Invited Paper

The photonic lantern wavefront sensor and imager: focal plane wavefront sensing and optimal imaging at the diffraction limit and beyond

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ABSTRACT

The use of a photonic lantern as focal plane wavefront sensor has seen recent widespread interest – it can remove non-common-path aberrations, accurately sense low-wind-effect and petal modes, and provide wavelength resolution. It encodes both the PSFs phase and amplitude into the intensities of its single-mode-fibre outputs, from which the wavefront is reconstructed (by neural network or other algorithm). It also offers exciting potential as an imager to resolve structure at and beyond the telescope diffraction limit, filling in a coronagraphs IWA blind spot. This can utilise interferometric techniques, or an oversampled photonic lantern, having sufficient measurement dimensions that the amplitude, phase and spatial coherence of the science field can be entirely constrained by the output fluxes, and so the wavefront-error-induced components can be disambiguated from the source spatial structure. Other applications such as fibre nulling, optimal single-mode fibre injection, spectroastrometry, and others are also in development. Here, a brief overview of the photonic lantern sensor and these various applications will be given, along with key references.

Keywords: photonic lantern, astrophotonics, image reconstruction, photonic imaging, machine learning

1. INTRODUCTION

The use of a photonic lantern (PL) as a focal plane wavefront sensor (WFS) has seen rapidly growing interest in recent years. It allows removal of non-common-path aberrations, provides sensitivity to blind modes (especially low-wind-effect and petal modes, of particular importance to ELTs), provides wavefront measurement as a function of wavelength, is optimal in detector usage, and is compact and simple to deploy. Unlike a conventional imaging detector, which measures only intensity, the PL is sensitive to both the phase and amplitude of the PSF. Placed at the focal plane, it stably encodes the PSFs complex wavefront information into the intensities of a robust single-mode fibre output array, from which the wavefront can be reconstructed (by a non-linear algorithm such as a neural network, or linear reconstructor for smaller wavefront error magnitudes). It can also be used to optimally inject starlight into a single-mode fibre by using a hybrid mode-selective photonic lantern, ideal for

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single-mode spectrographs and long-baseline interferometry instruments. Here we will briefly describe the latest developments of the photonic lantern wavefront sensor, including closed-loop operation and on-sky tests at the Subaru telescope.

Beyond wavefront sensing, the photonic lantern offers exciting potential as an optimal imaging device to resolve structure with scales at - and even smaller than - the telescope diffraction limit, filling in the blind-spot imposed by a coronagraph's inner working angle limit. This can be achieved by an 'oversampled' photonic lantern, which is built to have sufficient measurement dimensions that the amplitude, phase and spatial coherence properties of the science field can be entirely constrained by the single-mode fibre output fluxes. As such, the wavefront-error (WFE) induced components can be disambiguated from the source spatial structure, and so a seeing-free science image can be reconstructed. Other applications such as nulling and spectroastrometry will also be outlined.

2. THE PHOTONIC LANTERN

A photonic lantern (PL)[1–3] is a device which converts the distribution of light present in a multi-mode fibre (MMF) or waveguide into a set of single-mode fibres (SMF) or waveguides, with low loss. In order to preserve light and achieve high efficiency, spatial information must also be preserved, and so the number of output single modes must be at least equal to the number of input modes (analogous to the principle of etendue conservation). Although originally designed as a means to efficiently inject seeing-affected starlight into SMFs for photonic spectroscopy,[4] subsequently it has been realised that the spatial information of the astronomical PSF encoded in the different SMF output intensities can be exploited.[5,6]

This is possible since the relationship between the input complex mode coefficients and output complex amplitudes (and, consequently, intensities) is given by some complex transfer matrix. The central advantage here is that, unlike a standard imaging detector (which is only sensitive to the intensity, or square of the complex amplitude), the output intensities are a function of both the *phase and amplitude* of the incident PSF. This makes it ideal as a focal plane wavefront sensor, as described in Section 3.

