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Photonic Analog-to-Digital Converters
A Tutorial

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Outline

- What is a photonic ADC?
- Electronic ADC basics—sampling and quantization
- State of the art:
  - *ADCs*
  - *Interleaved digitizers*
  - *Digital oscilloscopes*
- Classes of photonic ADCs: Photonic-
  - *Assisted*
  - *Sampled*
  - *Quantized*
  - *Delta-sigma modulator*
- Microwave photonic links in photonic ADCs
- Examples of photonic ADCs
- Recent results time-stretch ADCs
  - *10 Terasample/second transient digitizer*
  - *7-ENOB 10 GHz 2-channel ADC*
  - *150 Gigasample/second continuous time digitizer*
- Summary

What is a photonic analog-to-digital converter?

- Optical signal
  - *Input analog optical signal*
  - *Output digital optical signal*

    Relatively little work here

    Most analog optical signals are incoherent light

- RF signal
  - *Input analog electronic signal*
  - *Do something to electronic signal using photonics*
  - *Output digital electronic signal*

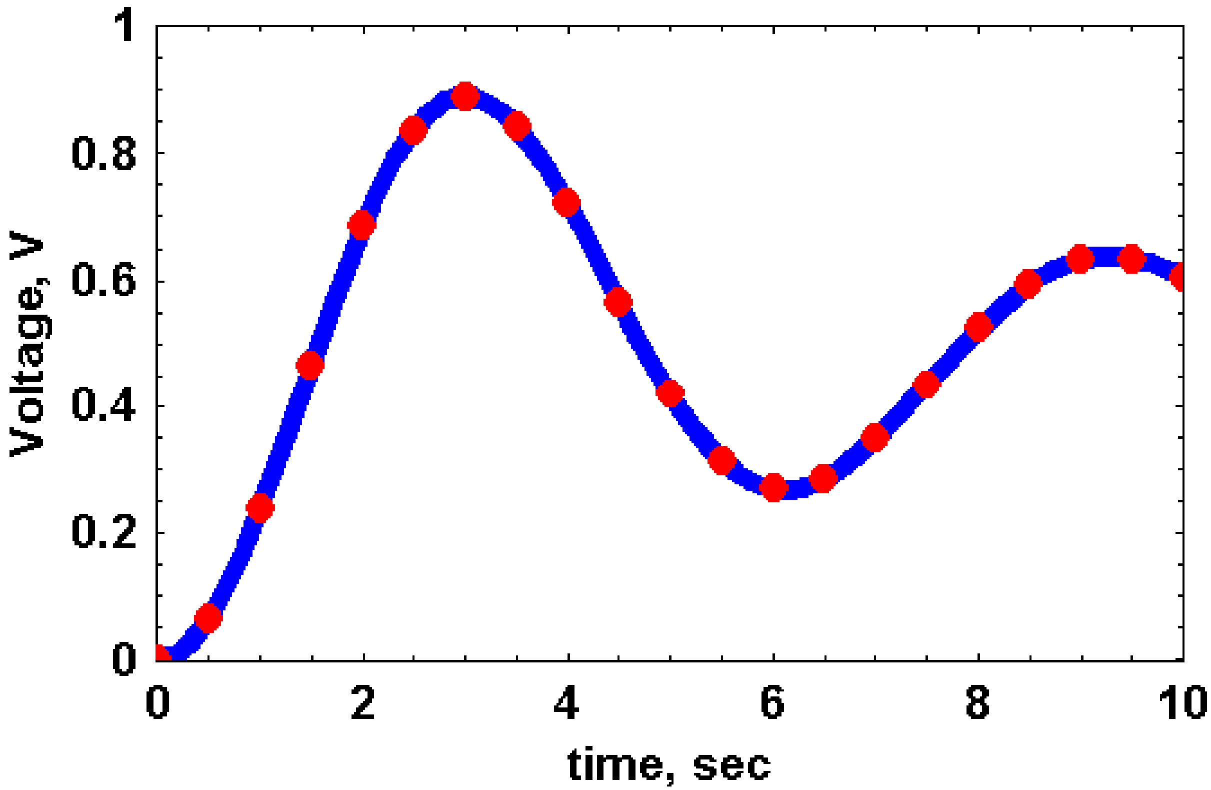
    Most photonic ADC work is here

Sampling rate and number of bits

- Familiar quantities
  - *Sampling rate—e.g. CD 44.1 kHz or kilo sample/sec (kS/s)*
  - *Number of read-out bits (stated bits)—CD 16 bits*
- More useful characterizations of ADC performance
  - *Input bandwidth—e.g. CD 20 Hz to 20 kHz*
    - Nyquist sampling theorem says sampling rate must be > 2 x bandwidth
    - ADC noise bandwidth = input bandwidth
  - *Effective number of bits (ENOB)*
    - Depends on Signal-to-Noise-and-Distortion Ratio (SNDR)
    - Factor of 4 (6 dB) in SNDR gives 1 additional bit.
    - Need SNDR > 96 dB to fully utilize CDs 16 bits
    - Need SNDR > 144 DB to fully utilize the DVD audio disk's 24 bits

Sample and Hold

ADC Step 1: Sample and hold an RF signal in time



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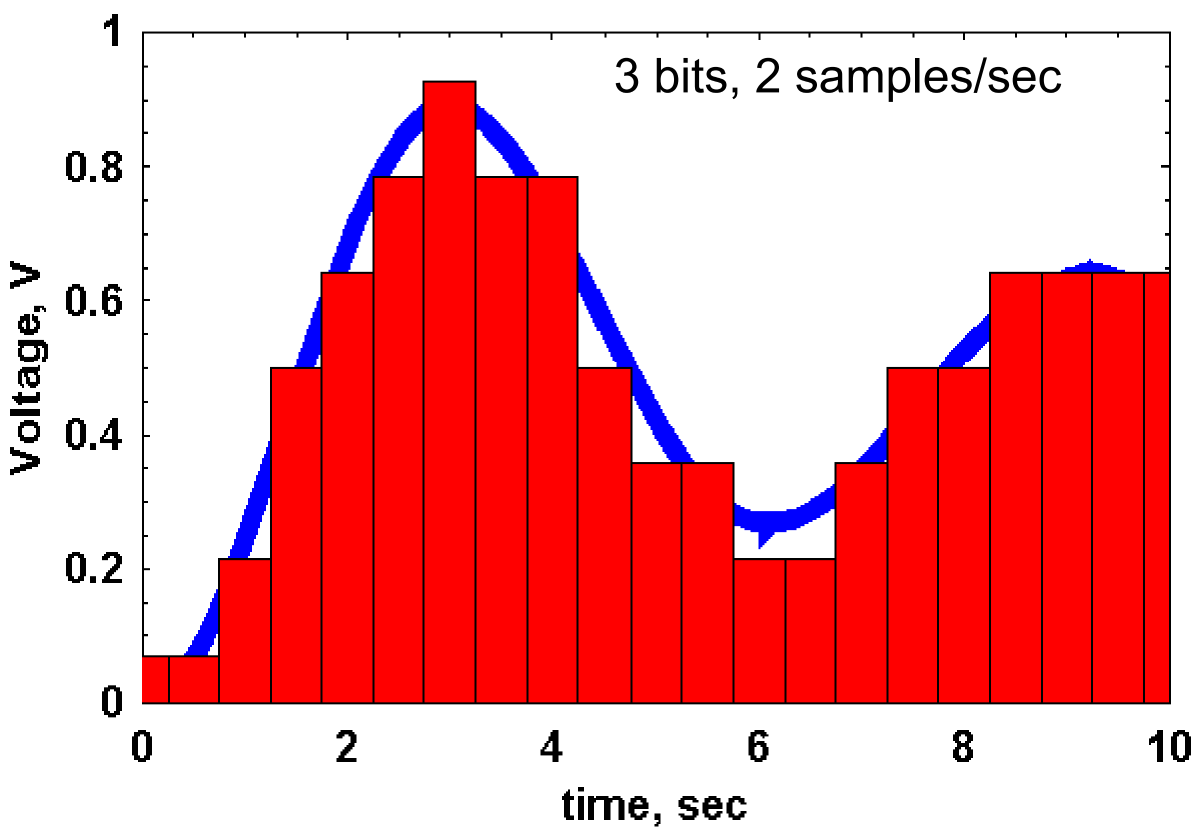
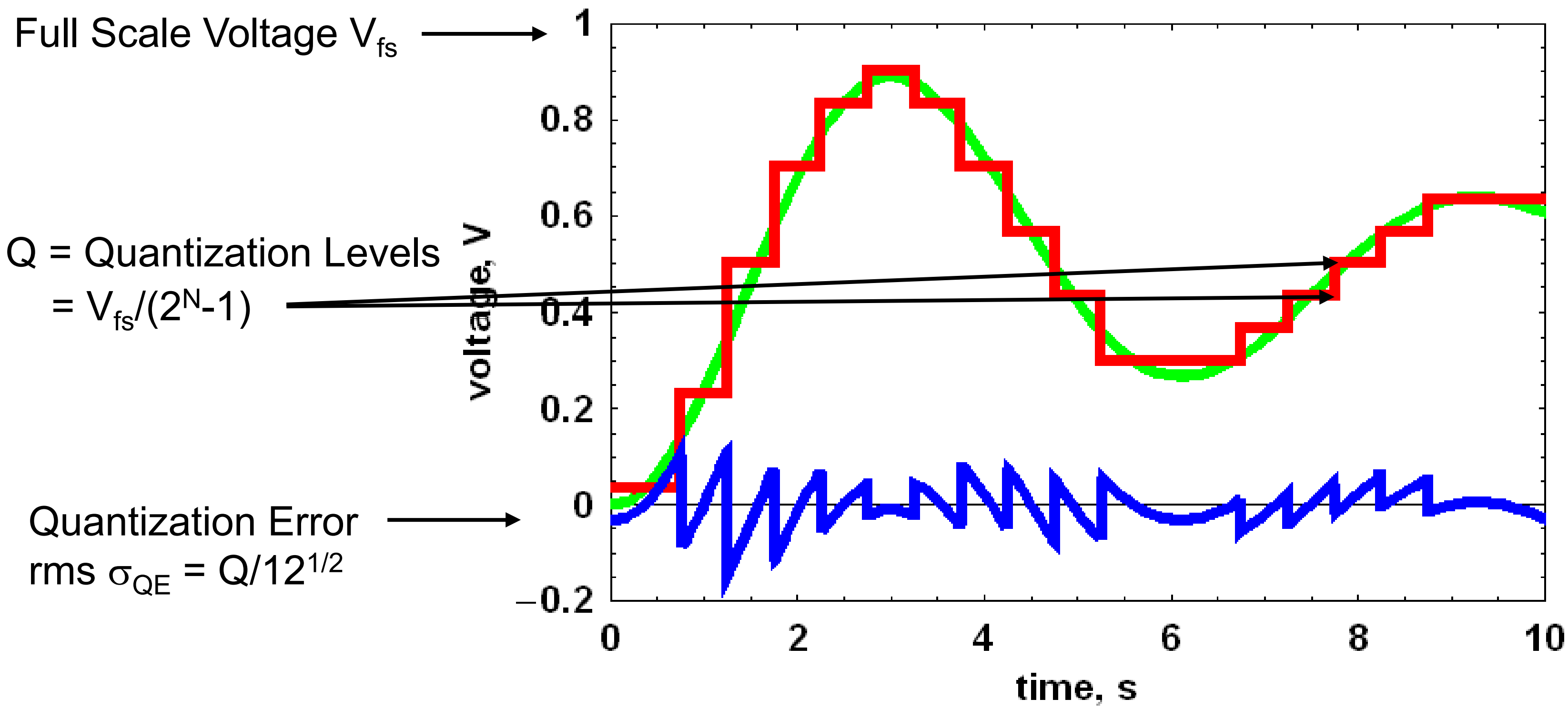
Quantize Voltage

ADC Step 2: During sample time quantize the voltages in 2^N-1 levels. N = number of bits (stated bits or read-out bits)



Quantization Error



Quantization error is intrinsic to an ADC
Non-idealities usually cause errors with rms greater than $Q/12^{1/2}$

How do you calculate ENOB?

- Relate the number of bits N in an ideal ADC to the signal-to-noise ratio
- Quantization noise is the only noise in an ideal ADC
  - $SNR_{QE} = 20 \log_{10}(V_{rms}/\sigma_{QE})$
  - $V_{rms} = V_{fs}/(2^{3/2})$ *for a sine wave*
  - $V_{fs} = (2^N - \cancel{1})Q$
  - $\sigma_{QE} = Q/12^{1/2}$ *for a sine wave*
- Solve for N in terms of SNR_{QE}
  - $N = [SNR_Q - 20 \log_{10}(12^{1/2}/2^{3/2})]/(20 \ln 2/\ln 10)$
  - $N = (SNR_Q - 1.76)/6.02$
- The effective number of bits (ENOB) is defined by analogy as
  - *ENOB = (SNDR-1.76)/6.02 with SNDR in dB*

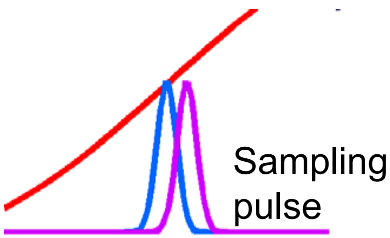
The factor of 6.02 reflects the notion that to improve ENOB by 1 bit, either the full-scale voltage must be increased by 2 x or the rms noise (and distortion) must be reduced by 2 x.

