High-performance 3D waveguide architecture for astronomical pupil-remapping interferometry

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Abstract: The detection and characterization of extra-solar planets is a major theme driving modern astronomy. Direct imaging of exoplanets allows access to a parameter space complementary to other detection methods, and potentially the characterization of exoplanetary atmospheres and surfaces. However achieving the required levels of performance with direct imaging from ground-based telescopes (subject to Earth’s turbulent atmosphere) has been extremely challenging. Here we demonstrate a new generation of photonic pupil-remapping devices which build upon the Dragonfly instrument, a high contrast waveguide-based interferometer. This new generation overcomes problems caused by interference from unguided light and low throughput. Closure phase measurement scatter of only $\sim 0.2^\circ$ has been achieved, with waveguide throughputs of $> 70\%$. This translates to a maximum contrast-ratio sensitivity between star and planet at $1A/D$ ($1 \sigma$ detection) of $5.3 \times 10^{-4}$ (with a conventional adaptive-optics system) or $1.8 \times 10^{-4}$ (with ‘extreme-AO’), improving even further when random error is minimized by averaging over multiple exposures. This is an order of magnitude beyond conventional pupil-segmenting interferometry techniques (such as aperture masking), allowing a previously inaccessible part of the star to planet contrast-separation parameter space to be explored.

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References and links


planetesimals then go on to form either Earth-like planets or giant, gaseous planets. The outcome of this process leading from dust grains to planetary cores, one outstanding question is that of how these small dust grains to planets thousands of kilometres in size - but the mechanisms behind this process are not yet properly understood [3]. While many questions remain regarding the growth mechanism from dust grains to planetary cores, one outstanding question is that of how these planetesimals then go on to form either Earth-like planets or giant, gaseous planets. The out-

1. Introduction

Ever since the beginning of the modern era of extra-solar planet discovery [1], the detection and characterization of exoplanets has been one of the most active areas in contemporary astronomy. Precise observations of exo-planetary systems promise to reveal the underlying physical mechanisms by which planetary systems - such as our own solar system - were formed, and estimate the ubiquity and diversity of earth-like planets in the galaxy. The vast majority of exoplanets detected thus far have been via techniques such as transits (wherein the light of the host star caused by the pull from its orbiting planets is detected via doppler shift) [2]. While these techniques have been very successful in detecting and measuring a large number of exoplanets, they are limited to a restricted parameter space (for example, there are heavy observational biases favoring large planets and close orbits).

A key goal in current exoplanetary astronomy is a proper understanding of the mechanisms by which planetary systems are formed and evolve. The formation of a planetary system requires the growth of dust particles through at least 12 orders of magnitude, from sub-micron scale dust grains to planets thousands of kilometres in size - but the mechanisms behind this process are not yet properly understood [3]. While many questions remain regarding the growth mechanism from dust grains to planetary cores, one outstanding question is that of how these planetesimals then go on to form either Earth-like planets or giant, gaseous planets. The out-


come of the planetary formation process seems to depend on whether the cores are located inside or outside the ‘snow line’ - the radius from the star beyond which low temperatures allow ices to condense from gas. Cores within this radius become terrestrial-type planets, but those beyond the snow-line are believed to become gas giants.

One proposed mechanism for this is core accretion [4], wherein the cores gradually capture various gases, forming their extended atmospheres. But there are various competing models, including planetary migration [5] wherein cores migrate from the orbit of their formation to different orbits where the accrete their atmospheres, and also the significantly different model of gravitational collapse of protoplanetary disks [6]. The key to distinguishing between these models is to have a proper understanding of the frequency of planets as a function of their mass and separation [7]. To achieve this, the entire parameter space of planetary systems ideally needs to be sampled. However detection techniques each have their own biases and limitations in this regard (e.g. [8–10]).

Direct imaging of exoplanets – wherein the star and nearby planet are separately resolved at an image plane – promises to provide critical answers to these questions of planetary formation and evolution. This technique has already begun to constrain the frequency of giant planets; null results from direct imaging surveys have set an upper limit on the fraction of stars having young planets with masses above 4 $M_{\text{Jupiter}}$ at separations between 20 and 100 AU as being 20% or less [11]. Direct imaging at multiple epochs allows the orbital parameters (and hence mass) to be directly determined. It also allows the possibility of spectroscopic observations of planetary atmospheres, as well as characterization of exoplanet surfaces, major goals in exoplanetary science. However the few exoplanets imaged thus far have been limited to wide apparent separations [12] due to the challenging nature of high contrast measurement at very small spatial scales. Coronagraphs fed by AO systems represent the most developed class of high contrast imaging techniques, and although they have demonstrated exceptionally high contrast at large separation, performance is more limited at spatial scales of order $1 \lambda/D$ (corresponding to the Earth-Sun separation at a distance of $\sim 30$ parsecs), even with the most advanced refinements [13]. To some extent this problem of the most productive search space lying within the so-called inner working angle of the coronagraph is inherent to the basic design of the instrument, and in practice is compounded by residual phase-aberrations present in the imaging system (largely from imperfect AO correction).

But this inner region is of critical importance to understanding planetary formation - it encompasses inner solar-system scales around the snow-line, and is the region of critical interactions between dust populations and protoplanetary bodies [3]. Additionally, this parameter space overlaps significantly with existing transit and radial-velocity planet detections, allowing these known planetary systems to be targeted and have their orbital parameters measured. Imaging young giant planets at these inner solar-system scales forms the major goal of the instrument described in this paper.

