Time-stretch Analog-to-Digital Conversion

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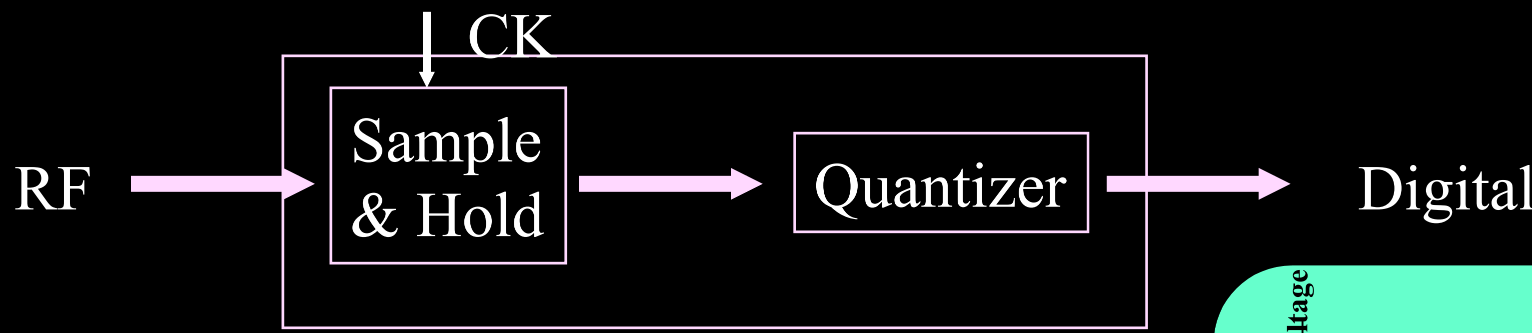
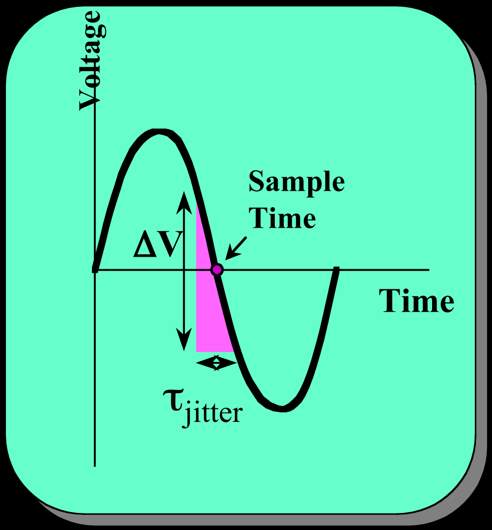
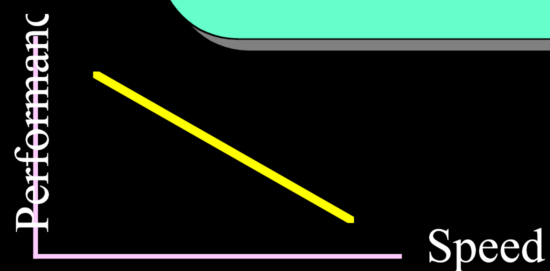
What Limits the Performance of Electronic Digitizers?





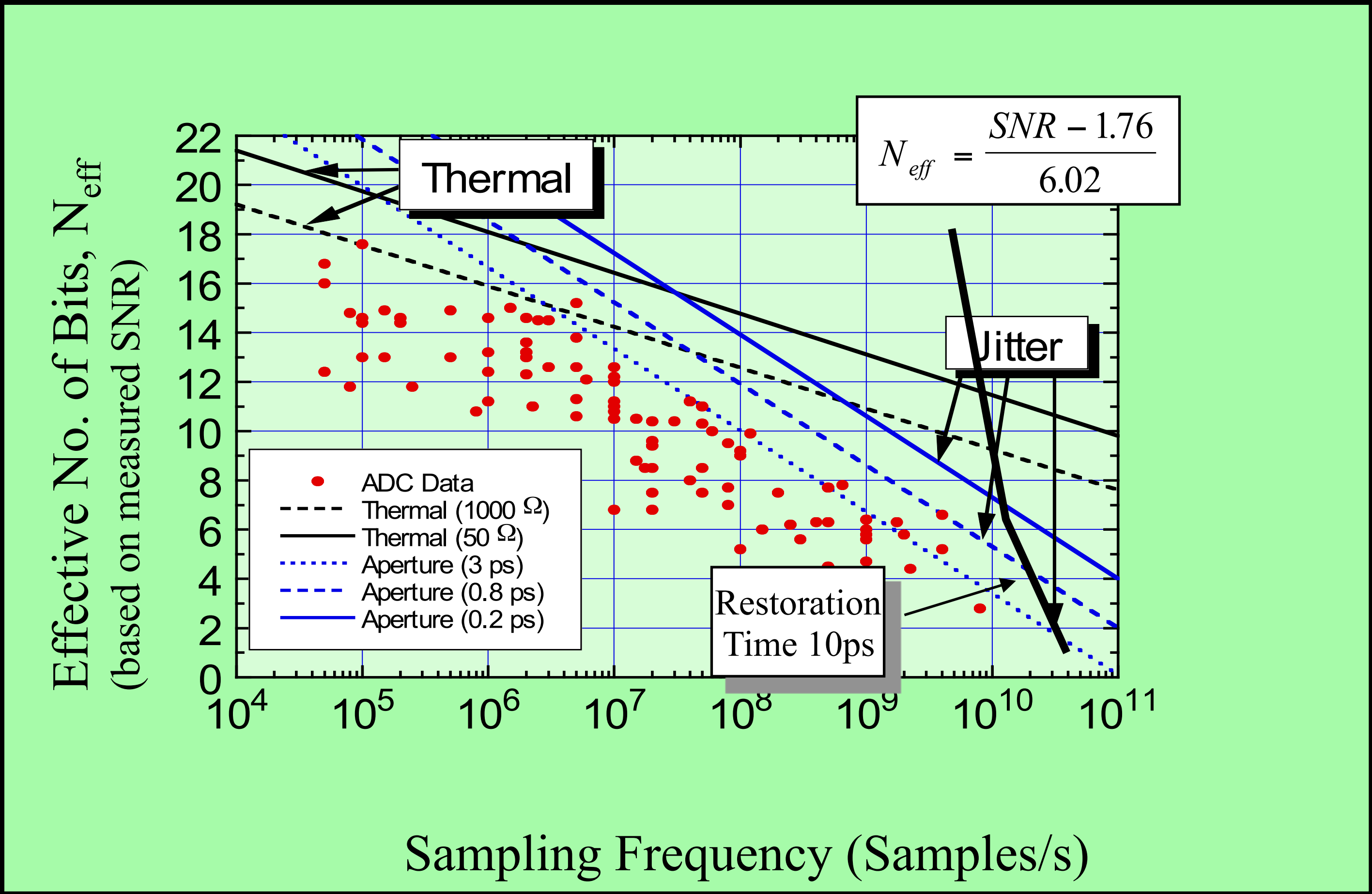
- Switching speed of a quantizer
- Settling time of the sample-and-hold
- Jitter in sampling clock
- Mismatch among transistors, capacitors, etc.
- Circuit heating
- Other …

