Using optical speckle in multimode waveguides for compressive sensing

George C. Valley, George A. Sefler, T. Justin Shaw, Andrew Stapleton

The Aerospace Corporation, Los Angeles CA

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Outline

- Motivation for Compressive Sensing for GHz-band RF signals
- Compressive sensing
  - *Sparsity*
  - *Mixing down in dimension*
  - *Recovery*
- Electronic CS system
- Photonic CS systems
  - *Measurement matrix*
  - *Calibration*
  - *Path to photonic integrated circuit for CS*
- Photonic CS using speckle in multimode waveguide
- Other speckle-based photonic systems
- Conclusions

george.valley@aero.org
Photonics Technology Department

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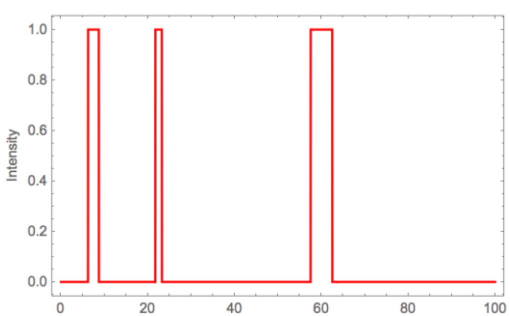
Motivation for compressive sensing

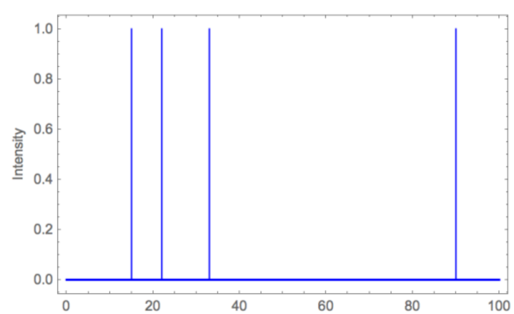
- Nyquist-rate ADCs for GHz-band RF signals …
  - *generate a tremendous amount of data*
    - *Rapidly fill storage buffers*
    - *Overwhelm processors*
    - *Swamp communication links*
  - *have limited performance*
  - *consume significant power*
- Signals of interest in GHz band are often sparse

Frequency domain



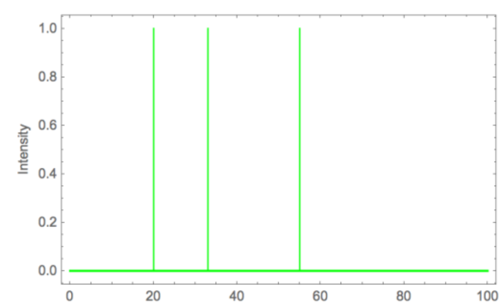
Frequency, GHz

Frequency domain (tones)



Frequency, GHz

Time domain (pulses)



Time, ps

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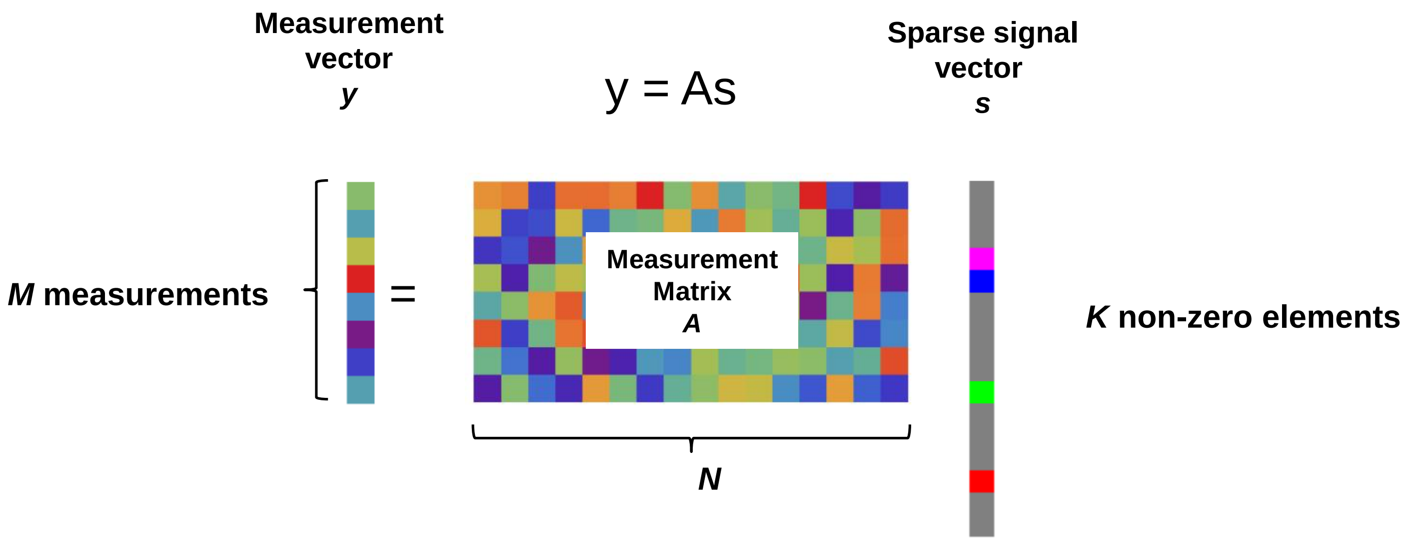
Compressive Sensing--pulses



- *N* is # measurements needed to measure the signal at Nyquist rate
- *K* is the sparsity (# of pulses, sinusoids,…)
- *M* is the # CS measurements needed to recover the signal s

$$N >> K \text{ and } M > K$$

- CS theorems show that for certain classes of Measurement Matrix *A*, one can recover *s* with high probability if

$$M > c\, K \log(N/K) \qquad (c \sim O[1])$$

Accurate knowledge of the Measurement Matrix A is critical for CS recovery calculations

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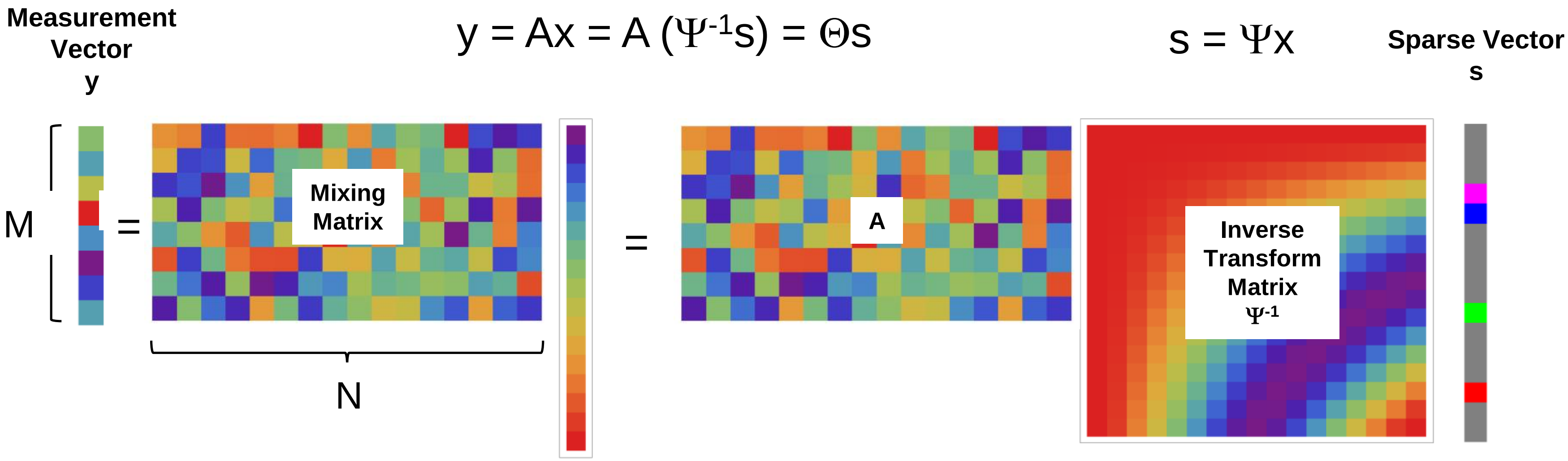
Compressive Sensing—arbitrary waveforms

$$y = Ax = A(\Psi^{-1}s) = \Theta s \qquad s = \Psi x$$



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Photonics Technology Department

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The 3 fundamental aspects of CS

- Sparse signals/images
  - *Subtract off known background*
  - *Threshold noise*
  - *Transform to a basis in which signal is sparse*

- Analog Mixing
  - *Wideband converter—mix with pseudo-random waveforms (e.g. PRBS)*
  - *Single pixel camera—mix with pseudo-random images*

- Signal/Image Recovery
  - *Need accurate knowledge of analog measurement matrix*
  - *Exploit sparsity to limit solution space*
  - *Wide range of algorithms and codes now available*
    - Penalized ℓ_1-norm
    - Orthogonal matching pursuit

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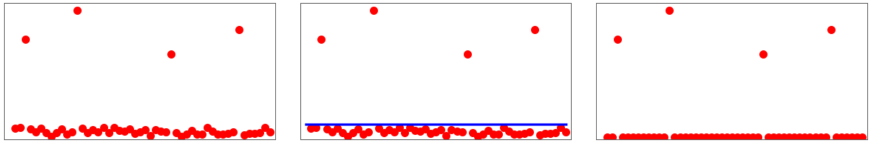
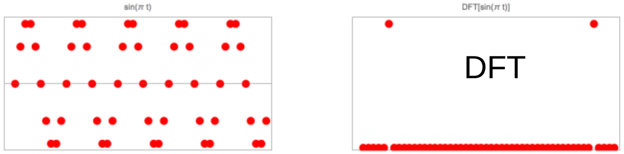
Sparsity

- A sparse vector/matrix–mostly 0's
  - What percentage is sparse?

