Time Stretched Enhanced Recording Oscilloscope

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Outline

- Motivation for ultra high-speed analog-to-digital conversion
- Photonic Time-Stretch Analog-to-Digital Converter (TS-ADC)
- Advantages of Time Stretch Technique
- High resolution Time Stretch ADC experiment
- Time Stretch Enhanced Recording (TiSER) Oscilloscope
- Some results using TiSER
- Summary

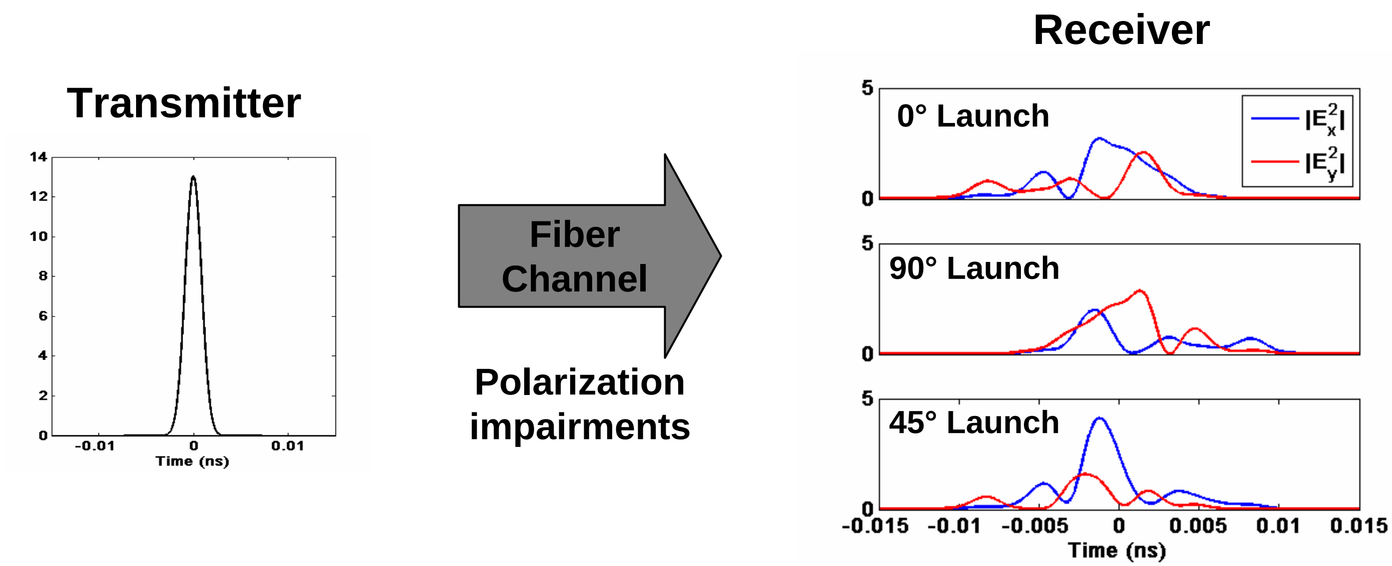
Motivation

- High bandwidth and resolution ADCs are in great demand
  - Next generation optical communication systems
  - High speed serial links
  - High speed test and measurement equipment
  - Radar systems
  - Wireless base-stations and software defined radios
- CMOS technology is making rapid advances but may be lagging behind the demand!
- Can photonics help?

Next generation (>100 Gbit/s) optical links

>100 Gbit/s data rates per wavelength channel required to satisfy increasing bandwidth demands

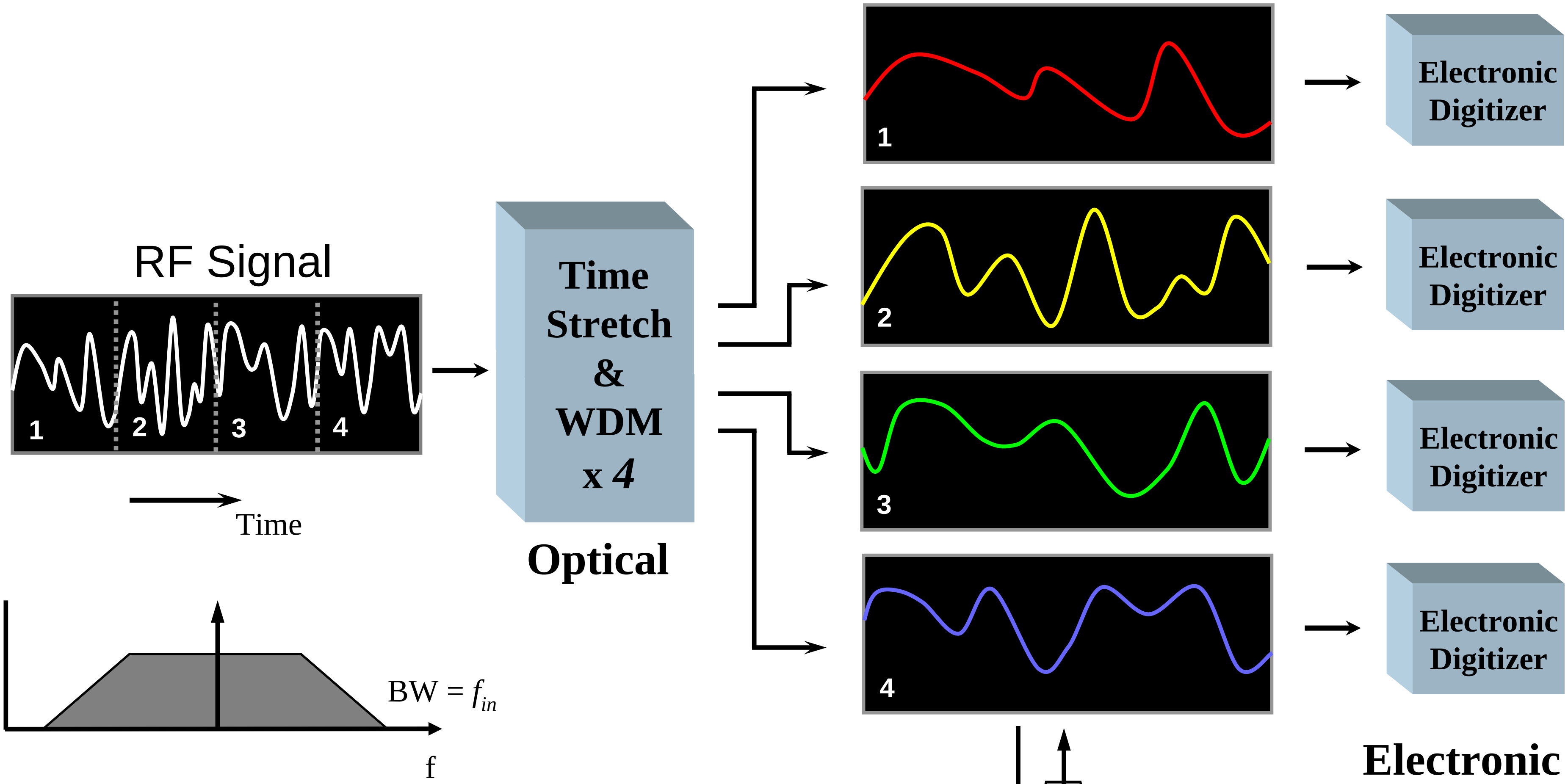
- Polarization multiplexing and bandwidth efficient modulation formats being developed
- Dynamic behavior of polarization impairments (pol. rotation, pol. dependent loss and group delay) make receiver design extremely challenging
- Chromatic dispersion and optical non-linearities can also become important