Problem scales with speed

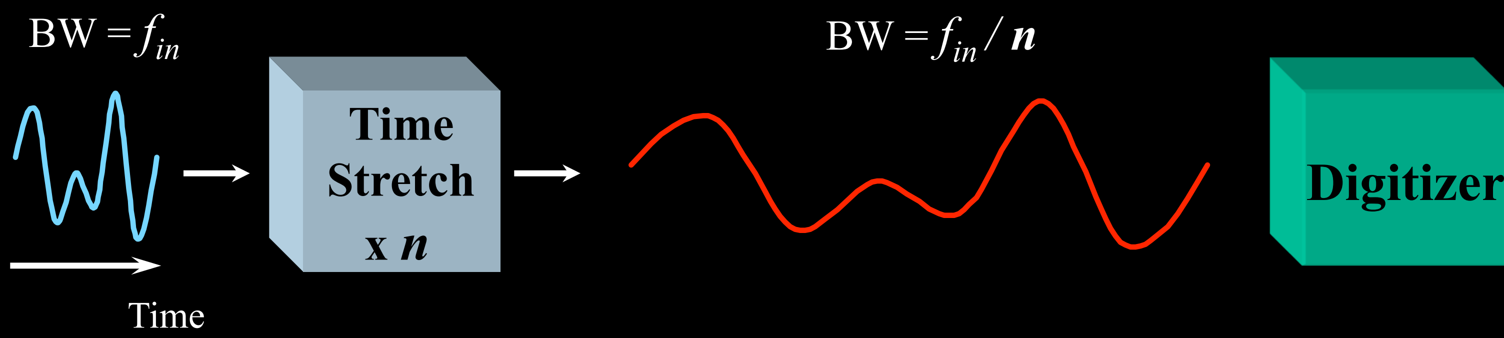


ADC Performance Trends

Walden Curves



Time-Stretch A/D Conversion
Transient input



<u>Benefits:</u>

• Sampling rate & Input bandwidth

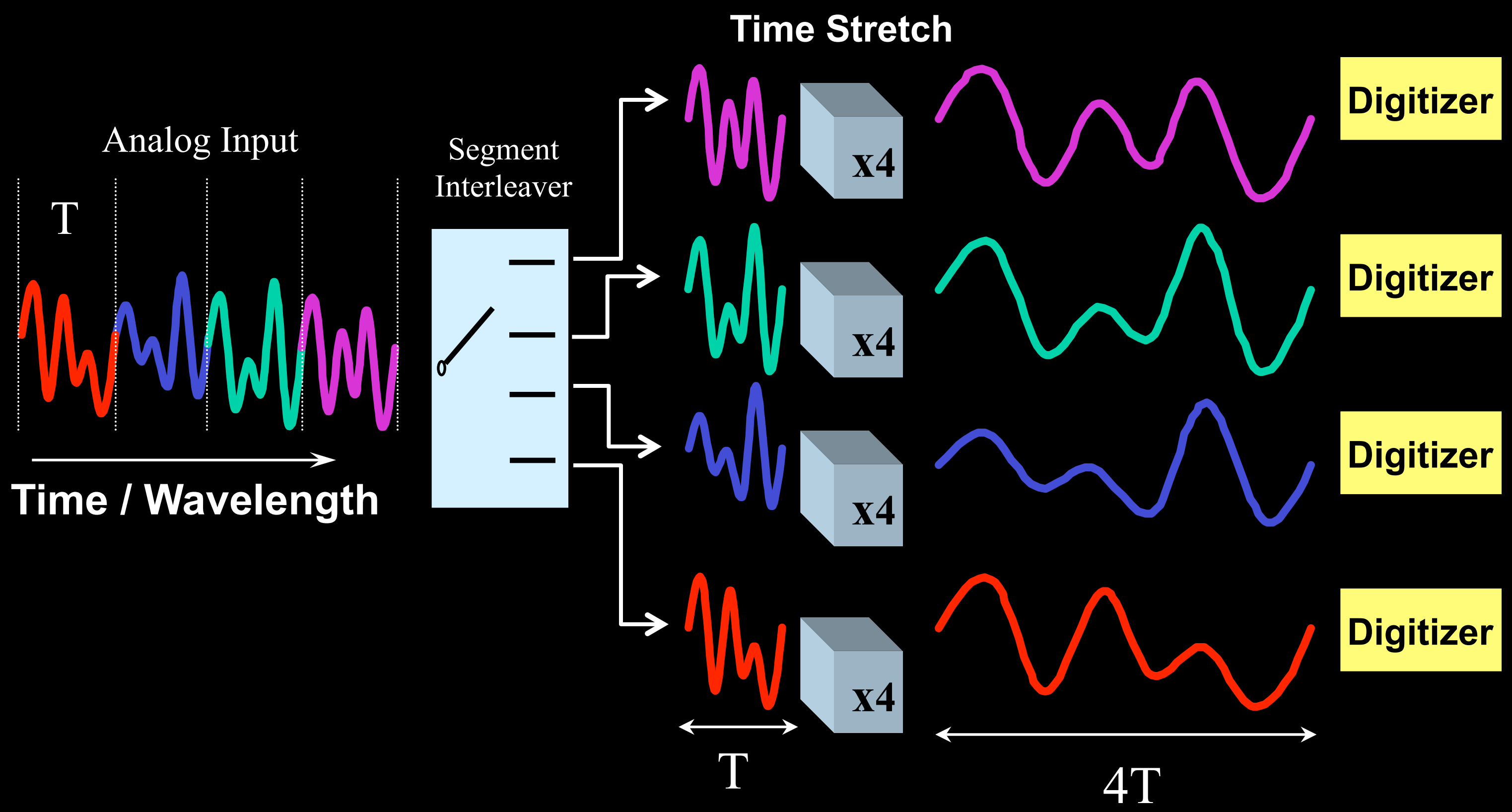
•No need to interleaving

• Reduces jitter noise

•No need for fast sample-and-hold

F. Coppinger, A. Bhushan, B. Jalali, *Electronics Letters*, 34 (4), 1998.
B. Jalali, F. Coppinger, US Patent # 6,288,659, 2001.

Continuous Input



F. Coppinger, A. Bhushan, B. Jalali, *Electronics Letters*, 34 (4), 1998.
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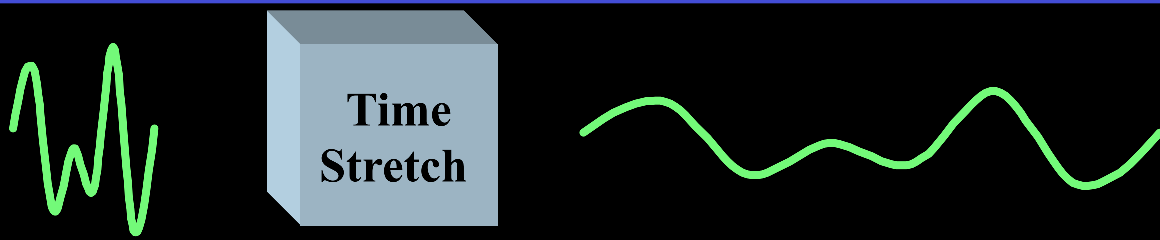
Influence of Time Stretch on Thermal and Shot Noise



For a stretch factor of m:

Optical power reduced by m
=> RF current reduced by m
=> RF power reduced by m^2

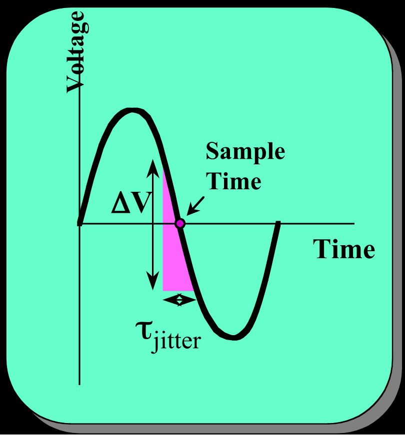
Thermal noise: $\langle i^2 \rangle = 4kT/R^2C$
=> reduced by m^2

