A New Method of Imaging: Photonic Integrated Interferometric Telescopes (PIITS)  
Multi-Spectral, Low-Mass, High-Resolution Integrated Photonic Land Imaging Technology  

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Multi-Spectral, Low-Mass, High-Resolution Integrated Photonic Land Imaging Technology
NASA Grant #NNX16AP60G; PI: S.J. Ben Yoo, UC Davis

Objective

• Design, fabrication and testing of an electro-optical (EO) imaging sensor concept that provides a low mass, low-volume alternative to the traditional bulky optical telescope and focal plane detector array
• Scalability and Feasibility studies for future SLI applications
• Assessment and TRL demonstration of PIC technologies for SLI.

Approach:

• Conventional approach for imaging interferometers requires complex mechanical delay lines to form the interference fringes resulting in designs that are not traceable to more than a few simultaneous spatial frequency measurements
• SPIDER achieves this traceability by employing micron scale optical waveguides and nanophotonic structures fabricated on a silicon PIC with micron scale packing density to form the necessary interferometers.

Collaborators: Drs. Alan Duncan & Rick Kendrick (Lockheed Martin)

Key Milestones

- M1: Complete an SNR model for SPIDER (1/31/2017)
- M2: Multi-layer PIC design for SPIDER-SLIT complete (5/31/2017)
- M3: 10 channel spectrometer PIC successful operation. (9/30/2017)
- M4: Multi-layer PIC fabrication complete. (11/30/2017)
- M5: Multi-layer PIC achieves fringe generations on > 8 baseline, > 10 spectral bin, 1x5 waveguide input array. (4/30/2018)
- M6: Achieve image reconstruction and simulations. (6/30/2018)
- M7: Multi-layer PIC achieves fringe generations on > 10 baseline, > 10 spectral bin, 2x5 waveguide input array. (1/15/2019)
- M8: Complete scalability and feasibility assessment on SLI missions. (3/31/2019)
- M9: Conduct feasibility and design studies SWIR1 SWIR2 Thermal1 & Thermal2 (4/30/2019)
- M10: Conduct radiation effect experiments and TRL5 (7/30/2019)
- M11: Complete a SPIDER spectrometer conceptual tradeoff (8/31/2019)
- Multiple photonic layer: TRL_{in} = 3 \Rightarrow TRL_{out} = 5
Motivation

Conventional imaging system’s (i.e. telescope) SWaP

1) Aperture Size: ~2.4m in diameter
2) Volume: ~ 5m³
3) Weight: ~500kg
4) Power: ~ 500W

Hubble Telescope

IKONOS satellite

Segmented planar imaging detector for EO reconnaissance (SPIDER)

1) Based on multi-baseline interferometric imaging
2) Reduce SWaP by the factor of 10~100
Basic Idea--Young’s Two-Slit Experiment

- Light source at infinity at $\alpha = 0$
- Intensity pattern $\sim 1+\cos$ as a function of $\alpha$
  period length: $\lambda/B$
- OPD $> $ coherence length
  $\Rightarrow$ fringes disappear
- Light source at angle $\alpha_0$
  $\Rightarrow$ fringe pattern shifts accordingly

(First and last picture of a movie)

Figure Courtesy of Andreas Glindemann
**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
SPIDER PIIT Approach

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

Waveguides
- 10 \(\mu\)m channels
- 24 x 24 per lens

Single field point, Single wavelength
Phase & Amplitude

Spectrally Resolved High Resolution Interferometric Telescope
Our Previous SPIDER Photonic Integrated Circuits (NIAC I & II)
10-Spatial-Channel × 3 Spectral Band SPIDER PIC Single Layer

5 Waveguide Inputs for Each Lenslet

From Lenslet +2

Demux

Phase Shifter

2×2

60 Outputs

Linear Detector Array

Matched Pathlengths

From Lenslet -2

From Lenslet +2

To Demux

Matched Pathlengths

From Lenslet -2

From Lenslet +2

To Demux

Matched Pathlengths
10-Spatial-Ch ×3 Spectral Band
SPIDER PIC Layout

Layer#1: waveguide
Layer#2: heater
Layer#3: electrode
Layer#4: trench
Layer#11: waveguide keep out

NASA NIAC and DARPA funded work
Packaged PIIT-SPIDER PIC

NASA NIAC and DARPA funded work

PIIT: Photonic Interferomic Integrated Telescope
Our New SPIDER Photonic Integrated Circuit Design
Our New Photonic Integrated Circuit Draft Plan (NASA SLIT)

What’s New:

