Real Time Photon-Counting Receiver for High Photon Efficiency Optical Communications

Session 8: Detectors and Receivers I

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Scalable Real Time Photon Counting Ground Receiver System

Motivation:

- Affordable real time photon counting optical ground receivers are needed to enable space to earth communications for both public and private applications.

Strategy:

- Develop a photon counting Real Time Optical Receiver (RealTOR) that includes the aft optics, single photon counting detector, and real time FPGA-based receiver.
  - Scalable → Lower production cost and enable expandable architecture
  - Create path to commercialization.

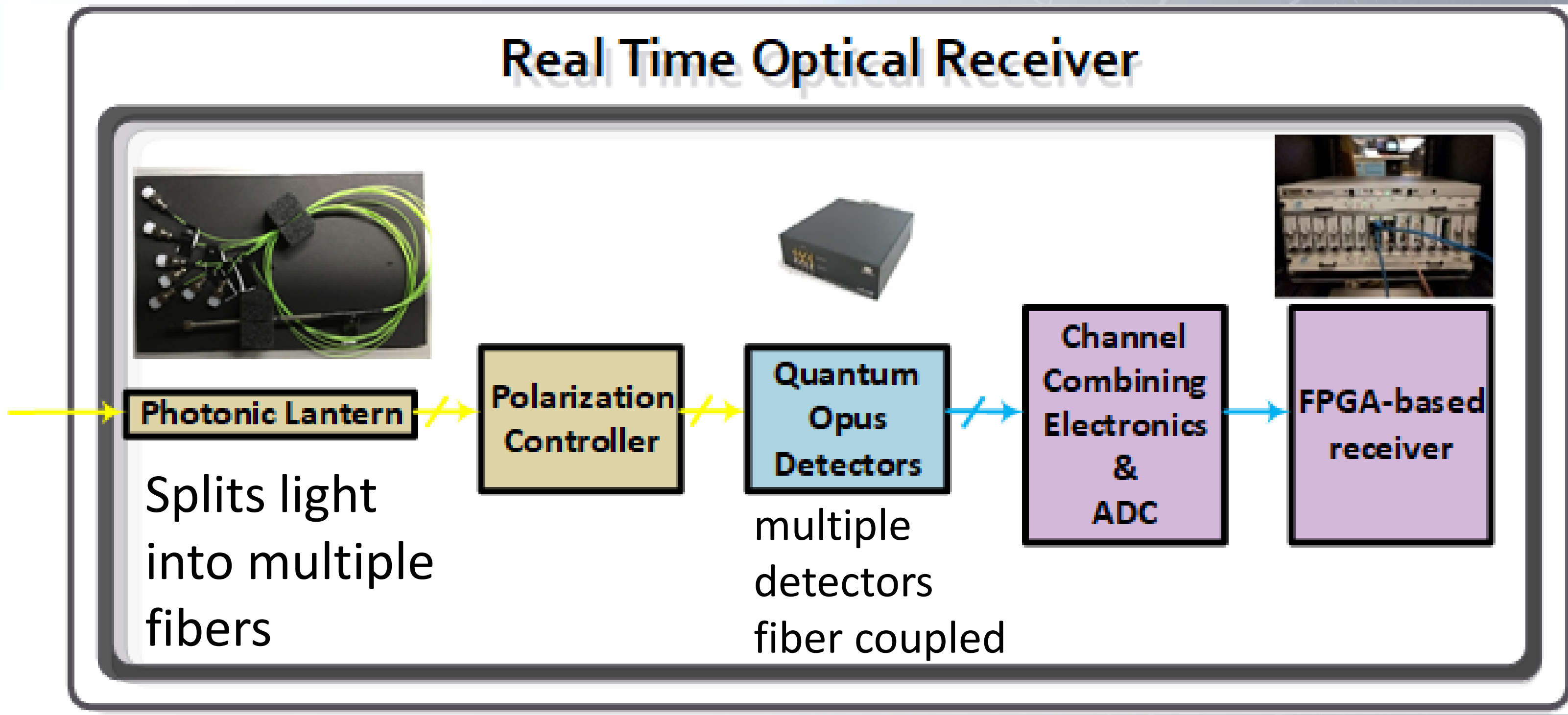
Goals:

- Use components already on the market as much as possible.
- Create a scalable design that can be used for a variety of:
  - data rates (up to 528 Mbps)
  - telescope aperture sizes
  - environmental factors (background light and atmospheric turbulence levels).

RealTOR a scalable COTS ground receiver concept

- **Considering many COTS components and architecture solutions**
- **Current solution under investigation:**
  - **Photonic lantern**
  - **Single-pixel array of commercial off the shelf single photon detectors sharing one cryostat. Detectors are fiber coupled to cryostat with SMFs or FMFs.**
  - **CCSDS telemetry (downlink) optical waveform on a real time FPGA-based receiver**

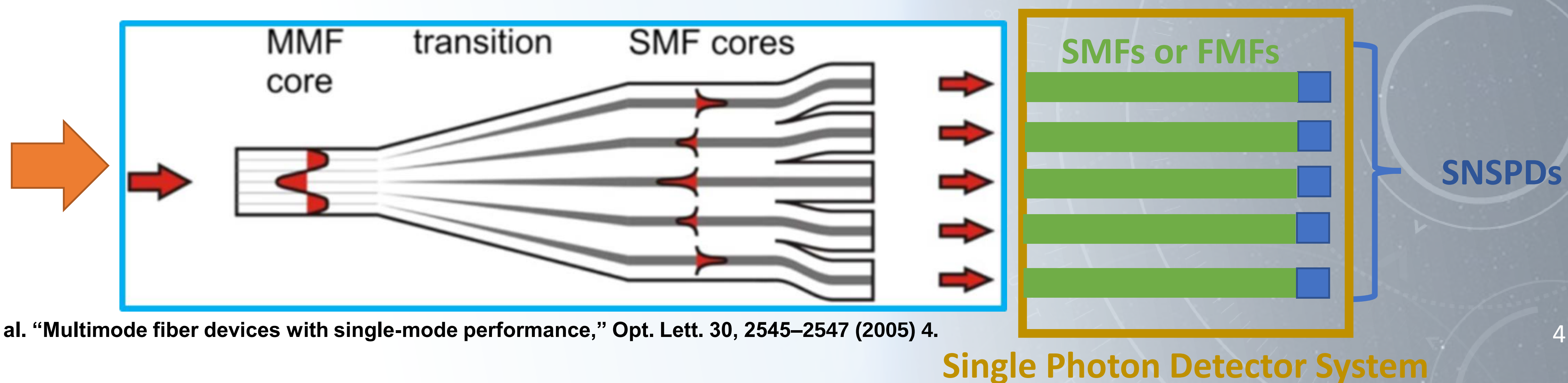
Light from Back-end Telescope Optics



Photonic Lanterns: an aft optics solution

- **A solution to deliver light from receiver telescope to detectors will:**
  - ❑ Maximize collection of atmospheric distorted light (multi-moded) aft of the telescope.
  - ❑ Evenly split light to detectors to minimize detector blocking loss.
  - ❑ Maximize light coupled into multiple, single mode fiber (SMF) or few mode fiber (FMF) coupled detectors.
  - ❑ Minimize pulse dispersion (jitter) added to system.
- **Photonic Lanterns:**
  - ✓ Collects the light aft of the telescope into a multi-mode fiber.
  - ✓ Splits the multimode light to multiple smaller core fibers (traditionally SMFs).
  - ✓ Majority of length is in graded index small core fiber minimizing jitter.

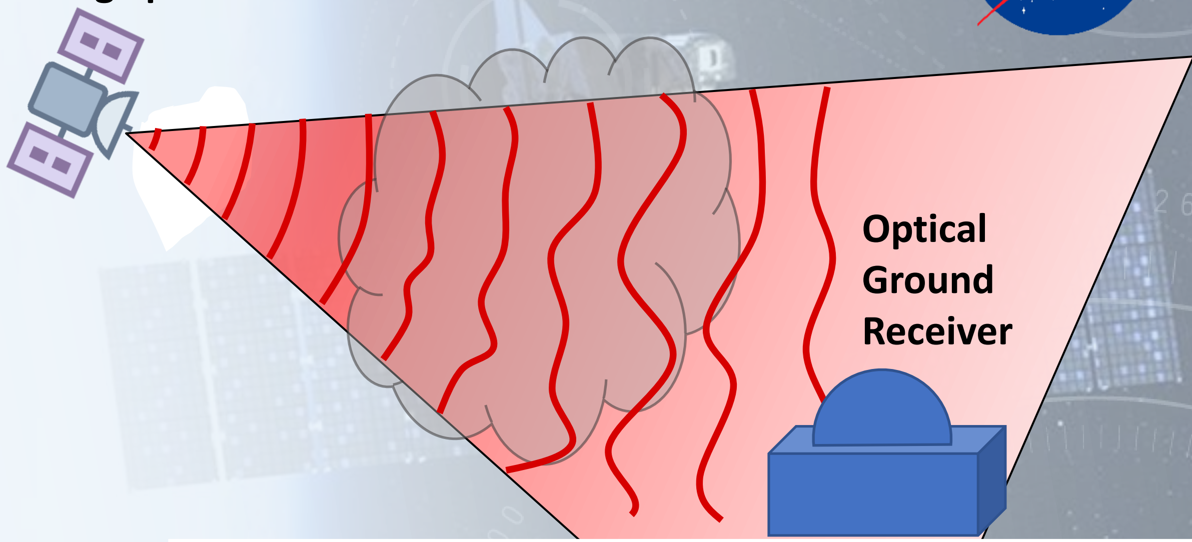
Multi-moded Light from aft of Receiver Telescope

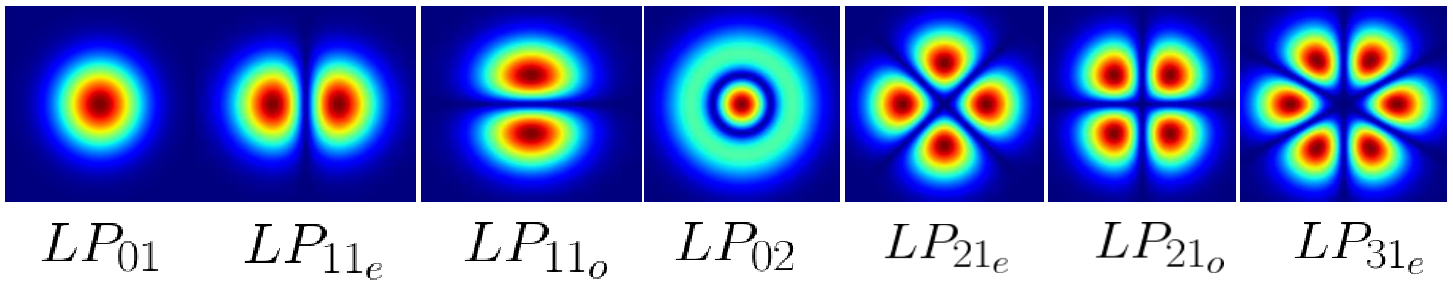


From: S. G. Leon-Saval et al. "Multimode fiber devices with single-mode performance," Opt. Lett. 30, 2545–2547 (2005) 4.