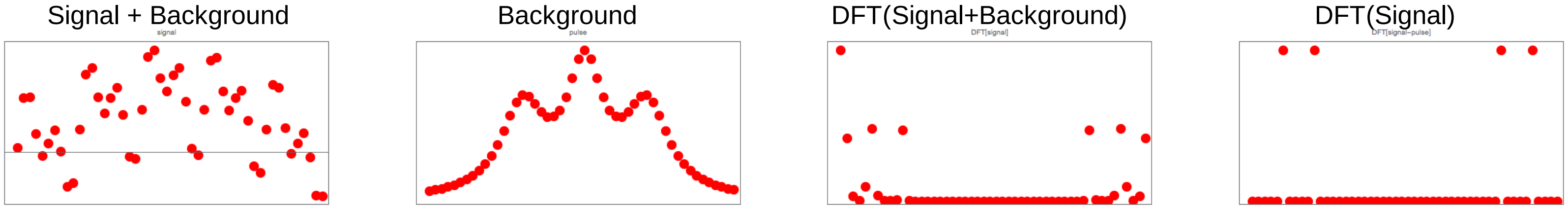


- Noise—threshold signal
- Sine waves—Transform signal
  - Sin(π t)



- Beware of off-grid frequencies
  - Sin(1.1 π t)

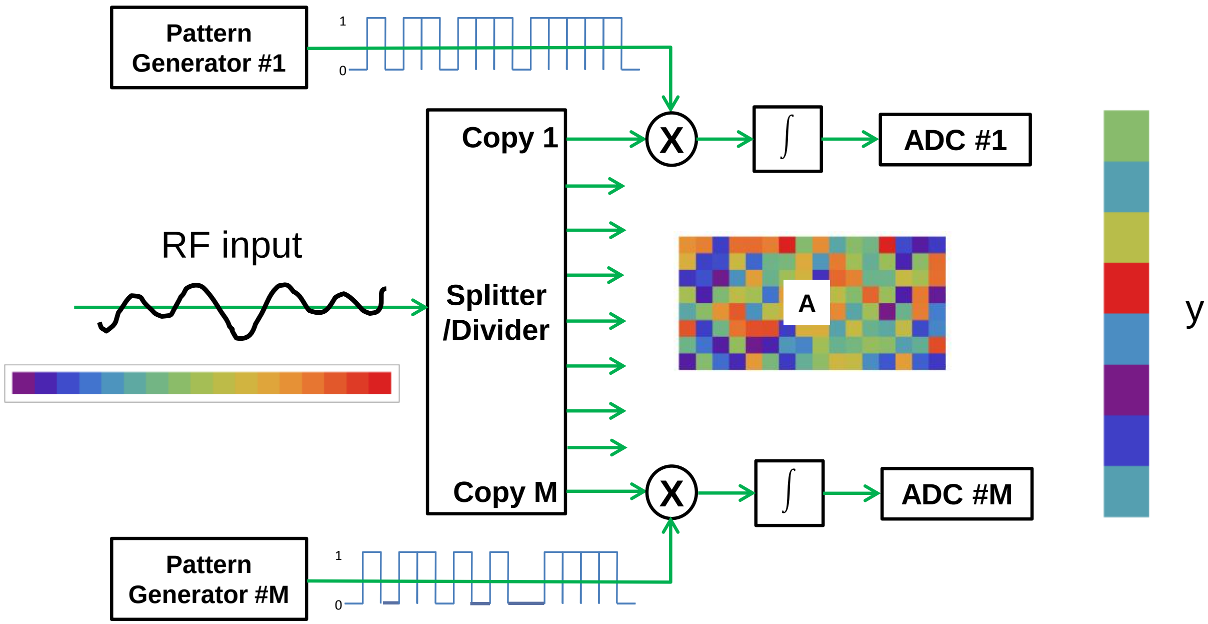
- Subtract off non-sparse background



There is always a transform that makes a signal sparse—but you may not know it!

Electronic CS system for GHz-band RF Signals

- Split signal into M copies
- Multiply each copy by different pseudo-random bit sequence (PRBS) of length N
- Integrate for duration of PRBS, sample, and digitize
- Issues:
  - *Requires M electronic pattern generators*
  - *Size, weight, and power*
  - *Random noise and jitter within PRBS limit recovery*



Mishali and Eldar, IEEE Journal of Selected Topics in Signal Processing, Vol. 4, pp. 375 (2010).

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Photonic undersampling and compressive sensing Origins

Before 2008

- Photonic ADC work
- Photonic down-conversion/down-sampling

2008

- Moshe Horowitz’ group Technion: Multi-rate asynchronous sampling
- Johns Hopkins U. Appl. Phys. Lab: Non-uniform sampling

2010 Photonic CS

- Technion group use CS techniques to recover signals
- JH APL group recognizes non-uniform sampling is a form of CS
- Aerospace group proposes parallel multi-rate sampling CS

2011-2016

Approximately 30 papers on Photonic CS

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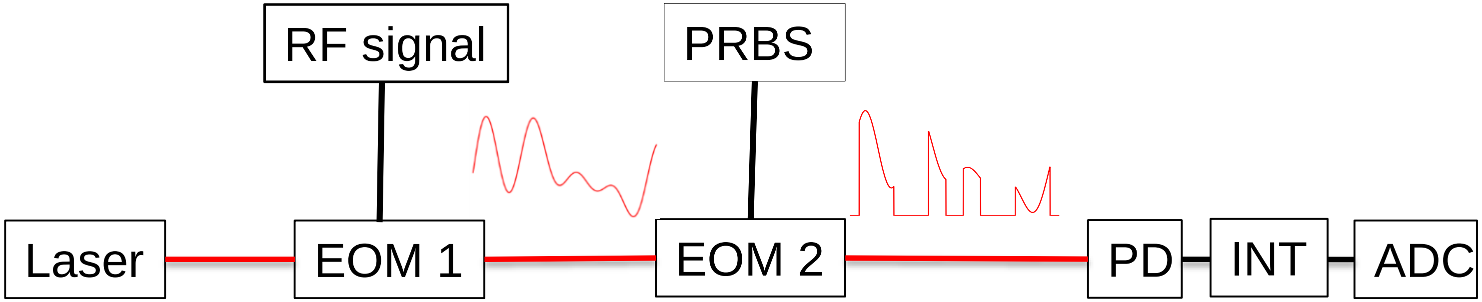
Serial CS system using PRBS and EOMs



Nichols and Bucholtz 2011
Chi et al. 2012
Yan *et al*. 2012
McKenna *et al*. 2013
Chen et al. 2013
Yin *et al*. 2013

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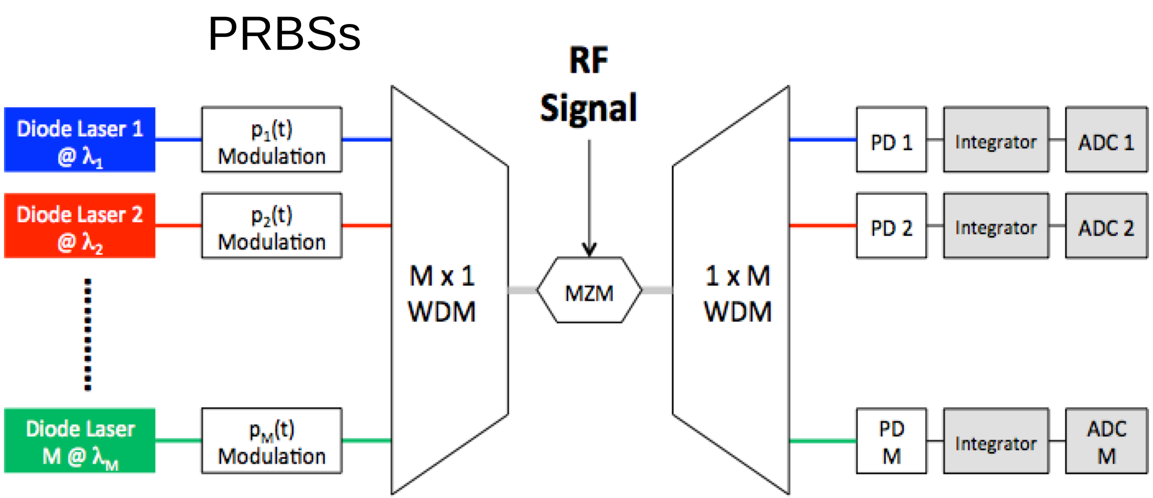
Parallel CS system using PRBSs and EOM



Proposed WDM pair to obtain simultaneous measurement of all elements in measurement vector ***y*** (Nan *et al*. 2011)

Pseudo-random bit sequences impressed on cw diode lasers prior to RF signal

Still has amplitude and timing jitter of electronics

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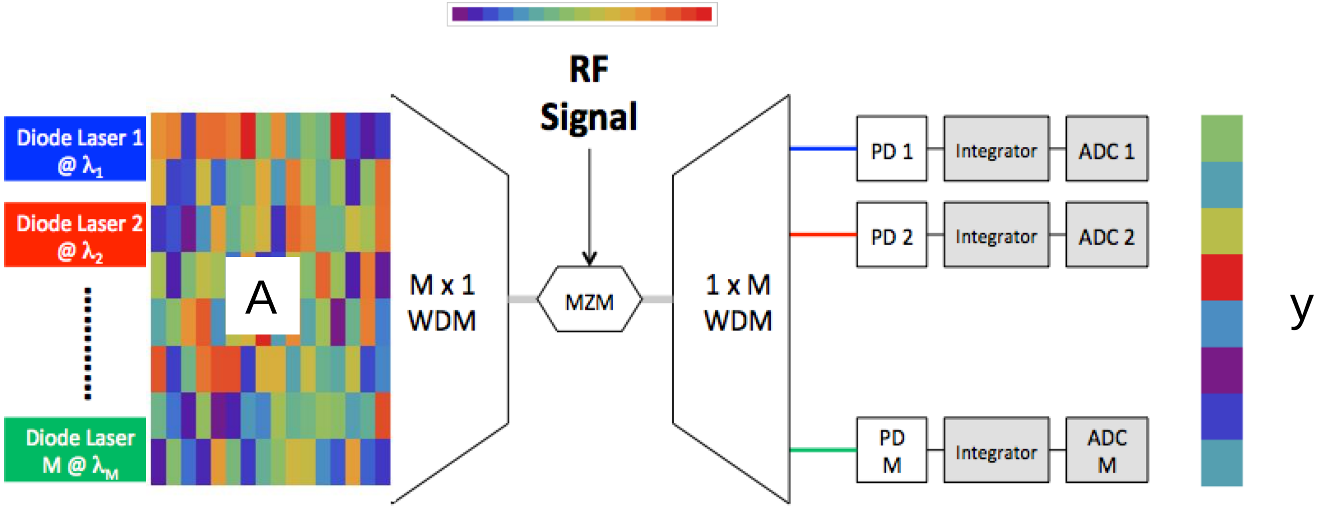
Proposed Parallel CS system using PRBS and EOM



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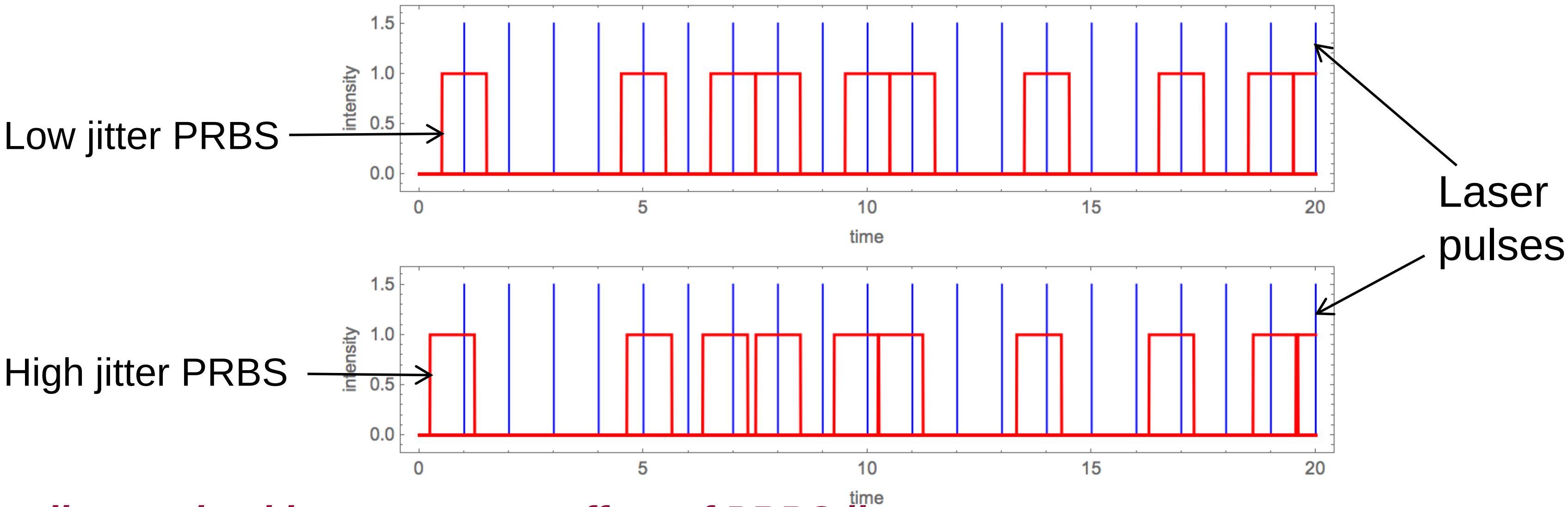
george.valley@aero.org
Photonics Technology Department

CW or pulsed laser?

