

Photonic Lanterns applied to Deep Space Optical Communication Receivers

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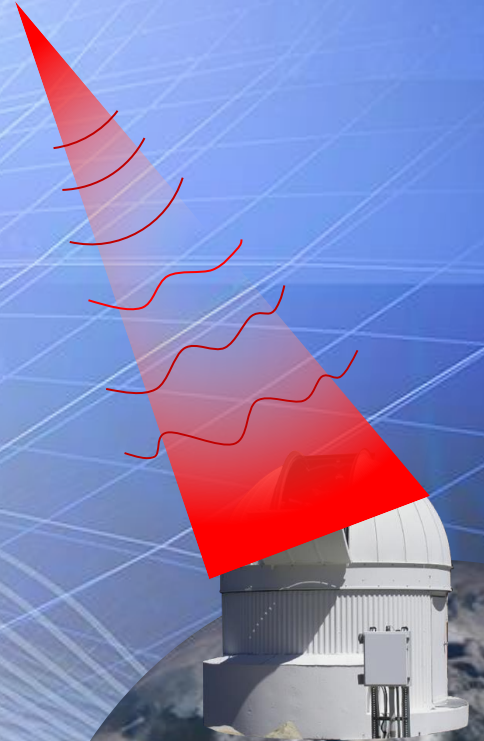
Photon Starved Laser Satellite Communications Environments

Motivation for Laser Satellite Communications:

- Need to transfer larger amounts of data from space to ground.

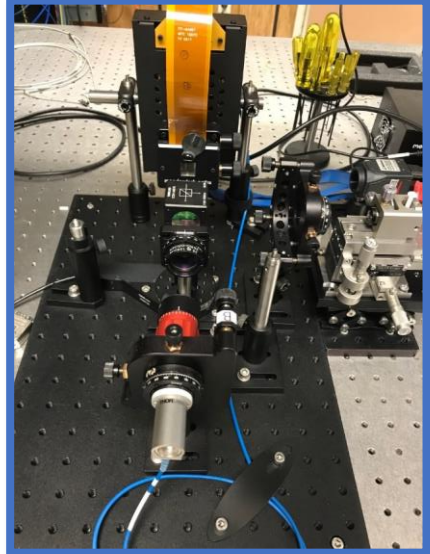
Examples of Photon Starved Environments:

- Deep space
- Low earth or Geosynchronous earth orbits applications with small signal strength
 - Cloud cover
 - Size, weight, and power constrained systems
- Quantum communication applications



Photon counting ground receiver

Telescope



Back end optics



Super Conducting
Single Photon
Nanowire Detectors



Channel
combining
electronics



Optical Waveform

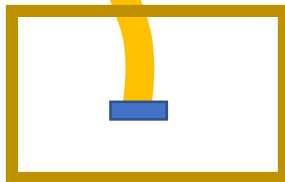
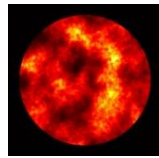


Possible Aperture/Detector Architectures

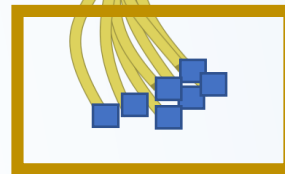
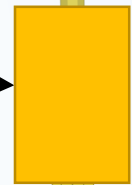
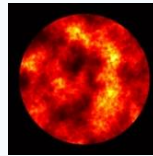
Fiber device to multiple single-pixel detectors or multi-element detector

Free Space to a multi-element detector

Multi-moded light from aft of Receiver Telescope

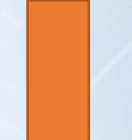
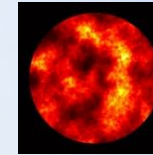


Fiber device



Detectors

Multi-moded light from aft of Receiver Telescope



Multielement detector

Single Photon Detector System

Aperture/Detector Architectures-considerations

Goal: Lower recurring costs

Strategy: Use commercial off the shelf (COTS) parts, design for scalability

Fiber device to multiple single-pixel detectors or multi-element detector

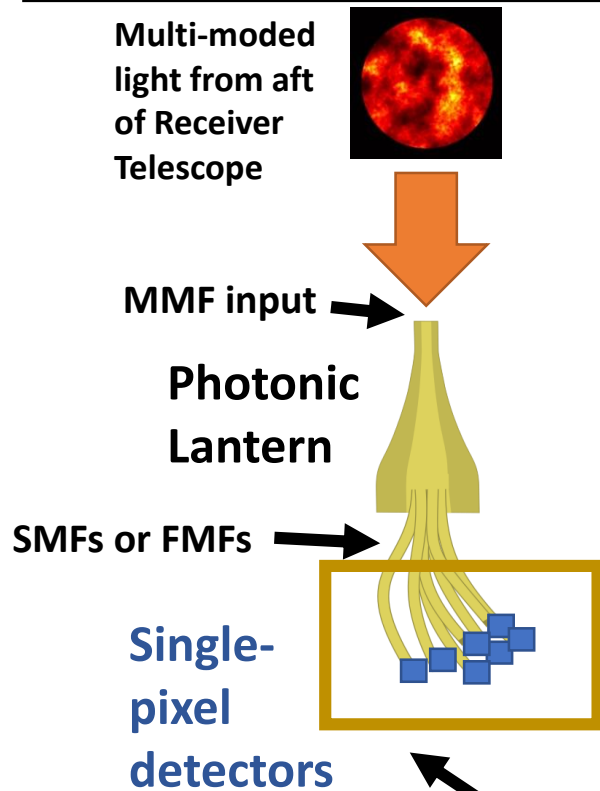
- Some fiber devices are COTS
- Smaller area detectors
- Fiber allow flexibility of location of Detectors
- Detectors are COTS
- Enables scalable flexibility

Free Space to a multi-element detector

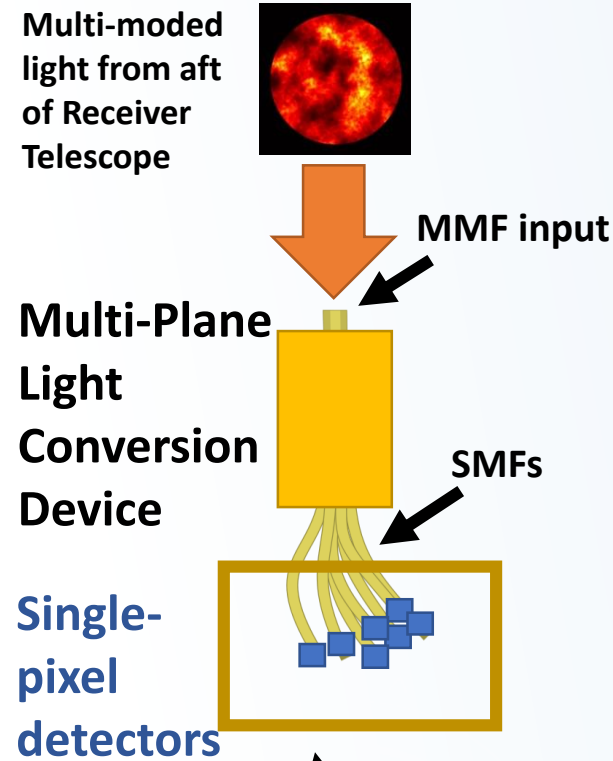
- Backend optics are COTS
- Custom filters (not COTS)
- Larger area detectors
- Detectors have windows
- Detector not COTS
- Less scalable flexibility

Possible Fiber/Detector architectures

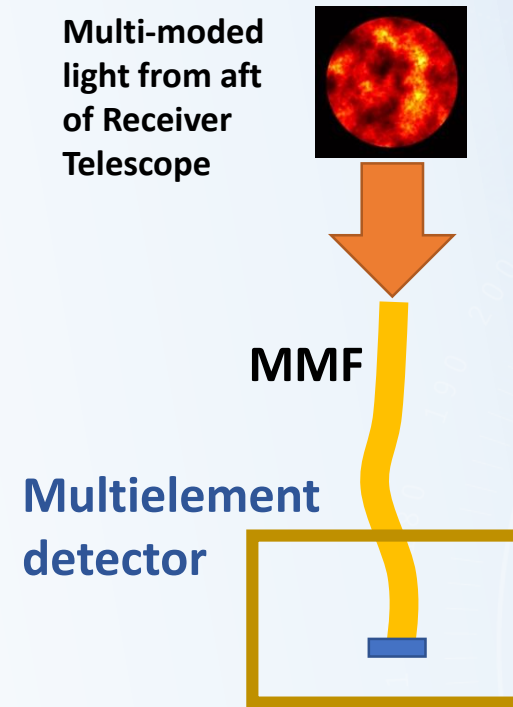
Photonic Lantern to multiple single-pixel detectors



