Low-Mass Planar Photonic Imaging Sensor

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Key to Affordability – Low SWaP

Orders of Magnitude SWaP Reduction Achievable

Conventional Telescope and focal plane

SPIDER: Radial Blade Design Option
B: outer ring

SPIDER: Radial Blade Design Option
A: full sensor

SPIDER: Single Chip Design
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
Basic Idea--Michelson Stellar Interferometer

\[ \alpha_0/2 \]

- Stellar source with angular size \( \alpha_0 \)
- Add fringe patterns (i.e. intensities) between \( \pm \alpha_0/2 \)

Figure Courtesy of Andreas Glindemann
Advantages of Interferometric Imaging

Figure Courtesy of Andreas Glindemann

Small star

Big star

Objects

Single Telescope

Interf. Fringes

Angular Resolution: $\sim \frac{\lambda}{D}$

$I_{\text{im}}(\alpha) \sim F(D)$

$I_{\text{im}}(\alpha) \sim F(B)$

$\sim \frac{\lambda}{B}$
Basic Algorithm

- Sample the fields at $r_1$ and $r_2$.
- Optical train delivers the radiation to a lab.
- Delay lines assure that we measure when $t_1 = t_2$.
- The instruments mix the beams and detect the fringes.
- Measure the fringes
- Interpret the Fourier spectrum of the target

Courtesy of C. Haniff
The Output of a Two-element Interferometer

- A combination of E fields from the two collectors can be described as:
  \[ \Psi_1 = A \exp\left(ik\left(\hat{s}.B + d_1\right)\right)\exp(i\omega t) \] and
  \[ \Psi_2 = A \exp\left(ik\left(d_2\right)\right)\exp(i\omega t) \]

- Summing these at the detector yields:
  \[ \Psi = \Psi_1 + \Psi_2 = A \left[ \exp\left(ik\left(\hat{s}.B + d_1\right)\right) + \exp\left(ik\left(d_2\right)\right) \right] \exp(i\omega t) \]

- Thus, the time averaged intensity, \( \langle \Psi \Psi^* \rangle \), is given by:
  \[ \langle \Psi \Psi^* \rangle \propto \left[ \exp\left(ik\left(\hat{s}.B + d_1\right)\right) + \exp\left(ik\left(d_2\right)\right) \right] \times \left[ \exp\left(-ik\left(\hat{s}.B + d_1\right)\right) + \exp\left(-ik\left(d_2\right)\right) \right] \]
  \[ \propto 2 + 2 \cos\left(k\left(\hat{s}.B + d_1 - d_1\right)\right) \]
  \[ \propto 2 + 2 \cos\left(kD\right) \]

- Measure the fringe visibility at \( D = 0 \) and the fringe phase (with respect to a ref):
  \[ V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

The fringe amplitude and phase measure the amplitude and phase of the Fourier transform of the source at one spatial frequency.

Adapted from C. Haniff – The theory of interferometry
SPIDER Provides Low Cost Option to Enhance Resolution of a Conventional Telescope

- Objectives
  - Enhanced quality imagery using sparse high resolution image sampling and hyperspectral data
  - Increase effective aperture diameter by 2X - 3X (9X mass reduction)

- Concept Description
  - Moderate aperture diameter conventional imaging telescope with staring focal plane
  - White light waveguide coupled interferometers with integrated combiner / phase shifters / detectors

- Performance Characteristics
  - Moderate resolution full field of view panchromatic image
  - Selectable subfield regions enhanced with high resolution and hyperspectral content
**SPIDER Concept Enables Next Generation Imaging Capabilities**

- **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

![Diagram of SPIDER concept](image)
Spectrally Resolved High Resolution Interferometric Telescope
Photonic Integrated Circuit (PIC) Design

- Specify spectral bin widths, bin spacing, interferometer phase shift requirements, desired optical mode size, etc.
- Simulations of individual photonic components (spectral demultiplexer, splitters, etc.)
- Packaging design
- Layout of waveguide and metal mask layers including test structures
- Design review
10-Spatial-Channel \times 3 \text{ Spectral Band PIC}