One solution to this inner working angle problem is aperture-masking [14], wherein the pupil of a large telescope is divided into a number of small sub-pupils using an opaque mask placed at the pupil plane, turning the telescope into a sparse interferometer array. Each pair of holes in the mask forms a baseline, and the key requirement is that the vector separation between any two holes in the mask is unique: such a mask is said to be non-redundant. By analysis of the resulting interference pattern in the Fourier domain, phase-independent observables such as the squared visibility (the power spectrum of the image) and the closure phase (described in Section 1.2) can be derived. Since these observables are largely robust to residual wavefront phase aberration, the telescope’s diffraction-limited performance can be recovered.

This technique has been successfully used to recover diffraction-limited images at high contrasts, including the recent detection of sub-stellar companions undergoing the process of plan-
etary formation [15, 16] wherein contrast ratios of $\sim 300 : 1$ have been achieved. However, while this is a powerful tool for high-resolution imaging, its applicability to exoplanetary imaging is limited by several aspects of the experimental design. Firstly, the requirement that the sub-aperture positions be non-redundant severely limits the fractional pupil area passed by the mask. For example, a commonly used 9-hole mask has a throughput of only $\sim 12\%$, restricting the technique’s use only to bright targets. A further limitation to the signal-to-noise ratio is imposed by the non-zero size of the sub-apertures and integration times. Closure phases are strictly immune to wavefront phase errors only in the limit of a point-sample of the wavefront in both space and time. In practice, neither is possible for the case of masking interferometry, which fundamentally limits the precision attainable by this technique.

1.1. The Dragonfly instrument

To address these limitations, the concept of a pupil-remapping interferometer was born [17,18]. Instead of using an aperture mask, the pupil of the telescope is divided into a number of segments, and each segment is injected into a single-mode fiber or waveguide. These then coherently remap the 2-dimensional pupil into a linear array, which then forms a 1-dimensional interference pattern. This accomplishes several things. First, while the output arrangement of fibers or waveguides needs to be non-redundant, the input arrangement does not, therefore allowing the entire pupil to be sampled, resulting in overall throughputs that at least in principle approach 100%. Alternatively, the 1-dimensional output array is now suitable to feed a lithographic photonic beam combiner [19]. Complete sampling of the pupil also provides much better Fourier coverage than an aperture mask. Second, since the light guides are single-moded, any phase-variation across a single ‘sub-aperture’ is removed; it is spatially filtered. This means that the assumption of single phase for each sub-aperture is now valid, and the criterion for closure phases will strictly apply. Thirdly, since the output array is 1 dimensional, spectrally dispersing the output becomes trivial and a low resolution dispersing element (such as a prism) allows the bandwidth limitations of aperture masking to be overcome. This principle was demonstrated on-sky in an earlier prototype [17], wherein the entire astronomical J and H bands ($\sim 1.0$ to $1.8 \mu m$) were simultaneously observed, with each spectral channel having a bandwidth of $\sim 30$ nm.

However, this technique introduces a new stringent requirement: since the light in all waveguides must remain coherent in order to form the interference pattern, the optical path-lengths of each of the fibers/waveguides must be precisely matched. For typical astronomical spectral channel widths ($\sim 50$ nm at $\lambda = 1.5 \mu m$), this means path lengths must all be matched to within a few microns. For an optical fiber based remapper (such as in the FIRST instrument [18]), this is a challenging tolerance since not only must the physical lengths of all fibers (and accompanying connectors) be precisely matched, but also any strain or temperature differences between the fibers must be carefully managed to avoid varying optical path lengths.

The Dragonfly instrument uses an alternative technique – the pupil is remapped using a monolithic photonic pupil-remapping chip. Here, a set of waveguides is inscribed into a single block of glass using the femtosecond laser direct-write technique [20–22]. In addition to the interferometric application described here, this technique is also being used in the development of diffraction-limited astronomical spectrographs [23,24]. By focusing a femtosecond laser into a block of glass (causing a local, permanent refractive index change), and translating the glass in three dimensions, an arbitrary set of waveguide trajectories can be sculpted. The key advantage here is that since the routing of the waveguides can be precisely specified, path-length matching is relatively straightforward. Moreover, since the device is embedded within a single, monolithic block, differential strain or temperature changes between waveguides are eliminated. This photonic chip (referred to henceforth simply as the ‘pupil remapper’) is integrated into the larger Dragonfly instrument, which provides beam handling, injection optimization and
detection. Further discussion of challenges and features of pupil remapper design is given in Section 3.

This technique was demonstrated on-sky with the Dragonfly instrument in 2011 [17], and while this validated the photonic pupil remapper concept, levels of performance were insufficient to be competitive in astronomical research (particularly closure-phase precision and throughput). Subsequent refinements have produced a new generation of pupil remappers which address these concerns and provide performance levels approaching ideal. These improvements, which promise a fully science-ready instrument in the next generation, are the subject of this paper.

1.2. The closure phase observable

The key data product delivered by Dragonfly is the closure phase [25]. This observable has been the key to successful high resolution, high contrast studies with conventional aperture-masking interferometry [26], and becomes significantly more powerful when implemented with Dragonfly.

For an ideal imaging system, the observed phase of fringes from each baseline can be used to construct an image (or fit to a model.) However for astronomical imaging, the phase at each sub-aperture is randomized by the Earth’s turbulent atmosphere. Even when adaptive-optics systems are employed, residual phase variation can be between 20° and 60° RMS, depending on conditions and wavelength. However, the closely related closure-phase is largely immune from these effects.