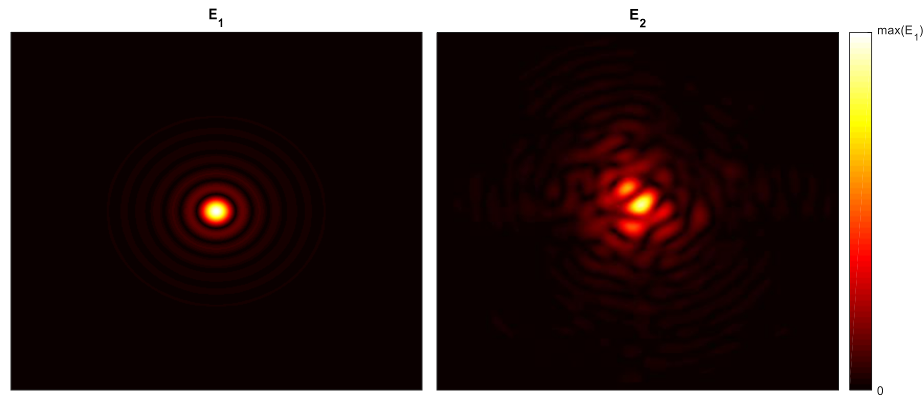
Atmospheric Effects on Lantern Coupling Efficiency

- The laser transmitted from a spacecraft originates as a Gaussian shape (L_{01})
- Atmosphere distorts the beam profile and scatters energy into higher-order spatial modes
- The number of fiber spatial modes coupled by a photonic lantern matches the sum of the modes supported by the output fibers





A 7:1 SMF photonic lantern can couple these 7 spatial modes

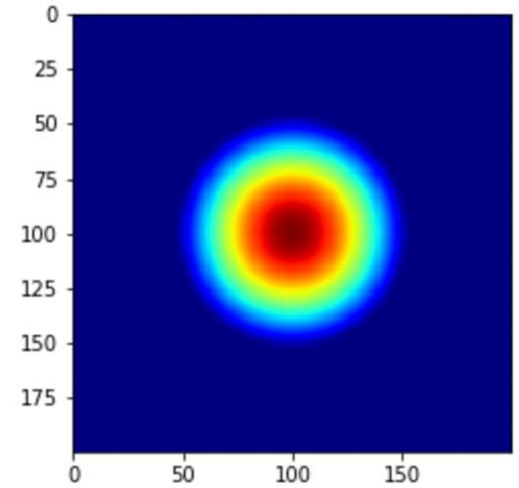


Effect of atmosphere on beam intensity profile

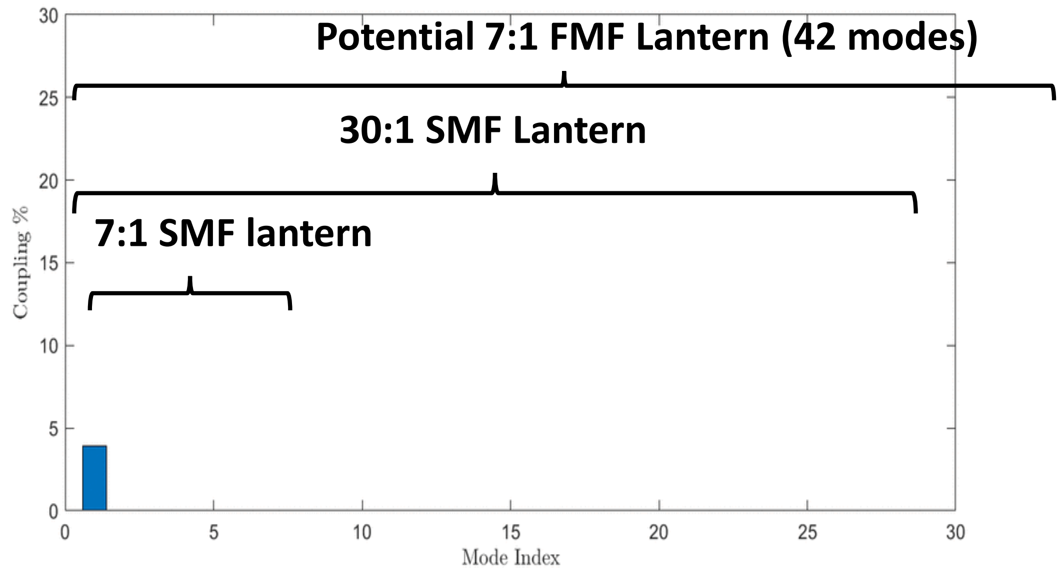
Therefore: Higher turbulence → higher number of lantern output fibers needed for efficient coupling → higher number of detectors → increased cost.

A possible solution: Few Mode Fiber Lanterns

- **For higher turbulence applications another solution to is needed to increase mode coupling capacity**
- **Since single photon detectors can be coupled with FMFs without loss, we can create a new type of lantern with FMFs**
  - **Increase the number of modes supported by each fiber output leg (1 mode→6 modes)**
  - **Enables higher number of modes coupled with same number of detectors (7 fibers → 42 modes)**
- **Compare 7:1 SMF lantern to 7:1 FMF lantern**
  - **Coupling efficiency of fiber modes**
  - **Effect on Coupling efficiency of:**
    - > Free space Gaussian input numerical aperture
    - > Free space Gaussian input mode field diameter
  - **Analysis of Jitter added to system**
  - **Evenness of power splitting to each lantern leg.**

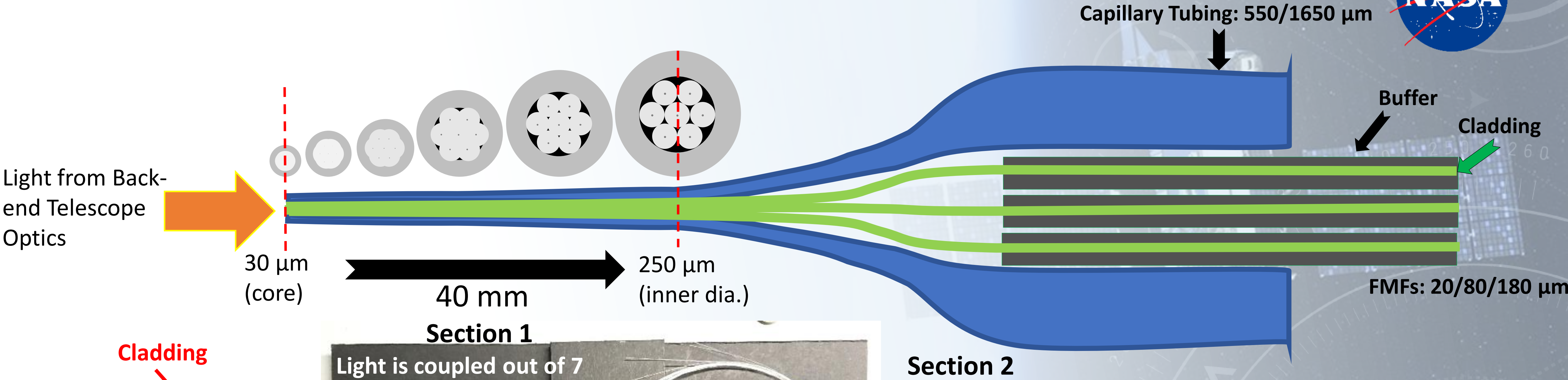


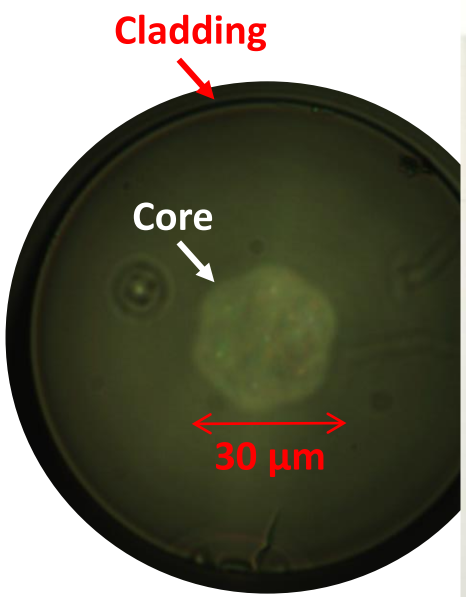
Modes summing to form distorted beam profile



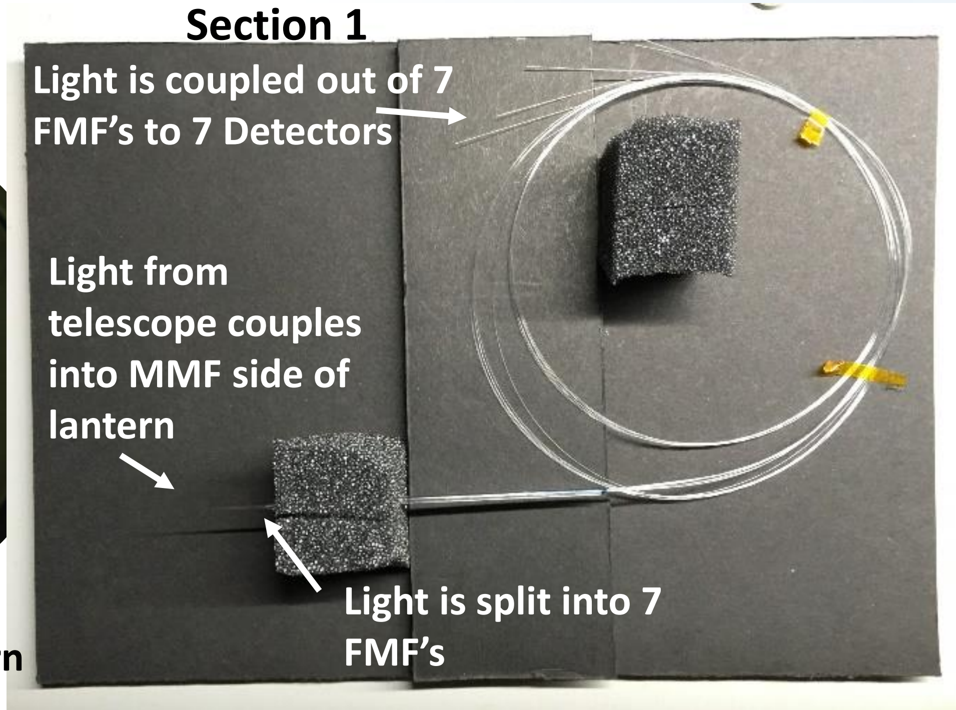
Power distribution of modes in atm. distorted beam profile

