact 2: Anomalous Dispersion

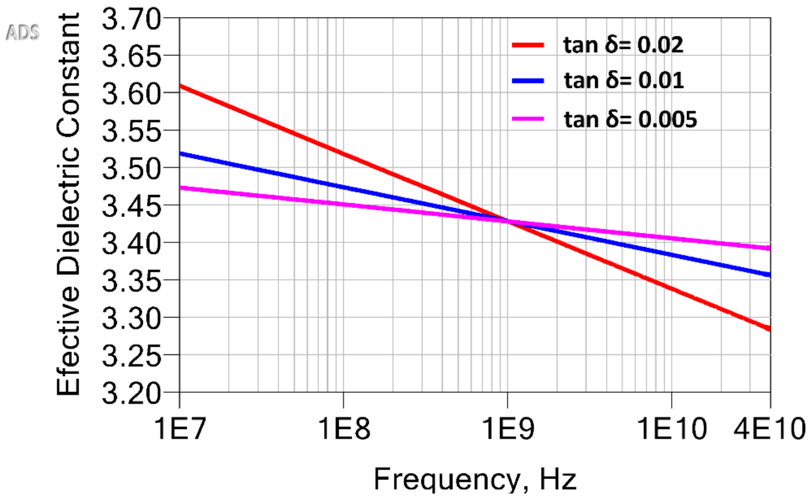
- TDR will time gate the reflections.
- Comparison with frequency domain result and TDR shows correlation.
- The anomalous dispersion depends on the magnitude of the discontinuity.
- A longer discontinuity with a smaller magnitude reduces anomalous dispersion.





Artifact 3: Losses

- Losses introduce dispersion.
- Different frequencies travel at different speeds.
- Virtual simulation environment has models with dispersion built in.
- TDR method gives one number for the dielectric constant, which frequency is it measured at?



Artifact 3: Losses

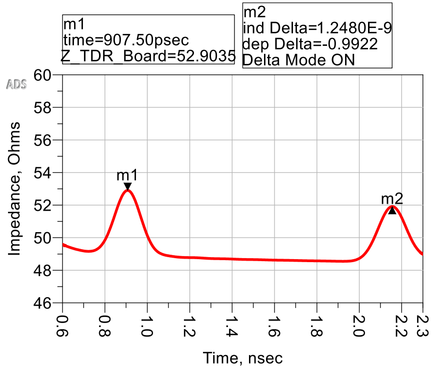
- TDR result measured at the bandwidth of the rising edge.

$$BW\ (Hertz) = \frac{0.35}{Rise\ Time\ (Seconds)} \quad (5)$$

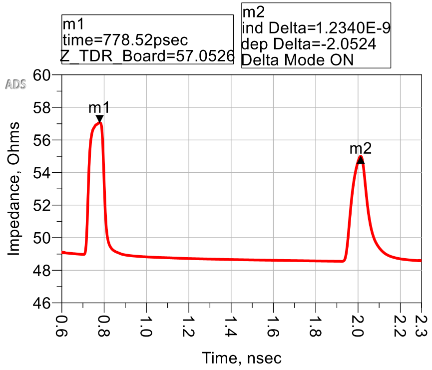
- The dispersion from optimized discontinuities is negligible.

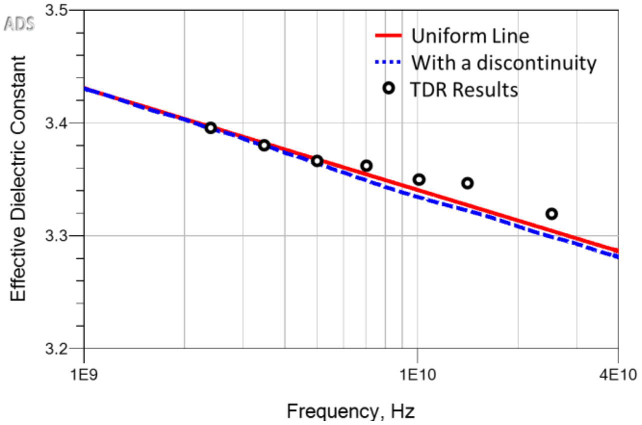
- The frequency at which the TDR measures the Dk is the bandwidth of the edge.