Shot noise: $\langle i^2 \rangle = 2qIB$
=> reduced by m^2

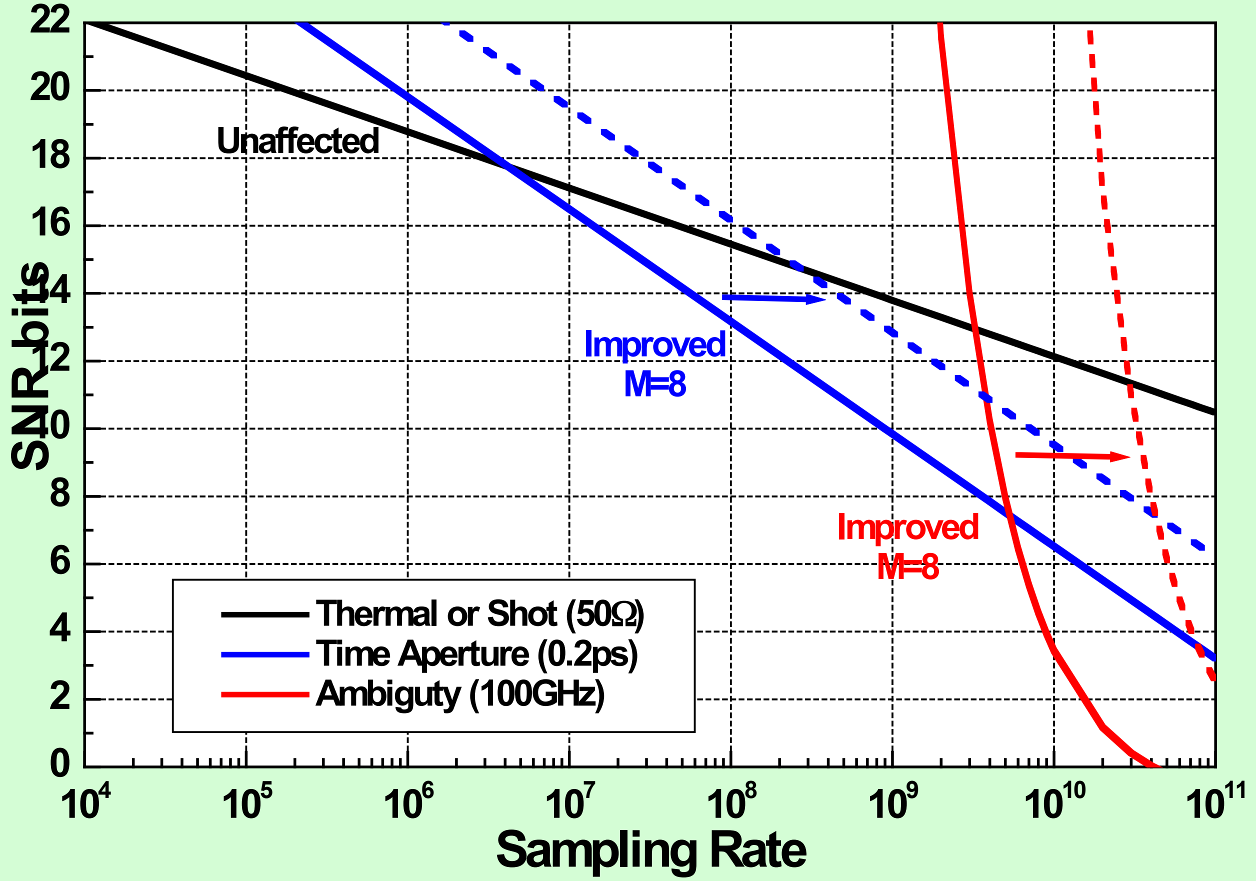
No change in thermal and shot noise SNR

Impact on Noise

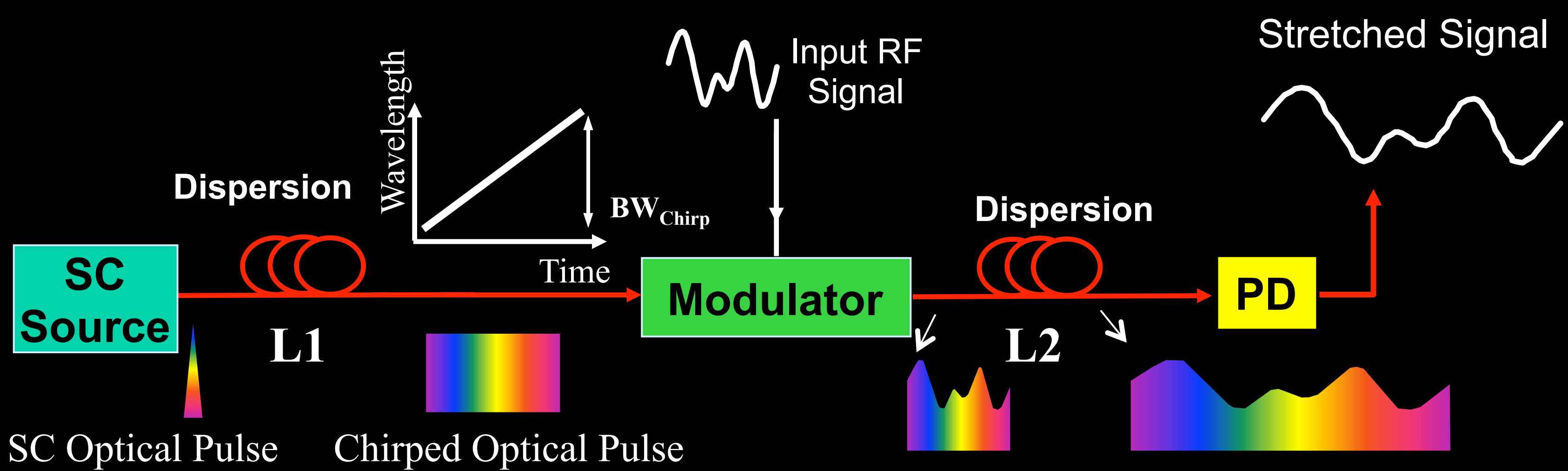
- Thermal noise: no change
- Shot noise: no change
- Digitizer Jitter Noise: reduced
- Quantizer restoration time limit: improved



TSADC Performance



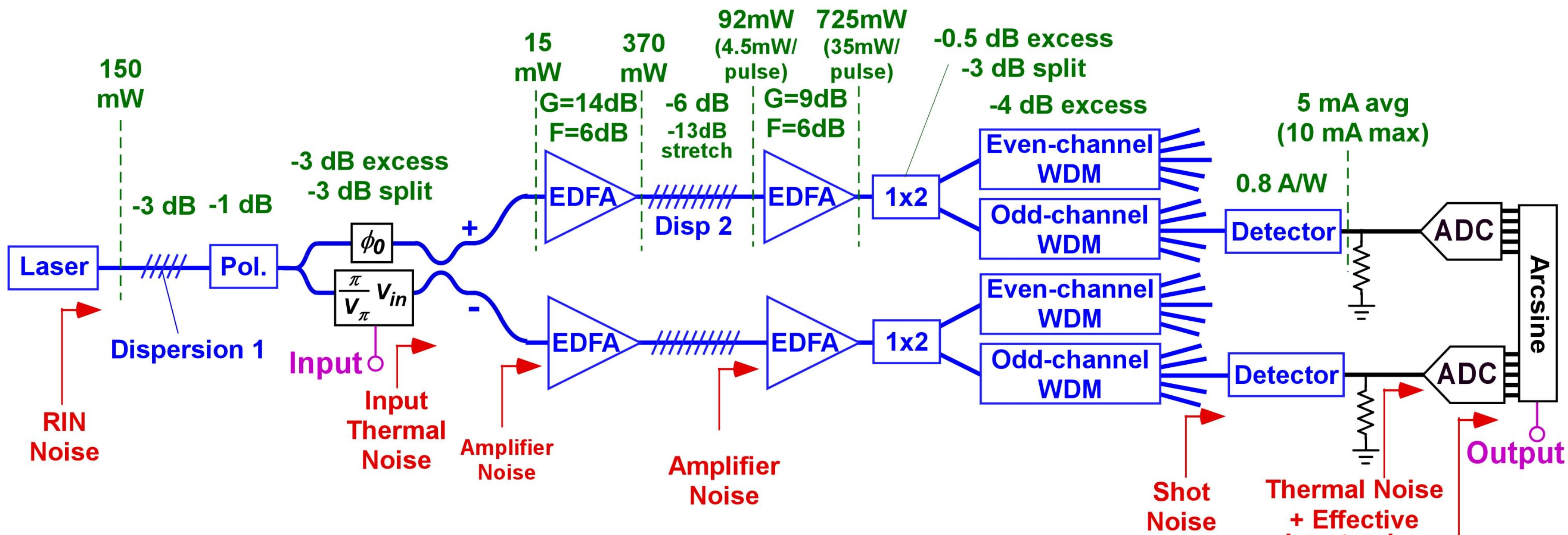
Fundamental Physics of Time Stretch



Optical Bandwidth	⟵ Uncertainty Principle ⟶	Time Ambiguity
V		Λ
V		Λ
Electrical Bandwidth	⟵ Nyquist Theorem ⟶	Sampling Interval

Stretch Factor: M = 1 + L2 / L1
Loss in Dispersive Element Limits Maximum Stretch Factor

What Resolution Can be Achieved?



Basic Parameters

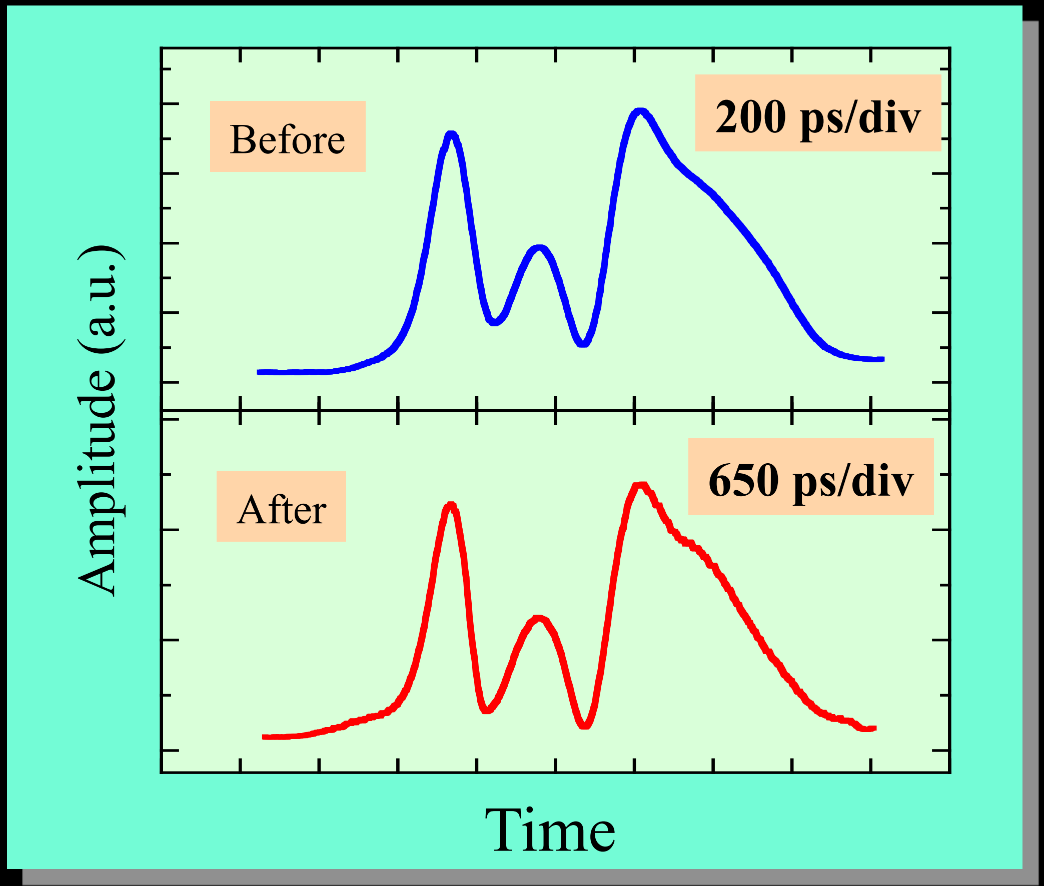
Laser RIN = -150 dB/Hz
Pulse overlap in modulator = 5%
Modulation depth = 0.9
Stretch Factor = 20
Detector load = 50 Ω
Effective input noise = 6 dB above thermal
Full-scale : max signal voltage = 1.1:1
ADC ENOB = 10.0 bits
Channel noise bandwidth = 500 MHz
Input sampling rate = 20 GS/s
ADC sampling rate = 1 GS/s
Output SNR = 62 dB

Performance depends on:

- Laser power and relative intensity noise
- Dispersive element loss
- Optical amplifier noise figure
- Photodiode saturation