Other sources of error

Noise and other non-idealities reduce ADC resolution

- Amplitude Errors
  - *Noise*
    - Thermal
    - Shot
    - Spontaneous emission
    - RIN
  - *Nonlinearities*
    - Harmonics at frequency: $2\omega_S$ $3\omega_S$ …
    - Intermodulation products (spurs) at freq.:

      $\omega_1 - \omega_2$, $\omega_1 - 2\omega_2$, $\omega_2 - 2\omega_1$
    - Optical nonlinearities
- Timing Errors
  - *Clock jitter*
  - *Circuit response time (RC time constant, carrier lifetimes, Comparator ambiguity)*



Comments on timing error

- Estimate required timing jitter
  - *Voltage error roughly $V_{fs}/(12^{1/2}\, 2^{ENOB})$*
  - *Equivalent error in the time domain suggests*

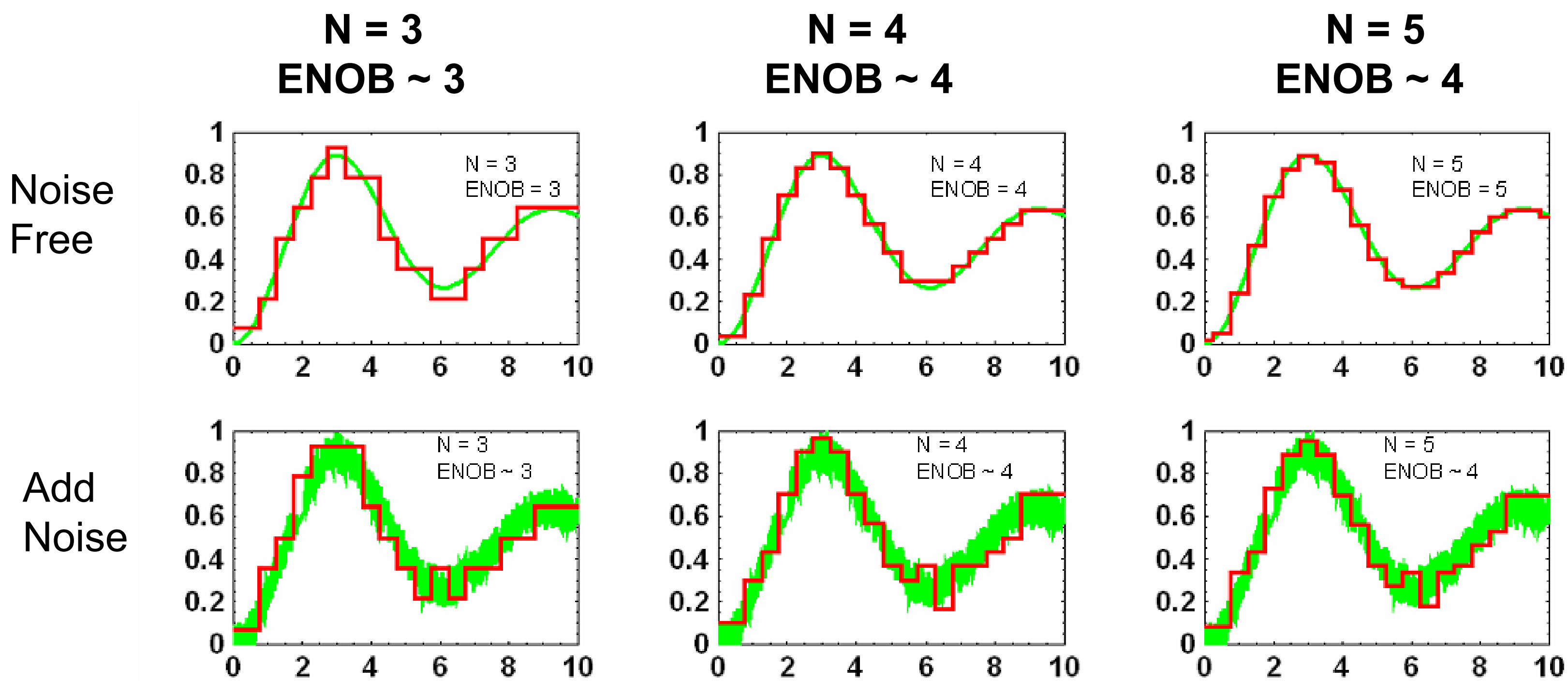
    Timing jitter should be $T_{sample}/(12^{1/2}\, 2^{ENOB})$
  - *Detailed calculations give*

    $ENOB = \log_2[1/(3^{1/2}\, \pi\, f_s\, \sigma_j)]$
  - *Example: ENOB = 24, 96 kS/s requires ~100 fs jitter*
- Time to perform quantization is 1/(sampling rate)
  - *Electronic comparator must decide between two adjacent voltage levels in time $1/f_s$*
  - *For voltages midway between levels quantization, this is relatively easy*
  - *For voltages near a quantization level, the decision process slows down*

Timing jitter and comparator ambiguity are the most important limitations on the performance of high speed ADCs

Difference between ENOB and read-out bits N

Example: amplitude noise limits effective number of bits (ENOB)



Achieving one additional effective bit requires 6dB increase in SNDR

Taking a 4-ENOB prototype system to 10 ENOB requires increasing SNDR by 36 dB ~ 4,000 !

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Nyquist-Shannon Sampling Theorem

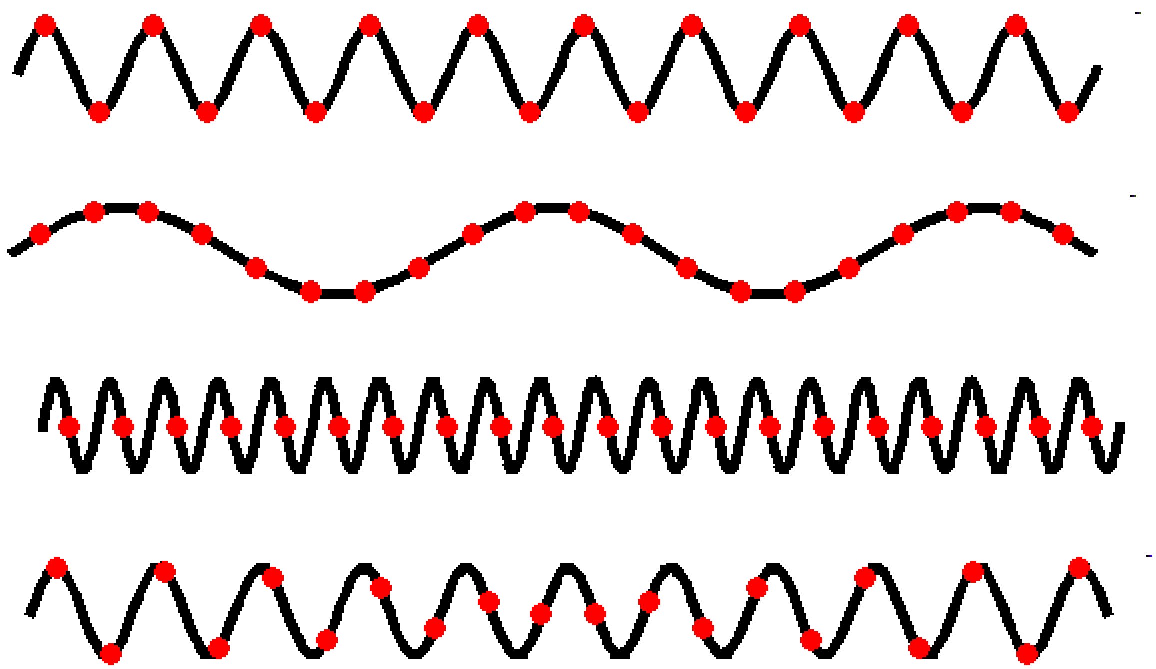
Given a continuous time signal whose maximum bandwidth is B, perfect reconstruction can be obtained if the sampling rate f_s is greater than 2 B.

$f_s = 2B$

$f_s > 2B$

$f_s = B$

$f_s < 2B$



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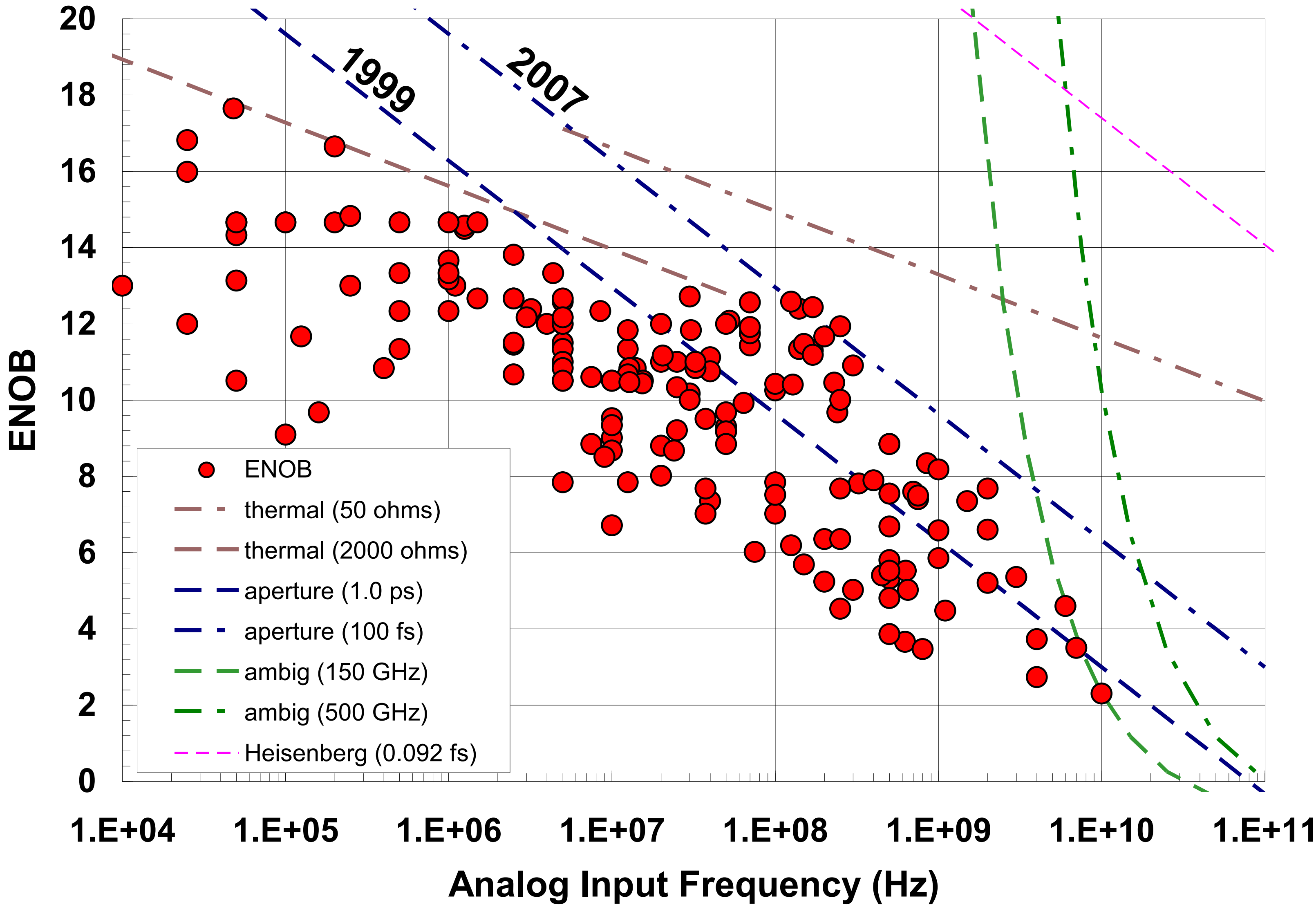
ADC State-of-the-Art (Walden 2008)



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Modules and Digital Oscilloscopes

- Maxtek Data Converter Module: 6.25 GHz, 6.6 ENOB
- Agilent Digital Oscilloscope: 13 GHz, ~5 ENOB
- Tektronix Digital Oscilloscope: 20 GHz, ~ 5 ENOB
- LeCroy Digital Oscilloscope: 18 GHz, ~ 5 ENOB

- ADC Definitions
  - *Real-time digitizers*
    - Single chip ADC
    - Interleaved digitizer (2 or more ADC chips)
    - Digital Oscilloscope (Interleaved digitizer plus storage, display, processing etc.)
  - *Sampling Oscilloscope—not real time*
    - Digitizes repetitive waveforms

Where are photonic ADCs needed?

- Rule of Thumb:

  Viable photonics systems must either provide substantial improvement over electronics or provide completely new functionality unavailable in electronics.

- Why?
  - *High rate of progress of electronics*
  - *Non-recurring engineering costs of photonic systems*
  - *Complexity of photonic systems*

- From Walden's chart a 2 ENOB margin over electronics implies

Input Bandwidth	ENOB
1 GHz	>10-11
6 GHz	>8-9
20 GHz	>7
>20 GHz	>3

Estimate power consumption for a photonic ADC?

- Figure of merit for ADCs
  - *Energy per conversion step (pJ/cs)*

$$\frac{\text{Power}}{2^{ENOB} f_s}$$

  - *Best electronic results: ~0.2 pJ/cs @ ~50MHz*
  - *At 1-10 GHz electronic ADCs consume 10-100 pJ/cs!*
- Estimate power consumption for

  10 ENOB, 10 GS/s (10/10) electronic ADC
  - *@ 0.2 pJ/cs: P = 2 W*
  - *@ 10 pJ/cs: P = 100 W*
  - *@ 100 pJ/cs: P = 1000 W*
- Photonic 10/10 ADC would be attractive at P < 10W

Can a photonic ADC achieve < 1 pJ/cs in the GHz band?

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Classes of Photonic ADCs

Photonic Assisted

RF signal not modulated on optical beam. Photonics helps electronic ADC.

Photonic Sampled

RF modulated on Pulsed optical beam. Use low Jitter of mode-Locked pulses To reduce Sampling jitter

Photonic Quantized

RF modulated on cw optical beam. Photonic process aids or replaces electronic quantizer.

