

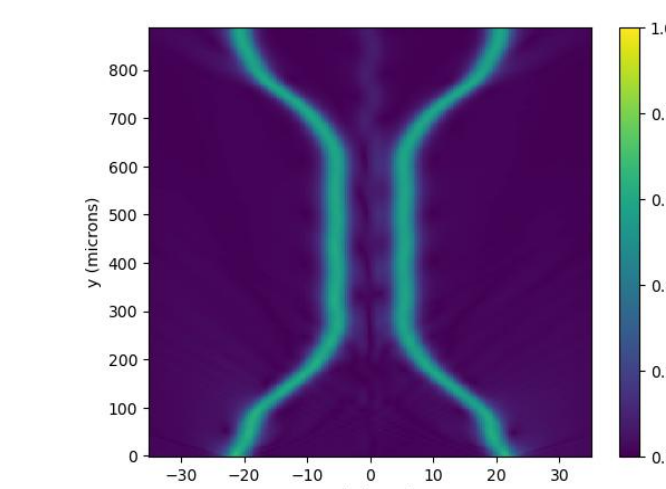
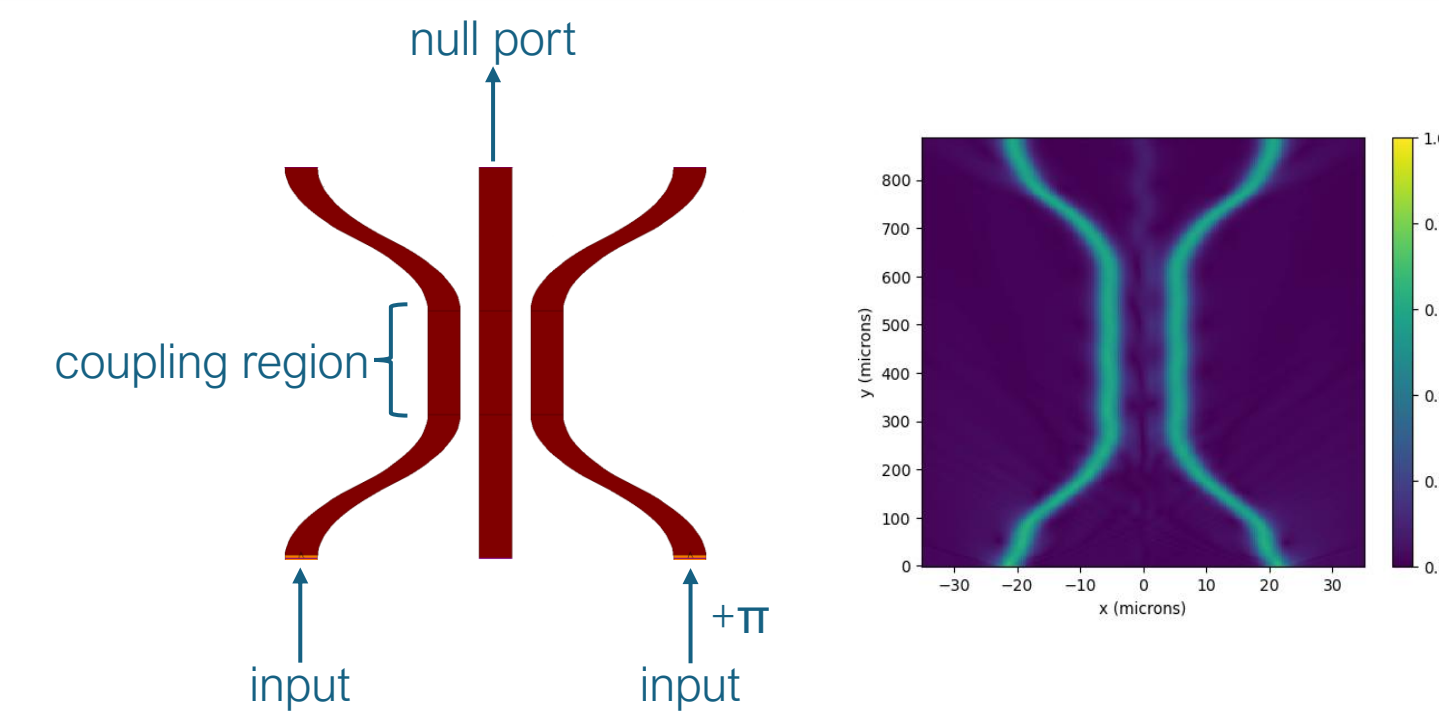
Tricouplers for nulling with photonic integrated circuits

