

AstroPIC III: Advancing the near-infrared photonic coronagraph for the Habitable Worlds Observatory

Dan Sirbu^{*1}, Ruslan Belikov¹, Eduardo Bendek^{1,2}, Kevin Fogarty¹, Jonathan Lin¹, Rachel Morgan^{1,2}, Kevin Sims¹, Jaekwon Lee³, Carson Valdez^{3,4}, Anne Kroo³, Olav Solgaard³, David A. B. Miller³

¹ NASA Ames Research Center, Moffett Field, CA

² SETI Institute, Mountain View, CA

³ Ginzton Laboratory, Stanford University, Stanford, CA

⁴ Spark Photonics, Waltham, MA

ABSTRACT

AstroPIC is a photonic integrated coronagraph concept for the Habitable Worlds Observatory (HWO) that uses a programmable Mach-Zehnder interferometer mesh to perform coronagraphic mode-sorting of starlight while preserving off-axis exoplanet light. This paper presents a Gen-2 technology update and modeling study. The Gen-1 photonic chip laboratory demonstrations achieved $3.8 \pm 0.8 \times 10^{-10}$ on-chip suppression and $8.70 \pm 1.1 \times 10^{-8}$ raw contrast with a system-level free-space coupled input. We then describe the Gen-2 photonic chip update, which scales the main mesh from 9 to 16 input channels and from 72 to 240 thermo-optic phase shifters while adding improved high-efficiency normal incidence grating-couplers, routing, isolation and packaging. Finally, we use numerical wavefront-control simulations to quantify the benefits of the added degrees of freedom, including larger and deeper dark zones, faster convergence, improved narrowband performance, and DAC-resolution limits for achieving target contrast levels.

Keywords: Astrophotonics, Photonic Integrated Circuits, Exoplanets, Coronagraphy, High-Contrast Imaging, Wavefront Control, Habitable Worlds Observatory, Near-Infrared Channel

1. INTRODUCTION

The Habitable Worlds Observatory (HWO), identified as the top-priority flagship for astrophysics in the 2020 Decadal Survey, requires coronagraphic starlight suppression sufficient to directly image Earth-like planets. Astrophotonics,¹ and photonic integrated circuits (PICs) in particular, offer a compact and reconfigurable route to implementing advanced nulling architectures at small inner working angles. AstroPIC applies this approach using a programmable Mach-Zehnder interferometer (MZI) mesh that can implement linear optical transformations for separating stellar leakage from off-axis planet and disk light.²

This paper, the third in the series, has a central goal of providing an update on the AstroPIC project and the photonic coronagraph's technology development building on last year's overview³ to advance the photonic coronagraph towards HWO infusion. The small inner working angle and high throughput potential of AstroPIC makes it uniquely well-suited as a near-infrared coronagraph. Recent demonstrations obtained with the Gen-1 chip⁴ included both chip-based nulling that has reached suppression of $3.8 \pm 0.8 \times 10^{-10}$ on-chip and $8.70 \pm 1.1 \times 10^{-8}$ contrast with free-space coupling. These build on a series of continually improving contrast demonstrations that have resulted in higher contrast achieved with the AstroPIC Gen-1 chip⁵ as well as with a prototype chip with fewer degrees of freedom.⁶ We have also recently shown that the programmability of the chip can be used for on-chip wavefront control,⁷ and that it can be used in both stand-alone and hybrid configurations.⁸ We have shown that a photonic-based coronagraph has the potential to increase the science yield by 2-4x beyond a traditional bulk optic coronagraph,⁹ improve robustness to low-order aberrations and can be utilized with a wide range of apertures being considered by HWO.

We outline the Gen-2 chip recently submitted for manufacture, which represents a scale-up in terms of number of spatial channels (to $N = 16$ input channels, nearly 50% more than $N = 9$ for the Gen-1 chip) and integration

*email: dan.sirbu@nasa.gov

of normal incidence grating couplers with 85% coupling efficiency.¹⁰ Other changes include usage of balanced MZIs with reduced numbers of bends to reduce stray, compact path-length-matching structures, added optical and thermal isolation trenches to improve phase/loss matching, and reduce crosstalk at the output. The Gen-2 chip maintains a 22-channel FAU optical interface, while the number of programmable thermo-optical phase shifters on the main mesh increased from 72 to 240. A secondary Gen-2 chiplet adds two 9-channel evaluation meshes that feature improved thermal isolation and components designed for operation at 1% narrowband, as well as test structures for comparing coupler, routing, dual MZIs, and cutback performance.

The Gen-2 chip significantly increases the number of degrees of freedom available for wavefront control on the chip. In this paper, we highlight model comparisons between the Gen-1 chip and the Gen-2 chip that demonstrate the expected performance improvements provided by additional phase shifters on the chip including improved convergence, achievable contrast levels, and bandwidth. We also investigate the estimated contrast achievable in the presence of different quantization levels. A companion paper presents the high-contrast experimental results obtained with the photonics testbed using the Gen-1 chip in both single-input and free-space coupling input configurations reaching $3.8 \pm 0.8 \times 10^{-10}$ suppression and $8.70 \pm 1.1 \times 10^{-8}$ contrast respectively, and details both calibrations required for operation of the photonic coronagraph chip and off-axis throughput measurements.¹¹ In a separate companion paper, wavefront control optimization via gradient descent is used to generate broadband dark zones that are robust to multiple Zernike modes¹² for the Gen-1 chip, as well as generating robust wavefront control solutions with respect to model. A companion paper¹³ describes the free-space coupling approach used for the system-level demonstration used for the Gen-1 chip and describing the current packaging approach baselined for the Gen-2 chip. Finally, the starlight output modes from the PIC can be used for wavefront sensing including near-optimal settings, and this was recently demonstrated with AstroPIC for a test piston-mode¹⁴ in addition to configuration of the PIC for the first time in an imaging configuration. Recently, the Gen-1 chip has also been tested downstream of a deformable mirror in a hybrid configuration.¹⁵