Photonic Sampled & Quantized

RF modulated on Pulsed optical beam. Photonic process aids or replaces electronic quantizer.

All photonic ADCs in these classes contain analog optical links

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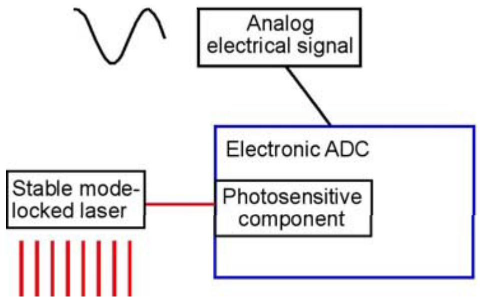
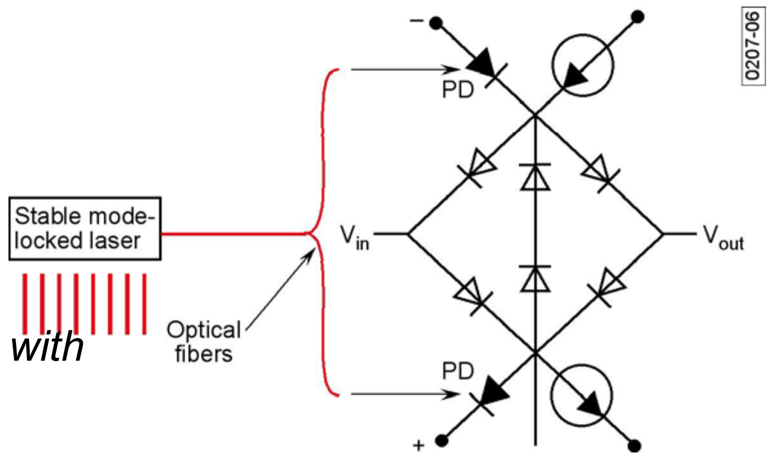
Photonics Assisted ADCs

- Generic version
  - *Origins in Auston switch (1975)*
  - *Mode-locked laser at Nyquist rate*



- Optically clocked Track and Hold (Jacobs et al. 2004)
  - *Ultra-stable mode-locked laser source switches electronic track and hold circuit-*
  - *Bridge turns off when photodiodes are illuminated*
  - *Benefits*
    - Reduced aperture time
    - High clock isolation
    - Low clock jitter
    - Optical clock distribution
  - *Results—1 GS/s track and hold consistent with*
    - 11.8 SFDR bits, 9.6 SNR bits



Photonics-assisted approach—no RF modulator
Careful path matching required to maintain timing

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Analog Optical Links

Consider a *lossless* analog optical link with shot, thermal and RIN noise

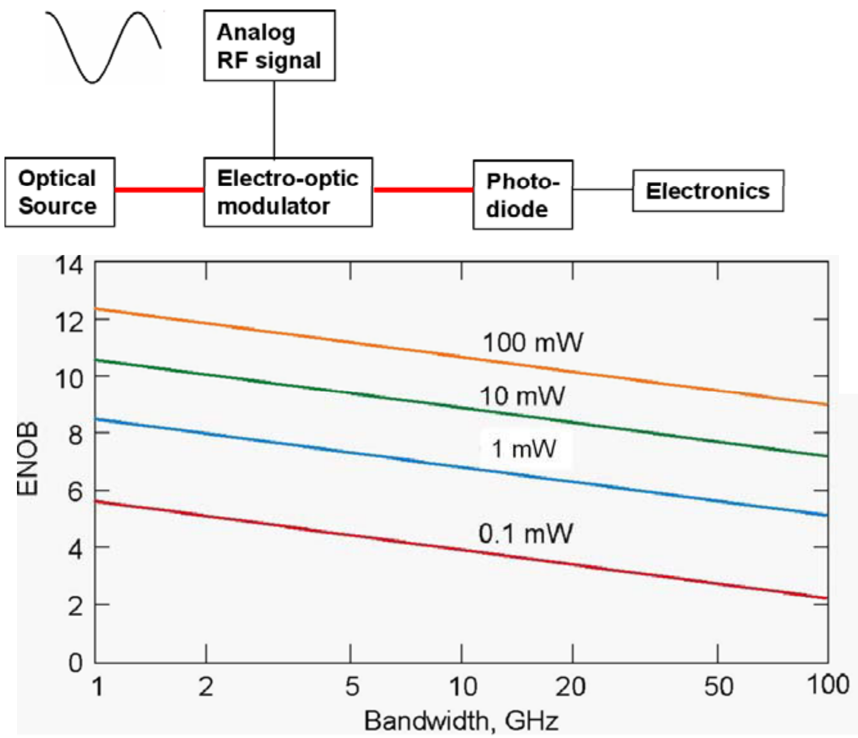
$$\mathrm{CNR} = \frac{(m\,R\,P)^2/2}{(\sigma_s^2 + \sigma_{\mathrm{th}}^2 + \sigma_{\mathrm{RIN}}^2)}$$

With no nonlinear distortion

ENOB = [CNR(dB)-1.76]/6.02

Best case parameters

$m = 0.5$, $R = 1$ A/W, $R_{\mathrm{load}} = 50\ \Omega$, RIN = 0



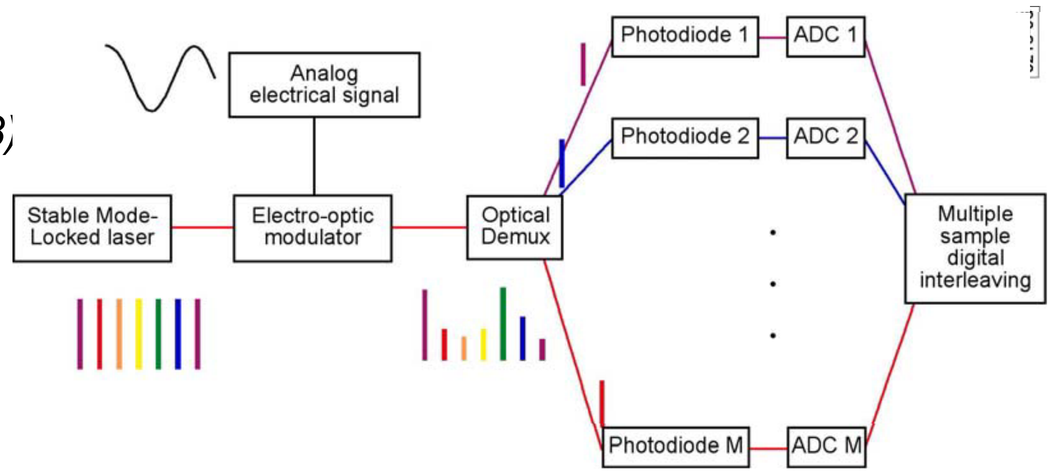
10 ENOB at 10 GHz requires > 30 mW at the Photodiode

Photonic Sampled ADC

- Three variants
  - *Optical sampling to a single high rate ADC*
  - *Optical sampling with wavelength or time demultiplexing to a bank of lower rate ADCs*
- Requirements on laser source @ 5 GHz

Effective Bits	Amplitude jitter σ_M, %	Timing jitter σ_j, fs
6	**0.46**	**210**
8	**0.11**	**51.**
10	**0.028**	**13.**
12	**0.007**	**3.2**
14	**0.002**	**0.8**

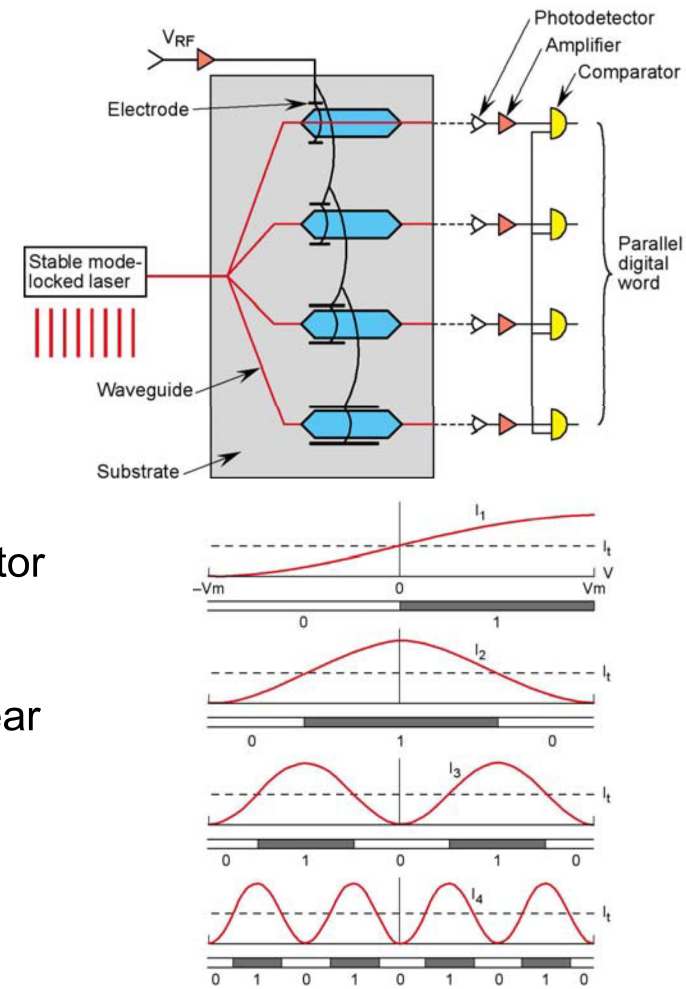
- Results
  - *12 ENOB at 208 MS/s*
  - *10 ENOB at 505 MS/s (Williamson et al. 2003)*
  - *4 ENOB at 100 GHz (Clark et al. 1999)*



Photonic sampled and quantized: Intensity quantization

- Taylor scheme (1979) and variants produced interesting photonic ADCs thru the 1980s.
- Issue: each extra bit requires another factor of 2 in the longest modulator. Eventually drive voltage or insertion loss become prohibitive.
- Recent work

  quantizing optical intensity with semi-conductor saturable absorbers,n_2 nonlinearity, cross-phase modulation, self-phase modulation, solitons, supercontinuum generation, nonlinear optical loop mirrors, microring resonators …



Low loss modulators (V_{pi} ~ 0.1 V) would revive interest in Taylor's scheme

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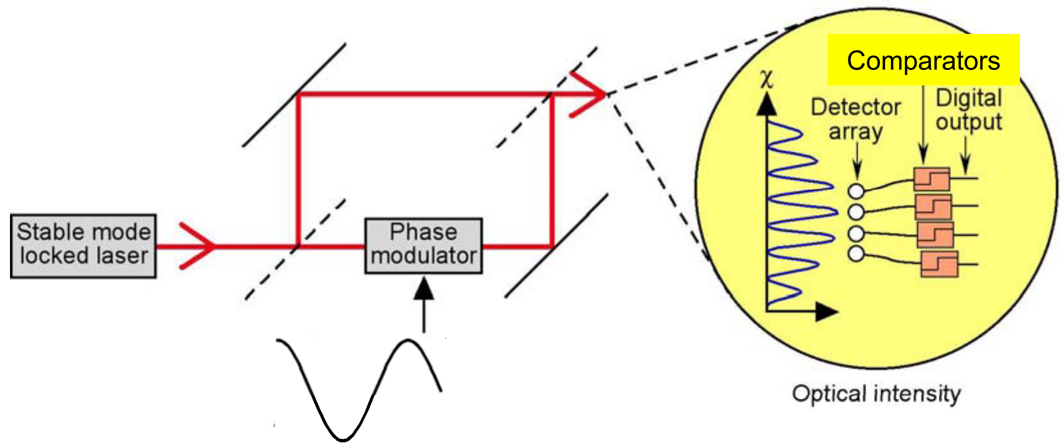
Photonic sampled and quantized:Angle quantization

- The very first photonic ADC (Wright et al. 1974) used angle modulation
- Most angle modulators are too slow to compete with today's electronics
- Stigwall and Galt (2005, 2006) developed a system in which an electro-optic phase modulator shifts an optical interference pattern incident on an array of detectors.
- Issues
  - *Speed*
  - *ENOB*
  - *Path Loss*



Advantage: phase modulation is linear

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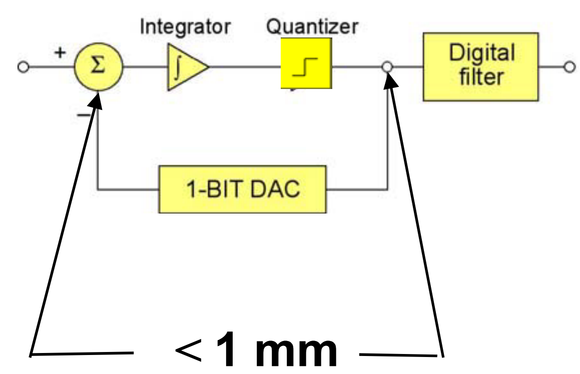
Photonic sampled and quantized:Photonic ΔΣ modulator

First order ΔΣ modulator



Required components for a ΔΣ modulator

- Adder
- Integrator
- Quantizer
- Feedback DAC

Electronic ΔΣ modulators now operate at ~20 GHz

Photonic ΔΣ modulator at 200 GHz. Clock period = 5 ps => 1 mm (n = 1.5)