The PL performs the multi-mode to single-mode conversion by a specially designed taper transition. As shown in Figure 1, the cores of the SM fibres gradually vanish, and their cladding transforms into the core of the new multimode fibre, which has a low refractive index capillary cladding. Initially these devices were made by placing individual SM fibres into a capillary and tapering the combined assembly. Recently, multi-core fibres (MCF) have become common, simplifying the manufacturing process and enabling more modes/cores by including multiple single-mode cores in one fibre.[7] Integrated photonic lanterns can also be produced using the laser direct write process,[8] though they are less mature than fibre-based devices.

3. WAVEFRONT SENSING

The fact that the easily-measured single-mode output fluxes of a PL are a function of both the phase and amplitude of the incident PSF makes it an ideal focal-plane WFS. Placed at the telescope image plane it allows AO correction to be performed using the actual instrument PSF, rather than (or in addition to) a separate pupil-plane wavefront sensor such as a pyramid or Shack-Hartmann device. This has a number of advantages – it eliminates the non-common-path aberrations (NCPA) between the pupil plane and image plane, it is ideal for SM-fibre fed instruments, and it is sensitive to 'blind' modes such as petalling, low-wind-effect and mirror-segment phasing[9–12] that pupil-plane wavefront sensor are largely unable to sense. These aberrations, caused by phase shears arising from thermal effects of telescope secondary-mirror supports or imperfectly phased mirror segments, are one of the most dominant limitations in current high-contrast imaging and will be especially important for the coming generation of ELTs. Moreover, since the outputs are simply an array of single-mode fibres it is straightforwards to spectrally disperse the outputs, allowing wavefront error to be measured as a function of wavelength, extremely important for dealing with phase-wrapping and increasing sensitivity and WFE range.

The first challenge is that while the transfer function between input mode coefficients and output SMF amplitudes is stable, it is not possible to exactly specify this function at time of fabrication. Instead, it needs to be characterised after the PL is made, either in the laboratory or in-situ in the instrument. This can be

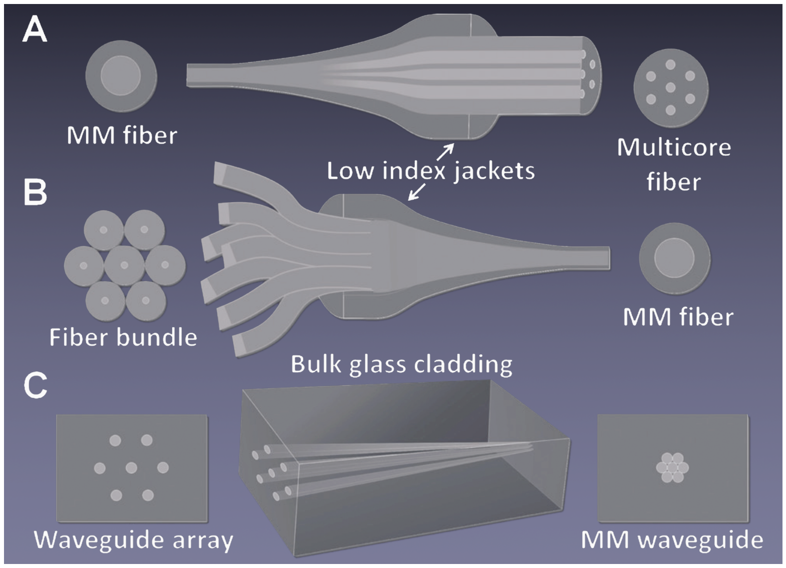

Figure 1. Three ways of fabricating photonic lanterns: a) using a single-mode multicore fibre, b) using a bundle of individual single-mode fibres, and c) using laser direct-write. In all cases the PL operates the same way: along the taper transition the individual single-mode cores effectively disappear, and their cladding (or equivalent) forms the core of a new multi-mode waveguide.

performed using various machine learning techniques, similar in concept to the response-matrix approach used in standard AO, but with one important, extra complication – non-linearity.