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MOTIVATION

- Exoplanets near the snow line (peak of giant planet occurrence) or habitable zone are observationally elusive
 - Low transit probability, low RV signal, too close to host star for direct imaging with traditional coronagraphs (IWA $\sim 2 \lambda/D$)
- Long-baseline nulling interferometry performs starlight suppression at high spatial resolution, enabling direct detection for demographics, orbital dynamics, and atmospheric spectroscopic characterization
 - Beam combination and phasing are technologically challenging to control, especially with bulk optics
- Photonic integrated circuits are a promising platform for performing optical operations needed for interferometry, i.e. beam combination and phasing
 - Photonics allow full electric field control as light propagates within a waveguide via total internal reflection
 - Miniaturized footprint facilitates scalable fabrication and finer control than fibers
 - Integrated platform minimizes wavefront errors from misalignment or thermal/mechanical perturbations
 - Successfully demonstrated on-sky for beam combination with *GLINT* on *GRAVITY+VLTI* (Spalding et al. 2024)

PHYSICS OF TRICOUPLERS

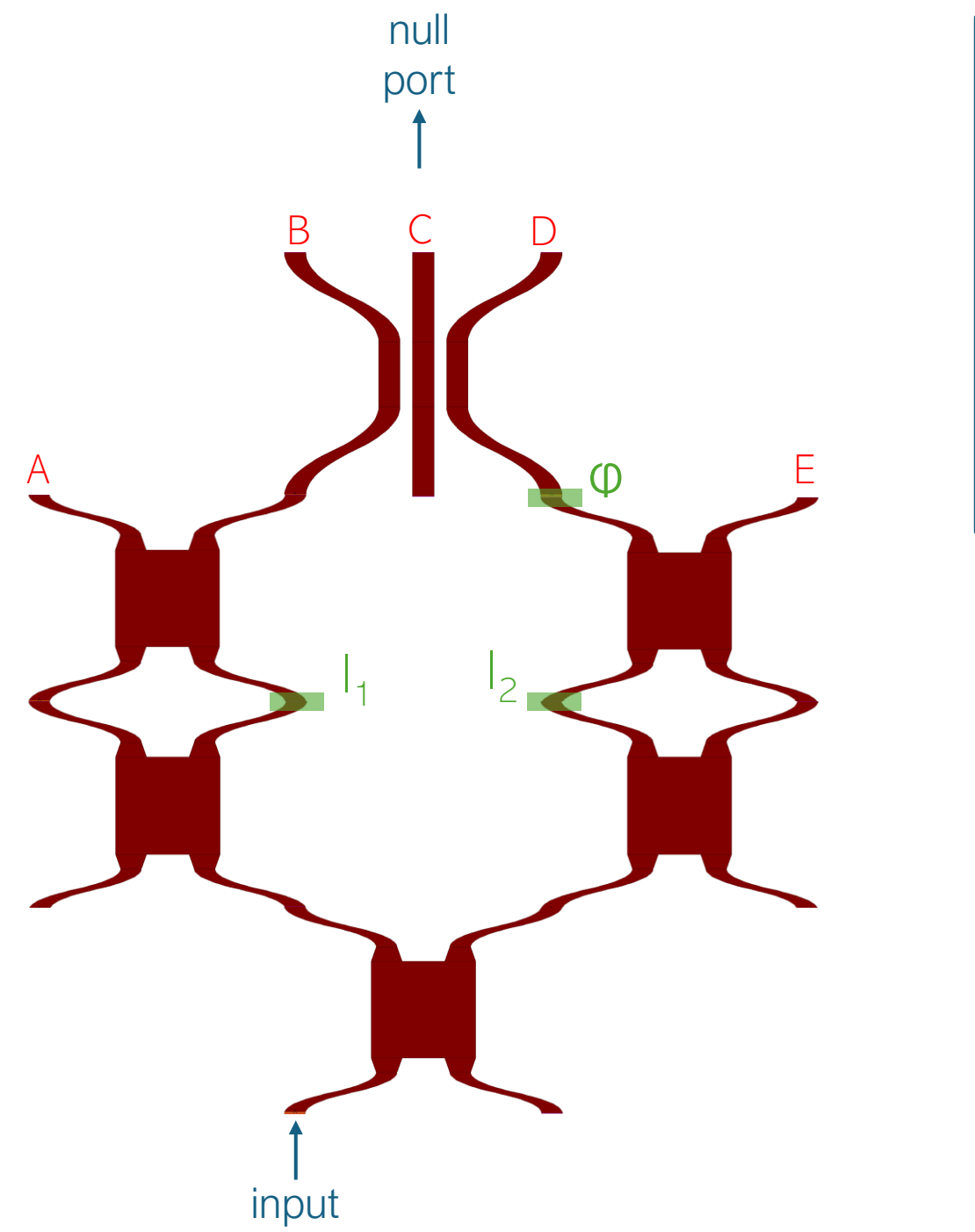


(Left) Schematic of tricoupler. (Right) Beam propagation through a tricoupler. When the inputs are intensity-matched and offset in phase by π , light coupled in the central port is nulled.

