Multi-Spectral and Low-Mass Photonic Integrated Interferometric Telescopes

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In collaboration with

Lockheed Martin Advanced Technology Center, Palo Alto, CA, 94304 USA
1990 STS-31 Mission (Shuttle Discovery)
Future Imaging Systems with Low SWaP

Key to Affordability – Low SWaP

Orders of Magnitude SWaP Reduction Achievable

Example: MRO HIRISE
0.5 m aperture
0.7m x 1.4m
64.2 kg

Conventional Telescope and focal plane

Estimate
0.5m x 0.5 m
~ 30kg

SPIDER Ring Blade Design: Outer ring enhances resolution of conventional telescope

Estimate
0.75m x 0.1 m
~ 6kg

SPIDER Radial Blade Design: Full sensor replaces conventional telescope

Estimate
0.25m x 0.01 m
~ 0.6kg

SPIDER Single Chip Design

Link to review article on emerging large scale silicon photonics / CMOS integration for optical system applications
http://www.osa-opn.org/home/articles/volume_24/september_2013/features/the_road_to_affordable,_large-scale_silicon_photon/

SPIDER: segmented planar imaging detector for electro-optical reconnaissance
Basic Idea--Young’s Two-Slit Experiment in PICs

Figure Courtesy of Andreas Glindemann
Lenslets couple light into PIC waveguides

Interferometric beam combination performed on PIC

Arrayed Waveguide Grating

Mach-Zehnder Interferometers

Interferometer baseline

Estimate coherence function from intensity data

Image reconstruction

Photonic circuits are used to create a dense imaging interferometer
### Objectives
- Planar “flat panel” telescope with NO large optics
- Large field of view with NO precision gimbals for line of sight steering

### Concept Description
- Light input by large area lenslet array “wired” into interferometer channels using nanophotonics (leverages commercial high density optical interconnect 3D computer chip technology)
- Scalable to larger apertures using fiber coupling of multiple interferometer chips

Linear arrays of lenslets arranged in spoke-like pattern to fill $u,v$ (Fourier) imaging plane.
SPIDER with PICs

- **Lenslet Array**
  - 150 lenses
  - 1mm diameter
  - f/10

- **Waveguides**
  - 10 µm channels
  - 24 x 24 per lens

- **Single field point, Single wavelength Phase & Amplitude**

- **Balanced four-quadrature receiver**

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**“Experimental demonstration of interferometric imaging using photonic integrated circuits”, Tiejun Su, Ryan P. Scott, Chad Ogden, Samuel T. Thurman, Richard L. Kendrick, Alan Duncan, Runxiang Yu, and S. J. B. Yoo, Optics Express, 2017.”**

**“Photonic integrated circuit-based imaging system for SPIDER”, Katherine Badham, Richard L. Kendrick, Danielle Wuchenic, Chad Ogden, Guy Chiriq, Alan Duncan, Samuel T. Thurman, S. J. B. Yoo, Tiejun Su, Wei-Cheng Lai, Jason Hein, Wei-Chun Liao, Guanyao Liu, OSF Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR), 2017.”**


1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band)

5 Waveguide Inputs for Each Lenslet

From Lenslet +2

Demux

To Demux

Matched Pathlengths

From Lenslet -2

Phase Shifter 2×2

60 Outputs

Developed under NASA NIAC Phase I & II DARPA TTO SeeMe
1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band) Layout

DARPA funded work

6/19/19

9/
Imaging with Photonic Integrated Circuits
Unclassified

1st Gen SPIDER PIC

Figure: 1st Gen SPIDER PIC setup with labeled components: Linear Detector Array, PIC, Lenslets, Relay Optics, Turning Mirror, To DUT, and Extended Scene Generator. The figure also includes a DARPA SeeMe funded work citation.
For a given input port, the power is first split into three wavelength channels through the two stage MZIs; Then it’s split half by 2x2 MMIs.

Figure a): the three wavelength channels from the first 2x2 MMI output branches.

Figure b): the three wavelength channels from the second 2x2 MMI output branches.

*Slight color distortion and slight misbalance observed, but the PIC expected to work*
(a) Visibility magnitude of a variable width slit for both 5 mm and 20 mm baselines.

(b) The visibility phase of a variable width slit for baseline width $B = 20$ mm.