RT = 140ps Dk = 3.395



RT = 14ps Dk = 3.319



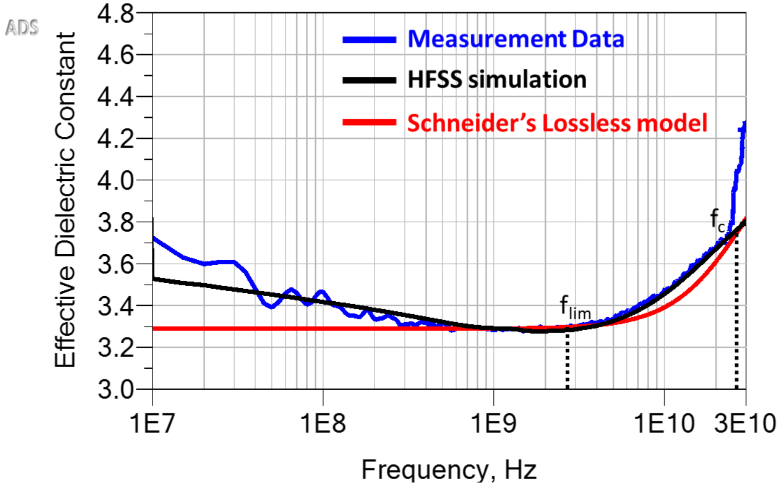


Artifact 4: non-TEM propagation

- Past a frequency limit, the static TEM approximation is not valid.
- Hybrid mode propagation suggests the phase velocity will decrease at microwave frequencies.
- Schneider provided an approximation for phase velocity at high frequencies

$$v_p(f) = \frac{1}{\sqrt{\varepsilon_r \varepsilon_{eff}}}\left[\frac{\sqrt{\varepsilon_{eff}} f_n^2 + \sqrt{\varepsilon_r}}{f_n^2 + 1}\right] \quad (6)$$

- Where, $f_n = \left(\frac{f}{f_c}\right)$ and $f_c = \frac{c_0}{4\boldsymbol{h}\sqrt{\varepsilon_r - 1}}$



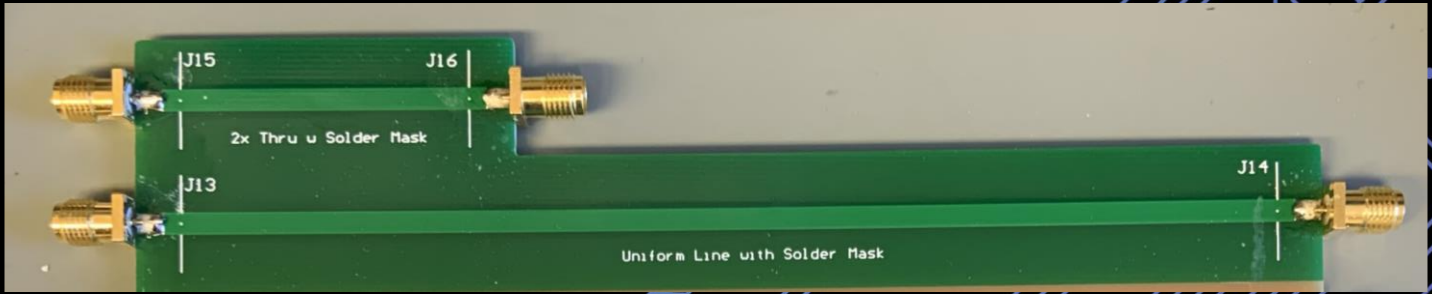
Where, $f_{lim} = \frac{f_c}{10}$

To avoid the impact of higher order modes: $h(inches) \leq \frac{0.295(inches/nsec)}{f_{lim}(GHz) \times \sqrt{\varepsilon_r - 1}} \quad (9)$

To use a 50ps rise time (**7GHz**), the maximum height for a dielectric constant of 4 is **24 mils**