In a ΔΣ modulator need feedback delay < clock period

In a ΔΣ modulator need quantizer response time << clock period

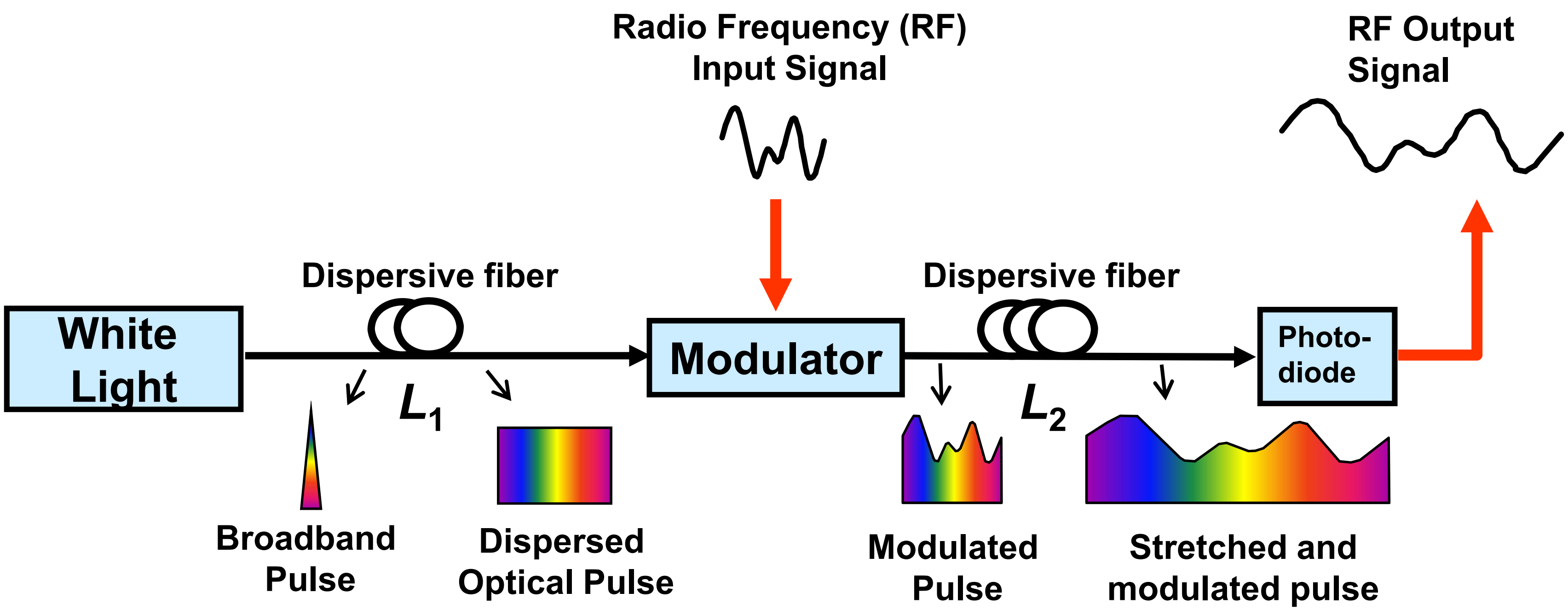
Really want at least 2nd order ΔΣ modulator to take advantage of oversampling

The challenges of building multiple, integrated, all-optical adders, integrators and quantizers in 1 mm seem daunting

Recent results on time-stretch ADCs

- 10 Tera-sample per second digitization of 90 GHz waveform
  - *Stretch ratio 250*
  - *ENOB ~ 3 @ 50 GHz*
  - *Transient digitizer*
  - *Chou et al. 2007*
- 2-channel 10 GHz system
  - *Stretch ratio 10*
  - *ENOB ~ 7 @ 10 GHz*
  - *Scalable to continuous time*
  - *PHOBIAC, Sefler et al. 2008*
- 150 GS/s 4 channel system
  - *Stretch ratio 3*
  - *Continuous time*
  - *Input bandwidth to 48 GHz*
  - *ENOB ~ 3 @ 10 GHz*
  - *Chou et al. 2008*

Conceptual Diagram—Time-stretch ADC



- RF signals are modulated on to the envelope of a dispersed optical pulse
- Dispersion is used a second time to temporally stretch the RF signal and optical pulse
- Stretch Ratio M is related to the fiber dispersions D_1, D_2 ~ fiber length

$$M = (L_1 + L_2) / L_1$$

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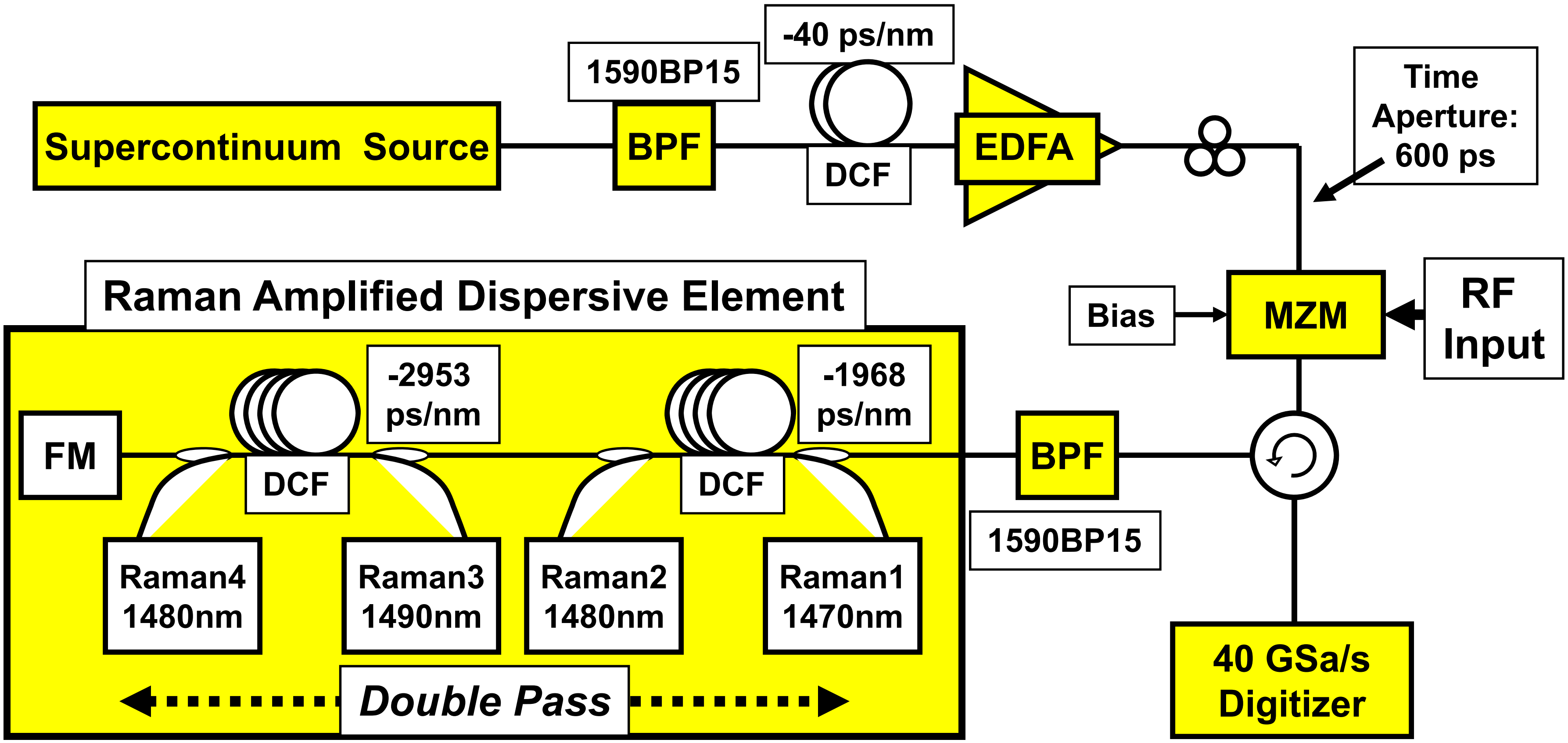
10 TSample/s Real-Time Digitizer Schematic (Chou et al. 2007)



Time Stretch Factor = 250
Eff. Sampling Rate = 40 GSa/s x 250 = 10 TSa/s
Eff. Sampling Interval = 25 ps ÷ 250 = 100 fs

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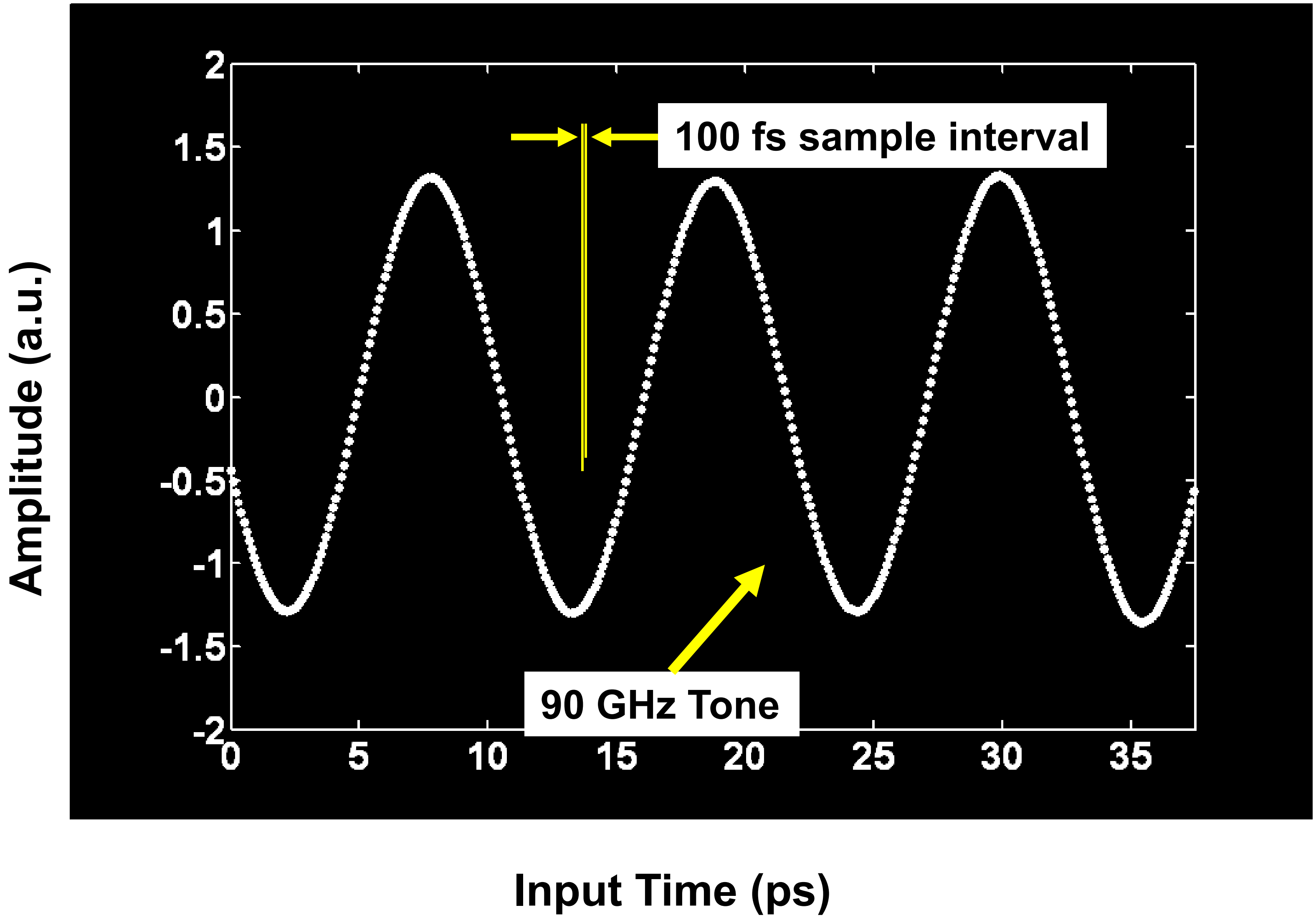
Direct digitization with 100 fs sample time

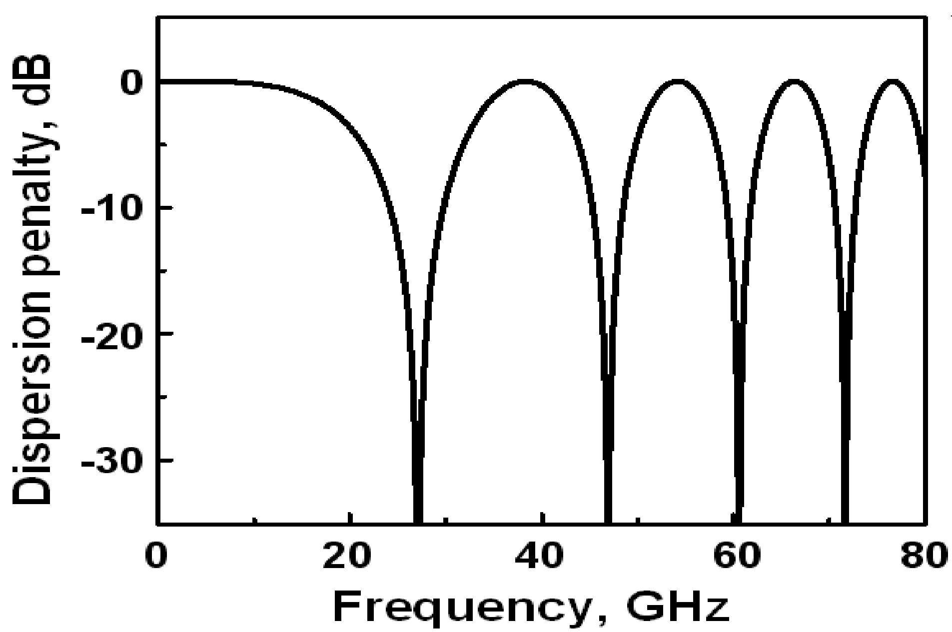


Dispersion Penalty

Optical signal after modulator consists of upper sideband, $f_{Opt}+f_{RF}$,
lower sideband, $f_{Opt}-f_{RF}$
carrier, f_{Opt}