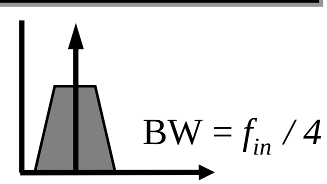


Solution: Polarization diverse digital coherent receiver (with processing in digital domain) commonly suggested

- Requires ADCs with huge bandwidth (~20GHz bandwidth with >6 ENOB resolution)

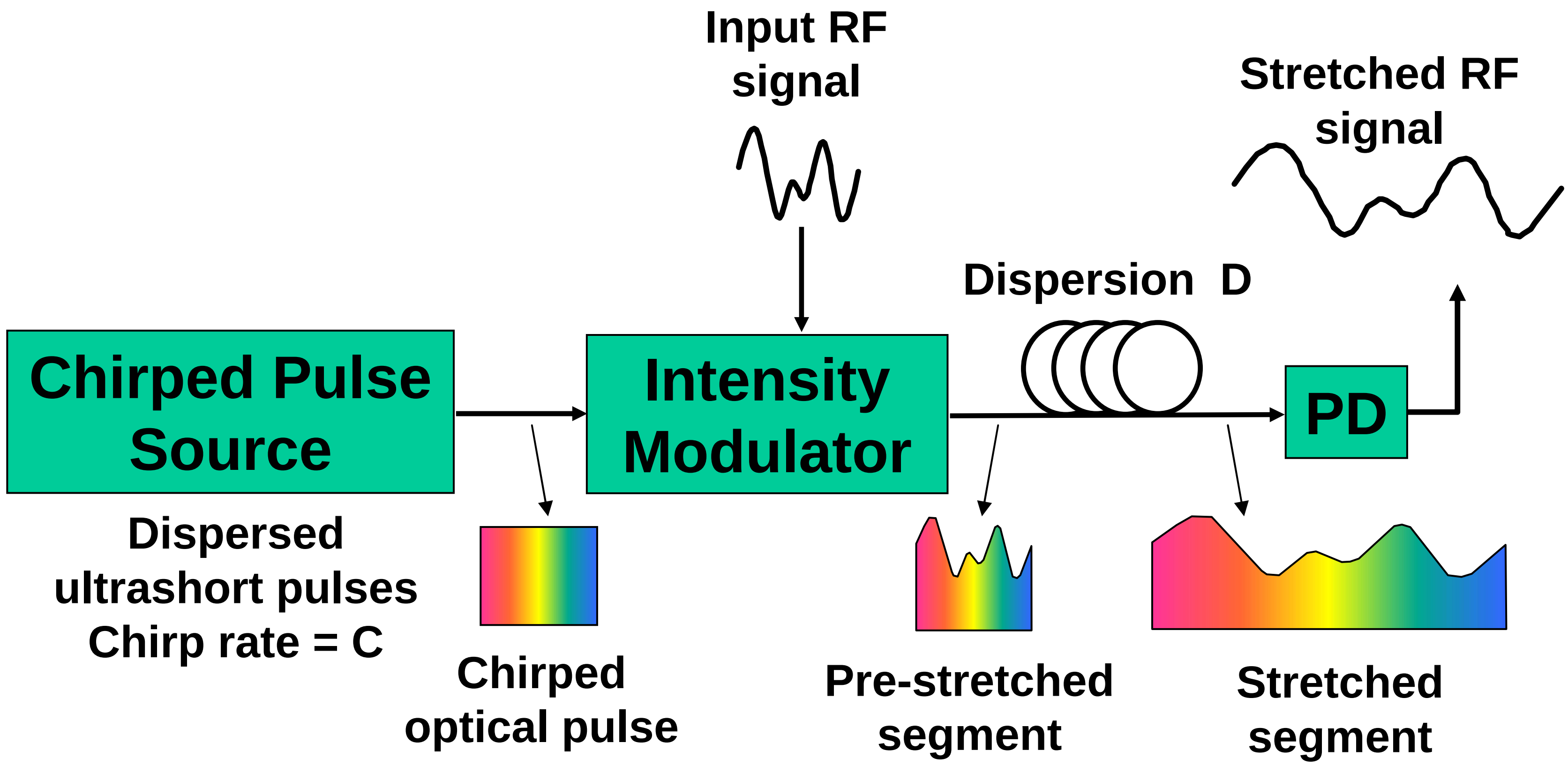
Introduction to Time Stretch ADC





A. S. Bhushan et al., Electronics Letters, 34 (4), 1998.
B. Jalali et al., US Patent # 6,288,659, 2001.

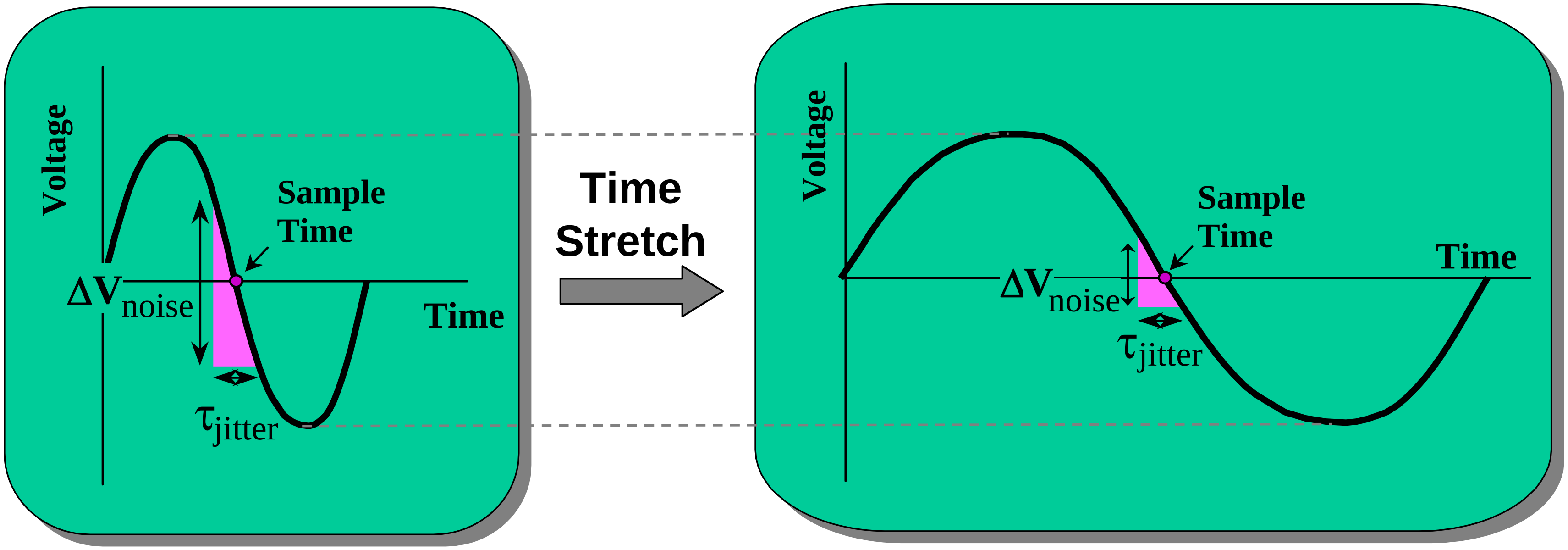
Photonic Time Stretch System



Photonic Time Stretch is a dispersive analog optical link that uses a broadband chirped carrier