Consider a set of three sub-apertures (labelled 1, 2 and 3), forming three baselines (1-2, 2-3 and 3-1) in a closed triangle. Each sub-aperture is considered to have a random phase error from the atmosphere – \( \epsilon_1 \), \( \epsilon_2 \) and \( \epsilon_3 \). Since the absolute value of these errors is arbitrary, \( \epsilon_1 \) is set to zero, and so the phases measured on the three baselines are then

\[
\begin{align*}
\Psi_{1-2} &= \phi_{1-2} + \epsilon_2 \\
\Psi_{2-3} &= \phi_{2-3} + \epsilon_3 - \epsilon_2 \\
\Psi_{3-1} &= \phi_{3-1} - \epsilon_3
\end{align*}
\]  

where \( \phi_{ab} \) is the true phase of baseline \( ab \) and \( \Psi_{ab} \) is the phase measured on baseline \( ab \). The closure phase (CP) is then defined as the sum of these three baselines:

\[
CP = \Psi_{1-2} + \Psi_{2-3} + \Psi_{3-1}
\]

\[
= (\phi_{1-2} + \epsilon_2) + (\phi_{2-3} + \epsilon_3 - \epsilon_2) + (\phi_{3-1} - \epsilon_3)
\]

\[
= \phi_{1-2} + \phi_{2-3} + \phi_{3-1}
\]  

The atmospheric terms \( \epsilon \) cancel and hence the closure phase is purely a function of the true phase. Interferometric observations usually consist of a large number of frames of fringes (each with short integration times). Instead of simply averaging the closure phase of each set of fringes, the bispectrum is instead accumulated. The bispectrum is defined by the triple-product of the complex visibilities of each baseline, i.e.

\[
Bispectrum = V_{1-2}^* \cdot V_{2-3}^* \cdot V_{3-1}^*
\]  

The bispectrum of each frame is added together, and the argument of this sum is the closure phase. This method has the advantage that frames with low visibilities (e.g. due to particularly bad seeing at that time) contribute less to the final closure phase than frames with high visibilities.
The derivation above assumes that the phase error at each sub-aperture can be characterized by a single scalar phase term \( \epsilon \). In the case of aperture masking this is only approximately true, limiting the precision of closure phase measurement. However when using a single-mode waveguide based remapper, such as in Dragonfly, the phase structure within each sub-aperture is filtered into a single mode with a single phase term, meaning the closure-phase assumption is now rigorously true, allowing more precise calibration and greater closure phase accuracy. In other words, the intensity distribution at the waveguide output is constant (defined by the waveguide's mode field profile) and has lost all information regarding the intensity distribution - such as atmospheric variations - at the input [27–29]. This spatial filtering comes at the expense of coupling efficiency however, which will be described in more detail in Section 4.3.

The closure phase precision directly relates to the contrast ratio obtainable at a given resolution. Simulations [26] have shown the following relationship between closure phase precision (\( \sigma_{CP} \), in degrees) and contrast ratio achievable (at 1\( \sigma \) detection), at a separation between star and planet at the telescope diffraction limit (\( \lambda/D \)):

\[
\text{Contrast ratio detection}(1\sigma) = 2.5 \times 10^{-3} \times \sigma_{CP}
\]  

Therefore the observation of faint planetary companions is directly a function of the closure phase stability. This makes closure phase precision the primary figure-of-merit when discussing this type of interferometer.

2. Experimental setup

The optical testbed which produced the measurements presented in this paper is shown in Fig. 1. Light from a super-luminescent diode (\( \lambda = 1550 \) nm, bandwidth FWHM = 50 nm) was propagated via a single-mode fiber to an off-axis parabolic collimator, from which the beam passes through the laser-cut aperture mask before being directed onto a MEMS segmented deformable mirror. The pupil-plane mask is reimaged onto the MEMS by the relay optics. The MEMS, manufactured by IrisAO, consists of 37 hexagonal segments, each of which can be precisely controlled in tip, tilt and piston (to a precision of \( \sim 0.01 \) milliradians). The mask ensures that only segments corresponding to the 8 waveguides in the prototype device (or fewer, if the experiment requires it) are illuminated. The reflected beam is then re-imaged by beam-reducing optics onto a hexagonal microlens array (MLA) with 30 \( \mu \)m pitch, such that there is a one-to-one correspondence between MEMS mirror segments and individual MLA lenslets. This in turn is matched one-to-one with the injection points of the array of waveguides on the input face of the photonic chip, such that each MLA lens injects the light from a single MEMS mirror segment into a single waveguide, with a matched numerical aperture. Light then propagates to the output end-face of the chip via the waveguides, whereupon each is re-collimated by another matched microlens array (with 250 \( \mu \)m pitch). The set of collimated beams are then all focused onto an infrared array detector (Xenics Xeva InGaAs camera) forming an interference pattern. The two microlens arrays and the remapper chip are each mounted on 5-axis translation stages to allow precise (\( \sim 1 \) \( \mu \)m) alignment, and injection for each waveguide individually optimised by steering the tip and tilt of the corresponding MEMS segment under computer control. The setup used here was developed from that tested on-sky as described in 2011 [17].

The experimental aim is to measure the performance of the Dragonfly instrument, with the primary metric being closure phase precision, when subjected to phase errors typical of the Earth’s turbulent atmosphere. First a set of three waveguides are selected which form a non-redundant array at the chip’s output face (depicted in Fig. 2). For example, if the 1\(^{st} \), 3\(^{rd} \) and 7\(^{th} \) waveguides were chosen then this would form baselines of length 2, 4 and 6 units. Remaining waveguides are ‘switched off’ by steering the appropriate MEMS mirror segment, preventing light from coupling at the waveguide input. The effect of atmospheric seeing was quantified by
varying the input wavefront phase using piston introduced at the corresponding MEMS mirror segment, then recording the effect on the interference pattern (ideal performance would imply the closure phase remains constant regardless of phase errors introduced at the input). The quantitative behavior of closure phases extracted from each interference pattern, in particular their variation as a function of input wavefront phase error, allows the inherent measurement stability of the instrument to be measured and extrapolated to on-sky performance.

