

High contrast imaging with the AstroPIC integrated photonic coronagraph

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ABSTRACT

Integrated photonics is a promising coronagraph technology option for increasing the Exo-Earth science yield of NASA's Habitable Worlds Observatory and relaxing key observatory requirements. A photonic integrated circuit (PIC) coronagraph is theoretically capable of achieving extremely high performance because arrays of integrated interferometers can implement any optical transformation, including a near-optimal coronagraph. However, PIC coronagraphs require maturation before use in a space telescope mission. The AstroPIC project is advancing this technology by developing a proof-of-concept silicon-photonic PIC coronagraph in the near-infrared. In this talk, we will review the design of AstroPIC and present results from laboratory testing of the first set of PIC devices fabricated for the project, including experiments that achieve over 90 dB extinction ($<10^{-9}$ contrast) of a single input channel and over 60 dB extinction ($<10^{-6}$ contrast) of multiple illuminated inputs.

Keywords: astrophotonics, coronagraphy

1. INTRODUCTION

Photonic integrated circuit (PIC) technology has enormous potential for astrophysics instrumentation because it enables many optical components to be fabricated on a common substrate with a protective top cladding to produce optical systems that are small, stable, and reconfigurable.¹ The AstroPIC photonic coronagraph applies recent advances in programmable integrated photonics technology to develop a high contrast imaging instrument for exoplanet imaging missions such as the Habitable Worlds Observatory.²

Direct imaging of Earth-like exoplanets is an extreme technological challenge because the instrument needs to reach extremely high contrasts of 10^{-10} and be able to measure planet signals at very small angular separations from their host star.³ Bulk-optic coronagraph systems are designed to carefully block or separate starlight while preserving the planet signal. These are very complex devices to design and implement, leading to large and expensive instruments. The instruments designed to date do not reach the fundamental physical performance limit of an optical coronagraph.^{4, 5} With sufficient technological maturation, a PIC coronagraph provides a path to approach the performance limit of an optimal coronagraph even at very small planet-star separation angles.^{5, 6}

A PIC coronagraph applies programmable photonics technology to implement a coronagraph operation on the light coming from a telescope in order to separate starlight from the planet signal light. Programmable photonics uses active components such as thermal phase shifters to manipulate light on a photonic chip.⁷ The AstroPIC instrument uses a mesh of Mach Zehnder Interferometers (MZIs) to form a Universal Photonic Component.^{8, 9} Each MZI has two integrated thermal phase shifters that allow it to implement any 2x2 linear operation on pairs of input channels. The photonic mesh combines these MZI building blocks in a triangular configuration (shown in Figure 4) which allows it to perform a complex interference in order to implement any linear operation on the input fields.⁸ The large number of programmable degrees of freedom in a PIC coronagraph allow it to perform a more efficient mapping between the input and output electric field planes in order to reach closer to the theoretically optimal coronagraph operator at small inner working angles.^{4, 5, 10, 11}

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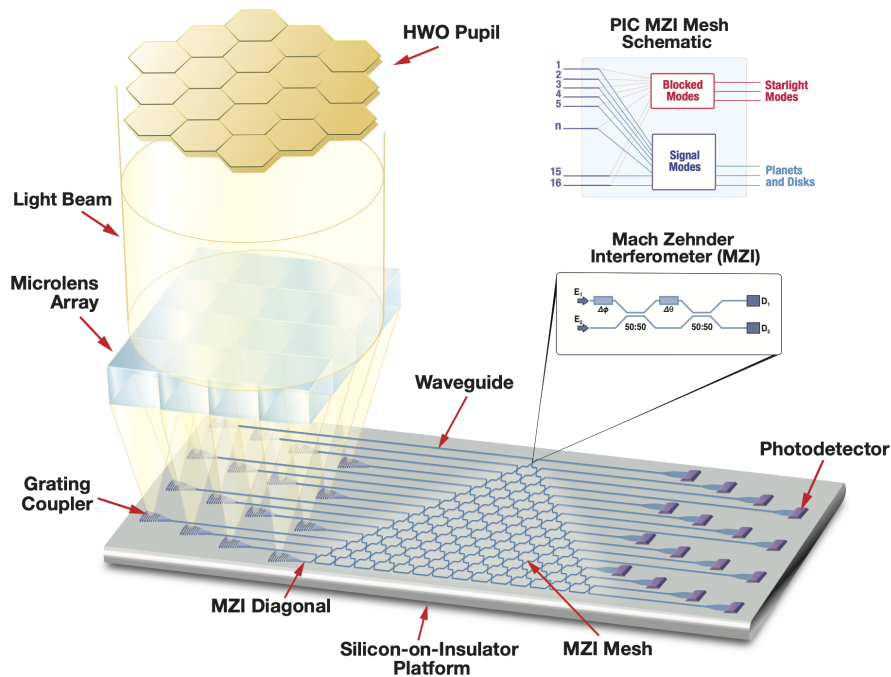


Figure 1. Diagram of AstroPIC coronagraph concept: light is coupled from a telescope pupil plane into an integrated photonic chip using a microlens array and a 2D array of grating couplers. The PIC uses a mesh of MZIs to implement a near-optimal coronagraph operator to separate the planet light from the starlight. Note: the MZI mesh shown in this diagram has more channels than are used in the first AstroPIC prototype, which is shown in Figure 4.

The AstroPIC coronagraph concept, shown in Figure 1, demonstrates the utility of integrated photonics for exoplanet characterization by implementing a PIC-based coronagraph instrument.^{6,12,13} Light is sampled from a telescope pupil plane using a microlens array that concentrates the light onto a 2D array of integrated grating couplers that couple the light into waveguides on the PIC. Once the light is coupled into on-chip waveguides, an array of tunable integrated MZIs can be controlled to interfere the input channels to implement any desired matrix operation on the input field to separate starlight from planet light. The planet light signal can then be analyzed with a spectrometer (either on- or off-chip) for the detection of biosignatures in the planet signal. End-to-end simulations of the AstroPIC concept predict excellent high-contrast performance at small inner working angles while being much less sensitive to the telescope pupil shape compared to bulk-optics coronagraph designs.^{13,14} The current 9-channel coronagraph prototype uses a 3×3 array of input grating couplers to sample light in a pupil plane, leading to a narrow outer working angle of $1.5 \lambda/D$ that can be increased in the future by increasing the number of input channels.^{6,12,13}

In this paper, we describe the development of an integrated photonic coronagraph testbed at NASA Ames Research Center that has been used to demonstrate high-contrast imaging using the first generation AstroPIC prototype. The design and implementation of the PIC testbed, including characterization and calibration of the PIC instrument, is described in Section 2. Section 3 summarizes the first high-contrast experiment that reaches a record-breaking on-chip extinction ratio of $3.83 \pm 0.8 \times 10^{-10}$ for a single input channel illuminated with $1,550 \text{ nm}$ wavelength light. Section 4 describes the design and implementation of the free-space coupling module that reimages a realistic telescope pupil plane and couples it into the chip using a microlens array. Finally, Section 5 summarizes a demonstration of high-contrast coronagraphy with the AstroPIC instrument that achieves a raw contrast ratio of $8.70 \pm 1.1 \times 10^{-8}$ for a circular pupil coupled into the chip with monochromatic light at $1,550 \text{ nm}$ wavelength. These results also include data on the wavelength dependence of the high-contrast state and a demonstration of tilting the input source angle in order to measure the effective planet throughput into the high-contrast channel of over 40% at a star-planet separation of $1 \lambda/D$.