- $\text{Si}_3\text{N}_4$ instead of $\text{SiO}_2$: nearly 10x reduced dimension or 100x reduced footprint area
- Three Layers instead of One: More compact footprint with lower crosstalk
- Projection Lithography instead of Contact Litho: higher yield, higher resolution (0.18 $\mu$m instead of 1 $\mu$m)
- Silicon CMOS compatible manufacturing platform instead of silica PLC: more ubiquitous foundry availability; possibility of integration of CMOS and detectors.
Multilayer 150nm/50nm/150nm Si$_3$N$_4$ 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 modes
### SiN Arrayed Waveguide Gratings - Design

<table>
<thead>
<tr>
<th>No. Channel</th>
<th>Channel Spacing (GHz)</th>
<th>No. Waveguide</th>
<th>FSR (THz)</th>
<th>Foot Print (mm²)</th>
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</thead>
<tbody>
<tr>
<td>16</td>
<td>100</td>
<td>34</td>
<td>1.8</td>
<td>2.2X0.7</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>34</td>
<td>0.9</td>
<td>3.7X0.7</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
<td>34</td>
<td>0.45</td>
<td>6.8X0.7</td>
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</tbody>
</table>

**16X100 GHz AWG**

**16X50 GHz AWG**

**16X25 GHz AWG**
SiN Arrayed Waveguide Gratings – Fabricated Device Photo

16 channel X 50 GHz AWG

Bending

Star Coupler

6.787 mm

150um

10um
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
Spectrometer Design for the new SPIDER: 18 Ch (3.3THz) Arrayed Waveguide Gratings

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

Symmetric Dual Arm Design for Interfacing with Mach-Zehnder Interferometer

<table>
<thead>
<tr>
<th>WL (nm)</th>
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<tbody>
<tr>
<td>1223</td>
</tr>
<tr>
<td>1240</td>
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<tr>
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<td>1533</td>
</tr>
<tr>
<td>1559</td>
</tr>
<tr>
<td>1586</td>
</tr>
</tbody>
</table>

North Set
Input

South Set
Input

From MMI

Towards Detectors

North Set

South Set

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

$\lambda_1 = 1223 \text{ nm}$
$\lambda_{18} = 1586 \text{ nm}$

$\lambda_1 = 1223 \text{ nm}$
$\lambda_{18} = 1586 \text{ nm}$

North Set

South Set

Earth Science Technology Office
Our New SPIDER PIC Design and Layout
Ronchi Ruling – 5 mm Baseline

Ronchi Ruling illuminated by the lamp with 12 nm filter and polarizer

After a sinusoidal fit:
- The amplitude is 0.75
- The RMSE of the fit is 0.017
- Estimated signal to noise ratio for a single data point is 44
- Estimated SNR of the amplitude would be $44 \times \sqrt{29/4} = 118$
- The visibility should be close to 50% for this case

This indicates that it is possible to measure visibilities down to ~0.5% for this scene (if we could adjust the baselines) before we get to the SNR = 1 noise floor
5 mm Baseline Measurement and Curve Fit

- Curve Fit shows Offset = 300 µm (Suspect there is an additional offset between the individual lenslet FOV’s)
- In the future, measure photometric signal levels for individual lenslets to obtain direct information about offset
20 mm Baseline Measurement and Curve Fit

- Curve fit quality is good
  - Offset between slit and FOV = 250 mm
  - Adjusted constant + linear phase terms of visibility data
Image Reconstruction Simulations: Scene Data used for Imager Simulations

Judiciary Square, Washington, D.C.

USGS High Resolution Orthoimagery (16cm GSD)
Collection Date: April 2-3, 2010
Reference: This data is public domain and available from the United States Geological Survey through http://nationalmap.gov.

Lockheed Martin IRAD work
Simulation for a Single Sub-Image

1. User selects FOV for sub-image

2. Crop scene and apodize (fiber coupling)

3. Make a conventional comparison sub-image

4. Compute $u$-$v$ data & make “dirty” image

5. Reconstruct sub-image

Lockheed IRAD work

NASA ESTF 2017
Motivation for MWIR and LWIR

“Notional reflectance spectra for ice-rich regions (blue curves) and ice-poor regions (red curves) on Europa … in the 1–5 µm spectral range.”
3D Integrated Photonics by Ultrafast Laser Inscription
3D Waveguide Writing at UC Davis

~150 mm/s writing speed
Precision and Low Loss 3D waveguide Fabrication by fs Laser Inscription

3D waveguides CAD Design

Accuracy at 10 ppb

3D waveguides output pattern

output facet view
Possible Impacts on SLI-T
Ref: Jupiter Icy Moons Orbiter Reference Mission
Possible Impacts on SLI-T  
Ref: SPIDER-based Topographical Imager (TI)