(c) The visibility phase of a variable width slit for baseline width $B = 5$ mm.
**2nd Gen SPIDER Concept Design – Interferometry**

### 2D Interferometer Array

- **Scene light**
- **Lenslets couple light into PIC waveguides**
- **Interferometric beam combination on PIC**
- **Output waveguides with fringe information imaged onto detector**

#### Planar Photonic Integrated Circuit (PIC)

- **Interferometer Baseline**
- **Electrodes for adjusting interferometer OPD**
- **2x2 Beam Combiner**
- **Arrayed Waveguide Grating (AWG)** disperses light among narrowband spectral channels
- **FOV** = \[ \frac{2.44 \lambda}{d_{lenslet}} \]

**Observe interference of light collected for each baseline and spectral channel**

**Coherence function estimate from fringe intensity data**

**Image reconstruction**

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37 Blade SPIDER concept

NEXT GENERATION NETWORKING SYSTEMS LABORATORY

6/19/19

Imaging with Photonic Integrated Circuits
Unclassified
Spectrometer Design for the 2nd Gen SPIDER: 18 Ch (3.3THz) Arrayed Waveguide Gratings

Symmetric Dual Arm Design for Interfacing with Mach-Zehnder Interferometer

\[ \lambda_1 = 1223 \text{ nm} \rightarrow \lambda_{18} = 1586 \text{ nm} \]

<table>
<thead>
<tr>
<th>WL (nm)</th>
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<tbody>
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Towards Detectors

From MMI

North Set Input

South Set Input
2nd Gen SPIDER Photonic Integrated Circuit Design
12 baselines, 18 spectral bins, multi-layer Si$_3$N$_4$/SiO$_2$ PICs

Path length matching WGs

Demux

Interferometer

Heater

MMI

AWG

Detectors

Lenslets

Linear Detector Array
**Multilayer 150nm/50nm/150nm Si₃N₄ PIC Platform for the new SPIDER PIIT Design**

- Low propagation loss
- Edge coupling
- Small crossing loss
- Gap = bottom gap + upper gap

(a) Input mode
(b) Side view of Intensity Distribution
(c) Output mode

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SiN Arrayed Waveguide Gratings

16 channel X 50 GHz AWG

6.787 mm

Bending

Star Coupler

150μm

10μm
**Arrayed Waveguide Gratings – Fabricated Device Transmitted Spectrum Measurements**

- **16 ch X100 GHz AWG**
  - Insertion loss: 1.7 dB
  - Crosstalk: -21 dB

- **16 ch X50 GHz AWG**
  - Insertion loss: 1.8 dB
  - Crosstalk: -20 dB

- **16 ch X25 GHz AWG**
  - Insertion loss: 2.7 dB
  - Crosstalk: -13 dB

- **16 ch 3.3 THz spacing AWGs**

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**Table: AWG Wavelengths**

<table>
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<th>λ (nm)</th>
<th>Output</th>
<th>λ (nm)</th>
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<td>18</td>
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</table>
2nd Gen SPIDER PIC (12 baseline, 18 spectral bin) fabricated w/ CMOS Compatible Process @ UC Davis
Imaging Reconstruction Experiments – Results

Imaging Setup

- Scene on rotation mount
- Light source
- Bar target
- Train scene
- M1, M2, M3, M4
- OAP1, OAP2
- Projector
- Fringe Measurement
- Focal Plane Sensor (FSM)
- Lenslets
- PIC
- Detector

Chrome-on-glass mask

Object Image

Simulated Image

Reconstructed Image

After iterative reconstruction

Fringe Measurement

- Baseline 3
- Baseline 9
- Baseline 12

Intensity (counts)

Frames #

Provided by Lockheed Martin
Multi-resolution 2\textsuperscript{ND} Gen SPIDER PIC

- Number of Lenslets: 150, 144, 134, 100, 88
- Lenslet Array: 150 lenses, 1mm diameter, f/10
- Waveguides: 10 µm channels, 24 x 24 per lens
- Single field point, single wavelength, phase & amplitude

Balanced four-quadrature receiver

\[ (S_i + S_j), (S_i - S_j), (S_i - jS_j), (S_i + jS_j) \]

\[ I(t), Q(t) \]

50:50
2nd Gen SPIDER PIIT integration

Wafer-Scale Fabrication
(24 dies on 150 mm diameter silicon wafer; 96 dies on 300 mm silicon wafer)

Systems Integration with ~37 SPIDER PICs into SPIDER PIIT (Photonic Integrated Interferometric Telescope)
Enhancing Density and Functionality by Introducing Double-Stripe Waveguide Platform

To overcome the large bending radius problem of ultra-low loss Si$_3$N$_4$ waveguide platform
3D Integrated Photonics by Ultrafast Laser Inscription

3D waveguides output pattern

output facet view
Summary

- Potential reduction in Size, Weight, Power at ~100x
- Reduced cost in manufacturing using nanophotonic components and integrated circuits
- Potential to replace complex optical telescope / focal plane sensors with a “printed” sensor on a chip, substantially reducing schedule and size, weight, & power requirements
- Enables low cost space situational awareness and persistent surveillance missions that require large constellations of EO imaging sensors
- Compact and distributed sensor element geometries provide flexibility to accommodate a broad range of spacecraft and airborne platforms