7:1 FMF Photonic Lantern fabricated at GRC

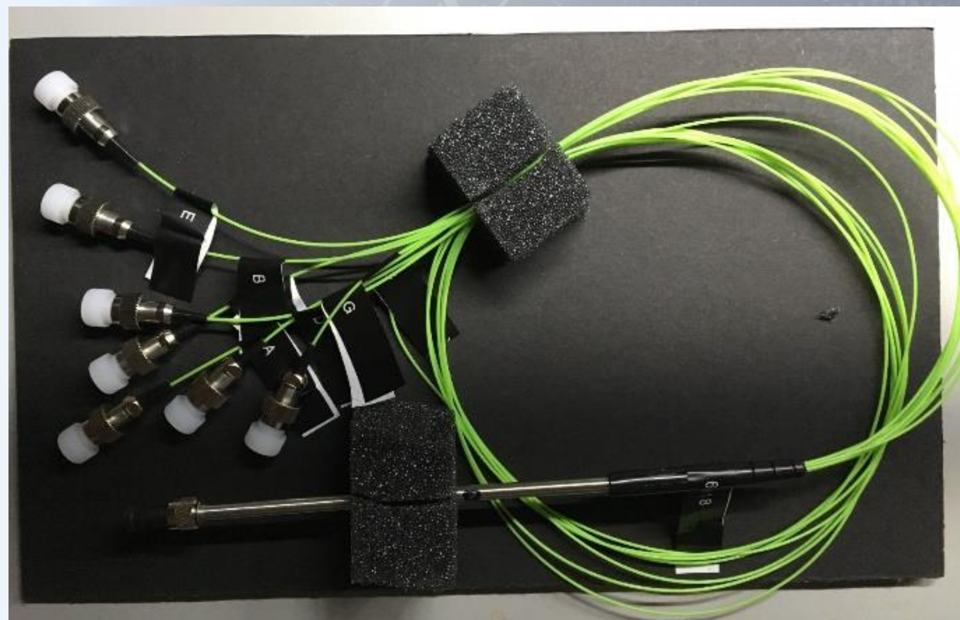




Multimode input of lantern

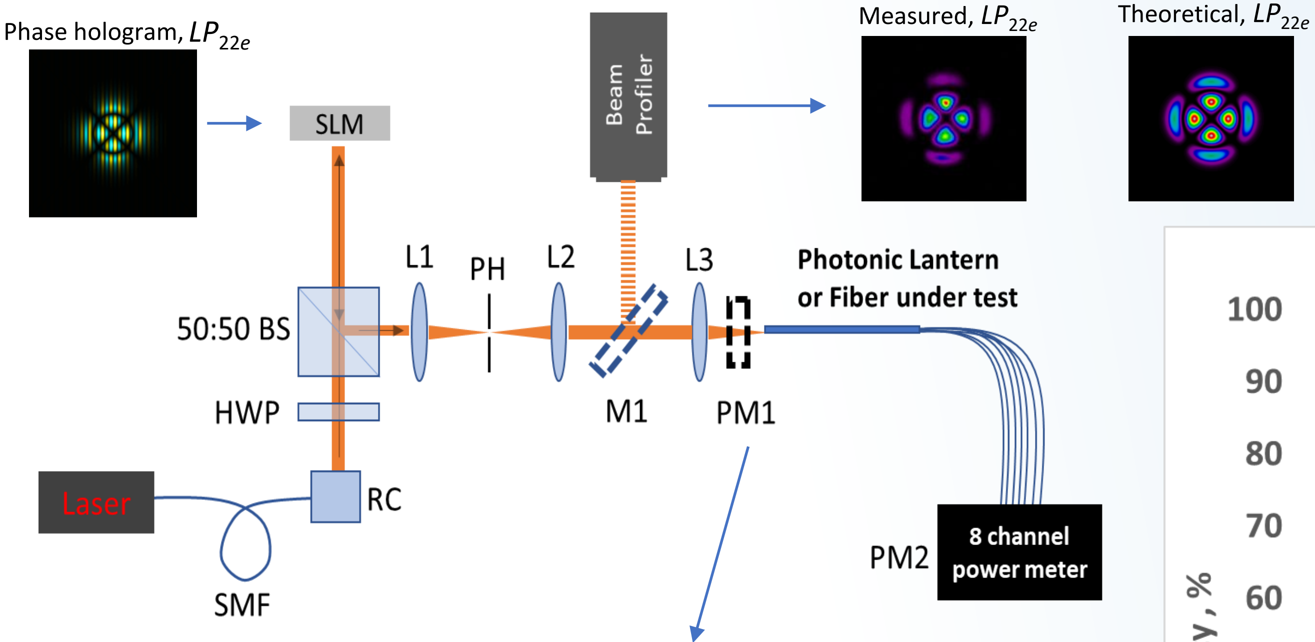


An unpackaged 7:1 FMF photonic lantern.



A packaged 7:1 FMF photonic lantern.

Measured Coupling Efficiency for Fiber Spatial Modes



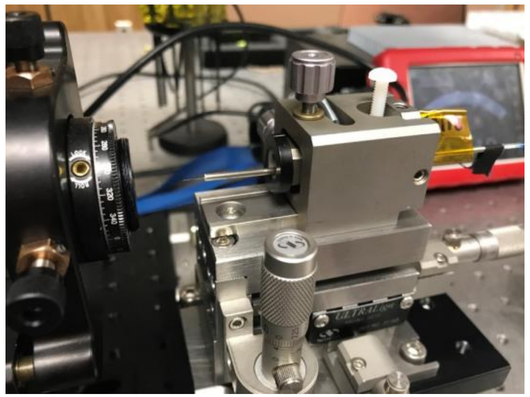
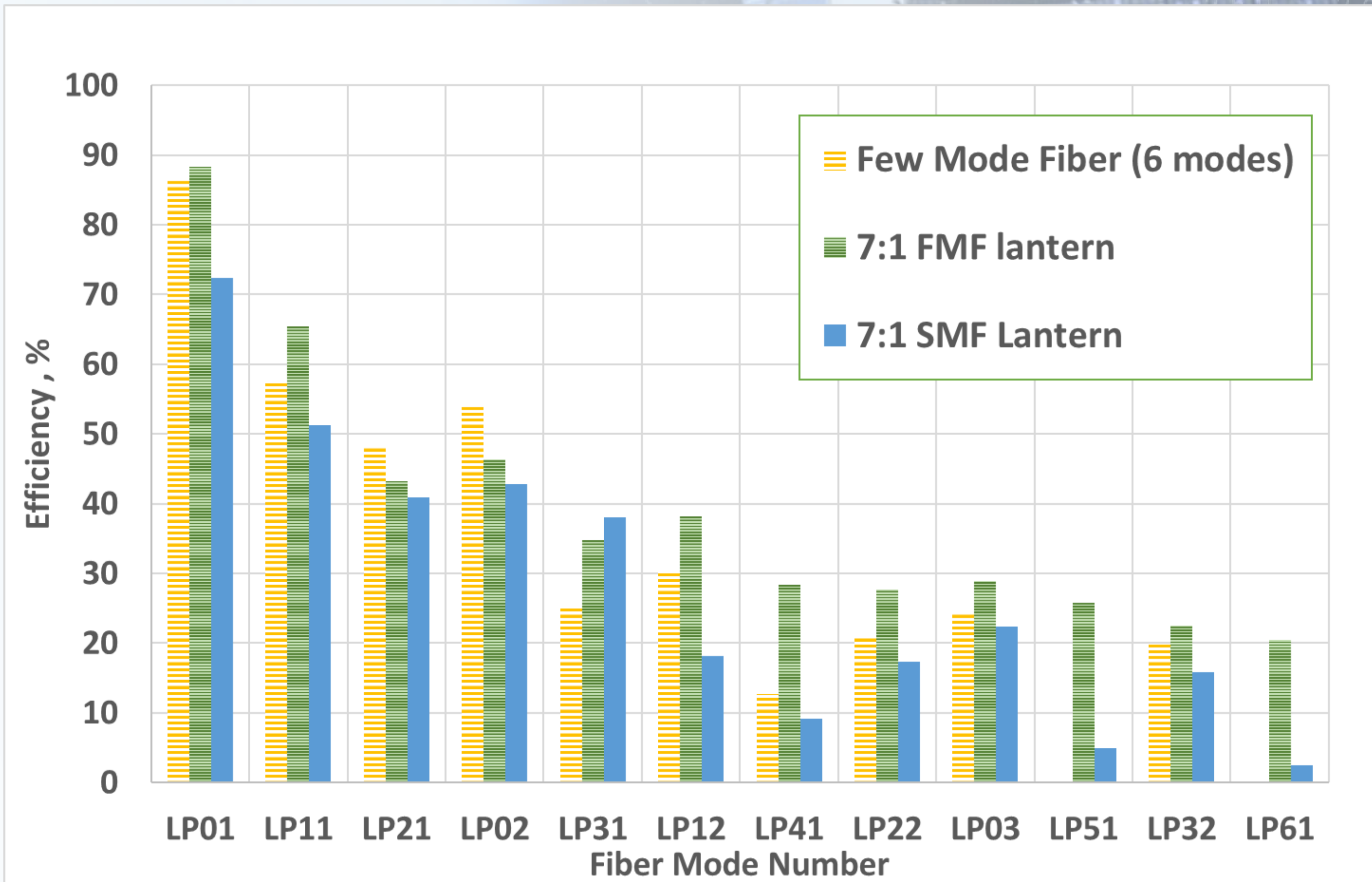


Photo close-up of the lantern in optical setup



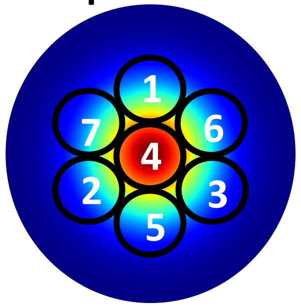
Results indicate FMF lanterns will have higher coupling efficiency at higher turbulence levels than the SMF lantern and FMF.