Fig. 1. Schematic diagram of the optical testbed used to produce interferometric data. See text for a full description. Inset: the fringe pattern produced on the detector. Three fringe frequencies are present, corresponding to the three baselines, which are extracted via Fourier transform.

3. Results: old-generation photonic pupil remappers

Using the measurement technique above, the closure-phase precision of old-generation pupil remapper chips was evaluated. While these early designs [17] were demonstrated on-sky to deliver the basic required functionality, their performance was limited. Poor performance was most clearly manifested as unstable closure-phase data. As described in Section 1.2, the performance metric we adopt here is the standard deviation of the closure phase of a baseline whilst the phase of one of its waveguides is pistoned through $2\pi$ radians (or multiple sets thereof), i.e. $\sigma_{CP}$. This phase perturbation is worse than the wavefront error encountered on-sky with an adaptive optics system, where typical values around 20° to 60° RMS are encountered in the near-IR. The appropriate corrections for calculating the actual on-sky precision of Dragonfly are discussed in Section 4.3.

The goal was to consistently obtain $\sigma_{CP}$ less than 1°. While $\sigma_{CP}$ as low as 0.4° were sometimes obtained with the original design, the performance was inconsistent and procedures such as optical realignment could result in large variations (as detailed in Section 4.3). Fig. 3 gives an illustration of this problem with data obtained using the original pupil remapper in a configuration with three waveguides illuminated. In the top panel the closure phase is seen to vary periodically by several degrees as piston is added to one waveguide, with a period of $1\lambda$ (ideal performance should remain constant). Furthermore, in the bottom panel some power is observed in the power spectrum (black line) outside of the three expected spatial frequencies (indicated by blue arrows), suggesting that “switched-off” waveguides have become illuminated, most likely by cross-coupling from the three guides in use. Obtaining $\sigma_{CP} < 1°$ was found to be
sensitively dependent on optical alignment, especially the precise positioning of the input and output microlens arrays with respect to the pupil-remapper chip. The limited performance encountered in early designs was found to be caused by two key problems: contamination from unguided ‘stray’ light and high bend losses.

3.1. Stray uncoupled light

The coupling of light from the input microlens array into the waveguides is imperfect for several reasons. The main ones are mismatch in numerical aperture, mode profile mismatch (the incoming beam is quasi-uniform, resulting in an Airy pattern at the focal plane, while the waveguide mode-field profile is Gaussian) and imperfect alignment of the microlens array. Measured coupling efficiency of a MEMS segment into a waveguide is between 60% and 80%. While in some applications the consequence of this would be limited to a mere loss in throughput, for coherent applications such as interferometry, the implications can be more serious.

The problem arises that stray un-coupled light propagates, unguided, through the bulk of the photonic device and interferes with the mode field at the waveguide outputs. A dramatic example of this is shown in Fig. 4, wherein the shape of the mode field at the waveguide output is seen to deform as the piston term of this waveguide is varied by half a wavelength. At this camera exposure level, while the unguided background light itself is not visible, its effect on the single-mode output waveguide profile, which distorts as a function of piston, is readily apparent. The same exposure level is used for the wider view in Fig. 2 (top), wherein all 8 waveguides are visible. However when the exposure is increased by a factor of 64 in Fig. 2 (bottom), the background stray light is clearly visible as a complex fringe pattern.

The effects of interference with stray light are quantified in Fig. 5. As the input waveguide
Fig. 3. A set of closure phase measurements, recovered while adding successive increments to the piston in one waveguide. Here, three waveguides for the original (straight-through) pupil remapper chip are illuminated. Top: the recovered closure phase as a function of applied piston. Ideally, the closure phase would remain constant, however a periodic variation of several degrees (of period $1\lambda$) is seen. Bottom: The phase as a function of spatial frequency, where the applied piston offset is encoded in the colour bar. The power spectrum is overplotted in black (arbitrary units), showing three large peaks corresponding to the illuminated baselines. The phase is sampled at the spatial frequency corresponding to each of the peaks of the three waveguides; the vector sum of these three phases forms the closure phase. Small amounts of power are also seen between the expected peaks in the power spectrum (blue arrows) suggesting other waveguides are partially illuminated.

Fig. 4. The mode field at the output of a waveguide in the original photonic chip design, at $\lambda = 1550$ nm, imaged with a 20X microscope objective. Panel (b) has a 775 nm ($\lambda/2$) piston added to it (using the MEMS mirror) with respect to panel (a). The mode field is seen to deform, due to interference with coherent unguided background light. The background light itself is not visible at this camera exposure level.
phase offset is smoothly ramped, both the power in each baseline and the spatial frequency of the baseline is seen to vary periodically. The latter point is especially surprising since the spatial frequency corresponds directly to the baseline length – that is, the physical separation of the waveguides at the output face of the photonic chip. However this can be understood when the deformation of the waveguide’s mode field profile (Fig. 4) is taken into consideration. The end result of interference caused by unguided stray light is to violate the fundamental assumption underlying closure phase – that each of the three baselines in a closed triangle yields a single defined baseline length and a single phase, with no phase structure within a sub-aperture. Stray light, in short, directly causes closure-phase measurement error. The stray light was found to not only reduce the closure phase precision by more than a factor of 2, it also made good closure phase precision far less reproducible – these impacts are described in detail in Section 4.3.

