Experimental Demonstration of a Quantum-Optimal Direct Imaging Coronagraph

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Abstract: We implement a direct imaging coronagraph that rejects all light from an on-axis star using a double-pass spatial mode sorter. Our experimental setup can precisely localize exoplanets below the diffraction limit at 1000:1 star-planet contrast.

1. Introduction

Discovering exoplanets via direct-imaging is fundamentally limited by the extreme brightness contrast between an exoplanet and its host star. Recently, we theoretically demonstrated [1] that exclusively rejecting the fundamental mode of a telescope prior to imaging yields a quantum-optimal measurement for detecting and localizing an exoplanet. Conceptually, this approach enhances shot-noise limited sensitivity to exoplanet signatures by discarding all light emitted by an on-axis star whilst maximizing throughput for an off-axis exoplanet. In this work, we develop an experimental demonstration of the quantum-optimal direct imaging coronagraph shown in Fig. 1(a) which employs two cascaded spatial mode sorters to: (1) optically null the fundamental mode, and (2) reconstitute the field for a direct imaging measurement. Using this system, we are able to localize synthetic exoplanets below the diffraction limit at $10^3 : 1$ star-planet brightness contrast.

2. Experimental Coronagraph Design and Measurement Model

Our experimental setup depicted in Fig. 1(b) consists of a multi-plane light conversion (MPLC) spatial mode sorter [2] retrofitted with polarization elements that enable path splitting between forward-propagating and backward-propagating beams. On the forward pass, the mode sorter spatially demultiplexes the incident optical field into a subset of Zernike modes $\{\psi_0, \psi_1, \psi_2, \psi_3\}$ which collectively couple most of the light emitted by a vertically-displaced point-source (i.e. the planet) in the sub-Rayleigh range $y/\sigma \in [-1, 1]$, where σ is the Rayleigh resolution limit. Light in each mode focuses to a well-separated spot on an intermediate sorting plane, which coincides with the surface of a pinhole mirror. The fundamental mode ψ_0, containing all light from on-axis star, is directed to the opening of the pinhole mirror and absorbed at a beam dump. The remaining modes reflect off the pinhole mirror and propagate backward through the mode sorter. The unitary nature of spatial mode sorting ensures that the backward pass inverts the Zernike basis transformation. Through this process, the field at the detector matches the field at the focal plane, but with the fundamental mode removed.

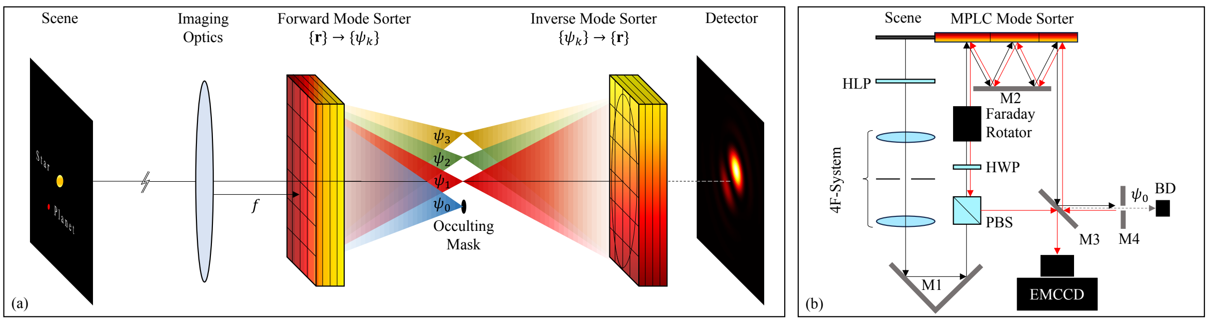

Fig. 1. **(a)** Conceptual design for a quantum-optimal direct-imaging coronagraph implemented with two cascaded spatial mode sorters. **(b)** Experimental setup for the quantum-optimal coronagraph implemented by double-passing the field through a Zernike mode sorter.

When imaging a single point-source located at position y on the vertical axis, the number of photons (intensity) measured at each pixel of the detector is modeled as a random vector $\mathbf{X}(y) \in \mathbb{R}^M$. We invoke a theoretically and empirically-driven probability distribution for the measurement described by,

$$\mathbf{X}(y) \sim \text{Poiss}(\lambda_0 \mathbf{p}(y) + \mathbf{s} + \lambda_D \mathbf{1}) \tag{1}$$

