Photonic Lantern Testing on Lick Observatory's 3m Shane Telescope

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ABSTRACT

Astrophotonics, with its potential for creating low-cost, mass-producible devices, offers a path to dramatically reduce the cost of future astronomical spectrographs. However, coupling the light from large astronomical telescopes into small, photonic chip-based instruments remains a challenge. Photonic lanterns offer a potential solution. Photonic lanterns predictably decompose the inherently multimode light from a ground-based telescope into a series of single-mode outputs, thus eliminating the need for exotic optical elements or extreme AO to achieve high efficiency.[1] We have built a custom assembly for the AO system at Lick Observatory's 3m Shane Telescope to test photonic lantern behavior on-sky. Here we report on multiple nights of observations over the past year using a lantern with a design wavelength of 1550 nm. Our data reveals the lantern's basic performance over a 605–1000 nm band and its time domain response to turbulent PSFs with AO correction residuals. These measurements are important for determining the efficacy of future efforts to preferentially select or combine output modes in "real-world" scenarios across scientifically useful bandwidths.

Keywords: photonic lanterns, photonics, astrophotonics, photonic spectrographs

1. INTRODUCTION

Astrophotonics, the integration of photonics and astronomical instrumentation, has emerged as a promising field with the potential to revolutionize observational astronomy. By leveraging the advancements in optical fibers, waveguides, and integrated photonic circuits, astrophotonics offers several advantages over traditional astronomical instrumentation, including improved efficiency, stability, and compactness.[1,2]

One key area in astrophotonic research is the development of photonic lanterns (PL). PL enable the efficient coupling of multimode light from telescopes into single-mode fibers. These devices have the potential to significantly enhance the performance of spectrographs and other fiber-fed instruments by minimizing modal noise and increasing throughput.[1,3–5] To further explore the capabilities of photonic lanterns, we have conducted a series of tests at Lick Observatory, located on Mount Hamilton, California.

The integration of photonic technologies into astronomical instrumentation promises to address several long-standing challenges faced by astronomers. Astrophotonics offers solutions for efficient beam transportation, wavefront control, and spectral filtering, among other applications. By leveraging the inherent advantages of photonic components, such as low weight, compactness, and thermal stability, astrophotonics paves the way for the development of more efficient and robust instruments for ground-based and space-based observatories.[6]

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As the field of astrophotonics continues to evolve, the testing of photonic lanterns at Lick Observatory represents a crucial step in evaluating their performance under real-world observing conditions. These tests will provide valuable insights into the practical implementation of astrophotonic technologies, enabling further refinements and advancements in the field.

2. PHOTONIC LANTERNS

Astrophotonic devices operate almost exclusively with single-mode light. The direct coupling of a telescope point spread function (PSF) into single-mode fibers (SMFs) presents a significant challenge however.[1] Factors such as atmospheric turbulence, imperfect optics, and diffraction around telescope structures can distort planar wave fronts and broaden the PSF. This distortion leads to a mismatch between the shape of the incident wavefront and the mode profile of the SMF, resulting in a significant reduction in coupling efficiency. Photonic lanterns offer a potential solution to this problem.

2.1 Photonic Lanterns

Photonic Lanterns (PL) collect light at one end with an MMF-like input and deliver an output at the other end in the form of multiple, single-mode channels. Leon-Saval et al. 2013[5] and Birks et al. 2015[4] both offer excellent overviews of photonic lantern theory and operation. Briefly, by providing an adiabatic, or gradual, transition from the MMF input to the SMF outputs, the modes of the MMF are efficiently ($> 90\%$) coupled into a set of single mode fiber outputs. See Fig. 1 for a schematic depiction of a simplified photonic lantern. As long as the input mode decomposition results in an equal or fewer number of modes as there are output single-mode channels in the lantern, this set of discrete basis states fully accounts for the input signal flux.[4,5]

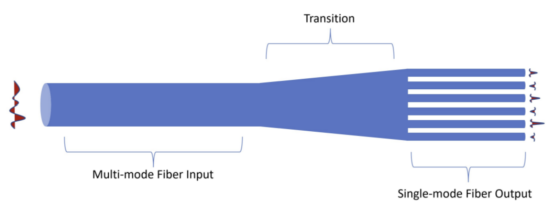

Figure 1. A simplified schematic of a photonic lantern. The multi-mode fiber input on the left takes the input waveform and decomposes it through an adiabatic transition region into a series of single mode outputs.

