

Coupling free space light into the AstroPIC photonic coronagraph

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ABSTRACT

The Habitable Worlds Observatory (HWO) aims to reach a planet-to-star contrast near 10^{-10} to detect and characterize Earth-like planets in reflected starlight. The mission exoplanet yield is sensitive to the coronagraph inner working angle and to the end-to-end observatory throughput, including the telescope, intermediate optics, and the coronagraph. Free-space coronagraph optics face stability and wavefront-control constraints at this contrast. Photonic integrated circuits (PICs) offer an alternative with improved stability, compactness, and reconfigurable control relative to bulk optics, and enable architectures capable of reaching smaller inner working angles. Efficient coupling of the light collected by the free-space telescope into a PIC has a large impact on the coronagraph throughput and therefore the observatory mission ExoEarth yield. The AstroPIC laboratory at NASA Ames is developing and characterizing the injection optics for a PIC coronagraph. We report the progression from single-fiber illumination of one grating coupler to a microlens array that reimages the pupil onto the grating-coupler array to maximize coupling efficiency by increasing the effective fill factor.

Keywords: Astrophotonics, photonic integrated circuit, coronagraph, exoplanets, high-contrast imaging, grating coupler, microlens array, fiber coupling, Habitable Worlds Observatory

1. INTRODUCTION

The Habitable Worlds Observatory (HWO) is the highest-priority large strategic mission identified by the Astro2020 Decadal Survey,¹ with a goal of detecting and spectroscopically characterizing on the order of 25 potentially Earth-like planets around nearby stars.^{2,3} Imaging an Earth twin in reflected light requires suppressing the host starlight to a planet-to-star contrast near 10^{-10} at small angular separation.^{3,4} The mission exoplanet yield (total number of exoplanets characterized over the mission lifetime) is highly sensitive to the coronagraph inner working angle (IWA) and to the end-to-end observatory throughput, which includes the telescope, the intermediate optics, and the coronagraph.^{5,6}

Any coronagraph that maps an input field to an output field can be described as a linear operator.^{4,7} The operator that maximizes exoplanet yield can be numerically optimized for a given observing scenario, and its performance is substantially less sensitive to aperture segmentation and obscurations, which has the potential to relax the wavefront stability requirements.⁷ A programmable mesh of Mach-Zehnder interferometers (MZIs) can synthesize any discrete unitary operator,^{8,9} and can therefore approximate an optimal coronagraph on a photonic integrated circuit (PIC). Relative to bulk optics, a PIC coronagraph reduces size, weight, and power,

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and allows per-observation reconfiguration.^{10,11} AstroPIC is a near-infrared PIC coronagraph under development for HWO;¹⁰⁻¹² related photonic-coronagraph efforts are reported in Refs. 13 and 14.

A PIC coronagraph manipulates light only after it has been coupled from the free-space telescope beam into the on-chip single-mode waveguides. The injection efficiency therefore sets the coronagraph throughput and, through it, the observatory exoplanet yield. Coupling light collected by a multi meter-class telescope into micron-scale waveguides is one of the key terms in the photon throughput of the architecture. This paper reports the AstroPIC injection optics under development and characterization at the NASA Ames AstroPIC laboratory.

1.1 Coupling light into the photonic integrated circuit

Three requirements drive the injection design. First, throughput: each decibel of coupling loss reduces the off-axis (planet) throughput and the survey yield, so the injection efficiency must be maximized. Second, bandwidth: HWO science requires operation over a finite spectral band, so the coupler must maintain efficiency across the widest band possible rather than at a single wavelength. Third, channel count: the coronagraph order, and hence the achievable OWA, scale with the number of sampled modes,^{7,12} so we aim for the architecture to scale-up the number of channels.

Three coupling approaches are relevant for a PIC coronagraph. *Grating couplers* diffract a near-normal free-space beam into in-plane waveguides; paired with a microlens array that focuses each pupil sub-aperture onto one grating, they support dense two-dimensional channel arrays. Foundry-standard grating couplers reach about 30% efficiency, while inverse-designed normal-incidence three-wave interaction gratings (TWIGs) on silicon-on-insulator reach sub-decibel insertion loss, with 81–85% coupling measured over a ~20 nm band;^{15,16} the TWIG values are separately published results targeted for future AstroPIC generations, not measurements of the current device. *Edge (butt) coupling* injects light into a polished waveguide facet, typically through an inverse-taper spot-size converter; it is broadband and efficient but provides only one-dimensional edge access, which limits two-dimensional pupil sampling, and it adds packaging complexity from facet polishing and sub-micron facet alignment. A third approach injects the free-space beam directly onto the waveguide using an on-chip parabolic coupler which is 3D printed in a cavity manufactured using photolithography.¹⁷ Adapting AstroPIC to this coupler would require reworking the front-end delivery f-number and fill-factor optics to match the parabola design, which is feasible but represents a non-trivial redesign of the injection optics.

AstroPIC adopts the grating-coupler approach with a microlens array, the only one of the three that supports dense two-dimensional pupil sampling at wafer scale. Table 1 compares the three approaches against the three driving requirements. The efficiency values are for the silicon-on-insulator (SOI) platform at $\lambda = 1.55\text{ }\mu\text{m}$ used by AstroPIC; the broadband-support and channel-scalability entries are qualitative. The grating-coupler efficiency is bounded below by the foundry-standard value and above by the measured normal-incidence TWIG result.^{15,16} Broadband and scalability entries are qualitative.

Table 1. Comparison of coupling approaches for a PIC coronagraph on the SOI platform at $\lambda = 1.55\text{ }\mu\text{m}$. Grating-coupler efficiency is bounded by foundry-standard (~30%) and measured normal-incidence TWIG (81–85%) values.^{15,16} Broadband and scalability entries are qualitative.