A. S. Bhushan et al., Electronics Letters, 34 (4), 1998.
B. Jalali et al., US Patent # 6,288,659, 2001.

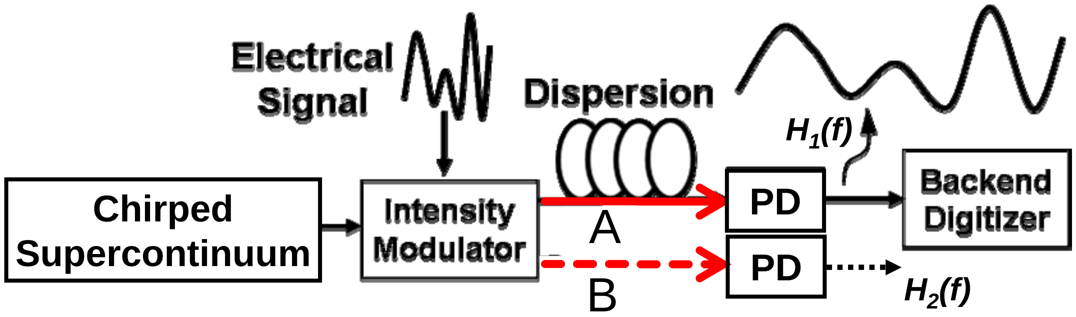
Advantages of Time Stretch Technique

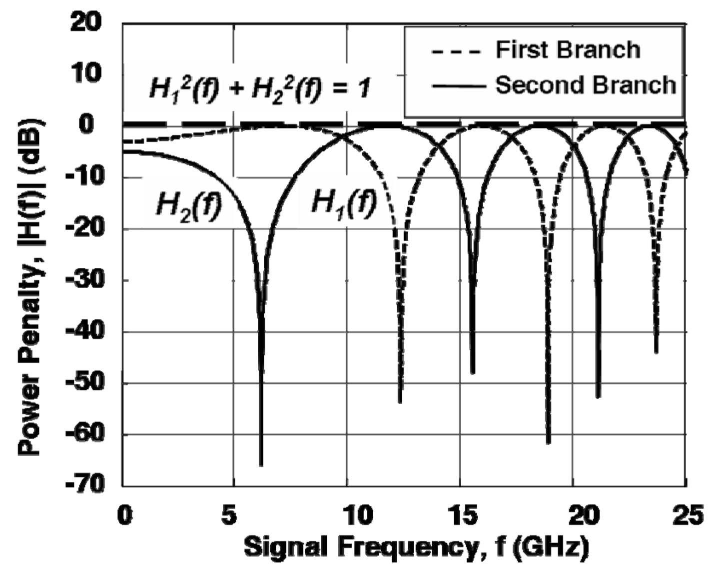


- In high speed ADCs, random noise due to jitter in sampling clocks becomes dominant:
  - Time-stretch effectively reduces it by *(stretch factor)*^{2} or M^2
- With time stretch, digitizing electronics now need to capture slower signals
  - Comparator ambiguity, noise bandwidth are reduced
  - ADC frontend bandwidth can be reduced

