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An Astrophotonics Platform for Lick Observatory: Testing Adaptive Mode Extraction with Photonic Lanterns

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ABSTRACT

Astrophotonic technologies, specifically mass-produced "spectrometers-on-a-chip," offer an exciting path toward dramatically reducing the cost-per-spectrum of astronomical spectrographs. This technology could one day enable significant multiplexing upgrades to fiber-based instruments and inspire new facilities capable of collecting 100,000 simultaneous spectra in both single-fiber and IFU formats. Here, we report on a new astrophotonics platform at Lick Observatory for on-sky testing of such technologies. Our initial focus is on the problem of efficiently coupling telescope light into photonic devices, which are typically optimized to work with a single mode, i.e., with diffraction-limited light. While photonic lanterns can deliver multiple single-mode outputs given multi-modal input, here we introduce the concept of Adaptive Mode Extraction (AME), which uses a second, reference lantern to select the brightest instantaneous mode or modes for injection into photonic devices. Analogous to "speckle spectroscopy," this technique has the potential to increase the signal-to-noise ratio for faint sources by spatially filtering out the sky background. We have deployed our testing platform behind the AO system at the Shane Telescope and demonstrate that it meets requirements for our planned on-sky tests of AME, namely the ability to couple AO-corrected light from two nearby stars (within 2″) into two dynamically-positioned lanterns, with adequate throughput (>40%) and image quality (0.15″).

Keywords: photonic lanterns, photonics, astrophotonics, photonic spectrographs

1. INTRODUCTION

Photonic technologies are increasingly finding their place in astronomical instrumentation, from advanced fiber optic technologies, such as OH-suppression fibers,[1] to chip-based waveguide circuits used in the VLT Interferometer.[2] Among a variety of applications highlighted in recent calls for investments in astrophotonics instrumentation,[3–5] photonics technologies, specifically mass-produced "spectrometers-on-a-chip," offer a means towards dramatically reducing the cost-per-spectrum of astronomical spectrographs.[3] This is an urgent need given that the projected costs of next-generation conventional spectrographs that are an order-of-magnitude more powerful than today's instruments would be a significant fraction of the construction costs of the large telescopes on which they would deploy.

The first chip-based astronomical spectrometer was successfully tested on the Subaru Telescope in 2016.[6] Based on a modified arrayed waveguide grating (AWG) architecture developed for the telecom industry, this device achieved $R \sim 7000$ at 1550 nm with a free spectral range of 52 nm. Measured from the collecting fiber to the detector, the spectrometer-only throughput was 42%. While this accomplishment is a milestone in advancing astrophotonic spectrometers, such devices face challenges. Because they require "single-mode" input light, i.e., diffraction-limited input, extreme adaptive optics (AO) systems are needed for efficient coupling at the focal plane. Indeed, because of coupling challenges, Jovanovic et al 2017 [6] reported a final end-to-end throughput of just 5%, while identifying several avenues for improvement.

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When considering the mass production potential of chip-based spectrometers for high-multiplex instruments, the coupling challenges are particularly acute because such instruments necessarily demand a wide field-of-view (FOV), on the order of (at least) several arcminutes. Extreme AO corrections with high Strehl ratios across such wide fields would be very expensive, if not infeasible.

Photonic lanterns (PLs) have long been proposed as a potential solution. PLs use a multi-mode fiber (MMF) input, with a larger physical cross-section (200μm), that adiabaticly transitions to a set of single-mode fibers (SMF). PLs offer the promise to take the point-spread function (PSF) from a ground-based telescope with modest AO correction (and possibly no correction at all) and decompose it into a series of single-mode outputs that can be fed to photonic devices.,[7,8] The large cross section of the MMF captures more of the PSF, and by ensuring an adiabatic transition within the PL, coupling losses can be minimized.

Recently, Norris et al.,[9] demonstrated that lanterns employing multi-core fibers (MCFs) provide a complex but deterministic mapping between the input wavefront shape and the output mode intensity distribution. They show that MCF lanterns can therefore be used as wavefront sensors, once a machine-learning algorithm is trained to recognize the mapping parameters. Here we introduce a new application of MCF lanterns that is inspired by this result. With such mappings learned for an array of lanterns targeting faint sources across a field, a single reference lantern placed on a star can be used to identify the brightest instantaneous modes excited in the target lanterns. Analogous to "speckle spectroscopy," extracting just these modes for injection to coupled photonic spectrometers holds promise for increasing the signal-to-noise (S/N) by filtering out much of the sky background. Such a technique, which we call Adaptive Mode Extraction, may make multiplexed photonic spectrometer arrays deployed behind a ground-layer AO system (GLAO) compelling.