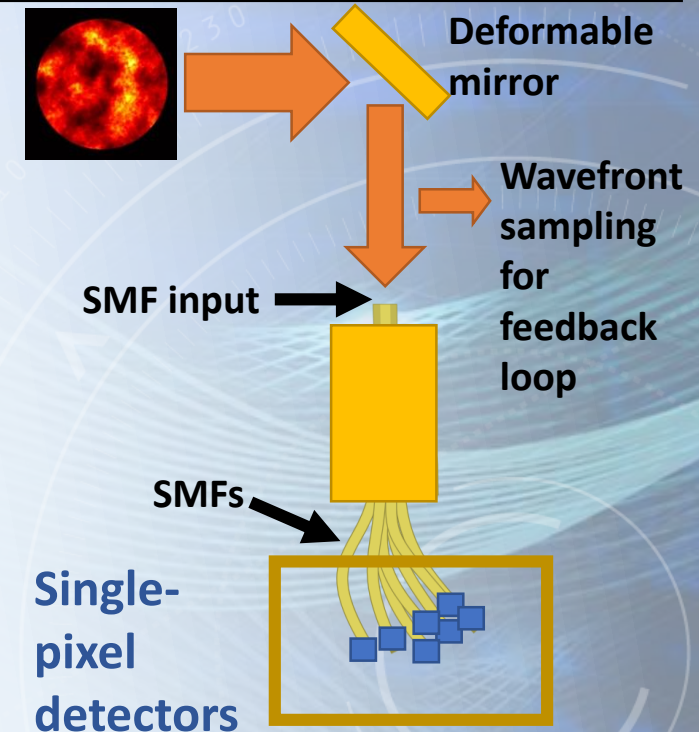
Multi-Plane light conversion device to multiple single-pixel detectors



MMF to a multi-element detector



Adaptive optics to single mode fiber to multiple single-pixel detectors



COTS Single Photon Detector System

Fiber/Detector architectures- evaluation criteria

Goal: Lower recurring costs

Strategy: Use commercial off the shelf (COTS) parts, design for scalability

Photonic Lantern to multiple single-pixel detectors	Multi-Plane light conversion device to multiple single-pixel detectors	MMF to a multi-element detector	Adaptive optics to single mode fiber to multiple single-pixel detectors
<ul style="list-style-type: none"> X Fiber device not COTS, Under development ✓ Detectors are COTS ✓ Enables scalable design 	<ul style="list-style-type: none"> • Fiber device newly COTS, not yet evaluated ✓ Detectors are COTS ✓ Enables scalable design 	<ul style="list-style-type: none"> ✓ Fiber device is a COTS part • Detectors newly COTS, not yet evaluated. X Unable to rescale detectors. <p>Note: Architecture previously used in NASA Optical Comm. Demo</p>	<ul style="list-style-type: none"> • AO newly COTS, not yet evaluated* ✓ Detectors are COTS ✓ Enables scalable design <p>Note: Architecture previously used in NASA Optical Comm. Demo</p>

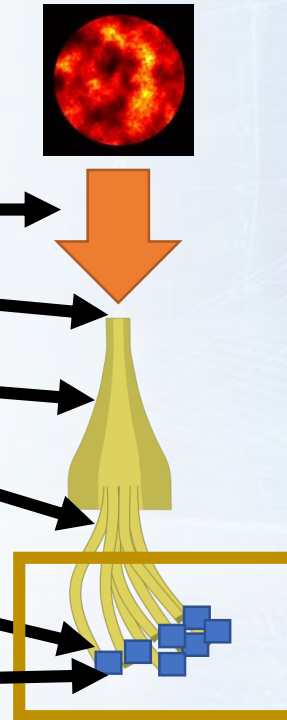
Fiber/Detector architecture evaluation criteria: signal loss

- **Effects of signal loss**

- Decrease signal to noise → constrains data rate capabilities
- Increases power, size and weight of space transmitter → increases cost
- Increases ground aperture size → increases cost

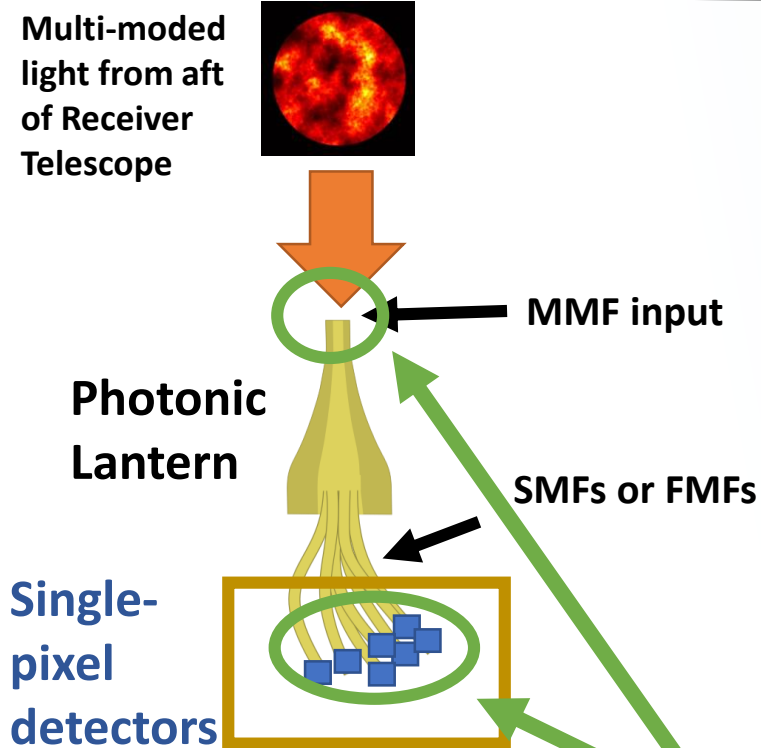
- **Contributions to loss**

- Back end optical train
- Fiber device insertion loss
- Fiber device jitter
- Uneven Splitting to detectors
 - > (causes loss during detector saturation)
- Fiber to Detector coupling loss
- Detector dead time
- Detector Jitter