where λ_0 is the photon flux at the system pupil generated by the point source, $\mathbf{s} \in \mathbb{R}^M$ is a constant structured background flux caused by imperfections in our experimental setup, λ_D is the dark count rate of the detector operating at room temperature, and $\mathbf{p}(y) \in \mathbb{R}^M$ is the non-normalized photon arrival probability distribution over the detector pixels given by: $\mathbf{p}(y) = |\Psi \Omega^\dagger C \Omega \mathbf{z}(y)|^2$. Here $\mathbf{z}(y) \in \mathbb{C}^4$ is a vector of expansion coefficients for the field at the focal plane in the subset of experimentally sorted Zernike modes. We have also introduced several system matrices: $\Psi \in \mathbb{C}^{M\times 4}$ is a truncated change-of-basis matrix whose columns are the vectorized Zernike modes, $C \in \mathbb{C}^{4\times 4}$ is the diagonal coronagraph matrix responsible for nulling the fundamental mode, and $\Omega \in \mathbb{C}^{4\times 4}$ is the Hermitian cross-talk matrix of the mode sorter. The system-specific parameters $\mathbf{s}$, λ_D, and Ω are characterized empirically. A measurement model of a star-planet system $\mathbf{Y} = \mathbf{X}_s + \mathbf{X}_e$ is constructed by adding multiple measurement realizations of equal integration time T for different source locations such that $\mathbf{X}_s = \sum_{k=1}^{N_s=10^3} \mathbf{X}_k(0)$ and $\mathbf{X}_e = \mathbf{X}(y_e)$. Thus the star-planet measurement model is given by,

$$\mathbf{Y} \sim \text{Poiss}\left(N\lambda_0 \left[(1-b)\mathbf{p}(0) + b\mathbf{p}(y_e) \right] + N\big(\mathbf{s} + \lambda_D \mathbf{1}\big) \right) \tag{2}$$

where $N = N_s + 1$ is the total number of integrated images and $b = 1/N$ is the relative brightness of the exoplanet to the star.

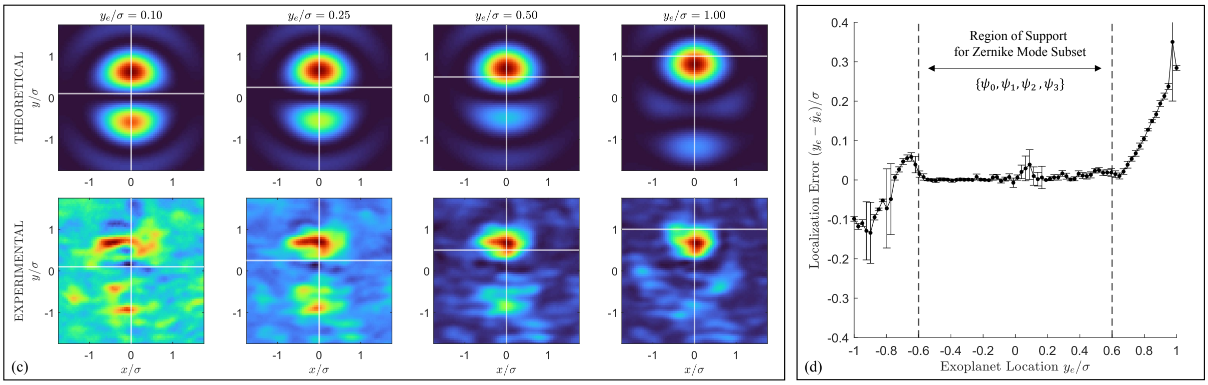

Fig. 2. **(c)** Theoretical (top) and experimental (bottom) direct-imaging measurements for different off-axis exoplanet locations (designated by white crosshairs). Structured background and detector dark click rates have been subtracted from the experimental images. **(d)** Localization error of the maximum likelihood estimator $\hat{y}_e$ plotted against the true exoplanet location y_e. Larger errors arise for $|y_e|/\sigma \gtrsim 0.6$ where the exoplanet excites modes beyond the truncated Zernike mode basis.

3. Results

We collect and synthesize 100 experimental measurements of a star-exoplanet system at $10^3 : 1$ contrast for 80 equally-spaced exoplanet positions in the range $y_e/\sigma \in [-1, 1]$. For each measurement, we numerically calculate the maximum-likelihood estimator for the exoplanet position $\hat{y}_e$. Fig. 2(d) depicts the mean localization error as a function of an exoplanet displacement from the on-axis star. We observe near-perfect exoplanet localization with high precision (low estimator variance) at sub-Rayleigh displacements $|y_e|/\sigma \lesssim 0.6$. Outside of this regime, the systematic localization error grows as light from the exoplanet couples to higher-order modes beyond the support of the truncated Zernike mode basis considered in our experimental setup. Extending the basis to include higher order modes would ameliorate systematic error at the cost of higher system complexity. Our experimental results constitute a proof-of-principle for quantum-optimal direct-imaging coronagraphs implemented with spatial mode sorters. Such systems may provide a new modality for discovering Earth-like exoplanets hidden below the diffraction limit of space-based telescopes.

References

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2. I. Ozer, M. R. Grace, and S. Guha, “Reconfigurable spatial-mode sorter for super-resolution imaging,” in *Conference on Lasers and Electro-Optics,* (Optica Publishing Group, 2022), p. JTh3A.28.