2. PHOTONIC TESTBED DESIGN AND IMPLEMENTATION

The primary goal of the integrated photonic coronagraph testbed at NASA Ames is to characterize the AstroPIC instrument with a realistic telescope pupil aperture input and understand the performance and limitations of the first prototype instrument. Figure 2 shows a diagram of the AstroPIC experimental setup and a photo of the testbed at NASA Ames Research Center. A near-infrared laser source (Optilab TWL-C-B, 1525-1565 nm wavelength range) is coupled to a single-mode optical fiber, and a half wave plate and quarter wave plate are used to control the polarization of the light. A 99:1 fiber splitter is used to tap 1% of the light to be measured with a monitor photodiode in order to detect fluctuations in input laser power. The remaining 99% of the light is then coupled onto the chip with either a cleaved single-mode fiber, which is mounted on a custom fiber mount to maintain an input angle of 12° into a single grating coupler (shown in the inset of Figure 2), or with a free-space coupling optics module that reimages a telescope pupil onto a microlens array that samples and concentrates the light onto the 2D 3×3 array of input grating couplers¹⁵ (described in Section 4).

Light is coupled off the PIC with a 22-channel fiber array unit (FAU) that is bonded to the line of grating couplers at the output of the mesh. The output fibers are connected to nine individual photodetectors that are read out using an NI PXIe-6361 data-acquisition unit (DAQ). Most channels are designed for relatively high incident powers, corresponding to the stellar spatial modes that are orders of magnitude brighter than the signal planet modes. These “bright” channels are coupled to 8 Thorlabs DET01CFC InGaAs detectors with variable resistance terminators that are measured to have a sensitivity range of $\sim 7 \text{ nW} - 5 \text{ mW}$ and can operate over a wavelength range of $800 \text{ nm} - 1,700 \text{ nm}$. One output channel is designated as the “high-contrast” channel and is coupled to a high sensitivity photodetector (Femto OE-200-IN2-FC, spectral range $900 \text{ nm} - 1,700 \text{ nm}$) with a variable gain amplifier that provides a measurement sensitivity of $\sim 100 \text{ fW} - 2 \text{ mW}$. An optical chopper can be placed in the path of the input signal between the half wave plate and quarter wave plate used for polarization

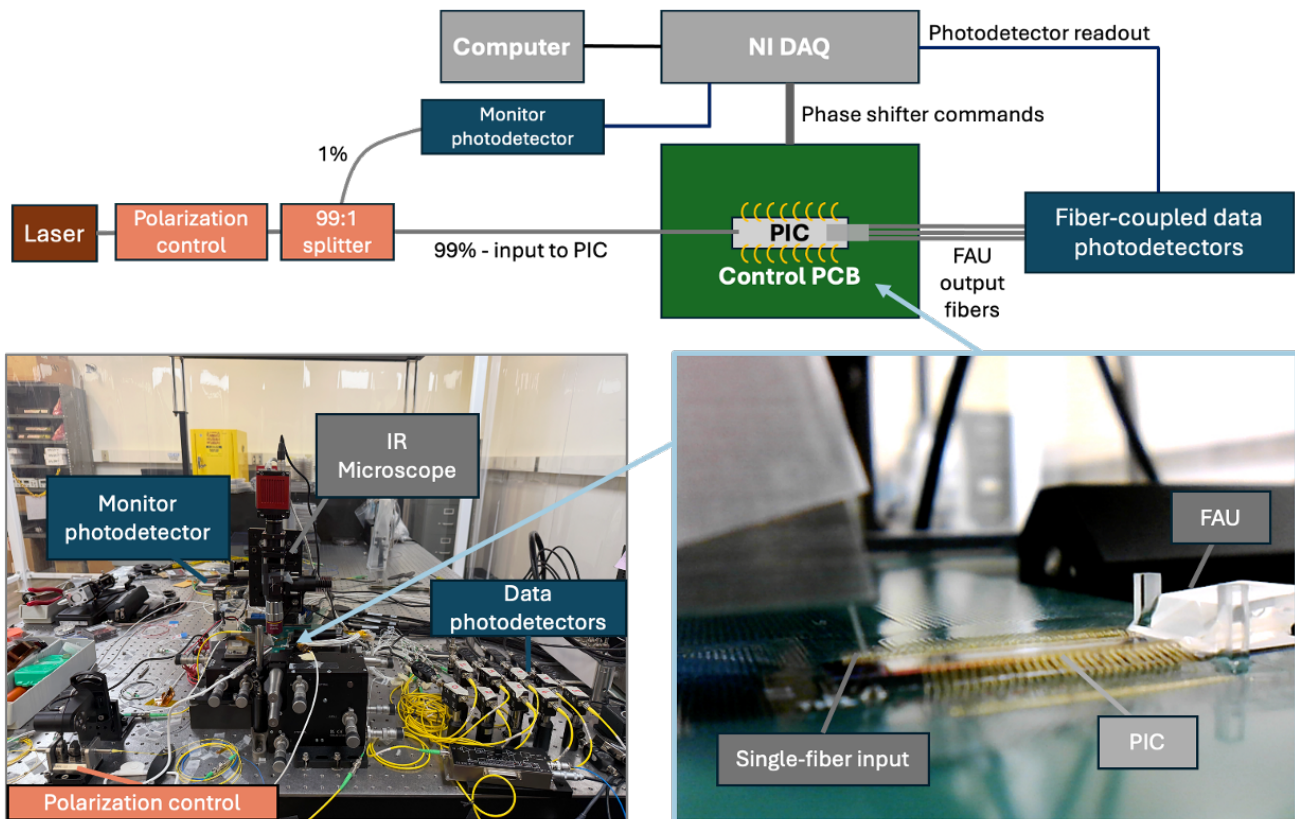


Figure 2. (Top) Diagram of AstroPIC experimental setup. (Bottom left) Photo of the AstroPIC photonics testbed setup at NASA Ames. (Bottom right) Side-view photo of the PIC wirebonded to the control PCB with a single optical fiber aligned to the input and a fiber array unit (FAU) bonded to the output.

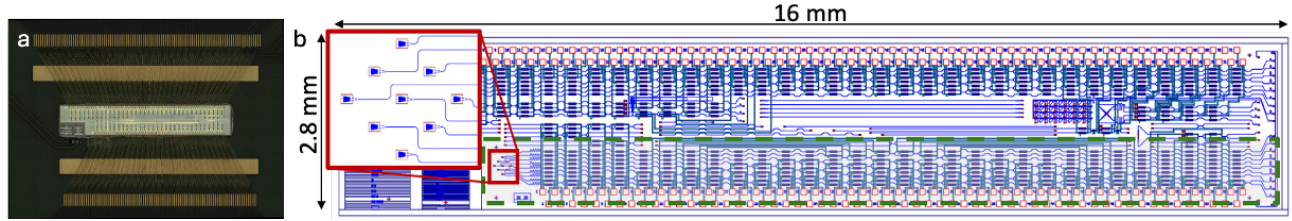


Figure 3. (a) Photo of AstroPIC coronagraph prototype chip (silver rectangle in center of image) wirebonded to the host PCB. (b) PIC layout showing the 9-channel full triangular mesh highlighted in gray with a dotted green border and a zoomed-in view of the 3×3 input grating array inset with a solid red border.

control in order to modulate the signal so that the photodetector output can be fed to a SRS510 lock-in amplifier to increase the signal-to-noise ratio of the high-sensitivity output channel. This lock-in detection scheme enables the Femto photodetector to measure optical powers as low as ~ 10 fW.

The PIC is epoxied and wirebonded to a host PCB that transmits the phase shifter control signals from an input connector onto the chip. The phase shifters are controlled with the NI PXIe-6361 DAQ using two PXIe-6739 cards installed to provide 128 control channels. Each channel has a voltage output of ± 10 V with 16 bit resolution. The PCB is mounted to a custom aluminum plate that contains a cutout underneath the PIC for a Peltier thermoelectric cooler (TEC) with 8.5 W max power draw (Same Sky model CP20251). The TEC is controlled with an Arroyo 5240 TEC controller that uses feedback from a thermistor on the host PCB near where the PIC is epoxied to provide thermal control to 0.01°C .