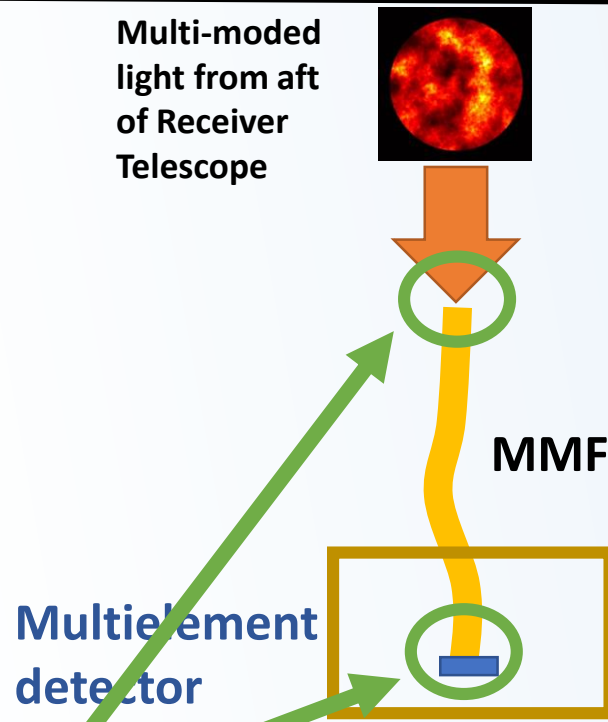


Fiber Device loss evaluation

Photonic Lantern to multiple single-pixel detectors



MMF to a multi-element detector

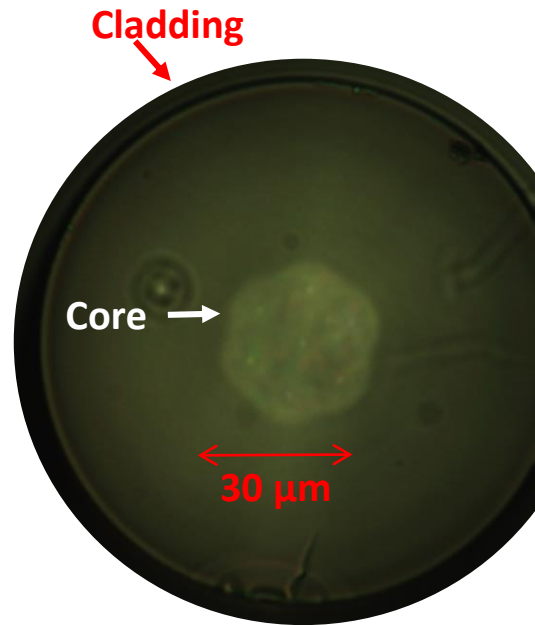
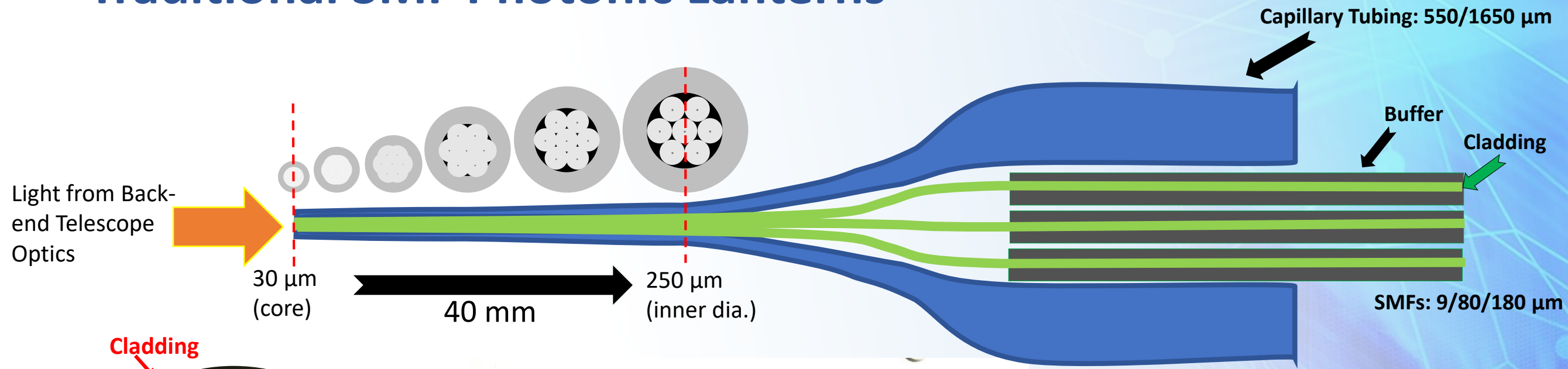


Power throughput efficiency (insertion loss) evaluated in this study

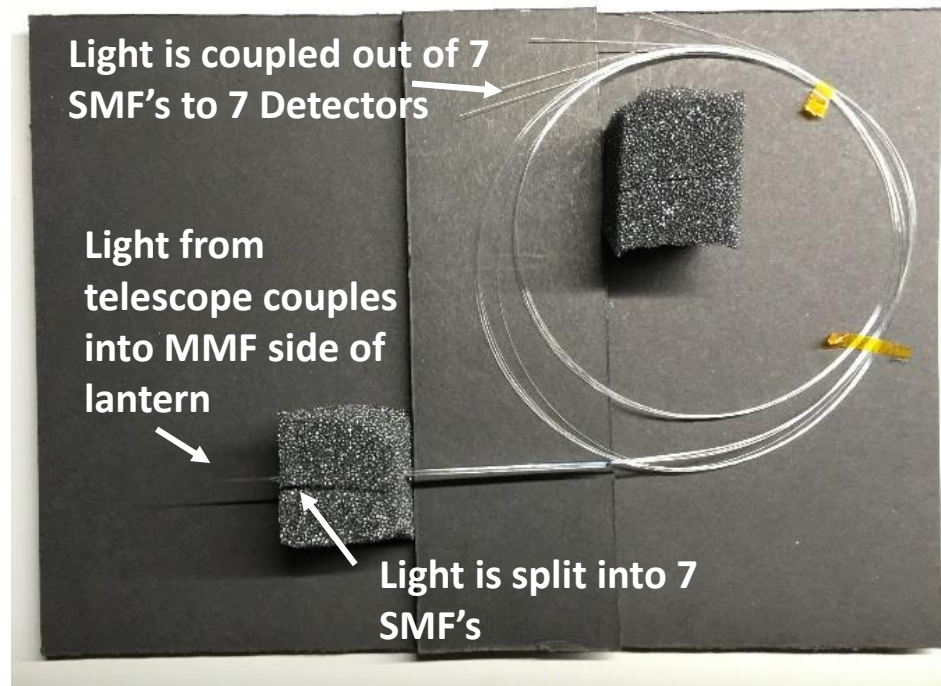
COTS Single Photon Detector System

- **Fiber device insertion loss**
 - > Coupling loss to detector **NOT** included
 - > Case study of emulated atmospheric conditions:
 - Low earth orbit
 - 60 cm receiver telescope aperture
 - Range of turbulence levels:
 - ($r_0=7-50$ cm \rightarrow $D/r_0 = 1.2-8.6$)
- **Fiber device jitter**
 - > Analysis (no measurement)
- **Uneven Splitting to detectors**
 - > Initial measurements
 - > Photonic lantern only

Traditional SMF Photonic Lanterns



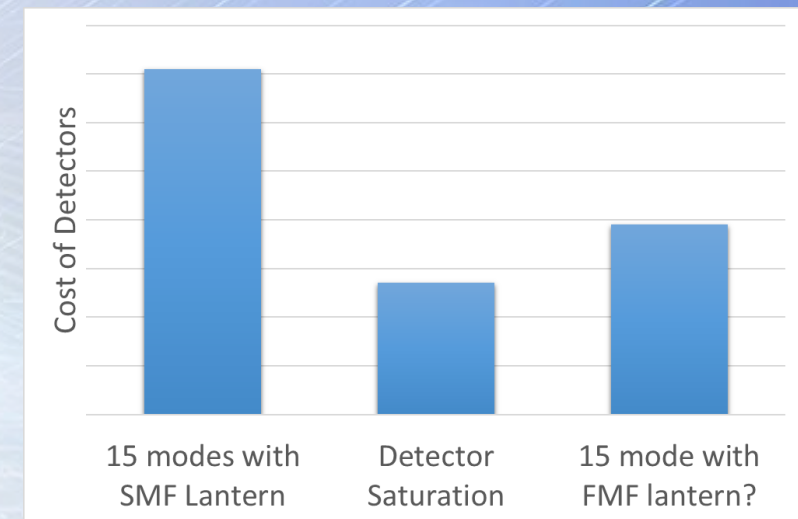
Multimode input of lantern 10



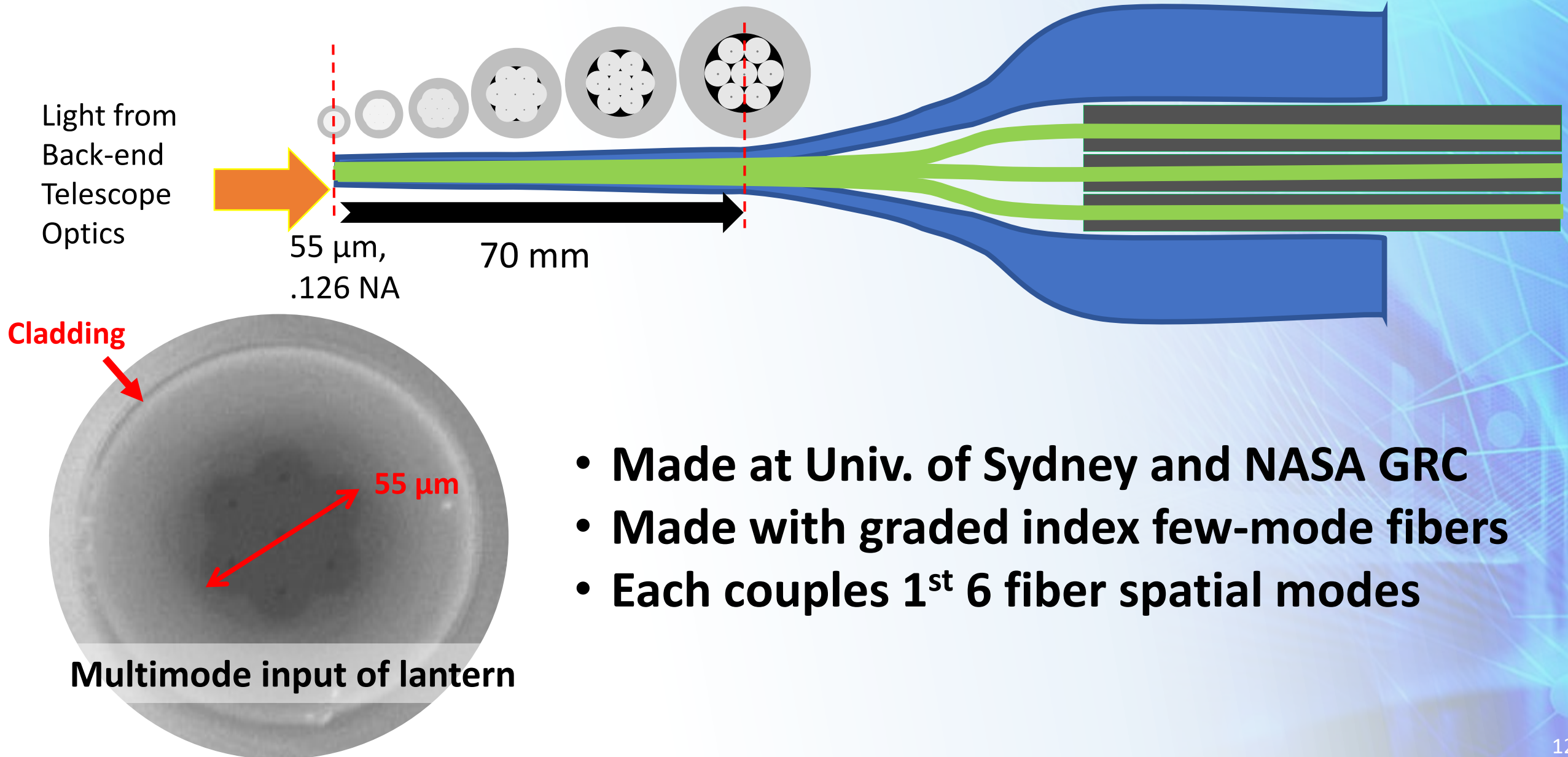
An unpackaged 7:1 SMF photonic lantern.