Upper limit is about 10 ENOB for 10 GHz BW

Experimental Results

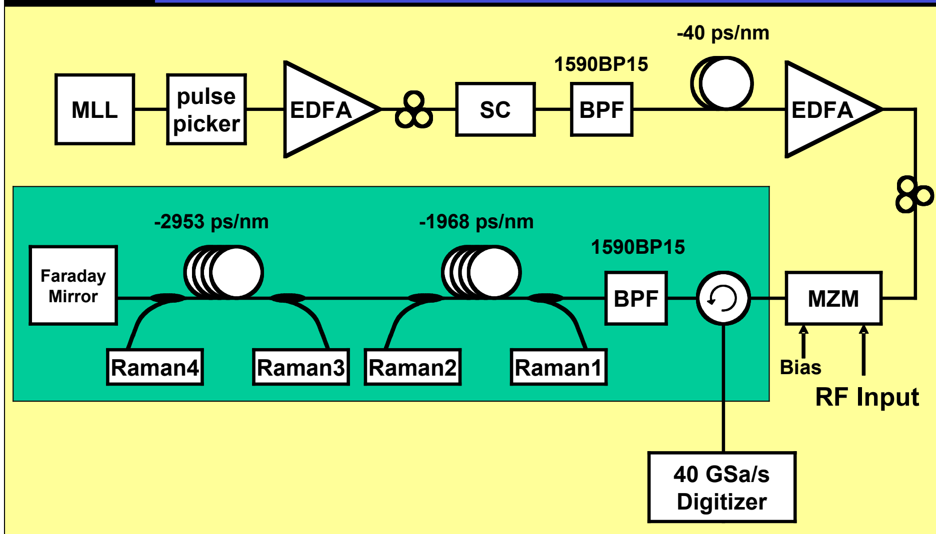


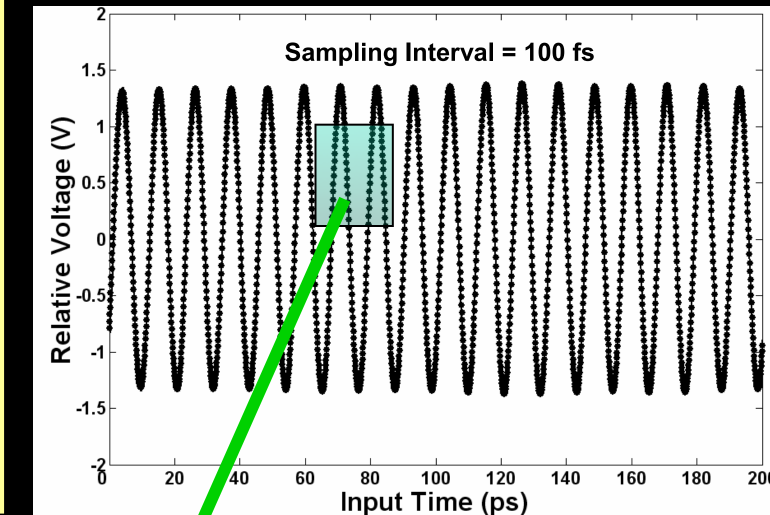
L_1=2km
L_2=5.5km

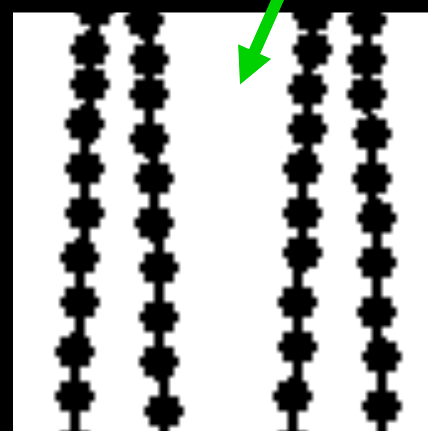
Stretch Factor: 3.25

F. Coppinger, A. Bhushan, B. Jalali, *Electronics Letters*, 34 (4), 1998.

10 Tera-sample/s Real-time Transient Digitizer



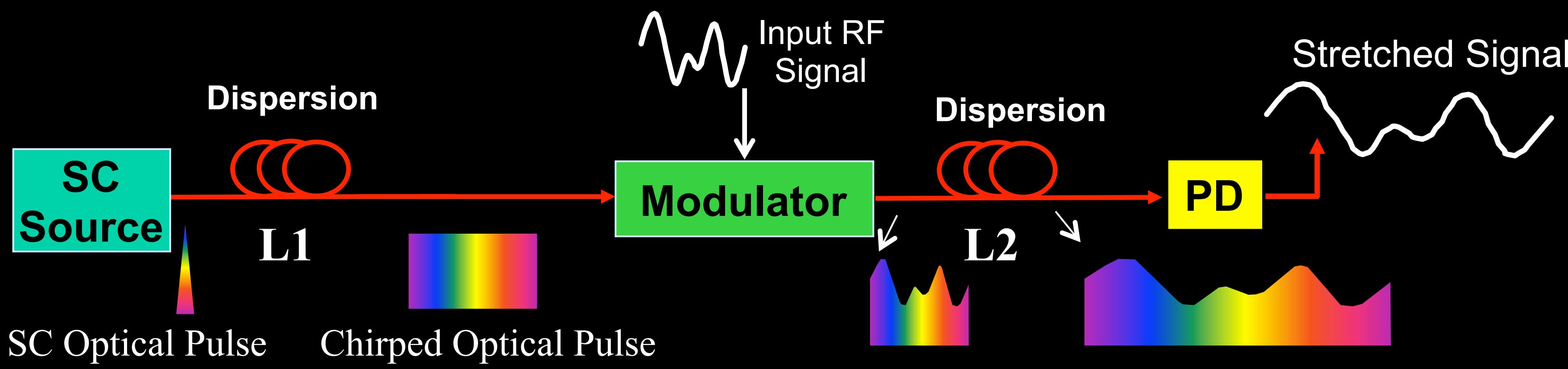




- Stretch factor = 250
- Real-time digitization of 95 GHz millimeter wave
- A/D conversion at 100 fs intervals

- J. Chou, et al "Femtosecond real-time single-shot digitizer," Applied Physics Letters, October 2007

Challenges

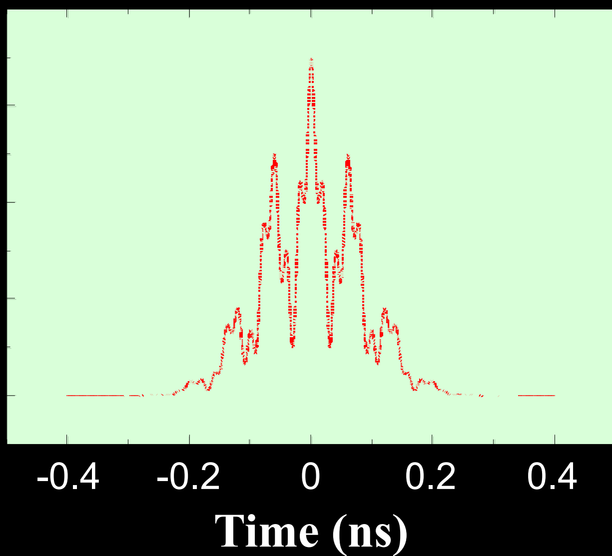


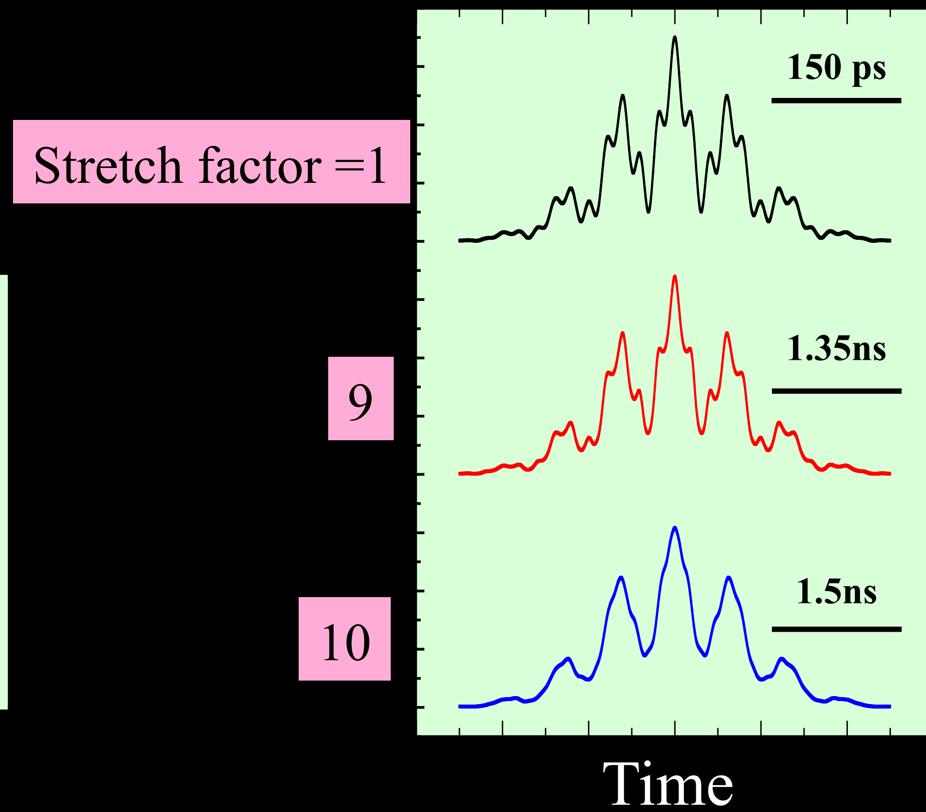
- RF Bandwidth: dispersion penalty
- Distortion: non-uniform optical spectrum, modulator nonlinearity
- Noise: shot noise, optical amplifier noise, laser RIN
- Segment stitching