2.1 PIC Design and Fabrication

The first AstroPIC prototype design is a 9-channel full triangular photonic MZI mesh with the input grating couplers arranged in a 3×3 array to enable the input grating couplers to sample a telescope pupil plane. The mesh design layout is shown in Figure 3 with the 9-channel device under test highlighted and an inset showing a zoomed-in view of the 3×3 input grating coupler array with $100\ \mu\text{m}$ pitch. The 9-channel full triangular mesh occupies a footprint of $\sim 13\ \text{mm} \times 8\ \text{mm}$.

The AstroPIC mesh is made with standard $220\ \text{nm}$ tall $\times 500\ \text{nm}$ wide silicon rectangular waveguides with silicon dioxide cladding. The chip uses thermal phase shifters for on-chip phase control and air trenches are placed around the phase shifters to mitigate the effects of thermal cross-talk between nearby MZIs. The chip used in the experiments presented in this work was fabricated by the Applied Nanotools (ANT) foundry in Canada using their standard silicon-on-insulator processes. The ANT foundry uses electron beam lithography to pattern waveguide features, which can accommodate small feature sizes that enable the fabrication of high-efficiency inverse-designed grating couplers^{16,17} that will be used for future generations of the AstroPIC instrument.

2.2 PIC Characterization and Calibration

Once the AstroPIC prototype chip was installed in the testbed, initial testing used a cleaved single mode fiber as shown in Figure 4 to characterize the chip loss and calibrate the instrument. Test structures on the same chip but outside of the main mesh device were used to characterize individual components such as grating couplers and MZIs.

The AstroPIC chip loss is dominated by coupling losses from the grating couplers that couple light from an optical fiber or the free-space input module into the waveguides. The coupling loss is measured to be 4.6 dB/coupler (35% efficiency per coupler) using cleaved single mode fibers aligned to the input/output grating couplers of a straight waveguide test structure. The grating loss through the FAU is slightly higher because the fiber array inputs are not able to reach as close to the grating couplers compared to a single fiber aligned above a the chip. This coupling loss was measured to be 6.9 dB/coupler (20% efficiency) using a loopback test structure that connects two gratings at the outer edges of the FAU that is bonded above the output gratings. The other main source of loss is propagation loss due to material absorption or scattering in the silicon waveguides, which is measured to be 2.2 dB total loss (60% efficiency) for the 9×9 full triangular mesh, matching the expectation of $\sim 1\text{--}2$ dB/cm propagation loss for SOI waveguides.

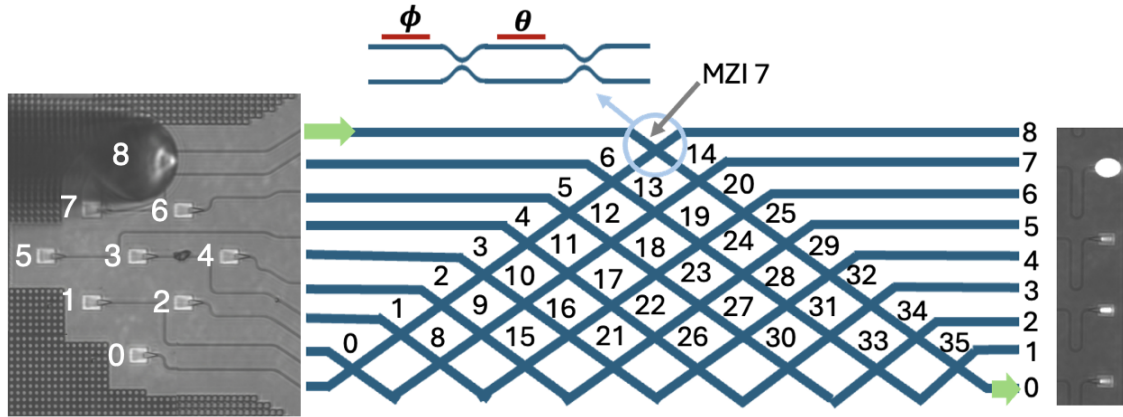


Figure 4. Diagram of experimental setup for testbed characterization and single-channel minimization experiments showing (left) a photo of the input fiber aligned to the top input grating coupler with the input grating channels labeled, (center) a diagram of the 9-channel full triangular mesh with each MZI and output channel labeled with a number and a single MZI diagram inset to denote the ϕ and θ phase shifters, and (right) a photo of the output grating couplers for the bottom four channels illuminated with no voltage settings applied to the mesh.

The full throughput of the chip is measured to be 3.6% (14 dB total loss) using a cleaved single-mode fiber at the input and a bonded FAU at the output. The fiber optics and polarization control components contribute an additional 1.6 dB of loss to the system (70% efficiency), which means that the testbed has a measurable dynamic range of ~ 100 dB (1×10^{-10}) with an input laser power of 40 mW and a minimum detectable power of ~ 100 fW. With a circular pupil input, the measurable dynamic range of the testbed is reduced to ~ 90 dB (1×10^{-9}) because additional losses are introduced by the pupil reimaging optics and coupling with the microlenses.

2.2.1 Calibration

The 9-channel full triangular mesh was calibrated to measure the transfer function of each MZI and find the bar (or pass-through) state for each MZI theta phase shifter. This was achieved by aligning a single mode fiber to each input grating coupler in series starting from the top of the array (the numbering of input/output channels and MZIs is shown in Figure 4). Then, each MZI in the corresponding diagonal (for input 8, this was MZI 7, 14, 20, 25, 29, 32, 34, and 35) was calibrated by sweeping the voltage applied to the theta phase shifter. This data was then fit to the expected transfer function of an MZI with a single illuminated input:

$$y = A \sin^2(B * P + C^2 + \theta_0) + E \quad (1)$$

where y is the measured output signal, A is a normalization factor, $B * P + C * P^2$ describes a quadratic relationship between the heater power ($P = V^2/R$, where V is applied voltage and R is total resistance) and the applied phase shift, θ_0 is a phase offset term introduced by fabrication variation across the chip, and E is a constant offset. The heater resistance was found by comparing the transfer functions of each MZI measured with different resistances introduced in the electronic path to control each heater. By equating the power required for a 2π phase shift, the resistance of each heater was solved for algebraically using the formula:

$$P_{2\pi} = \frac{V_2^2 - V_1^2}{R_{int} + R_{heater}} \quad (2)$$

where R_{int} is the resistance in the interface board between the DAQ and the PIC (either 50Ω or 500Ω), V_2 and V_1 are the start/end voltages for an applied phase shift of 2π , and R_{heater} is the desired heater resistance. Across the chip, this heater resistance was found to be $298 \pm 10\Omega$. An R_{int} of 50Ω was used for the coronagraph demonstration results presented in this paper.

Once the heater resistance was found for each MZI, the MZI transfer function in Equation (1) was fit to the calibration data measured from both bar and cross outputs of each MZI in order to find the phase offset θ_0 .

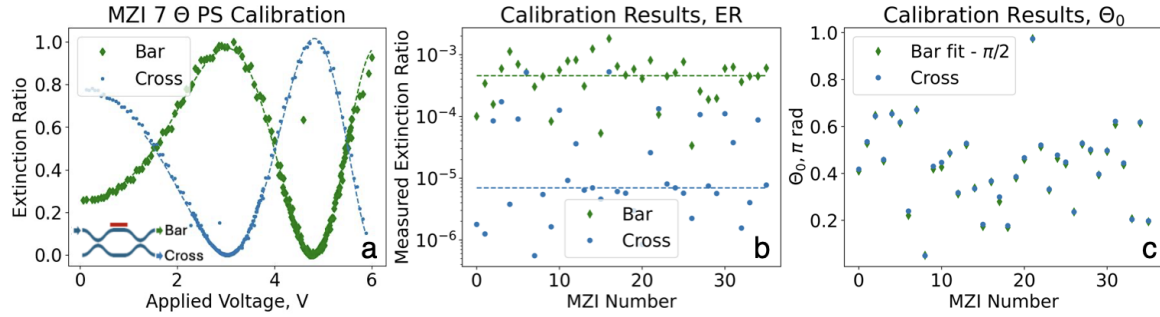


Figure 5. (a) MZI calibration data and corresponding transfer function fit for the θ phase shifter of MZI 7 measured in the bar and cross output channels as defined in the inset MZI diagram. (b) Plot of the measured extinction ratio (ER) for each MZI θ phase shifter in the mesh with the median measured value in bar/cross indicated with horizontal dashed lines. (c) Plot of θ_0 phase offset from the transfer function fit for each θ phase shifter in the mesh. The fit was repeated for the bar and cross measurement, and an offset of $\pi/2$ was subtracted from the bar fit result to compare to the cross result to match the expected transfer function into each output. MZI numbers match the labels in Figure 4.