2. PHOTONIC INTEGRATED CORONAGRAPH

The AstroPIC integrated photonic coronagraph is implemented using a mesh of Mach-Zehnder Interferometers (MZIs) fabricated with silicon photonics on a PIC. We utilized a full upper triangular Reck mesh¹⁶ to enable decomposition of any unitary matrix through the MZI mesh utilizing symmetrical, balanced paths using path length matching structures added for phase matching along each. Two integrated phase shifters in each MZI block can be tuned across the entire mesh to implement a universal linear operation,¹⁷ providing a practical means to implement an optimal coronagraph (in the limit of a large number of modes).

Any conventional optical system (made up of a series of elements such as masks, mirrors, or lenses) can be represented as a linear transformation between an input plane and an output plane.^{18,19} The optimal linear operator for the coronagraph can be computed by removing specific low order modes from input to the output plane; corresponding science yields can be computed via DRMs such as AYO or ExoSIMS and show that the optimal coronagraph implemented as a PIC can achieve several times greater yields than is possible with the current bulk optic coronagraphs, and that further these yields are robust to any aperture obstructions, segmentations, or struts including EACs 1-3 currently being considered by HWO;⁹ the latest EACs 4-5 are similar to EACs 1-2 (off-axis, segmented) so the photonic coronagraph is expected to have similar robustness (but will need to be explicitly simulated in the future).

The AstroPIC photonic integrated coronagraph² for HWO is shown in Fig. 1 with a 16 spatial mode input design representative of the Gen-2 chip. This architecture uses a microlens that samples the telescope pupil and focuses light into an array of grating couplers that direct the light into single-mode waveguides on the PIC, a triangular MZI mesh that transforms the input modes into an output basis to optimally separate signal (planet/disk) from starlight, and on-chip photodetectors (or, alternatively, off-chip detectors fed by edge-coupled fibers). Each 2x2 MZI element comprising the MZI mesh contains two thermal phase shifters that locally modify the index of refraction controlling the amount of constructive and destructive interference in each of the output arms.

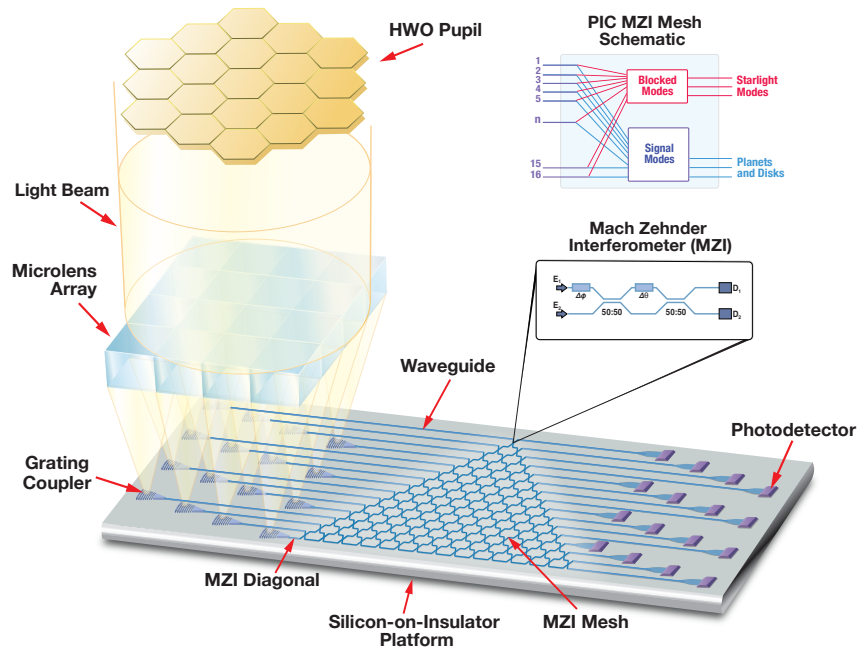


Figure 1: Illustration of the AstroPIC photonic integrated coronagraph for HWO, shown with 16 scalable input channels representative of Gen-2. The telescope-pupil beam is coupled by a microlens array by a set of grating coupler feeding waveguides onto the PIC. The full triangular MZI mesh implements a programmable unitary transformation that routes selected stellar modes into rejected bright outputs while preserving off-axis planet and disk signals in science outputs. Outputs are measured by on-chip photodetectors or coupled to an external detector, and may be configured for individual planets or image/Lyot-plane samples. Equal path lengths (using equalization structures not shown) preserve coherence at each MZI.

3. CONCEPT OF OPERATIONS

The AstroPIC mesh operates by mode sorting: the programmable MZI mesh is configured so that the dominant on-axis stellar field components interfere constructively in a small set of rejected bright output channels, while the science-designated output channels have suppressed stellar leakage (with the goal of reaching 10^{-10} suppression in each channel). Off-axis planet and disk light has a different input-field structure and therefore propagates through a different modal combination of the same mesh, allowing it to retain throughput in the science outputs (with recent off-axis testbed measurements performed with the Gen-1 chip¹¹). This is shown in the artistic illustration in Figure ??

