Measurements of few-mode fiber photonic lanterns in emulated atmospheric conditions for a low earth orbit space to ground optical communication receiver application

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Introduction

• NASA GRC is developing a low cost scalable photon counting optical ground receiver that includes:
  • Fiber optic devices to deliver light to detectors
  • Commercial of the shelf single photon counting detectors
  • Real time FPGA-based receiver compliant with CCSDS HPE Standard
### Fiber/Detector architectures under evaluation

<table>
<thead>
<tr>
<th>Photonic Lantern to multiple single-pixel detectors</th>
<th>MMF to a multi-element detector</th>
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</thead>
<tbody>
<tr>
<td>Multi-moded light from aft of Receiver Telescope</td>
<td>Multi-moded light from aft of Receiver Telescope</td>
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<td>MMF input</td>
<td>MMF</td>
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<td>SMFs or FMFs</td>
<td></td>
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<tr>
<td>Single-pixel detectors</td>
<td></td>
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<tr>
<td>COTS Single Photon Detector System</td>
<td>Power throughput efficiency (coupling loss)</td>
</tr>
<tr>
<td>evaluated in this study</td>
<td>evaluated in this study</td>
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</tbody>
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- **Focus of this study**
  - Fiber devices
  - Evaluate main purpose: efficiently deliver light to detectors
    - Measured power throughput efficiency
    - Coupling loss to detector **NOT** included
- **Case study of emulated atmospheric conditions:**
  - Low earth orbit
  - 60 cm receiver telescope aperture
  - Range of turbulence levels:
    - \( r_0 = 7-50 \text{ cm} \rightarrow D/r_0 = 1.2-8.6 \)
Creation of emulated atmospheric conditions

**Simulation**

- 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.

**Emulation**

- 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
Fiber devices tested

<table>
<thead>
<tr>
<th>Fiber Device</th>
<th>Core Size, μm</th>
<th># of modes supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graded Index Multi-Mode Fiber</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>7:1 Single-mode fiber lantern</td>
<td>30</td>
<td>7</td>
</tr>
<tr>
<td>7:1 Few-mode fiber lantern</td>
<td>55</td>
<td>41</td>
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</tbody>
</table>

- Power throughput efficiency of fiber devices depends on number of supported modes
  - Light arriving to the telescope is multi-moded
  - Energy scattered into higher-order modes

- Standard photonic lanterns (single-mode fiber)
  - 1:1 output leg to mode ratio. Ex: 7 legs → 7 modes

- 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


- Made at NASA GRC
- Made with graded index few-mode fibers
- Each couples 1st 6 fiber spatial modes

Light from Back-end Telescope Optics

55 µm, .126 NA

70 mm

Multi-mode input of lantern

Cladding

55 µm
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/r₀’s

The input NA at which the FMF lantern minimum coupling loss occurs depends on the emulated D/r₀. 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 $D/r_0$. 

Increasing Turbulence
Coupling loss at emulated $D/r_0$’s (at best input NAs)

Results shown at each devices’ NA with minimum coupling loss. FMF lantern coupling losses: between SMF lantern and GI-MMF.
Conclusion

• A preliminary case study of a 60 cm diameter telescope receiving light from low earth orbit was performed for two types of lanterns and a GI-MMF.

• Best input NA → Lanterns are dependent on the atmospheric condition.

• Emulated turbulence →
  • FMF lantern had increased coupling efficiency over SMF lantern
  • FMF lantern have slightly less coupling efficiency than a 30 micron GI-MMF.

• Future Work on FMF lanterns
  • Study dependence on input NA
  • Refine design and fabrication process to reduce losses.
  • Perform system-level comparison to GI-MMF with corresponding detectors
Acknowledgements

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