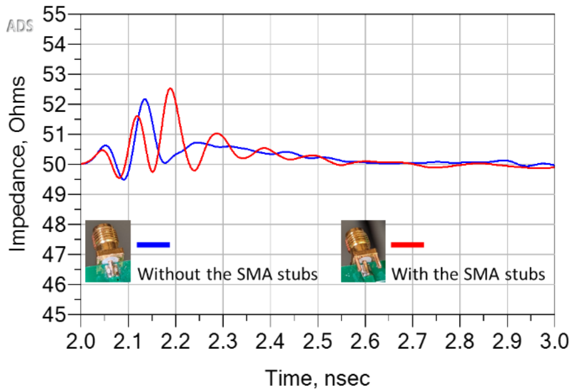
Low Cost 2-Layer SMA Launches

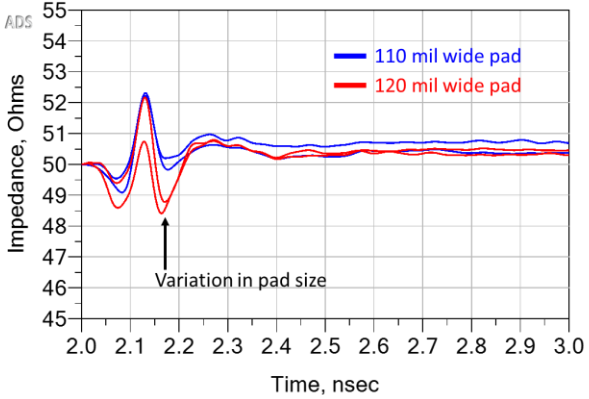
Using $0.35 SMA connectors at microwave frequencies.



Low-Cost SMA Connectors

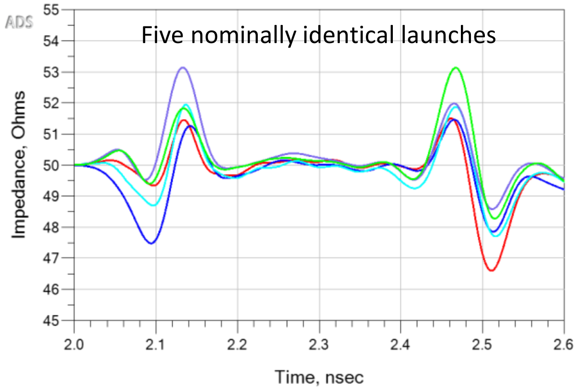
- $0.35 through hole SMA used as Edge Launched Connectors
- Unused SMA legs need to be clipped off to avoid resonance.
- Optimize pad side to reduce the discontinuity.
- $0.35 has a peak impedance variation less than 2 ohms at 50ps edge.





$0.35 SMA connectors have a 11 GHz Bandwidth

- Sample size of 5 connectors shows peak impedance variation of 3 ohms.
- Frequency domain S-parameters show consistency with a S11 -10dB bandwidth of 11.5 GHz
- Wide traces, so non-TEM behavior begins at 3 GHz



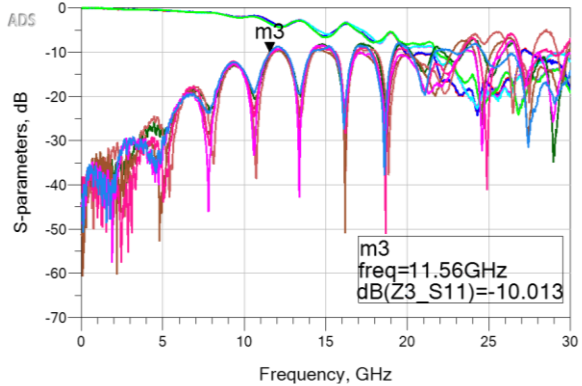
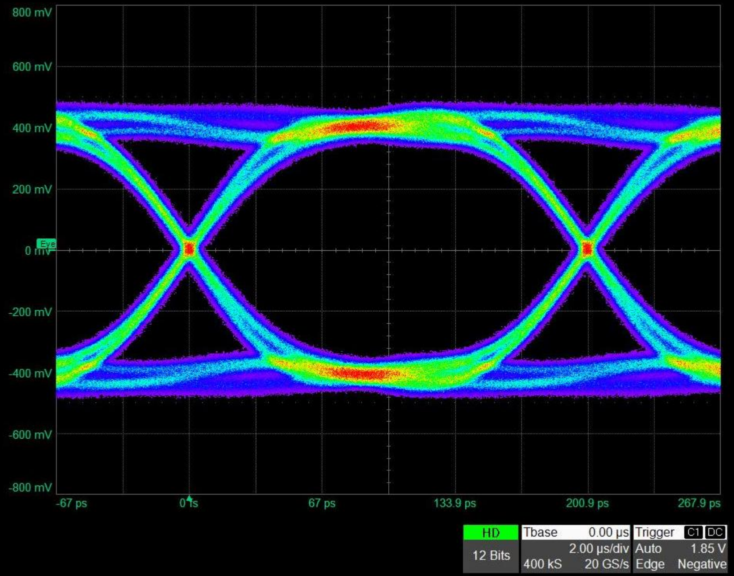