Measured Power Split

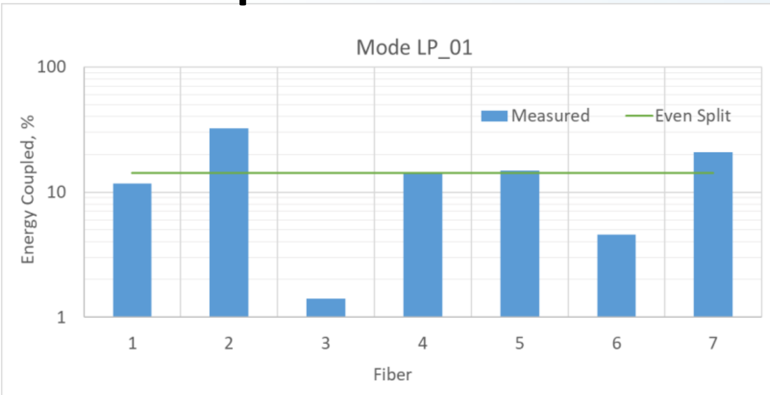
MMF input of lanterns

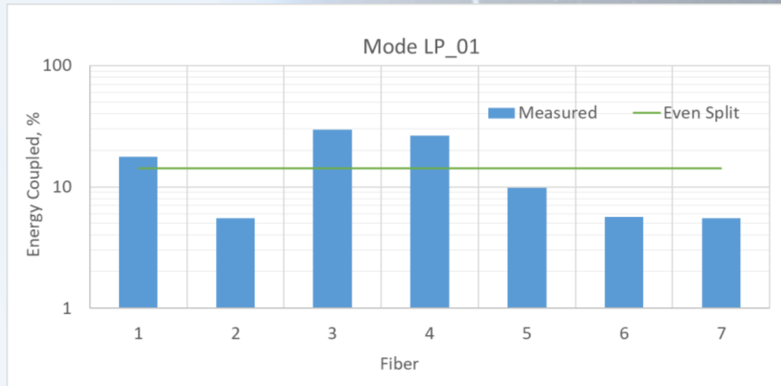
SMF photonic lantern

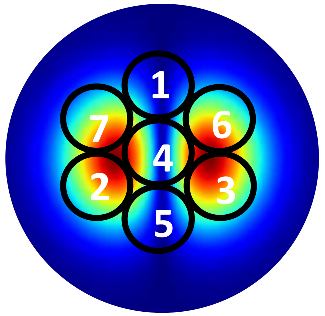
FMF photonic lantern



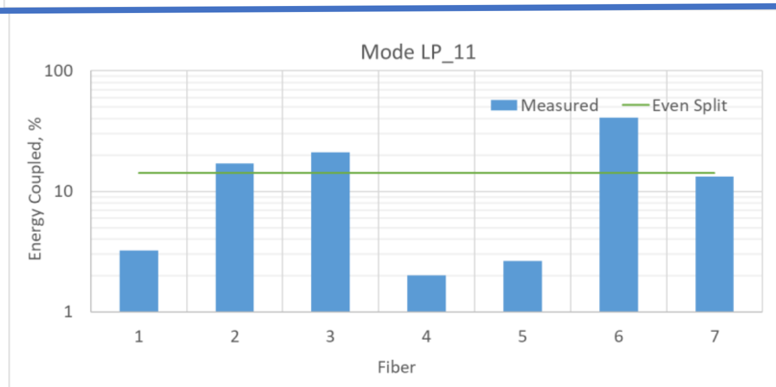
LP_{01}

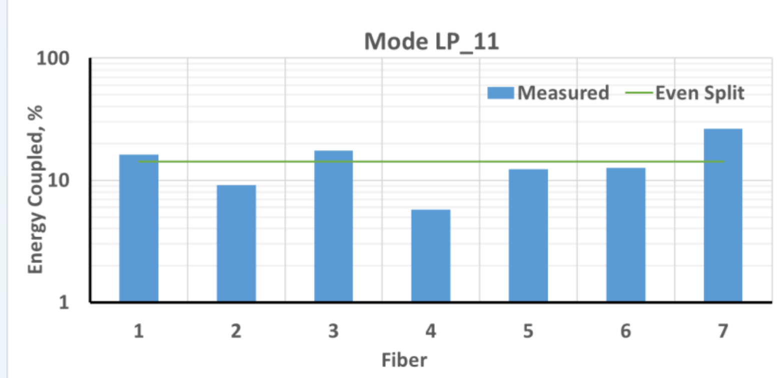


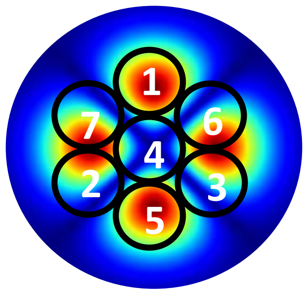




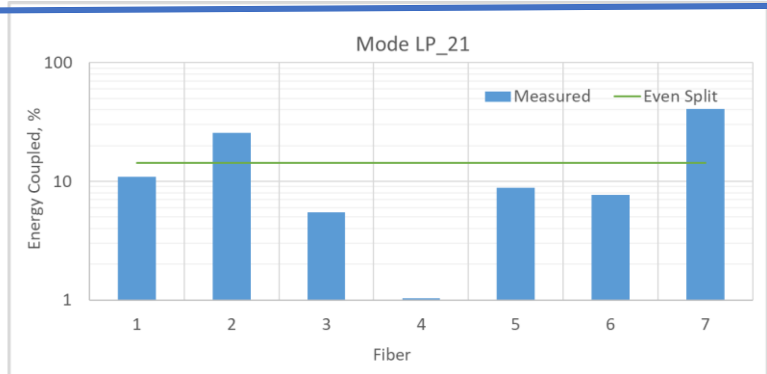
LP_{11_e}

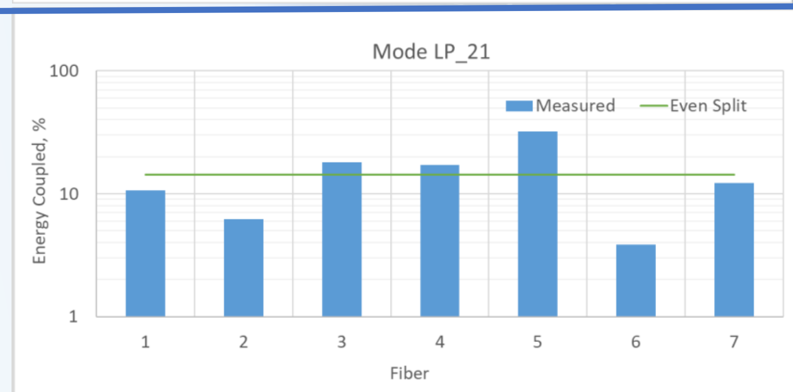






LP_{21_e}





Results imply that a beam varying in distortion caused by atmospheric conditions would produce less varied splitting with a FMF lantern. Therefore a FMF lantern would have lower detector blocking loss.

Commercial SNSPD Detector System Description

Opus One™ from Quantum Opus, LLC

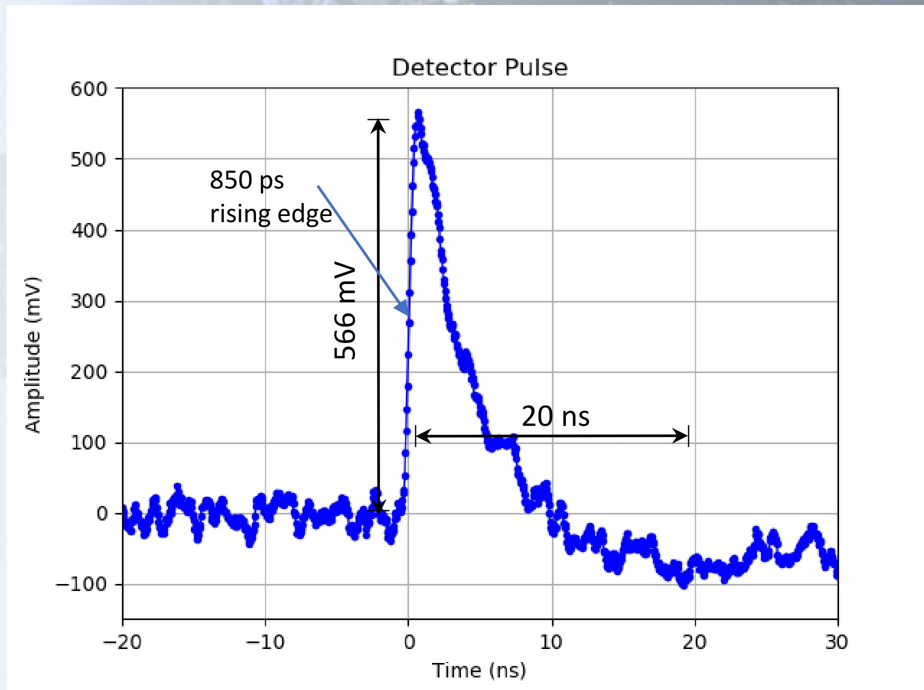
System Parameters	Previous Specs	Current Specs
Wavelength	1550 nm	1550 nm
Fiber coupling	SMF	SMF and FMF
Dark counts	< 100 cps	< 10^3 cps (SMF) < 10^5 cps (FMF)
Reset time	50 ns	20 ns
Jitter (SNSPD + Amp)	< 100 ps	45 - 60 ps min
Electronics	Room temp amplifiers, 500 MHz, AC-coupled	Room temp amplifiers, 500 MHz, DC-coupled

Evaluating differences versus previous year's data set: DC-coupled electronics and few mode fiber coupling

Quantum Opus SNSPD and electronics

Helium compressor

Typical output pulse

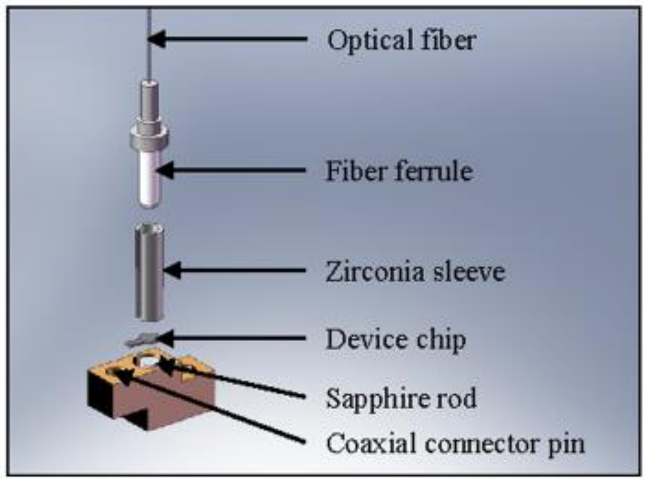


Parameter	Measured
Reset time (90/10)	20 ns
Pulse height	300 – 600 mV
Rising edge	850 ps

Single-Mode and Few-Mode Fiber Coupling

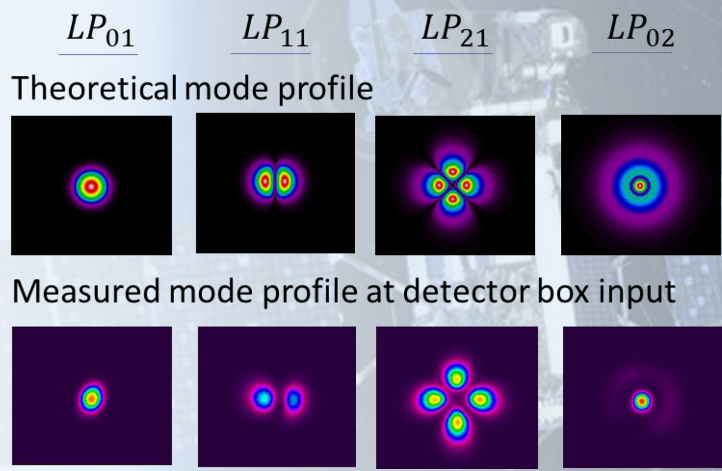
- Single mode fiber is standard SMF-28
- Few mode fiber (FMF) is 20-micron core graded index
- FMF propagates up to 6 LP modes (ignoring polarization): $LP_{01}, LP_{11e}, LP_{11o}, LP_{21e}, LP_{21o}, LP_{02}$