5 Waveguide Inputs for Each Lenslet

- From Lenslet +2
  - Demux
  - To Demux

- Matched Pathlengths
  - +2
  - +1
  - 0
  - -1
  - -2

- 5 mm
- 20 mm

- 2\times2 Phase Shifter

- 60 Outputs

Linear Detector Array

Inputs for Each Lenslet

- Matched Pathlengths

- Linear Detector Array
10-Spatial-Ch ×3 Spectral Band
Main Device Layout

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

DARPA funded work
Packaged PIC

- Linear Detector Array
- PIC
- Lenslets
- DARPA funded work
Measuring Fringes from One and Two Sources

(a) Bright Source

(b) Faint Source

(c) Binary Object

\[
\text{Path Delay} \quad + \quad \text{Path Delay} = \quad 16
\]
Fringe Measurements of Point Sources

- Fringe extinction >10 dB
- The ASE sources are incoherent with respect to each other

**Source 2 in Position 2**

- 1.2 nm-ASE source 1 alone
- 1.2 nm-ASE source 2 alone
- 1.2 nm-ASE source 1 and 2 combined

**Source 2 in Position 3**

- 1.2 nm-ASE source 1 alone
- 1.2 nm-ASE source 2 alone
- 1.2 nm-ASE source 1 and 2 combined
Integrated SPIDER Blade

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

90° optical hybrid 90°

Si + Sj

Si - Sj

Si - jSj

Si + jSj

I(t)

Q(t)

50:50

2×2 Demux

Phase Shifter

From Lenslet +2

From Lenslet -2

Matched Pathlength s

To Demux

CCD

PIC

Self-aligned to
Silicon Photonics

Electronics Board

Digital Signal Processing
Integrated SPIDER Blade PIC: two approaches
Our Previous Experience:

~8000 waveguides with 1200 independently addressable devices on a chip developed at UC Davis

1 THz (100ch x 10 GHz) OAWG Transmitter (DARPA DSO)
Modeling / Simulation Flow Chart

Array Configuration

Input Parameters
- Baseline lengths, orientations
- Spectral: width, # of bins
- Integration times
- Etc.

Interferometer Model

Scene Characteristics

Collection Throughput

Line of Sight and Pathlength Errors

Transmission and Signal Mixing

Spectral Dispersion and Binning

Fringe Detection

Simulated Raw Fringes

Fringe Tracker

Visibility Amplitude / Phase Algorithm

Image Reconstruction Algorithms

Image Quality Assessment
We start here with a model for the target spectral irradiance at lenses. We then consider throughput losses and integration time, which affect the signal at the focal plane. Simulate a noise-free fringe pattern with OPD errors. Finally, we calculate the signal level at the focal plane. We then proceed to the EMCCD model, considering raw or photon counting, as well as pixel size and gain. We also account for read noise and dark current, and calculate the quantum efficiency (QE) and quantum efficiency standard error (QSE).
Image Reconstruction Flow Chart

- Developed by University of Rochester (Dr. Jim Fienup) under Lockheed Martin’s IRAD funding
- Image reconstruction details will be tailored to imager conceptual design
**Image Simulations**

**Visibility**

- 131 spectral bands uniformly spaced in wavelength between 0.5-1.8 μm
- Each band uses the units of W/cm²-str-μm at the top of the atmosphere
- Resolution of image is 1.65 cm
- More details elsewhere

**Example Simulated Fringe Data (Noise Free)**

**Example Simulated Fringe Data (Noisy)**

Lockheed Martin IRAD work
Visibility and Signal Calculation

- Complex visibility at a distinct wavelength is the scaled and normalized Fourier Transform of the target:

\[
V(B_x, B_y; \lambda) = \frac{\int \int R(x, y; \lambda) \exp\left(-i \frac{2\pi}{\lambda z} (xB_x + yB_y)\right) dxdy}{\int \int R(x, y; \lambda) dxdy}
\]

\(V\) = Complex Visibility, \(B_x, B_y\) = Baseline, \(\lambda\) = Wavelength
\(R(x, y)\) = Target Radiance, \(z\) = slant range to target