In Figure 3, we show a simulated Gen-1 configuration with $N = 9$ input channels and $K = 3$ rejected bright channels. The on-axis stellar field is sorted primarily into output row 1, with residual stellar modes in rows 2 and 3, while the off-axis exoplanet signal field is directed to output row 8. The output intensities can be measured with on-chip photodetectors or coupled to an external detector, enabling stellar suppression, planet/disk extraction, and wavefront-sensing feedback from the rejected bright channels.

Before an exoplanet location is accurately known, the mesh can be configured in an imaging mode analogous to a conventional camera, with output channels sampling a conventional image plane (similar to the testbed demonstration recently performed with the Gen-1 chip¹⁴). Once the exoplanet location has been identified, either from prior observations or from the initial imaging state, the same programmable mesh can be reconfigured to concentrate signal into a designated science output. This targeted characterization mode can increase the fraction of exoplanet flux measured in a single channel and improve signal-to-noise against a specified background, compared with conventional imaging in which the planet PSF is distributed over multiple detector pixels; the photonic coronagraph can match the expected electric field distribution.²⁰

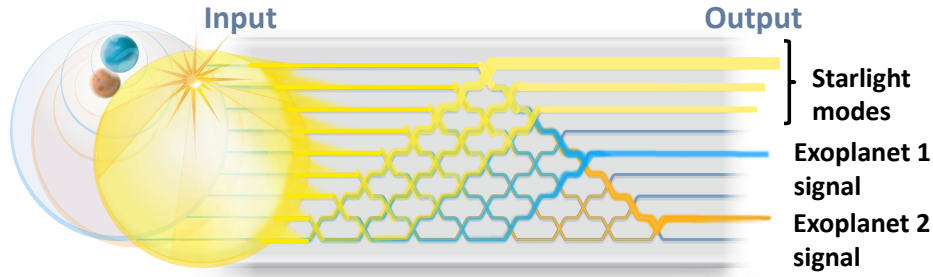


Figure 2: Illustration showing mode-sorting of starlight into a set of bright output channels in the output of a 9-channel triangular MZI mesh, and exoplanet signal directed into two output channels for characterization.

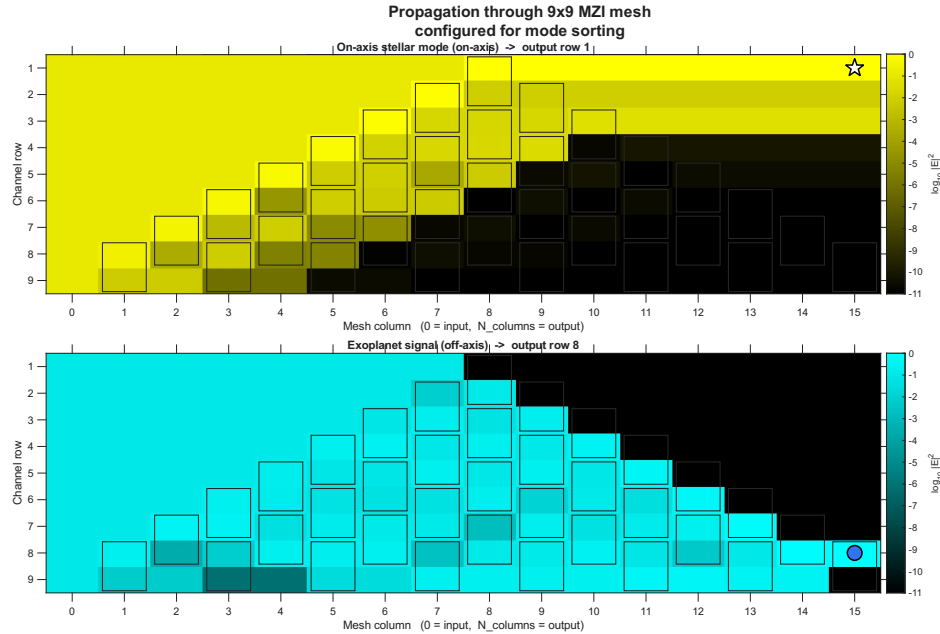


Figure 3: Computer simulation of electric-field propagation through a Gen-1 chip with 9 spatial input channel programmable MZI mesh ($N = 9$) for two operating configurations. The rows correspond to the 9 input waveguides with a uniform input on the left-hand side input across, and output after passing through the mesh on the right-hand side. Rectangles represent the 2x2 individual MZI building blocks of the triangular mesh with input light on the left hand side of the MZI element and output ports shown inside the rectangular element. In the top configuration, the on-axis (and near-on-axis) starlight field is spatially sorted into 3 constituent modes ($K = 3$) and concentrated into the top 3 bright output rows. In the bottom configuration, the same voltage settings are maintained on the MZI mesh but an off-axis exoplanet field propagates through a different modal path and exits primarily through a separate science channel. This simulation illustrates how the mesh performs coronagraphic operation: spatial sorting of starlight into a set of bright output channels passing through the exoplanet (and if the location is known a priori can be concentrated into a single output mode as shown resulting in improved PSF sharpness)

We configure the MZI mesh by tuning the two phase shifters in each interferometer (see Fig. 1). Actuation can be thermo-optic heaters (our current baseline), MEMS, or electro-optic devices. We assume ideal components, such as perfect phase shifters, lossless couplers, and no back-reflections. Each MZI implements a tunable beam splitter (a 2-input 2-output rotation of the input fields). Phase settings have been to date computed experimentally with a self-configuration algorithm,¹⁷ as a mode-sorting gradient-descent based optimization,⁷ and through linearized wavefront control, as described later in Section 5. The coronagraph's contrast, IWA, and throughput are determined by the number of starlight modes “blocked,” which defines the coronagraph order. These modes

can also be used for a low-order wavefront sensor (LOWFS). Setting the initial voltage settings on the phase shifters to configure the number of bright channels on the coronagraph is similar to selecting a coronagraphic mode on a traditional coronagraph, followed up by additional wavefront control iterations to suppress residual leakage in the dark zone.