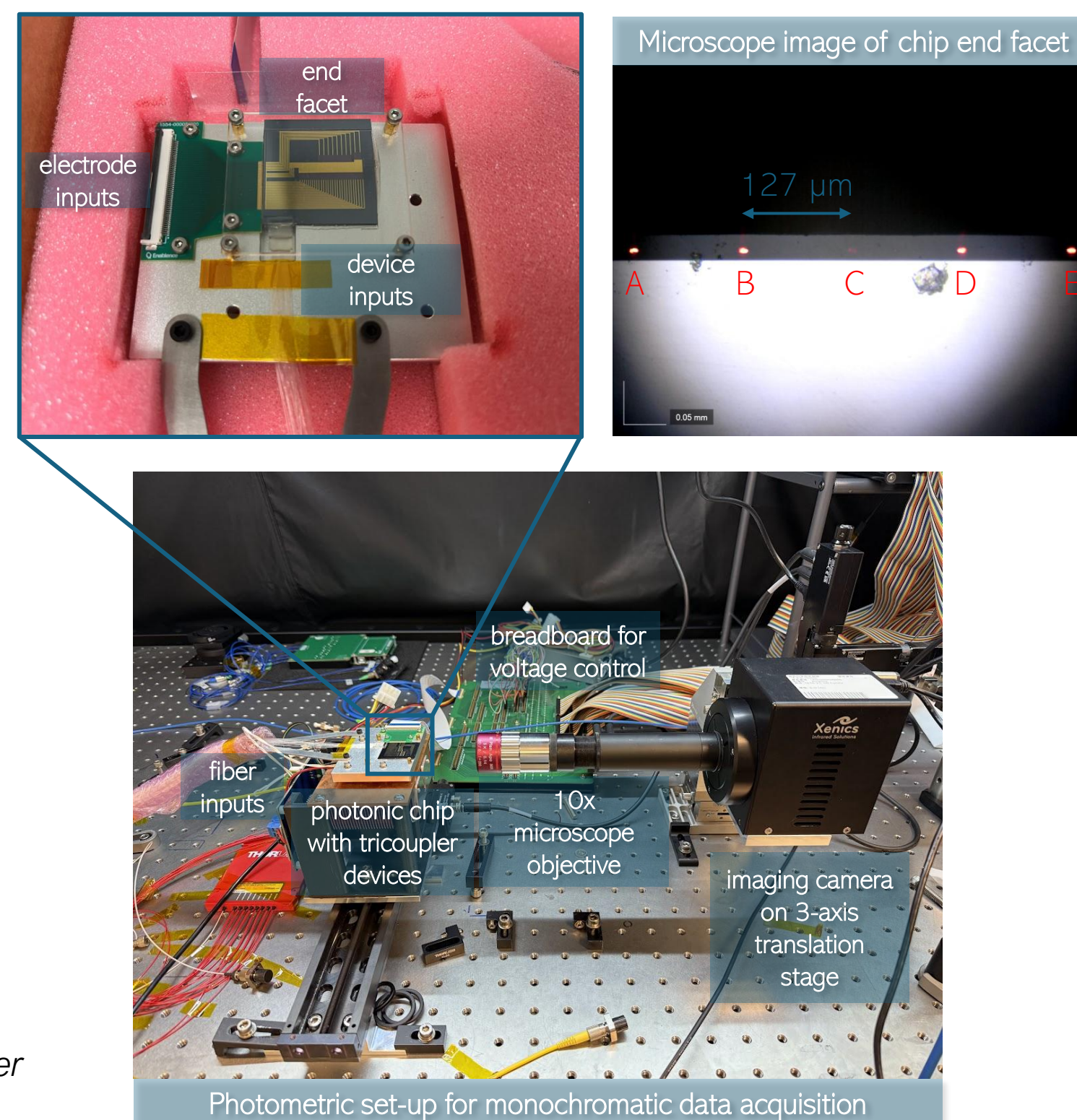
- Coherent light is injected in the two outer ports \rightarrow evanescently couples and interferes in central port
- π phase offset between the two inputs produces an achromatic null in the central port
 - When starlight is nulled, exoplanet throughput is maximized at $0.5 \lambda/D$