Dispersion Induced Bandwidth Limits

Input Signal

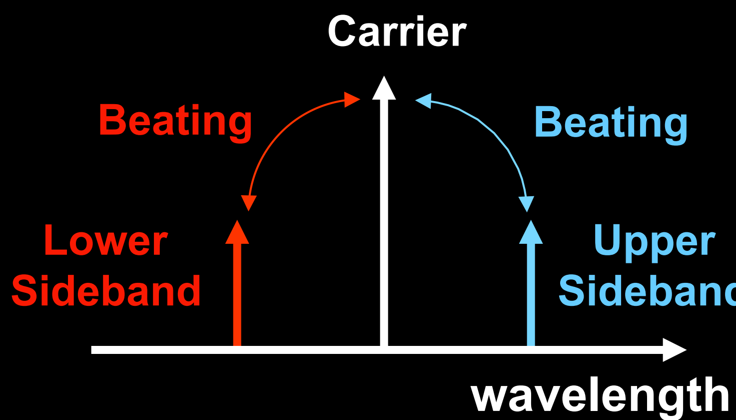
f_1=15GHz
f_2=60GHz

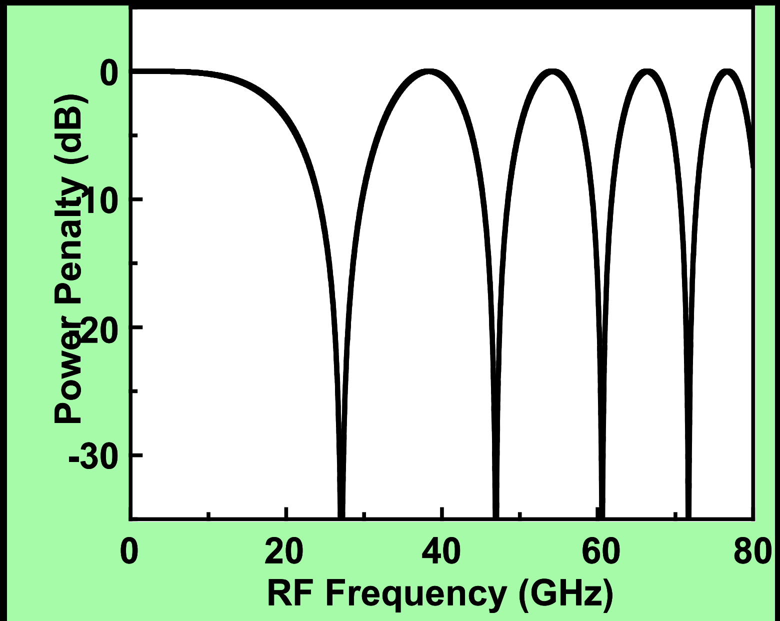




High modulation frequencies are attenuated

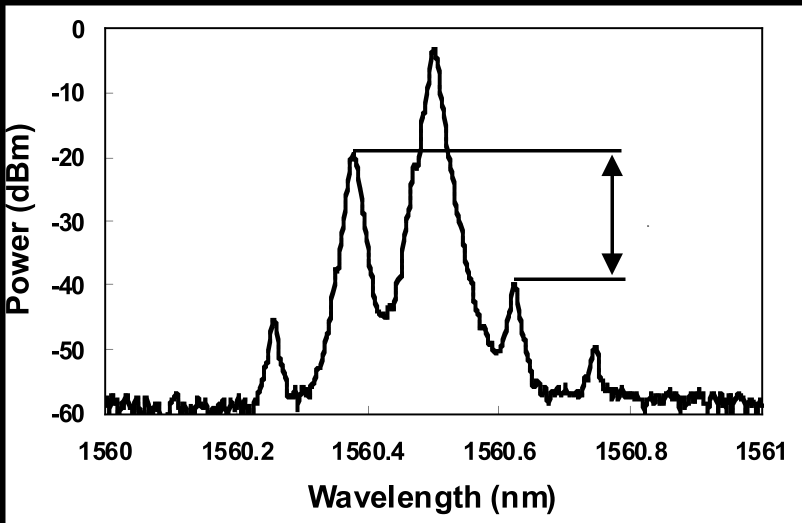
Dispersion Induced Bandwidth Limits

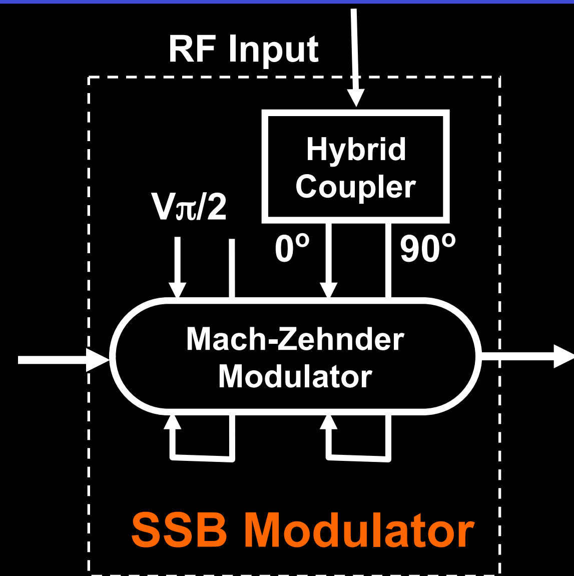


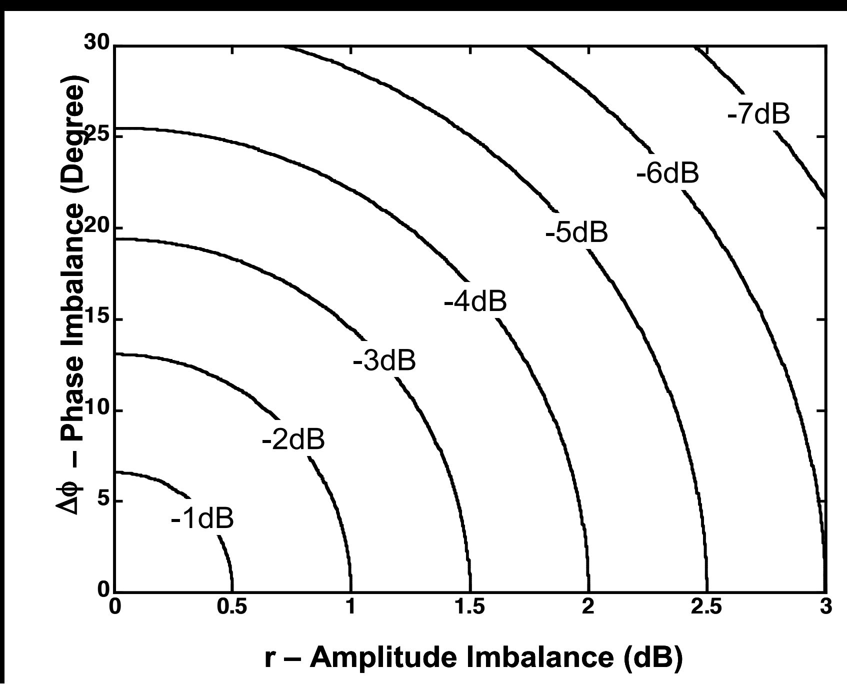


Frequency fading is created by the interference between the beating of the carrier with the upper- and lower-sidebands

Single Side Band (SSB) Modulation



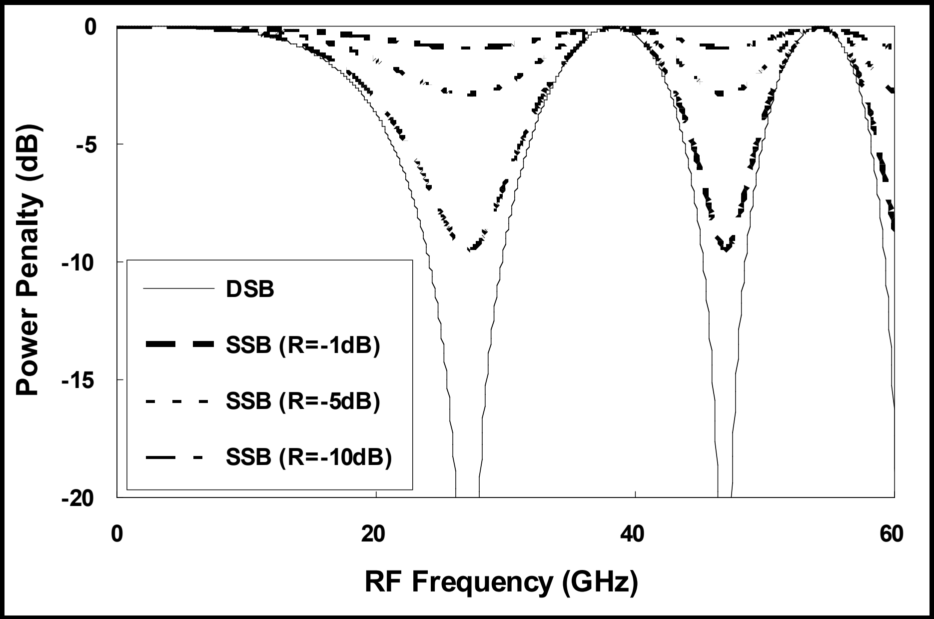




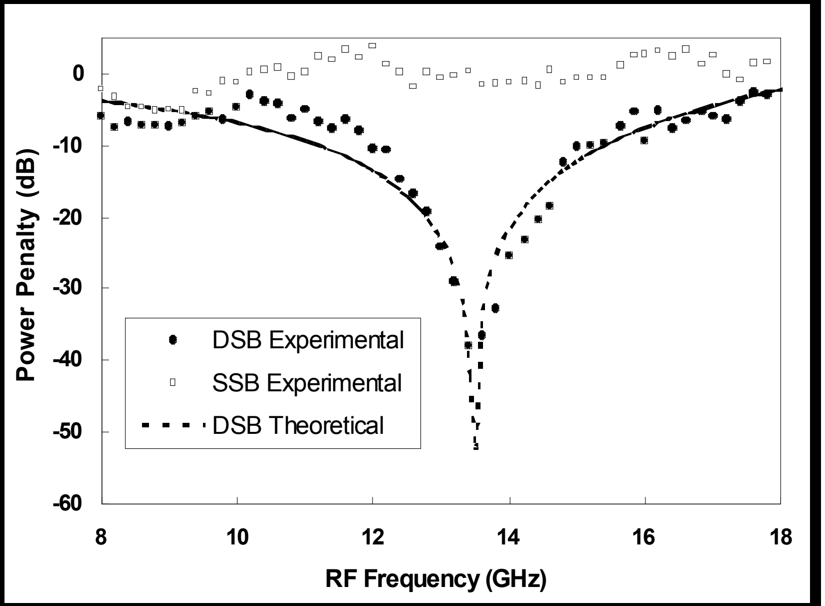
- To limit the null to 3 dB
  - Amplitude imbalance < 1.5dB
  - Phase imbalance < 20 degree