$$SNR_{jitter} = \frac{1}{8\pi^2 f_{RF}^2 \tau_{jitter}^2}$$

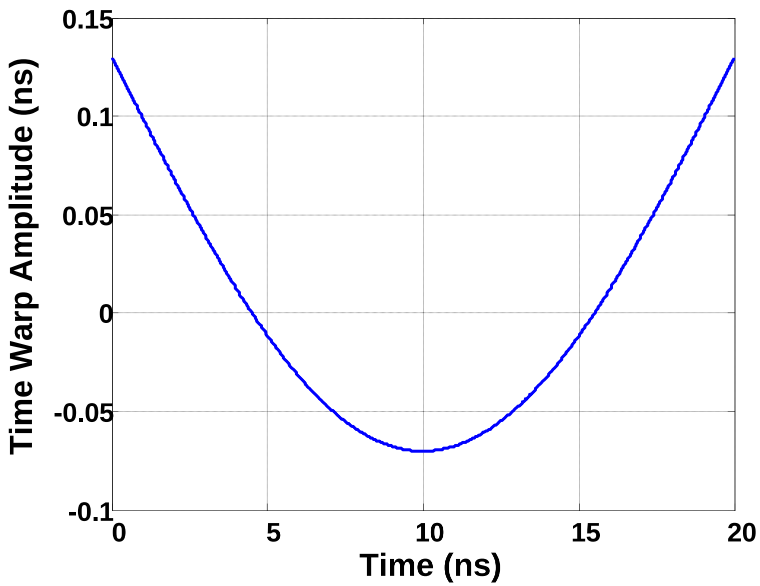
Bandwidth (impulse response) of the Time Stretch System

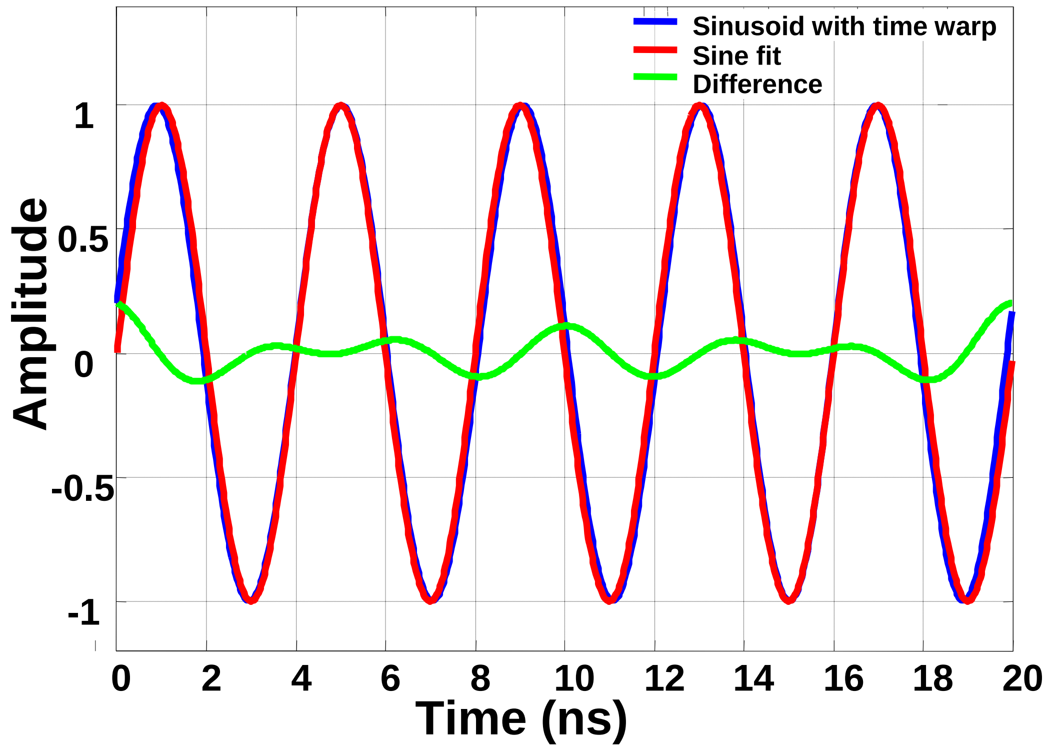




- Phase diversity operation eliminates dispersion induced high frequency attenuation
  - Y. Han and B. Jalali, IEEE Transactions on MTT, 2005
- No fundamental bandwidth limitation
- Only limited by the speed of the modulator
- Other techniques such as single sideband modulation, or optical back propagation can also be employed
  - Y. Han et. al. IEICE Trans. on Electronics, 2003
  - S. Gupta et. al., IEEE Microwave Photonics Conference, 2007

Time Warp Distortion

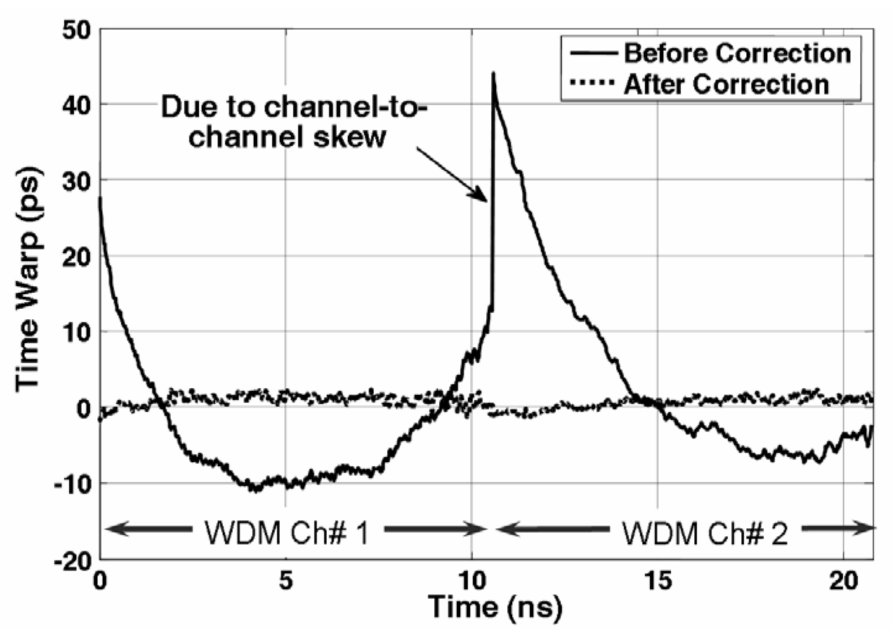




- Main causes are
  - Mismatches in non-linear group velocity dispersion in DCFs
  - Non-linear wavelength dependent group delay variation in filters
  - Self-phase modulation in fiber at high peak powers resulting in non-linear wavelength-to-time mapping