EXPERIMENTAL SET-UP

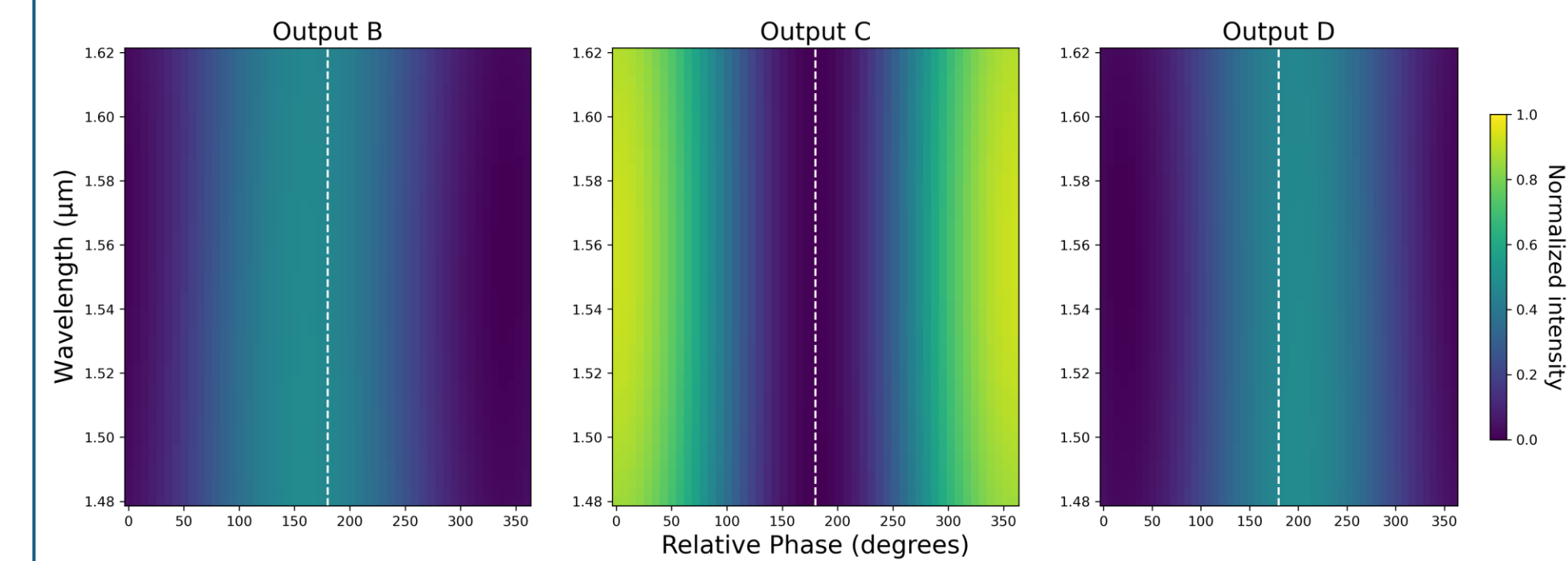
- We are testing tricouplers on a silica-on-silicon platform for nulling in the H-band
- Results presented are for a single input device with:
 - An initial splitter
 - A Mach-Zender interferometer for each arm with voltage control for intensity matching (I_1 and I_2)
 - Voltage control on one input to the tricoupler for phase modulation (ϕ)
- Metrics of interest
 - Dynamic range: null depth and exoplanet light throughput
 - Chromaticity
 - Stability
- Laboratory characterization can identify sources of null degradation such as:
 - Scattered light leaked from waveguides
 - Polarization contamination
 - Manufacturing imperfections



(Center) Schematic of on-chip single input tricoupler device. (Right) Photos of the chip and testbed.



EXPECTATIONS



Output intensities normalized to injected light at different input phase offsets (ϕ) and wavelengths for an ideal tricoupler simulated with RSoft BeamPROP.

- Simulated null depth: -33.19 dB (4.8×10^{-4})
- Null in the central port of the tricoupler (output C) is achromatic, i.e. null occurs at an input phase offset of 180° across the full simulated bandpass
- Exoplanet light throughput is maximized at $0.5 \lambda/D$ (phase = 0°), ranging from 85.5% – 92% between $1.48 - 1.62 \mu\text{m}$.

LABORATORY TESTING

MONOCHROMATIC

- Deepest measured null at $1.59 \mu\text{m}$: -36.5 dB (2.2×10^{-4})
 - Close agreement with simulation
- Measured null is highly sensitive to voltages applied to intensity modulators I_1 and I_2
 - Null depth depends on splitting ratio of light directed to tricoupler vs. dump ports (A and E)
- Measured null is relatively insensitive to voltage applied to phase modulator ϕ
- Imaging reveals hard edges, preliminarily suggesting light is possibly scattered and reflecting within the different layers of the chip
 - This interpretation remains to be robustly validated

