Imager Based on Integrated Photonics

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Outline

• Size scaling of conventional imaging systems

• Alternative interferometric imaging approach
  – Van Cittert-Zernike theorem
  – Michelson stellar interferometry

• Miniaturization using integrated photonics

• Proof-of-concept demonstration

• Design principles
  – Field of view
  – Spatial resolution
  – Spectral sampling

• Next generation design & future concepts

• Summary
Scaling of Conventional Optics

- System length $L$ scales with aperture diameter $D \rightarrow$ volume scales with $D^3$
- In many applications, system volume is either minimized or constrained to fit within a predefined envelope
- A variety of approaches have been proposed for thin form-factor systems
- This talk describes a concept based on interferometric imaging
Van Cittert-Zernike Theorem

- The mutual intensity function is related to the source intensity distribution through a Fourier transform relationship [Goodman, *Statistical Optics*]

\[
J(x_1, y_1; x_2, y_2) = \frac{\kappa e^{-i\psi}}{(\lambda z)^2} \iint I(\xi, \eta) \exp \left[ i \frac{2\pi}{\lambda z} (\Delta x \xi + \Delta y \eta) \right] d\xi d\eta
\]
Michelson Stellar Interferometry

- Reconstruct an image of a source from measurements of the mutual intensity function

(1920) Michelson & Pease used a 20 ft interferometer on the Hooker Telescope to measure the diameter of Betelgeuse (α Orionis) by finding the interferometer baseline corresponding to the first null of the mutual intensity function.

Astronomical Interferometers

Facilities like the Navy Precision Optical Interferometer can achieve $B > 400$ m baselines.

Measurements at baseline $B$ yield a radial segment of Fourier data covering angular spatial frequencies:

$$\frac{B}{\lambda_{\text{max}}} \leq \rho \leq \frac{B}{\lambda_{\text{min}}}$$

Cutoff frequency of an individual telescope:

$$\rho_0 = \frac{D}{\lambda_{\text{min}}}$$

Beam Combiner

Interference Fringes

Vacuum Delay Line

Telescope 1

Baseline $B$

Telescope 2

Spectral Band

$\lambda = \lambda_{\text{min}} - \lambda_{\text{max}}$

Star/Galaxy
SPIDER Concept

- Replace traditional telescope with dense interferometer array
- Goal is to eventually create meter-class effective apertures with system thickness of only a few centimeters

Conventional Telescope

Thin Form-Factor Imager

- Lenslets collect light
- Array of 1D interferometers
- Interference measurements made using photonics

SPIDER = Segmented Planar Imaging Detector for Electro-optical Reconnaissance
Miniaturization Using Photonics

• Integrated photonics design for proof-of-concept demonstration

![Diagram showing miniaturization using photonics with 4 lenslets, 5 input waveguides for each lenslet, 3 spectral channels for each waveguide, 60 output waveguides, and linear detector array with matched path lengths.](image)
Fabrication/Testing

Layout

Photonic Integrated Circuit (PIC)

PIC in Testbed

Linear Detector Array

Phase Shifting Electrical Interface

Lenslets
Fringe Data

• Measure
  – Dark/background signal level
  – Light throughput from individual lenslets
  – Interference fringes (using phase shifters to scan through fringes)

• Raw data is converted into normalized fringe signals (amplitude ≤ 1)
  – Normalized fringe amplitude = amplitude of complex coherence factor $\mu$

\[
\mu(x_1, y_1; x_2, y_2) = \frac{J(x_1, y_1; x_2, y_2)}{\sqrt{I(x_1, y_1) I(x_2, y_2)}}
\]
Simple Object

- Used a variable-width slit aperture as a simple test object
  - Two interferometer baselines only yield two spatial frequency measurements
  - If we collect data for different slit widths, the coherence estimates should follow the distribution of a sinc function (the Fourier transform of a rect)

- Experimental results agreed well with theory
Design Principles - FOV

• PIC waveguide coupling determines the imaging field-of-view
  – Input coupling efficiency varies with field angle
  – Assume lenslet f-number is matched to waveguide numerical aperture
  – Angular field-of-view $\theta$ is determined by diffraction angle

• Field-of-view can be reduced by lenslet alignment/pointing errors
  – Lenslets need to collect lights from the same area of source

$\theta = 2.44 \frac{\lambda}{d}$

$d = \text{lenslet diameter}$

“Antenna lobes” need to overlap in the far-field

Multiple input waveguides can be used to create a wide-FOV mosaic image
Spatial Resolution

- Lenslets are paired up to form interferometer baselines of length $B$
  - Measurements for baseline $B$ correspond to object spatial frequency $\rho = B/\lambda$
  - Image resolution is set by the cutoff spatial frequency
    \[
    \rho_{\text{max}} = \frac{B_{\text{max}}}{\lambda_{\text{min}}}
    \]
- Effective aperture size $D_{\text{eff}}$ is equal to the longest interferometer baseline $B_{\text{max}}$
Spectral Sampling

- Light from each lenslet is separated into various spectral channels before being combined.

- Nyquist sample spacing $\delta \rho$ is determined by the image FOV:

$$\delta \rho = \frac{1}{\theta} = \frac{d}{2.44\lambda}$$

- Fractional optical bandwidth of each spectral channel needs to satisfy Nyquist criterion:

$$\frac{B}{\lambda} - \frac{B}{\lambda + \delta \lambda} \leq \delta \rho \quad \Rightarrow \quad \frac{\delta \lambda}{\lambda} \leq \frac{d}{2.44B}$$

$$\frac{d}{2B_{\text{max}}} \approx \frac{1}{\text{image pixel width}}$$
Next Generation Design

- Near IR wavelengths $\lambda = 1.25-1.55 \ \mu m$
- More compact PIC (Silicon Nitride)
- Similar baseline (22 mm)
- More baselines (13) & more spectral channels (12)
- Continuous radial Fourier sampling
Miniature Camera Concept

Monolithic 3D PIC fabrication

20 mm wide

>10x better resolution than iPhone5 camera
Space Telescope Concept

- 4 inches thick
- 36 inches wide
Summary

SPIDER = Segmented Planar Imaging Detector for Electro-optical Reconnaissance

• Thin form-factor computational imager
• Based on long baseline interferometry and photonics
• Successful proof-of-concept experimental demonstration
• Design principles well understood
• Working towards future concepts

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