On the output side the photonic coronagraph, for current prototypes we are using a fiber array unit or individual fibers to couple into photodetectors for signal readout. Alternatives include an integrated photodetector including potentially an energy-resolving microwave kinetic inductive detector (MKIDs) based detector and spectrometer,²¹ super-conducting nanowire detector (SNSPD).²²

4. GEN-2 TAPEOUT

In this section, we provide an overview of the key design features of the Gen-2 AstroPIC layout, which was recently submitted to a commercial photonic foundry (Applied Nanotools) completing the second cycle tape-out. We expect to receive the photonic coronagraph device in the fall to begin packaging and start a new round of experimentation to demonstrate additional PIC-based coronagraphic capabilities utilizing the additional degrees of freedom enabled by the Gen-2 layout. The overall Gen-2 photonic design consists of several individual chips that will be diced including a series of test structures to inform future designs, the main and a secondary Gen-2 chip.

The main Gen-2 chiplet is a 16-channel coronagraph photonic chip that is 28.5 x 14.5 mm in dimension; it uses a 16 spatial channel input with a 4x4 grating coupler array (compatible with either a microlens element or 3D-printed microlenses) and 15-diagonal full triangular MZI mesh featuring 120 MZIs (corresponding to 240 individually actuatable thermal phase shifters). Relative to Gen-1, the mesh layout uses balanced notch-free MZI cells to minimize bending losses with centered heaters, a more compact path-length-matched routing to improve phase and loss uniformity across channels. On the output side there is a 22-channel FAU-compatible grating array with 20 signal channels plus loopbacks at standard 127 μm pitch, with added optical/thermal isolation trenches, microlens compatibility. Electrical control is provided through 486 total bond pads wirebonded to the carrier PCB, including 315 signal channels for the main mesh and additional active test structures, with ground pads shared by up to three channels per bond pad. The packaging approach is designed to support low-loss optical interfaces, especially at the output FAU-chip interface and the input microlens-chip interface. Bond pads are designed as two staggered rows of Au pads exposed through SiO_2 passivation openings with a 200 μm pitch per row. The wiring from phase shifters to bond pads is routed in a single metal layer using rectilinear river routing, where the bond pads are assigned center-outward, most congested column first.

The secondary Gen-2 AstroPIC chip is a smaller individually diced chiplet with die dimensions of 14.0 mm x 9.3 mm. It includes two 9-channel MZI mesh variants: a wider 127 μm -pitch implementation to mitigate and test the impacts of thermal cross-talk, as well as a more compact curved-directional-coupler implementation intended for achromatizing the bandwidth response for narrowband implementation at a component-level. These meshes will enable direct comparison of routing density, bandwidth dependence on coupler behavior, as well as measurements of loss and control performance. The output of the secondary uses a similar 22-channel FAU-style interface with 20 signal channels (9 per each 9-channel mesh and an additional 2 signal channels for dual MZI test structure) plus 2 loop backs at 127 μm pitch with optical/thermal isolation trenches and additional passive test structures.

In addition, several test structures, utilizing micro-electromechanical system (MEMS) phase shifters instead of thermal phase shifters, are taped out. MEMS phase shifters here are specially designed to fit the foundry process with 220 nm-thick silicon-on-insulator wafers and minimize the phase-dependent loss. The MEMS test structures are intended to evaluate whether MEMS phase shifters can eliminate thermal crosstalk for better contrast, simplify the circuitry so that all phase shifters can have a common ground, and potentially provide faster control (e.g., MHz) for the optimization process. A small 4-input-channel programmable MZI mesh was designed to compare the performance against thermal-phase-shifter-based 4-input meshes.

Table 1: Summary of theoretical simulations of Gen-1 vs Gen-2 photonic coronagraph chips degrees of freedom, and suppression capabilities enabled.

Parameter	Gen-1 ($N=9$)	Gen-2 ($N=16$)
Input/output channels	9	16
Triangular-mesh MZIs, $N(N-1)/2$	36	120
Control DOF ($2 \times$ MZIs)	72	240
Deepest contrast, 1% band	$\sim 10^{-11}$	$\sim 10^{-15}$
Max simultaneous deep dark channels	up to ~ 6	up to ~ 13

5. CAPABILITIES ENABLED BY EXPANDED PHOTONIC MESH

The AstroPIC Gen-2 chip grows the programmable Mach-Zehnder interferometer (MZI) mesh from 9 to 16 input channels, raising the number of independently controllable phase shifters (i.e., “actuators,” growing the control degrees of freedom, DOF) from 72 to 240 which represents a $3.3\times$ increase. These are summarized in Table 1 with the deepest contrast reported over the mean of 6 suppressed dark channels.