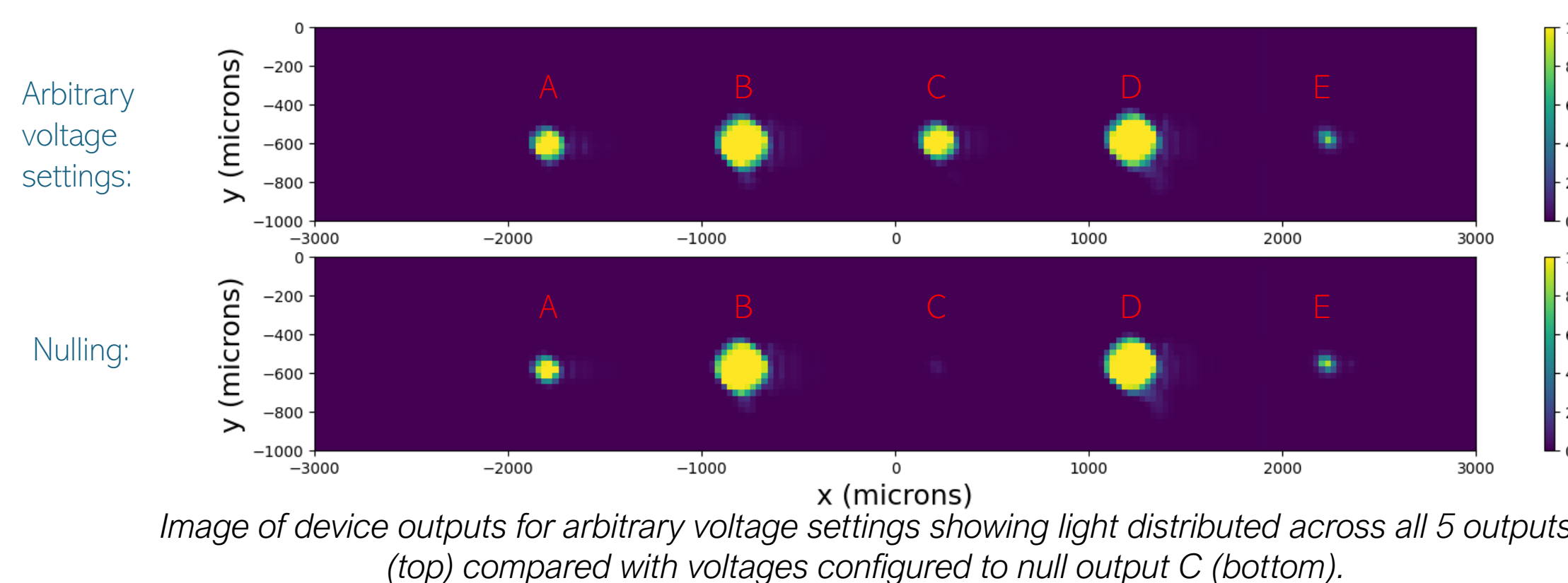
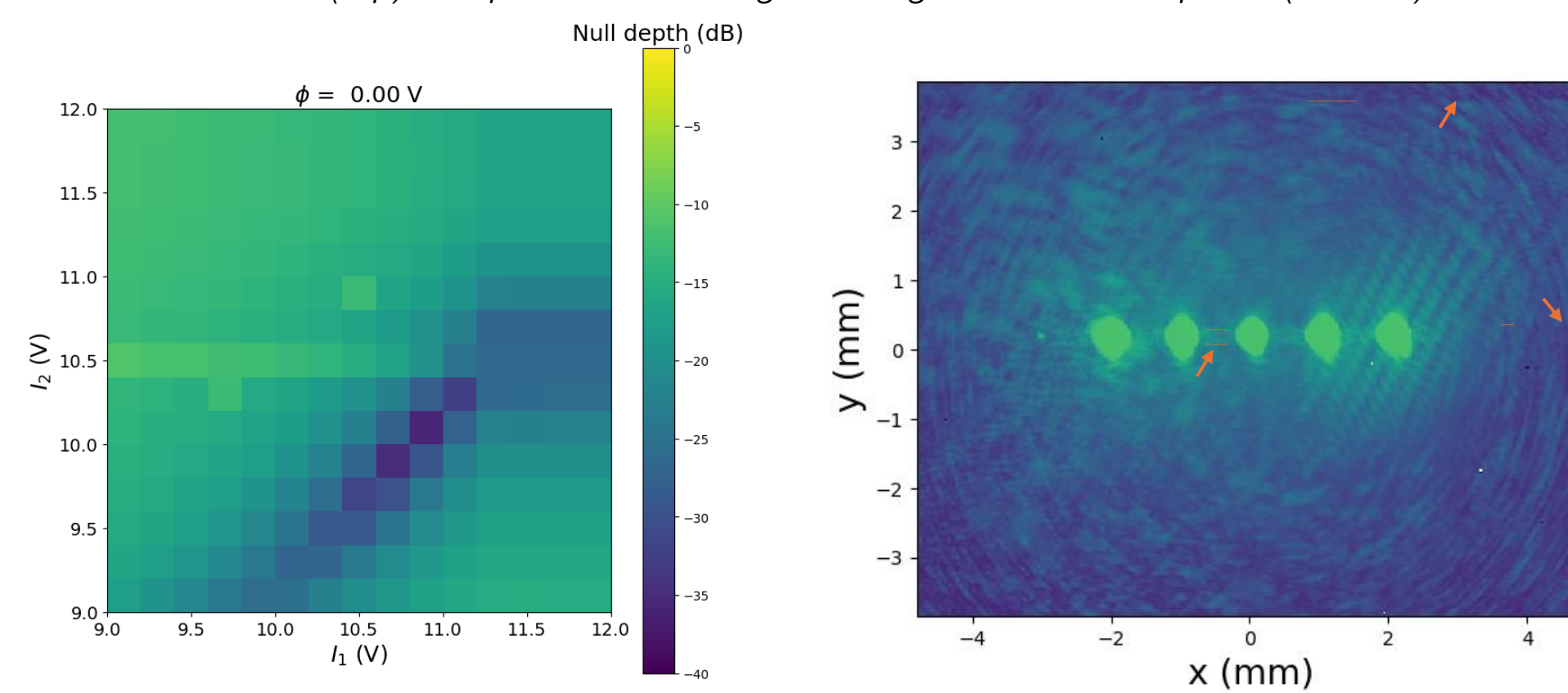