3.2. Waveguide bend losses

Waveguides in the old-generation pupil remapper chips suffered from high bend losses [30], and hence required large bend radii in order to maintain useable throughputs. The waveguides in the original design discussed thus far had throughputs of between 54% and 66% (not counting coupling loss), which is somewhat lower than the 82% throughput expected purely from loss due to absorption in the Eagle 2000 substrate [31]. The low throughput problem was compounded by the strong effect of excess unguided light on closure-phase precision (Section 3.1). Losses increase rapidly with decreasing bend radii. Bend-loss from a tight bend with ROC = 20 mm is 2.9 times higher than that of a wider bend with 40 mm ROC. As will be detailed in Section 4, an attempt to combat the problem of stray-light interference was made by positioning the waveguide’s outputs outside of the cone of unguided light, using a ‘side-step’ design (see Fig. 6(b)). However the decreased bend radii required to reroute the guides along a more tortuous path led to unacceptable bend losses, with throughputs of these waveguides being at most 50% and as low as 0.6%. Whereas when these problems were avoided in the new design all waveguides had throughputs of approximately 70%. The quantitative details of the effect on throughputs of these bend radii, and on the improvements seen when this effect was ameliorated, are given in Section 4.2. Beyond the obvious undesirability of low throughputs in astronomical applications, the high bend losses had two additional effects which impacted negatively on closure phase stability.

Firstly, light lost in bends contributed to the overall amount of unguided stray light within the chip, compounding the severity of the interference problem described in the previous section. This was exacerbated by the fact that light lost from waveguide-bends located near the output
end of the chip has propagated along a similar optical path-length to – and hence has a high
degree of coherence with – the guided light, resulting in stronger undesired interference at the
output.

Secondly, light lost at bends may recouple into adjacent waveguides, causing cross-coupling.
The average cross-coupled power between a pair of waveguides in the original remapper chip
was of order $10^{-5}$, while in the side-step design the cross-coupled power ranged from $\sim 10^{-4}$
to as high as $6 \times 10^{-3}$.

Cross-coupling of this magnitude causes closure phase error of order $1^\circ$. Inspection of the
power spectrum in Fig. 3 reveals small peaks at spatial frequencies in between the expected
peaks, located at integer multiples of the unit baseline. This is consistent with dark waveguides
being excited by cross-coupling with illuminated waveguides. This erodes the non-redundant
property of the output array, with small amounts of power (and associated phase components)
from diverse optical paths being blended into the measured baseline phases, again violating the
closure-phase conditions.

A further limitation imposed by high bend loss is that it strongly limits the number of waveg-
uides that can be incorporated into a device. The more waveguides incorporated into a device,
the more complex their routing needs to be in order to maintain path-length matching and avoid
clashes between adjacent tracks. For such designs to be feasible, much better optical perfor-
ance at small bend radii than in the original 8-waveguide straight-through design (which is
already at the limit of acceptable bend loss) was required. Ultimately the goal is to remap
the entire telescope pupil into a guided structure, which will require several tens of waveguides
(e.g. 37 with the current MEMS mirror).

![Fig. 6. Diagrams showing the three pupil-remapper topologies tested. The ‘side-step’ and
‘90-degree’ versions are designed to mitigate the interference effects of unguided light, by
moving the waveguide outputs outside the cone of unguided stray light (shown in red).
Additionally, topologies (a) and (b) have been manufactured and tested in two versions:
the original design (denoted ‘old-generation’) and the improved design (denoted ‘new-
generation’) which feature the advancements described in the text. The sketches given are
illustrative only: actual waveguides are carefully designed (in three dimensions) to be of
equal optical path-length.

4. Results: new-generation photonic pupil remappers

4.1. Eliminating interference from unguided light

Light which is focused onto a waveguide by an individual microlens, but which does not couple
into the waveguide, continues to propagate through the glass substrate in a cone corresponding
to the numerical aperture of the focusing microlens – see Fig. 6(a). This light interferes with the guided light from the waveguides, compromising closure phase measurements as previously described. A solution is to move the outputs of the waveguides outside of this cone of unguided stray light, as illustrated in Fig. 6(b), so that it no longer enters the downstream optics. This technique was previously attempted, however the small bend radii required to execute the sideways step led to extremely high bend losses, with waveguide throughputs as low as 0.6% and not viable for astronomical science.

These bend losses have been essentially eliminated with the new generation of chips fabricated using a thermal annealing process to optimize the refractive index profile of the waveguides [32]. In this refinement to the original direct-write technique, the original waveguides are inscribed with higher pulse energy, resulting in larger core guides (multimode at our wavelength). The device is then subject to a thermal annealing process, wherein the device is raised to a temperature above the substrate’s annealing point, (but below its softening point) and then cooled adiabatically, both at precisely controlled rates. This has the effect of washing out a fraction of the refractive index modification in the originally inscribed waveguides, in particular removing unwanted structures in the periphery and leaving behind a single-mode waveguide with an optimized refractive index profile. Such annealed waveguides are now highly resistant to bend loss for two main reasons. Firstly, the core region of the waveguide has a higher refractive-index contrast due to the higher pulse energies during inscription. Secondly, the index profile of the resulting waveguide consists only of a Gaussian-like core, a geometry known to exhibit low losses during bends [32].

The annealing technique allowed the production of remapper chips with routing designed to avoid the impact of unguided light, such as the ‘side-step’ design mentioned above, while still maintaining excellent throughput. Additionally, a ‘90 degree bend’ design was created, which placed the inputs and outputs of the waveguides on adjacent orthogonal faces of the chip - see Fig. 6(c).

As seen in Fig. 7, the amount of unguided light visible at the end-face of the chip, together with the error due to stray light interference, was greatly reduced in the new chips.