Figure 5(a) shows an example fit to data measured with MZI 7 in Figure 4. Figure 5(b) shows the measured extinction ratio (ER) for each MZI measured in the bar and cross outputs across the mesh. The median ER measured in the bar output was 4.6×10^{-4} (32 dB) and the median ER measured in the cross output was 7.0×10^{-6} (51 dB). Figure 5(c) shows the θ_0 offset from the transfer function fit for each MZI for both bar and cross measurements. To match the expected phase offset between the two output ports of the MZI, $\pi/2$ was subtracted from the θ_0 extracted from the bar output fit in order to be compared to the θ_0 from the cross output fit. The average θ_0 found for all MZIs across the fit was $0.44 \pm .17\pi$, and the bar/cross fits showed excellent agreement across all MZIs in the chip with an average difference of 0.002π .

This calibration procedure was used to find the setting that maximized the signal going to the top (bar) output and minimized the signal going to the bottom (cross) output of each MZI. These bar state voltage settings were recorded in order to provide a pre-calibrated pass-through state that directly maps each input channel to the corresponding output directly across the chip, which is useful for testbed calibration and alignment. This “mesh bar state” was evaluated by aligning a cleaved optical fiber into each input channel and measuring the signal in all outputs, as shown in Figure 6(a), which is normalized to the maximum output signal measured for the input channel 8 $\rightarrow$ output channel 8 measurement. This measurement allowed us to evaluate the coupling efficiency of each input/output channel individually, which varies by $< 10\%$ across all channels, likely due to a small tilt in the FAU alignment relative to the surface of the PIC. This data also allows us to characterize the expected cross-talk between the output channels, which is generally $< 1 \times 10^{-3}$ for adjacent output channels and lower for output channels that are further from the target illuminated output.

Figure 6(b) compares the power measured in each output channel when light is input to channel 8 with a full bar state vs a full cross state applied to the mesh. The results show that the cross talk is lower for the mesh bar pass-through state compared to the mesh cross state that directs the light to the output opposite the input (output 0 for input 8). This is to be expected because the achievable extinction ratio is lower in the bar outputs compared to the cross outputs as shown in Figure 5.

In the mesh bar state, additional output channels of the FAU were also measured. The FAU is used to contact all the output gratings of the AstroPIC chip from multiple integrated meshes (shown along the right edge of Figure 3(b)), so output grating couplers that are not connected to the 9-channel full triangular mesh being tested can also be measured. The output positions in Figure 6(b) are all separated by $127 \mu\text{m}$ pitch, and output positions 0-8 correspond to the 9 output channels of the 9-channel mesh while the other positions are outside of the mesh. These measurements show that there is non-negligible scattered light that is coupling into the output channels on the order of $1 \times 10^{-7} - 1 \times 10^{-9}$ normalized to the signal from channel 8. This implies that stray light is a limiting factor in the current implementation of the AstroPIC chip, caused by the relatively low coupling efficiency of $\sim 35\%$ of the input/output grating couplers. We expect the level of scattered light to decrease in upcoming generations of the AstroPIC coronagraph design that will use a more efficient grating

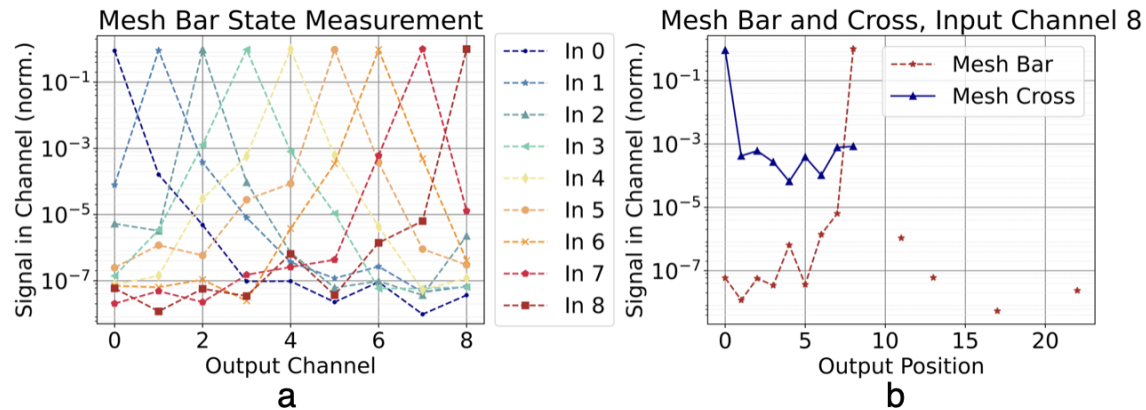


Figure 6. (a) Characterization measurement of the calibrated full mesh bar (or pass-through) state for a cleaved optical fiber aligned to each input channel and measured in each output channel (following the labels in Figure 4). (b) Comparison of the calibrated full mesh bar and cross states for light input to channel 8, as well as measurements of stray light in additional output channels of the FAU with the mesh in the full bar state. The output FAU channel positions in (b) are all separated by a $127\text{ }\mu\text{m}$ pitch, and positions 0-8 correspond to output channels 0-8 in (a).

coupler design^{6,17} to keep more light in the primary waveguide path instead of scattering through the cladding layer of the chip.

The AstroPIC testbed was then used to characterize the MZI minimization routine, which follows the procedures described in Valdez et al. 2025,¹⁸ where the optimal voltage for each phase shifter is found iteratively by sweeping the voltage across progressively smaller voltage ranges around the minimum state measured on the photodetector until the voltage sweep step size reaches the resolution limit of the DAQ (0.3 mV). Each photodetector measurement takes the average of 100 samples in order to reduce the influence of photodetector noise on the minimization routine.

Figure 7(a) shows the ER vs applied voltage applying the minimization procedure to the θ phase shifter of MZI 7 and measuring output channels 0 and 8 (after having set MZIs 14-35 to a cross state to direct all light output from the bottom arm of MZI 7 to output channel 0). The ER is the ratio of each measurement to the maximum signal measured in the channel during the voltage sweep, which avoids complications due to potential differences in loss due to different grating coupler efficiencies between the two output channels. This measurement shows that the minimization routine can reach very high ERs by controlling just a single MZI, with a peak ER of 82.6 dB measured in the output diagonally across from the input (cross) and 65.8 dB measured in the output directly across from the input (bar). However, this minimum state is only achieved for a single voltage setting on the MZI, and small environmental changes such as TEC temperature corrections can lead to signal drift. The achievable ER with MZI 7 was higher in Figure 7(a) compared to Figure 5(a) because the output channels were further separated, implying that the scattered light between adjacent output channels can limit the achievable ER of each MZI.

Laboratory testing also showed a strong dependence of achievable ER on the dwell time, which is the waiting time between applying a phase shifter voltage command and recording the corresponding photodetector measurement, shown in Figure 7(b). We believe this dependence results from longer dwells giving time for transient thermal effects to settle, while excessively long dwells leave time for environmental conditions such as TEC temperature to cause drift in the signal that degrades the performance. Based on these results, a dwell time of 0.1 s is used for most experiments, which means that the minimization routine takes about a minute to complete for each phase shifter.