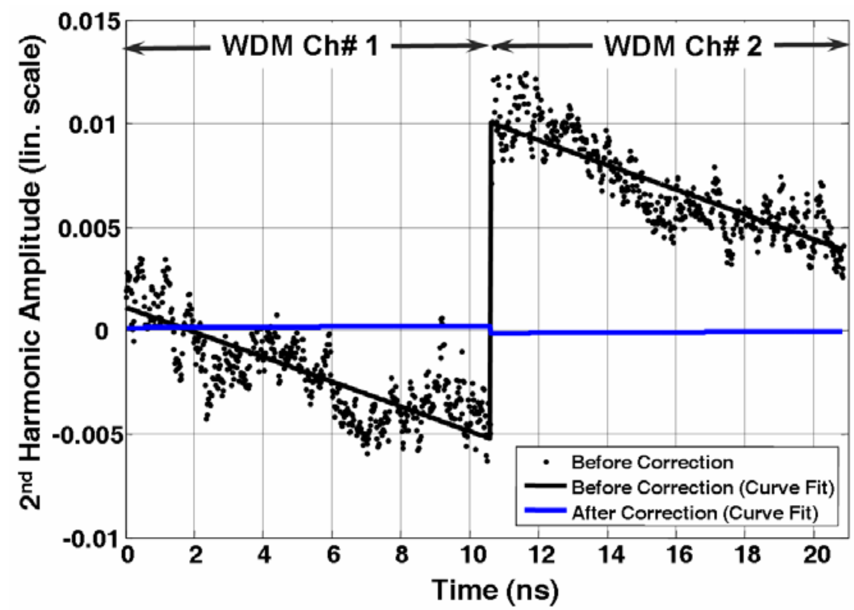
Distortion removal in 7-ENOB 10-GHz TS-ADC

Measured time warp before and after correction



Second order polynomial interpolation is used for the correction

Measured and corrected second order non-linear distortion due to Mach-Zehnder bias offsets

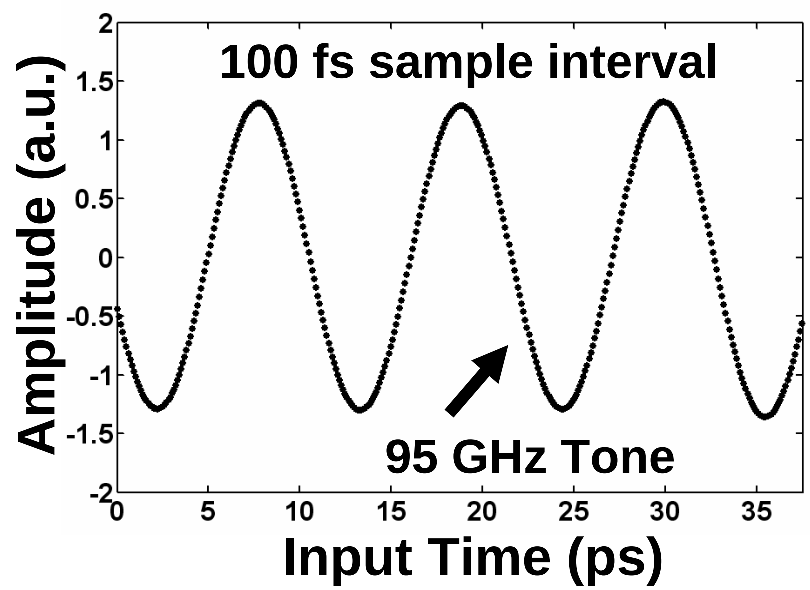


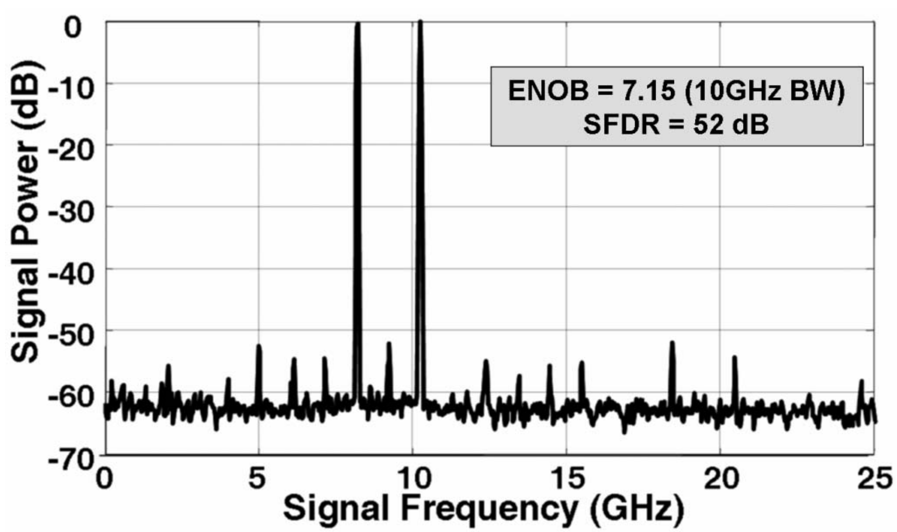
S. Gupta and B. Jalali, *Opt. Lett.* **33** (2008)