We have built an on-sky testing platform for this concept that utilizes Lick Observatory's Shane 3m telescope's ShARCS Adaptive Optics System. Section 2 of this work briefly reviews photonic lanterns which are at the core of the AME concept. In Section 3, we describe how AME could be implemented as well as the performance uncertainties we seek to test on-sky. Finally, we present more details on our Parallel Lantern Injection Unit (PLIU) and its initial on-sky validation in Section 4. Over the course of 6 nights at Lick Observatory we have characterized the performance of this platform, demonstrating its readiness for near-term tests with custom built photonic lanterns.

2. PHOTONIC LANTERNS

Many photonic devices only work with single-mode light, but direct input coupling of single mode light, e.g., via single-mode fibers (SMFs), is difficult. A SMF fiber only guides light at a fundamental mode, which has a flat phase profile and near-Gaussian shape. The atmosphere, along with imperfect optics and diffraction around telescope structures, distorts planar wavefronts and causes a mismatch between the incident wavefront shape and the SMF mode profile, greatly reducing coupling efficiency.[10] To help visualize the problem, we see that as the Strehl ratio degrades, it becomes necessary to increase the diameter of the input fiber to capture more of the now-broader PSF. When the input diameter significantly exceeds the wavelength of the light, this is equivalent to adopting a standard multimode fiber (MMF). Hundreds of modes can now be excited, rendering any coupling to a single-mode photonic device untenable.

Photonic lanterns were introduced to solve this problem. These devices collect light on one end with a MMF-like input, but deliver an output end in the form of multiple, single-mode channels.[8]

2.1 Background

Leon-Saval et al 2013 [7] and Birks et al 2015 [8] 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 coupled into a series of single mode outputs in the form of SMFs. 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.

With a standard lantern, there is not necessarily a deterministic, one-to-one relationship between the modes in the MMF and the SMF output. For example, the fundamental mode of the MMF does not necessarily excite

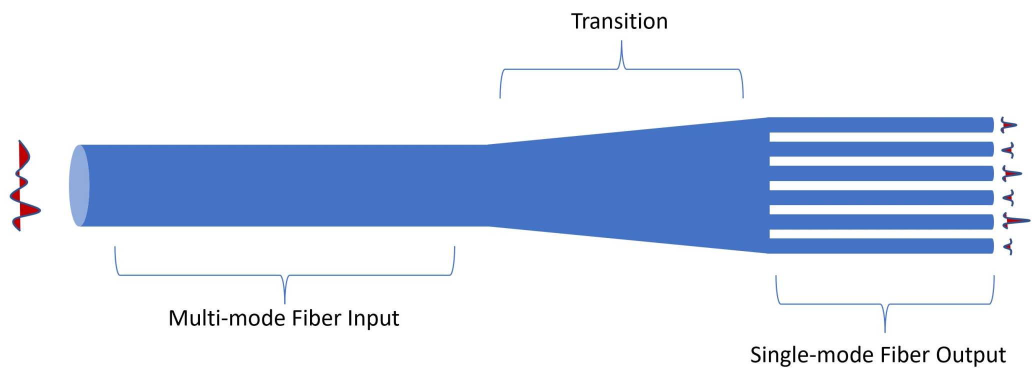

Figure 1. A simplified schematic of a photonic lantern. The multi-mode fiber input on the left takes the input waveform and decomposes it through an adiabatic transition region into a series of single mode outputs.

a single SMF output, but rather excites multiple SMF channels in a way that can vary with stress changes and motion of the lantern. However, as discussed in Leon-Saval et al 2014 [11] and Norris et al 2020 [9], a photonic lantern can be manufactured in such a way as to impart a deterministic relationship between the MMF input and the SMF output.