3. SINGLE CHANNEL MINIMIZATION

The first type of experiment performed with the Ames testbed used a cleaved single-mode fiber aligned to the grating coupler at the top of the input grating array and controlled the mesh to minimize the signal reaching the

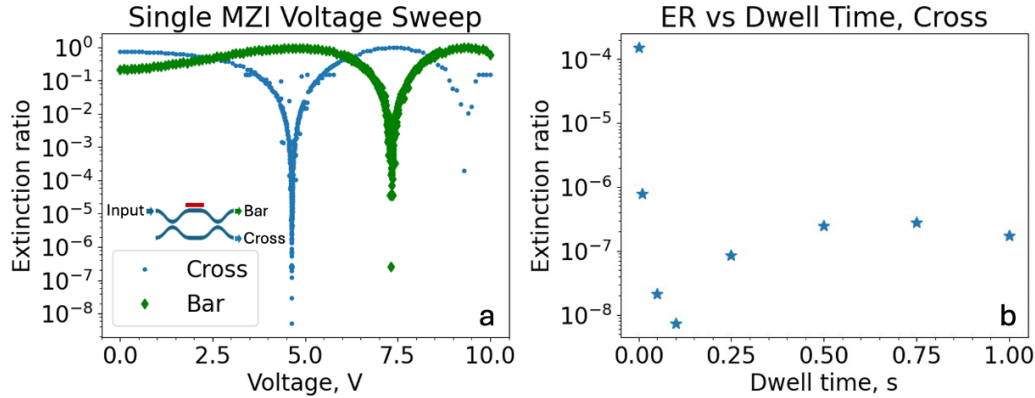


Figure 7. (a) MZI transfer measurement for MZI 7 showing a peak extinction ratio for a single controlled MZI of > 80 dB measured in the output diagonally across from the input (cross, output 0 in Figure 4) and > 60 dB in the output directly across from the input (bar, output 8). The extinction ratio is defined relative to the maximum signal seen in each respective channel and a small diagram explaining bar vs cross output definition is included above the legend. (b) Minimization routine extinction ratio dependence on the dwell time between voltage commands and photodetector measurement. The data in (a) were taken with a dwell time of 0.1s.

bottom output channel, as shown in Figure 4. The total extinction ratio (ER) is defined as the signal measured in the output channel divided by the maximum possible signal that can be measured in that channel, which is calculated by multiplying the peak signal measured in the top output channel by a factor that accounts for a small difference in coupling loss between the different output grating couplers (calculated from the data shown in Figure 6). The goal of this experiment was to demonstrate a high degree of control over the light and validate the testbed's ability to measure high contrast ratios, making it an important precursor to the demonstration of coronagraphic functionality described in Section 5.

With the input fiber aligned to the top input (input 8 in Figure 4), loading the pre-calibrated bar state gave a starting ER of ~ 85 dB at a wavelength of 1550.007 nm. The phase shifters on the mesh were then controlled to find the minimum possible signal in the bottom output channel (channel 0 in Figure 4) by correcting the starting bar state and controlling the path of any light reflected from the output grating coupler back into the mesh.

Figure 8(a) shows the ER measured throughout the experiment, which reached a final extinction ratio of $3.83 \pm 0.8 \times 10^{-10}$ (over 94 dB). To our knowledge, this is the highest extinction ratio recorded for suppressing a monochromatic signal on-chip, improving on the team's prior published result.¹⁸ The uncertainty is calculated based on the variation of the output measurement during a post-minimization dwell for 60 s, which we believe to be driven by thermal drift from small corrections to the TEC temperature to maintain the set point. This thermal instability is also seen in Figure 6a around 280 s when the experiment reaches a high contrast but later degrades. The experiment continued until a setting was reached that could maintain the high-contrast state for longer than a few seconds. The signal in the top output channel (channel 8) was monitored throughout the experiment to detect changes due to misalignment of the input fiber caused by thermal expansion/contraction in the metal fiber holder. The input fiber position was periodically realigned to maximize the signal in the top output channel in order to maintain alignment throughout the experiment.

The wavelength dependence of the instrument was assessed by holding the voltages applied to the AstroPIC chip constant and sweeping the wavelength of the laser source. The resulting extinction ratios are plotted as a function of wavelength offset from the central wavelength of 1550.0007 nm in Figure 8(b), showing that the high extinction ratio is only achieved over a very narrow bandwidth of ~ 5 pm. In the future, testing will be conducted with a broadband laser source to experiment with broadband channel nulling algorithms being developed by the team.¹⁴ This monochromatic demonstration is a promising first step towards full coronagraphic performance and demonstrates the high stability and programmability offered by integrated photonics technology. These results also validate the AstroPIC testbed's ability to measure extremely high contrast ratios in the laboratory environment.

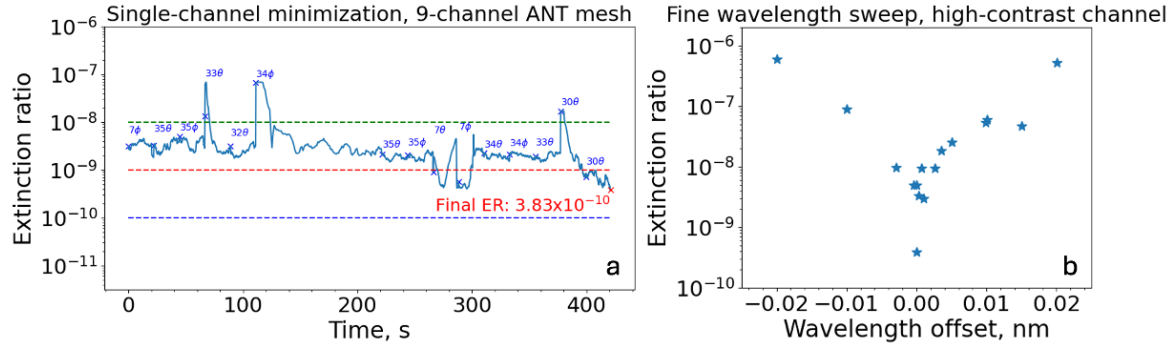


Figure 8. (a) Data from single-channel minimization experiment showing an extinction ratio of $3.83 \pm 0.8 \times 10^{-10}$ (> 94 dB) using a 9×9 full triangular mesh at 1550.0007 nm wavelength. The blue crosses indicate the start of each minimization routine using the adjacent phase shifter number corresponding to the labels from figure 4. The green, red, and blue dotted lines mark $1e-8$, $1e-9$, and $1e-10$ extinction ratios respectively. (c) Extinction ratio as a function of wavelength offset from the 1550.0007 nm central wavelength.

4. FREE-SPACE COUPLING MODULE

A key capability of the AstroPIC testbed at NASA Ames Research Center is the ability to test the PIC corona-graph performance using realistic telescope pupil inputs. To enable this, a free-space coupling module has been designed and built to compress a ~ 3 mm diameter pupil by a factor of ten and reimage it onto the 300 μ m wide 3×3 array of input grating couplers, shown in Figure 9. The reimaged and compressed pupil is sampled by a 3×3 rectangular grid microlens array, which has a 100 μ m pitch to match the grating coupler spacing. We selected the VIAVI MLA-S100-f4 off-the-shelf microlens array operating at f/4.2 which is close to the f/5 lens needed to match the size of the grating coupler output mode. The input source is mounted in a cage-mountable XY stage with Polaris P20A piezoelectric actuators that can control the input source lateral position in order to change the output angle of the reimaged pupil.