CW laser
- Advantages: Simple, efficient, low average power
- Disadvantage: Timing jitter of PRBS mapped onto optical intensity

Pulsed laser
- Advantage: Timing jitter of PRBS removed by low jitter mode-locked laser
- Disadvantages: high peak power on photodiode

Neither system avoids amplitude noise of PRBS generator



Low-jitter pulsed laser removes effect of PRBS jitter

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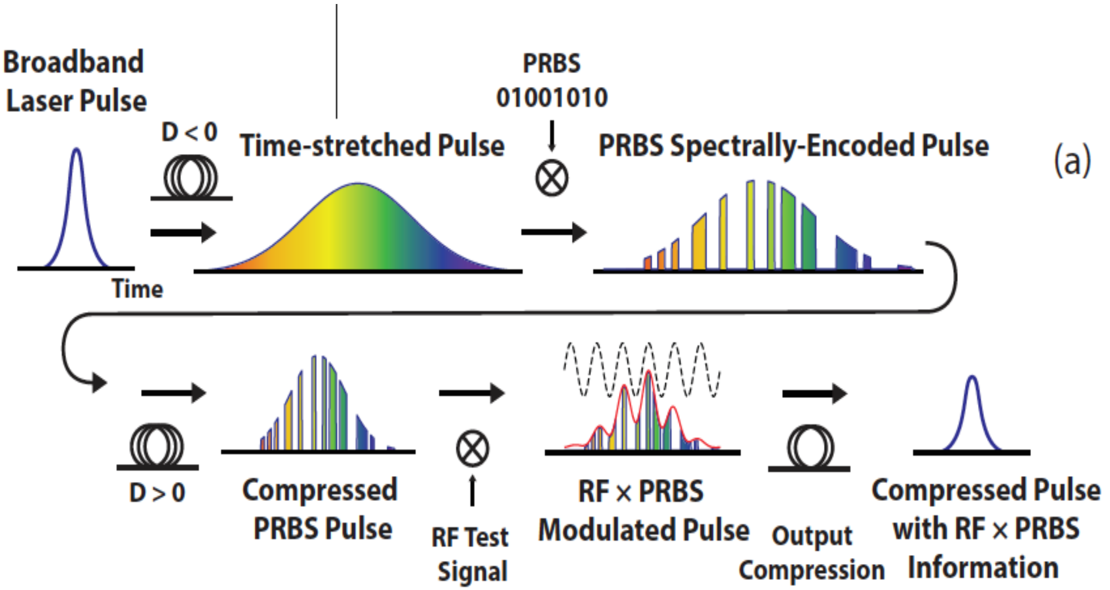
Time stretching/compression to decrease effective amplitude and timing jitter in PRBS



Demonstrated use of stretching/compression to increase effective rate of PRBS (Bosworth and Foster Optics Letters 2013)

Time-stretching allows use of lower rate PRBS with less jitter

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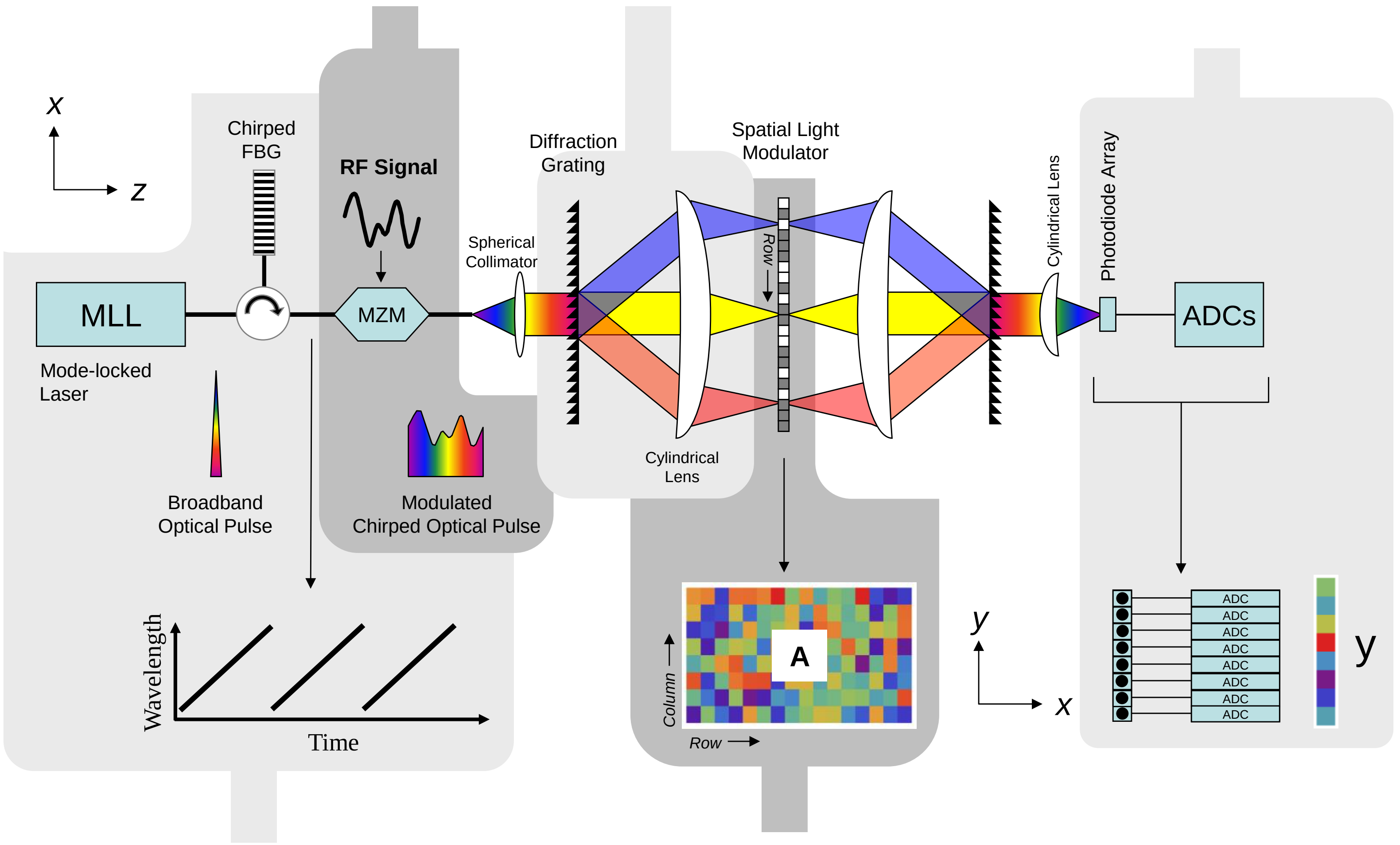
Parallel CS system with PRBS addressing 2D Spatial Light Modulator



Valley and Sefler 2010

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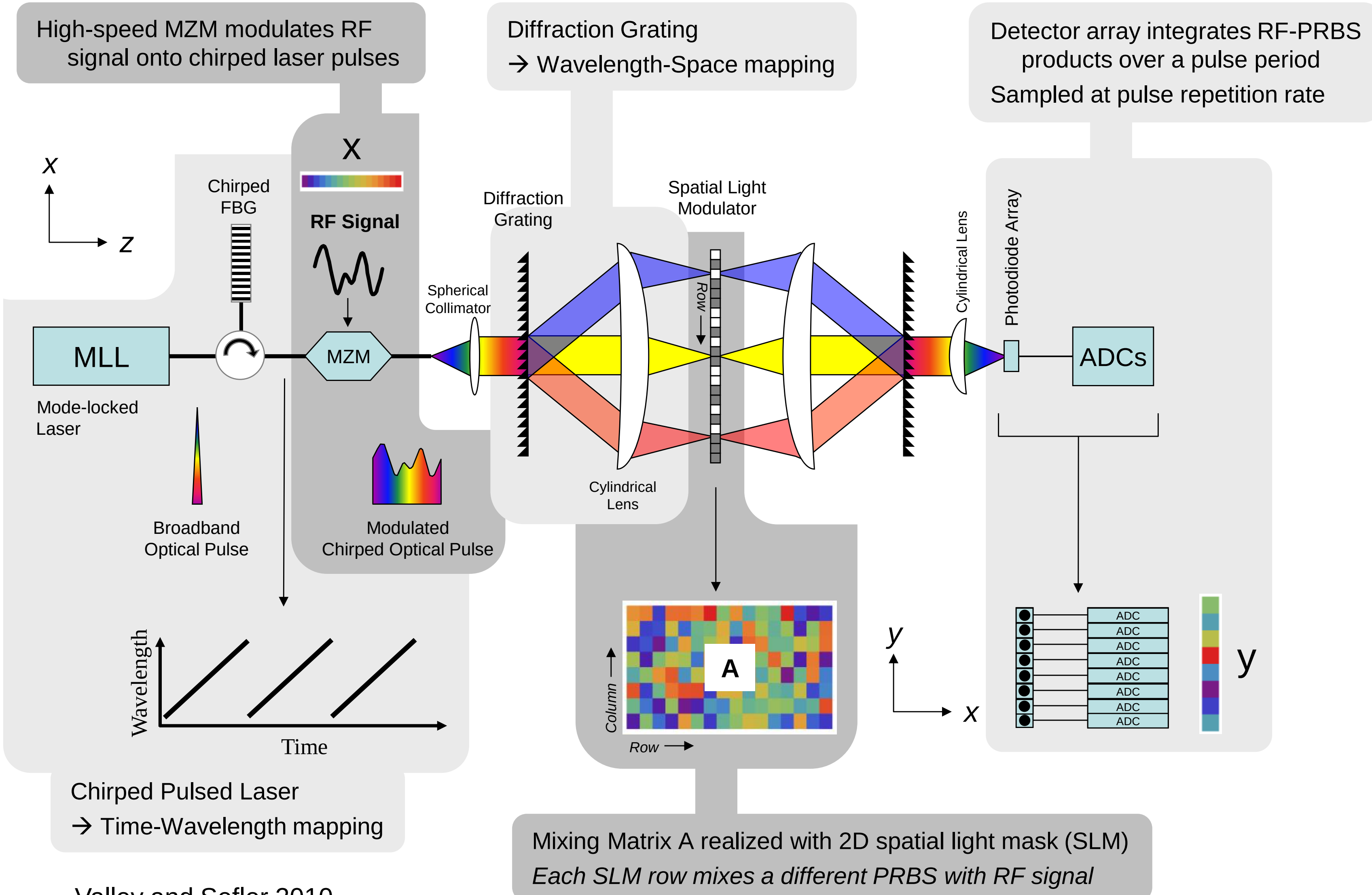
Parallel CS system with PRBS addressing 2D Spatial Light Modulator