This is achieved through two primary manufacturing techniques. The first is to use a multi-core fiber and place it in a low index-of-refraction sleeve. A multi-core fiber (MCF) is a fiber with several distinct, uncoupled, single mode cores in one large cladding. A section of this MCF is then heated and stretched until it forms a single, multimode core. The monolithic nature of this structure ensures that the deterministic relationship between the SMF outputs and excited MMF inputs remains stable.[9,12] Similarly, a group of dissimilar SMFs (usually with varying radius) can be grouped into a low index of refraction sleeve and merged in a similar way through heating and stretching. Again, this preserves the mode-selectivity of the lantern.[11] Either technique is plausible, and through selection of the either MCF or SMF bundle, one can tailor the performance of the lantern to their individual need.[8,9,11,12]

Norris et al 2020 [9] use this deterministic behavior to demonstrate the performance of a PL as a wavefront sensor. In their paper, they use a MCF lantern with a MMF input which transitions to a multi-core fiber with 19 single-mode outputs to deterministically map the multi-mode input phase profile to a series of differing intensity single-mode outputs. Because the relationship between input phase and output intensities is non-linear, Norris et al. utilize a deep neural network to perform the input wavefront reconstruction. Characterizing the behavior of their set-up in the lab, the neural network accurately predicts the Zernike terms of the wavefront injected into the lantern, with a root-meansquared-error of 5.1e-3 π radians.[9]

3. ADAPTIVE MODE EXTRACTION CONCEPT

3.1 Concept

While Norris et al 2020 [9] were interested in describing the input wavefront, the AME concept takes advantage of the fact that multiple MCF lanterns collecting light subject to the same distortions and therefore having the same input phase profile will result in output single-mode intensities that are deterministically related. Because this relationship can be "pre-learned" in the laboratory and is stable, it should be possible to use the measured output distribution of one lantern to predict the output of a second lantern. With a downstream device capable of selective switching or per-channel integration and a sufficient mode concentration, the instantaneous mode with the brightest source flux can be extracted while ignoring modes dominated by sky background.

As shown in Fig. 2, the AME concept requires at least two lanterns, one positioned on a brighter reference star to infer modes—we will call this the "guide" photonic lantern—and the other lantern positioned on a faint, background-limited target (the "target" lantern). The two sources must be close enough on-sky to experience the same phase modulation or AO correction (i.e., within roughly the isoplanatic angle). In analogy to speckle imaging or spectroscopy, AME records the outputs of the reference lantern in real time to track where the source flux is dominant. Note that AME could be performed on multiple target lanterns using a single reference lantern within close enough proximity.

The guide lantern requires monitoring from a high-speed, IR sensitive camera similar to those used for wavefront sensing in adaptive optic systems. AO systems typically utilize frame rates in the neighborhood of hundreds of Hz, but we most likely will be limited instead by the speed we can switch between SMF outputs of the target PL. There are two approaches we are considering for this. The first would be to physically cutoff the outputs of the SMF by coupling them into flexible waveguides made from a pliable polydimethylsiloxane (PDMS) material.[13] This has been demonstrated previously in optofluidic waveguide applications with speeds around 100 Hz.[13] The other approach is to utilize a charge transfer scheme for integrating multi-channel on-source output from on-chip spectrometers coupled to every channel. On-source frames from each channel would be combined in post-processing.

AME faces several potential challenges that we seek to address. First, the output single-mode intensity distribution must be sufficiently concentrated for a sufficient fraction of the observation to realize the gain in S/N. The mode concentration can be simulated, but a real-world test with an existing, modest AO system is critical. Depending on the nature of the AO system, it may be possible to custom-design lanterns that regularly achieve high mode concentrations. Bundles of lanterns also offer a means of multiple, singe-mode extractions for a single source. Second, in practice, the phase profiles will differ with on-sky separation, limiting the quality of the inference. This needs to be characterized. Differences may also arise from angular misalignments between the lantern normal and the chief ray (telescope-related spatial offsets should be identical for every lantern if they are accurately positioned). We seek to understand the angular and positioning tolerance. Third, each lantern's mapping may drift to some degree under temperature and stress changes. Finally, AME requires downstream fast switching or integration electronics whose cost and performance must be understood. The details here depend on the particular spectrometer solution employed.