We summarize here a few key capabilities that are enabled by the Gen-2 chip based on numerical simulations of closed-loop wavefront control wrapping a linearized controller similar to electric field conjugation (EFC)²³ around the previously developed mesh simulator:⁷

- **Larger dark zones.** Gen-2 nulls starlight in far more output channels simultaneously. For example, at 3% control bandwidth the Gen-1 ($N=9$) is already degrading at its 6-channel dark nulled ceiling, whereas Gen-2 ($N=16$) holds deep contrast out to 13 dark channels (a regime Gen-1 physically cannot address).
- **Faster convergence.** In cases where a similar number of dark channels is generated, additional degrees of freedom enable faster convergence of the dark zone under similar test conditions.
- **Deeper narrowband contrast.** In general, contrast achieved can be up to ~ 1 -2 orders of magnitude below the Gen-1 for the same dark zone and bandwidth configuration.
- **Improved bandwidth performance.** Additional degrees of freedom enable a wider narrowband across a single MZI mesh

This wavefront control implementation adapts coronagraph EFC to the AstroPIC triangular MZI mesh, using the internal and external phase shifters $u = [\phi; \theta]$ voltage settings to null the on-axis stellar leakage (and potentially additional off-axis modes) in selected dark output channels across one or more wavelength sub-bands. The wavefront control loop performs broadband propagation across the mesh with λ_c/λ phase scaling, building a stacked Jacobian, and applies regularized least-squares updates reporting dark-zone contrast, off-axis throughput, chromatic leakage, actuator quantization, and assessing low-order aberration sensitivity. Convergence can be improved by adopting starting initial voltages obtained from mode-sorting of the starlight (similar to selecting an initial coronagraph and then cleaning up dark zone residuals with a wavefront control loop). These simulations provide the framework for comparing the Gen-1 $N=9$, 72-DOF mesh against the Gen 2 $N=16$, 240-DOF mesh (and potentially future larger simulated DOF cases), to quantify how added control authority improves dark-zone size, broadband contrast floor, convergence, and robustness. As these simulations exclusively consider achievable control state as a function of architecture, wavefront reconstruction from intensity measurements is not yet implemented, and instead monochromatic complex field estimates are assumed to be available at the channel outputs (and which could be directly measured via interferometric measurements).

5.1 Larger, deeper dark zones

The Gen-2 chip is capable of suppressing starlight in many more output channels at once and to greater depth than Gen-1 due to a combination of additional output channels and additional degrees of freedom. Numerical studies have shown that at a fixed 1-3% bandwidth up to 6 dark channels can be suppressed with the Gen-1 chip (with $K = 3$ bright channel configuration).

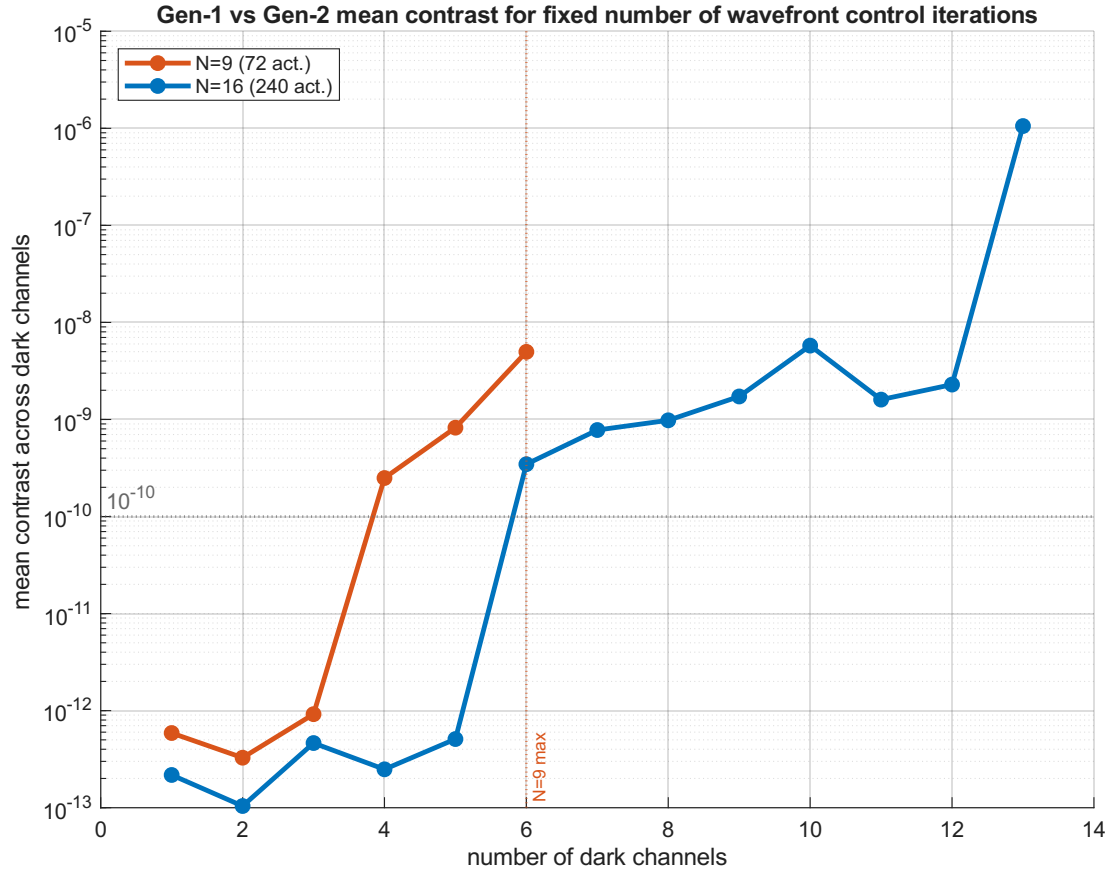


Figure 4: Mean contrast after 200 wavefront-control iterations for both Gen-1 and Gen-2 AstroPIC mesh configurations. Contrast is evaluated across an increasing number of dark output channels at a narrowband configuration of 3%. The Gen-2 (N=16), 240-actuator mesh maintains deep contrast over both a larger dark-channel space than the Gen-1 (N=9), 72-actuator mesh.