The photonic lantern used for this paper was constructed using a fiber tapering process,[4] where a set of 19 SMF-28 single mode fibers were inserted or "stacked" into a low-index glass capillary tube. Heat and tension were then applied to taper the capillary tube containing the fiber bundle. As the capillary is tapered, the fibers inside collapse and fuse together, forming a multimode waveguide at the input end. The tapered region where the fibers have merged acts as the multimode section of the photonic lantern. The tapering process is done in such a way as to create an "adiabatic" transition, ensuring efficient mode coupling between the multimode input and the individual single-mode outputs.[4] For this specific lantern, one of the 19 cores failed in the manufacturing process, resulting in an 18 core lantern. Images of both the input and output ends of our "18" port lantern are shown in Figure 2. The bright spot on the input end is a 635nm laser spot focused using the Photonic Lanter Injection Unit (PLIU), discussed below, in the lab.

2.2 Parallel Lantern Injection Unit (PLIU)

The Parallel Lantern Injection Unit (PLIU) is a custom-built instrument designed to test astrophotonics on-sky at Lick Observatory's Shane 3m telescope. The PLIU re-images two AO-corrected point sources from the Shane AO onto two dynamically-positioned photonic lanterns, while minimizing differential aberrations between the optical paths. It uses a mirrored right-angle prism to split the 20 arcsec field of view from the telescope into two, equal sub-fields. The two beams are then folded using a 90/10 beam-splitter and collimated before being re-focused and demagnified by a factor of 3 onto the fiber injection plane where the photonic lanterns are positioned. This results in taking the native f/28.5 beam from the telescope and converting it into a f/9 beam

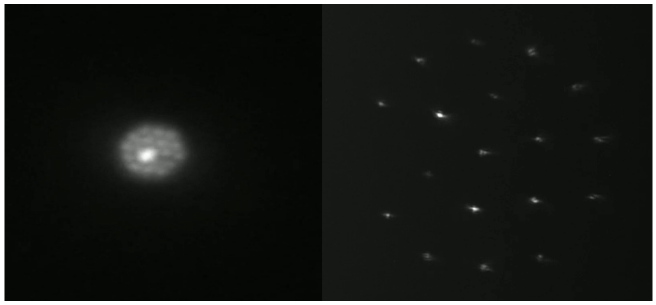

Figure 2. Images of both the input and output of the 18 port photonic lantern characterized in this paper. One can see on the right the missing port, resulting in an 18 port lantern.

for injection into the lanterns. Two targeting cameras aimed through the beam splitters assist in aligning the point spread functions with the lantern inputs. For the bottom photonic lantern, the PSF is adjusted using the Shane AO's internal wavefront sensor beam steering. For the top photonic lantern, the PLIU incorporates a 3-axis piezo-electric stage to allow independent positioning. Further design details can be found in our previous work, "An astrophotonics Platform for Lick Observatory: Testing Adaptive Mode Extraction with Photonic Lanterns".[2]