This second challenge is that since the output fluxes measured are the square of the complex amplitudes, the relationship between WFE mode coefficients and measurements is non-linear. The non-linear and non-monotonic relationship is most pronounced at larger wavefront errors ($\gtrsim 1\ rad$). One approach is to use a non-linear machine learning algorithm for the wavefront reconstruction, such as a neural network.[5] Alternatively, a linearised or even quadratic approximation can be used, especially effective for smaller magnitude WFE.[13] Understanding and modelling the expected transfer function of a PL as a function of its geometric and material parameters is an area of ongoing work.[14,15]

Neural-network based wavefront reconstruction can be performed by training a model on a set of training data, consisting of known probe wavefronts injected into the PL (using a deformable mirror or spatial light modulator) and the corresponding outputs. This can easily be done in-situ in an AO system. But unlike the linear response matrix used in conventional AO, which involves taking one or two (often plus and minus) measurements for each applied mode, the non-linearity here means that a large number of samples of (in this case random) combinations of modes must be measured. Figure 2 shows examples of wavefront reconstruction of a Kolmogorov phase screen created by an SLM and injected into a ∼20 mode PL in the lab, reconstructed using a neural network. It can be seen that the PL reconstructs a low-order version of the true phase screen, due to its low mode count. Also shown here is the PSF as reconstructed by the same PL measurement, demonstrating the basic imaging ability of these devices, which will be expanded upon in Section 5.

4. NOVEL SCIENCE MEASUREMENTS

4.1 Optimal SM fibre injection

Efficiently injecting starlight into single-mode fibres is crucial for photonic integrated circuits, fibre beam combiners, photonic spectrographs, and fibre Bragg gratings. However, seeing and AO residual WFE makes this challenging by turning the telescope's diffraction-limited PSF into a speckle cloud, poorly overlapping with the SMF mode. The resulting low injection efficiency can drop to ∼3% for 0.3" seeing on an 8 m telescope, and nearly zero for 0.6".[16] Standard adaptive optics can improve this, achieving 50% efficiency with the SCExAO system at the Subaru Telescope, but faces limitations like blind modes and non-common path aberrations.[17]

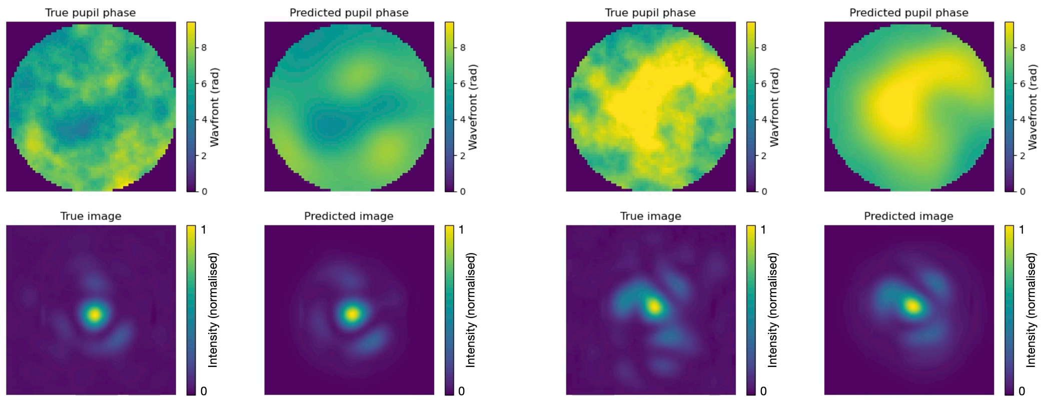

Figure 2. Two examples of wavefront and PSF reconstruction using a PL in the laboratory, utilising a neural network reconstruction algorithm. A Kolmogorov phase screen (with P-V wavefront error of ∼6 rad) is created with a spatial light modulator and injected into the PL. The PL used here had only ∼20 modes, and a low-order reconstruction of the wavefront is successfully produced. The PSF is also reconstructed from the same measurements.

A focal plane wavefront sensor, like the PL-WFS, itself offers advantages. But even better would be somehow directing maximum injected starlight to one of the PL's SMF outputs and sending this to the single-mode science instrument, which would eliminate non-common-path aberrations by unifying the wavefront sensor and science fibre. One method is setting the wavefront to maximally excite one output fibre via the system's DM, as shown in simulations.[15] However, this method is wavelength-dependent, only effective in monochromatic cases.