Fig. S-parameter data of the measurements shown above

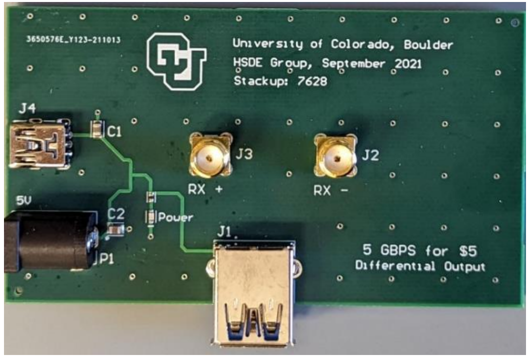
5 Gigabit for $5

Low-cost signal generator using a USB device



Breakout Board

- Self starting breakout board.
- Powered by 5V or external USB.
- RX+ and RX- with SMA connectors
- Differential 1V pk-pk 5Gbps output.
- USB 3.2 Gen 1 memory stick.
- PRBS like 5 Gigabit differential source for $5



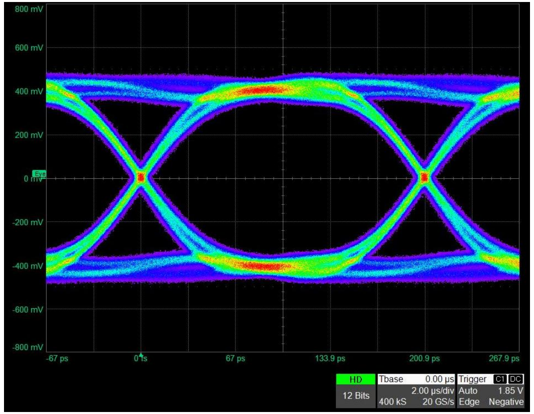
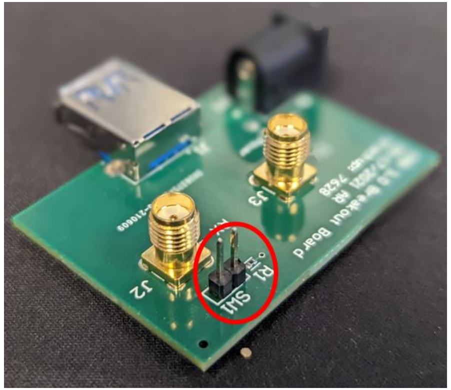


Fig. Eye diagram obtained from probing differential signal from RX+ and RX-

Early design

- Both lines need to be terminated for self starting.
- Adding a header switch to a resistor adds a big stub when not in use.
- Different breakout boards for single-ended and differential operation.