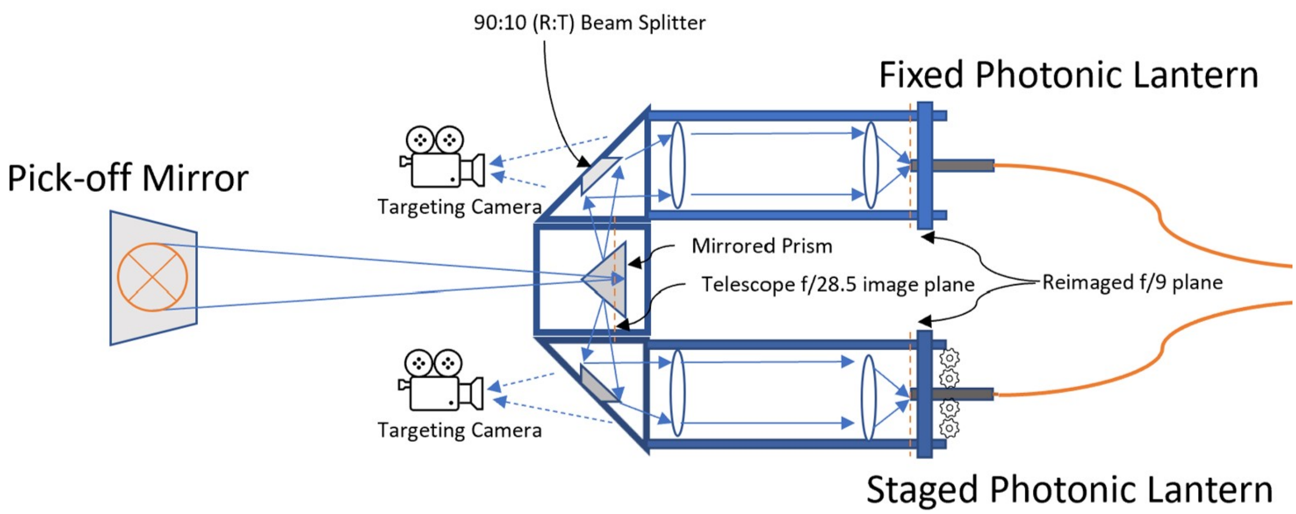

Figure 3. Schematic of the Parallel Lantern Injection Unit (PLIU).

The PLIU design allows interfacing with different types of photonic lanterns, including eventually coupling the lantern outputs to a photonic spectrometer array. Initial on-sky tests with the PLIU demonstrated the ability to couple AO-corrected light from two nearby stars (within 2") into two dynamically-positioned lantern positions with adequate throughput ($> 40\%$) and image quality (0.15").[2] The PLIU's pointing accuracy was approximately 0.05" (12 pixels), sufficient for centering stars on the $\approx 50\mu$m lantern inputs.

2.3 PLIU Throughput

A key characteristic of the photonic testing platform is its throughput. The Shane AO system originally utilizes a 900 nm dichroic to split the incoming beam in wavelength, with bluer light heading to the wavefront sensor for use in the AO correction, and redder light above 900 nm transmitted to the science camera. For our tests, to better align with the quantum efficiency of our CMOS science camera (FLIR BlackFly PGE-13S2M-CS), we replace the 900 nm dichroic with one that transmits light above 605 nm. This provides us with a detectable bandwidth between 605 - 1000 nm, sending light below 605 nm to the wavefront sensor. The PLIU itself utilizes protected silver mirrors, which have a reflectivity in excess of 97% for all wavelengths of interest, and a 90:10 beamsplitter, with the 90% being sent to the fiber port. The 2 lenses utilized within the PLIU are simple ThorLabs Bi-Convex Spherical lenses with their 650 - 1050 nm "B" anti-reflection coating. This coating averages a throughput of 99.6% over our bandwidth. Fig 4 is a plot of the combined theoretical throughput of the new dichroic, 90:10 beam splitter, and all optical surfaces and coatings. The total throughput, to include our science camera's quantum efficiency, is shown in Fig 5.

Figure 4. Combined optics throughput (Dichroic, Mirror, Lens, and Beam Splitter).

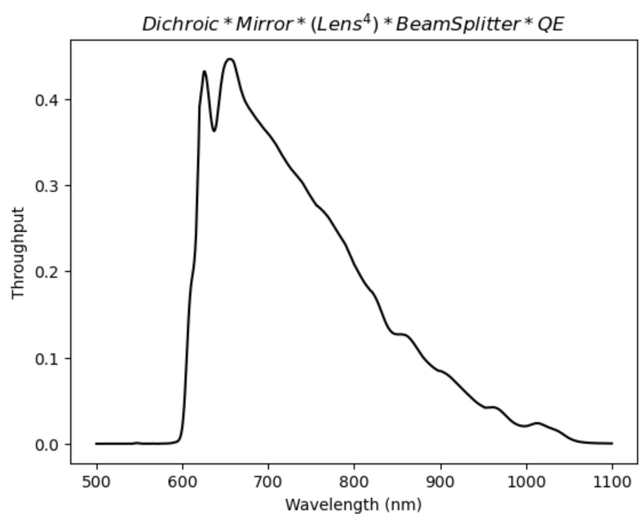

Figure 5. Combined optics with camera quantum efficiency.