Motivation for Photonic lanterns made from few mode fibers

- **SMF lanterns have 1:1 output leg to mode ratio.**
 - Light arriving to the telescope is multi-mode
 - Power throughput efficiency depends on number of supported modes
 - Example need to couple 15 modes → Need 15 legs
- **At higher turbulence level environment # of detectors to overcome saturation < # of modes needed for efficient coupling**
 - Increases cost of system.
- **New few-mode fiber lanterns:**
 - Increase modes supported by each output leg
 - Enables higher number of modes with same number of detectors. Ex: 7 legs → 42 modes

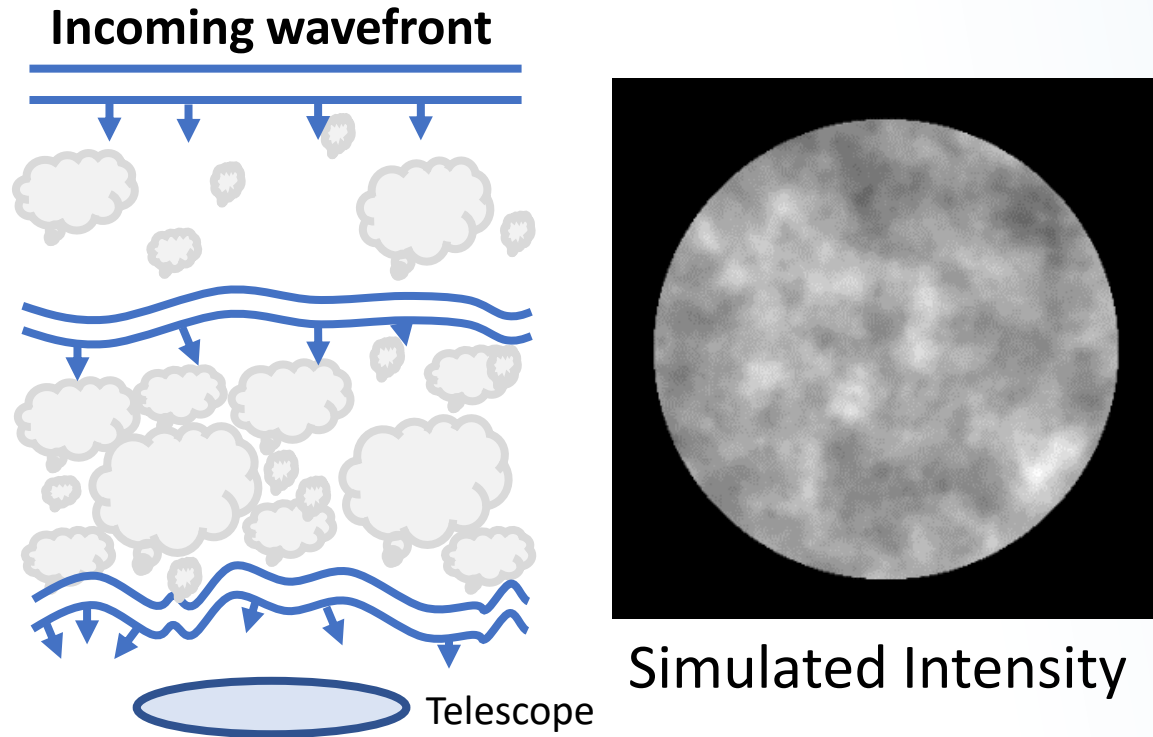


7:1 Few-Mode Fiber Photonic Lantern

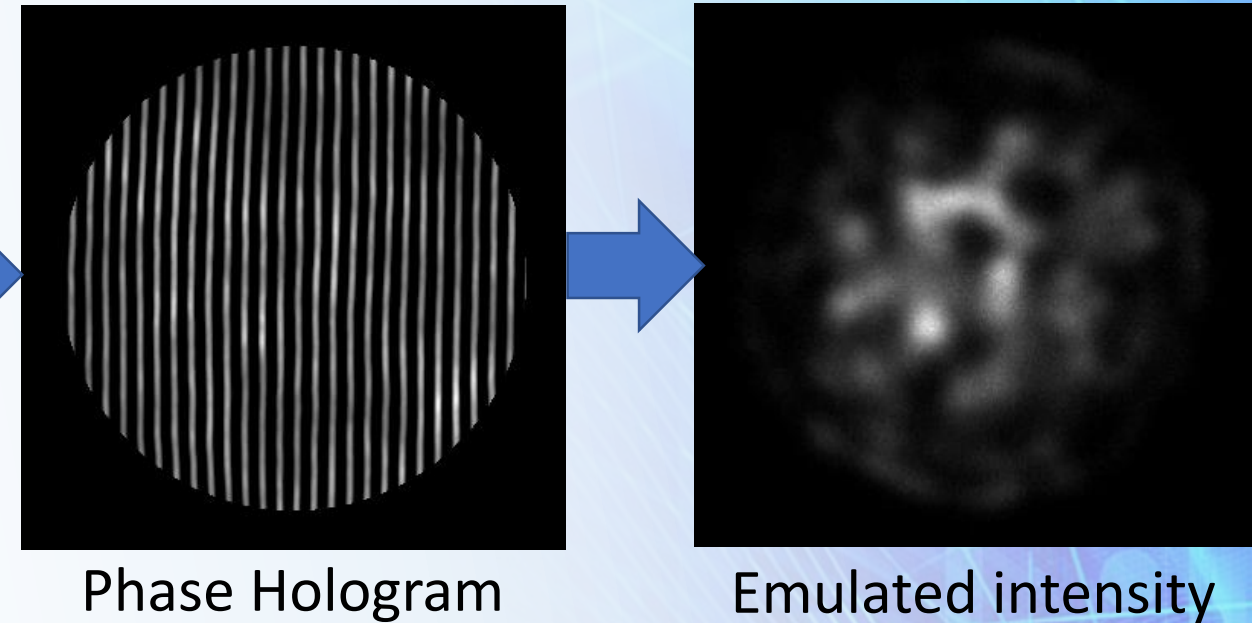


Creation of emulated atmospheric conditions

Simulation



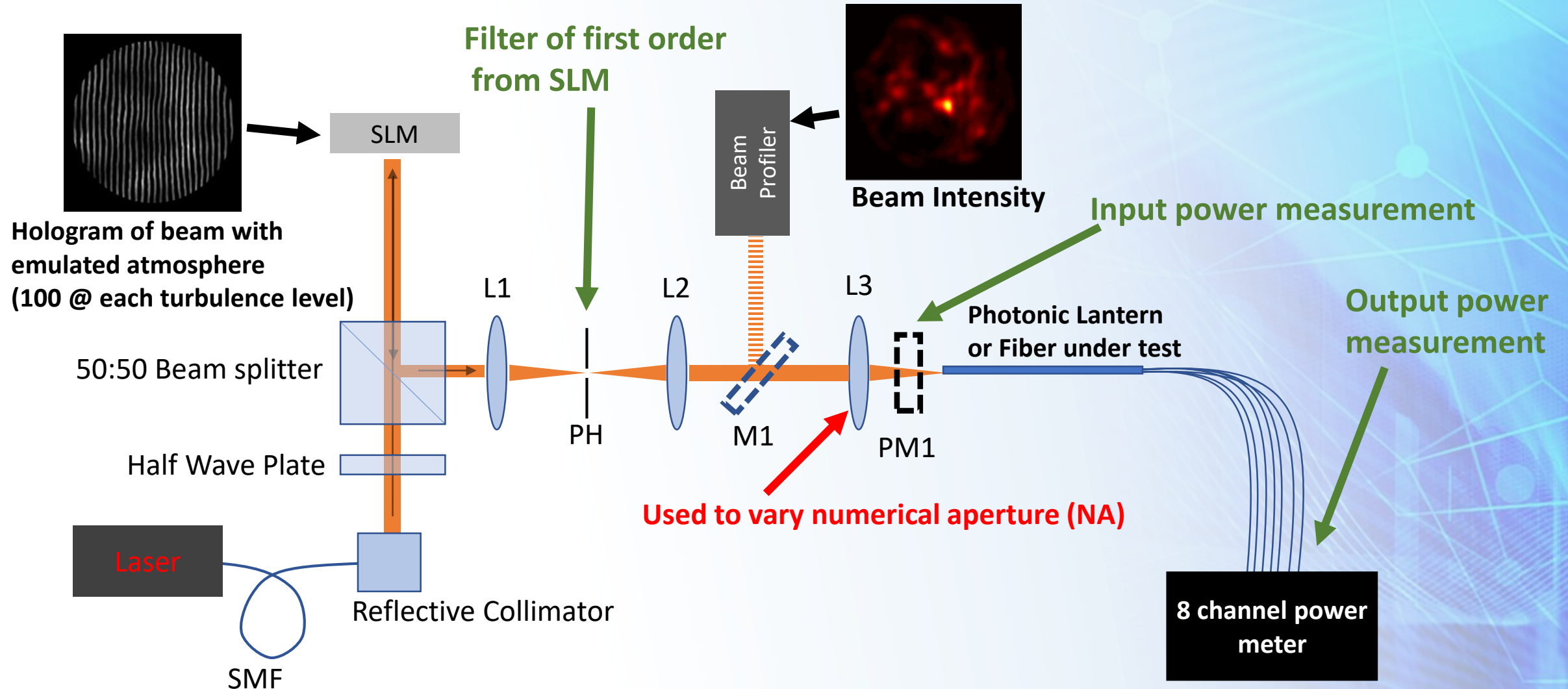
Emulation