Record breaking results

Time Stretch ADC captures

10 Tera Sa/s Digitization of 95 GHz Tone
J. Chou et al., *APL* **91** (2007)

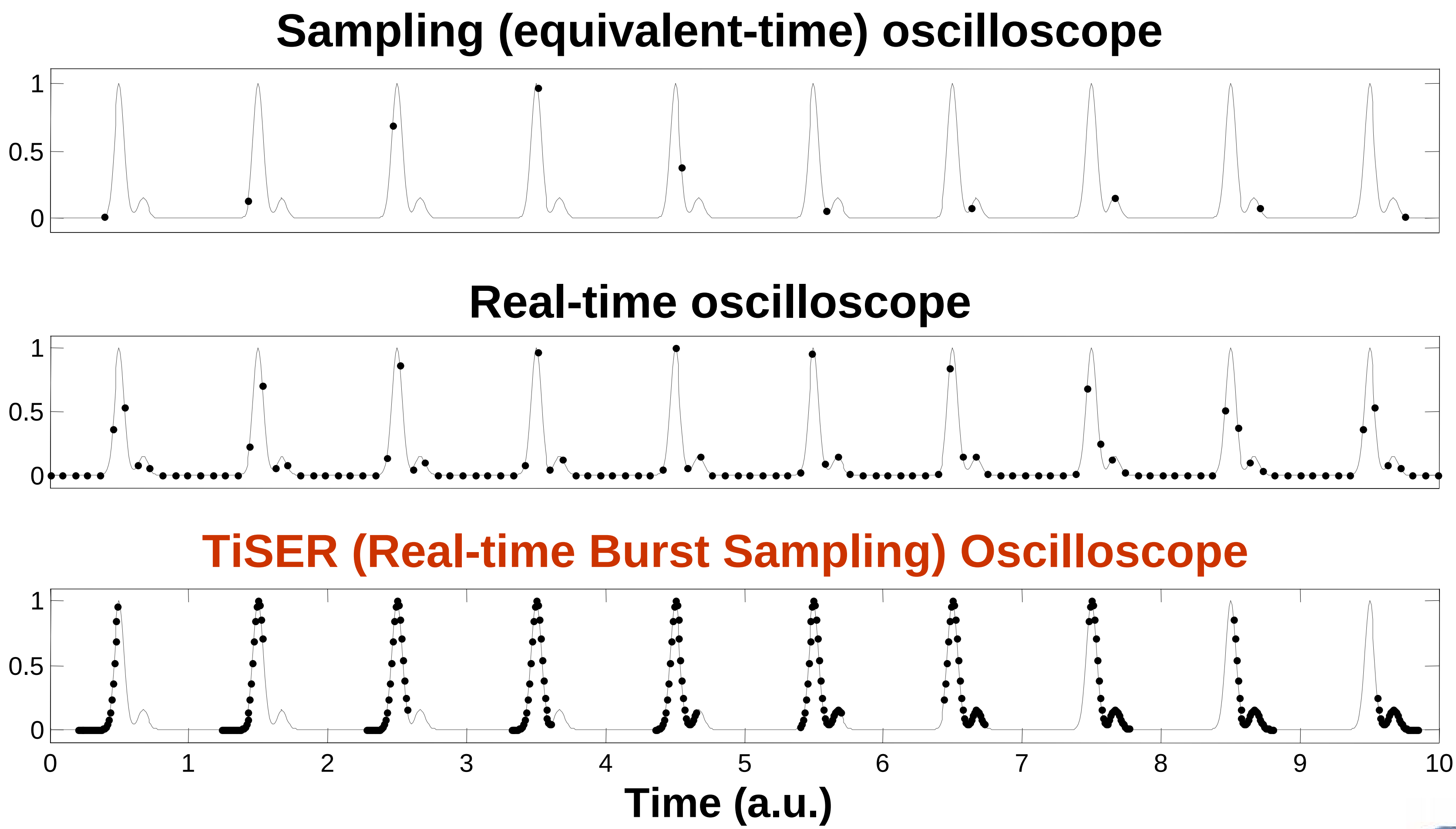




2-Channel 10-GHz bandwidth digitization with >7 ENOB and 52 dB SFDR
S. Gupta et. al., *Opt. Lett.* **33** (2008)

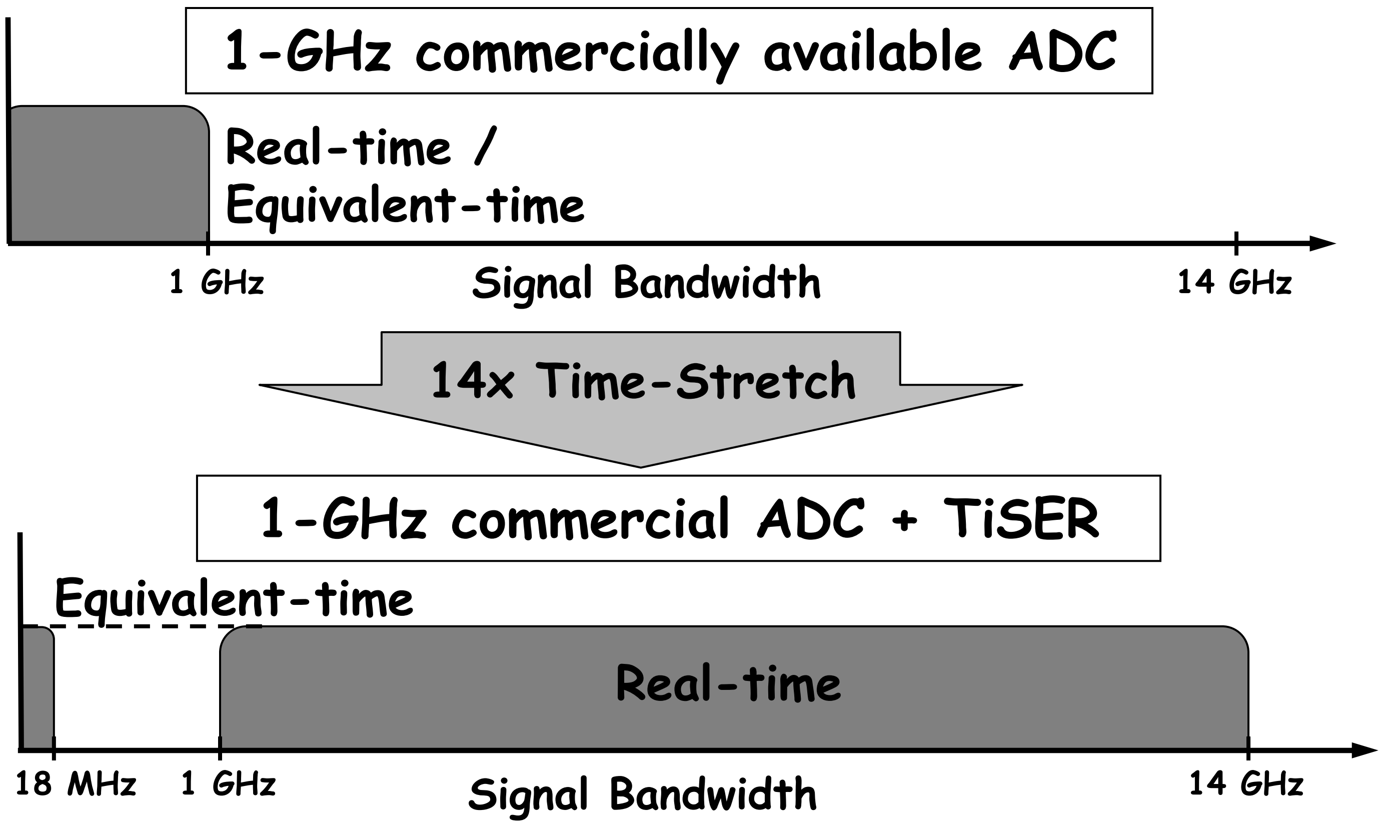
New Concept:
Time Stretch Enhanced Recording (TiSER) Scope