Approach	Coupling efficiency	Broadband support	Channel scalability
Grating coupler + microlens array (near-normal incidence)	~30% (foundry); 81–85% (TWIG) ^{15,16}	Limited; dispersive, ~20 nm 1-dB band demonstrated; broadband needs apodized/multi-layer designs	High; two-dimensional surface array, wafer-scale testable
Edge coupling (inverse-taper spot-size converter)	High (>80% achievable with SSC) ¹⁸	Broad; low dispersion	Limited; one-dimensional edge access, facet polishing and sub-micron alignment
Parabolic direct injection on waveguide (Lockheed Martin)	~80% ¹⁷	1 dB over 180nm (1.45 - 1.63)	Medium, 3D printing process takes time and requires alignment

2. THE ASTROPIC CORONAGRAPH

The AstroPIC architecture is described in detail in Refs. 10 and 19. A microlens array samples the telescope pupil and focuses each sub-aperture onto a grating coupler, which injects that portion of the beam into a single-mode waveguide on an SOI PIC. Each waveguide carries one spatial mode containing a mix of starlight and planet/disk light. A forward MZI mesh transforms the input modes into an output basis that concentrates starlight into a small number of “blocked” modes, leaving planet and disk light in the remaining “signal” modes.^{9,10} Output modes are read by on-chip photodetectors or coupled out through fibers. Because the mesh is programmable, it can be reconfigured per observation to trade IWA against tolerance to low-order modes.^{11,12}

The Cycle-1 AstroPIC chip is an SOI device on a $2.8\text{ mm} \times 16\text{ mm}$ chip with $1.55\text{ }\mu\text{m}$ directional couplers and input/output grating couplers. It integrates two coronagraphic meshes—a 9-input full upper-triangular MZI mesh and a 7-input perfect-MZI mesh. The chip was fabricated at two foundries, using photolithography (Advanced Microfoundries) and e-beam lithography (Applied Nanotools), and wirebonded to a host board for electrical control of the thermo-optic phase shifters.¹¹

Characterization is performed at the Ames Photonics Testbed, which supports free-space and fiber coupling, programmable control of the mesh phase shifters, and photodetector readout, with single-channel measurement sensitivity approaching 10^{-10} contrast in air; the testbed design and its high-contrast demonstrations are reported in Refs. 11 and 20. Using a single diagonal of the 9-input mesh, single-channel starlight suppression of 6.3×10^{-10} (92 dB) has been measured.²¹ Separately, the normal-incidence high-efficiency grating couplers reached 81–85% coupling.^{15,16} Detailed testbed and simulation results are given in the companion papers.^{11,12}

3. THE ASTROPIC FREE-SPACE COUPLER

We began with a single optical fiber directly illuminating one grating coupler. With a single-mode fiber feeding one input grating coupler and the suppression configured along a single diagonal of the 9-input MZI mesh, AstroPIC measured single-channel starlight suppression of 2.0×10^{-9} (87 dB) on the photolithography (AMF) chip and 6.3×10^{-10} (92 dB) on the e-beam (ANT) chip, improving on the previously reported 7.9×10^{-9} (81 dB).^{11,22} The end-to-end on-chip throughput in these tests was ~ 9 to 10%, dominated by the $\sim 30\%$ efficiency of the foundry-standard grating couplers and by $\sim 1\text{ dB/cm}$ waveguide propagation loss at $1.55\text{ }\mu\text{m}$.¹¹ These single-fiber experiments validated the testbed sensitivity to near 10^{-10} contrast in air and identified the input coupling as the dominant source of loss and scattered light. The free-space coupler replaces the single fiber with a reimaging relay that samples the telescope pupil and focuses each sub-aperture onto its own grating coupler through a microlens array, coupling the full input channel count simultaneously and maximizing the per-coupler fill factor.

3.1 Optical design and prescription

The free-space coupler reimages the telescope (or laboratory source) pupil onto the grating-coupler array on the chip. A 1550 nm single-mode fiber source is mounted on a cage-mounted XY stage driven by piezoelectric actuators, which set the source lateral position and thereby the tilt angle of the reimaged pupil. Light from the source is collimated by a first relay lens (Lens 1), passes through an interchangeable pupil stop at which the desired telescope pupil mask is mounted, and is reimaged by a second lens onto the microlens array above the PIC, compressing the pupil by a factor of ten. The focal length of Lens 1 was reduced from 100 mm to 50 mm to increase the throughput of the reimaged pupil and to reach a deeper contrast. A VIAVI MLA-S100-f4 microlens array ($f/4.2$, 2 mm fused-silica substrate) focuses each reimaged sub-aperture through a $\sim 400\text{ }\mu\text{m}$ air gap onto a grating coupler at a $\sim 12^\circ$ angle of incidence in air, measured from the surface normal and matched to the current grating design; the $\sim 100\text{ }\mu\text{m}$ microlens pitch matches the grating-coupler pitch on the SOI PIC, which carries a $3\text{ }\mu\text{m}$ SiO_2 cladding over the silicon waveguide layer. A long-working-distance objective images the chip surface for alignment.

Sampling the pupil rather than the focal plane is a design choice. Pupil-plane injection distributes the field across a fixed number of sub-apertures whose count is set by the PIC input channel count, and the assignment of sub-aperture to waveguide is achromatic to first order. Focal-plane injection, by contrast, would require the

sampling geometry to track a point-spread function that scales with wavelength. Fixing the mapping in the pupil plane matches the AstroPIC mesh, which operates on a fixed set of input modes.

The compression ratio follows from two fixed constraints rather than from free optimization. The grating-coupler pitch is set by the chip layout: a 3×3 grating-coupler array on a $100\text{ }\mu\text{m}$ pitch, rotated 45° with respect to the chip longitudinal axis, and the microlens array matches it. The front end reimages the telescope pupil at 10:1 compression. Two illumination strategies are available. Inscripting the reimaged pupil within the lenslet array couples all of the light but leaves the outer sub-apertures partially illuminated; in this case a 3 mm telescope pupil is reimaged onto a $300\text{ }\mu\text{m}$ pupil fully inscribed on the microlens array. Alternatively, circumscribing the array with a $430\text{ }\mu\text{m}$ reimaged pupil, equivalent to a 4.3 mm telescope pupil, provides full and uniform illumination of every grating coupler at the cost of throughput.

The microlens f -number is the principal design compromise. Matching the grating-coupler mode calls for a slower lens ($\sim f/5$) than the nearest suitable catalog part ($f/4.2$) provides, so the focused spot is somewhat smaller than the optimum and incurs a corresponding overlap-integral penalty. An off-the-shelf array was selected rather than a custom one for schedule and cost reasons; recovering this coupling efficiency and improving stability are the main motivations for the custom three-dimensional-printed lenses described in Sec. 4.3.2.