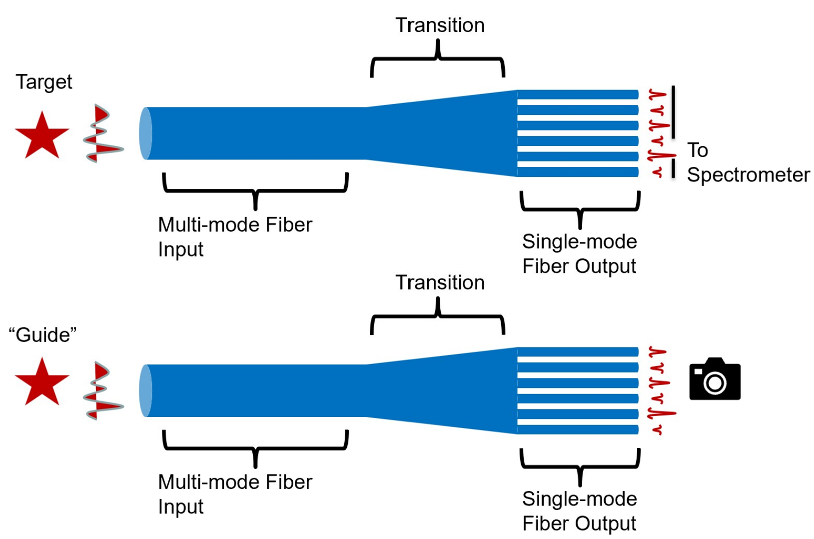

Figure 2. Adaptive Mode Selection Schematic. A guide PL is used to infer the modes of the target PL. Then, only those SMF outputs with significant target flux are measured by the spectrometer.

4. PARALLEL LANTERN INJECTION UNIT (PLIU)

For the reasons listed above, it is critical to develop a real-world platform for testing such technologies on-sky with the full set of complications and limitations that are difficult to completely simulate on a computer or in the lab. This is the purpose of the Parallel Lantern Injection Unit (PLIU). The PLIU re-images two, AO corrected point sources delivered by the Shane AO system image plane to a fiber injection plane while minimizing any additional differential aberration between the two optical paths. Since we are set-up behind an adaptive optics system, the guide and target objects can be chosen within the isoplanatic angle (in practice, their separation is of order arcseconds). The PLIU allows for interfaces to multiple kinds of lanterns and has the capacity for mounting the guide lantern camera and eventually coupling to a photonic spectrometer array.

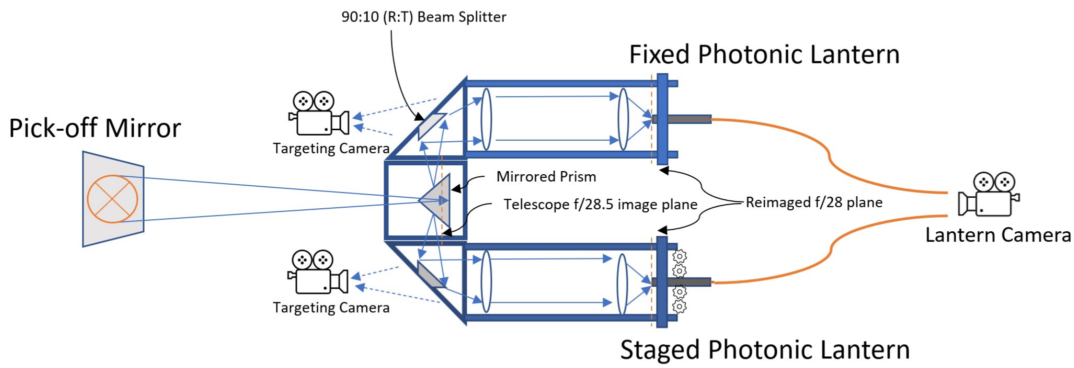

Figure 3. Our design for the Parallel Lantern Injection Unit (PLIU) to test our Adaptive Mode Extraction (AME) concept. In Subsection 4.2, we discuss our initial on-sky testing and characterization.

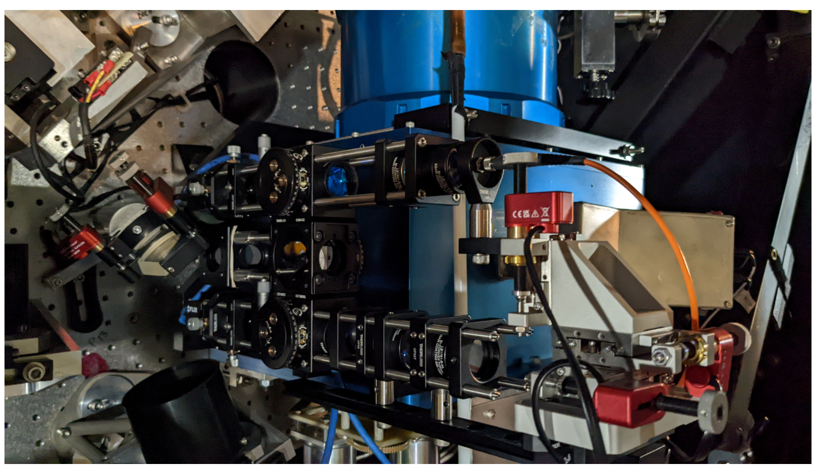

Figure 4. The PLIU installed on the Shane 3m telescope within the AO system. The anodized red structures to the right are the piezo stage motors. The orange testing MMF can be seen extending out the back of the upper arm. The large blue structure is the Dewar for the Shane AO IR camera, which is unused in our system.