The hybrid mode-selective photonic lantern (PL) offers a promising solution.[18] Unlike a standard PL, it maps a specific input mode (like the LP_{01} mode) to a particular output fibre across a broad bandpass. This is achieved by structural perturbations, such as tuning the central core size and spatial filtering. For a 19-core LP_{01} mode-selected lantern, simulations show it can couple only the LP_{01} mode to the science output fibres, suppressing other modes by over 20 dB across the H band (1.5μm to 1.8μm).[18] This mixed-mode approach is ideal for wavefront sensing, as fully mode-selective PLs aren't optimal for WFSing and can't support many modes.[6] In operation, the remaining fibres are used for wavefront sensing to control the AO system, which maximises the excitation of the LP_{01} mode in the PL. A unique control challenge is that optimal wavefront correction minimises the wavefront sensing signal/noise ratio since most light goes into the science fibre; when the correction deviates, light appears in other outputs, and the AO system corrects it. Fabrication and laboratory testing of these devices is now underway.

4.2 Nulling

A central challenge in high-contrast imaging, partulrly when the inner few λ/D around the star is to be probed, is contamination of the science signal (exoplanet, protoplanetary disk, etc.) by diffracted starlight. These speckles not only create a formidable calibration problem, but because the star can be many orders of magnitude brighter than the science target the photon noise from the star completely dominates the science signal, which no amount of post-processing can repair. It is very difficult for coronagraphs to decrease their inner working angle to reveal objects at separations of $\lessapprox 2\lambda/D$, and nulling is one alternative, wherein destructive interference is used to remove the contaminating starlight. While more conventionally done with bulk optics or in photonic chips,[19] the same principle has been done using a single mode fibre[20] and a pupil plane mask, such as with the vortex fibre nuller.[21]

But a similar process can be performed using a mode-selective photonic lantern,[22] a type of PL that – rather than having the input modes and output SMF amplitudes related by mixing as per some transfer matrix – maps a specific input mode to a specific output SMF. This allows one to create a photonic lantern nuller.[23] This takes advantage of the shape and symmetry of the modal basis of a multimode fibre (in this case the PL multimode region). While the fundamental LP_{01} is a roughly Gaussian shape and effectively couples light from an on-axis star, some higher order modes such as LP_{11} and LP_{21} have their power concentrated in lobes closer to the edge of the fibre core, reaching zero power (a null) in the centre. An off-axis object (such as a planet) will preferentially couple into these modes, and thus the measurement of the 'leakage' of light into these modes can give a high SNR measurement of the off-axis science target.

Laboratory experiments using broadband light have already demonstrated starlight rejection of a factor of $\sim10^2$ and planet injection efficiency of ~0.4.[23] More detailed analysis, such as the effect of polarisation and wavelength, is ongoing.

4.3 Spectroastrometry

The sensitivity of the PL to the spatial distribution of flux (and phase) at the image plane, along with its ability to be easily spectrally dispersed, makes it an ideal device to perform spectroastrometry.[24] Spectroastrometry is used to precisely measure the shape of objects where their morphology changes with spectrum – for example emission lines arising from a discreet feature in a scene, such as protoplanet accreting in a disk. A few-mode PL can used to measure the overall position (e.g. centre of mass) of a source as it is very sensitive to tip/tilt terms. If this tip/tilt signal is found to be a function of wavelength, this reveals some extended structure beyond an unresolved star, and provides information on the nature of the extended source(s) (e.g. the composition of the observed spectral lines).

The key advantage of this technique is that it can resolve structure of sizes far below the diffraction limit, since even a very small wavelength-dependent shift in the PL outputs can be measured. In fact very small shifts of magnitude $<< \lambda/D$ are the most straightforwards to analyse, as the PL's intensity response is approximately linear in this regime. Simulations of spectroastrometry using a standard 6-port PL have been performed, including realistic simulated seeing and telescope tip/tilt error.[24] These include mock observations of an accreting protoplanet within a disk, and demonstrate the feasibility of this approach.