Using a Thorlabs PM160 Power Meter, we detect 10.7 nW at the input to the PLIU, before the first fold mirror. This is just before the "Pick-off Mirror" labeled in Fig 3. After being folded twice and reflected off of the 90:10 beam splitter, we detect 8.3 nW for the demagnified f/9 beam at the fiber port. This equates to a PLIU efficiency of 78%. Finally, to test our coupling efficiency, we couple the beam into a 50 μm MMF fiber and measure 3 nW at the fiber's exit. This equates to a total throughput of the PLIU plus fiber coupling of 28%. While improvements can certainly be made, most notably with improved coupling optics, 28% is sufficient for our initial demonstration.

3. PHOTONIC LANTERN CHARACTERIZATION

Several experiments were undertaken to understand how a photonic lantern would respond to both a controlled, deliberate spatially varying input and to an on-sky, real world turbulent input PSF. The wavelength range for these experiments was ≈605-1000nm.

3.1 Controlled Response Experiment

To better understand the modal decomposition of the PL to a spatially varying input, we used the calibration source of the Shane AO system to place a spot in different positions across the MMF input face of our PL.

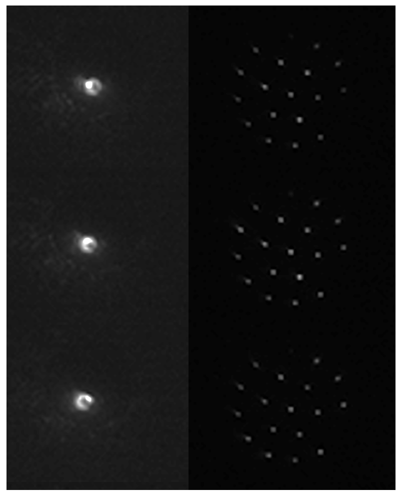

Figure 6. An example of moving the calibration source across the input end of the photonic lantern and the resulting distribution of output intensities. This process was repeated 45 times.

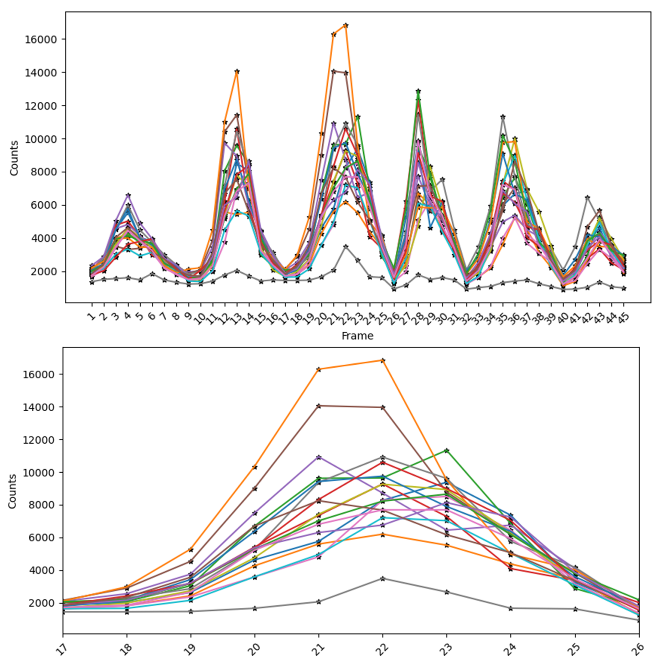

Figure 7. Counts, on a per SMF core basis, as a function of frame/time. The top figure shows the full 45 frame sample, with the bottom plot showing a zoomed in portion between the 17th and 26th frame. Lines crossing over each other is an indication of the SMF core outputs varying their relative intensities over time.