Efficient injection into single-mode devices is achievable but demanding of both pupil geometry and wavefront quality: laboratory coupling into a single-mode fiber has reached 86% of the theoretical maximum at 1550 nm , scaling linearly with Strehl ratio.²³ Pupil-remapping instruments have used microlens arrays with per-sub-aperture tip/tilt steering to optimize injection into individual waveguides. The AstroPIC front end applies the same principle at smaller scale: rather than steering each sub-aperture independently, the piezoelectric actuators steer the source to set the incidence angle of the reimaged pupil as a whole, since the overlap model shows coupling to be considerably more sensitive to angular error than to lateral decenter. The actuators provide a total pupil tip/tilt range of $\sim 1\text{ }\lambda/D$ in both axes.²¹

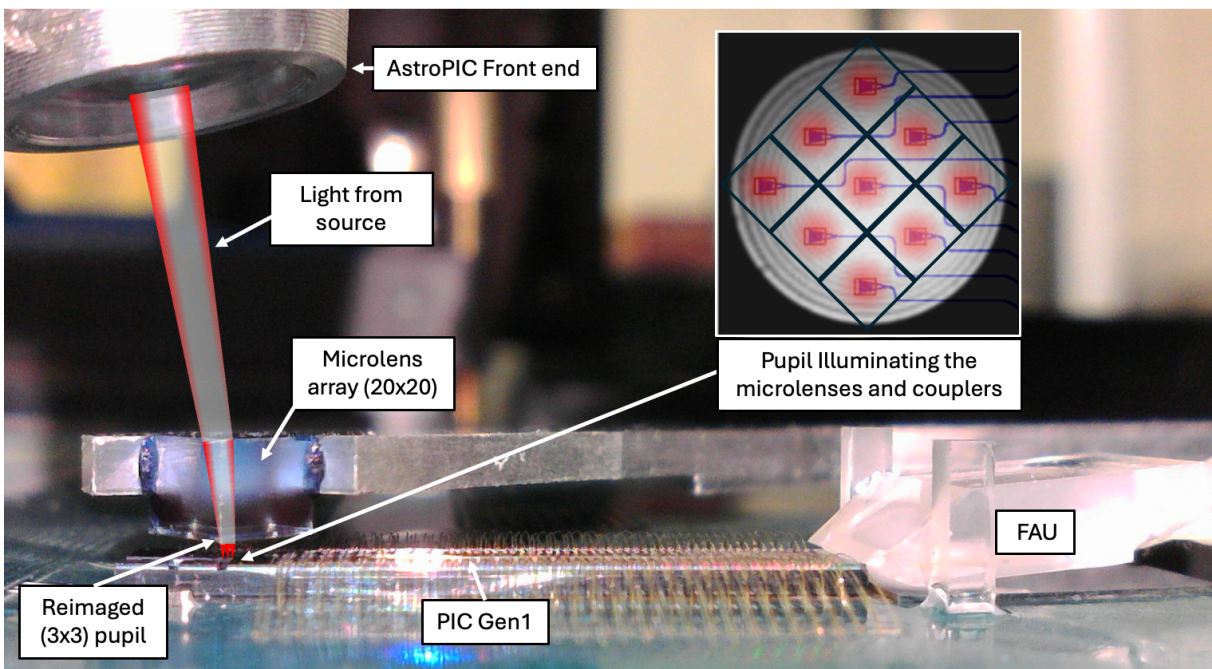


Figure 1. The assembled AstroPIC coronagraph. The optical front end (top left) delivers a compressed pupil onto the microlens array, which forms an array of focal spots on the grating couplers (top right) that inject the light into the first-generation PIC (labeled “PIC Gen1”). At the output (bottom right), a fiber array unit is bonded on top of the chip to collect the output modes and route them to the photodiodes.

Figure 1 shows the assembled coronagraph and the path of the light through it. The free-space front end at the top left compresses and reimages the pupil onto the microlens array, which concentrates each sub-aperture

onto one grating coupler in the 3×3 input array shown at the top right. The injected light propagates through the MZI mesh on the first-generation PIC, and the sorted output modes are collected at the bottom right by the fiber array unit bonded above the output grating couplers and routed to the detectors.

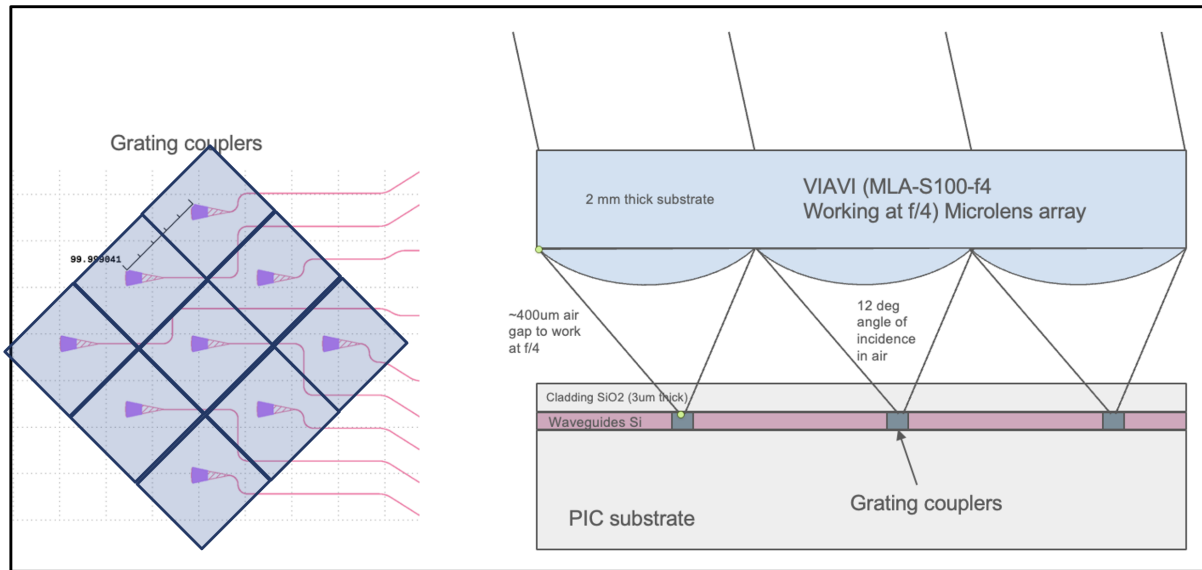


Figure 2. Microlens-array front end. (Left) Grating-coupler array on the PIC, with a $100\mu\text{m}$ pitch matched to the microlens array. (Right) Side-view prescription: a VIAVI MLA-S100-f4 microlens array ($f/4.2$, 2 mm substrate) focuses each reimaged pupil sub-aperture through a $\sim 400\mu\text{m}$ air gap onto a grating coupler at a $\sim 12^\circ$ angle of incidence in air; the PIC has a $3\mu\text{m}$ SiO_2 cladding over the silicon waveguides.

Figure 2 details the front end at the chip. The left panel shows the 3×3 grating-coupler array on the PIC, whose $100\mu\text{m}$ pitch is matched by the microlens array; the right panel gives the side-view prescription, in which each reimaged sub-aperture is focused through the $\sim 400\mu\text{m}$ air gap onto its grating coupler at the $\sim 12^\circ$ incidence angle set by the current grating design.