Comparison between sampling techniques:



S. Gupta et al., Appl. Phys. Lett. 94, 041105 (2009)

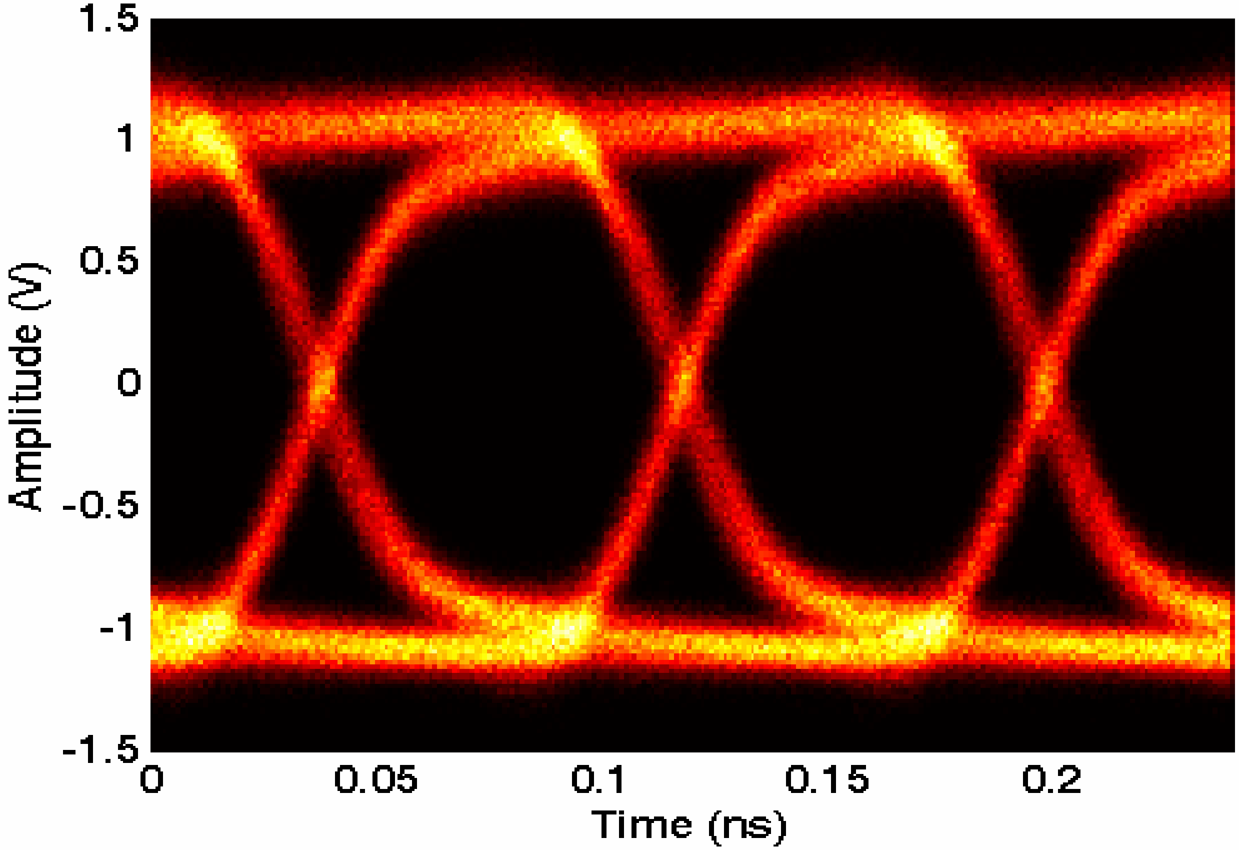
Bandwidth advantages of TiSER



- **Stretching enhances the real-time bandwidth by the stretch factor**
- **Digital data eye can be generated using laser and trigger periods**

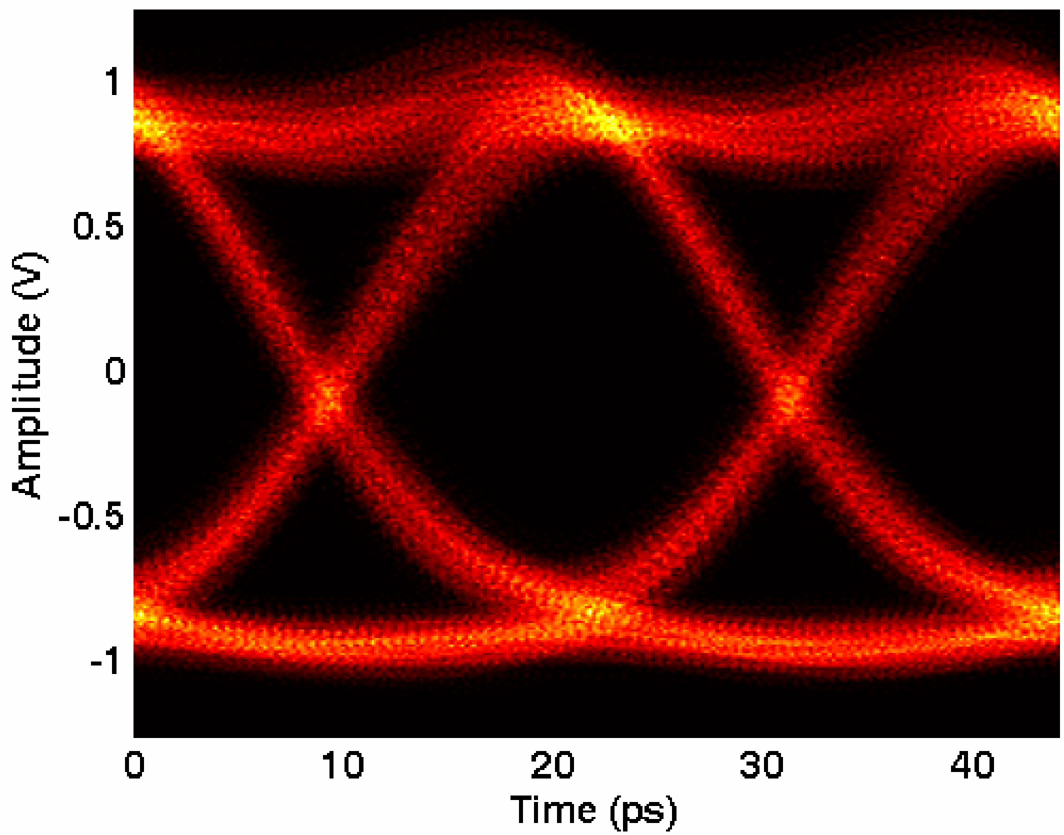
$$t_{out} = \left(n.T_{laser} + \frac{t - n.T_{laser}}{M} \right) \% \, T_{trigger}$$