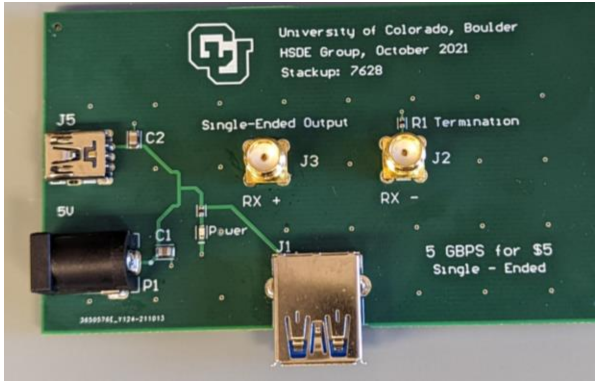
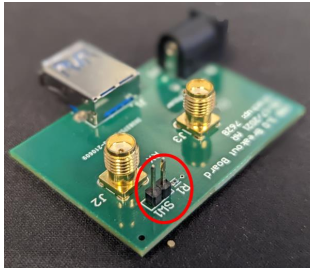
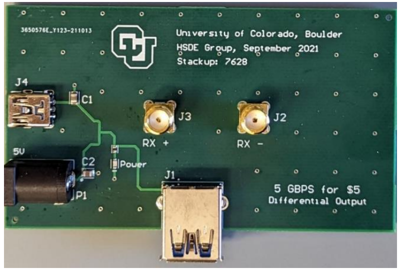
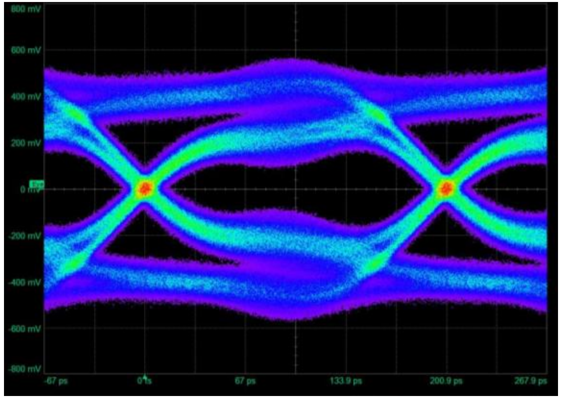


Fig. RX- terminated to 50-ohms to allow for single ended measurements on RX+.

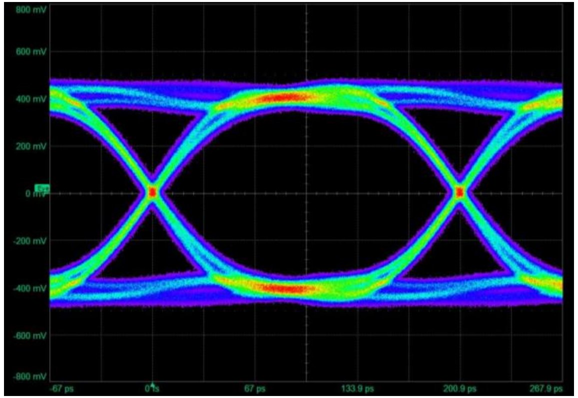
Comparison of Eye With and Without Stub







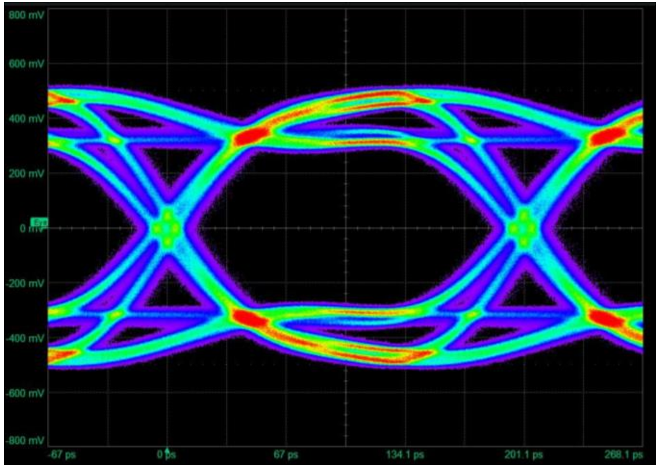
VS.



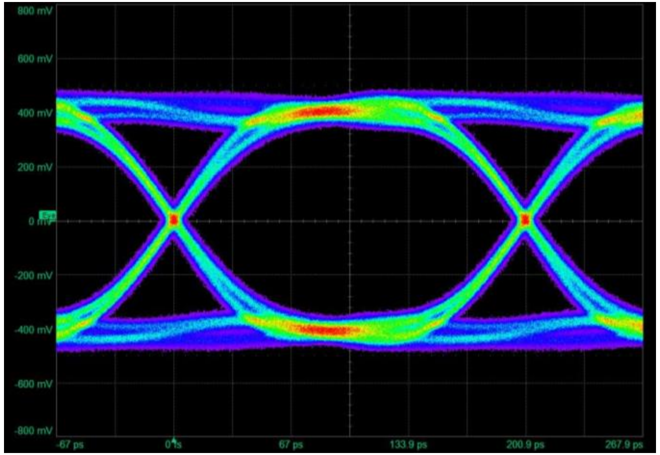
Differential measurement with an open stub