SSB vs. DSB Modulation

Simulations

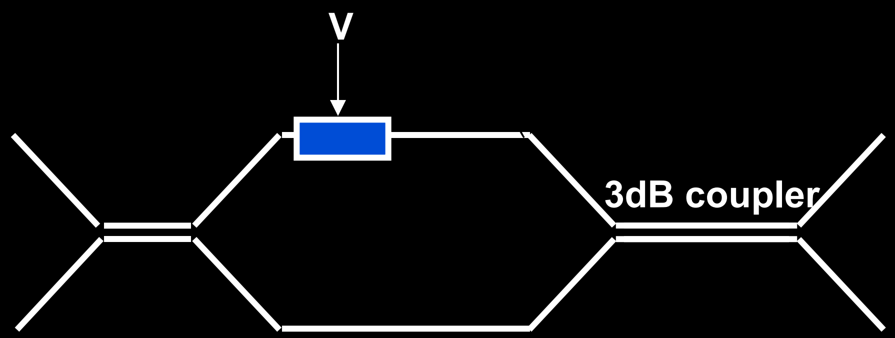


Experiments



Y. Han, B. Jalali, J. Han, B-J. Seo, and H. Fetterman, *IEICE Trans. Electron.,* Vol. E86-C, pp. 1276-80, July 2003.

Phase Diversity in Electro-optic modulations

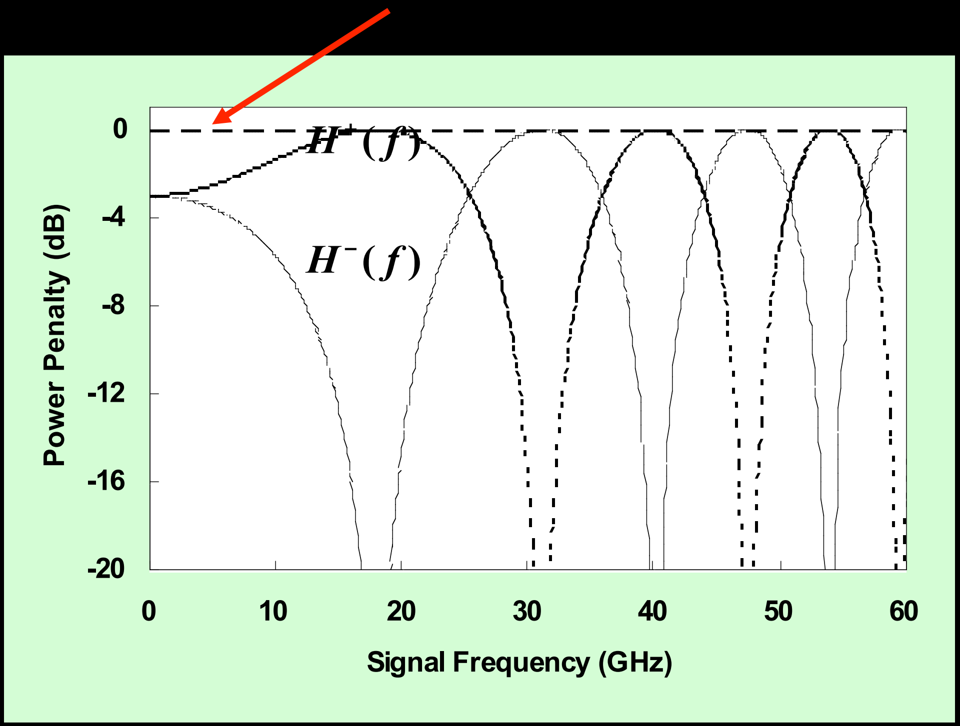


Phase difference between two ports

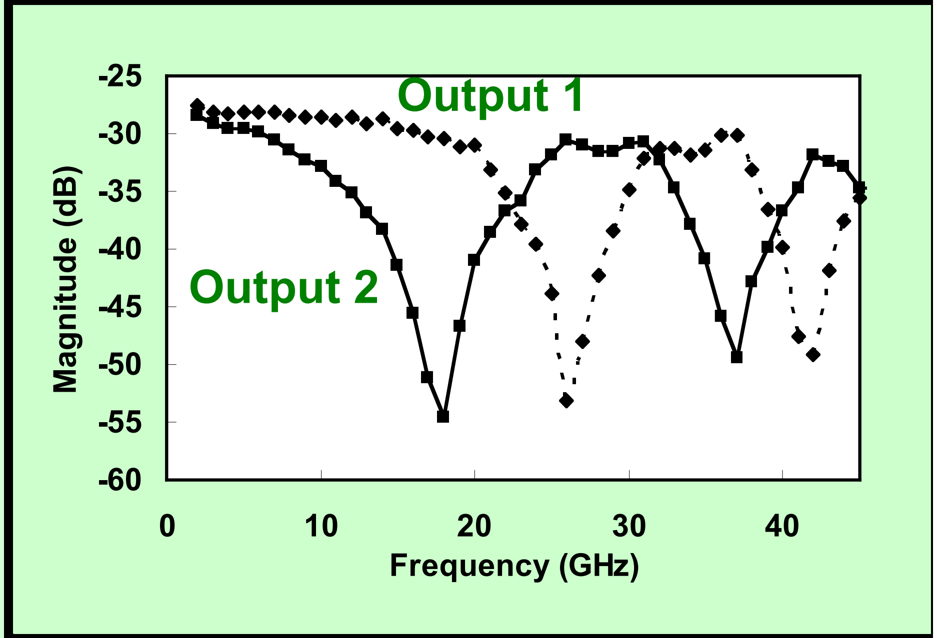
Output Optical E Fields are Orthogonal

Y. Han, B. Jalali, IEEE MWP Conference, October 2004.

Phase Diversity



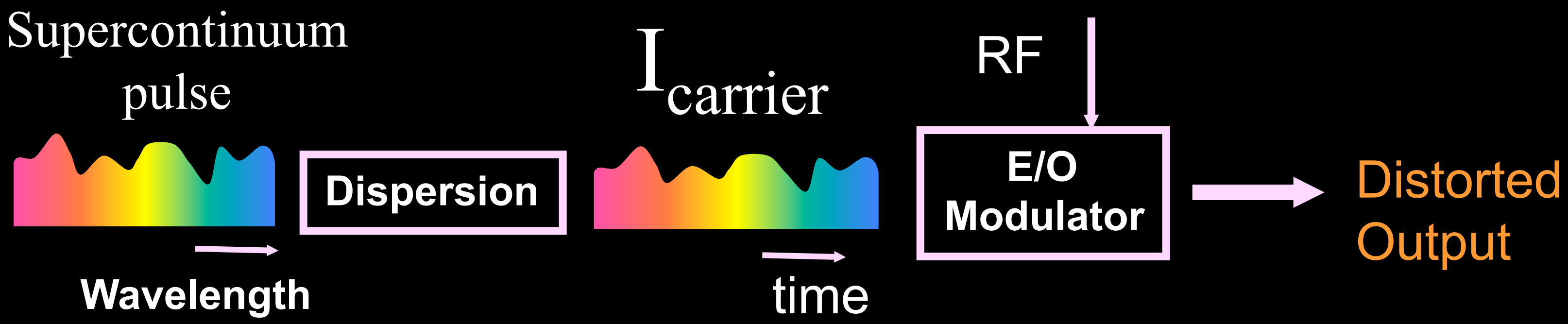
Experiment



Maximal Ratio Combining algorithm can fully overcome dispersion penalty

Y. Han, B. Jalali, IEEE MWP Conference, October 2004.

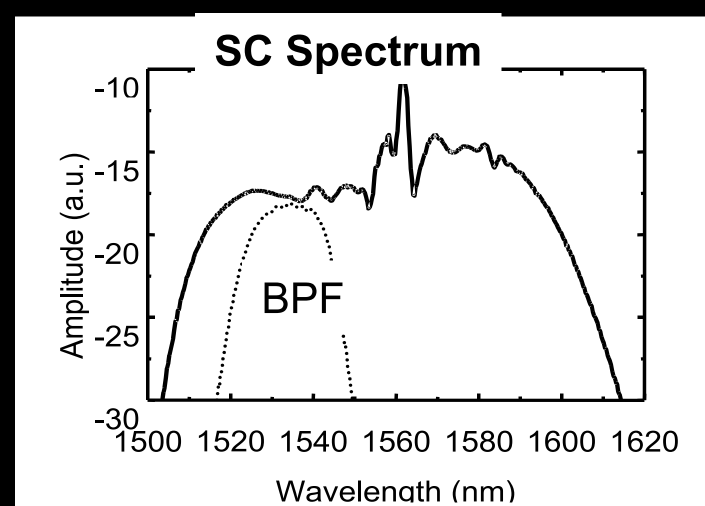
Issue: Nonuniform Pulse Spectrum



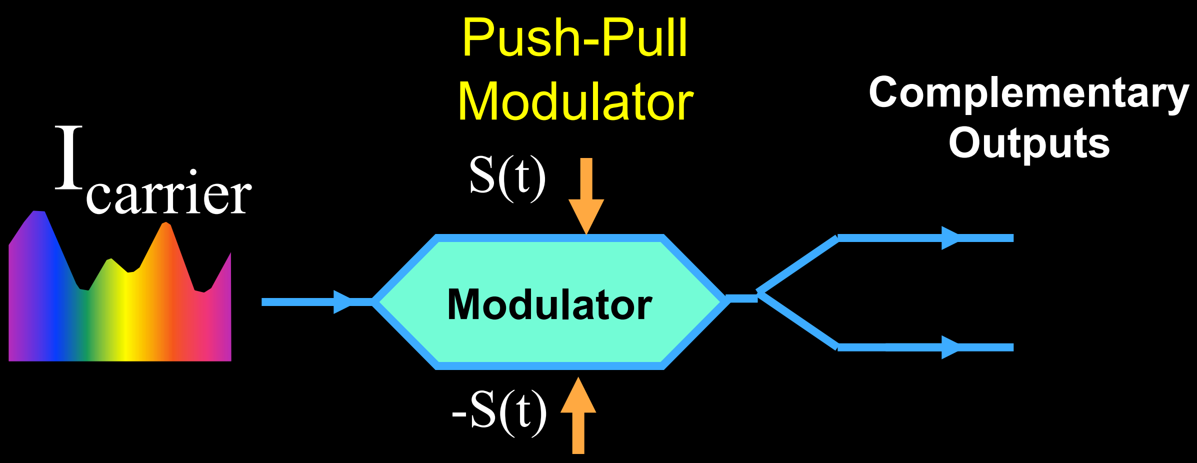
Modulator Transfer Function:

$$I_{carrier} \cdot \left[1 + \sin\left(V_{RF}\right)\right]$$

- Appears as temporal variation of optical carrier
- Produces additive and multiplicative distortion
- Distortion can be reduced by:
  1. digital filtering
  2. Balanced modulation