4.1 PLIU Design

Our design (Fig. 3) uses a mirrored right-angle prism to split the FOV at the telescope's image plane. The physical size of the corrected, unvignetted, Shane AO FOV is 5x5mm with a plate scale of approximately 4"/mm. Our split FOVs are 2.5x5mm rectangles. The two beams are then folded using a 90/10 beam-splitter and collimated using singlet lenses. These collimated beams are then refocused and demagnified by a factor of 3 onto the fiber plane. Two targeting cameras are aimed through the beam splitters parallel to the optical axis. They image the fiber plane and assist in aligning the PSF centroid with the PL. The polished fiber end itself is reflective enough to permit imaging by the targeting cameras of the PSFs on the image plane (Fig. 5). We use the Shane AO's internal WFS steering to place the "guide" PSF over the guiding PL. For the target PL, we have a 3-axis piezo electric stage for independent placement.(Fig. 4)

4.2 On-Sky Testing and Characterization

Initial testing of the fiber injection unit demonstrates that splitting the Shane AO FOV and injecting two photonic lanterns with light from close binary pairs is feasible. The telescope pointing for one PL and piezo stage alignment for the other is sufficient for the targeting and injection of two PLs.

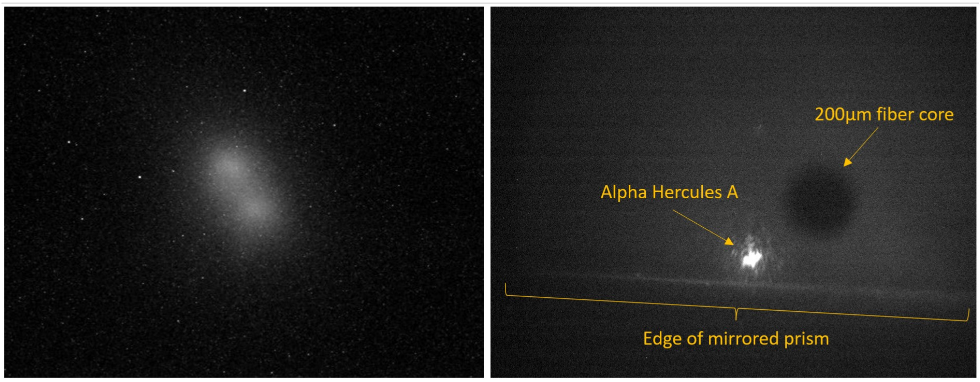

Figure 5. On the left is an image of Diadem, a 0.6 arcsec binary system, split and imaged using the Shane AO through our PLIU, demonstrating we have not negatively impacted the AO's performance significantly. The binary is being imaged by our targeting camera, reflected off a mirror placed at the fiber plane. The right image is of Alpha Hercules A, the brighter companion of the Alpha Hercules system, reflecting off the face of the polished fiber and imaged using the targeting camera. Within the image, the edge of the splitting prism, as well as the 200μm fiber core, are both clearly seen. The whole FOV is only about 2mm across. The edge of the mirrored splitting prism appears slightly askew due to the targeting camera being slightly rotated in relation to the prism.