- SPIDER Topographical Imager
  - 4 cm diameter aperture (same enclosure)
  - 15 μrad IFOV → 1.5 m Ground-Sampled-Distance (GSD) at 100 km
  - 10 Mpixel area, 150-ms integration time

For the same enclosure, SPIDER could collect 10× the area on ground with 17× the resolution
Possible Impacts on SLI-T
Ref: Traditional Topographical Imager


- Proposed Traditional Imager
  - 250 µrad IFOV → 25 m Ground-Sampled-Distance (GSD) at 100 km
  - 4096 detectors, 5.5-ms integration time
  - Push-broom mode collection
  - 5×5×4-cm radiation shielded enclosure (1.3 cm diameter lens)
  - 2.5 kg unshielded mass

Similar Imagers

MRO Mars Color Imager (MARCI)

New Horizons Multi-spectral Visible Imaging Camera (MVIC)
Summary

• A new *Multi-Spectral, Low-Mass, High-Resolution Integrated Photonic Land Imaging Technology*

• ~100x savings in size, weight, (and power) compared to traditional imagers with comparable spatial & spectral resolutions.

• Integrated Chip scale construction on silicon wafers (foundry fabrication capable)

• Integrated spectrally-resolved spatial imaging

• Proof-of-Principle Demonstration of Spectrally Resolved Interferometric Data

• Successful Image Reconstruction Simulations.

• Possible Extensions to SWIR, MWIR, and LWIR

• NIAC Europa preliminary studies indicate exciting possibilities for Landsat.
**Sub-Image Comparisons**

- **Apodized Scene**
- **Conventional Sub-Image**
- **SPIDER Sub-Image**

*No Wiener filter applied*

**SPIDER sub-image shows finer detail, but the point-spread function (PSF) sidelobes give a slightly noisy appearance (there was no measurement noise in the simulation)**

*Wiener filter is often used to remove blur in images due to linear motion or unfocussed optics*

Lockheed Martin IRAD work
Multilayer 200nm $\text{Si}_3\text{N}_4$ PIC Platform – Fabrication Process

- Silicon wafer
- LTO deposition
- $\text{Si}_3\text{N}_4$ deposition
- Layer 1 pattern
- LTO deposition
- CMP
- $\text{Si}_3\text{N}_4$ deposition
- Layer 2 pattern
- LTO deposition
- CMP

AFM measurement

- Silicon
- $\text{SiO}_2$
- $\text{Si}_3\text{N}_4$

2 nm
1 nm
SPIDER Provides High Resolution Capability

1.5 m diameter aperture SPIDER

Range of resolutions provided by SPIDER during 4 year Jovian mission

- **All Icy Moons** (> 4 years, 2cm to 200m)
- **Europa Low Radiation Zone** (3.3 years)
- **Europa High Radiation Zone** (Last ~ 8 months of mission)
- **All Icy Moons Spiral Orbits** (14 months, 2cm to 1m)
- **EOM Europa Quarantine** (8cm @ 400km)
- **All Icy Moons, Science Orbits** (7 mos, 2cm @ 100km)

Jupiter

PreJovian Cruise Mode

Io

Resolution

Range (km)

Resolution (meters)

1000.00

200m

100.00

70m

10.00

70m

1.00

1.00

0.10

2cm

0.01

100.

1,000.

10,000.

100,000.

1,000,000.

10,000,000.

MIDAS_046a
Europa Flyby Orbit

Europa Study Team, 1 May 2012, JPL D-71990 Task Order NMO711062 Outer Planets Flagship Mission

17x resolution provided by SPIDER sensor enables SWIRS data collection out to 1,122,000 km

17x resolution provided by SPIDER sensor enables TI data collection out to 17,000 km
Current Prediction for TI Coverage

SPIDER increases both the length (17X) and width (5X) of each swath

Figure C.2.5-6. TI instrument coverage.

Europa Study Team, 1 May 2012, JPL D-71990 Task Order NMO711062 Outer Planets Flagship Mission
Current Prediction for SWIRS Coverage

SPIDER increase both the length (17X) and width (5X) of each swath.

Figure C.2.5-4. SWIRS high-resolution coverage (under 2,000 km altitude).
Europa Study Team, 1 May 2012, JPL D-71990 Task Order
NMO711062 Outer Planets Flagship Mission
Demonstrated Silicon/Silicon Nitride waveguides and InP/InGaAsP waveguides at 4.6 micron in Phase I