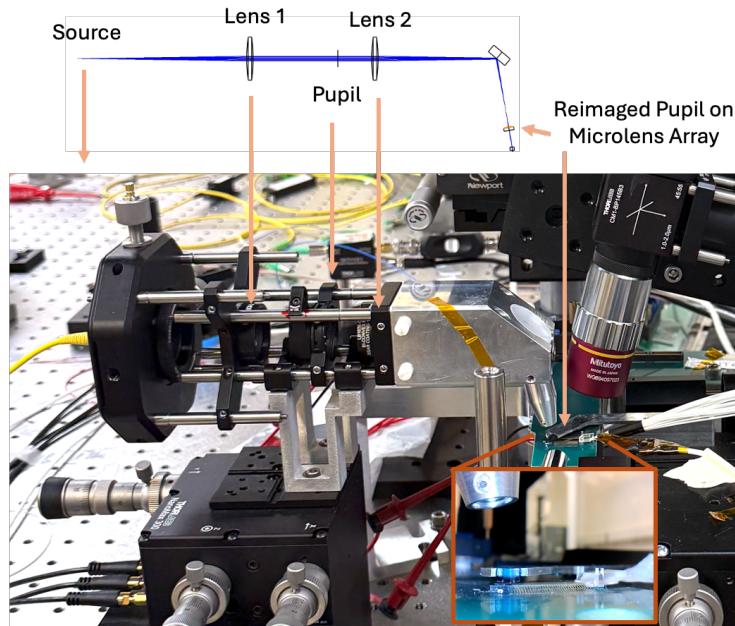


Figure 9. (Top) ZEMAXTM ray trace model of free-space coupling module optical design with arrows indicating corresponding positions in (bottom) photo of free-space coupling module installed in the AstroPIC testbed. A zoomed-in side-view image of the microlens array aligned above the PIC input is inset with a red border.

For the first experiments with the free-space coupler module, a 4.3 mm circular pupil was inserted into the setup to emulate an unobstructed circular telescope aperture slightly overfilling the $300\mu\text{m} \times 300\mu\text{m}$ input array of grating couplers. The throughput of the free space coupler module with this pupil was measured to be 35%. A separate setup was constructed to characterize the free-space coupler by aligning the pupil output directly onto the focal plane array of a Goldeye G-030 SWIR camera as shown in Figure 10(a). This setup was used to capture a photo of the reimaged circular pupil, shown in Figure 10(b) with the $100\mu\text{m}$ pitch input grating coupler array spacing overlaid for scale. This setup was also used to characterize the output angle of the reimaged pupil as a function of voltage applied to the piezoelectric actuators controlling the source launch position. To measure this, the camera focal plane was moved with a micrometer stage by a fixed amount to be further from the free-space coupler optics in order to defocus the pupil image and introduce a lateral displacement as a function of output angle. Then, the voltage applied to the X- and Y-axis piezoelectric actuators was swept from 0-150 V while recording images on the SWIR camera focal plane. The output pupil image center of mass (COM) in pixels was calculated for each applied voltage. An example of the defocused pupil image COM displacement as a function of applied voltage to the X-axis piezoelectric actuator is shown in Figure 10(c) with a linear fit to the data. The slope of the COM displacement in μm vs applied piezo voltage fit was then mapped to an effective angle per applied volt of 0.022 mrad/V using the known defocus displacement of the camera from the in-focus pupil location with the formula $\alpha = \arctan(\frac{\Delta x}{\Delta z})$ where α is the tilt angle, x is the lateral COM displacement, and z is the camera defocus displacement applied. This procedure was repeated for a range of camera defocus displacements to confirm that the resulting volt-to-angle mapping was repeatable and accurate. The total pupil tilt range provided by the piezoelectric XY actuators is measured to be $\sim 1\lambda/D$ in both X- and Y-tilt.

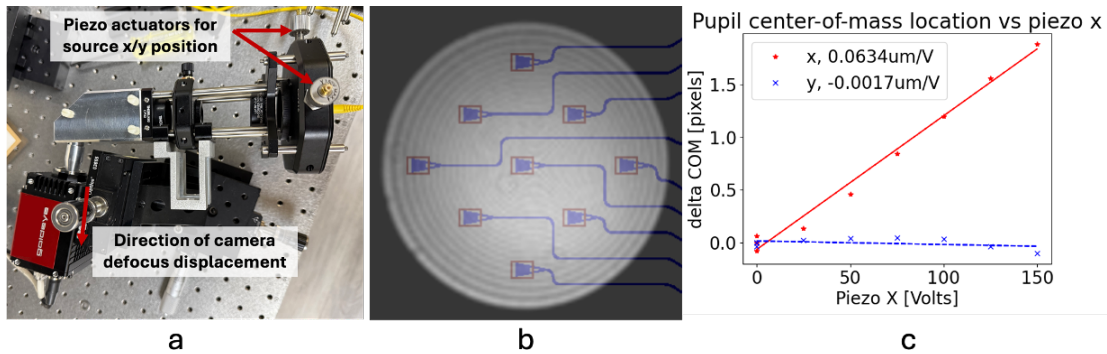


Figure 10. (a) Optical setup used to image the free-space coupler output directly on a SWIR camera focal plane array. (b) Image of a 4.3 mm diameter circular pupil reimaged with the free-space coupler optics. Input grating coupler array geometry is overlaid for scale. (c) Defocused pupil plane image center of mass (COM) as a function of voltage applied to the piezoelectric actuator installed in the x-axis of the source mount. This linear fit was used to calculate the mapping between applied voltage to the piezoelectric actuator and the output tilt angle of the reimaged pupil.

The free-space coupler module was then installed into the testbed as shown in Figure 9. The reimaged pupil was first aligned to couple into the input grating coupler array of the mesh, and then the microlens array was inserted in order to increase the coupling efficiency. The mesh was set to the pre-calibrated bar state in order to track the coupling into each input grating individually and ensure that the pupil was well aligned and providing balanced illumination to the input couplers. The fraction of power measured from each input channel with the front end aligned and the mesh in bar state is shown in Figure 13(a) overlaid on top of the pupil image and is also plotted in solid red line in Figure 13(b). This measurement shows fairly even illumination across the 9 input grating couplers, with the fraction in each channel varying from 9 – 15%. The throughput of the free-space coupler was measured to be 36%, and the end-to-end coupling including coupling through the microlens array into the PIC and coupling from the PIC to the detectors was measured to be 1%. This efficiency is lower than the 3.6% measured with a single fiber input because of increased coupling losses using the microlens array to focus onto the grating couplers compared to a cleaved optical fiber input. In the future, a new grating coupler design will be incorporated into the AstroPIC design in order to increase this coupling efficiency.⁶

4.1 Testbed Stability

In order to assess the stability of the testbed during experiments, the testbed was used to collect data overnight in different configurations. The results of these experiments are shown in Figure 11.