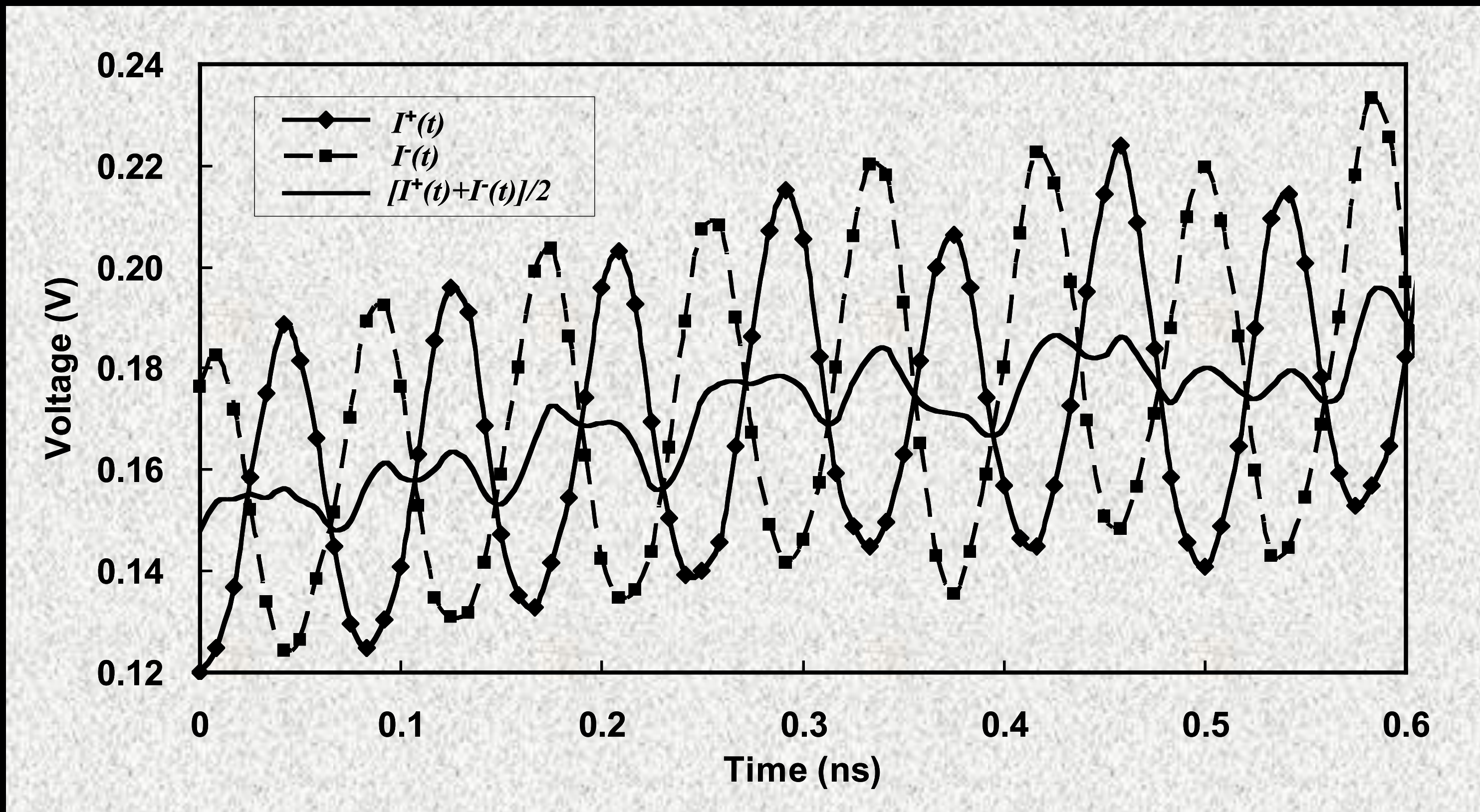


Differential Modulation



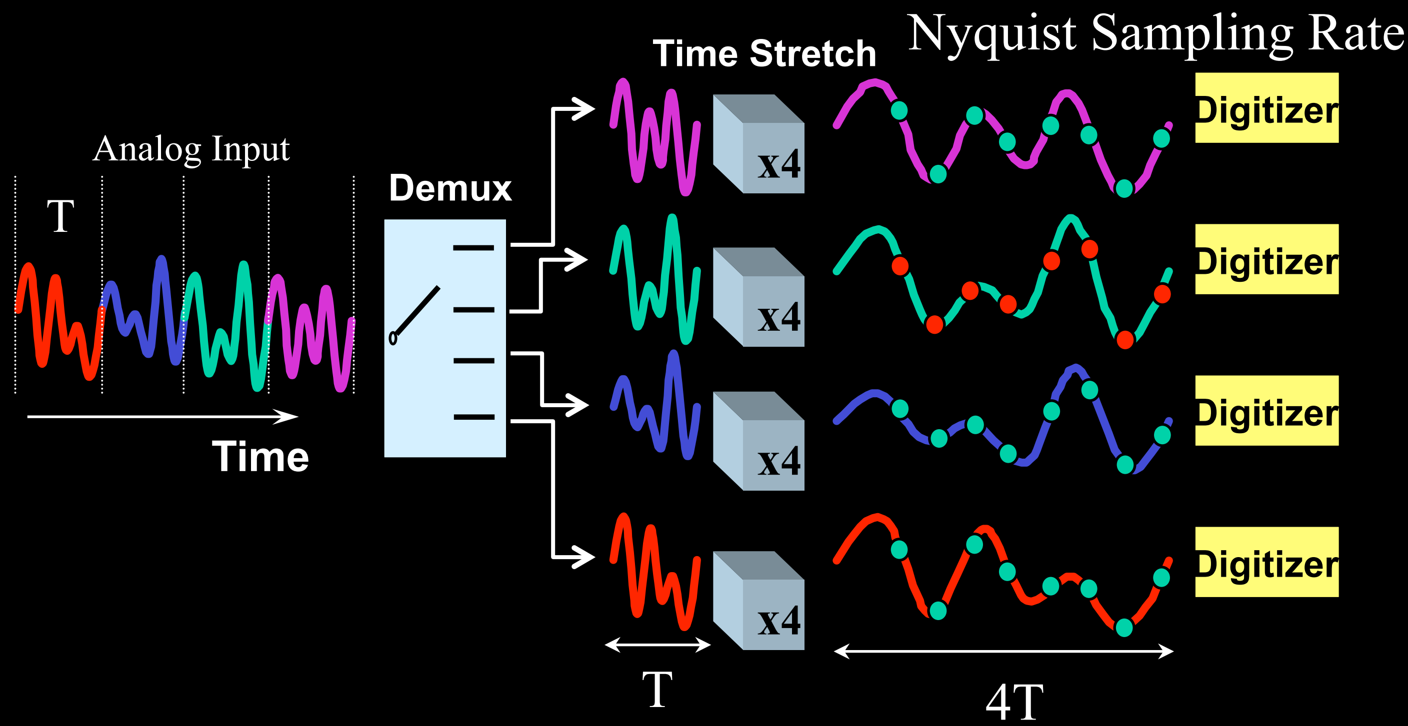
- Subtraction removes the additive distortion
- Division removes the multiplicative distortion
- inverse sine linearizes the transfer function

Differential Time Stretch Experiment



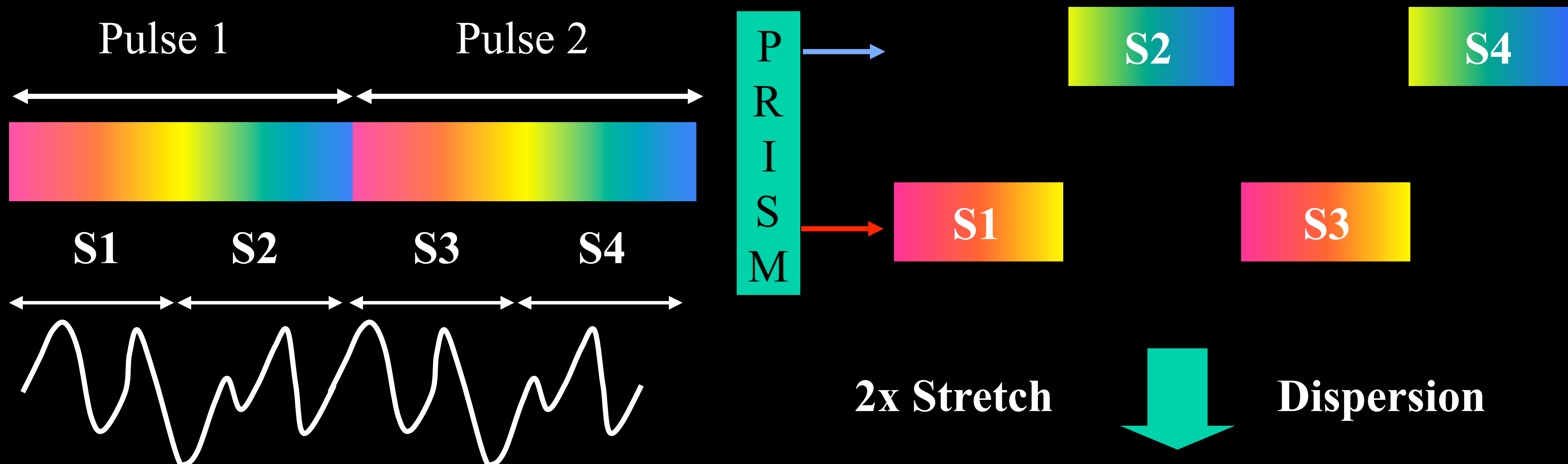
Continuous-time Operation

Continuous-time Operation



- Each ADC see reduced bandwidth
- Full Nyquist sampling by each ADC
- Mismatch error can be estimated from the signal itself – in real-time
- Power scales linearly with bandwidth