At photodiode upper sideband and lower sideband beat with carrier to produce current at f_{RF}

Upper and lower sidebands travel at differing group velocities in dispersive media between modulator and photodetector leading to destructive interference



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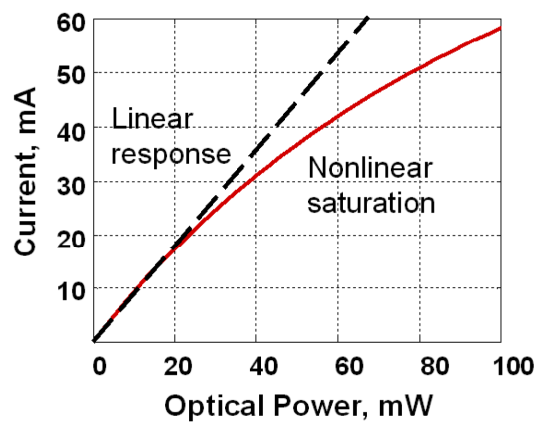
Major sources of nonlinearity

- Intensity Modulator
  - *Electro-optic modulators are very linear phase modulators*

    $\varphi_{\mathrm{opt}} \sim V_{\mathrm{RF}}$
  - *Conversion of phase modulation to intensity modulation nonlinear*

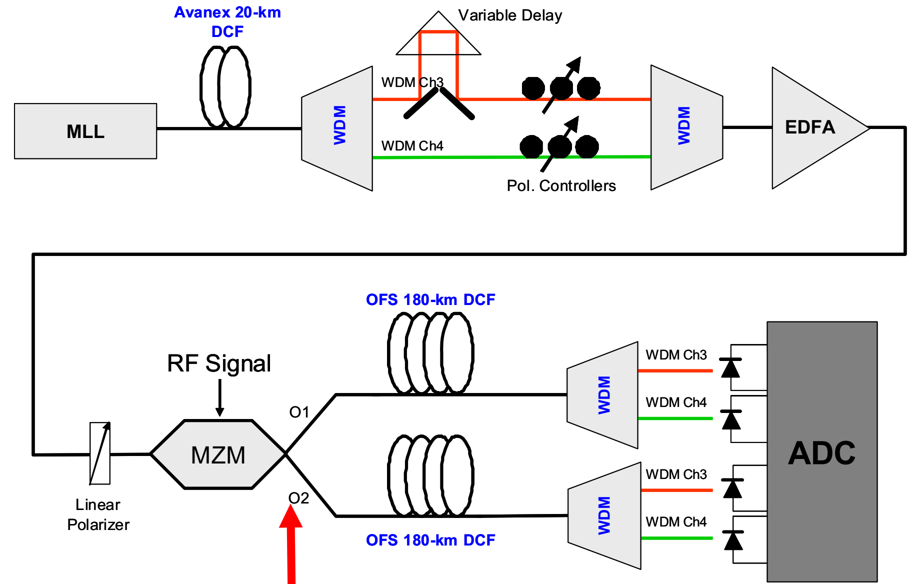
    $I_{opt} \sim \cos(\pi V_{RF}/V_{\pi})$
- Photodiode saturation

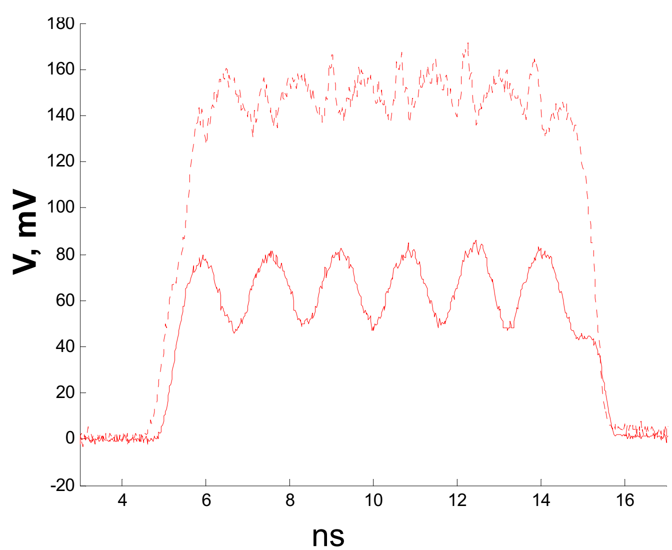


- Optical nonlinearities
  - *Kerr nonlinearity*
  - *Four-wave mixing*
  - *Stimulated Brillouin scattering*
  - *Stimulated Raman scattering*

Optical Nonlinearities in 2-channel 10 GHz system

- EDFA Power 23 dBm,
- MZM insertion loss ~4 dB,
- 3 dB split,
- ~16 dBm into 180-km DCF
- 5:1 duty cycle
- 200 mW launched power





Signal badly distorted at full power

Signal recovers with 3-dB attenuator between MZM and 180-km DCF

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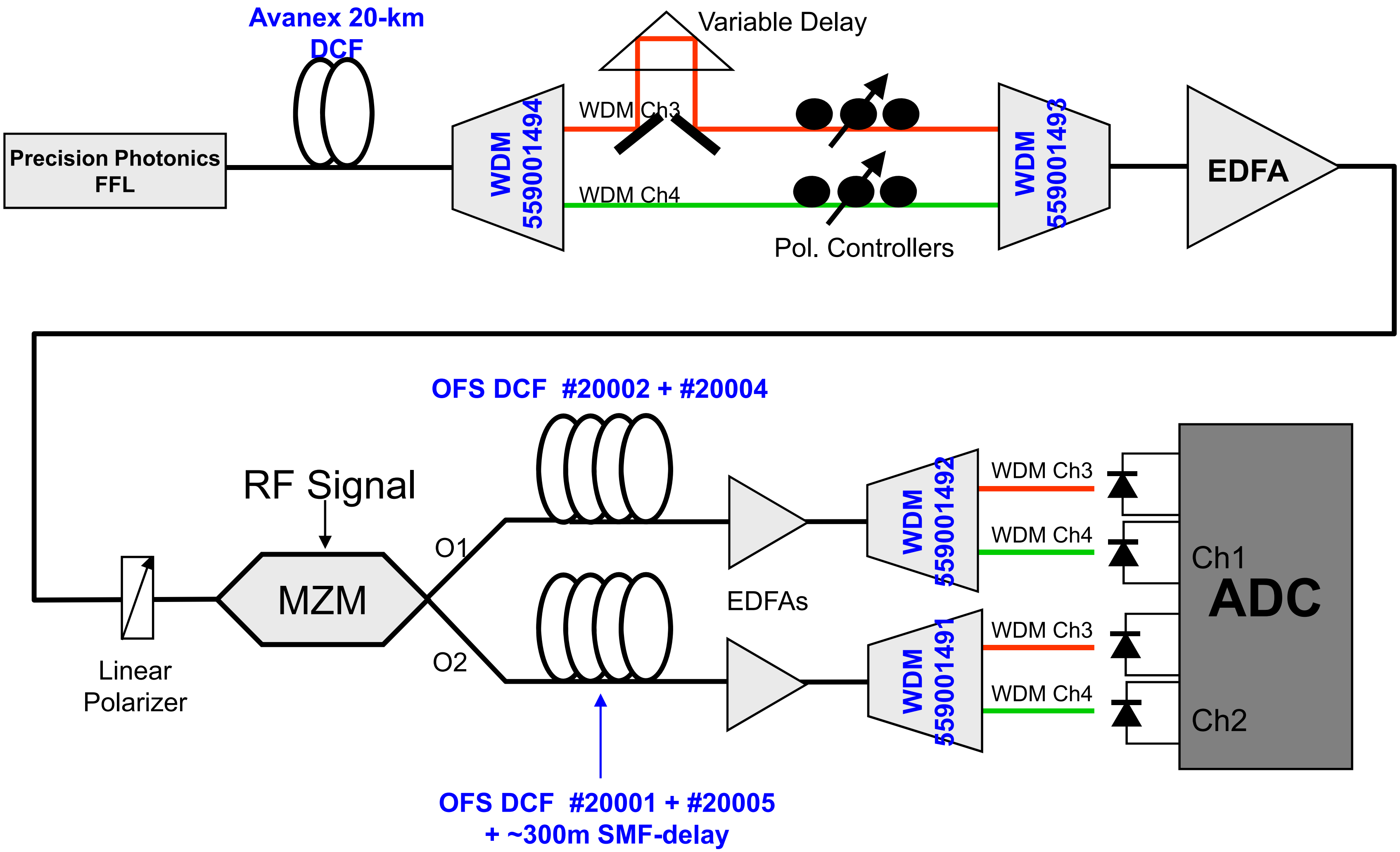
Revised 2-channel 10 GHz schematic—EDFAs after DCF



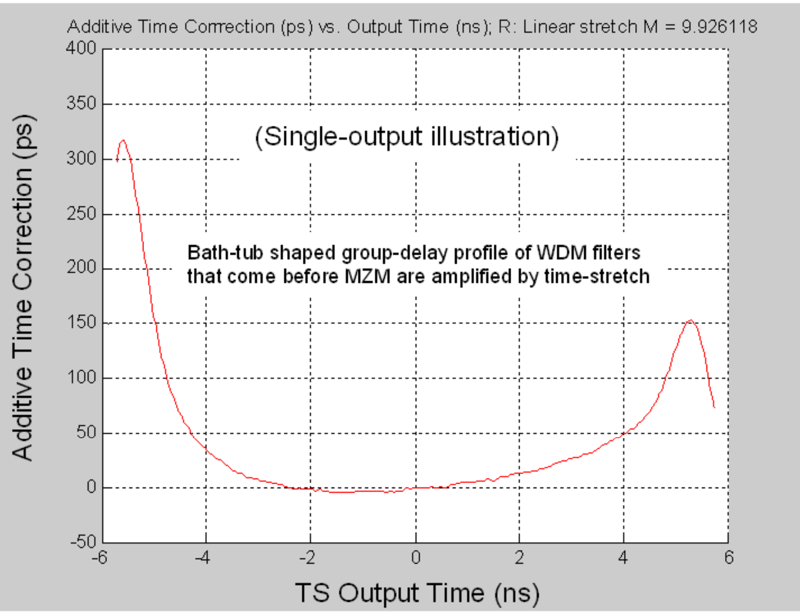
Distortion Corrections in 2-channel 10-GHz system

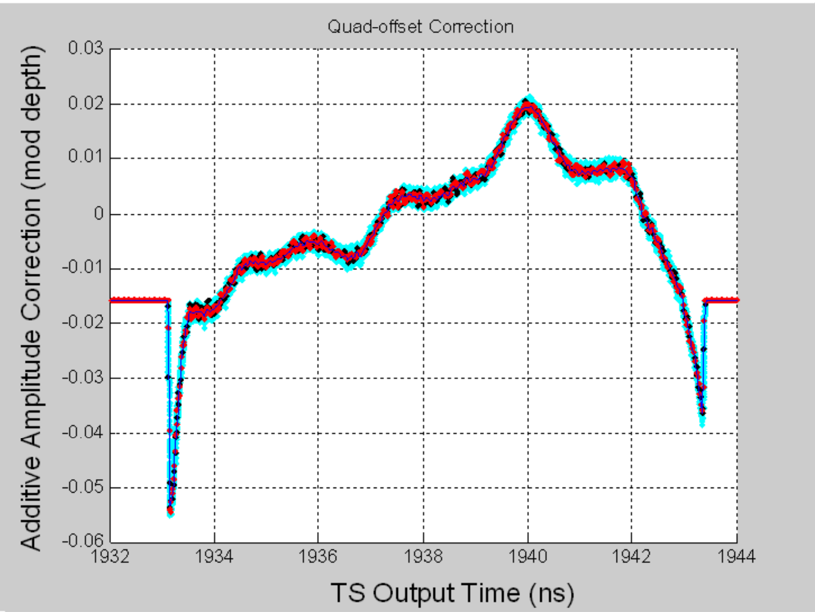
Time-mapping correction

Issue: wavelength dependence of group delay in the optical elements

MZM bias correction

Issue: wavelength dependece of modulator properties





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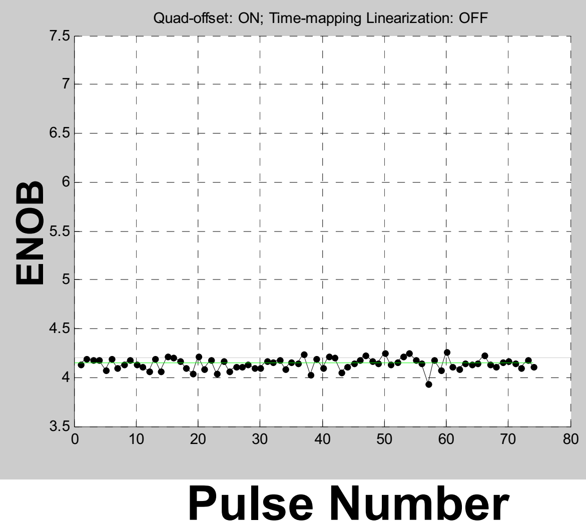
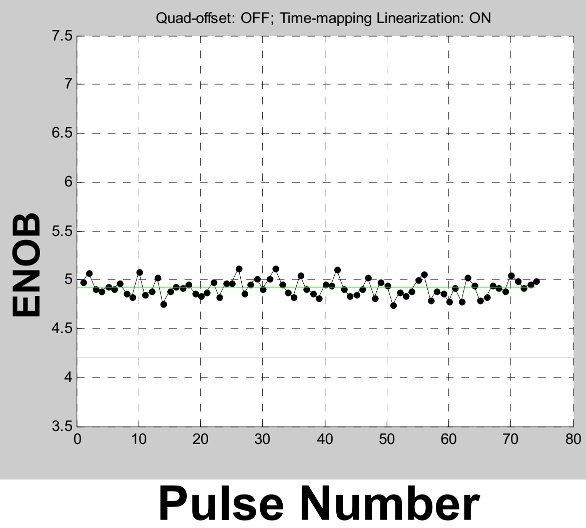
Single-Channel Performance @ 6.5 GHz