The free-space coupler has been installed on the Ames Photonics Testbed. Its alignment, measured coupling performance, and coupling stability are reported in the companion testbed papers.^{20,21}

4. NEXT STEPS

Several developments are planned to improve the injection efficiency, to extend it to representative apertures, and to integrate it with the rest of the instrument.

4.1 Photonic source chip with planet source

An upgrade of the Free Space Coupler is planned using a photonic source chip to provide a stable star-and-planet input for photonic coronagraph characterization, replacing the free-space single fiber source.

Goals. Provide a repeatable star-plus-planet input with controllable contrast and angular separation, to support end-to-end coupling and suppression measurements with a known input field. A star-and-planet simulator built from bulk optics ties both the contrast ratio and the separation to the alignment state of the bench, so the two drift together and neither is known independently of a calibration. Generating both sources on a single chip fixes their relative geometry lithographically and leaves the relative intensity as the only controlled variable. We will use two separate laser sources to ensure incoherence between the star and the planet. Attenuation will be achieved through a set of neutral density filters instead of reducing the laser power to very low levels where lasing is unstable.

Photonic design. The source chip is a silicon-nitride photonic integrated circuit carrying separate star and planet channels (Fig. 3). Star and planet light are injected at the top edge of the photonic chip into waveguides

arranged at a $30\mu\text{m}$ pitch. The first three waveguides on the left are intended to represent planets at different angular separations, those waveguides are routed to the left after a 90 degree turn to minimize coupling with the star. The planets have a separation of $200\mu\text{m}$. The fourth waveguide is intended to carry the source representing the star which is routed approximately 1.6 mm away from the planet sources. This arrangement is shown in Fig. 3.

Suppressing coupling between the stellar and the planet sources is a key design driver. The design goal is $\leq 10^{-9}$ coupling suppression between the star and planet channels. The sources of coupling include scattering at bends and interfaces, and light guided in the cladding or slab that reaches the output edge alongside the planet field, where it cannot be distinguished. The layout shown in Fig. 3 uses deep trenches across the propagation path between the star and planet routes, interrupting the slab and cladding paths that would otherwise carry stray power to the output, together with isolation structures separating adjacent channels.

Silicon nitride was selected because its transparency window extends from the visible to beyond $2\mu\text{m}$ with low propagation loss,²⁴ allowing the source chip to operate at visible wavelengths in addition to 1550nm. The chip has been manufactured as shown on the right of Fig. 3. The unit is ready for packaging and later integration on the free space coupler.

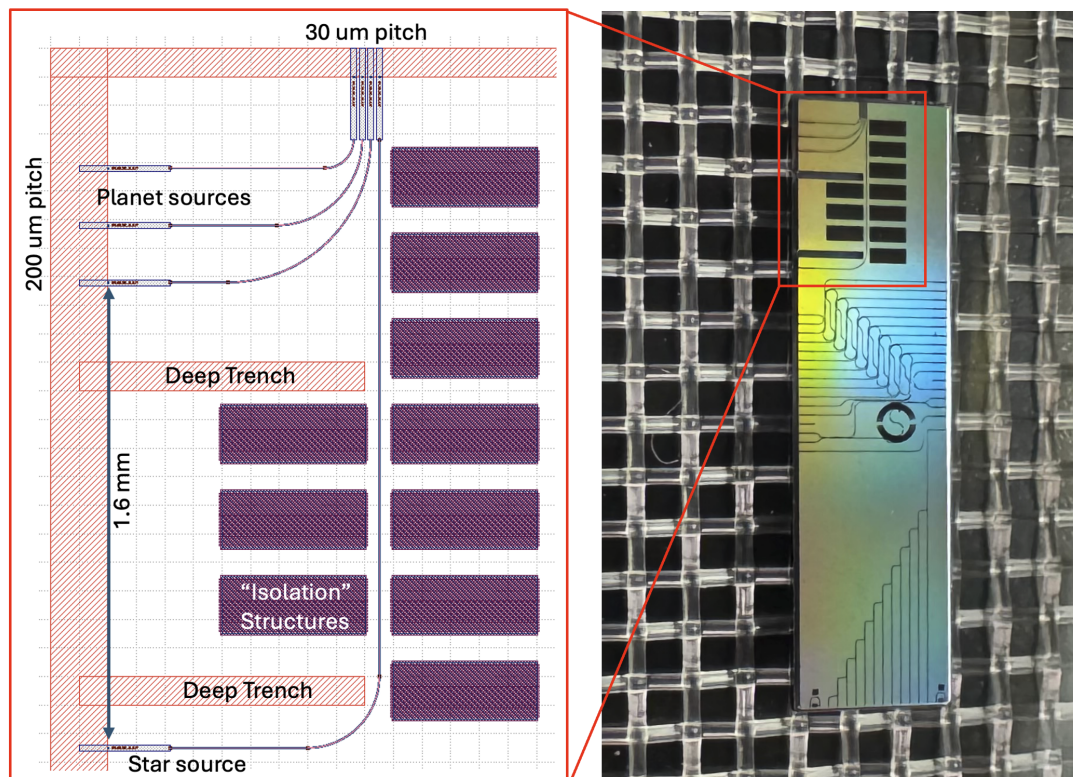


Figure 3. Layout of the star-and-planet photonic source chip. Input waveguides enter at the top edge of the die on a $30\mu\text{m}$ pitch and are routed to the left approximately three planet sources are separated by $200\mu\text{m}$ each and 1.6mm away from the star channels. Deep trenches cross the propagation path and isolation structures separate adjacent channels, interrupting the slab and cladding paths that would otherwise carry scattered light to the output edge and impose a source-limited contrast floor. On the right the as-built chip is shown ready for packaging.

4.2 Realistic HWO pupils: carbon-nanotube pupil masks

The coupling results reported above use a free standing circular pupil. An HWO primary is neither filled nor circular: segment gaps, secondary support struts, and a central obscuration all break the aperture into disconnected regions, and these discontinuities, rather than the segmentation itself, drive the difficulty of high-contrast imaging on complex apertures. Parametric yield studies for the AstroPIC architecture have covered the

three exploratory analytic cases (EACs) considered for HWO, including sweeps over segment gap width, strut width, and secondary obscuration diameter.¹¹ Those results are numerical, and the free-space coupler provides a route to testing them in hardware.