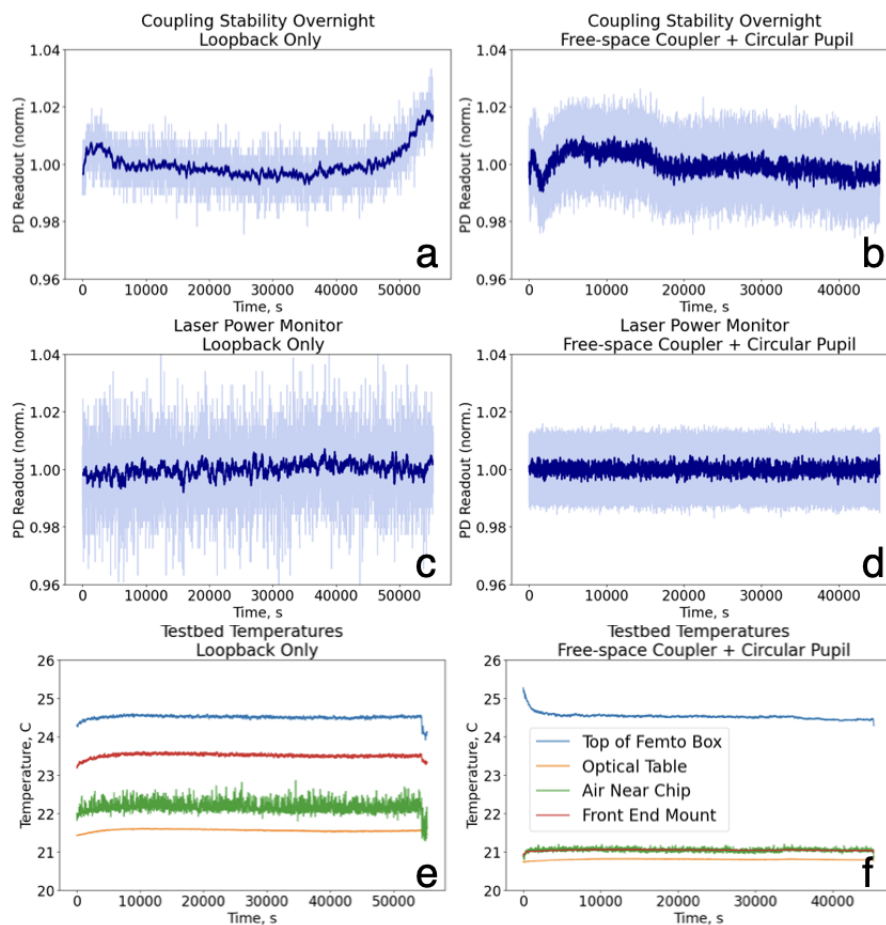


Figure 11. Summary of overnight stability measurements collected with the AstroPIC testbed. Overnight photodetector data of (a) coupling through the FAU loopback structure which connects two grating couplers on either side of the line of output grating couplers on the PIC in order to measure the FAU alignment and (b) coupling from the free-space coupler module with a circular pupil installed into the PIC with the microlens array (the PD readout shown in the sum of all PD channels). (c-d) Data from the laser power monitor photodetector during the overnight experiments. The dark lines in plots a-d show the rolling average with a window of 50 samples overlaid on the raw data in the lighter shade. (e-f) Recorded temperatures from four different thermistors installed in the testbed. The top of femto box sensor is taped on top of the high-sensitivity photodetector, the optical table sensor is taped to the optics table near the FC/APC connector that connects into the fiber leading into the free-space coupling module, the air near chip sensor is attached to the NanoMax stage so the sensor measures the air above the FAU, and the front end mount sensor is taped to the metal part of the front end module at the center of Figure 9.

The first overnight experiment configuration measured the coupling efficiency through the loopback structure on the PIC used to characterize the alignment stability of the bonded FAU. This experiment is summarized on the left side of Figure 11, showing normalized plots of the power through the FAU loopback structure and the laser power monitor photodetector as well as temperatures recorded from four temperature sensors installed in the testbed during the overnight data collection. The right side of Figure 11 shows equivalent measurements taken with the free-space coupler installed with a circular pupil and aligned with the microlens array to couple into the chip. The recorded photodetector readout in Figure 11(b) is the sum of all 9 output channels. The rolling averages of both measurements show a similar level of coupling drift of about $\pm 2\%$ (< 0.1 dB) throughout

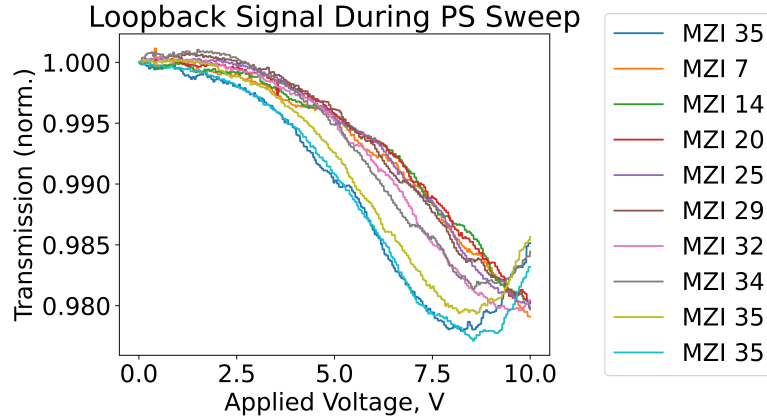


Figure 12. Plot of FAU loopback structure (which connects two gratings at opposite ends of the FAU and is used for to measure FAU alignment) normalized transmission during voltage sweeps of the θ phase shifter of several MZIs in the 9-channel mesh (following the labeling in Figure 4).

the overnight experiments.

The laser power monitor measurement is dominated by photodetector noise; the results do not indicate that there is noticeable drift in the laser power driving power fluctuations. The loopback measurement was taken with a lower laser power setting compared to the free-space coupler measurement, which explains the higher level of photodetector noise normalized to the average measurement. We believe that the measurement drift could be driven by thermal induced misalignments because time periods at the beginning and end of the overnight measurement samples saw higher amplitude fluctuations in the coupling measurement rolling average values and the temperature sensor measurements compared to more stable periods in the middle of the night.

The FAU loopback measurement drifts by a similar amplitude to the free-space coupler+circular pupil measurement, which implies that the mechanical alignment of the free-space coupler is quite stable and that the bonded FAU alignment quality is not static. In order to test the effect of temperature changes on the FAU coupling stability, the voltage applied to different thermal phase shifters in the main mesh was swept while recording the signal through the FAU loopback structure. Since the loopback is not connected to the main mesh of the AstroPIC chip, sweeping the phase shifters should not have had any influence on the optical signal beyond introducing thermal transients on the chip. In reality, the alignment varied by $\sim 2\%$ in response to a full sweep of the thermal phase shifters. This could be due to the thermal dependence of the grating coupler output angle or thermal expansion/contraction of the glue that bonds the FAU to the host PCB. In the future, the system packaging should be studied further in order to ensure stable operation of the PIC coronagraph instrument.

5. CORONAGRAPY DEMONSTRATION

After the single-channel minimization experiments validated the testbed's ability to control and measure light with high precision, the front-end optics module was installed and used for a demonstration of AstroPIC's coronagraphy function. For this demonstration, the 9×9 full triangular MZI mesh was used to implement the self-configuring mode sorting algorithm described in Miller 2013.⁹ The mesh started with 0 V applied to all phase shifters and the fraction of light in each output channel was recorded (blue dashed line labeled "0 V start" in Figure 13(b)). Then, each phase shifter along the upward diagonals of the triangular mesh were used in series to maximize the signal in the output channel corresponding to that diagonal. For instance, the first diagonal controlled the ϕ and θ phase shifters of MZIs 0-7 and maximized the signal in Output 8 using the labels in Figure 4. This procedure has the effect of coherently adding the highest-power spatial mode and concentrating it into the top output.⁹ Repeating this routine for the next diagonals further sorts additional spatial modes into corresponding output channels. After five diagonals had been controlled to pick out the five strongest spatial modes, there was no longer enough power remaining in the device to reliably run the coherent addition procedure, so the remaining actuators were tuned to directly minimize the signal in the bottom high-contrast output (channel 0).