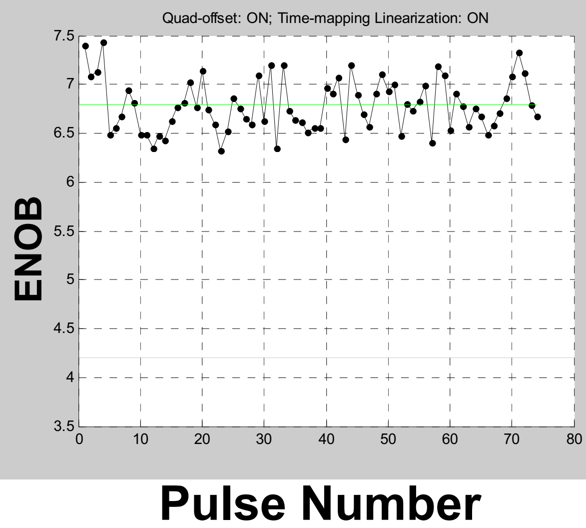
w/o MZM bias correction

w/o time mapping correction

with time mapping correction and MZM bias correction







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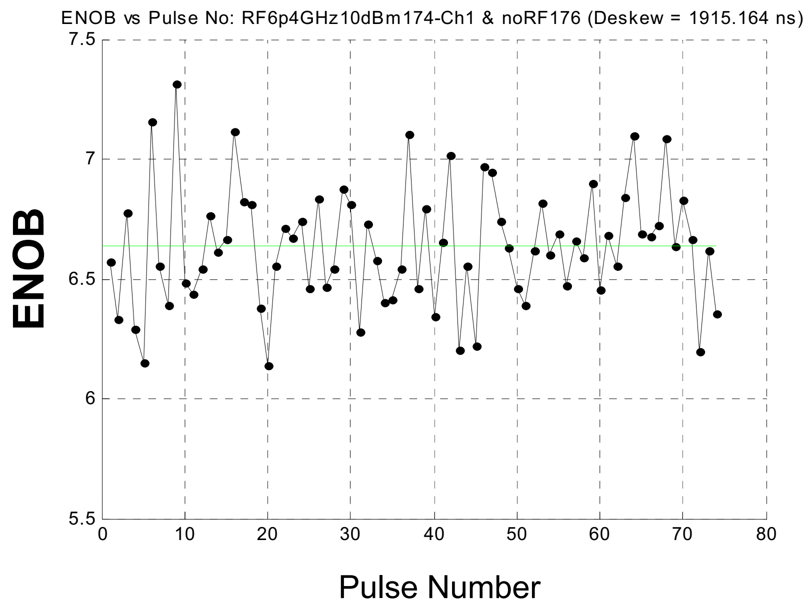
TS Output Time (ns)

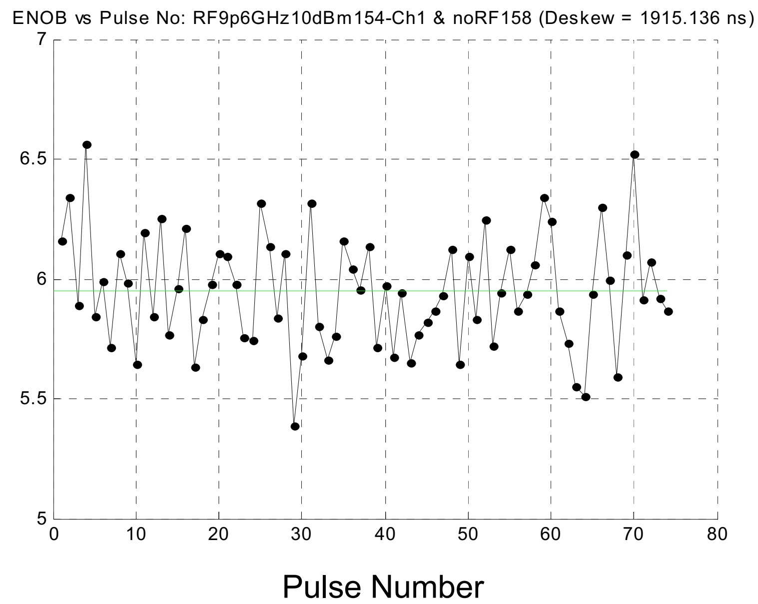
Sine-fit ENOBs

- Filter: DC to 10 GHz “Brickwall” Noise+Distortion
- 8-ns Time Window with time-mapping correction
- Stretch Ratio = 10
- ENOB drops at 10 GHz because of dispersion penalty

RF ~ 6.5 GHz



RF ~ 10 GHz



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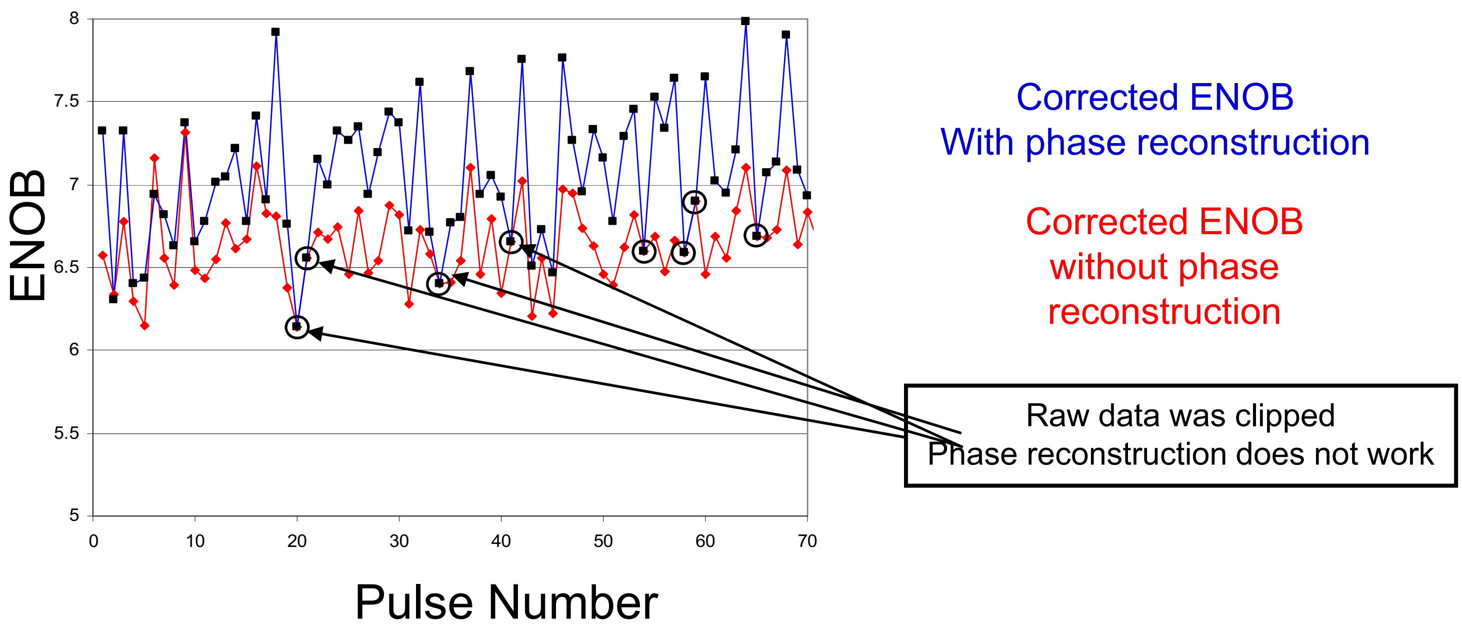
Phase Reconstruction Post-Processing used To further increase ENOB

- Technique originally developed for CFBGs (Conway et al. Opt. Lett. 2008)
- Use measured intensity and phase simulated by propagating through optical components with measured transfer functions
- Mean ENOB increased from 6.64 to 7.05 for 6.5 GHz data



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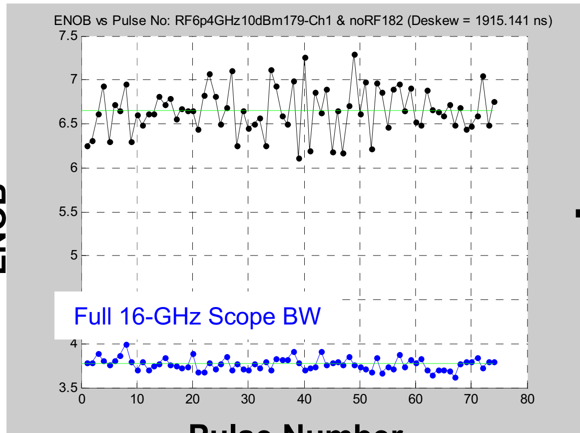
Stitching 6.5-GHz signals from 2 channels in 2-channel 10-GHz System

Ch1 Ch2 Ch1+Ch2

ENOB



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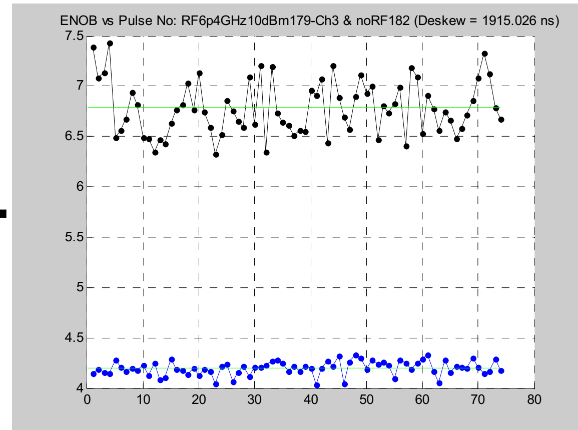

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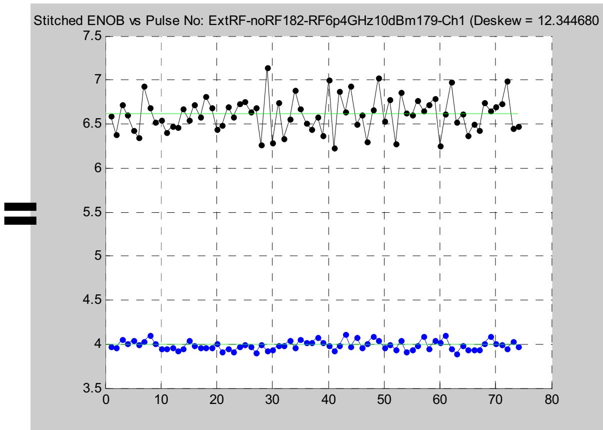
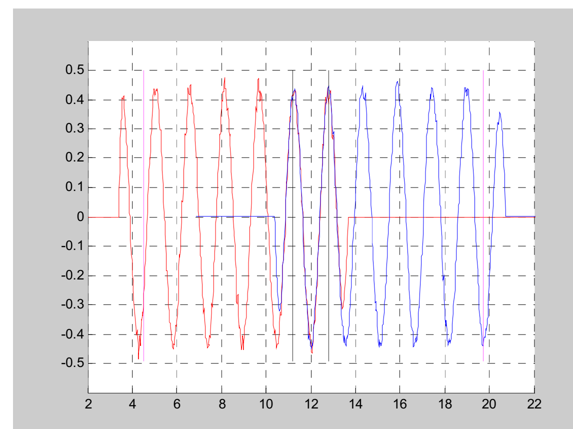


Pulse Number

Stitching algorithm

- Perform all single-channel calibrations/processing
- Equalize the modulation index in 2 channels
- Correlate channels within 1.6-ns overlap region
- Align 2 channels in time based on max correlation
- Average 2 channels in overlap region
- Calculate sine-fit ENOB for full 2-channel run



Stitched waveforms show several pulses ~7 ENOB

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AEROSPACE

Issues in the 7 ENOB 10 GHz experiments

- Backend digitizer single channel limited to $ENOB_{max}$ ~ 7. @ 1GHz
- Time domain vs Frequency domain ENOBs
  - *Ringing at pulse edges for brick wall TD filter*
  - *Different noise bandwidths*
  - *Different treatment of distortions*
- All commercial components
  - *Relatively inexpensive fs source—phase aberrations really unknown*
  - *WDMs have dispersion that looks minimal but effects are enhanced by stretching process*
- Effect of optical nonlinearities greater than anticipated
- Large pulse-to-pulse variations in ENOB
  - *Laser noise and non-idealities: phase, amplitude, wavelength vs time, random chirp*
  - *Oscilloscope noise*
  - *RF/laser timing variations*

Continuous-Time Operation

Operating the time-stretch ADC in continuous time requires:

1) stretching the pulses input to the modulator to the interpulse time
2) demultiplexing the signal to M or more photodiodes and ADCs