- **Optical turbulence is modeled with phase screens distributed based on the Hufnagel-Valley turbulence strength profile.**
- **Simulation model verified.**
- **Details in:** Chahine et al, "Beam propagation through atmospheric turbulence using an altitude-dependent structure profile with non-uniformly distributed phase screens", Tuesday poster session.

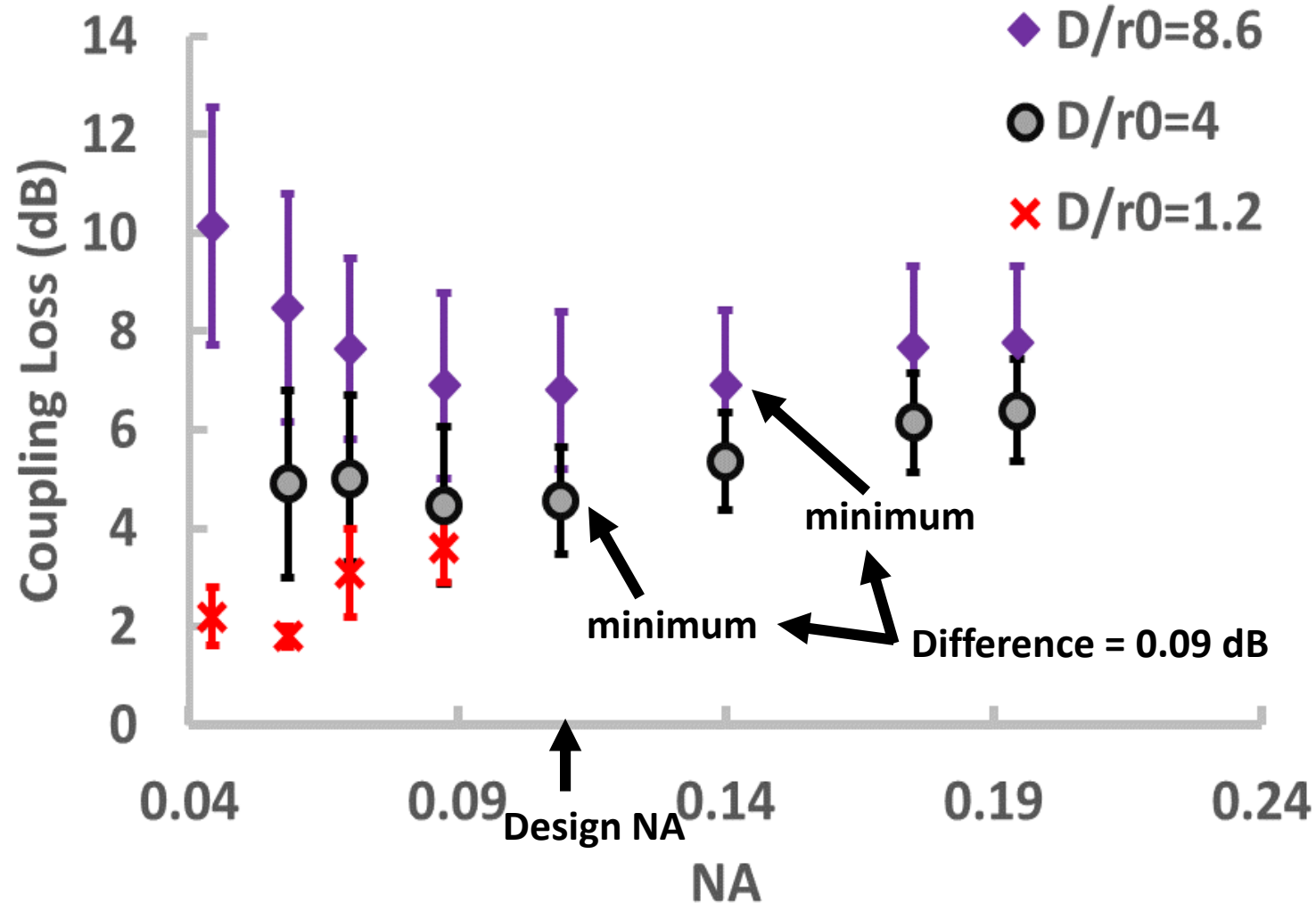
- **Complex amplitude phase hologram created from simulated wavefront.**
- **Hologram applied to beam with spatial light modulator generates emulated wavefront.**
- **Emulation accuracy not fully verified**
- **Results preliminary**

Experimental setup for coupling efficiency



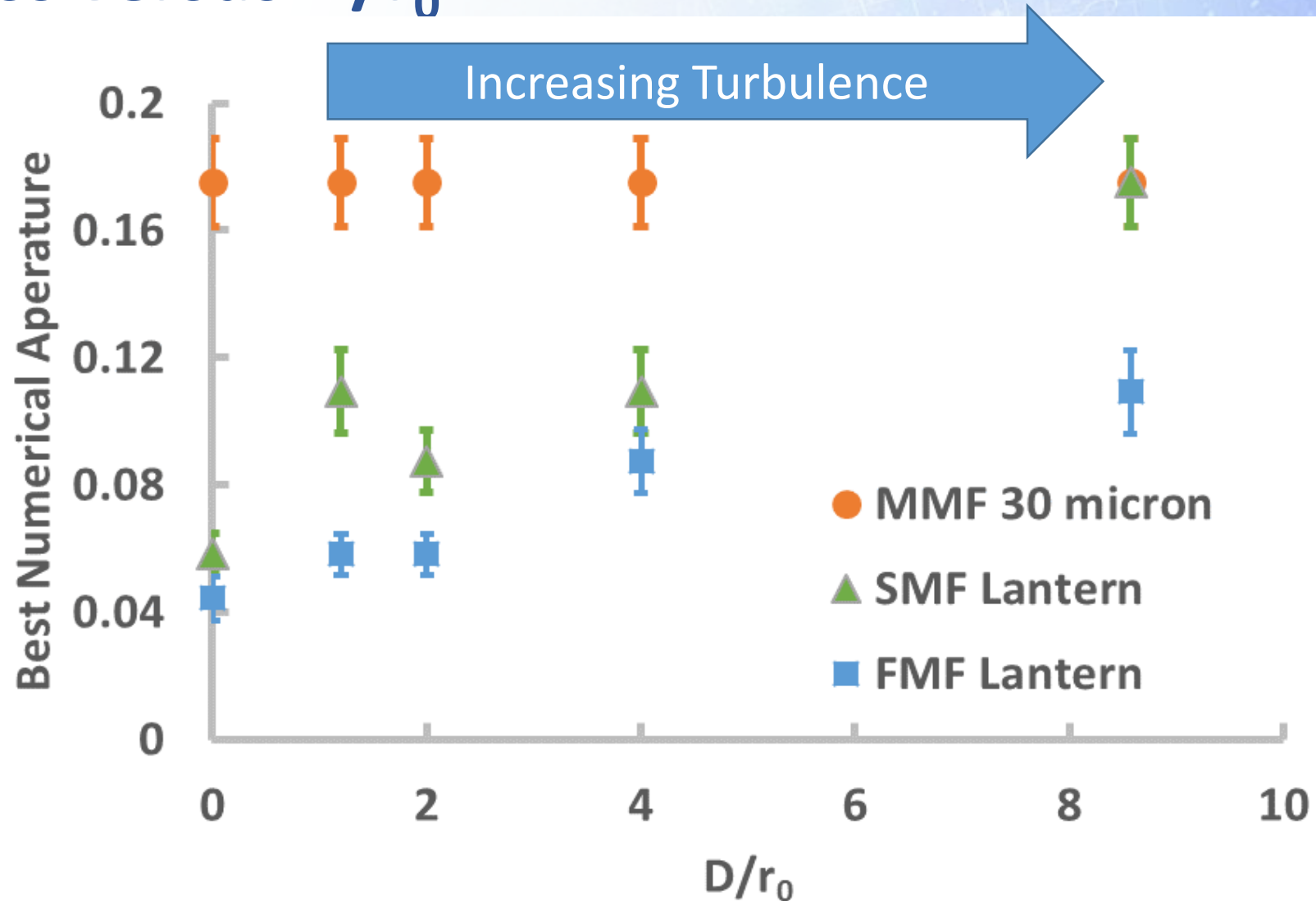
Test setup measures efficiency of lanterns and fibers over a range of input numerical apertures and emulated turbulences levels.