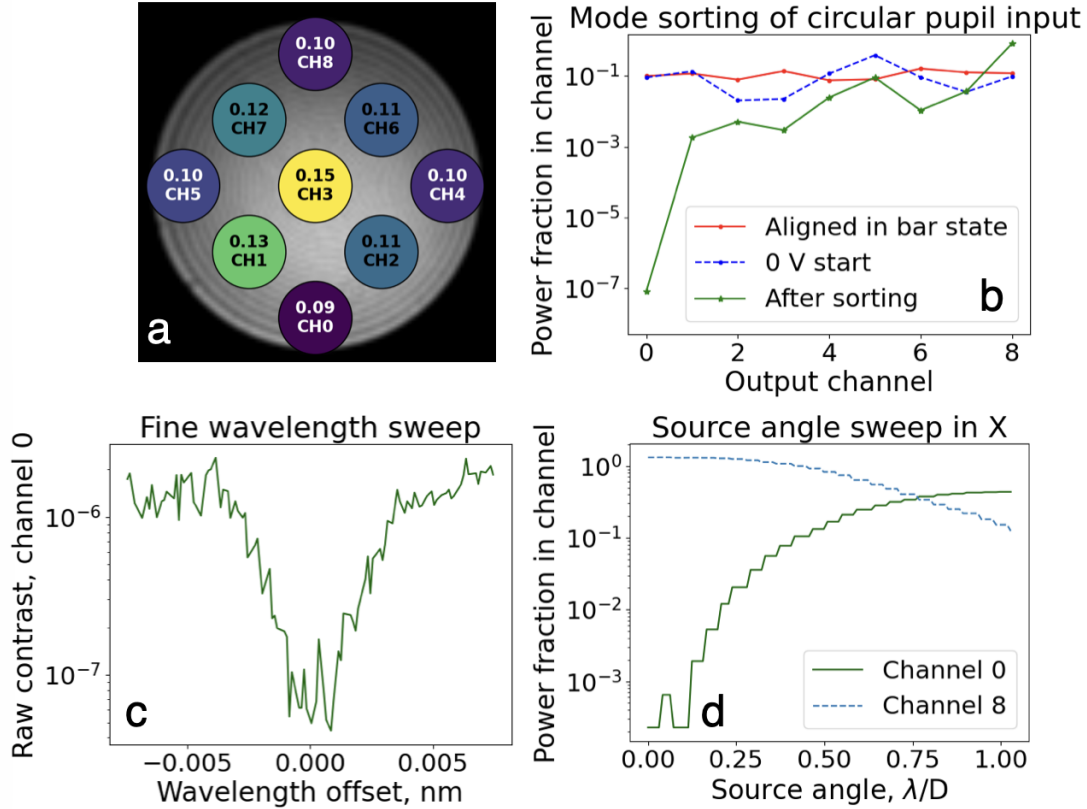


Figure 13. (a) Plot depicting the power fraction in each output channel with the free-space coupler aligned to the input grating couplers and mesh set to a pre-calibrated bar state overlaid on an image of the input circular pupil. (b) Power fraction in each output channel at different stages in the mode sorting experiment showing a final raw contrast of $< 1 \times 10^{-7}$ in channel 0. (c) Fine wavelength sweep showing the raw contrast in the high-contrast output channel (channel 0) as a function of wavelength offset from a central wavelength of 1550.007 nm. (d) Power fraction in output channels 0 (high-contrast channel) and 8 (primary star channel) as a function of pupil source tilt angle sweep showing an effective planet throughput into the high-contrast output channel 0 of $> 40\%$. Note: the photodetector gain needed to be reduced to avoid saturation in this measurement, so the minimum power at 0 source angle is below the noise floor of the photodetector.

This procedure eventually achieved a raw contrast of $8.7 \pm 1.1 \times 10^{-8}$ in channel 0 (shown in the green line in Figure 13(b)). Here, raw contrast is defined as the ratio of the signal measured in channel 0 divided by the total signal measured on the chip (including a calibration factor to account for differences in output grating coupling efficiency between channels). The measurement uncertainty was calculated by taking the standard deviation of the signal recorded during a 30 s dwell after the minimized state was achieved. The wavelength dependence was measured by sweeping the laser source wavelength and recording the signal in the bottom output channel while maintaining the same minimized state phase shifter settings, shown in Figure 13(c). In this measurement, channel 0 maintains high contrast over a narrow bandwidth of ~ 2 pm, but the team hopes to improve this in the future by using a broadband laser source to test out algorithms that take advantage of the large number of degrees of freedom in the mesh to optimize the state to achieve deep contrasts across a broader bandwidth.¹⁴

In order to measure the effective throughput of the PIC coronagraph, the input source position was swept with the piezo actuator to tilt the incident field and record the signal in all the output channels. The photodetector gain needed to be reduced to avoid saturation during this measurement, which increased the noise floor of the measurement. Figure 13(d) shows the measured power fraction in channel 0 (high-contrast channel) and 8 (primary star channel) as a function of incident source tilt angle. As the source angle increases, the relative power fraction in the primary star channel decreases while the relative power in the high-contrast channel increases to 43.5% at an angle of $1.03\lambda/D$ (which is the maximum tilt angle that can be applied with the current free-space

coupler design). This effective throughput measurement does not include losses due to on-off chip coupling and waveguide propagation loss (the free-space coupler+PIC setup has $\sim 1\%$ efficiency as reported in Section 4) as these can be improved with new component designs¹⁷ and waveguide material choice. In the future, the effective instrument throughput could be improved by applying different coronagraph operators to the mesh. For example, the mesh could be configured to sort the fundamental star modes into the star channels and then use additional degrees of freedom to concentrate light from a certain angle into a dedicated signal channel if the planet’s location is known in advance.

6. CONCLUSIONS

We have presented experimental results using the first-generation AstroPIC integrated photonic coronagraph prototype tested with the new integrated photonic testbed at NASA Ames Research Center. First, we described the implementation and calibration of the PIC coronagraph testbed. Then, we used the testbed to demonstrate a record-breaking extinction ratio of $3.83 \pm 0.8 \times 10^{-10}$, or over 94 dB, of a single input channel illuminated with monochromatic light at 1,550 nm wavelength using a 9×9 full triangular MZI mesh. This was achieved by first setting a pre-calibrated bar state to the mesh and then tuning additional phase shifters to further minimize the signal and control the path of back-reflected light. This measurement validates the photonic testbed’s ability to measure high contrast ratios and is an important intermediate step towards full coronagraphic performance. Achieving a contrast measurement on the order of 3×10^{-10} with bulk optics technology requires precise optical systems with advanced thermal control, typically operated in vacuum.^{5,19} This demonstration of extremely high extinction ratio in a standard laboratory environment shows the power of integrated photonics technology to manipulate light with high precision using systems that are significantly smaller and less complex than traditional bulk optics designs.

We have also demonstrated free-space injection of a reimaged telescope pupil into the PIC coronagraph using a free-space coupler module and evaluated the coupling stability. We used this module to couple light from a circular, unobstructed pupil into the 3×3 input grating coupler array using a microlens array aligned above the PIC input to improve coupling. The 9-channel full triangular MZI mesh was then used to implement a self-configuring mode sorting algorithm to coherently add the input light into different output channels based on their spatial mode. After sorting the source modes into 4 “bright” channels, the remaining MZI phase shifters were used to minimize the signal in a designated “dark” channel. This dark channel achieved a peak raw contrast ratio of $8.7 \pm 1.1 \times 10^{-8}$, or over 70 dB, relative to the total power coupled into the chip. The planet throughput of the system was measured to be $>40\%$ by changing the incident angle of the pupil using a piezoelectric actuator and recording the fractional power in each output channel. This is the first demonstration of high-contrast measurements using a PIC coronagraph operating with a realistic telescope-like pupil, representing an exciting step in advancing the technology readiness level of PIC coronagraphs.

The AstroPIC project is ongoing, and an upcoming second-generation prototype will scale up the instrument concept by increasing the number of input channels to 16 and incorporating higher efficiency input/output grating couplers. Testing with the first-generation chip will continue with more detailed chip calibrations that will enable the team to test applying coronagraph operators directly to the mesh instead of relying on the self-calibrating mode sorting algorithm used in this work. The team is also in the process of procuring more pupil shape masks to replace the circular pupil in the free-space coupling optics to be more realistic to the HWO mission. This will allow the team to demonstrate the AstroPIC instrument’s ability to achieve high contrasts in the presence of realistic mirror segment gaps and secondary struts, which is a major goal of the project.

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