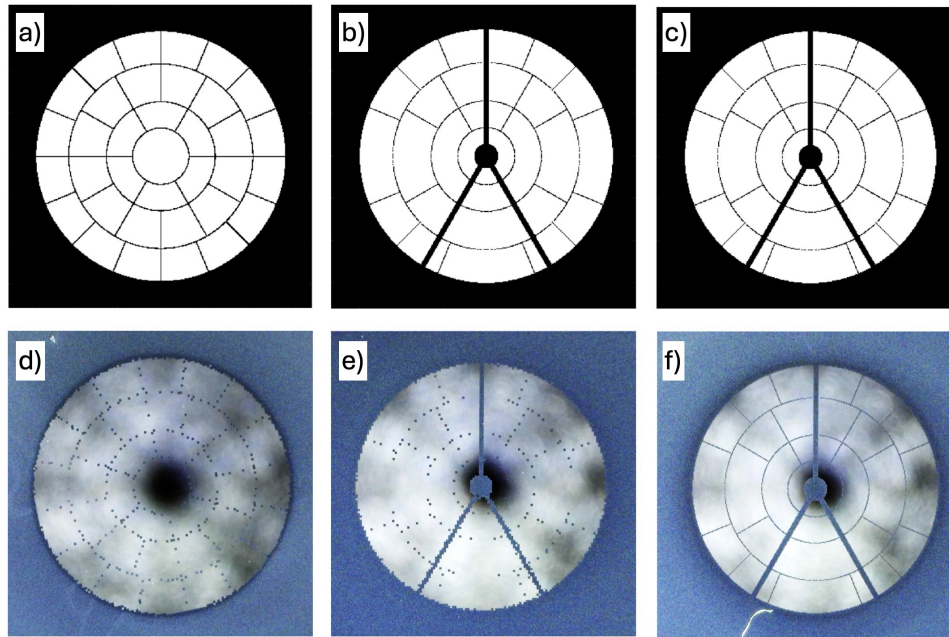


Figure 4. To match the front end optical layout the pupil mask should be 3 mm in diameter. The carbon nanotube fabrication process required to discretize the pupil to $10\mu\text{m}$ pixels. a) Unobstructed EAC3 represented in binary map and d) Microscope image of the manufactured counterpart, pixelation causes some segment to break, b) Obstructed EAC3 pupil and e) manufactured counterpart affected by pixelation, c) Obstructed EAC3 pupil with higher pixel resolution and f) Manufactured higher resolution version showing continuous segments.

To that end transmissive pupil masks reproducing the HWO EAC2 and EAC3 apertures have been designed (Fig. 4) for installation at the stop position of the free-space coupler, where the pupil is reimaged onto the microlens array. Placing the mask at the stop means the obscuration pattern is carried through the compression optics and it is reimaged on the microlens array, so each sub-aperture sees the transmission it would see behind a segmented primary.

The masks are manufactured by Advanced Nanophotonics, LLC funded by a NASA Phase II SBIR. Patterned carbon nanotubes are deposited on nanostructured fused-silica substrates by chemical vapor deposition. Carbon-nanotube coatings are the established choice for this application: they combine effectively complete blocking with very low reflectance, with total hemispheric reflectance below a percent across the visible and near-infrared,^{25,26} and the same technology has been used to manufacture the apodizers for segmented-aperture coronagraph demonstrations on the HiCAT testbed.^{27,28} Low reflectance matters here for a specific reason: light scattered from mask edges into the coupler would appear as an incoherent background at the grating-coupler array and would not be rejected by the mesh, so it would set a floor on the achievable contrast independent of the coronagraph itself. The nanostructured texturing of the mask substrate reduces its reflectance below 0.1 percent per surface.

The process supports a minimum feature size of approximately $10\mu\text{m}$, which is larger than the segment gaps at the scale of the reimaged pupil. Rather than allowing gaps and spider lines to break into disconnected features at that resolution, a dilation algorithm was applied at the design stage so that all gap and strut lines remain continuous at the achievable fabrication feature size. The resulting mask therefore obscures more of the aperture than a faithfully scaled replica of the EAC pupil would, which makes the resulting measurement a conservative bound on performance rather than an optimistic one.

4.3 Coupling design for normal-incidence (90°) grating couplers

4.3.1 New chip with normal-incidence grating couplers and free-space coupler design

AstroPIC Gen2, introduced in our companion paper²⁹ and incorporating the normal-incidence (vertical, 90°) three-wave interaction grating couplers,^{15,16} requires a redesigned free-space coupler, since the beam is delivered at normal incidence rather than at the current $\sim 12^\circ$ (Sec. 3.1). The normal-incidence TWIGs reach sub-decibel insertion loss (81–85% measured^{15,16}), which directly raises the input-coupling term that dominates the end-to-end throughput.

4.3.2 Three-dimensional-printed lens design and fabrication process

Direct three-dimensional (3D) printing of micro-optics onto or above the grating couplers is being investigated as an alternative to a discrete microlens array, with the lens profile optimized to maximize the overlap integral with the grating-coupler mode.