Valley and Sefler 2010

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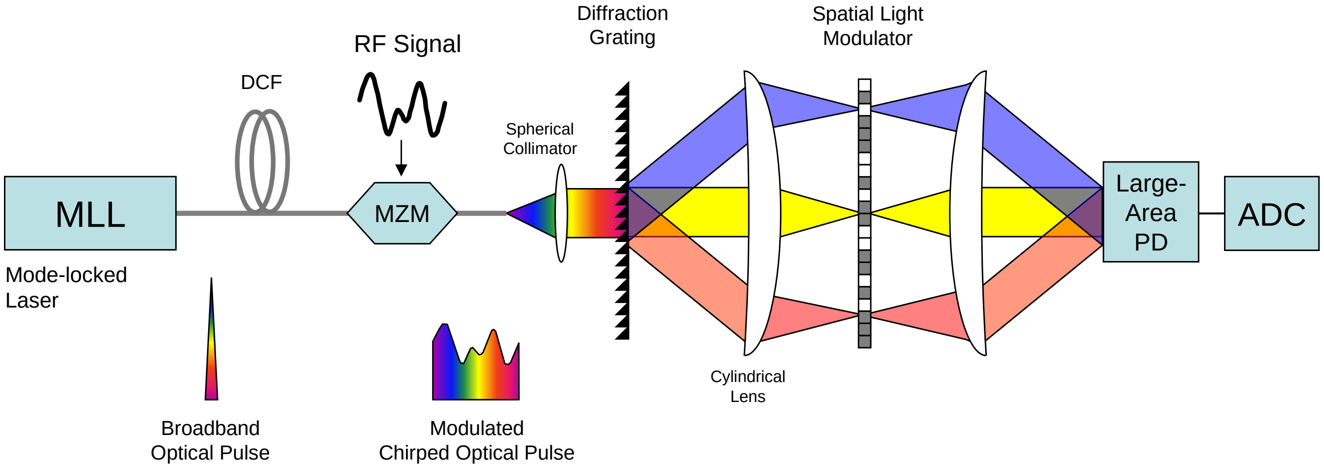
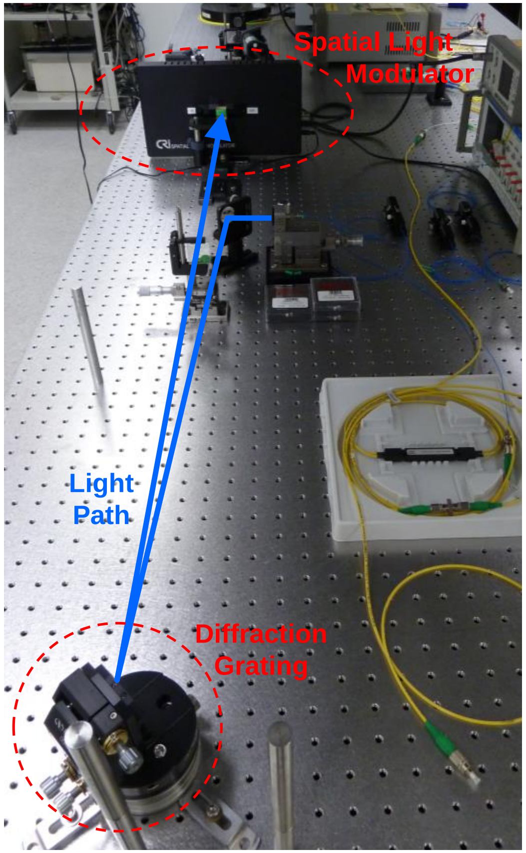
Serial Experimental Demonstration with 1D SLM

- Used 1D liquid-crystal SLM
- RF signals synchronized to laser pulse repetition rate
- Measurements *y* made sequentially by stepping SLM through rows of A
- RF tones (sparse in frequency domain) and pulses (sparse in time domain) recovered using penalized $\ell 1$-norm





Valley, Sefler, and Shaw, 2012

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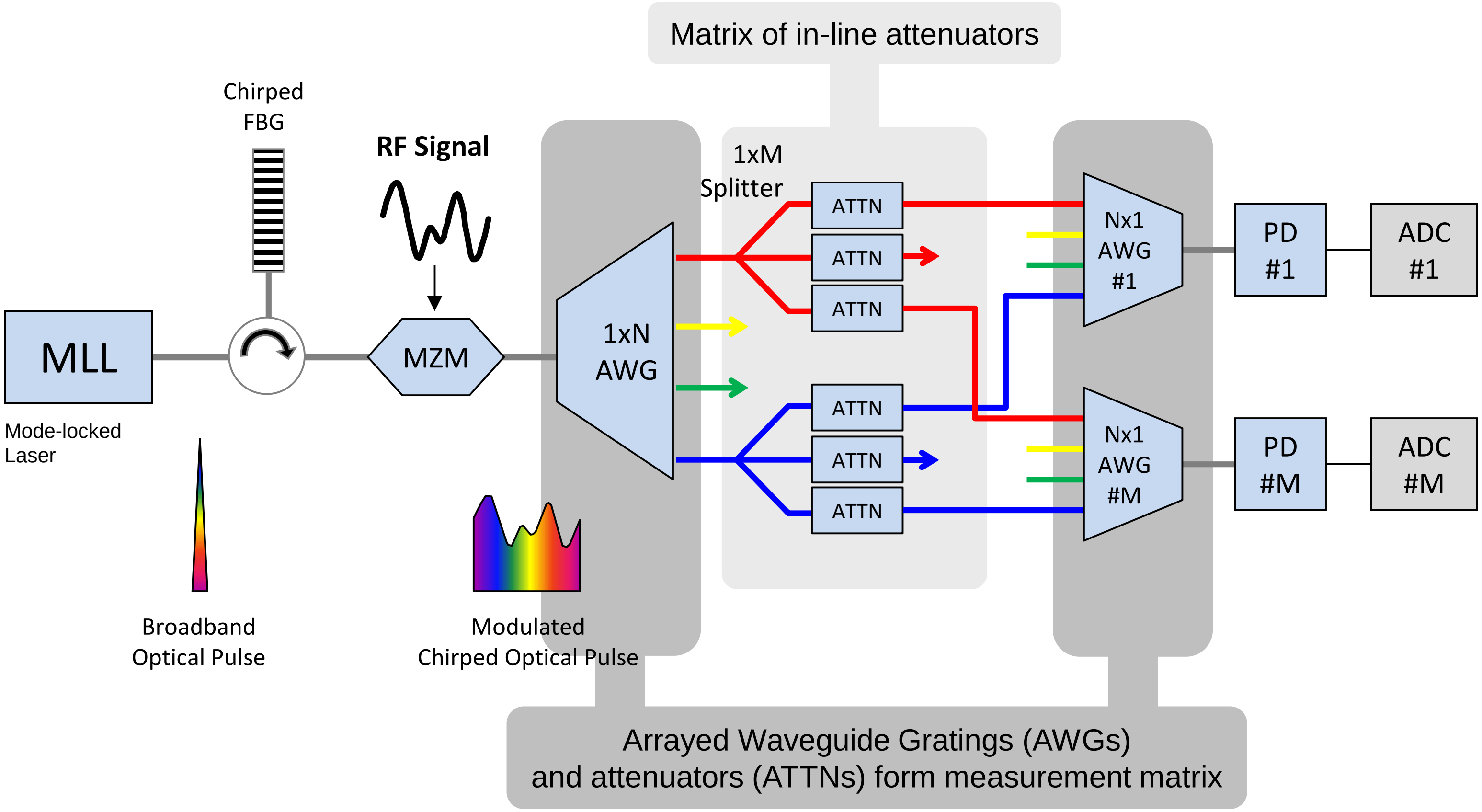
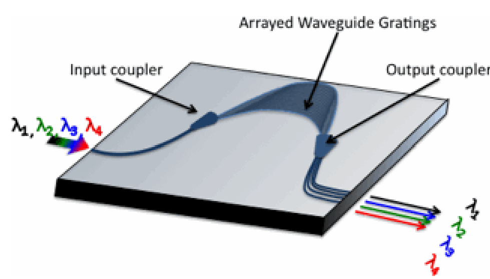
Parallel CS system using WDMs (AWGs)





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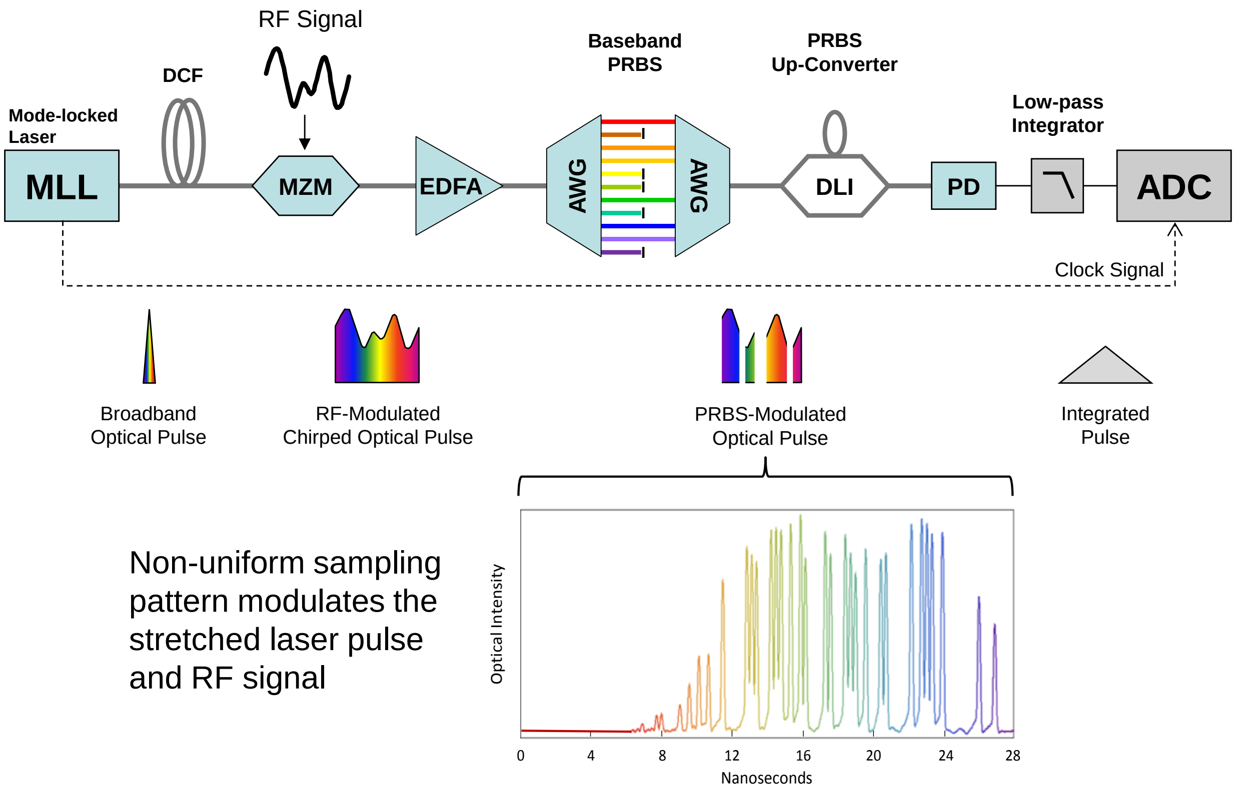
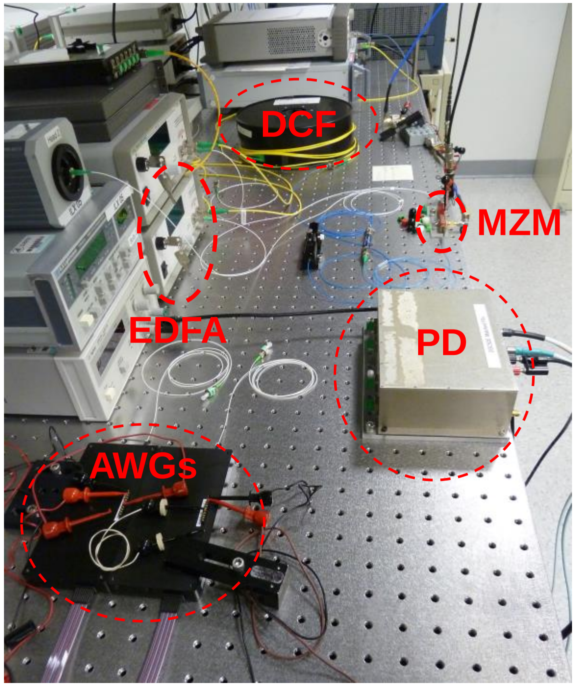
Serial experimental demonstration using AWGs