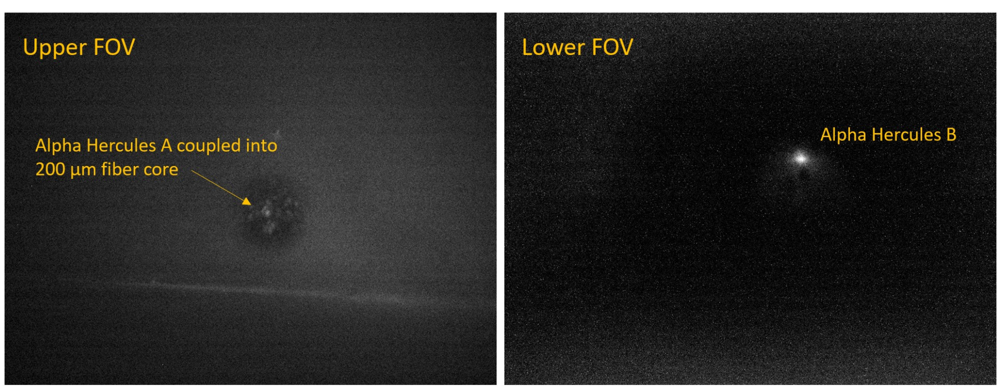

Figure 6. In this figure, the two panes are simultaneous images of the Alpha Hercules binary system. The left pane shows the upper FOV with the brighter companion, Alpha Hercules A, coupled into the 200μm fiber core. Because it is being coupled, only a small amount of light is being scattered back to the targeting camera. The right pane shows the dimmer companion, Alpha Hercules B, being imaged in the lower FOV at the same time. This demonstrates our ability to split the Shane AO FOV and image two closely spaced objects simultaneously using the PLIU.

For on-sky pointing accuracy, on the nights of April 15th and 16th 2022, we demonstrated the ability of the Shane AO beam steering to make adjustments on the order of 0.05". Utilizing the Teledyne FLIR BFS-PGE-

16S2M-CS PoE GigE Blackfly® S Monochrome Camera with a 3.45um pixel size for our targeting camera and taking into account 1/3 magnification, our plate scale is .004"/pix. With the 0.05" pointing accuracy, this gives us a 12 pix minimum step size in the targeting camera, which equates to 16.4 um. For the target PL, we use an XYZ piezo electric stage with 30nm positioning accuracy which is more than sufficient. Our expected fiber size is on the order of 200μm, so the 16.4μm pointing accuracy of the WFS steering allows us to centroid the PSF with an accuracy of approximately 8%.

On the night of July 13th 2022, using Arcturus as an initial test source, we achieved a coupled power of 3nW into a NA 0.22 multi-mode fiber optic, mimicking the parameters of a forthcoming photonic lantern. This was measured using a ThorLabs PM160T optical power meter calibarted for 950nm light. Using a conservative 80% throughput for the telescope and AO system, the 3nW measured power equates to a measured on-sky throughput for the PLIU of approximately 81%. The following night, July 14th 2022, we were able to split Alpha Hercules between the two FOVs, and using the 3-axis piezo stage, couple the brighter companion into a 0.22 NA MMF and measure a coupled power of 2.3nW. (Fig. 6) Shown in Fig. 5, was our attempt to characterize the optical performance of our PLIU. Using Diadem, a 5.22 and 5.32 V magnitude binary system with a separation of 0.2 arcsec, we just split the system. Shane AO advertises routinely reaching the diffraction limit (0.15") at 2.2 microns.

Given its high efficiency and optical quality, the PLIU is ready for use in testing PLs. However, there is room for improvement. Current concerns with the PLIU include the difficulty in set-up and calibration on the Shane AO system and its off-axis performance. Because the PLIU is a bolt-on device and given the tight spacial constraints, placing the apparatus back into the AO beam exactly as we did before is difficult. When combined with the poor off-axis performance, each observing run requires hours of set-up and re-characterization. Several convenience upgrades have helped in this regards. Mainly increasing knob size and collimating the PLIU before installation have helped. It still proves a major challenge however. For example, there are often large aberrations after the device is first set-up which require correction by the AO system's deformable mirror. In the latest run, July 13th and 14th 2022, these aberrations were reduced through careful collimation, but all the lenses in the device are currently biconvex singlets with poor off-axis performance. This was done mainly for cost and simplicity. In the future, a more sophisticated optical design would help in alleviating some of the aberrations.

5. FUTURE WORK

With the Lick Observatory testing platform now ready and delivering sufficient performance, we plan to install PLs for on-sky testing in the near future. In parallel it will be valuable to run computer simulations of lantern performance for different design parameters and explore needed requirements for an implementation behind a future GLAO system. We also intend to test a set of PLs installed in our PLIU utilizing the Santa Cruz Extreme AO Lab (SEAL).[14] In the future, the PLIU platform will be used to test an end-to-end system with a novel chip-based spectrometer being developed by team members from the the University of California, Santa Cruz Baskin School of Engineering. Combined with charge shuffling electronics, this photonic spectrometer is ideally suited to the AME application.