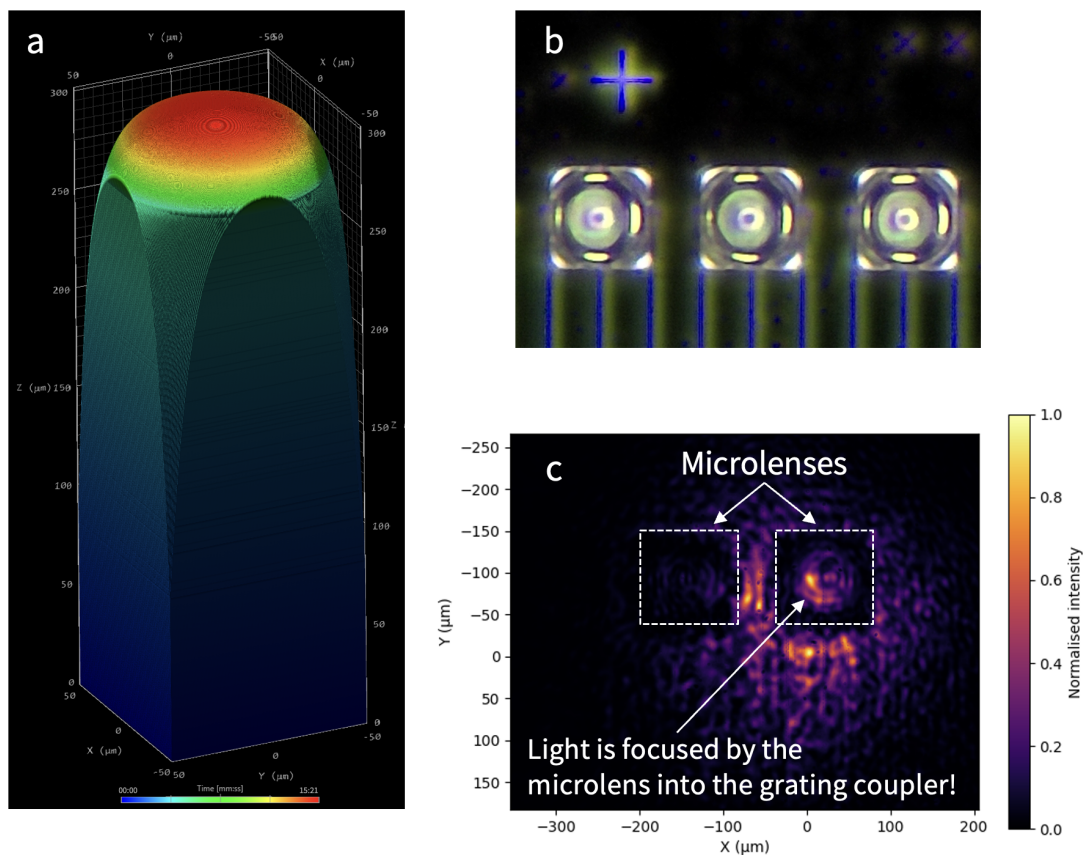


Figure 5. (a) Optimized 300 μm -tall lens, with slicing and hatching visualized and print time color-coded. (b) Microscope image of three printed microlenses on top of grating couplers. (c) Camera image of the microlens under a 250 μm -MFD Gaussian beam.

The microlenses were fabricated on a Nanoscribe Photonic Professional GT system using two-photon polymerization (2PP) with the photoresist IP-S. Aspheric lenses were optimized in Zemax OpticStudio for free-space coupling into the normal-incidence grating coupler, using the coupling efficiency into the grating coupler with a mode-field diameter of 10.4 μm as the figure of merit. The lenses were designed for square input apertures, with the goal of maximizing coupling efficiency. For a 100- μm square aperture, the optimal design requires a lens height of approximately 750 μm , with a coupling efficiency of 79 %. The achievable height in the current printing process is limited to 300 μm , which reduces the performance: for a 300 μm -high optimized lens, the simulated coupling efficiency drops to 61% (see Fig. 5(a)). Since the collection area of the 100 $\times$ 100 μm lens

aperture is much larger than that of the bare grating coupler ($10 \times 10 \mu\text{m}$), the coupling is still expected to improve significantly. For the printing process, a photonic chip with normal-incidence grating coupler pairs was fixed to a carrier wafer, the IP-S resin was drop-cast onto the chiplet, and the printing process was started. After printing, the resist was developed in SU-8 developer for 10 min. To reduce the printing time, the bulk of the lens (first $280 \mu\text{m}$) is printed using a slicing and hatching distance of $0.5 \mu\text{m}$, whereas the top $20 \mu\text{m}$ is printed with a finer distance of $0.1 \mu\text{m}$ to achieve low surface roughness and high optical quality (see Fig. 5(a)).

The optical characterization is performed using a free-space optical setup constructed on a cage system. Light from a fiber-coupled laser is collimated and imaged through a two-lens system onto the input grating coupler. A near-infrared LED illuminates the chip for imaging, and an InGaAs camera is used to image both the chip and the laser beam. At the photonic chip, the collimated laser beam illuminating the printed microlens has an approximately Gaussian profile with a measured mode-field diameter of $250 \mu\text{m}$, distinct from the $10.4 \mu\text{m}$ mode-field diameter of the target grating-coupler mode. The beam is aligned to the input grating coupler, and the throughput of the grating coupler pair is measured by collecting the light with a fiber aligned to the output grating coupler, connected to a photodetector. The measurement is performed both with and without the microlens printed on top of the grating coupler. The microlens increases the optical power coupled into the chip by a factor of circa 25.

In the future, within the AstroPIC project, large arrays of such microlenses can be printed on top of grating coupler arrays (similar to Fig. 2). In-situ two-photon printing of free-form coupling elements has previously been shown to reach up to 88% coupling efficiency in hybrid photonic assemblies, which supports this approach as a scalable packaging route.³⁰

4.4 Fiber-array-unit bonding and its impact on the microlenses

The output fiber-array unit (FAU) carries single-mode fibers in V-grooves on a $127 \mu\text{m}$ pitch, the standard telecommunications fiber-array spacing. The fibers terminate at a facet polished at 45° , where the guided mode is redirected by total internal reflection and leaves the block vertically, propagating down onto the output grating couplers. Because total internal reflection at the polished facet requires no reflective coating, the assembly reduces to a passive glass component bonded above the die, and the fiber array lies flat against the chip rather than standing off at the near-vertical angle that direct fiber addressing of a grating coupler would demand. This quasi-planar geometry is the established approach to grating-coupled packaging in silicon photonics: peak coupling within 0.2 dB of the theoretical grating-coupler maximum has been demonstrated with angle-polished fibers, using capillary-driven adhesive distribution and passive alignment.³¹

Mechanically the unit is a fused-silica wedge with the V-grooves cut into its lower surface. The fibers are laid into the grooves, fixed, and the assembly is then polished to form the reflecting facet, so that the fiber ends and the facet are figured together as one piece. The unguided path from that facet to the grating coupler is the sum of three contributions, labelled *A*, *B*, and *C* in Fig. 6, and holding their sum below the $55 \mu\text{m}$ budget drives the specification of each.

The first, *A*, is the standoff introduced by an additional glass slab bonded at the reflecting face. Some manufacturers include such a slab as a convenience in polishing, placing the reflecting interface on the added piece rather than on the wedge itself. We have specified its omission, so that the reflection occurs directly on the polished wedge surface. The second, *B*, is the depth of the fiber core below the lower surface of the wedge, set by the V-groove depth. The grooves are nominally cut so that the cores lie flush with that surface, but the achievable tolerance leaves a residual offset, so *B* is minimized rather than removed. The third, *C*, is the epoxy bond line between the wedge and the chip, typically $20\text{--}40 \mu\text{m}$ and controlled by beads dispersed in the adhesive that act as spacers. With *A* eliminated and *B* held to the groove tolerance, the bond line is the dominant term in the budget. The same geometry ties the lateral placement requirement to the vertical one, since each fiber's reflected beam must land on its corresponding coupler to within a fraction of the coupler aperture.

The reflection at the polished facet relies on total internal reflection at a fused-silica-to-air interface, and the angular margin available is small. For fused silica at 1550 nm ($n \approx 1.444$) the critical angle is 43.8° , so a facet polished at 45° satisfies the condition by little more than one degree. Polish-angle tolerance, index variation, and any contamination or stray adhesive on the reflecting face consume that margin directly, which makes the facet angle one of the tighter manufacturing tolerances in the assembly.