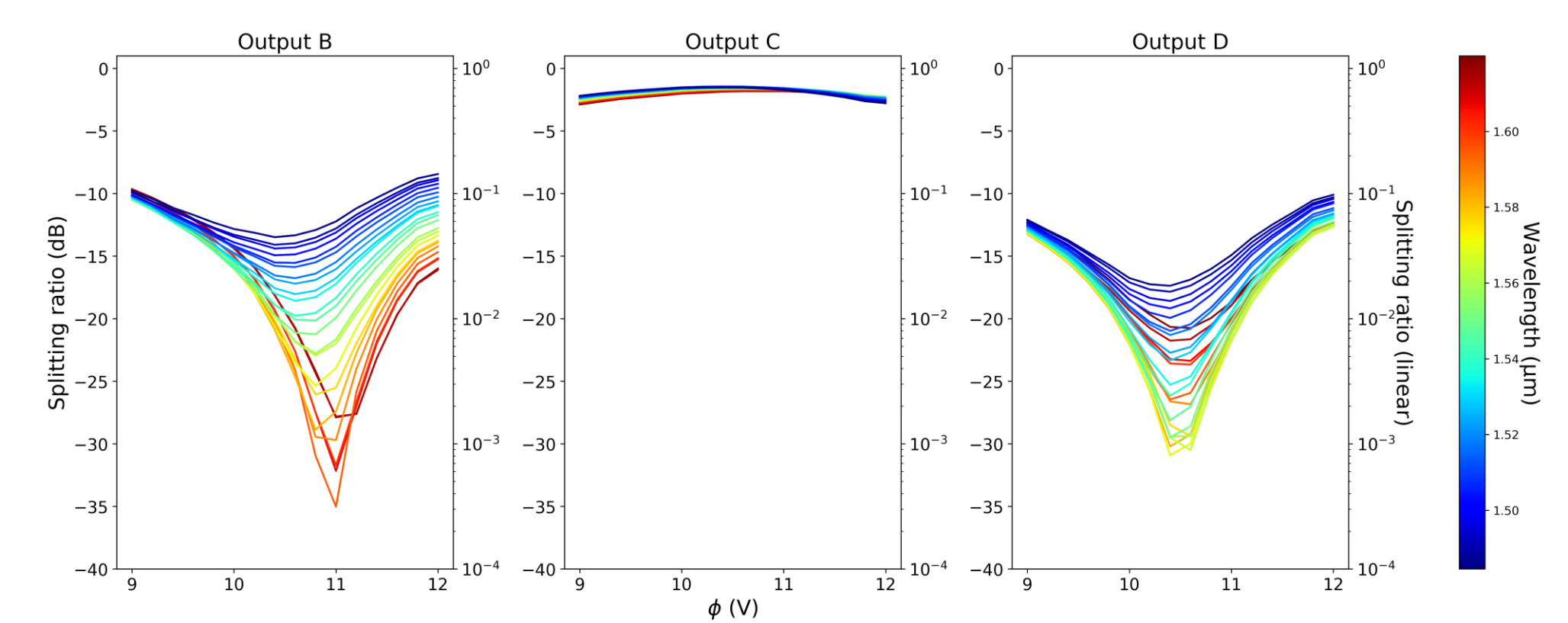
Image of device outputs for arbitrary voltage settings showing light distributed across all 5 outputs (top) compared with voltages configured to null output C (bottom).



(Left) Null depth at different voltage settings for intensity modulators I_1 and I_2 with ϕ fixed at 0.0 V. Such contour maps show little variation when ϕ is modulated up to 2 V. (Right) Image taken with the outputs oversaturated to look for scattered light from chip, e.g. hard edges bracketed by orange dashed lines.

POLYCHROMATIC

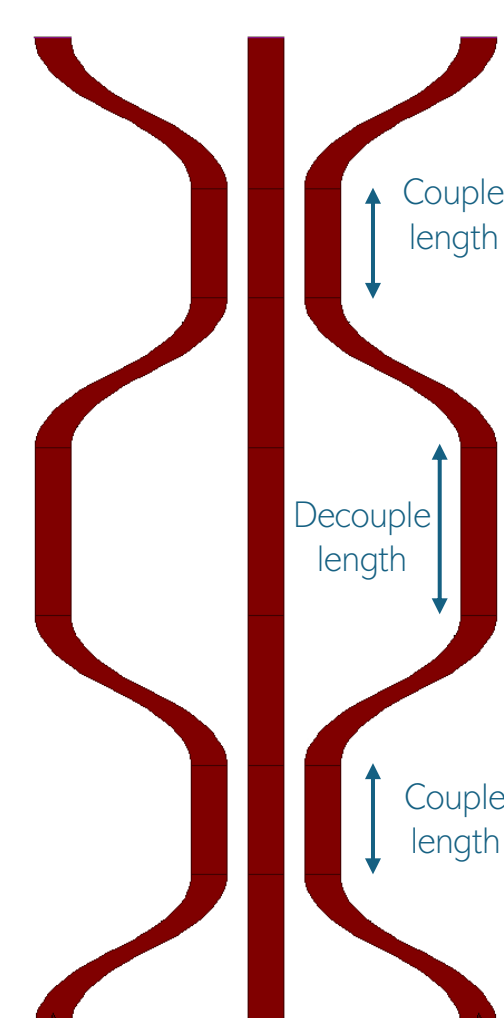
- Polychromatic spectra from each output present a dynamic range ($\sim 30-35$ dB) consistent with the monochromatic null depth
- Nulls of outputs B and D show more chromatic variation than simulations of an ideal tricoupler \rightarrow voltage modulation induces a wavelength-dependent phase offset
 - Consistent with expectations; applying a voltage heats the waveguide, inducing a phase delay by altering the effective index in a manner dependent on wavelength and temperature.
- Chromaticity of null in output C remains to be characterized