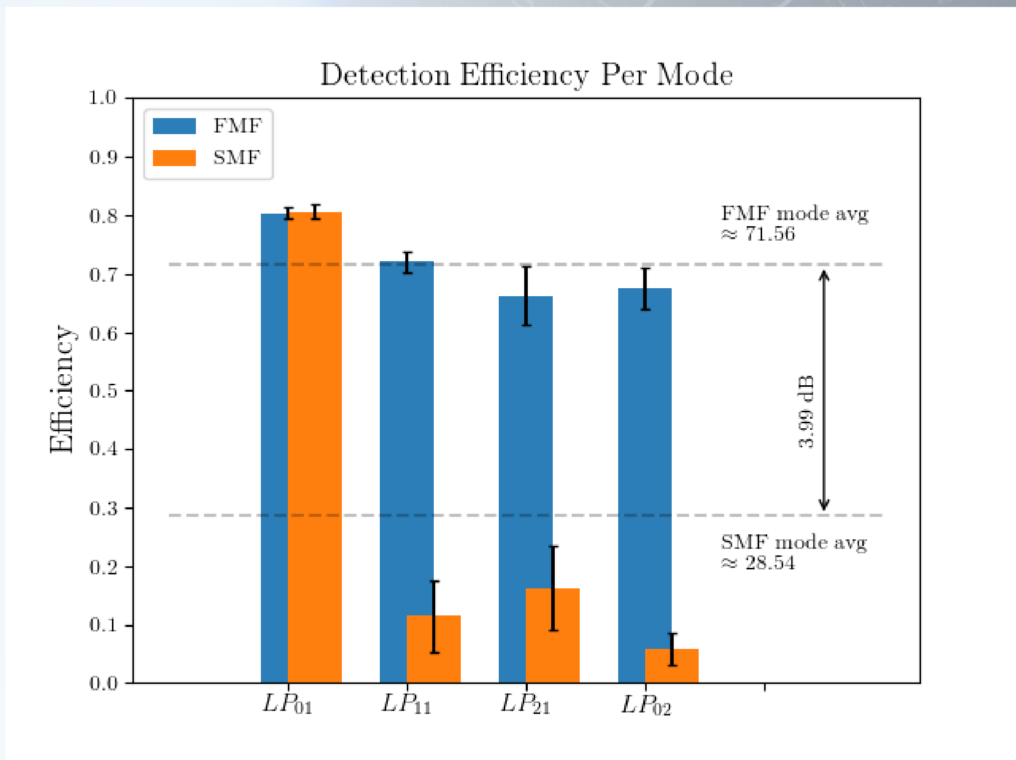
Fiber "butt-coupling" to detectors



Miller, et. al. Optics Express 2011

http://www.quantumopus.com/web/product-info/custom-products/



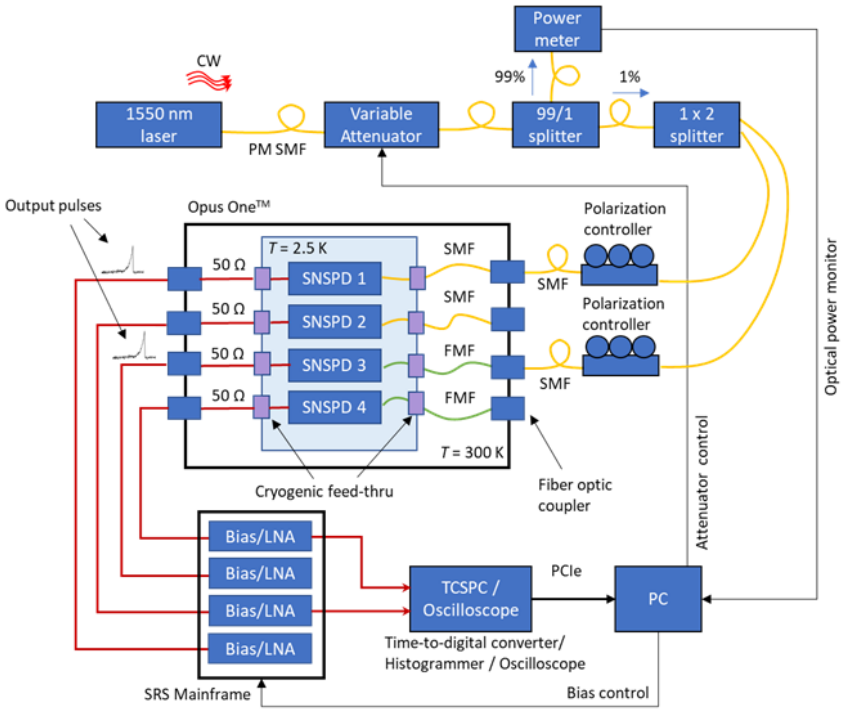


FMF-coupled max detection efficiency ≈ 60% – 80% per mode, ≈ 71% average over all modes – about 4 dB improvement over SMF coupling

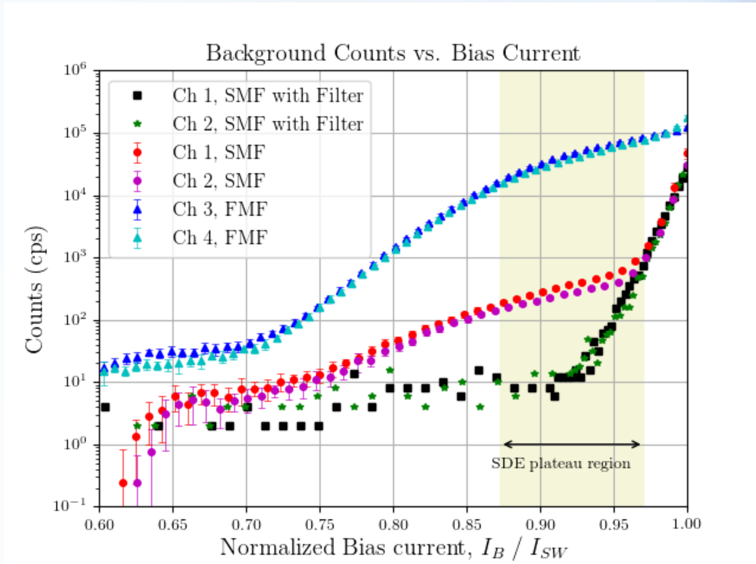
System Detection Efficiency (SDE) vs. Bias Current

$$SDE = (R_{out} - BCR)/R_{in}$$

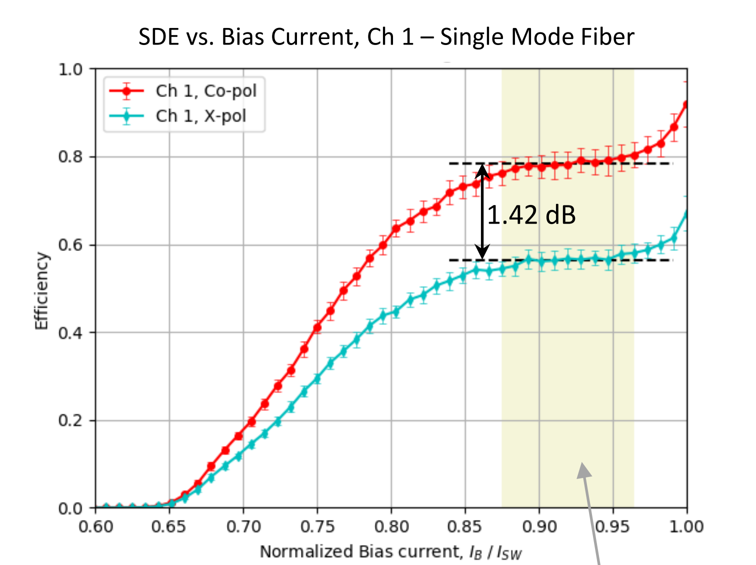
R_{out} = measured output count rate
BCR = measured background count rate
R_{in} = estimated input photon rate

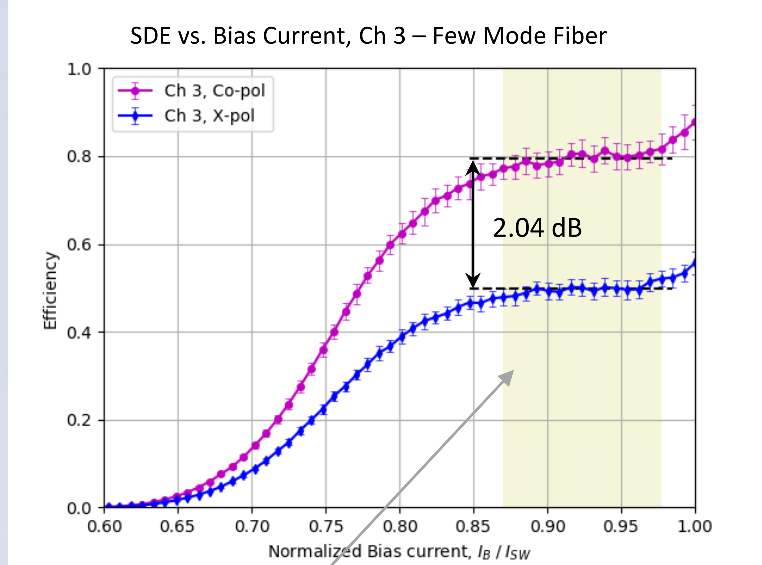


Measurement diagram



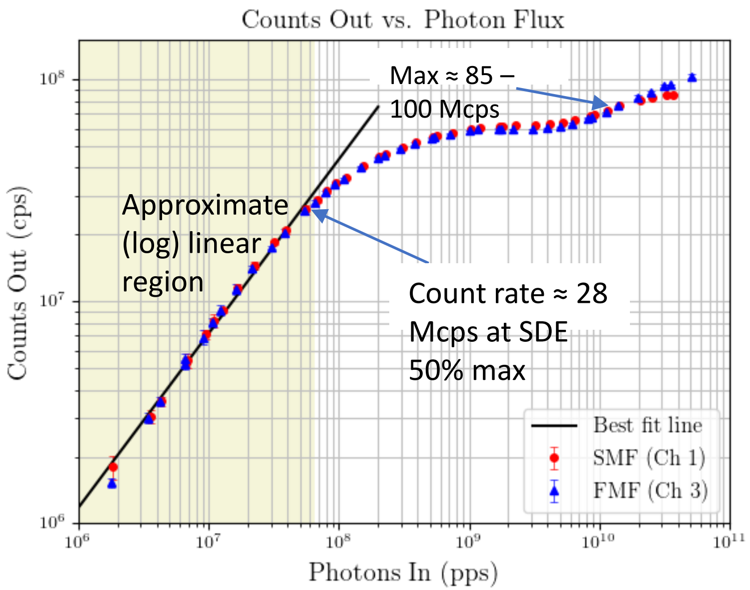
- Background counts measured with the input ports to the box closed.
- Note standard COTS systems includes 25 K SMF background filter
- With SMF filter BCR < 100 cps
- With new FMF blackbody filter expecting ~ 10 dB reduction

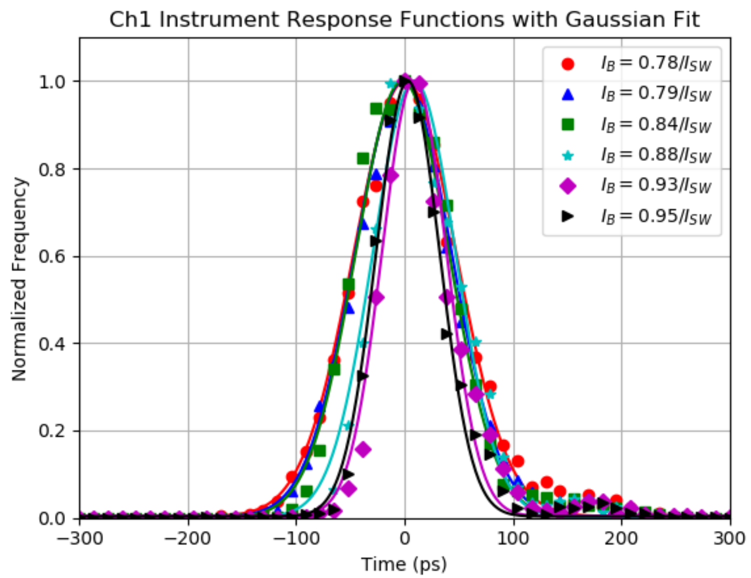




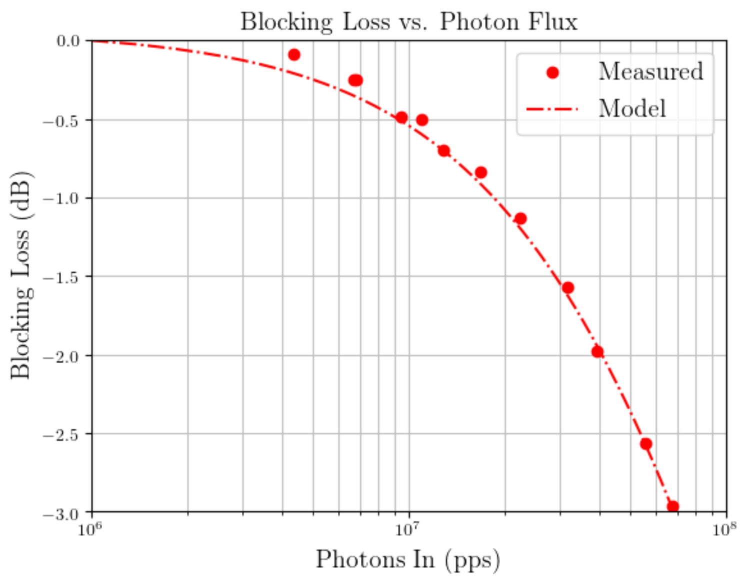
Detection efficiency plateau operating regions – Δ*SDE* < 2%