TiSER capture: 12.5-Gbit/s PRBS data eye



Backend Digitizer: NI-5154
(1-GHz bandwidth, 2-GS/s sample rate)
Stretch Factor: 23

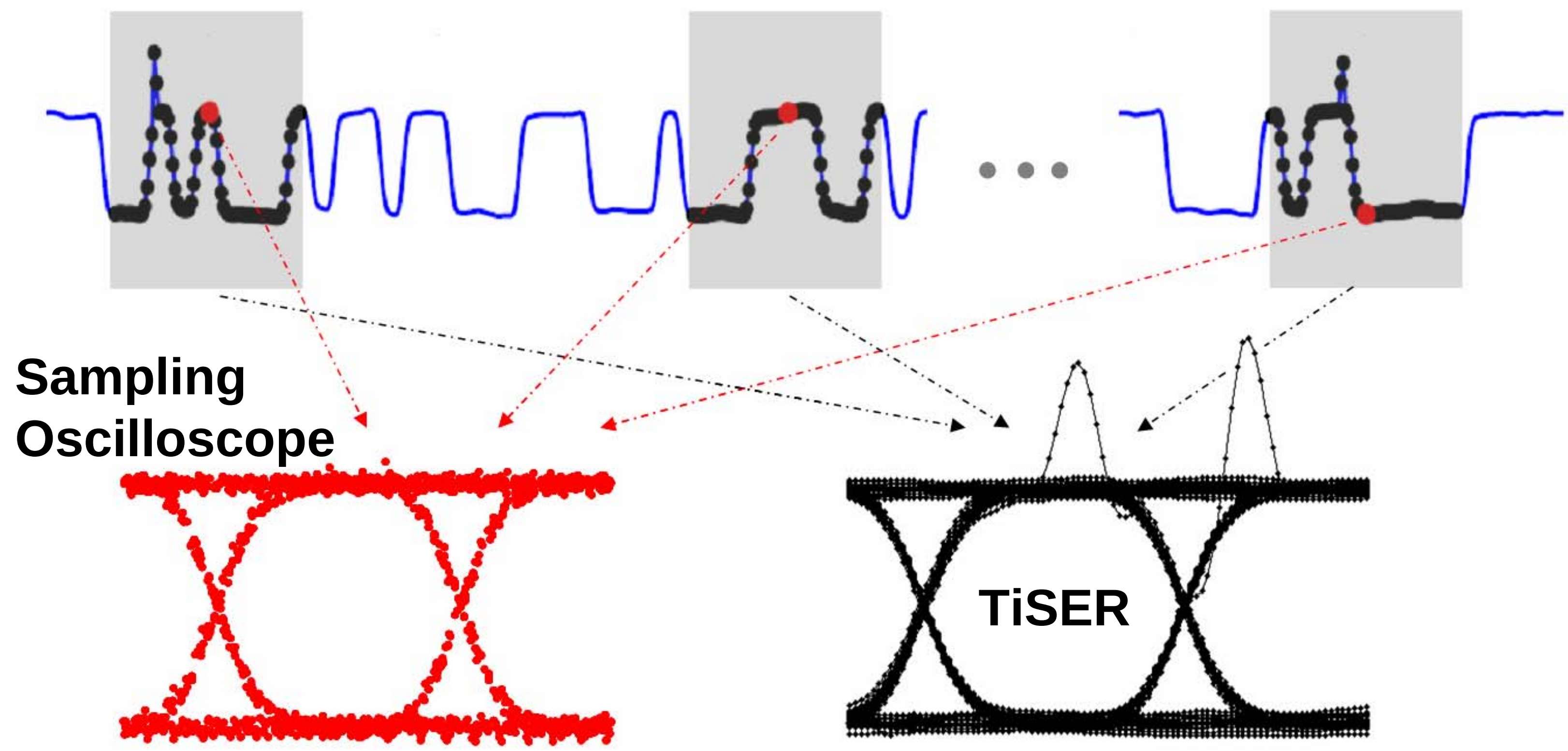
Capture of 45-Gbit/s PRBS data eye



Stretch Factor = 34, Backend digitizer BW = 1.5 GHz

S. Gupta et al., Appl. Phys. Lett. 94, 041105 (2009)

Capture of rare events



- Rare Events
  - missed by sampling scope due to under-sampling
  - missed by real-time oscilloscopes due to bandwidth limitation
  - can now be captured by **TiSER oscilloscope**

Summary

- **Real-time burst sampling technique using Time-Stretch ADC is introduced**
  - **Combines advantages of real-time digitization with very large bandwidths so far restricted only to sampling oscilloscopes**
  - **Can capture high bandwidth repetitive signals, non-repetitive signals and rare events**
  - **Can capture data at >100 times faster rates than sampling oscilloscopes**
  - **Provides real-time capture of analog waveforms needed for development of equalization algorithms**
- **Fast capture of 45 Gbit/s data eye with a 1.5-GHz bandwidth backend digitizer is demonstrated**