Virtual Time Gating

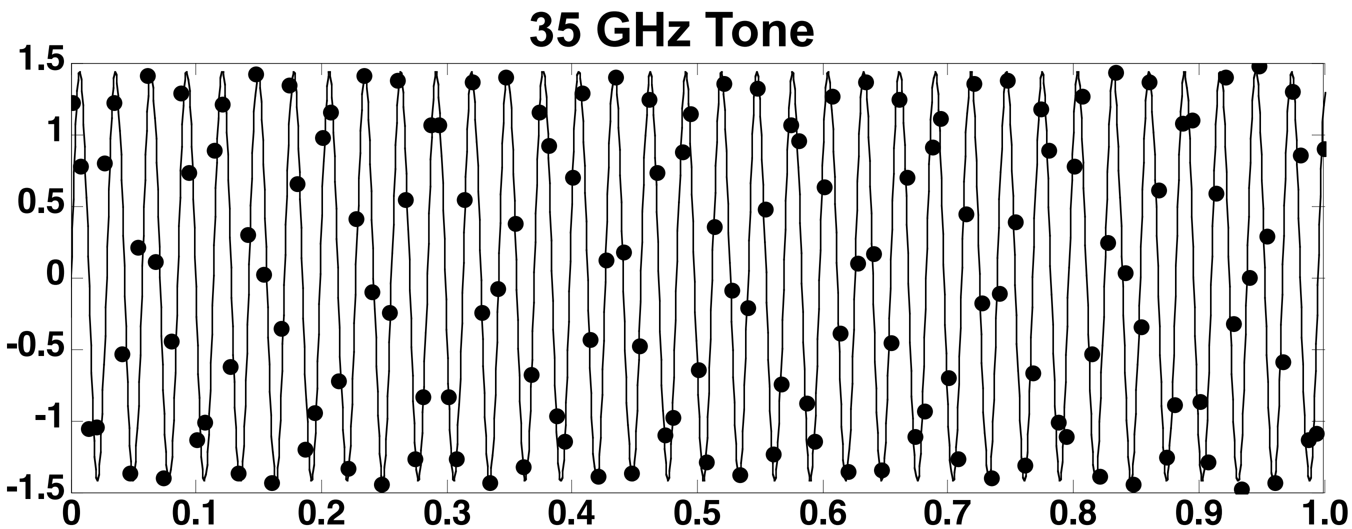


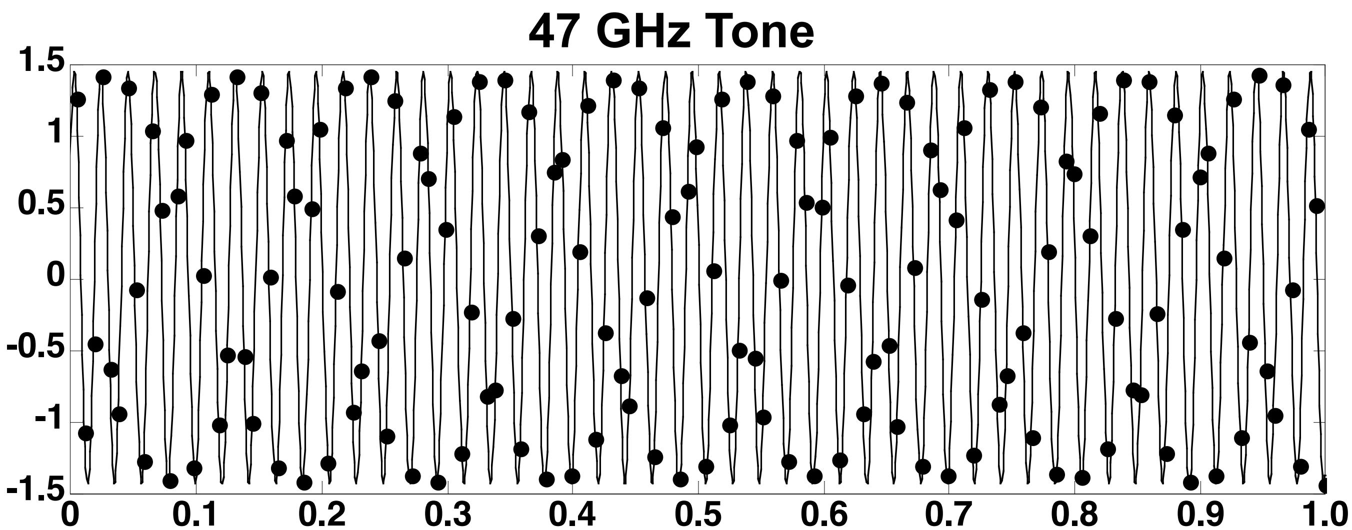
A *n*-channel WDM allows continuous-time stretch factor of *n*

Digitizer reconstructs the signal *segment-by-segment*

Drastically different than time interleaving

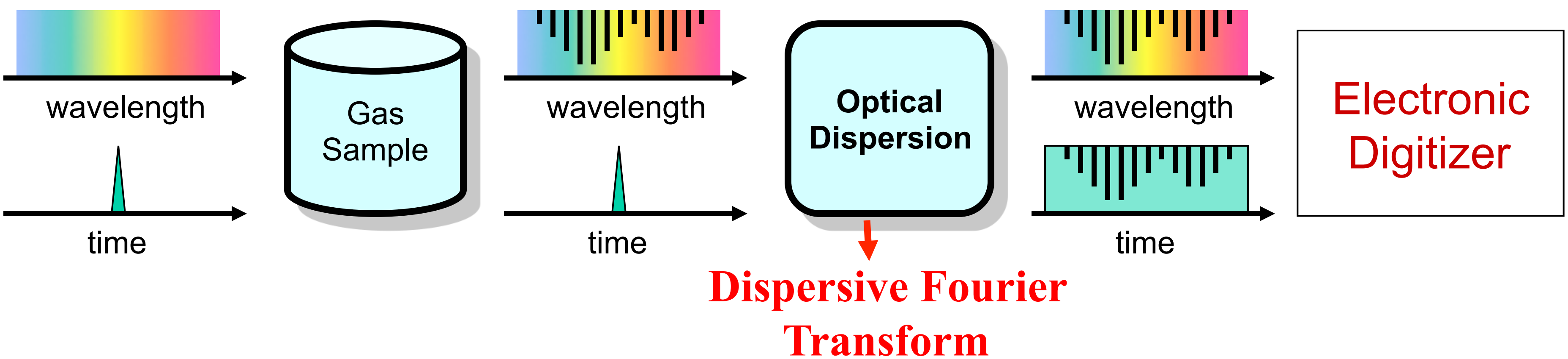
150 Gsa/s continuous-time ADC

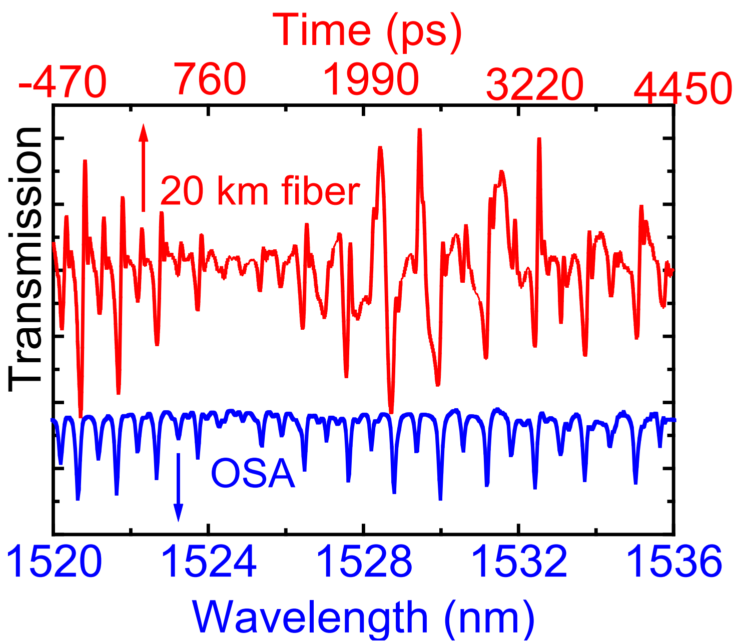




Time Wavelength Spectroscopy

Time-domain Real-time Spectrometer





- **Digitizer replaces spectrometer**
- **Single broadband source**
- **Single shot, real-time spectroscopy**
  - **explosive detection, etc.**

P. Kelkar et al. Electronic Lett. , 1999

J. Chou et al., Photonic Tech Lett., 2004

D. Solli et al, Nature Photonics, 2008

Conclusion

- Time-stretch A/D provides revolutionary improvement in bandwidth and sampling rate
  - For up to 10 ENOB
- Will not be overtaken by electronic digitizers
- Has better power scaling than all-electronic digitizers