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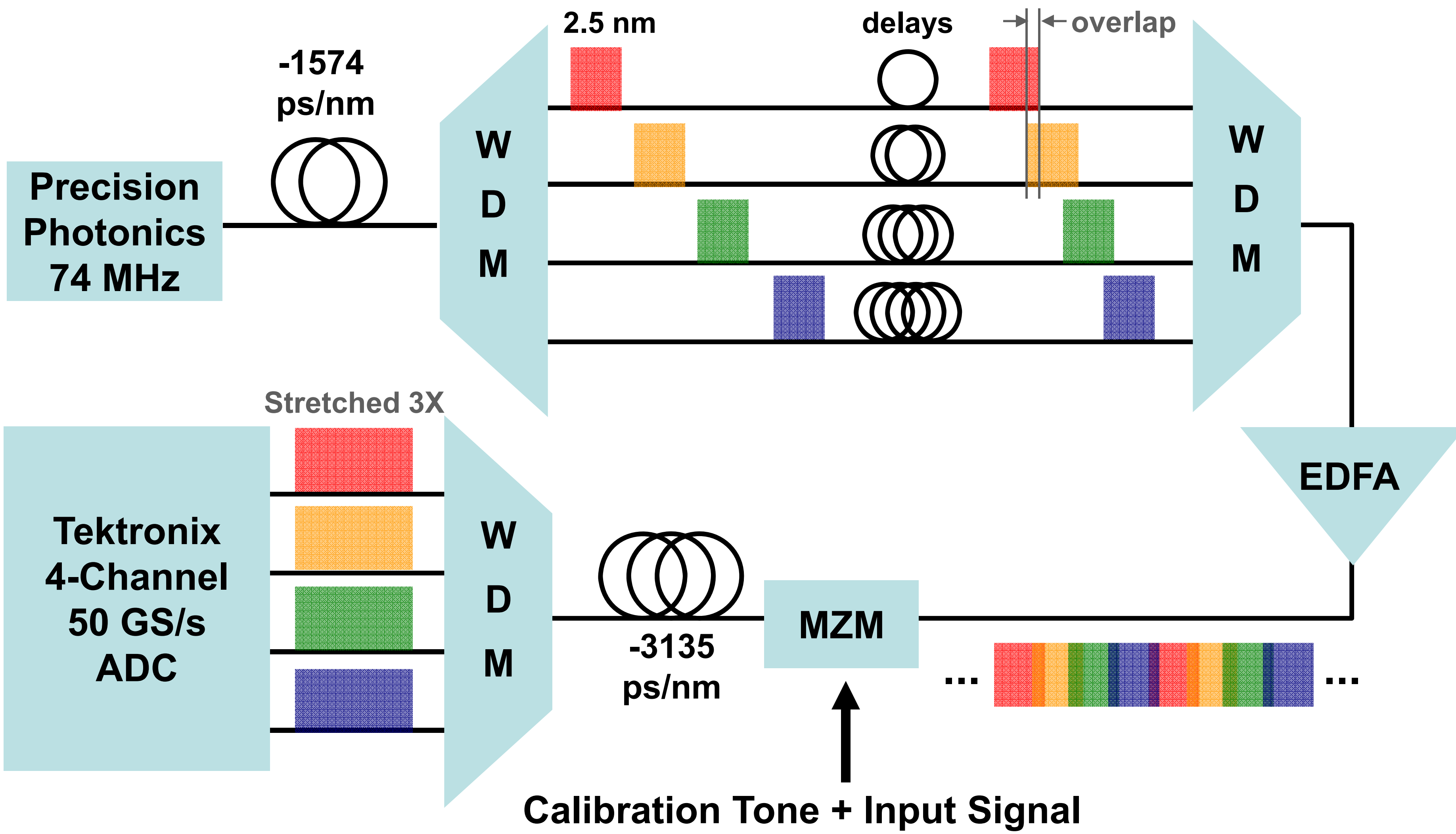
Experimental Configuration 150 GS/s continuous time ADC



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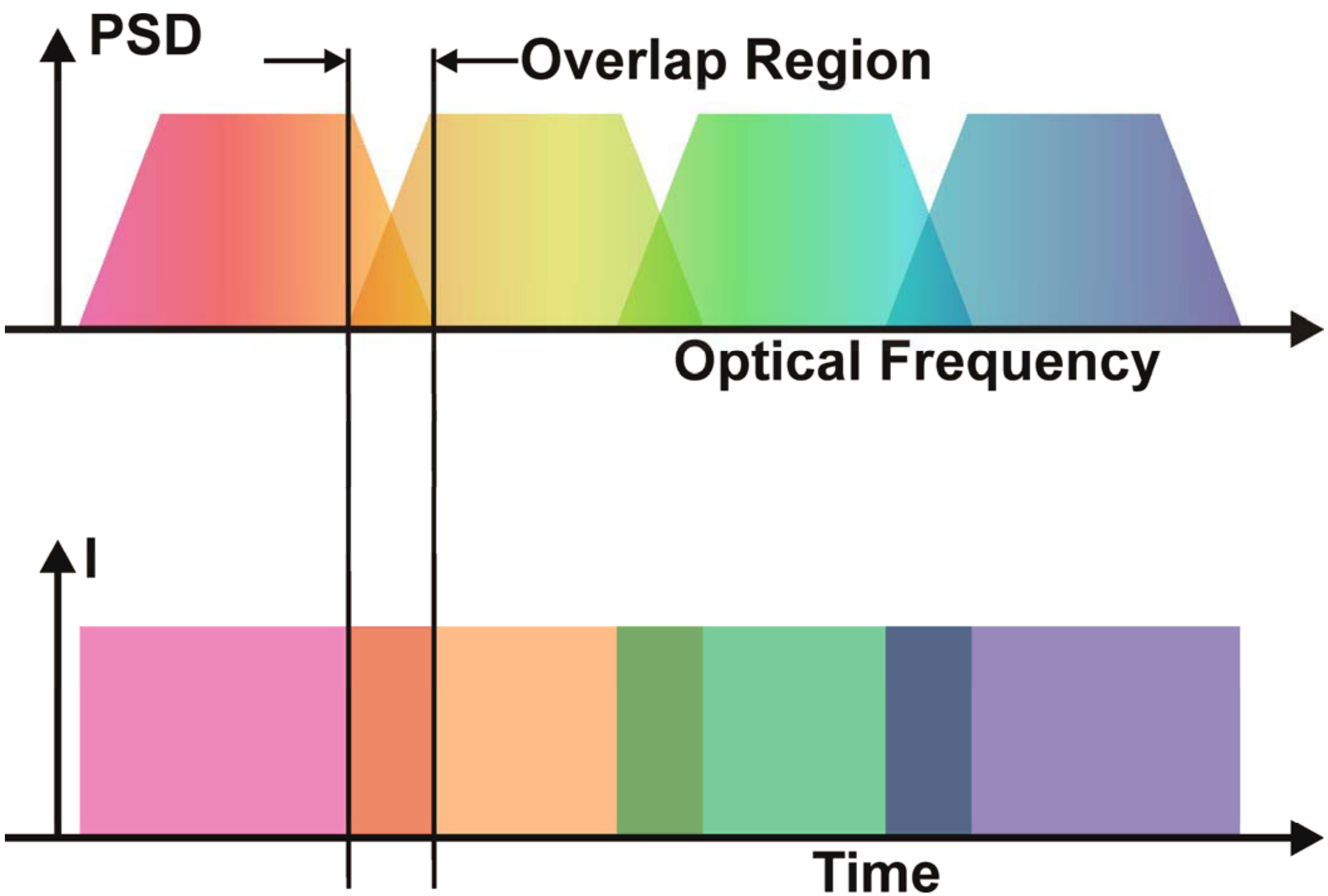
Overlap options



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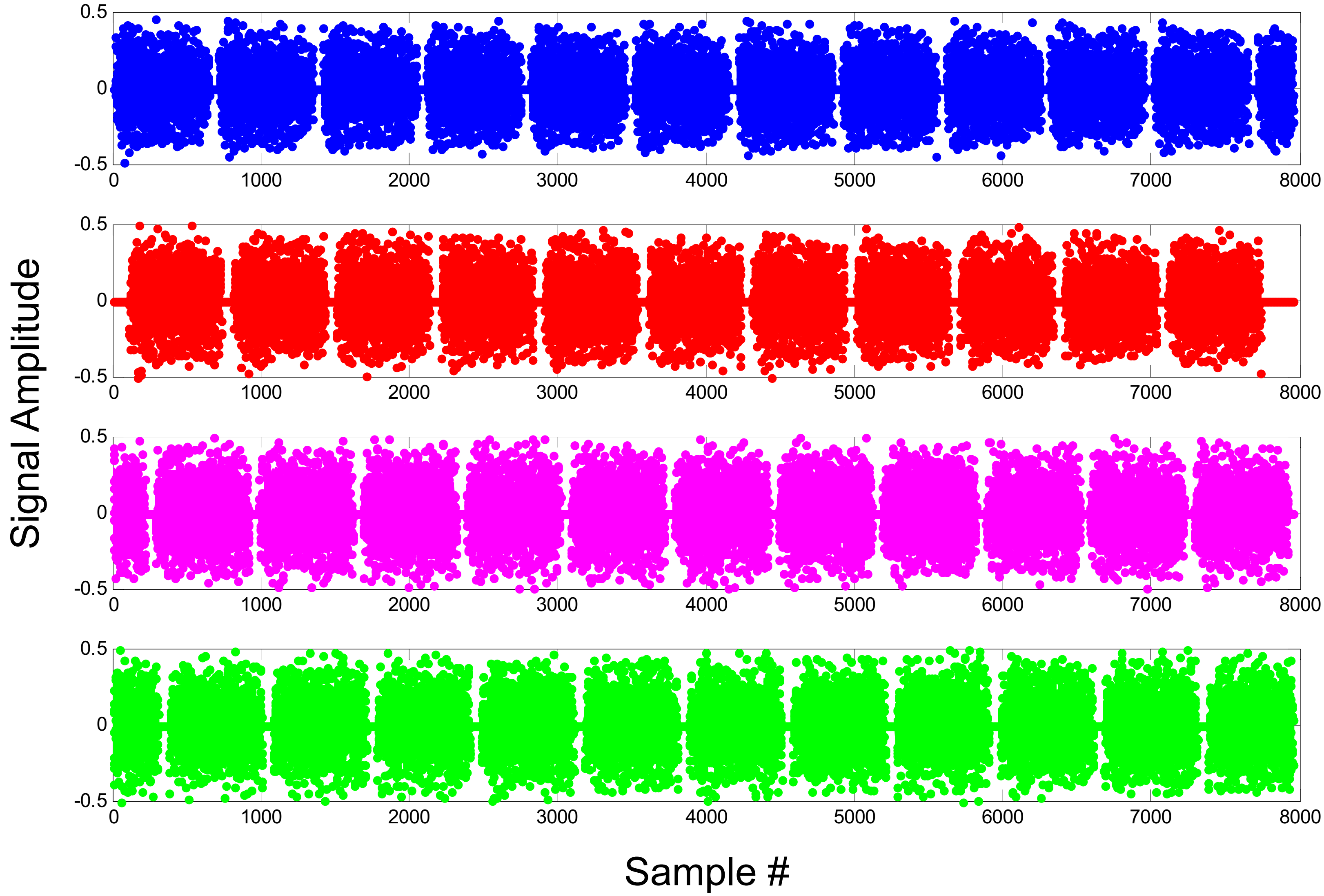
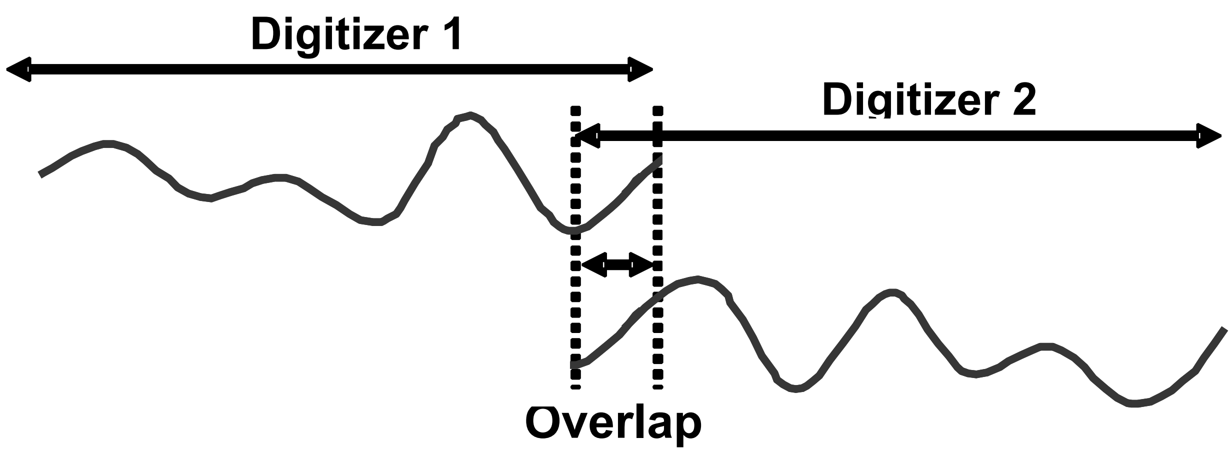
4 Channels at 150 GS/s