4.2. Optical performance of new-generation remapper chips

The throughputs for the new devices, along with those of the original device, are given in Fig. 8. In panel (a) it is seen that while the old-generation side-step design suffered from very low throughputs, the new-generation side-step chip has throughputs approaching the maximum possible values set by material absorption. Moreover, the throughputs for the new-generation side-step chip exceed those of the old-generation straight-through chip. This design provides mitigation of the aforementioned unguided-light issue while maintaining high throughputs across all waveguides. Waveguides in the annealed chips show negligible bend-losses for radii of curvature as tight as 20 mm [32]. In all these designs, in both generations, the minimum bend radius was limited to 25 mm.

In panel (b) of Fig. 8, the throughputs of the new-generation ‘90-degree’ design are given, along with each waveguide’s minimum write-depth – that is, the minimum distance between the surface of the glass and the waveguide. While most waveguides perform well in terms of throughput, waveguides with smaller minimum write-depths are seen to have lower throughputs. This is due to problems with the oil-immersion objective lens and the high average laser powers (~500 mW) used during the fabrication process. The high average power causes a thermal lens within the oil layer resulting in defocusing of the laser beam. The thicker oil layer between objective and sample for low writing depth results in a stronger thermal lens and thereby causes a stronger distortion of the writing laser beam which impairs the waveguide quality. Future generations of 90-degree chips will avoid this by using a more conservative minimum
Fig. 7. Images of the output face of three chip designs, at various camera exposure times. The exposure time for the first (left-most) image was set such that the waveguides themselves just saturate. It is seen that the new-generation chips exhibit far less unguided light at the output face. Note that at the exposure levels needed to see any stray light for the new chips (right panels), the background light levels for the original chip saturate the detector.

New-generation chips also exhibited superior cross-coupling properties. The old-generation straight-through chip cross-coupling between waveguides was estimated to be $\sim 10^{-5}$ while for the old-generation side-step it ranged from $\sim 10^{-4}$ up to $6 \times 10^{-3}$ (a more precise value could not be measured due to stray light contamination). However the cross-coupling for the new-generation side-step design was below the measurement threshold of $\sim 2.5 \times 10^{-6}$ for 80% of measurements, the exception being six waveguide-pairs which show cross coupling ranging between $2.8 \times 10^{-6}$ and $1.2 \times 10^{-5}$. Here, we define a waveguide pair to be a given input waveguide and a given output waveguide, resulting in 56 pairs for the 8 waveguide chip.

Cross-coupling in the new-generation 90-degree chip was found to be higher. The median cross-coupling was less than $4 \times 10^{-6}$ (most waveguide pairs being below the detection limit) however several pairs exhibited high cross-coupling, with 13 of the 56 pairs having cross-coupling $> 1 \times 10^{-5}$ and 3 pairs ($7 \rightarrow 8, 8 \rightarrow 7$ and $5 \rightarrow 3$) having cross-coupling $> 1 \times 10^{-4}$. Waveguide 5, seen in Fig. 8 to have low throughput, exhibits the worst cross-coupling. Thus the new-generation side-step performs better than the old-generation straight-through design while mitigating stray light, although the new-generation 90-degree chip performs relatively poorly.

4.3. Interferometric performance of Dragonfly with new-generation pupil remapper chips

The design goal of the pupil-remapper is to enable the Dragonfly instrument to consistently obtain closure-phase precisions (denoted $\sigma_{CP}$) of less than $1^\circ$ when input phase errors $> 2\pi$ radians are applied. An example of the closure-phase results of the new-generation of side-step chips is shown in Fig. 9. Excellent closure phase stability is now recorded, with $\sigma_{CP} = 0.22^\circ$ achieved while input wavefronts are pistoned through multiples of $2\pi$ radians, in a single
measurement set.

Furthermore, the performance of the new-generation remappers is also far more robust and reproducible, no longer sensitive to small misalignments of the microlenses and the photonic chip. This is a key requirement, since deployment to an instrument platform on a telescope is dependent on fast alignment in hard-to-access spaces, tolerance of vibration and possibly a moving gravity vector if the instrument is mounted to the telescope itself (such as at a Cassegrain focus). To test this, the microlenses and photonic chip were deliberately misaligned, and then realigned and the closure-phase tests performed again. This cycle was repeated multiple times for each of the different chip designs. Each realignment took less than 1 minute and involved manipulating the translation of the chip and microlenses in X, Y and Z, and the roll angle (i.e. rotation about the axis parallel to the direction of propagation) of the chip. The goal in each realignment was simply to produce fringes on the detector, which have power visible in all three baselines of a triangle (indicating all three waveguides in the triangle are illuminated) and where the fringes appear parallel (eliminating any rotational misalignment).

A histogram of the test results is shown in Fig. 10. While occasionally good performance is seen from the old-generation (straight-through) chip, this is not reliably reproducible and is highly sensitive to each realignment, with $\sigma_{CP}$s ranging from 0.4° to 1.5°. On the other hand, the new-generation side-step chip performs far better, with a median $\sigma_{CP}$ of 0.42°. Moreover, this chip exhibited this performance consistently, with $\sigma_{CP}$s better than 0.7° in all but one measurement, and as low as 0.15°. The new-generation 90-degree design does not perform as well, with a median $\sigma_{CP}$ of 0.74°. This is consistent with stray light arising from bend losses within the chip (due to its tighter bend radii than the side-step design) contaminating the measurements.