Meanwhile, the Gen-2 chip enables contrast at or below $1\text{e-}9$ for many additional channels out to 13 dark channels (as a note the Gen-1 chip is physically limited up to about 6 channels, as a 2nd order coronagraph with only piston suppression not robust enough to operate on a non-ideal point source). Thus, the Gen-2 chip's additional degrees of freedom enable both a larger (more output channels) and deeper contrast levels than the Gen-1 chip.

5.2 Faster convergence

Additional DOFs available to the Gen-2 chip can enable wavefront control to more quickly converge to a deeper contrast solution. For this numerical evaluation, we run wavefront control for 100 iterations for a 3% bandwidth across the mesh while suppressing 4 dark channels for both Gen-1 (N = 9) and Gen-2 (N = 16) chips as well as for a chip with N = 36 representing additional degrees of freedom. The initial setting corresponds to a mode-sorted configuration that routes on-axis starlight toward the bright output channels, which speeds up convergence compared to a randomized 0-V initial state (and matches the operational concept of operation in the photonic testbed). Increasing the DOFs available results in both faster convergence and deeper contrast achieved in the output channels – at 3% bandwidth the mean contrast across 4 suppressed channels for N = 9 (Gen-1 chip) stalls near $4.4\text{e-}9$ while the Gen-2 chip is able to converge more quickly to $7.0\text{e-}11$ mean contrast for the same number of output channels, while a larger chip with N = 36 reaches an even deeper contrast of $1.1\text{e-}12$ exceeding the $1\text{e-}10$ contrast goal within a small number of iterations (approximately 30 wavefront control iterations, or 3x faster than the N = 16 case).

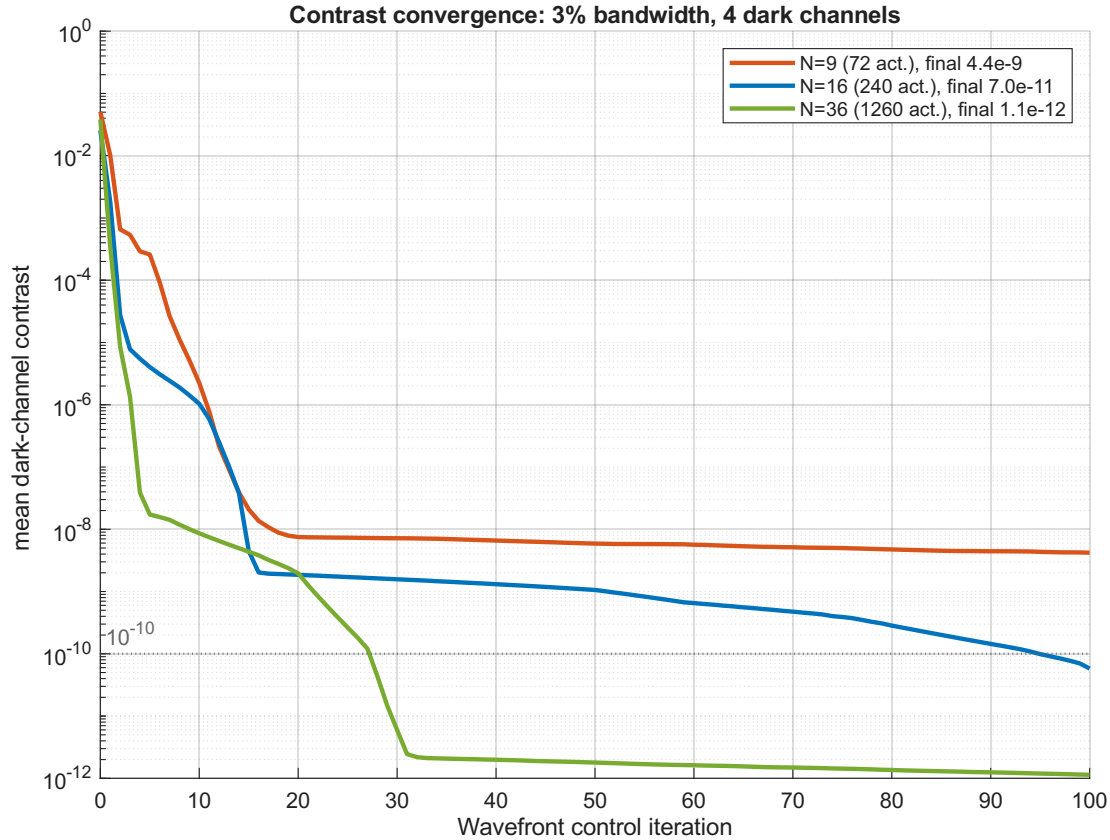


Figure 5: Mean dark-channel contrast convergence for wavefront control over a 3% bandwidth with four dark channels. Increasing the mesh degrees of freedom noticeably improves both convergence speed and final achievable contrast: the 9-channel mesh with 72 actuators stalls near $4.4\text{e-}9$, while the 16-channel mesh with 240 actuators reaches $7.0\text{e-}11$. With 36 channels and 1260 actuators, the controller converges below $1\text{e-}10$ in roughly 30 iterations and reaches a final contrast of $1.1\text{e-}12$, demonstrating the benefit of additional controllable modes.

Figure 5 shows this numerical simulation and that adding mesh degrees of freedom gives the wavefront control algorithm an improved correction space, enabling both faster suppression of dark-channel leakage and a much lower final contrast floor.