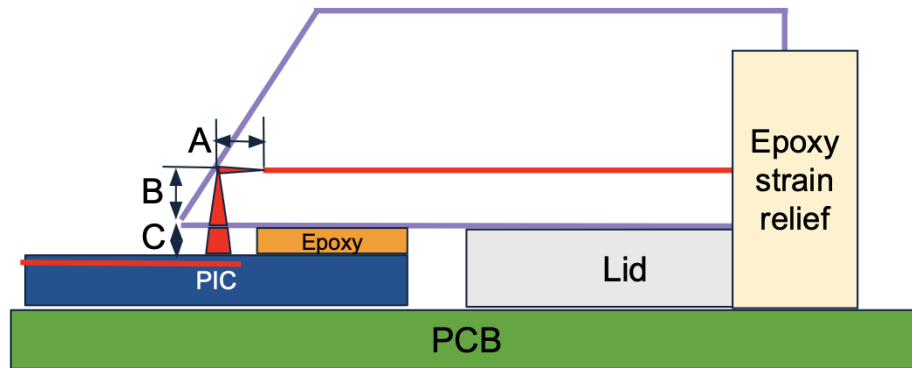


Figure 6. Schematic of the fiber-array-unit (FAU) output coupling geometry. Single-mode fibers sit in V-grooves on a $127\text{ }\mu\text{m}$ pitch in the lower surface of a fused-silica wedge. Light reaching the end of each fiber is turned through 90° by total internal reflection at the 45° polished facet and propagates down onto the output grating coupler. The unguided path is the sum of A , the standoff due to any added glass slab at the reflecting face; B , the depth of the fiber core below the lower surface of the wedge, set by the V-groove depth; and C , the epoxy bond line. The assembly is tied to the carrier board through an epoxy strain-relief structure so that load on the fiber pigtails is not reacted through the bond at the chip surface.

The margin is further eroded by the angular content of the beam itself. The mode leaving the fiber is not collimated but fills an exit cone set by the fiber numerical aperture, which for standard single-mode fiber ($\text{NA} = 0.14$) subtends a half-angle of approximately 5.6° inside the glass. That cone is several times wider than the roughly one-degree margin between the polish angle and the critical angle, so rays on the low-angle side of the distribution fall below the critical angle and refract out of the wedge instead of reflecting. A fraction of the light is therefore lost at the facet irrespective of how well the polish angle is controlled, and the loss is set by the mode's angular distribution rather than by workmanship. To solve this problem we are considering a gold coating on the 45° polished facet. Gold reflects approximately 98 to 99% at 1550 nm , a solid and reliable value, whereas the total-internal-reflection efficiency carries substantial uncertainty from the polish-angle tolerance, index variation, and possible facet contamination noted above. A coated facet guarantees reflection, removes the sensitivity to contamination, and relaxes the polishing tolerances. Alternatively, we are considering direct vertical coupling to the output grating couplers, which removes the reflecting facet from the optical path altogether at the cost of a less compact package.

The wedge is bonded to the PIC with epoxy. The bonding pattern is chosen to keep adhesive away from the coupler apertures where practical, but the epoxy transmits at the operating wavelength, so adhesive that does encroach on the beam is tolerable: it contributes an index change within the propagation budget rather than an obstruction. This is distinct from adhesive reaching the 45° facet, which would raise the index on the far side of the reflecting interface and defeat total internal reflection outright. A separate epoxy strain-relief structure ties the assembly to the carrier board, so that mechanical load applied to the fiber pigtails is reacted through the board rather than through the bond line at the chip surface, allowing the fibers to be handled and routed with confidence.

Several bonding configurations are under evaluation. Adhesive applied across the full contact area between the FAU and the chip maximizes bond strength and seals the interface, but places cured epoxy directly in the optical path, so its thickness, index, and homogeneity enter the coupling budget. Confining the adhesive to regions away from the coupler apertures leaves the beam to cross an air gap instead, at the cost of a smaller bonded area and a less robust joint. A further constraint is thermal: the adhesive cure cycle must be compatible with the two-photon-polymerized microlenses already present on the input side of the chip. Curing temperatures should stay within what the IP-S printed lens can tolerate without deforming or detaching from the chip surface. Preliminary tests performed at Stanford showed resilience to deformation and detachment up to 300°C which is significantly higher than any epoxy curing temperature. Additional testing is necessary to confirm these results.

Two analyses complete the end-to-end picture:

- **Complex-aperture coupling efficiency.** Planned simulations evaluate the coupling efficiency for segmented and obstructed apertures (e.g., LUVOIR/HWO pupils) using the overlap model and the AstroPIC design-to-yield pipeline.^{12,32}
- **End-to-end efficiency.** Combine the input coupling, waveguide propagation, mesh, and output coupling into a single end-to-end efficiency budget, and compare with the $\sim 9\text{--}10\%$ measured on-chip throughput of the single-fiber tests (Sec. 3).