Using the tip-tilt adjustable pick off mirror on the PLIU, we walked the Shane AO calibration source across the MMF input end in a raster fashion. At each position, we pause to take an image of the output intensity distribution, illustrated in Figure 6. This is meant to simulate a time-varying PSF. In total, we took 45 frames. For each frame, we calculated the total counts for each SMF core and plotted that value as a function of frame number. Figure 7 shows the results. This plot is meant to provide a qualitative feel for the lantern's response. One of the first features to notice is the 6 pronounced peaks in the data. This is a result of the bulk coupling efficiency on the MMF end. The spot was allowed to walk completely off the fiber end to ensure we were capturing all possible behavior. Of primary interest is the response within each peak. If each core responded identically to the varying input, we would see a series of parallel lines, changing in-step with the coupling efficiency. Instead, what we see are lines crossing from frame to frame. This is most apparent in the bottom portion of the figure, which is a zoomed in plot of the highest peak.

Lines crossing represents a change in the relative intensity of the cores. This is an interesting result given the broad wavelength range of the input source. The number of supported modes at the lantern input should vary with the inverse square of the wavelength, i.e., as $(R_{MM}/\lambda)^2$, where R_{MM} is the lantern's effective input core radius. Over the 605-1000 nm bandwidth, the number of modes therefore varies by a factor of nearly 2.8. And yet, the distribution of output intensities varies coherently and systematically as the spot is moved across the input face. This motivates further studies of schemes (such as those we have proposed in DeMartino et al. 2022[2] in which specific output channels are tracked according to the instantaneous flux they transmit.

3.2 On-Sky Characterization

To characterize the lantern on-sky, we chose a bright target, Arcturus, in order to utilize a higher frame rate and thus shorter exposure. If the exposure were too long, the resulting images would represent the integrated flux in each core over a time-frame potentially too long to capture the turbulence response. While turbulence, and thus the speckle pattern, can vary on the order of a few milliseconds, we were constrained by equipment to sampling rates closer to 30ms integration time per frame. We took a series of images of the lantern output at 30fps for approximately 2 seconds, using a FLIR BlackFly camera, resulting in 200 total frames.

A plot similar to one created for the calibration source experiment, but this time for a real-world on-sky PSF is shown in Figure 8. Again, we can see a rapidly changing distribution of intensities as a function of time indicated by lines crossing in the plots. Again, this is most apparent in the bottom plot, which is a zoomed in portion of the top plot. And again, we can observe the relative distribution of intensities vary as a function of time, necessitating a switching scheme for AME.

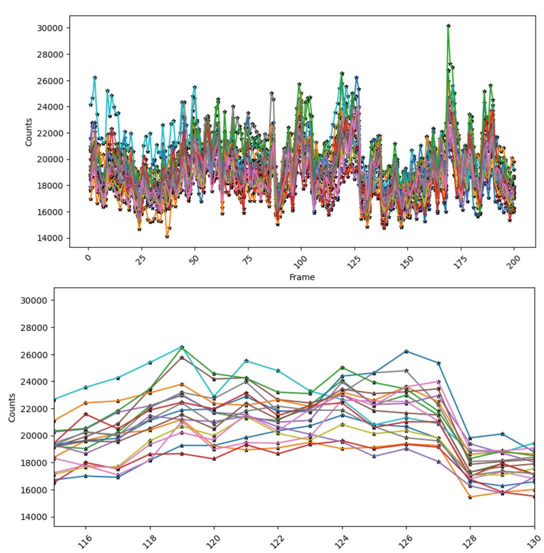

Figure 8. Counts, on a per SMF core basis, as a function of frame/time. The top figure shows the full 200 frame sample, with the bottom plot showing a zoomed in portion between the 115th and 130th frame. Lines crossing over each other is an indication of the SMF core outputs varying their relative intensities over time.

3.3 Future Work

The fact that the relative intensities of the photonic lantern on-sky vary with time strongly suggests we were able to capture the lanterns response to a turbulent PSF. Repeating this experiment over several nights under different conditions would help to better understand how seeing affects the results. Similarly, improving the hardware to increase frame rates would allow for a better analysis of AME on shorter time-scales. In addition, we know that lanterns have a wavelength dependence and that the outputs will vary as a function of varying bandwidths. Repeating these experiments with varying bandwidths would help to disentangle wavelength vs time variability.

3.4 Acknowledgments

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