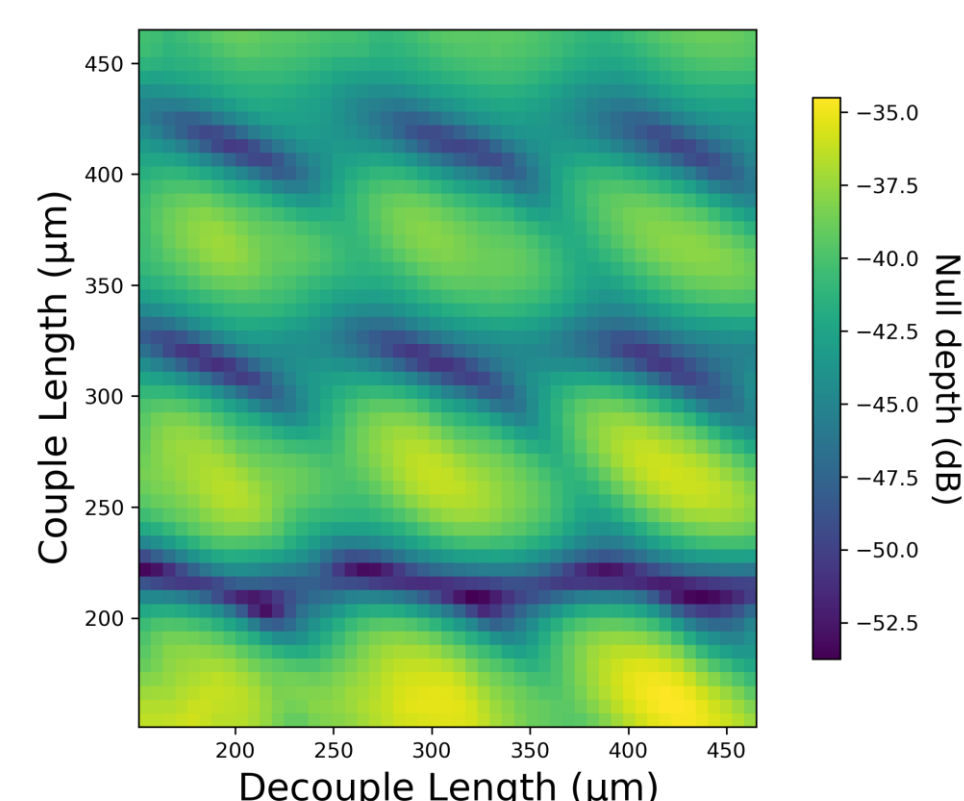
Chromaticity of the light splitting ratio across the tricoupler outputs as ϕ is modulated.