Differential measurement without a stub

Variation in Eye Quality



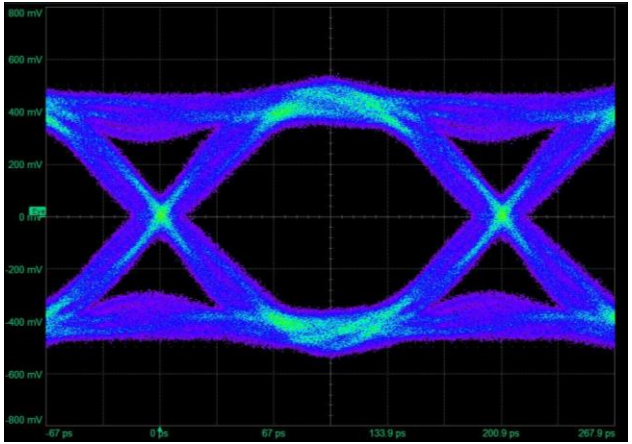
VS.



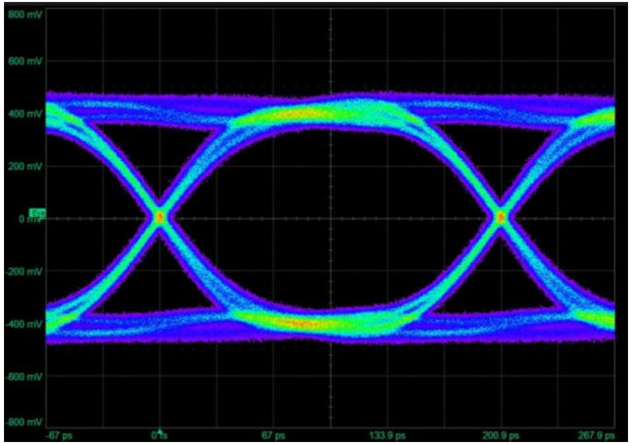
$5 USB device

$30 USB device

Sample Rate of the Oscilloscope



VS.



10GS/s Sample Rate
2 samples per Unit Interval

20GS/s Sample Rate
4 samples per Unit Interval

Conclusions

- Always connect both channels to a 50-ohm load.
- Obtain single ended eye by looking at only one channel.
- $5 5 Gigabit per second differential source.

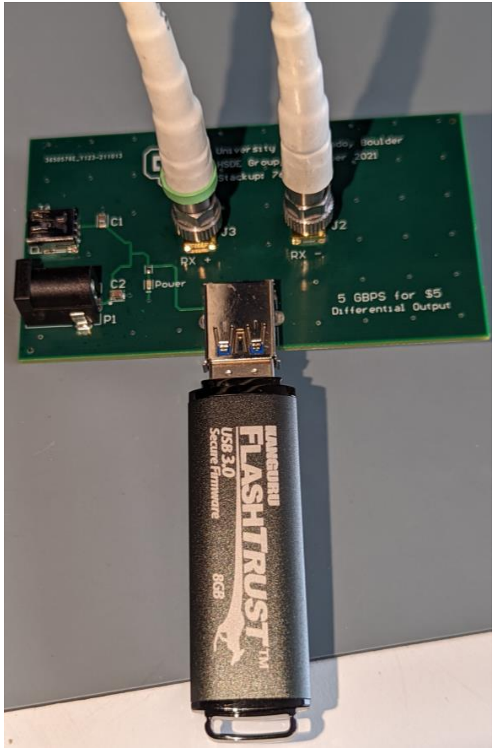


Fig. Final Breakout board in use

Acknowledgement

- We would like to acknowledge the following companies for their generous support:
  - GE Healthcare.
  - Keysight Technologies
  - Ansys
  - Teledyne LeCroy

Thank you!

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QUESTIONS?