5.3 Improved bandwidth performance

Potentially the tallest pole for a photonic-based coronagraph is demonstrating improved bandwidth across a single mesh; this would reduce the requirement for number of multiplexed PICs needed for covering a larger spectral bandwidth. The bandwidth challenge arises (similarly as for a deformable mirror with a traditional coronagraph) due to path difference as a phase setting applied at the central wavelength scales as λ_c/λ for other wavelengths. Initial measurements from the Gen-1 chip show that a monochromatic solution therefore degrades quickly with increased bandwidth.¹¹ A finite set of controlled actuators can suppress the output dark channels exactly at specified control wavelengths but in-between and beyond the residual leakage establishes a chromatic floor. Expanding the field about the band center with sufficient DOFs can improve the chromatic performance and expand the bandwidth coverage possible on a single mesh. On-chip wavefront-control based broadband optimization is covered in detail and more thoroughly in our companion paper¹² which uses a conjugate gradient descent method and can establish more robust solutions.

Here we have setup a numerical experiment running the linearized wavefront-control loop starting from a 3% narrowband performing a deep search on regularization parameters and then progressively reducing the bandwidth down to monochromatic and continuing from the previous solution on an ideal mesh for both the

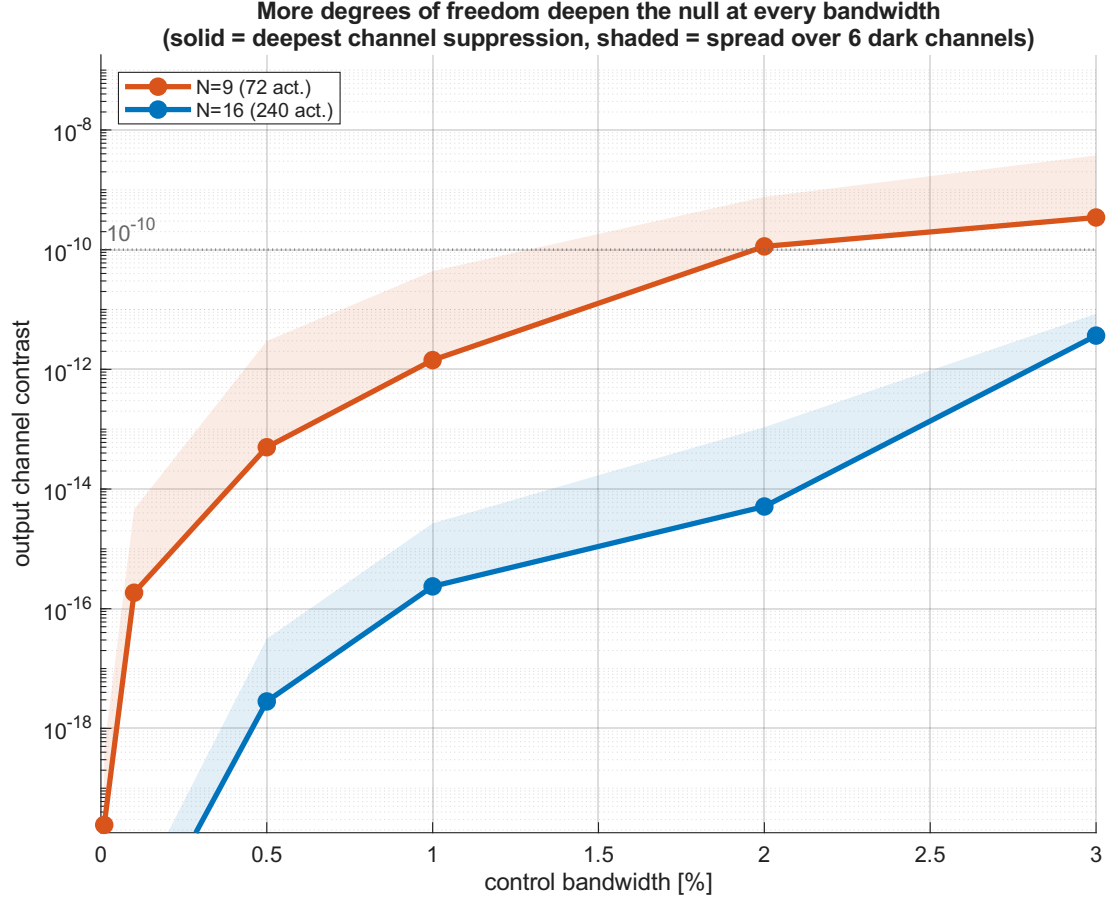


Figure 6: Comparison of control bandwidth ranging from monochromatic to a 3% bandwidth with six dark channels and an ideal mesh, showing the deepest achieved null in a single channel (solid line) and the spread in contrast over all channels for both the Gen-1 chip ($N = 9$) and the Gen-2 chip ($N = 16$). Increasing the mesh degrees of freedom results in contrast improvements both for the deepest achieved contrast in a single output channel and contrast across all 6 output channels for the Gen-2 chip.

Gen-1 ($N = 9$) and the Gen-2 ($N = 16$) chips, and in both cases suppressing 6 dark channels. The results of this numerical experiment are shown in Figure 6; here we report in a solid line the deepest channel suppressed at the end of each run as well as in shaded the contrast obtained across the 6 dark channels. Both the deepest contrast and the output channel contrast spread is improved for usage of the Gen-2 chip ($N = 16$) due to the increase in DOFs available.