- Single row of Mixing Matrix A
- AWG: 96 wavelength channels @ 0.4-nm channel spacing
  - Selected channels blocked to form PRBS
- Delay-line interferometer (DLI) Up-converter
- RF bandwidths from 4 to 20 GHz





Non-uniform sampling pattern modulates the stretched laser pulse and RF signal

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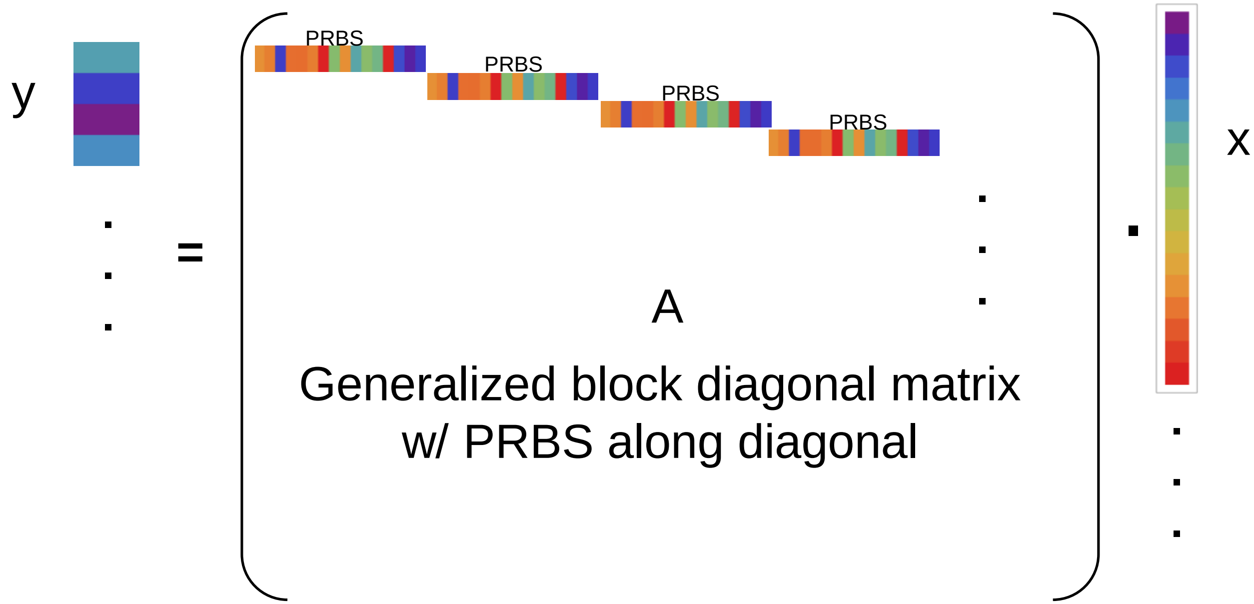
Periodic non-uniform sampling with integration

- Periodic non-uniform sampling and integration
  - *Single PRBS repeated*
  - *Measurement Matrix has generalized block diagonal structure*
  - *Arbitrary number of measurements y_i*
  - *Arbitrary length of Signal x*
- Effective sampling rate is PRBS/laser rep rate
- No RF-to-laser synchronization required
- Useful for long duration RF signals (e.g. chirped pulses



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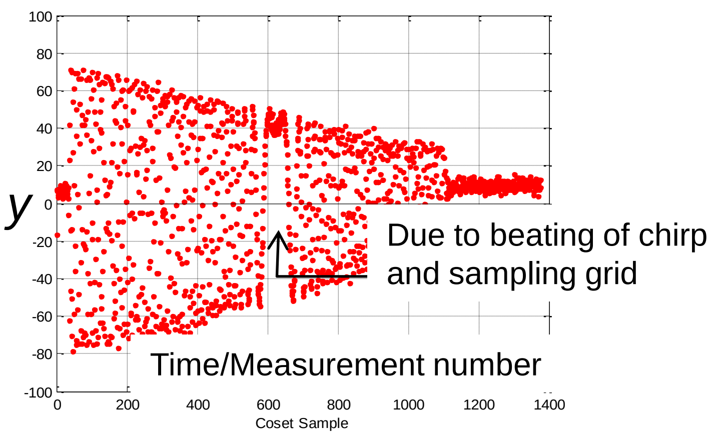
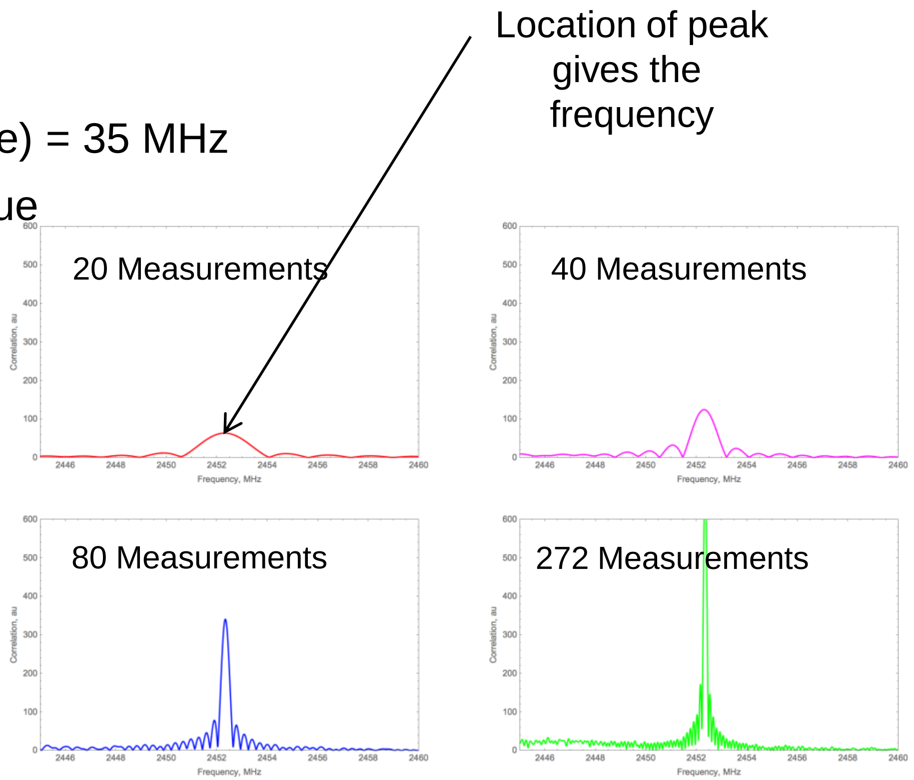
Experimental results for RF chirped pulses

Carrier Recovery *vs*. Number of Measurements WDM mixing

- RF Parameters:
  - Chirp = 20 MHz / 30 μs
  - Carrier Freq = 2.453 GHz
- PRBS Rep Rate (effective sample rate) = 35 MHz
- Maximum likelihood recovery technique





george.valley@aero.org
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Desirable Properties for Photonic CS System

- Components integrable in one or more photonic integrated circuits
  - Avoid free-space optics
  - Minimize fiber-coupled devices

- Static or low-error PRBS generation that can be calibrated
  - Spatial light modulators
  - Pulse or bandwidth compression (Bosworth and Foster 2013)
  - Optical pulse in the center of each PRBS bit (Chi *et al*. 2012)
  - WDMs

- Operation as real-time digitizer
  - Unrestricted time window
  - Arbitrary number of independent CS measurements
  - Arbitrary RF signals
    - Optical pulses and RF signal unsynchronized
    - Pulses, chirps, sinusoids, communication waveforms …

george.valley@aero.org
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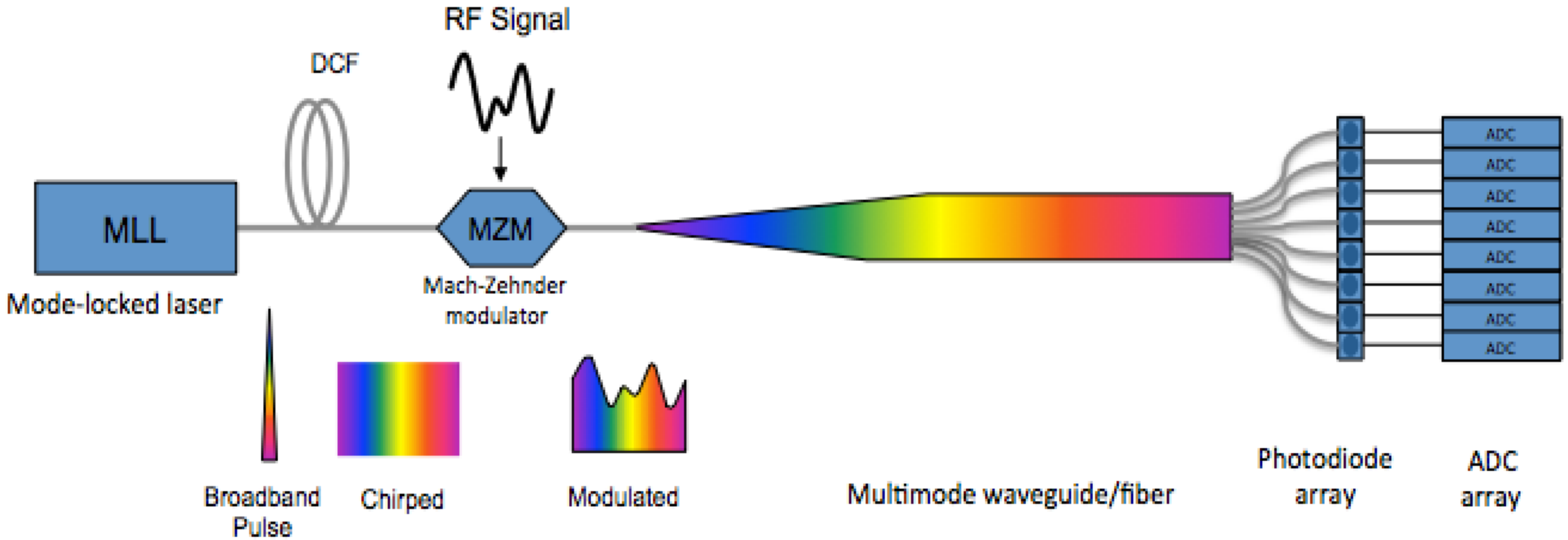
Photonic CS system using multimode waveguide speckle



