Laboratory Demonstration of the PIAA/Binary-Mask Hybrid Coronagraph

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The PIAA (phase-induced amplitude apodization, Guyon 2003) coronagraph uses two mirrors to realize the apodization needed for high contrast imaging for extrasolar planet searches. It achieves a very high throughput and a very small inner working angle (IWA) simultaneously, without being affected too much by resolved stellar disks or telescope tip-tilt errors. However, the PIAA designed to give high contrast by itself would suffer from optics shapes that are difficult to polish, as well as the reduced bandwidth because of chromatic diffraction. Both these problems can be simultaneously solved by adopting a hybrid PIAA design (Pluzhnik et al. 2006), where the apodization created by the two-mirror system is made moderate combining a classical apodizer with PIAA apodization. We report here the implementation of a hybrid PIAA system with properly designed binary apodization masks, and show in the laboratory that such a combination is a robust approach to high contrast imaging. Thanks to thermal stabilization and mechanical isolation of the whole PIAA optics, the image drift on the final focus is kept quite small (～ a few pixels in 1-2 hours). Under this stability, standard speckle nulling technique successfully killed broad speckles in half the image plane, and the contrast reached 6.5 ×10^(-7) at a separation of ～1.5 λ/D.

PIAA (Phase-Induced Amplitude Apodization, Guyon 2003)

- The PIAA produces an apodized beam from a non-apodized beam using a two-mirror system without losing light.

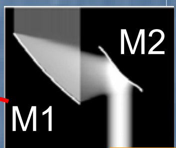
→ Very high throughput

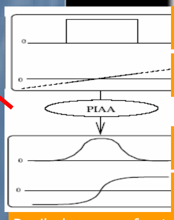
- Phase slope for an off-axis wave front is amplified through PIAA.

→ Small inner working angle

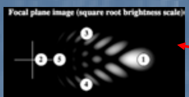
(IWA, smallest angular separation where planets can be detected)

‥‥ ～1/3-1/4 of that from classical apodization

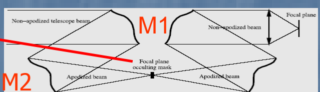




Pupil-plane wavefront before/after PIAA



Off-axis source image



Off-axis planet images are distorted due to the phase slope amplification. They can be restored by putting an "inverse PIAA" after the starlight is removed behind a focal-plane mask.

Difficulty in a Pure PIAA Coronagraph

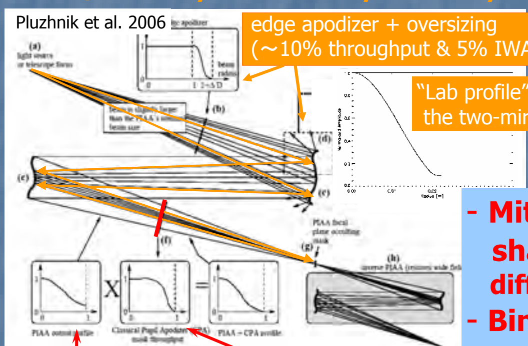
(Pluzhnik et al. 2006)

- The PIAA designed to give a 10^(-10) contrast in visible (targeting exo-earths) by itself suffers from:

1. Mirror shapes that are difficult to polish
2. Diffraction effects (difference between Fourier/geometrical optics and true propagation)

→ Chromatic effect → **Reduced bandwidth**

PIAA/Binary-Mask Hybrid System



Pupil amplitude after a two-mirror system

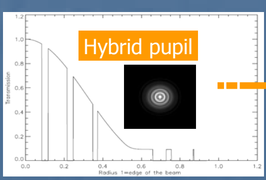
Additional apodizer (binary mask) for an "ideal" apodization

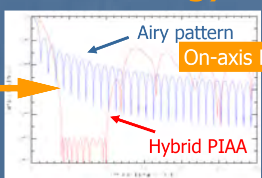
Advantages

- **Mitigates mirror shapes (and therefore diffraction effects).**
- **Binary masks are easier to manufacture and highly achromatic.**

Binary Mask Design (Concentric Ring)

Optimized using LOQO (Vanderbei 1999)

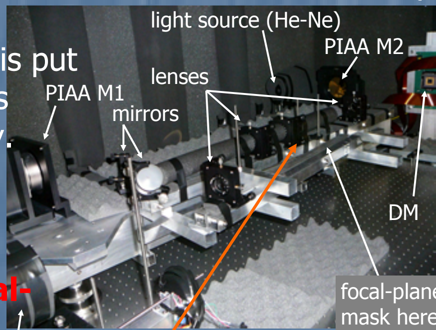


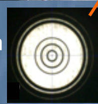


Design IWA=4/3.5 ～1.2λ/D、
Total throughput ～ 75 %

Laboratory Set-up

- PIAA/Binary-mask hybrid optics designed at Subaru
- All the elements (source, mirrors, lenses, DM, camera) are attached to the PIAA bench and thermally well-isolated.
- The whole PIAA unit is put on air-pressure mounts for mechanical stability.
- **Lyot stop is put to block the light diffracted outside the pupil by the focal-plane mask (see below).**



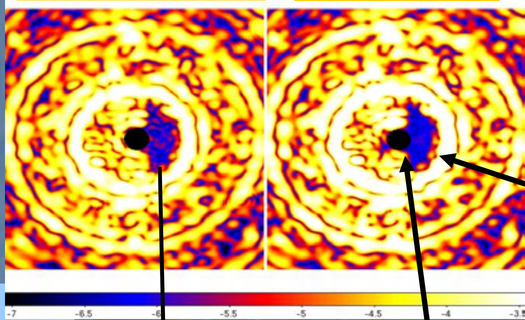


binary mask manufactured on an ARC Quartz plate (ϕ = 5.93 mm)

Wavefront Control by a 32×32 MEMS DM

- Zernike modes are scanned for low-order correction.
- Employs speckle nulling to kill individual speckles in the dark hole (half the image plane).

Latest Results (log images)

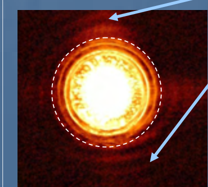


Model PSF

Average contrast 6.5×10^(-7) in the dark hole

Separation ～ 1.5 λ/D

Without a Lyot stop, contrast is limited by fine speckles that the DM cannot kill. They come from outside the pupil (shown as dashed circle).



Pupil-plane intensity after focal-plane mask (log scale).

Image Stability

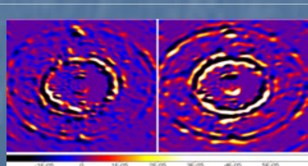


Image differences within 1 hr (left) and 2 hrs (right), shown in contrast

Images are so stable (physical drift is a few pixels) that the change in dark hole contrast when DM is frozen for 2 hours is only a few times 10^(-7).