5. IMAGING AND FULL-WAVE SENSING

A major goal is to enable full imaging capability with the PL. The key advantage will be that, by completely measuring the complex PSF, it will be able to distinguish between real structure and artefacts from seeing, and undo the effects of seeing to produce an uncorrupted image (see Figure 3). It will simultaneously act as a focal plane WFS, providing realtime correction feedback to the AO system yielding the various advantages discussed above. This requires several innovations beyond the current PL systems:

1. **Sufficient degrees of freedom to unambiguously measure phase and amplitude.** While the standard photonic lanterns discussed thus far are sensitive to both phase and amplitude at the focal plane, they do not themselves provide enough independent measurements to constrain both independently. This is because even though the number of input modes equals the number of output fibres, each input mode has 2 components (real and imaginary parts) while the output intensities just have a single scalar value.

2. **Ability to also measure spatial coherence.** To disambiguate WFE artefacts such as speckles from true astrophysical structure, the degree of spatial coherence of each position in the scene must be measured, equivalent to the visibility measurement performed in an interferometer. This places a PL imager in the realm of coherent differential imaging (CDI).[25]

3. **Sufficient spatial elements to image desired field-of-view.** Sampling the entire imaging area at diffraction-limited resolution will require more input modes and output fibres than PLs currently used for wavefront sensing.

4. **Innovative data analysis and image reconstruction algorithms.** This is a fundamentally new type of data and observing mode, and so there are no existing algorithms or software able to interpret this. This will likely draw from machine learning approaches (to determine and calibrate the response function of the PL and surrounding system) and astronomical intrerferometry.

To give a naive estimate for the number of independent measurement outputs needed to fulfil requirement 4, one can consider the following: If the goal is to image the innermost 3 λ/D (the region most challenging for coronagraphs), roughly 30 independent λ/D spatial components must be measured, resulting in 60 outputs (to

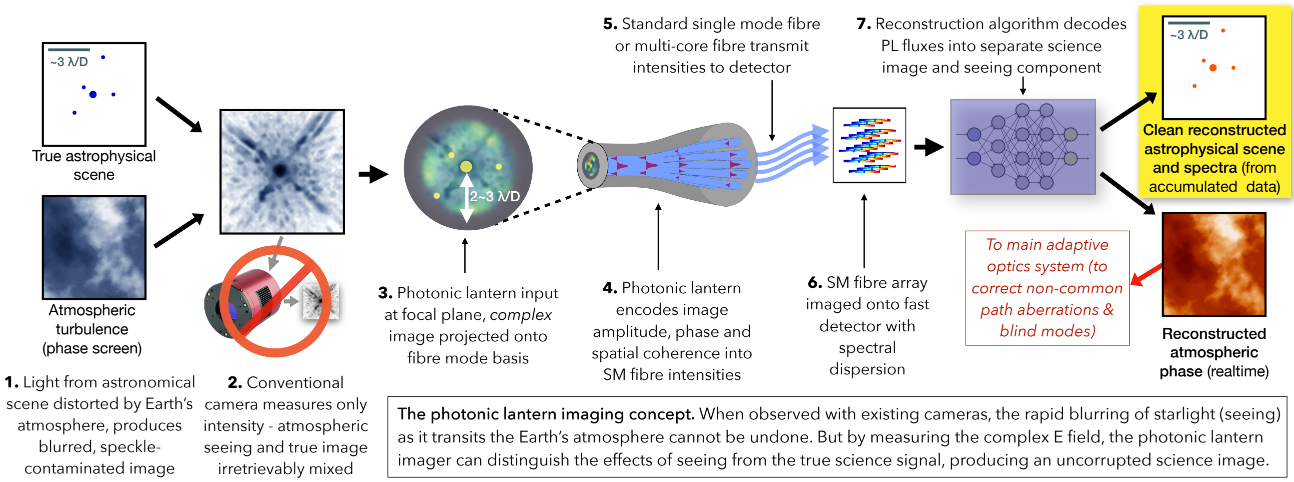

Figure 3. A conceptual diagram outlining the oversampled photonic lantern imaging concept.

constrain amplitude and phase). Then to measure spatial coherence another 30 would be needed. Thus of order $\sim$100 independent measurement outputs would be required.