- Multimode waveguide/fiber replaces 2D SLM or WDM-Attenuator-WDMs subsystem
- Exploit spatial randomness and wavelength sensitivity at output of multimode guide
- Time-wavelength mapping multiplies RF signal by speckle wavelength dependence

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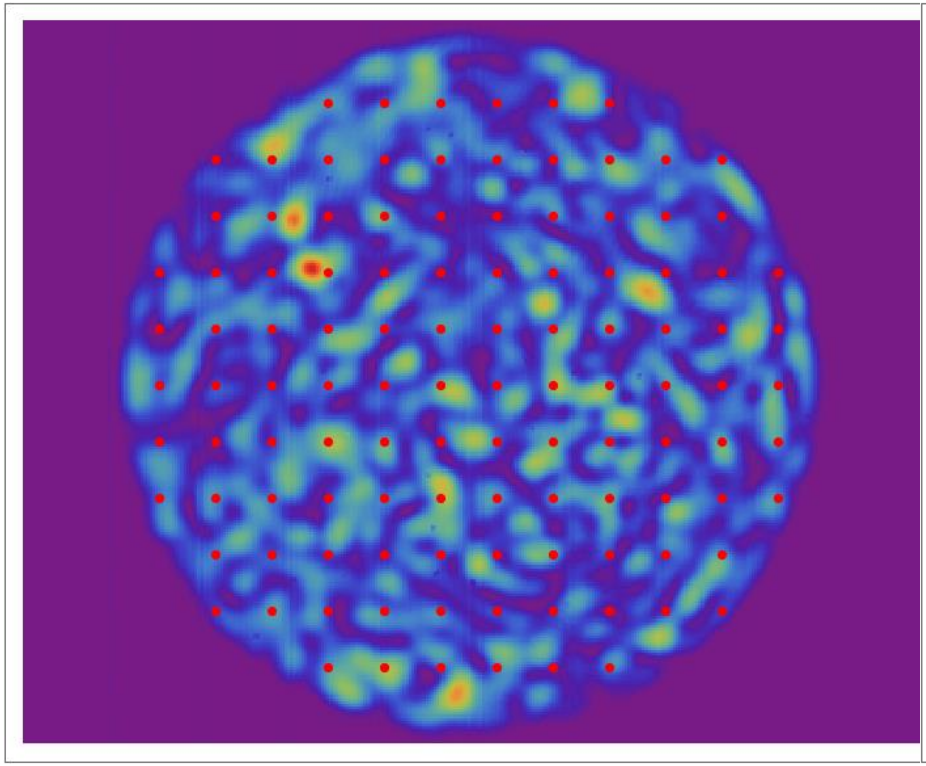
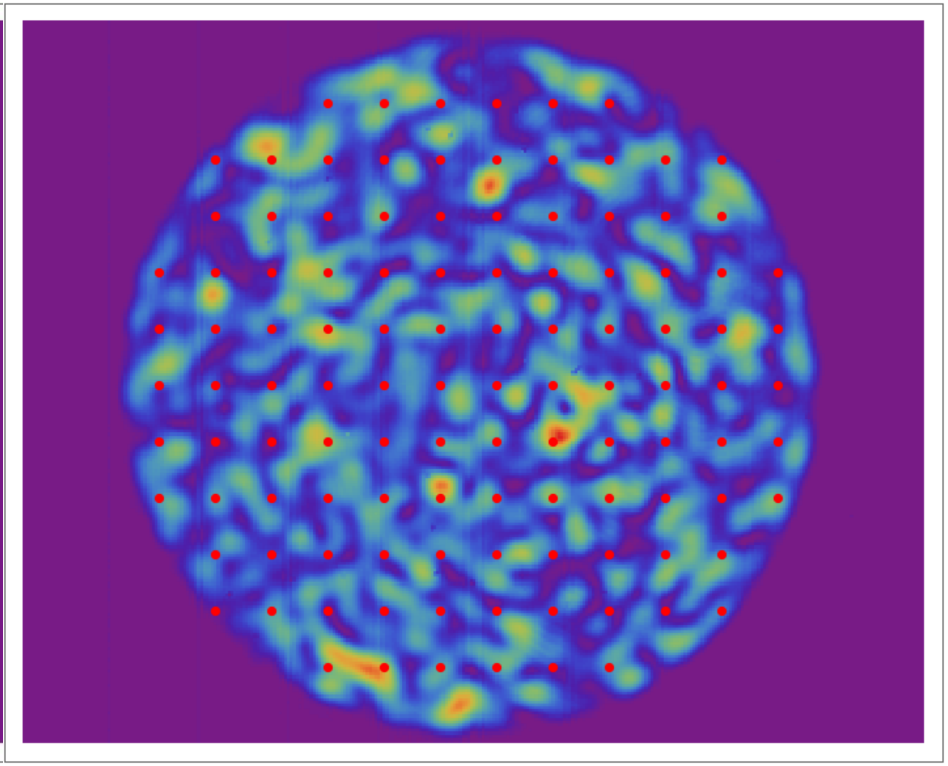
Speckle Patterns at the output of a 1m, 105μm, 0.22NA step-index fiber





λ = 1539.44 nm

1539.52nm

Small changes in wavelength can produce significant changes in speckle pattern

Speckle at each red dot uncorrelated with that at other dots

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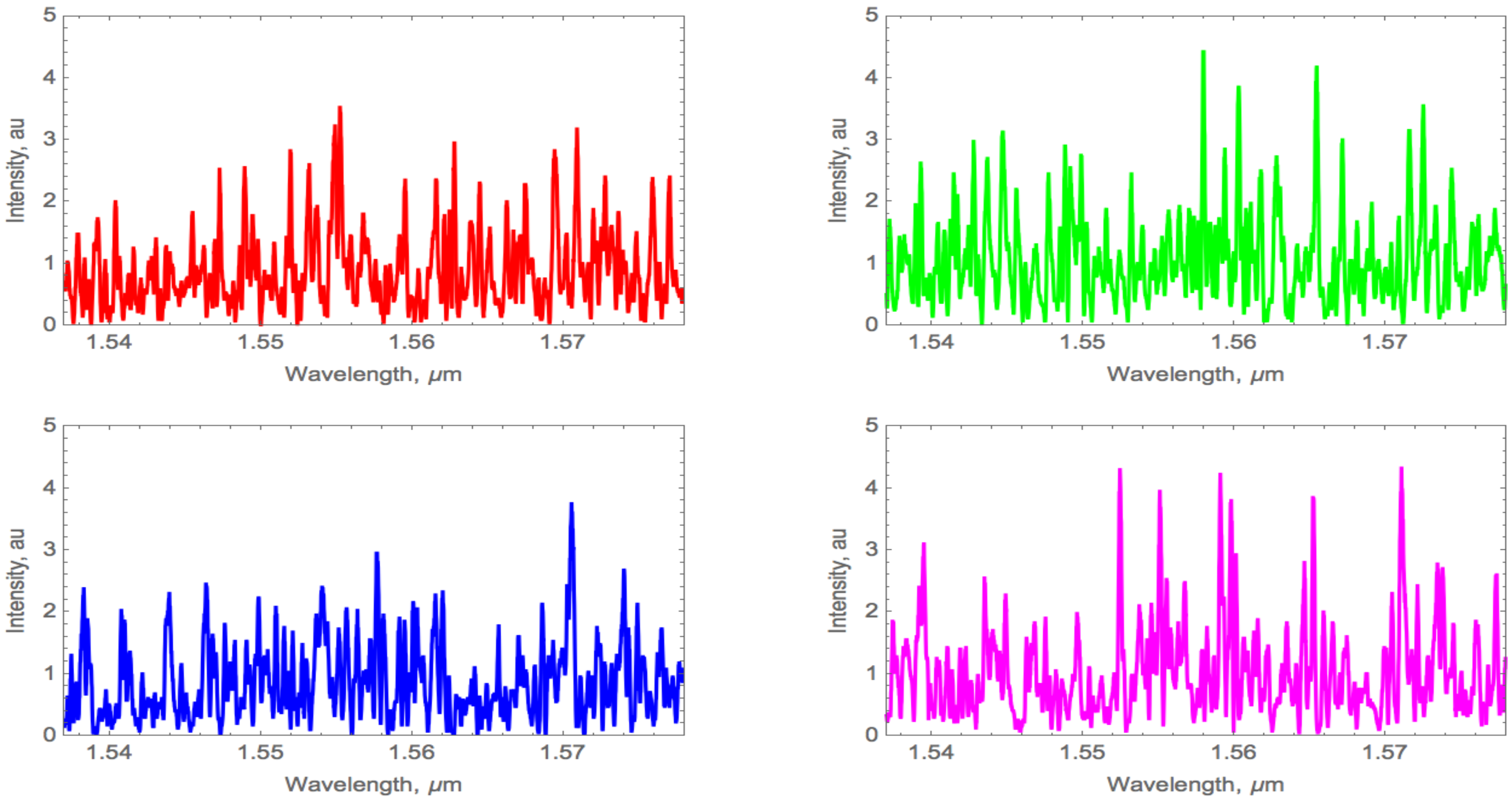
Typical Rows in Speckle Measurement Matrix

Measured intensity as a function of wavelength for 4 locations in the output plane of a 1m, 105μm, 0.22NA fiber