Correction for detector non-linearity was also important. The detector exhibited relatively little non-linearity, with $R^2 = 0.993$, with the most non-linear region being at the ‘toe’ of the response function (where counts are < 1000 ADU). However this still had a large impact on the closure phase precision. When the non-linear correction is applied (derived from a polynomial fit to the measured detector response) the side-step chip exhibited $\sigma_{CP} \approx 0.2°$, but these same data yield $\sigma_{CP} \approx 2.4°$ when non-linear correction is neglected. This suggests careful non-linear correction should be applied whenever closure phases are measured from such interferograms,
Fig. 9. A set of closure phase measurements taken while successively incrementing piston in one waveguide for the new-generation side-step design pupil remapper chip. Here, three waveguides are illuminated forming a single closing triangle. Top: the closure phase is far more consistent as piston is applied (as compared with the old-generation chips shown in Figure 3), with $\sigma_{CP} = 0.22^\circ$. Bottom: the phase as a function of spatial frequency, for each piston offset (colors). The power spectrum is overplotted in black (arbitrary units). In contrast to the old-generation chip, only the three expected peaks in the power spectrum are seen.

Fig. 10. A histogram showing the distribution of $\sigma_{CP}$ when the pupil-remapper and microlens-array are subjected to repeated realignments. The frequencies have been normalized such that the integral of each histogram is unity.
e.g. in aperture masking interferometry.

To convert these experimental results to real-world performance, a correction must be made for the fact that $2\pi$ radian phase error applied is worse than the actual phase error encountered behind an adaptive optics system, which is the intended platform for Dragonfly (use without an AO system is not feasible because the tip/tilt errors in the wavefront greatly reduce the efficiency of the coupling into the waveguides, leading to very low throughput). The phase errors applied were uniformly distributed between 0 and $2\pi$ radians, so the RMS error is 1.8 radians. On the other hand, the phase error was only applied to one of the three sub-apertures at a time, whereas in on-sky use all three sub-apertures would be subject to the error, so the resulting closure-phase error is $\sqrt{3}$ times worse. So, if the predicted AO-corrected phase error encountered is $\epsilon_{AO}$ (in radians), then the predicted closure-phase error is

$$
\sigma_{CP}^{On-sky} = \sqrt{3} \cdot \frac{\epsilon_{AO}}{1.8} \cdot \sigma_{CP}^{Expt}
$$

where $\sigma_{CP}^{Expt}$ is the experimental $\sigma_{CP}$ measured in these tests and $\sigma_{CP}^{On-sky}$ is that predicted on-sky. This assumes the closure phase error is linear with phase, a good approximation when the closure phase error is small as it is here [33].

For a standard adaptive optics system, the residual RMS wavefront error is $\sim 250$ nm, while for the new-generation extreme-AO systems this is as low as 80 nm [17]. Thus the previously measured performance metric $\sigma_{CP}^{Expt}$ of 0.22$^\circ$ (from the new-generation side-step design) translates to 0.21$^\circ$ for a conventional AO system and 0.07$^\circ$ for an extreme-AO system. This results in a contrast-ratio sensitivity limit at $1\lambda/D$ (1$\sigma$ detection) of $5.3 \times 10^{-4}$ and $1.8 \times 10^{-4}$ respectively (see Equation 4). If instead the median performance of this chip of 0.42$^\circ$ is considered, then the $1\lambda/D$ contrast ratio detectable is $1.0 \times 10^{-3}$ and $3.3 \times 10^{-4}$ respectively. This is well within the performance range required to directly detect young planets in star-forming regions (e.g. [16]).

If no AO correction is used, then the RMS wavefront error can be several wavelengths. Assuming a wavefront error of 2 $\mu$m, then the previously $\sigma_{CP}^{Expt}$ of 0.22$^\circ$ (from the new-generation side-step design) would translate to 1.7$^\circ$ in the seeing limited case. However in reality the performance is significantly worse: it was found experimentally in on-sky tests [17] that in this regime, the tip-tilt errors dominate and prevent efficient injection into the waveguides. For successful closure-phase measurements, well-measured visibilities must be obtained for at least three (closing) baselines at once, however tip-tilt errors from the uncorrected wavefront meant that one or more waveguides in a given triangle frequently had negligible flux, and measurement was not possible. It was thus found that it is uncompetitive to operate Dragonfly in the seeing-limited regime.

However these calculations are extremely conservative. The $\sigma_{CP}$ values quoted here refer to the standard deviation of the closure phase for a single measurement set (around 100 ms total integration time). In practice, the astronomical source would be observed for minutes or hours and a large statistical sample of measurements taken. The resulting closure phase would be the mean of the closure phases and the uncertainty would be the standard error in the mean. Ideally (in the absence of photon noise and systematic errors that are unable to be removed by observing a point-spread-function calibrator star) this error would go as $1/\sqrt{N}$ (where $N$ is the number of measurements), so a 1 hour observation, consisting of $\sim 30\,000$ such measurements, would have a best-case closure phase precision of $0.22^\circ/\sqrt{30\,000} = 10^{-3}^\circ$, or a contrast ratio detection limit of $\sim 2 \times 10^{-6}$. This level of performance puts the instrument in reach of the ultimate goal of imaging mature planetary systems [34]. This is a theoretical limiting best case; in practice other error processes such as photon noise may come to dominate. For a typical 4th magnitude star (H band), assuming 20% total throughput, after 1 hour of integration the photon noise reaches a level of $\sigma = 10^{-6}$. It is also possible that some separate error process may come
to dominate at a presently unknown level.