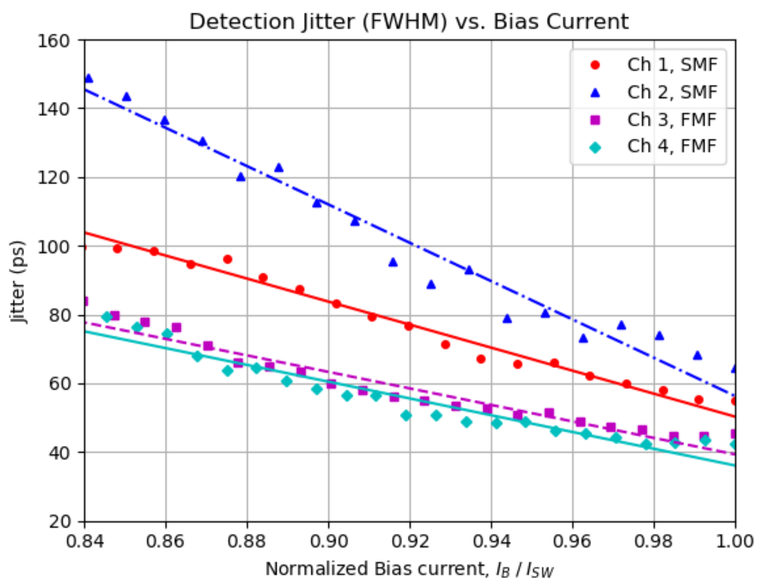
Single Detector Count Rate and Jitter

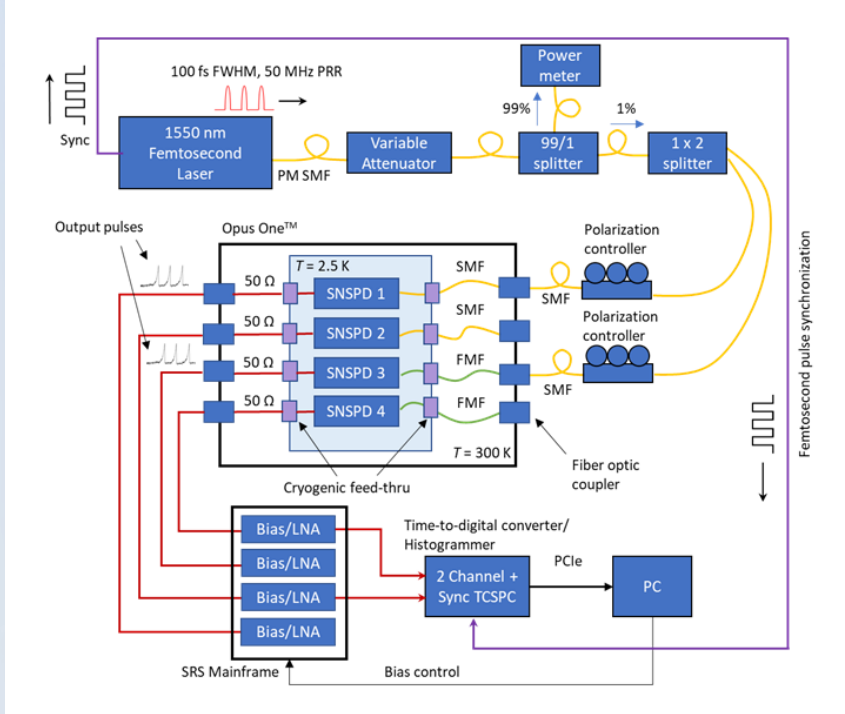




- Linear response to input photon flux up to ≈ 28 Mcps for ≈ 65 M-photons/s input; 3 dB blocking loss
- Maximum achievable count rate on the order of 85 – 100 Mcps
- Trade-off between count rate and detection efficiency