These patterns multiply the RF signal through time-wavelength mapping

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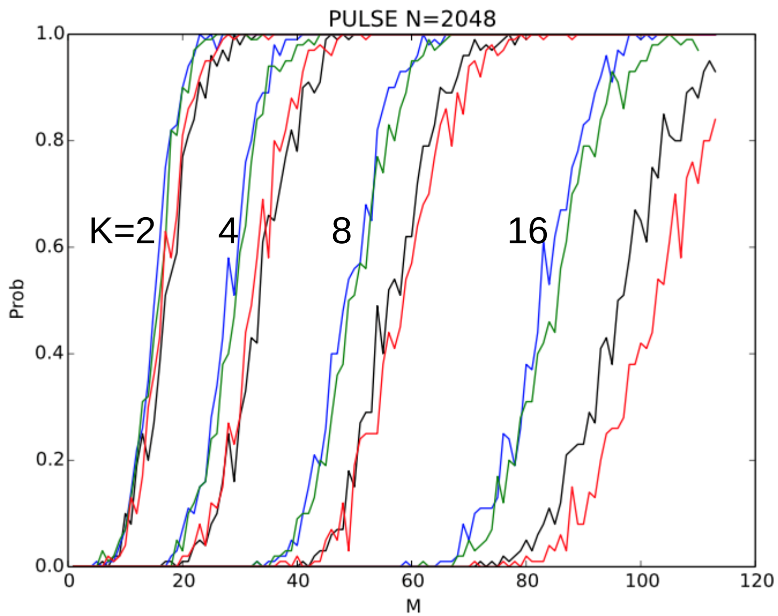
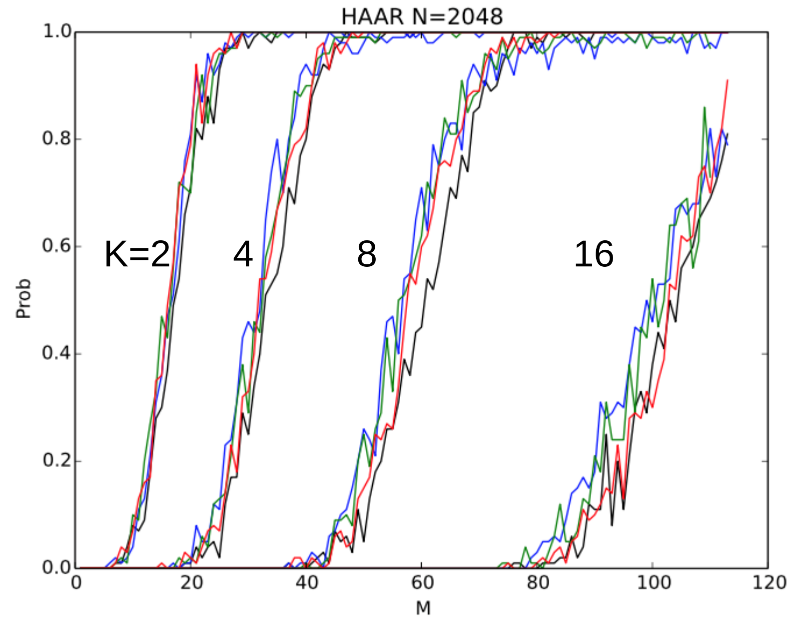
Simulated CS Results for Measured and Calculated Measurement Matrices (MM)

Signal sparse under Identity Transform



sparse under Haar Wavelet Transform



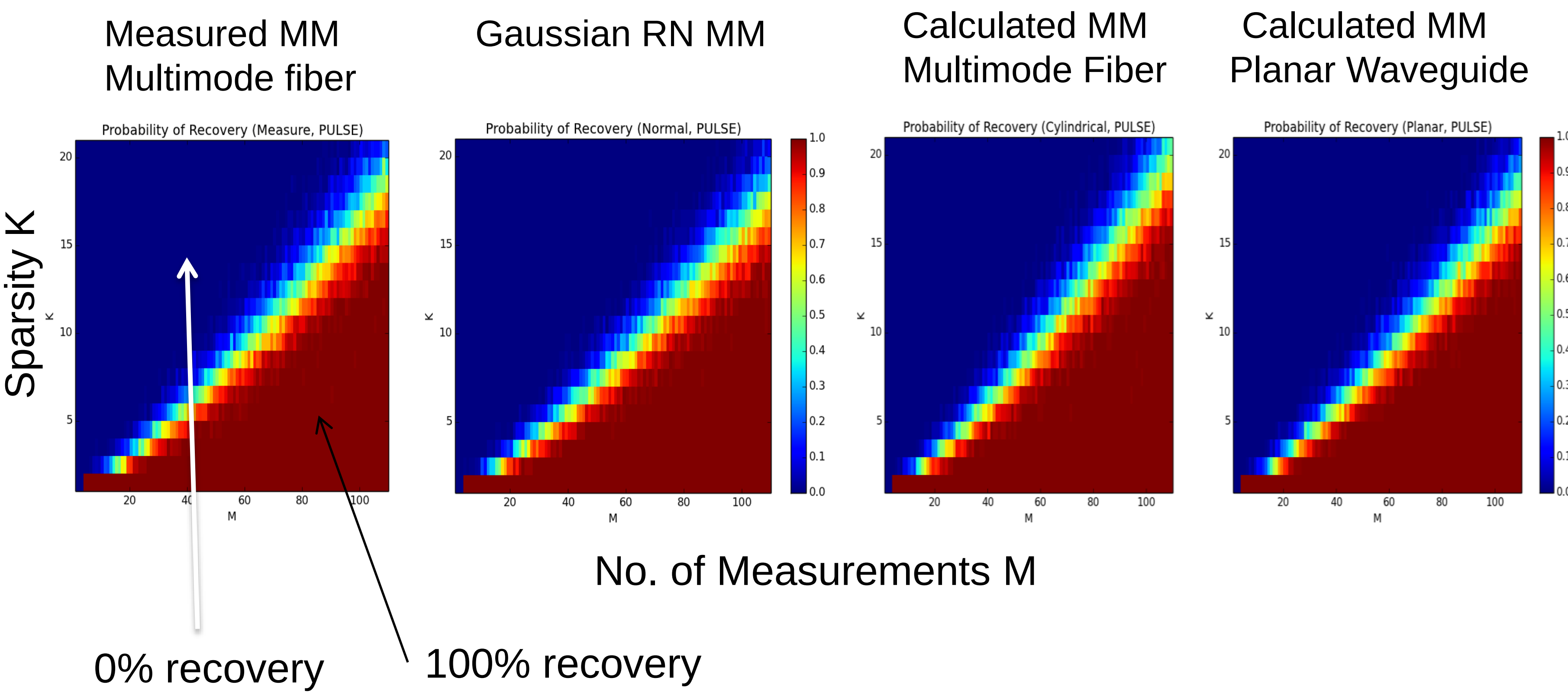
Four Measurement Matrices:

- Measured for multimode fiber (1m, 105μm, 0.22NA)
- Calculated from Gaussian random numbers with same mean and standard deviation as measured
- Calculated MM for multimode fiber with same dimensions as measured
- Calculated MM for Planar waveguide (10cm, 25μm, SOI)

Good agreement measured and calcuated MMs for multimode fiber
Speckle MMs as good as Gaussian RN MM

CS Probability of Recovery – 4 measurement matrices

Signals sparse under identity transform



Sharp "phase transition" from no recovery to 100% recovery typical of good CS measurement matrices

Planar waveguide performance comparable to multimode fiber

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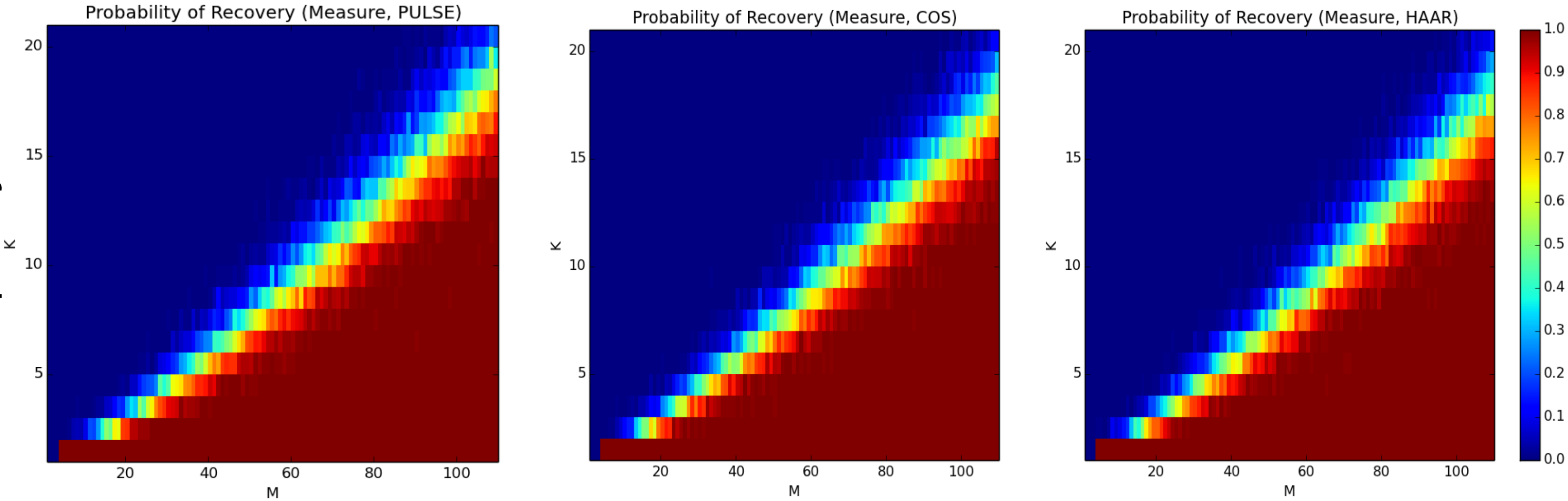
CS Probability of Recovery – measured fiber MM

Signals sparse under different transforms

Identity | Discrete Cosine | Haar Wavelet

Sparsity K



Number of Measurements M

Slightly better performance for signals comprised of pulses (Identity transform)

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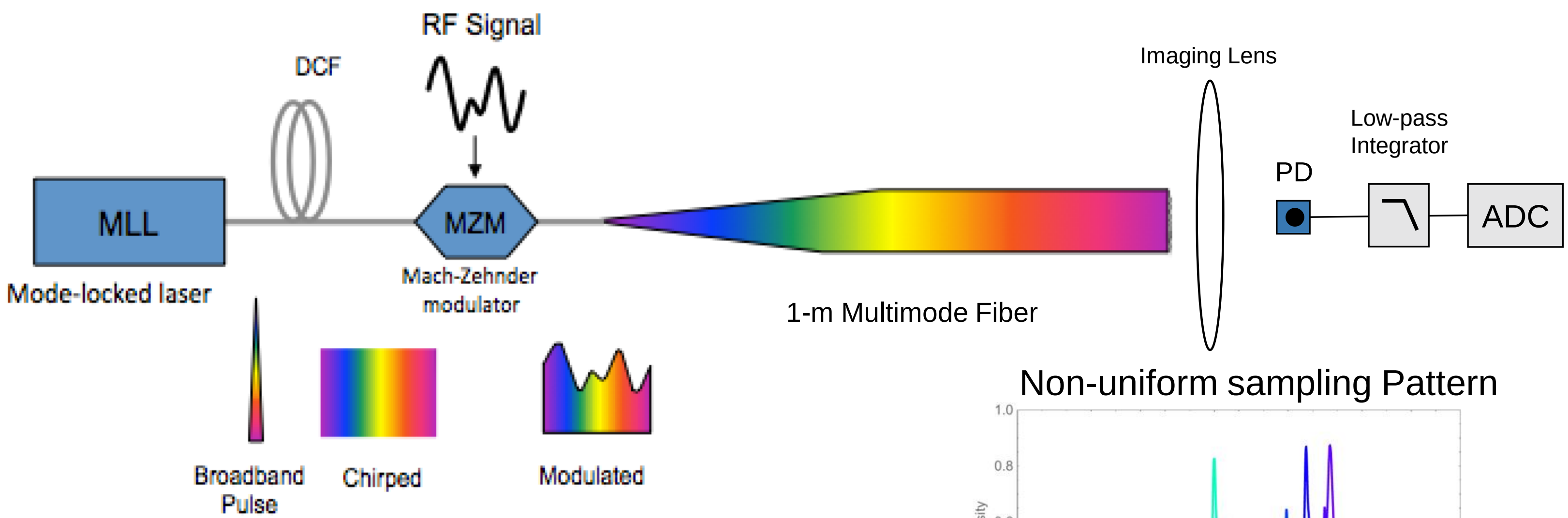
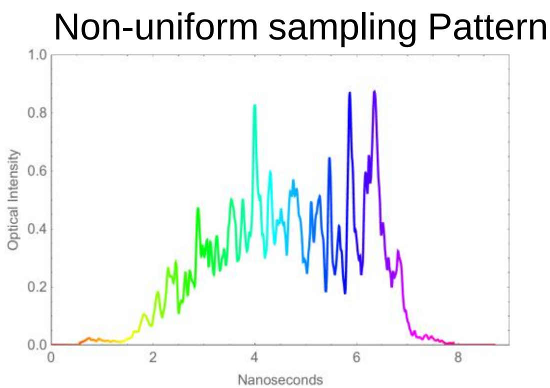
Demonstration of single channel of Speckle system