FMF Lantern coupling loss over a range of input numerical apertures at a few emulated D/r_0 's



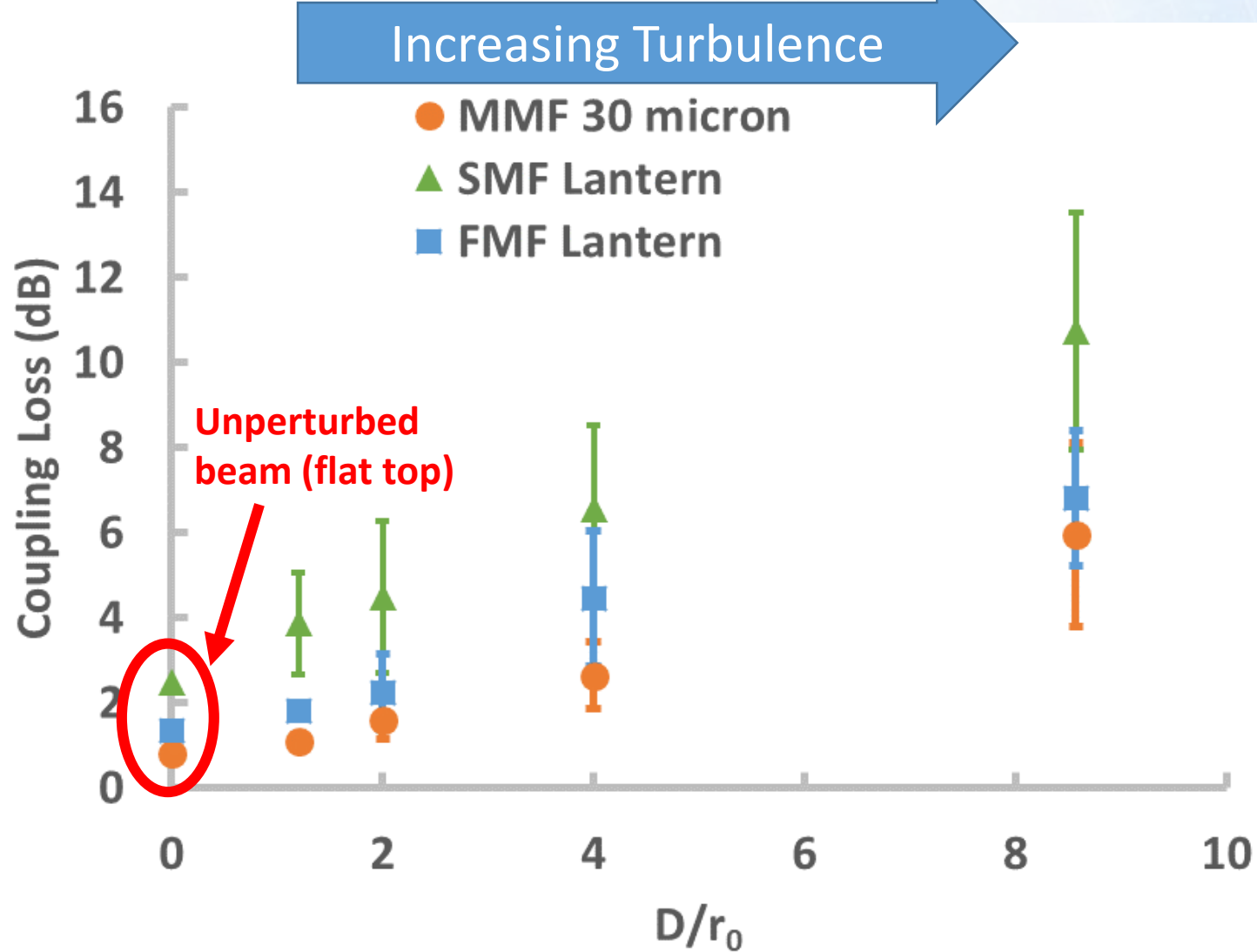
The input NA at which the FMF lantern minimum coupling loss occurs depends on the emulated D/r_0 . This indicates a fixed optical design wouldn't be ideal for a FMF Lantern.

Best input numerical aperture for minimum coupling loss versus D/r_0



The GI-MMF's best coupling NA is independent of D/r_0 .
The lanterns' best NA is dependent on D/r_0 .

Coupling loss at emulated D/r_0 's (at best input NAs)