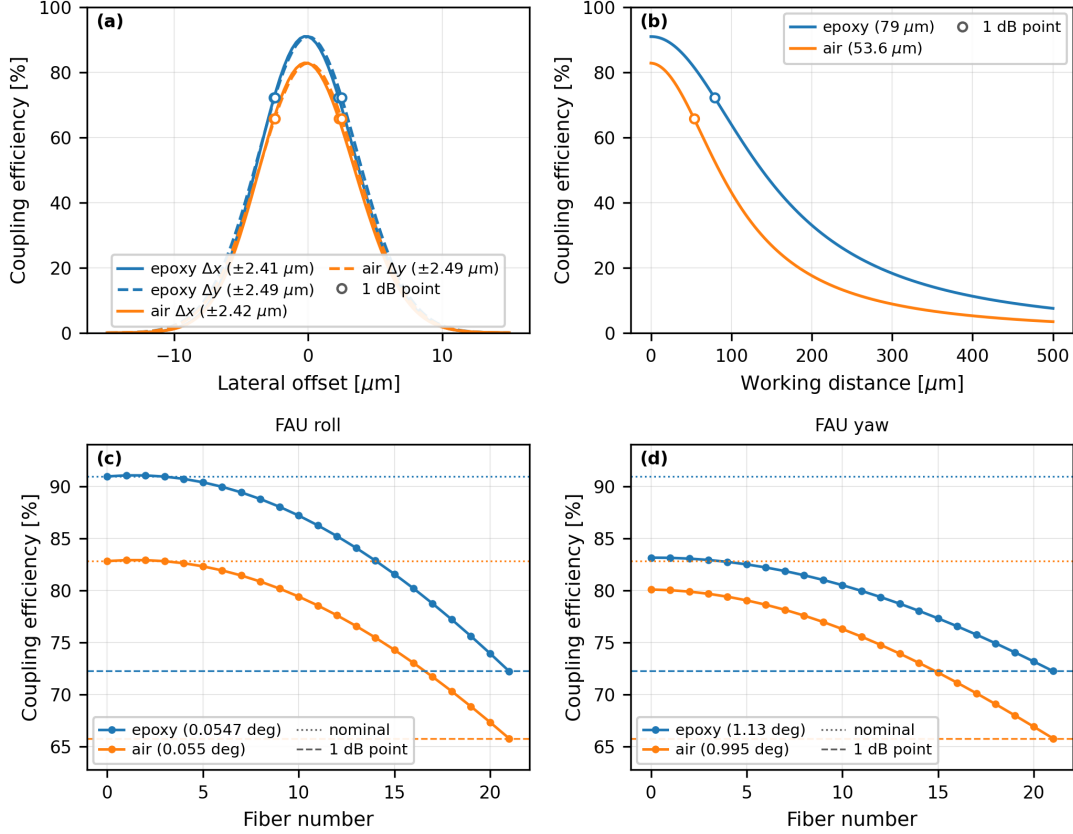


Figure 7. Alignment tolerance of the TWIG grating-coupler array to the FAU, for two cladding schemes: an index-matched epoxy fill (blue) and a bare air gap (orange). The air-gap case includes Fresnel loss at the oxide-air interface and at the fiber end face, which reduces peak coupling from 91.0% to 82.8% (0.41 dB). (a) Coupling versus lateral misalignment of a single fiber, along the in-plane axis dx (solid) and the out-of-plane axis dy (dashed). (b) Coupling versus working distance; the air gap falls off faster because its shorter Rayleigh range leads to the beam defocusing sooner. (c, d) Per-fiber coupling across the 22-fiber array with the FAU rigidly rotated to its 1 dB limit in roll (c) and yaw (d); dotted lines mark each cladding's nominal coupling and dashed lines the 1 dB threshold.

In this section, we present a simulation study that analyzes the alignment tolerance between a linear array of TWIG couplers and an FAU. Coupling is computed from a two-dimensional finite-difference frequency-domain (FDFD) solve of the grating cross-section, which yields the field radiated into the cladding; the coupling efficiency is then the overlap of that field with the fiber mode. Because the grating is uniform along the direction transverse to the plane of the simulation, the three-dimensional problem is treated as separable: the in-plane response comes from the FDFD field, while the out-of-plane response is treated analytically as a Gaussian mode. The FAU itself is modeled as a rigid body of 22 fibers on a $127 \mu\text{m}$ pitch, spanning 2.67 mm. The pose of the FAU is described by three translations of a reference fiber and three rotations about its tip. A rigid pose maps to a per-fiber misalignment and each fiber's coupling follows from the in-plane and out-of-plane overlaps evaluated at its own

misalignment. We report tolerances for two cladding scenarios: an index-matched epoxy fill, and a bare air gap with the fiber launching through its own end face.

For each pose axis we quote the excursion at which the worst fiber in the array falls 1 dB below its nominal simulated coupling at $1.55\text{ }\mu\text{m}$. The translational and common-tilt axes behave as a single-coupler tolerance study would suggest, since they displace every fiber equally. The impact of lateral misalignment is governed by the mode field diameters of the fiber and grating modes, regardless of the cladding material. As a result, we observe similar 1 dB alignment tolerances for both the air and epoxy claddings, as shown in Fig. 7(a). Additionally, it can be observed that the in-plane and the out-of-plane alignment tolerances are nearly symmetric; this is a result of the intentional design of the grating coupler mode to match a circularly symmetric gaussian mode.

The impact of an increasing working distance between the fiber tip and grating coupler is twofold: an increasing beam width and a steepening radius of curvature of the phase front. As can be seen in Fig. 7(b), both effects reduce the modal overlap between the fiber and the grating coupler. The 1 dB excess loss threshold resulting from working distance alone is determined by the Rayleigh range of the fiber mode. In the case of an epoxy filled gap this is estimated to be $79\text{ }\mu\text{m}$. Replacing the epoxy with an air gap costs 0.41 dB of peak coupling ($91.0\% \rightarrow 82.8\%$) from the two air-interface Fresnel reflections, and shortens the Rayleigh range from $79\text{ }\mu\text{m}$ to $55\text{ }\mu\text{m}$, which tightens the defocus budget in proportion.

In contrast with the lateral alignment tolerances of the system, rotational degrees of freedom about the reference fiber result in an increasing misalignment for fibers further from said reference. Fig. 7(c) and 7(d) give the impact of small angular misalignment in FAU roll and yaw, respectively, for increasing fiber count. The rotational misalignment is dominated by the length of the FAU and minimized in practice via loop back alignment structures at the extremes of the FAU.

5. CONCLUSIONS

We have described the injection optics for the AstroPIC photonic integrated coronagraph and their development at the NASA Ames AstroPIC laboratory. Coupling the free-space telescope beam into the single-mode waveguides sets the coronagraph throughput and, through it, the observatory exoplanet yield, so the injection efficiency is a primary design driver for a PIC coronagraph.

The coupler progressed from single-fiber illumination of one grating coupler to a microlens array that reimages the telescope pupil onto the grating-coupler array. Single-fiber tests reached single-channel starlight suppression of 6.3×10^{-10} (92 dB) on the e-beam chip at an on-chip throughput of ~ 9 to 10%, and identified the input coupling as the dominant loss and stray-light term. The free-space coupler reimages a 3 to 4.3 mm pupil onto the 300 to 430 μm grating-coupler array at 10:1 compression, sampling the pupil across the nine input channels. Its alignment, measured coupling performance, and stability are reported in the companion testbed papers.^{20,21}

Several developments target higher injection efficiency and operation on representative apertures. A silicon-nitride source chip will provide a star-and-planet input with lithographically fixed geometry, and carbon-nanotube pupil masks reproduce the HWO EAC2 and EAC3 apertures for injection tests on obstructed pupils. A redesigned free-space coupler will feed the normal-incidence three-wave interaction grating couplers, whose sub-decibel insertion loss raises the input-coupling term that limits the end-to-end throughput. Two-photon-polymerized microlenses printed directly on the grating couplers, together with characterization of the output fiber-array-unit bond, complete the packaging path toward flight-representative HWO pupils.

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