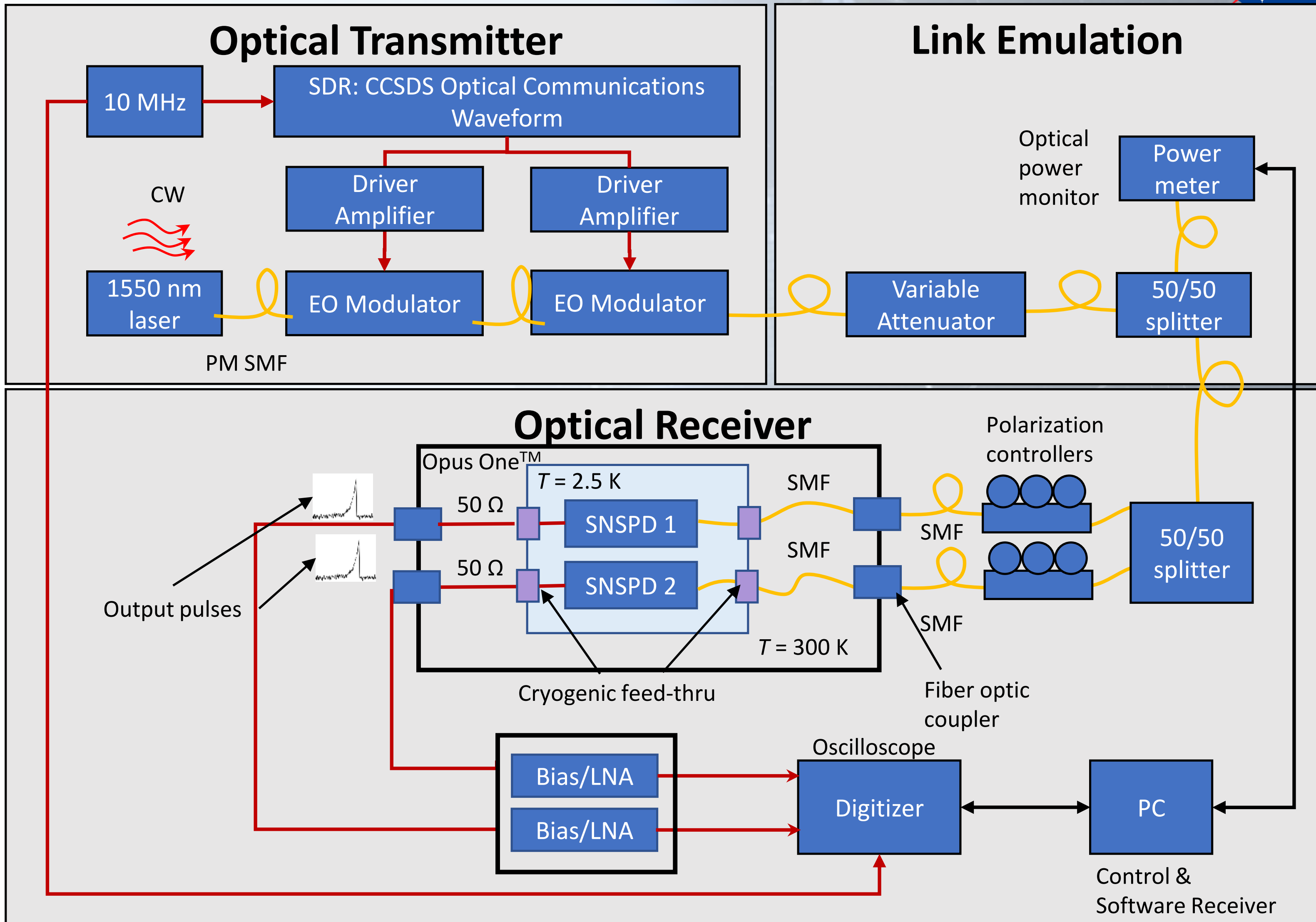




Jitter measurement diagram

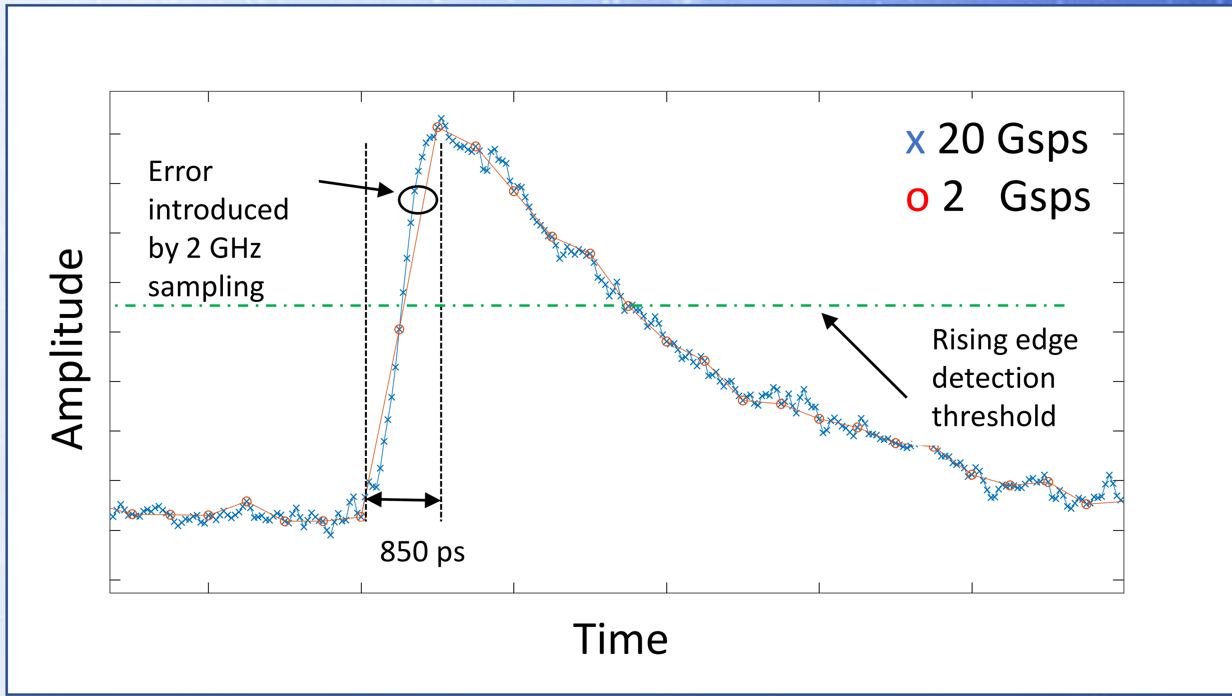
Optical Communications System Test Bed

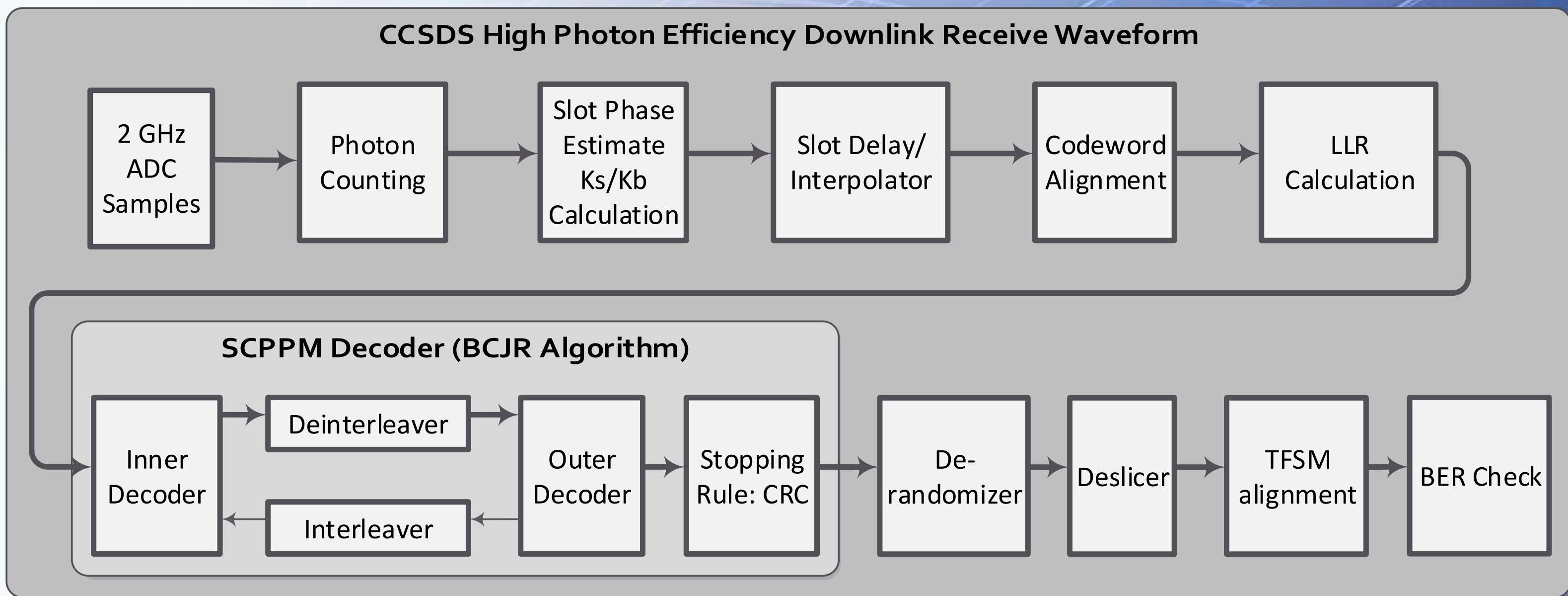
- **Testing performed with the following CCSDS HPE waveform:**
  - **PPM-32**
  - **Code rate: 1/3**
  - **Slot width: 1 ns**
  - **Data rate: 40 Mbps**
- **Includes two EO modulators in cascaded in series with a time offset in the electrical signal driving the modulators, improving the extinction ratio**
- **No additional noise inserted**
  - **Kb≈ 0.0001 background photons/slot**



Optical Receiver – Waveform

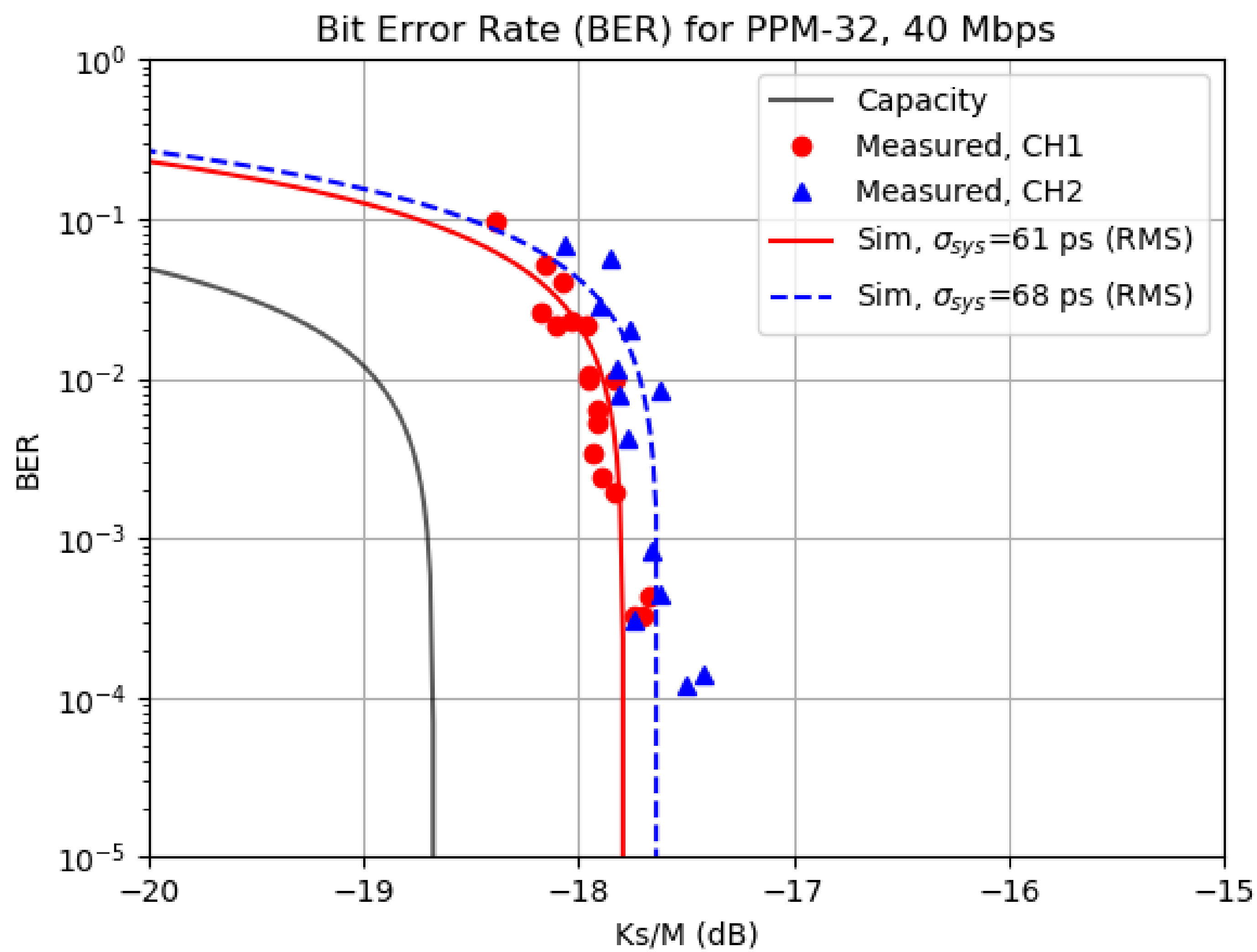
- **Detector pulses are sampled at 2 GHz with an oscilloscope and post-processed using a Matlab receiver model**
- **SCPPM decoder performs iterative decoding using the BCJR algorithm**
- **Sample jitter introduced by 2 GHz sampling of 850 ps detector pulse is ~45 ps RMS**
- **Calculated total receiver jitter:**
  - **Channel 1: 61 ps RMS**
  - **Channel 2: 68 ps RMS**





System Testing Results

- **PPM-32**
- **Code rate 1/3**
- **1 ns slot width**
- **Guard band: 8 slots (25%)**
- **40 Mbps data rate**
- **Kb ≈ 0.0001 background photons/slot**



Vadatech Platform Overview

Description

- **Industry standard modular µTCA form factor – same as SGSS**
- **High bandwidth backplane connects multiple FPGA or CPU cards together**
- **Ethernet interfaces for control and data**
- **GPS Receiver – can act as the master clock, IEEE1588**
- **Remote reconfiguration/debugging through JTAG over Ethernet**
- **FMC follows VITA 57**

Common Carrier Card: AMC 516

- **Xilinx Virtex 7 690T -2 speed grade**
- **FreeScale QorIQ P2040 PowerPC running Linux**
- **2 GB RAM to FPGA, 1 GB RAM to PowerPC**

Receiver:

- **FMC211: ADC EV10AS150B 10-bit @ 2.6 GSps**
- **Final solution dependent on channel combining method**

Transmitter:

- **FMC218: AD9739 DAC 14-bit at 2.5 GSps**
- **Custom Card commercialized**

Vadatech Chassis (12 slots)

AMC516 (V7 FPGA)

FMC211 (ADC)

FMC218 (DAC)

Custom Card

Upgrades are planned to the platform once the necessary capability is determined

FPGA-based Simple Receiver

Purpose:

- Implement a simple receive waveform which checks for bit errors produced by the transmitter.

Accomplishments:

✓ Completed development of VHDL for simple receiver.

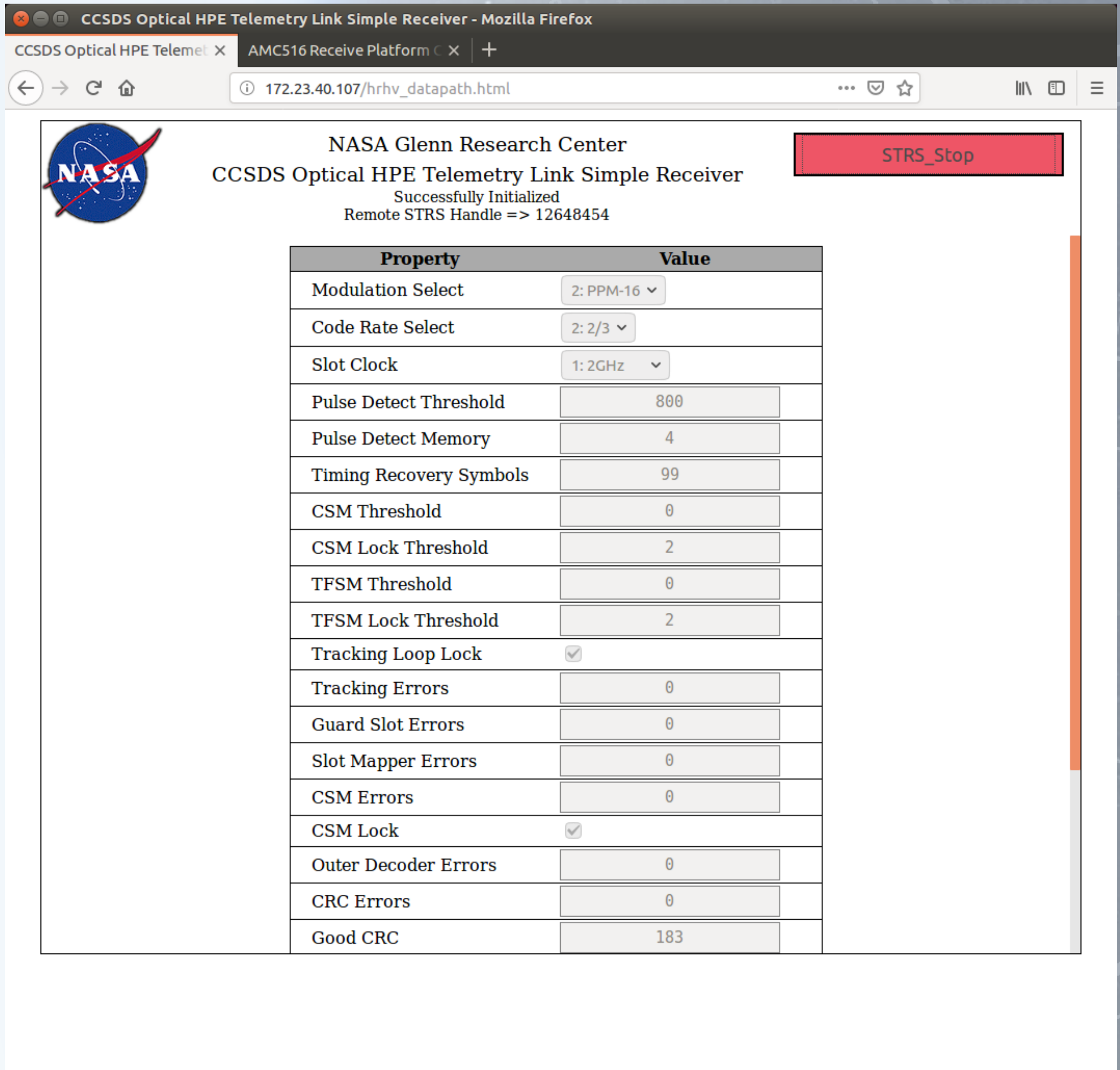
✓ Completed development of GUI, based on the STRS Core Flight implementation.