NEXT STEPS

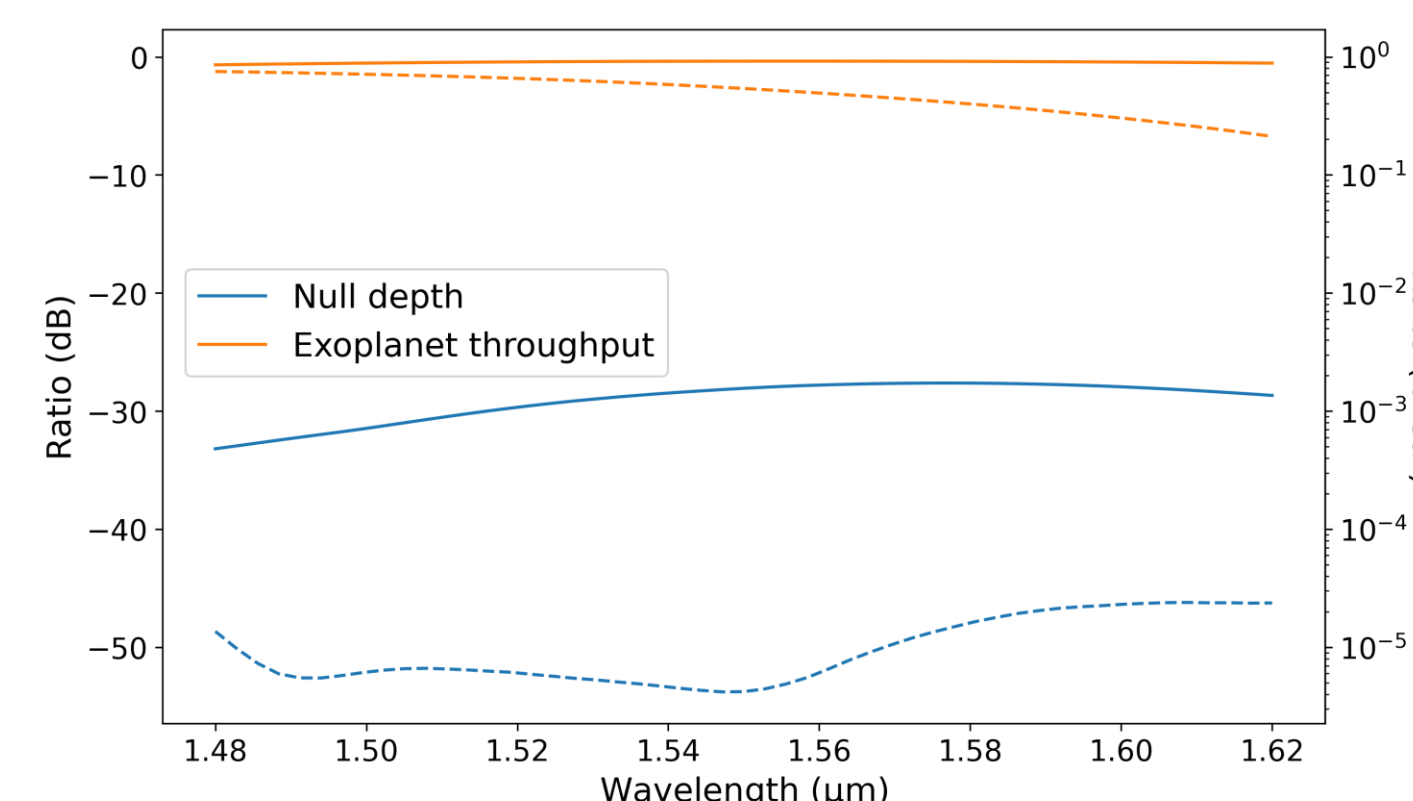
- We are exploring novel tricoupler architectures and conducting parameter searches to optimize for broadband nulling, exoplanet throughput, wavefront sensing
- Our models will inform tricoupler designs for our next batch of devices



Schematic of a cascaded tricoupler.



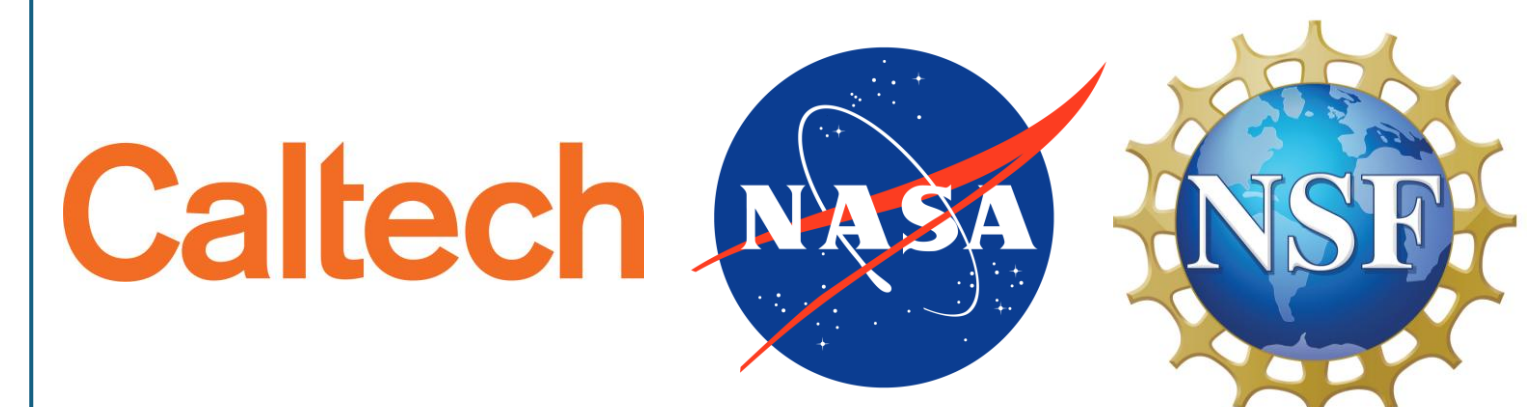
Simulated null depth for different combinations of couple and decouple lengths.



Chromaticity of null depth and exoplanet throughput for a classical tricoupler (solid curves) and a cascaded tricoupler (dashed curves).

- Cascaded tricouplers can achieve deeper nulls at the expense of reduced exoplanet light throughput

ACKNOWLEDGEMENTS



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