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REFERENCES

[1] Ellis, S. C., Bland-Hawthorn, J., Lawrence, J. S., Bryant, J., Haynes, R., Horton, A., Lee, S., Leon-Saval, S., Löhmannsröben, H.-G., Mladenoff, J., O'Byrne, J., Rambold, W., Roth, M., and Trinh, C., "GNOSIS: an OH suppression unit for near-infrared spectrographs," 773516 (July 2010).

[2] Benisty, M., Berger, J.-P., Jocou, L., Labeye, P., Malbet, F., Perraut, K., and Kern, P., "An integrated optics beam combiner for the second generation VLTI instruments," *Astronomy & Astrophysics* **498**, 601–613 (May 2009).

[3] Gatkine, P., Veilleux, S., Mather, J., Betters, C., Bryant, J., Cenko, S. B., Dagenais, M., Deming, D., Ellis, S., Greenhouse, M., Harris, A., Jovanovic, N., Kuhlmann, S., Kutyrev, A., Leon-Saval, S., Madhav, K., Moseley, S., Rauscher, B., Roth, M., and Vogel, S., "Astro 2020 State of the Profession: Astrophotonics White Paper," 14.

[4] Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020), Space Studies Board, Board on Physics and Astronomy, Division on Engineering and Physical Sciences, and National Academies of Sciences, Engineering, and Medicine, [*Pathways to Discovery in Astronomy and Astrophysics for the 2020s*], National Academies Press, Washington, D.C. (2021). Pages: 26141.

[5] Bland-Hawthorn, J. and Leon-Saval, S. G., "Astrophotonics: molding the flow of light in astronomical instruments [Invited]," *Optics Express* **25**, 15549 (June 2017).

[6] Jovanovic, N., Cvetojevic, N., Norris, B., Betters, C., Schwab, C., Lozi, J., Guyon, O., Gross, S., Martinache, F., Tuthill, P., Doughty, D., Minowa, Y., Takato, N., and Lawrence, J., "Demonstration of an efficient, photonic-based astronomical spectrograph on an 8-m telescope," *Optics Express* **25**, 17753 (July 2017).

[7] Leon-Saval, S. G., Argyros, A., and Bland-Hawthorn, J., "Photonic lanterns," *Nanophotonics* **2**, 429–440 (Dec. 2013).

[8] Birks, T. A., Gris-Sánchez, I., Yerolatsitis, S., Leon-Saval, S. G., and Thomson, R. R., "The photonic lantern," *Advances in Optics and Photonics* **7**, 107–167 (June 2015). Publisher: Optica Publishing Group.

[9] Norris, B. R. M., Wei, J., Betters, C. H., Wong, A., and Leon-Saval, S. G., "An all-photonic focal-plane wavefront sensor," *Nature Communications* **11**, 5335 (Dec. 2020).

[10] Jovanovic, N., Schwab, C., Guyon, O., Lozi, J., Cvetojevic, N., Martinache, F., Leon-Saval, S., Norris, B., Gross, S., Doughty, D., Currie, T., and Takato, N., "Efficient injection from large telescopes into single-mode fibres: Enabling the era of ultra-precision astronomy," *Astronomy & Astrophysics* **604**, A122 (Aug. 2017).

[11] Leon-Saval, S. G., Fontaine, N. K., Salazar-Gil, J. R., Ercan, B., Ryf, R., and Bland-Hawthorn, J., "Mode-selective photonic lanterns for space-division multiplexing," *Optics Express* **22**, 1036 (Jan. 2014).

[12] Birks, T. A., Mangan, B. J., Díez, A., Cruz, J. L., and Murphy, D. F., ""Photonic lantern" spectral filters in multi-core fibre," *Optics Express* **20**, 13996 (June 2012).

[13] Parks, J. W. and Schmidt, H., "Flexible optofluidic waveguide platform with multi-dimensional reconfigurability," *Scientific Reports* **6**, 33008 (Dec. 2016).

[14] Jensen-Clem, R., Dillon, D., Gerard, B. L., van Kooten, M. A., Fowler, J., Kupke, R., Cetre, S., Sanchez, D., Hinz, P., Laguna, C., Doelman, D., and Snik, F., "The Santa Cruz Extreme AO Lab (SEAL): design and first light," in [*Techniques and Instrumentation for Detection of Exoplanets X*], Shaklan, S. B. and Ruane, G. J., eds., 35, SPIE, San Diego, United States (Sept. 2021).