✓ Successfully received the transmitted signal from FPGA-based transmitter.

Next Steps →

> Verify receiver Ethernet output interface

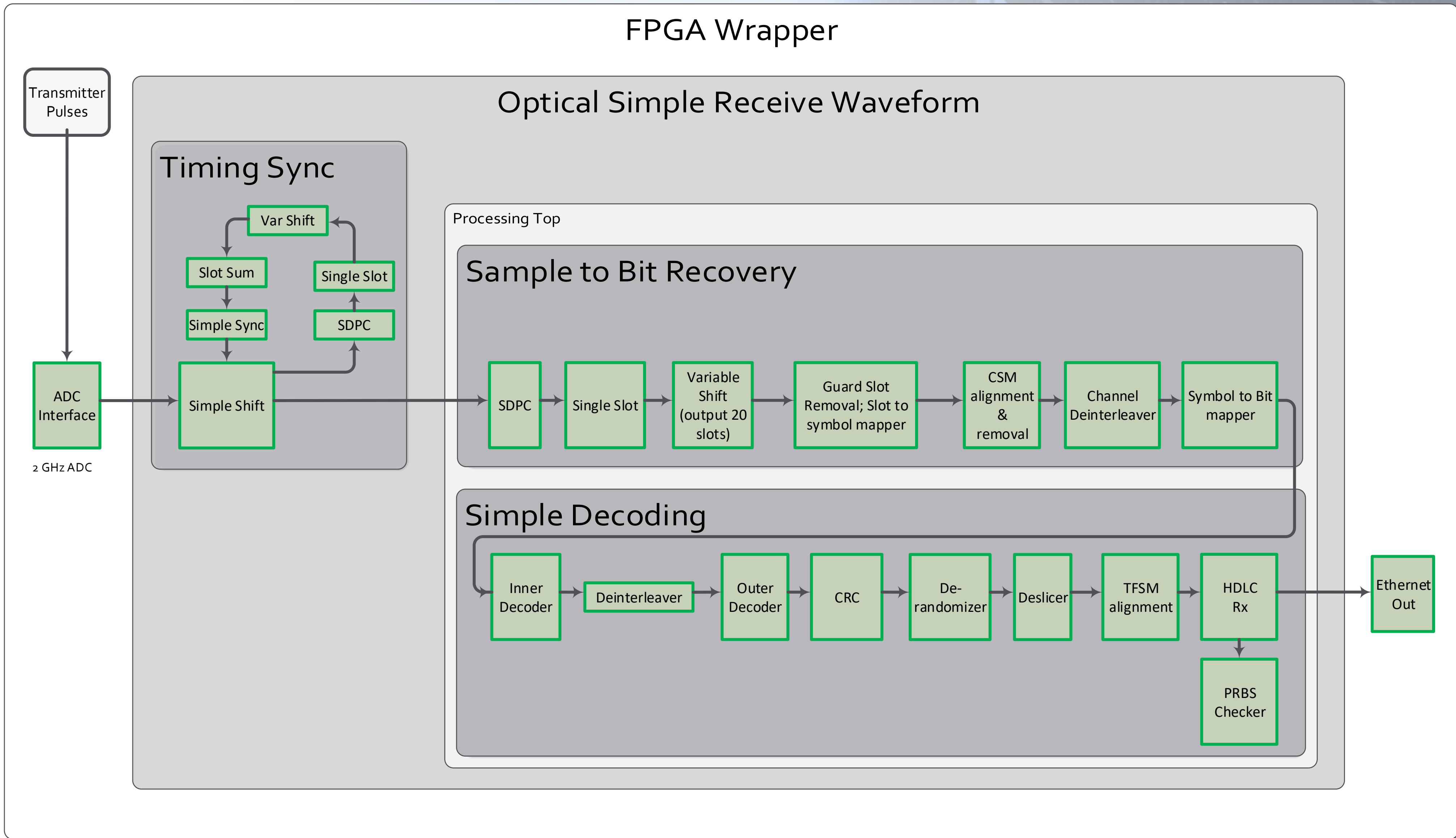
> Resume development on SCPPM decoder and timing recovery tracking loop



Picture shows the optical simple receive waveform GUI in operation. The GUI is based on the STRS Core Flight implementation on the Vadatech platform.

Simple Receive Waveform Block Diagram

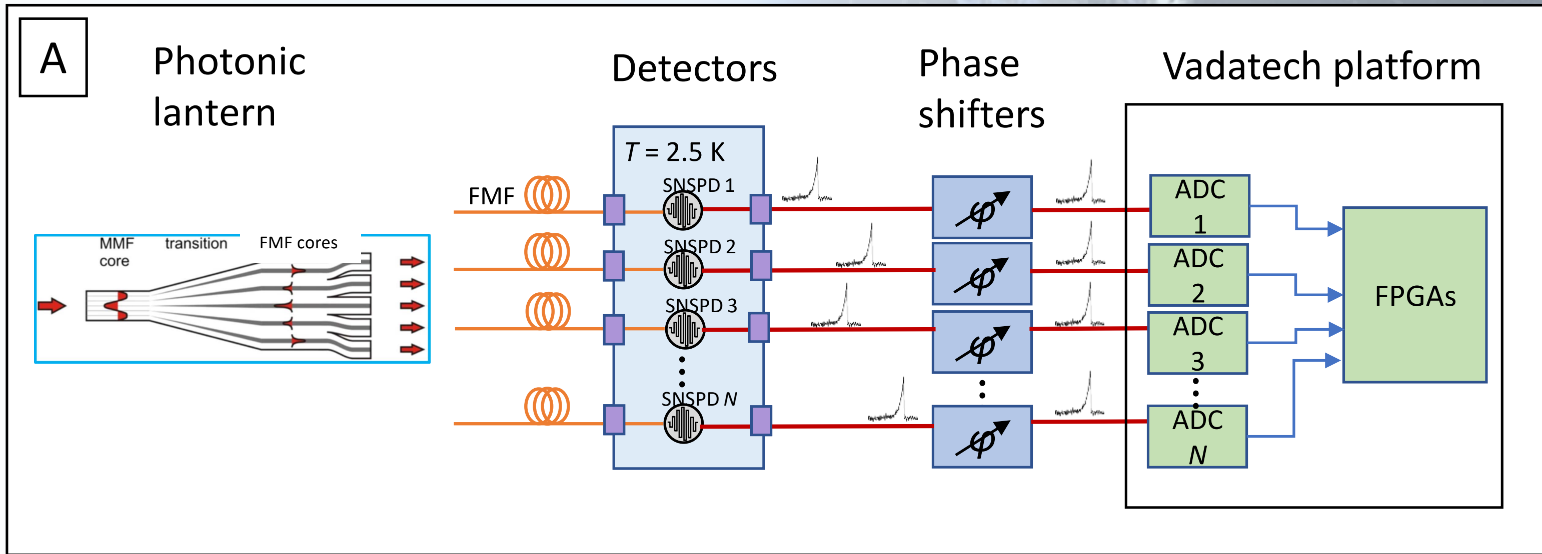
- Implements a simple receive waveform for the CCSDS HPE transmitter
- Checks for bit errors produced by the transmitter.
- Sends out received Ethernet packets for analysis

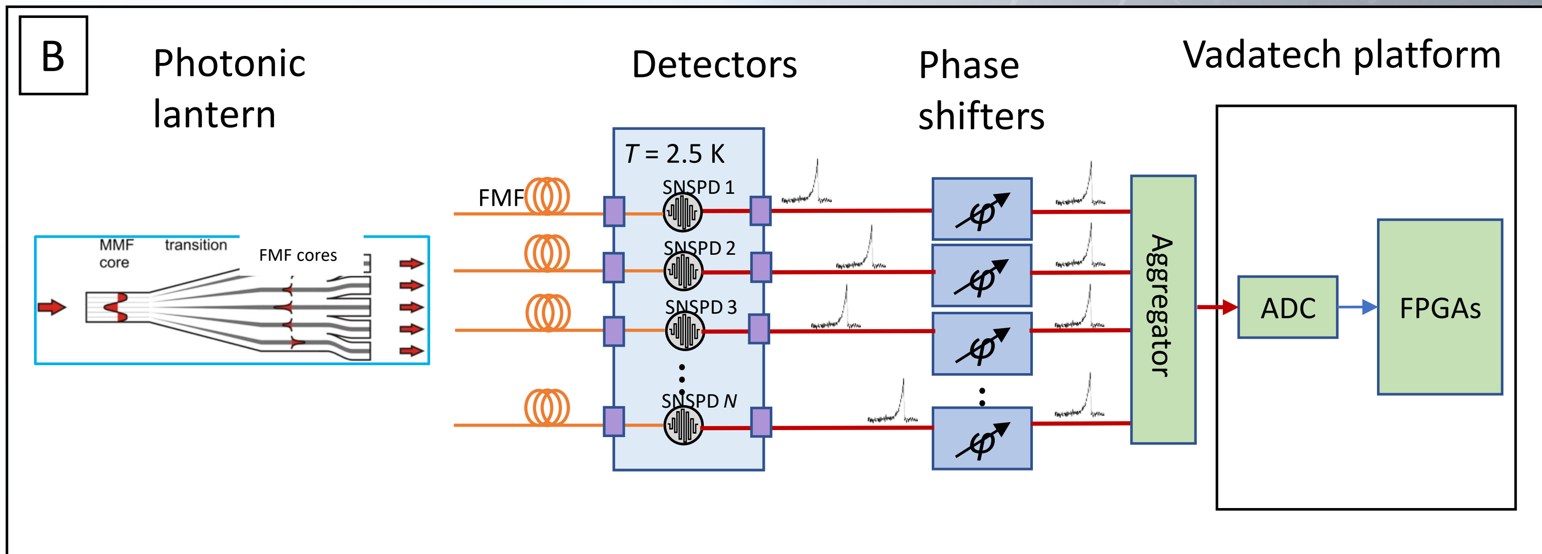


Channel Combining

- **10-bit ADC per detector channel**
- **2GHz Sample clock with interpolation in FPGA**
- **Can be commercialized through Vadatech**

- Passive channel combining reduces phase alignment difficulty and hardware required making system more scalable.





Summary

- **Few mode fiber coupling is a viable solution for a scalable photon counting ground receiver, adding additional performance without detector redesign**
  - Increases mode coupling capacity at higher the turbulence levels without increasing number of detectors.
  - Splitting is more even than SMF lantern leading to reduction in detector blocking loss
- **Commercial SNSPDs can be arrayed in parallel to reduce blocking loss and scaled to reach higher data rates**
  - Can achieve 40 Mbps with a single SNSPD in an SCPPM link
  - Can be coupled to FMF with minimal loss for ~ 4 dB detection gain vs. SMF
- **BER curve results from the system test bed align with simulation results**
  - Sources of loss in the system have been accurately characterized
  - Model can be used to predict performance of other waveforms
- **Real-time receiver VHDL implementation in progress**
  - Simple receiver for transmitter bit error successfully implemented
  - Proceeding with development on SCPPM decoder and timing recovery tracking loop
  - Determining channel combining options for performance and scalability

Acknowledgements

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Thank You!

www.nasa.gov/SCaN