5.4 DAC resolution limits for control

As part of the numerical study identifying performance limits for the Gen-2 chip, we investigated the contrast floor imposed by finite digital-to-analog converter (DAC) resolution. We assume a 0–10 V control range corresponding to a 2π phase stroke for each phase shifter. For an N_{DAC} -bit DAC, the phase increment is $\Delta\phi = \frac{2\pi}{2^{N_{\text{DAC}}}}$, and using a conservative full-step phase-error estimate, the corresponding quantization-limited leakage scales as

$$C_{\text{max}} \sim \left(\frac{2\pi}{2^{N_{\text{DAC}}}} \right)^2.$$

Thus, each additional DAC bit improves the quantization-limited contrast by approximately a factor of four, and adding two DAC bits improves it by approximately a factor of 16. This expression should be interpreted as a conservative scaling estimate; a half-LSB or RMS quantization-error model would reduce the prefactor but preserve the same $2^{-2N_{\text{DAC}}}$ dependence.

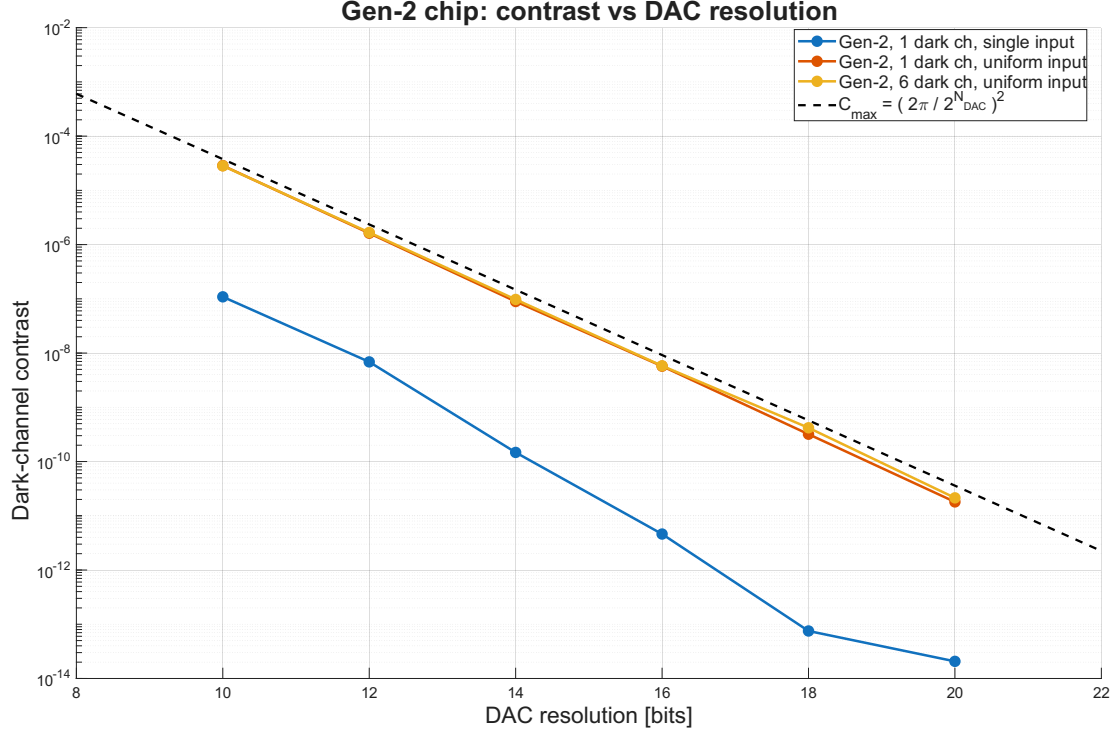


Figure 7: Predicted dark-channel contrast for the Gen-2 chip as a function of DAC resolution for a single input with one dark channel (blue), a uniform input with one dark channel (orange), and a uniform input with six dark channels (gold). Markers show numerical optimization results with quantized actuator commands. The black dashed curve shows the conservative analytical scaling estimate of contrast due to the DAC ($C_{\max} = (2\pi/2^{N_{\text{DAC}}})^2$).

We have adopted this quantization framework to verify the conservative analytical estimate above as shown in Figure 7; a uniform-input wavefront control simulation in monochromatic 1.55 μm light across the mesh reaches approximately 3×10^{-5} contrast at 10 bits and 4×10^{-10} contrast at 18 bits needing 20-bits to reach 2×10^{-11} and thus better than the 1×10^{-10} goal. We have compared here uniform input representative of a free-space coupling scenario with both a single and 6 dark channel outputs, suggesting that expanding the controlled dark region has a modest effective DAC-resolution requirement. We note, however, that model-aware quantization limits (as opposed to quantizing the voltage after computing the optimal voltage as in the current approach) could potentially improve the achieved contrast limits beyond the conservative analytical estimate.

The single-input case is less sensitive to DAC quantization, reaching approximately 10^{-10} contrast at 14 bits. Therefore, a 16-bit DAC is sufficient for the single-input operating mode and is consistent with the deep single-input contrast demonstrated on the AstroPIC photonic testbed.⁴ For the uniform-input free-space-coupled case, however, the simulations indicate that a 16-bit controller is expected to limit contrast near $\sim 2 \times 10^{-9}$, while approximately 20 bits are required to reach the 10^{-10} level.

6. CONCLUSIONS

In this paper, we provided an overview on the continuing progress on technology development for the AstroPIC photonic coronagraph. Beyond recent papers covering the recent experimental progress and yields for the photonic coronagraph, we have summarized the updates on the recent Gen-2 chip tapeout. We have demonstrated through numerical wavefront control simulations expected benefits of increasing the number of degrees of freedom by a factor of 3.3x. These include generating both larger and deeper dark zones that span more output channels, improved wavefront control convergence, and establishing the DAC resolution limits required for free-space coupling operation at the 1×10^{-9} level (16-bit) and 1×10^{-10} level (20-bit).

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