In these laboratory tests the phase aberration from the atmosphere was simulated by adding a piston term to the individual waveguides using the MEMS segmented mirror. However in on-sky operation phase variation would also occur across a given sub-aperture. As described in Section 1.2, phase variation across the individual sub-aperture does not affect the closure phase precision since the three baselines forming the closure-phase triangle can each be described by a single phase term (as determined by the single piston terms of each of the waveguides) - the key advantage of the spatial filtering in a single-mode fiber based interferometer [27–29]. However this comes at the cost of coupling efficiency. Since the light coupled into the wave-guide is effectively the intensity distribution at the input projected onto the wave-guide’s mode-field, coupling decreases with increased sub-aperture phase perturbations. For a perfect top-hat beam, the maximum theoretical coupling efficiency into the Gaussian mode of a single-mode waveguide is 78% [35], although this limit can be broken by use of phase-induced amplitude apodization techniques [13]. This efficiency is then reduced further by atmosphere-induced phase errors. It can be shown that the coupling efficiency (with respect to an ideal, apodized pupil) is in fact directly proportional to the Strehl ratio of the incident wavefront [35]. In practice, injection efficiencies have been obtained using conventional AO systems of 25% for an entire 8 m telescope pupil [36], a figure heavily influenced by the existence of the central obstruction of the secondary mirror. In the case of a Dragonfly sub-aperture, assuming an extreme-AO corrected wavefront error of 80 nm, which corresponds to a Strehl ratio of ∼0.9, the injection efficiency would be ∼90% for an apodized beam or ∼70% for a top-hat beam. In the worst case, this drops to 40% (apodized) or 30% (top-hat) if a conventional AO system is used instead. However this is highly conservative; in practice the Strehl ratio for a single sub-aperture (as its size approaches the Fried parameter) is expected to be much better than that of the entire 8 m telescope. Assuming the entire (un-obstructed region of) the telescope pupil is sampled, these coupling efficiencies combined with a absorption loss of ∼20% effectively represent the difference in instrumental throughput between Dragonfly and a conventional full-pupil imager. This is a significant improvement over aperture-masking, where the non-redundant mask requirement means that between 80% and 95% of the pupil is blocked.

In Section 1 the science case for a high angular resolution direct imager for exoplanetary astronomy was outlined. Specifically, that direct imaging stands to answer critical questions about planetary formation and evolution, especially due to its ability to properly constrain orbital elements (and hence mass) and potentially provide spectroscopic observations. To properly characterize the population of planets as a function of separation and mass, the innermost region of planetary systems (corresponding to inner solar-system scales) must be accessible, however this is difficult for existing direct imaging techniques to achieve. State-of-the-art coronagraphic, differential, extreme-AO based imagers are limited by the coronagraph’s inner working angle (IWA), with the two newest instruments - SPHERE and GPI - have an IWA of ∼100 mas and ∼200 mas respectively [37]. These instruments have exceptional performance at wider separations, but based on laboratory tests SPHERE is predicted to achieve a maximum 1σ contrast ratio of between 10$^{-3}$ and 10$^{-4}$ at its IWA of ∼100 mas at λ = 1.6μm, depending on which method of differential imaging is used (assuming 90% Strehl ratio after AO correction and no photon noise) [37]. In comparison, Dragonfly will have a limited field of view (depending on shortest baseline length, of order 300 mas) but is predicted to achieve a 1σ contrast ratio of order 10$^{-6}$ at λ/D or 40 mas. Furthermore, the equivalent ‘inner working angle’ of Dragonfly is smaller than this, conventionally defined in interferometry as λ/(2D) or 20 mas. In summary, Dragonfly covers a parameter space – high contrasts at separations of order λ/D – which is complementary to advanced extreme-AO based coronagraphic methods, a parameter space critical to a fuller understanding of planetary formation.
5. Conclusions and further work

The direct imaging of exo-planets is a major goal in contemporary observational astronomy, but achieving the high spatial resolutions and contrast ratios required to image solar-system scales is hampered by the Earth’s turbulent atmosphere. Adaptive optics, interferometry, and the use of the closure-phase observable in concert has shown some success in addressing this problem. Pupil-remapping stellar interferometry using a monolithic photonic pupil remapper stands to vastly increase the precision of closure-phase measurement beyond the current state-of-the-art, allowing far more sensitive observations of exoplanetary systems.

This technology has been demonstrated on sky, but was previously so limited in terms of precision and throughput as to be uncompetitive. The root cause of these limitations was stray light propagating, unguided, from the input to the output and causing interference fringes at the output face.

Here we presented a new generation of pupil remapper chips which overcome these limitations. Three key advantages have been verified. Firstly, closure phase precision much better than one degree was demonstrated, with \(\sim 0.2^\circ\) obtainable in a single set of measurements. This scales to a negligible error in typical astronomical observing periods, at which point other error sources (imperfect PSF calibration, photon noise) become dominant. Secondly, this performance is now completely reproducible, with minimal sensitive dependence on alignment. Thirdly, waveguide throughputs are greatly improved, with average values of \(\sim 70\%\). Rerouting of the waveguides addresses the unguided stray light problem, but in turn presents the problem of low throughputs due to the smaller bend radii required. This is then addressed with the introduction of thermally annealed waveguides.

With these fundamental problems solved, the Dragonfly instrument is now set to perform the first science observations on-sky. Furthermore, development can now be focused on the next evolutionary stages of the instrument. The use of a lithographic photonic beam combiner, instead of a free-space Fizeau type beam combiner, is being explored. New chips that extend operational reach beyond the current near-IR (\(\sim 1.6\mu m\)) wavelengths into the mid-IR (\(\sim 4\mu m\)), where the contrast ratio between a star and thermal emission from its planet is more favorable, are also being developed [38, 39]. Finally the creation of a new photonic back-end which turns Dragonfly into a nulling interferometer [40], wherein the stellar light is interferometrically nulled to remove photon-noise from the planetary signal, is also undergoing development. These technologies stand to form the early steps in the photonic reformulation of astronomical imaging.

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