Periodic non-uniform Sampling with integration

- 1-m multimode fiber
  - 105-μm core diameter, 0.22 NA, step-index
- Single photodiode placed in image plane of fiber output
  - PD diameter at fiber output = 14 μm, accounting for 72x image magnification





Non-uniform sampling given by speckle pattern dependence on wavelength/time

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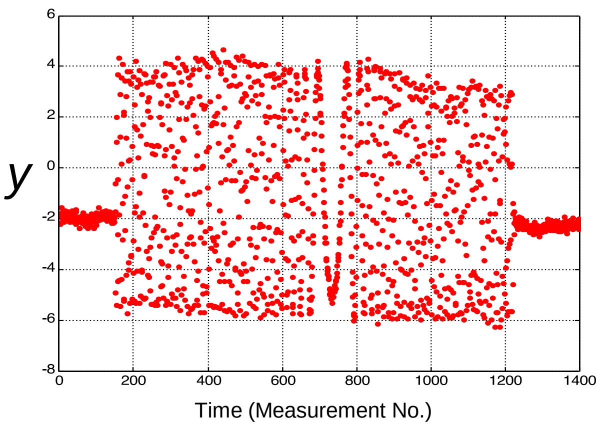
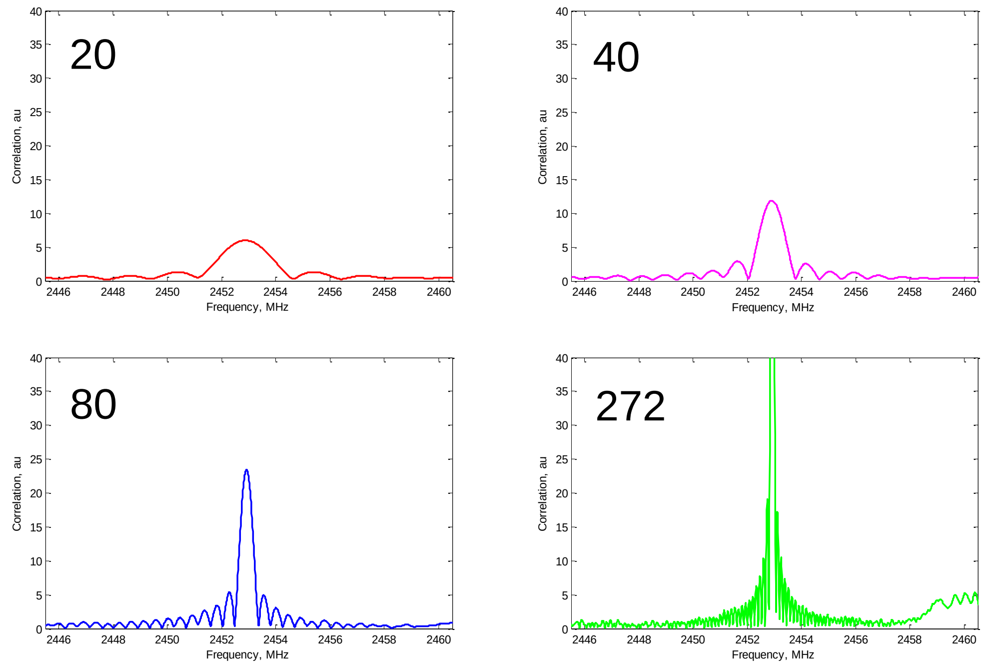
Experimental results for RF Chirped pulses

- RF Parameters:
  - Chirp = 20 MHz / 30 μs
  - Carrier Freq = 2.453 GHz
  - Maximum likelihood recovery



Carrier Recovery *vs*. Number of Measurements



WDM and Speckle non-uniform sampling results nearly identical

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Next steps

- Multi-channel CS demonstration with multimode fiber
- Fabrication of Si planar waveguide
- Demonstration of CS with planar waveguide
- Integration of optical source, optical modulator, speckle waveguide and photodiodes
- Demonstration of CS with integrated system

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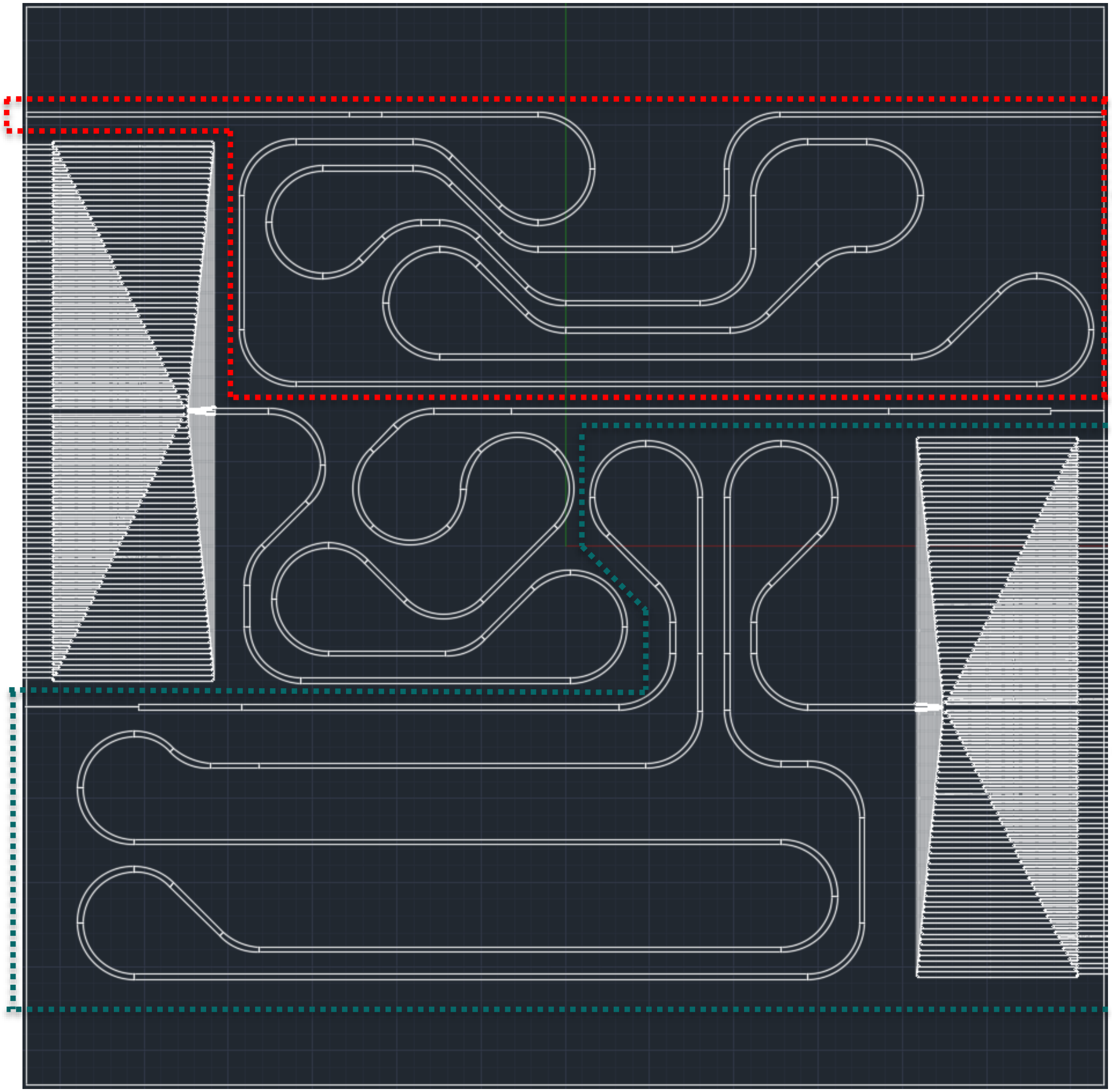
Compressive Sensing Receiver Reticle Design



- 10cm multimode waveguide
- 5cm multimode waveguide terminated with single mode input and 100 channel single mode fanout
- 10cm multimode waveguide terminated with single mode input and 100 channel single mode fanout

2.0 cm

george.valley@aero.org
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Other applicatons of laser speckle

- Machine learning
  - *Saade et al. “Random projections through multiple optical scattering: Approximating kernels at the speed of light” arXiv 2015*
- Spectroscopy
  - *Redding and Cao. "Using a multimode fiber as a high-resolution, low-loss spectrometer." Optics letters 2012 also Optics Express 2013*
- Wavelength meter
  - *Mazilu et al. "Random super-prism wavelength meter." Optics letters 2014*
- Strain sensor
  - *Varyshchuk,et al. "Using a multimode polymer optical fiber as a high sensitivy strain sensor." 2014.*
- Imaging
  - *Liutkus et al. "Imaging with nature: Compressive imaging using a multiply scattering medium." Scientific reports 2014.*
  - *Kolenderska et al."Scanning-free imaging through a single fiber by random spatio-spectral encoding." Optics letters 2015*
  - *Shin et al. "Single-pixel imaging using compressed sensing and wavelength-dependent scattering." Optics letters 2016.*

Conclusions

- Many undersampling strategies developed for measuring RF signals in the GHz band at sub-Nyquist rates
- Intense work in the past 8 years on photonic implementations
  - *Most multiply an RF signal by a PRBS using an EO modulator*
- Serial compressive sensing demonstrated with SLM applying PRBS
- Periodic non-uniform sampling demonstrated using
  - *WDM system*
  - *Speckle in multimode waveguide*
- Compressive sensing simulations
  - *Typical CS behavior with measured and calculated multimode fiber and calculated multimode waveguide measurement matrices*
  - *Sparsity/Measurement plots with sharp phase changes*
- Simulations for planar waveguides indicate a path to a photonic integrated circuit for a CS receiver in the GHz band

george.valley@aero.org
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