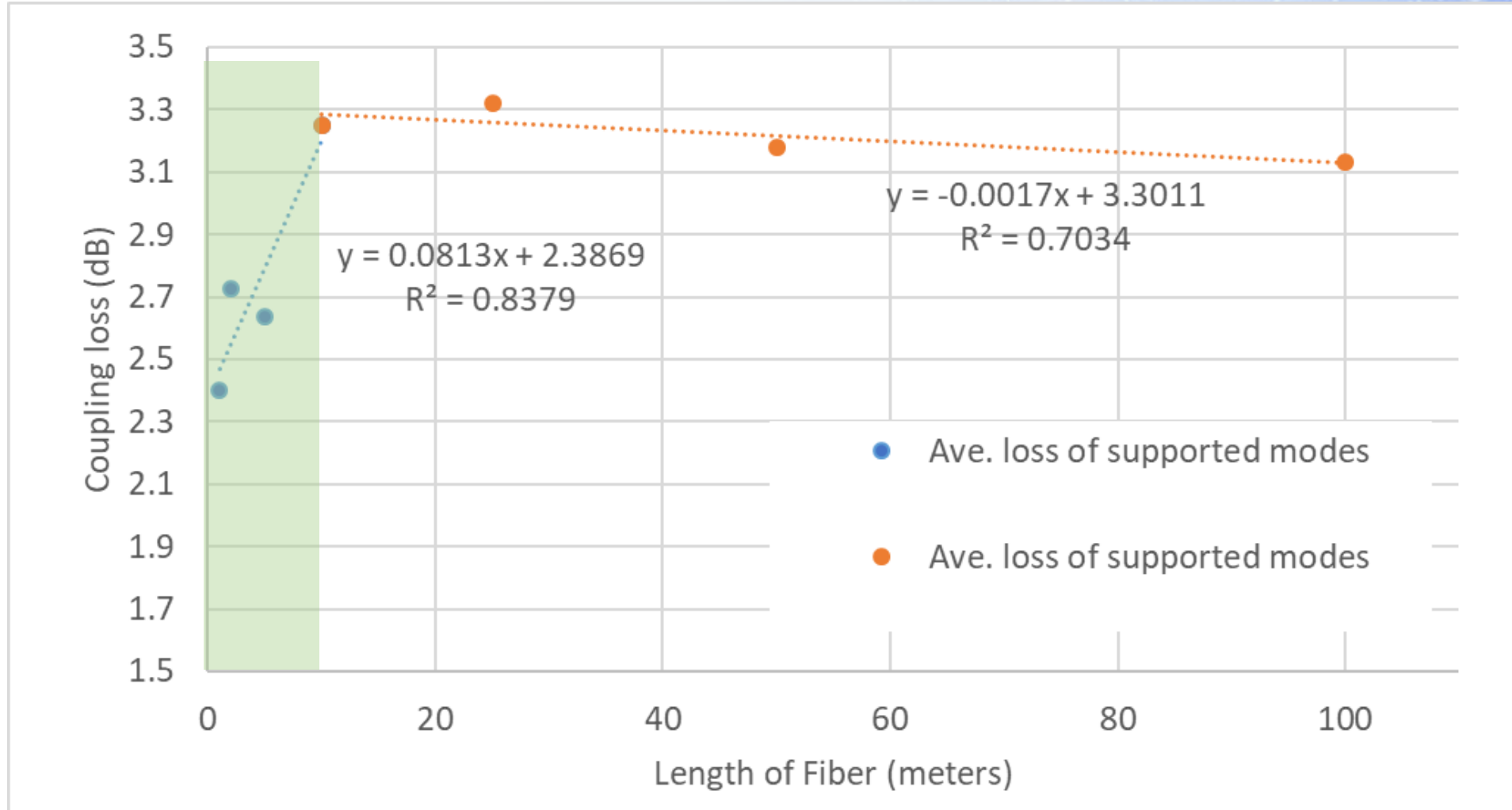


D/r_0	Gain Relative to the SMF Lantern (dB)	Loss Relative to the GI-MMF (dB)
8.6	3.92	0.86
4.0	2.10	1.83
2.0	2.25	0.66
1.2	2.07	0.69
0	1.17	0.53

Results shown at each devices' NA with minimum coupling loss.

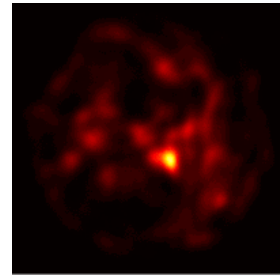
FMF lantern coupling losses: between SMF lantern and 2 meter GI-MMF.

Loss per meter for Multi mode fiber



- Most of the loss happens in first 5-10 meter length of the fiber
- Previous measurements were made with 2 meter fibers
- May explain difference between MMF and few mode fiber lantern insertion loss results

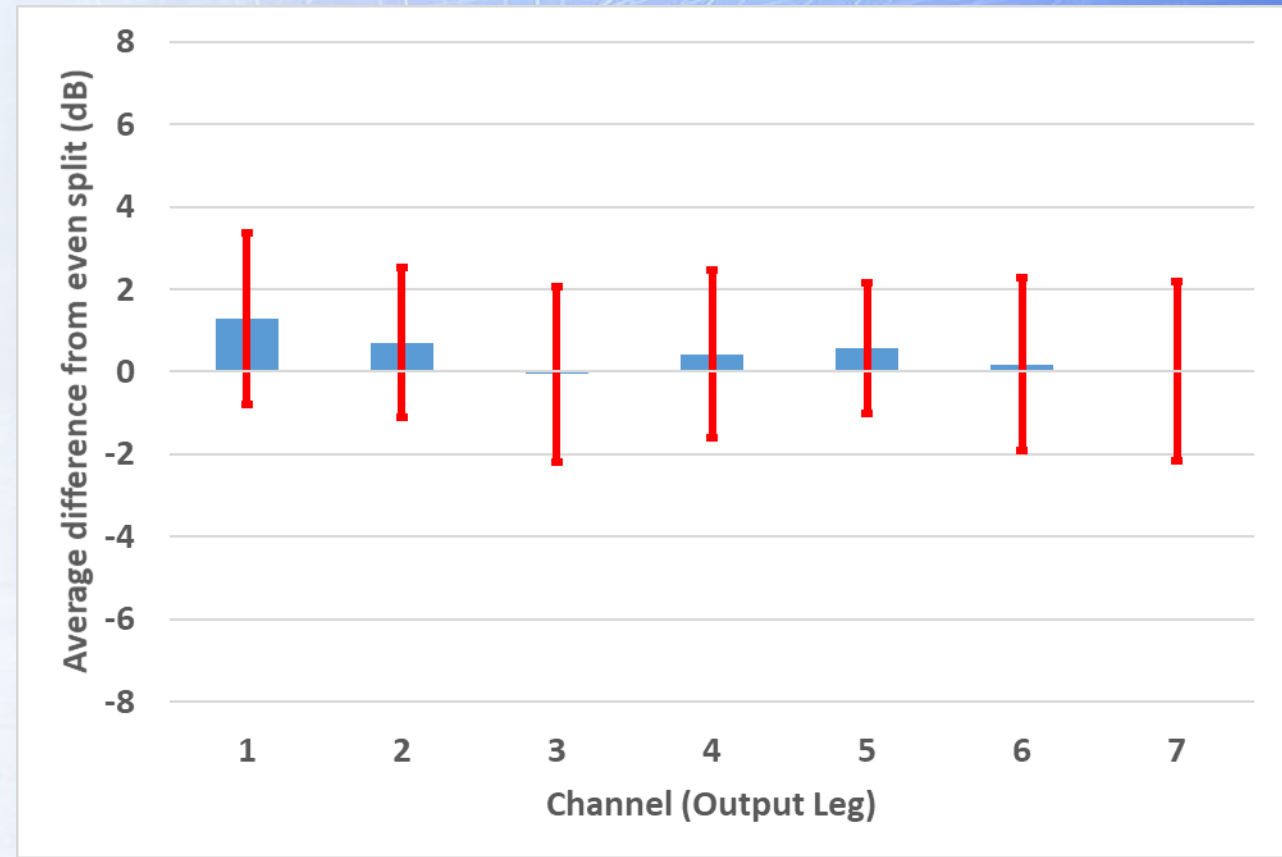
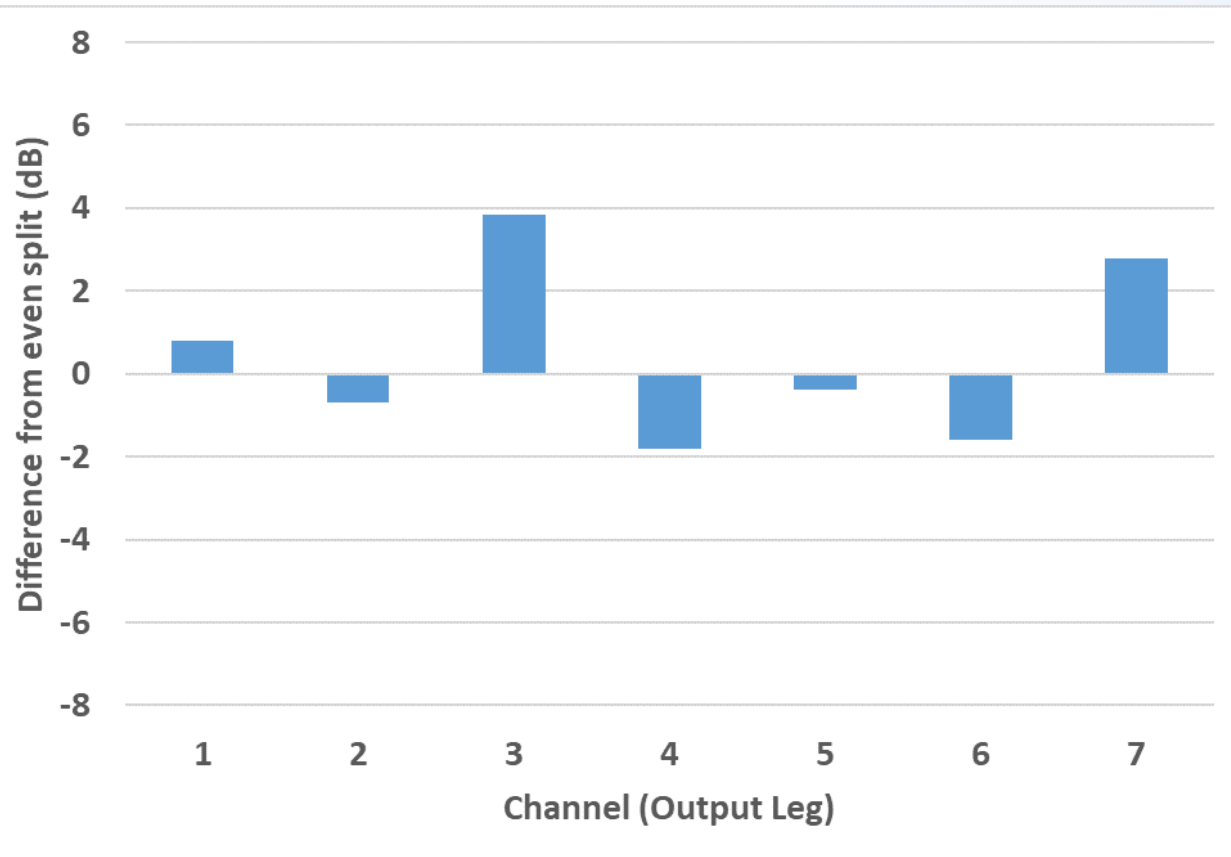
Photonic Lantern output legs power splitting