A few approaches have been proposed thus far. One is to adapt the approach taken in interferometry, and coherently recombine the outputs of the PL afterwards in a second stage in the same fashion as a beam combiner in an astronomical interferometer.[26] This addresses requirement 1 above by using the interferometer to measure both the amplitude and phase of each PL output, this matching number of output measurements to input mode degrees of freedom. This could be done by feeding each PL output into a photonic beam combiner chip.[26] This also addresses requirement 4, as interferometric techniques measure the visibility of the fringes which directly describes spatial coherence.

One challenge with this technique is that it requires all the single mode fibres leading from the PL to the beam combiner to stay very stable in terms of optical path length (OPL) matching and throughput, to maintain phase stability. This can be difficult as the effective OPL of SMFs is extremely sensitive to temperature, strain, and bending. Another challenge may be having sufficient degrees of freedom to fulfil requirement 4, as currently interferometric beam combiners do not exist which can handle the $\sim$100s of inputs, and resulting 1000s of baselines required here (most commonly they accept $\lesssim$10 inputs, one for each telescope in an array). But photonic chip technology is rapidly advancing and this may soon be a solvable problem, and of course a smaller field of view could be used.

Another method proposed is to use a so-called oversampled photonic lantern,[27] where the number of outputs are greater than the number of input modes. The goal here is to perform all coherent processing within the PL itself rather than in an external beam combiner. This would have the advantage of stability – accurate, stable OPL matching between output fibres is not required, plus the entire device fits inside a standard fibre connector, reducing cost and complexity. Using the above estimate, a PL of $\sim$30 input modes and $\sim$100 output fibres may be required, which is well within current fabrication capabilities, with PLs having 100s of modes and outputs having already been made.[28]

The challenge with this technique is being able to design and fabricate a PL which performs sufficient coherent mixing between all modes to produce a set of outputs which entirely constrains the scene's amplitude, phase and spatial coherence. The data analysis and image reconstruction algorithms also need to be developed. Nonetheless, initial laboratory tests show promising results, using a fully convolutional neural network to reconstruct the wavefront and image.[27] Another technique exploits quantum-inspired imaging algorithms, measuring the transfer matrix of the PL separately (e.g. by using off-axis holography) and using this to reconstruct the image.[29] In all these methods, spectral dispersion of the PL outputs would be used to provide additional constraints and resolve ambiguities (such as from phase wrapping).

6. CONCLUSION

Here we have seen a brief overview of the photonic lantern (PL) and some of its astronomical sensor applications, including as both a focal plane wavefront sensor and an optimal imaging device. The PL's unique ability to encode the phase and amplitude of the point spread function (PSF) into the intensities of its single-mode fibre outputs allows it to operate as focal plane wavefront sensor – unlike a conventional pupil-plane wavefront sensor, the PL WFS mitigates non-common-path aberrations and accurately senses low-wind-effect and petal modes, can easily be spectrally dispersed, and is compact and easy to deploy.

The PL's potential extends beyond wavefront sensing to high-resolution imaging, where it can resolve structures at and beyond the telescope diffraction limit. Its ability to fill in the coronagraph's inner working angle blind spot and disambiguate seeing artefacts and speckle from true spatially incoherent structure opens new possibilities for precise astronomical imaging. Furthermore, applications such as optimal single-mode fibre injection, nulling, and spectroastrometry are actively being developed, demonstrating the versatility and broad impact of this technology.

Wavefront sensing challenges include the non-linear relationship between wavefront error and single-mode fibre outputs, but there are promising solutions using machine learning techniques, quadratic reconstructors and linearised algorithms. The development of hybrid mode-selective photonic lanterns and oversampled PLs are significant steps towards achieving comprehensive imaging and wavefront sensing capabilities. These all lead towards the central goal of performing spectrally-resolved imaging of structures such as exoplanets, protoplanetary disks and stellar mass-loss shells at and beyond the diffraction limit, revealing new observational domains for these and other astronomical science cases.

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