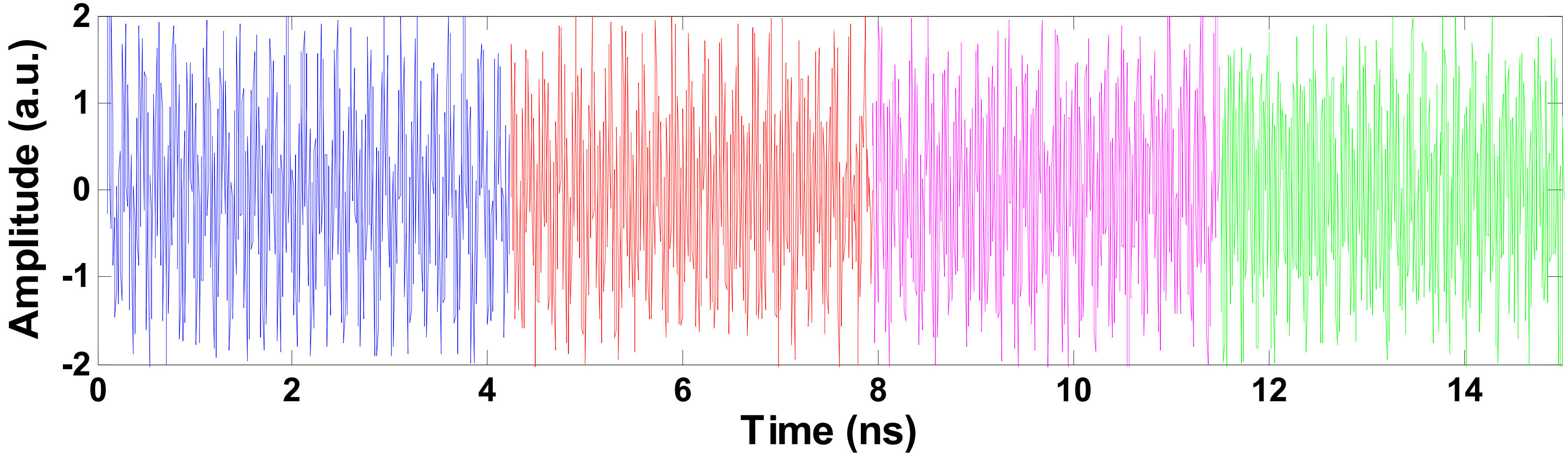


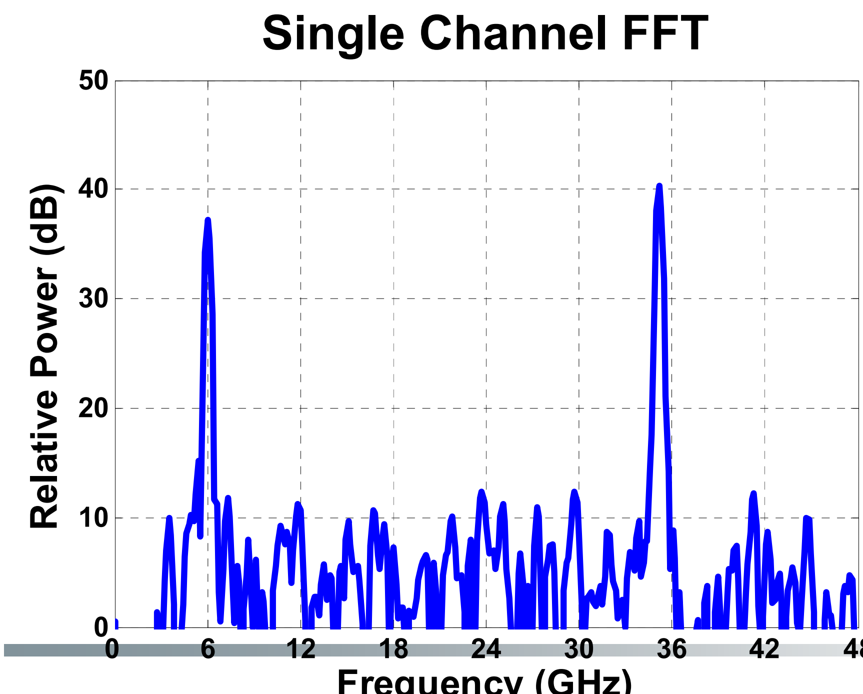
Segment-to-Segment Stitching

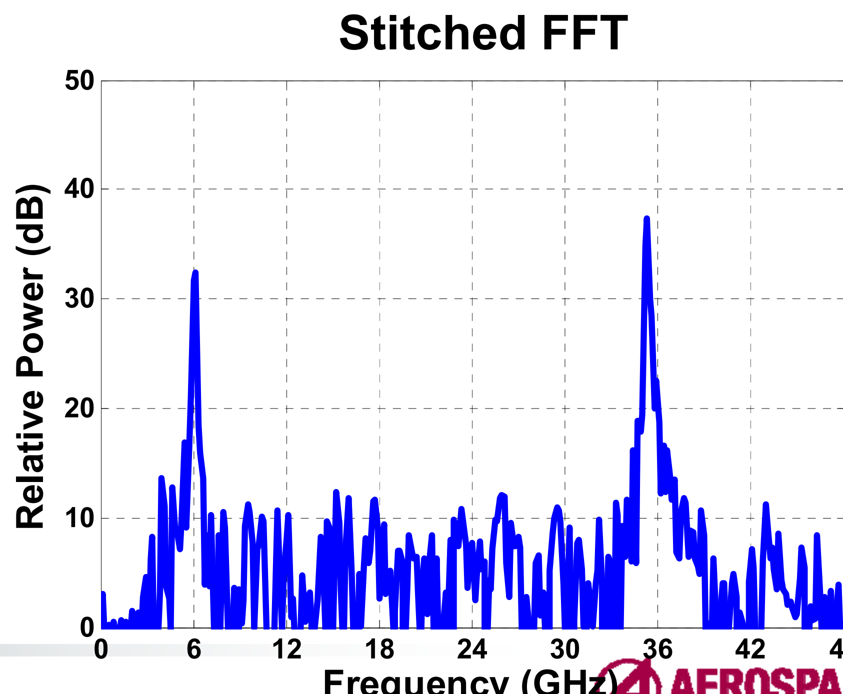
- Segments from all 4-channels are concatenated to form the continuous signal
- Out-of-band real-time calibration tone used to independently correct for gain and timing errors



4 Channel Stitching







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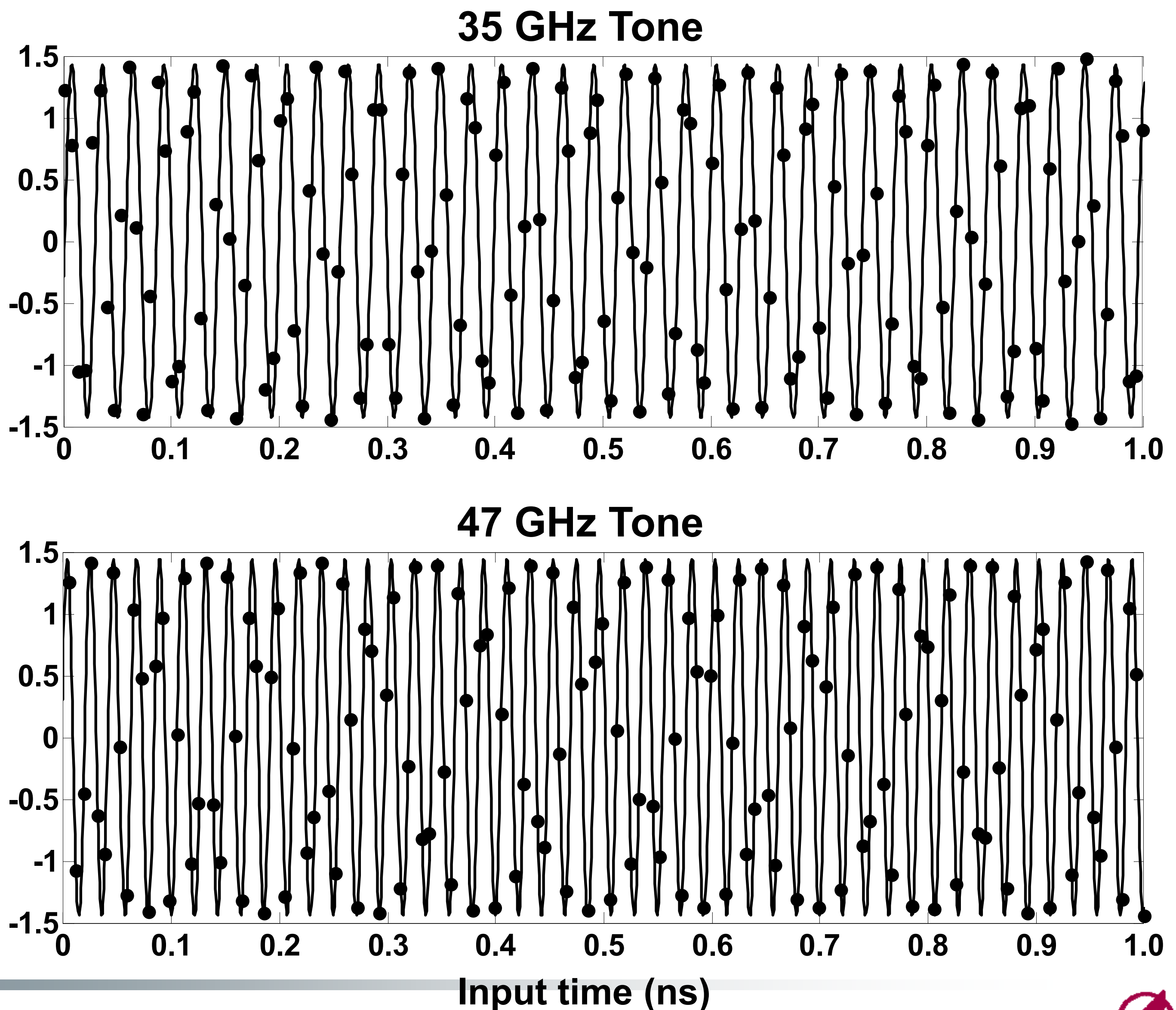
Reconstructed Signals at 150 GS/s



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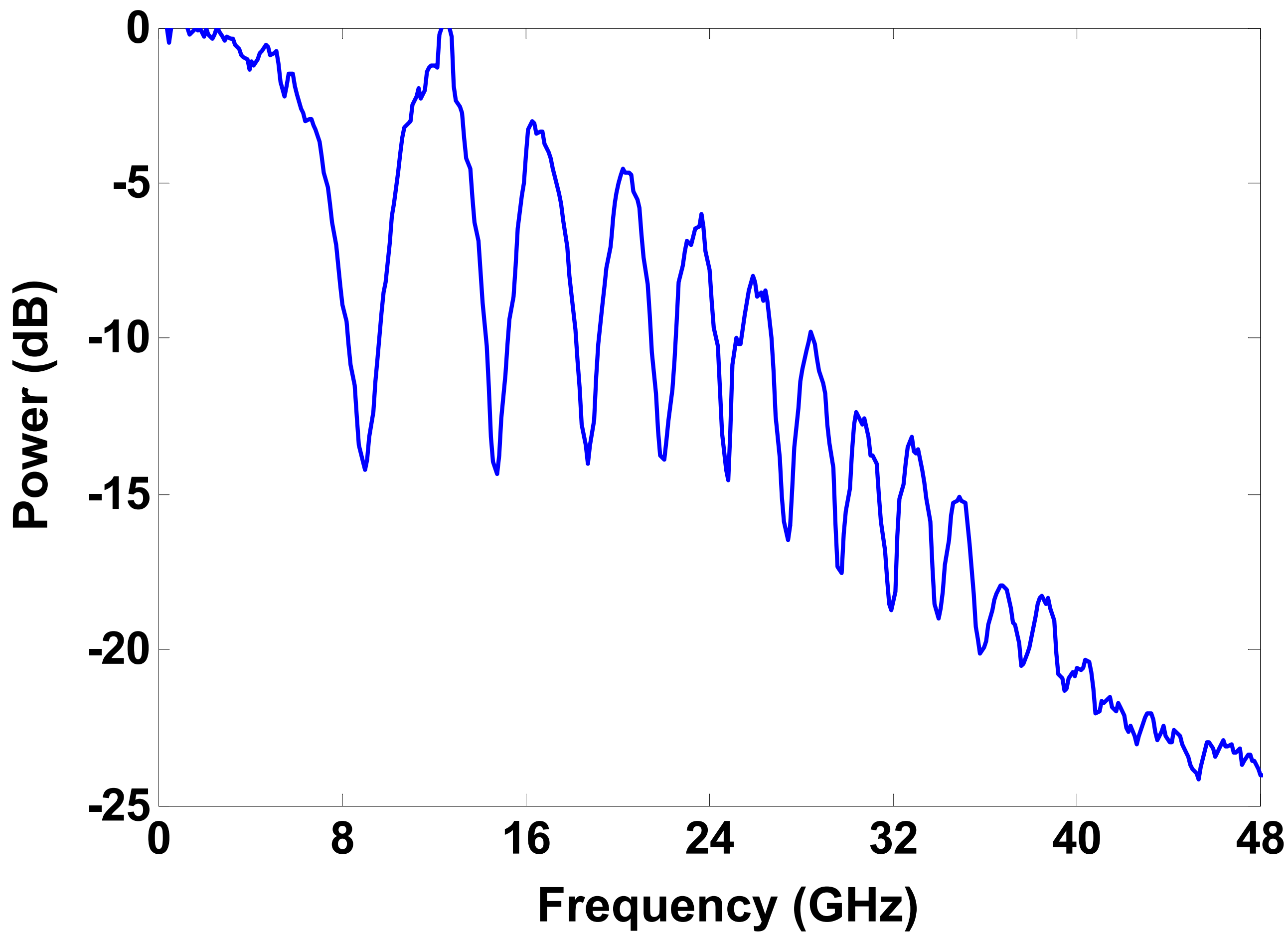
Dispersion Penalty and Roll-off in 150 GS/s system



Dispersion penalty is a big issue for ultra broadband time-stretch ADC

Best solution is single-sideband operation

Summary

- Each new bit of ADC resolution requires an increase in signal-to-noise-and-distortion ratio (SNDR) of 6 dB
- ENOB without noise bandwidth is meaningless
- Decreasing the noise bandwidth by a factor of 4 increases ADC resolution by 1 ENOB
  - *e.g. the Tektronix 50 GS/s digital oscilloscope has*
    - 5 ENOB over 16 GHz
    - 7 ENOB over 1 GHz
- Every time you sneeze, you lose a few 1/10's of an ENOB
- Optical photons are very energetic compared to RF photons
  - *Shot noise is irrelevant for electronic ADCs*
  - *Shot noise is a fundamental limit in photonic ADCs*
- Photonic ADCs usually contain a microwave photonic link
  - *Standard analysis gives the SNR/CNR*
  - *Max ENOB over a given noise bandwidth readily estimated*
- If commercialized, photonic ADCs will resemble data conversion modules and digital oscilloscopes rather than single chip ADCs

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