7 output legs

Difference from even split at $r_0=7$ cm

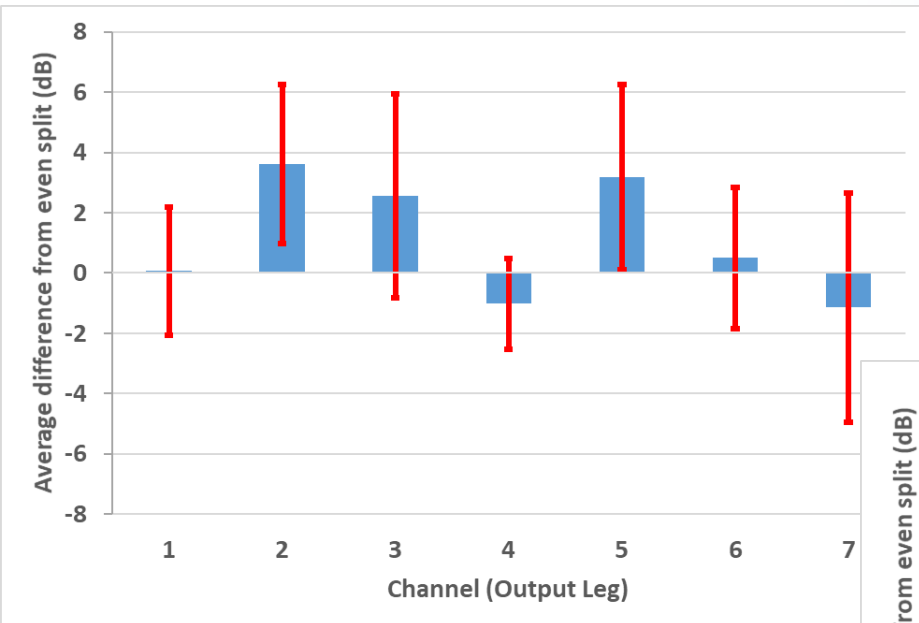
Average difference over 100 holograms at $r_0=7$ cm



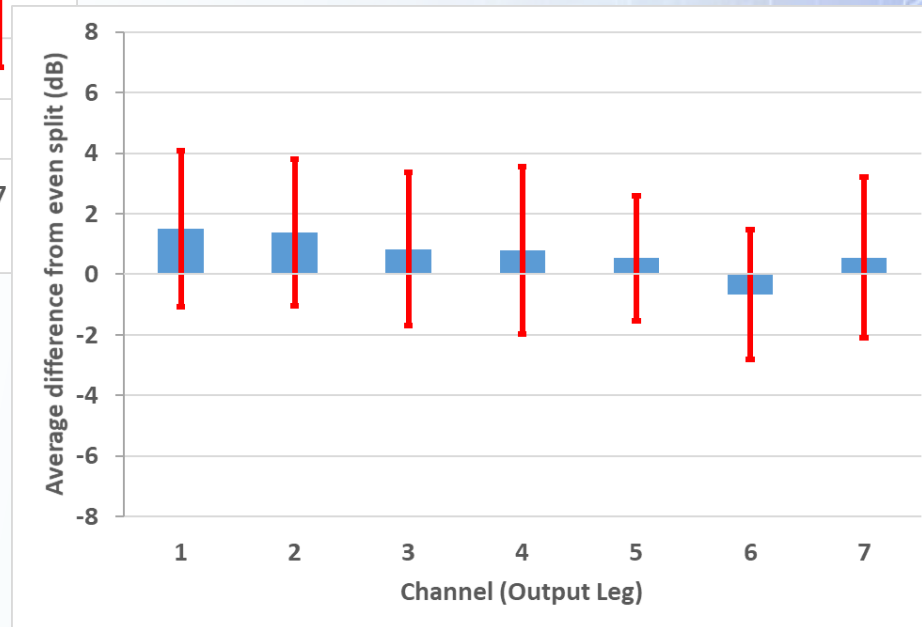
Ideally want even splitting to contribute no blocking loss to detectors. FMF lantern on average worst case is 1.5 dB

Preliminary measurements of splitting evenness between the FMF Lantern 7 output legs

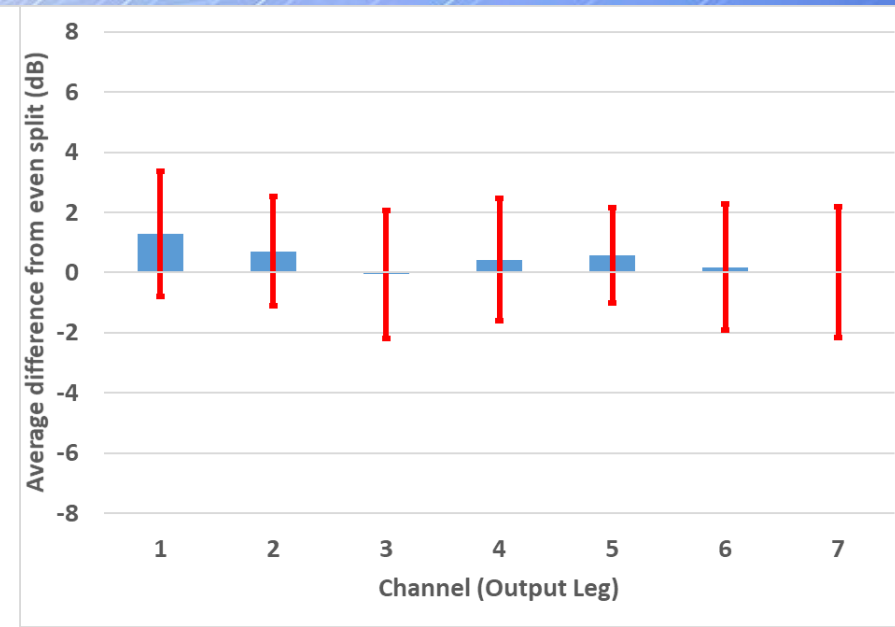
Increasing turbulence levels increases the evenness in the power split between output legs, indicating less detector blocking.



$r_0 = 50$ cm



$r_0 = 15$ cm



$r_0 = 7$ cm

Increasing Turbulence

Analysis of Fiber device Jitter

Fiber Device	Total Jitter Over 20 Meters (ps)
Multimode Fiber (Graded Index)	6.93
SMF 7:1 Lantern	0.22
FMF 7:1 Lantern	3.93

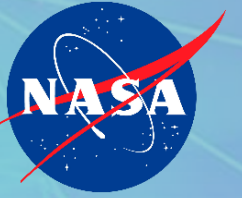
- Calculation includes differential mode delay and chromatic dispersion.
- FMF lantern contributes more jitter than a SMF lantern. But the amount of jitter is less than the MMF.
- The contribution to jitter is much less than the detectors (60-80 ps) so fiber devices are not the major contributor to loss.

Fiber/Detector architectures- Status of loss evaluation

Photonic Lantern to multiple single-pixel detectors	Multi-Plane light conversion device to multiple single-pixel detectors	MMF to a multi-element detector	Adaptive optics to single mode fiber to multiple single-pixel detectors <small>60</small>
<ul style="list-style-type: none"> • Back end optical train losses • Fiber device insertion loss ✓ Fiber device jitter • Even Splitting to detectors ✓ Detector coupling loss ✓ Detector dead time ✓ Detectors Jitter 	<ul style="list-style-type: none"> × Back end optical train losses × Fiber device insertion loss • Fiber device jitter × Even Splitting to detectors ✓ Detector coupling loss ✓ Detector dead time ✓ Detectors Jitter 	<ul style="list-style-type: none"> • Back end optical train losses • Fiber device insertion loss ✓ Fiber device jitter × Even Splitting to detectors × Detector coupling loss × Detector dead time × Detectors Jitter 	<ul style="list-style-type: none"> × Back end optical train losses × Fiber device insertion loss ✓ Fiber device jitter • Even Splitting to detectors ✓ Detector coupling loss ✓ Detector dead time ✓ Detectors Jitter

Next Steps

- **Complete verification of the accuracy of the atmospheric emulation**
- **Measure the 7:1 FMM lantern and MMF insertion loss with >10 meter fibers**
- **Complete splitting loss evaluation.**
- **Evaluate Multi-element detector for**
 - **Jitter**
 - **Coupling loss**
 - **Splitting**
- **Quantify and compare back end optic train losses for photonic lantern and MMF**



Acknowledgements

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