- Spectral irradiance calculation (ph/s-m²-nm)
- Visual magnitude of DIRSIG target is \(\sim 9.78\)
  - Spectral irradiance can be scaled by a factor of 0.324 to give \(m_v=11\)

\[
I(\lambda) = \frac{\int \int R(x, y; \lambda) \times \frac{c\lambda}{h} dxdy}{z^2} \times \frac{10000}{1000} \times \tau_{atm}(\lambda)
\]

\(c\) = Speed of light, \(h\) = Planck's constant
\(\tau_{atm}(\lambda)\) = Atmospheric Transmission

Lockheed Martin IRAD work
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

2/4/2014
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
Sub-Image Comparisons

*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
The “banding” in the SPIDER image is likely due to the lack of low spatial frequency $u$-$v$ samples near DC

Lockheed Martin IRAD work
Jupiter Icy Moons Orbiter Reference Mission

Jovian Science in All Transfer Orbits

Callisto
Global Dark Smooth Unit
Global-Regional Imaging in All Spiral Orbits
Ganymede
Middle aged

Jupiter

Dense Large Crater Population

Europa
Young

Light Terrain
Caldera ??

Composition

Ridges
Chaos

MIDAS_042B

SPIDER (Segmented Planar Imaging Detector for EO Reconnaissance)

Bottom View (plate removed)
Top View (with ray trace)

Low size, weight, power EO sensor enables high resolution, persistent imaging in the Jovian system

Atmosphere Dynamics

Spirals 30%

14.6 Months
26.5 Months
7 Months

Transfers 55%
On-Orbit 15%

Extended Mission Science
- Europa Quarantine Orbit
- Transit to Io
SPIDER Provides High Resolution Capability

1.5 m diameter aperture SPIDER

Range of resolutions provided by SPIDER during 4 year Jovian mission

- PreJovian Cruise Mode
  - Jupiter (>4 yrs, 150-400m)
- Io (>4 yrs, 50-300m)
- Europa Low Radiation Zone (3.3 years)
- All Icy Moons (> 4 years, 2cm to 200m)
- 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)
Europa Multiple Flyby Notional Topographical Imager (TI)


- 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
  - 2.5 kg unshielded mass

Similar Imagers

- MRO Mars Color Imager (MARCI)
- New Horizons Multi-spectral Visible Imaging Camera (MVIC)
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 mass, SPIDER could collect 10× the area on ground with 17× the resolution
“Improved spectral observations at significantly higher spectral and spatial resolution than is presently available, together with detailed laboratory analyses under the appropriate temperature and radiation environment, are needed to fully understand Europa’s surface chemistry.”


Athermal Photonics and Spectrometers

Ridge height 250nm, ridge width 300nm, etch depth 250nm

neff = 2.1669, ng = 3.7392,
Aeff = 0.224401, D = -6004.884 ps/nm/km
97% TE (3% minority field)
FWHM horiz. = 92.5nm 1/e horiz. = 141.6nm

\[ n_{eff} = \sum \Gamma_i \left( n_i + \frac{dn_i}{dT} \Delta T \right) \]

Athermalization means

\[ \frac{dn_{eff}}{dT} = \sum \Gamma_i \left( \frac{dn_i}{dT} \right) = 0 \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermo-Optic Coefficient (k^-1)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>+1.8x10^-4</td>
<td>3.467</td>
</tr>
<tr>
<td>SiO2</td>
<td>~ 10^-5</td>
<td>1.444</td>
</tr>
<tr>
<td>PUA</td>
<td>-4.2x10^-4</td>
<td>~1.45</td>
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<tr>
<td>TiO2</td>
<td>-3x10^-4 -2.3x10^-3</td>
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Thermo-Optic Coefficient and Refractive Index:

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SiO2 ~10^-5 1.444
PUA -4.2x10^-4 ~1.45
TiO2 -3x10^-4 -2.3x10^-3 ~2.483
Athermal Photonics and Spectrometers
e.g. Silicon Photonic Resonator with TiO$_2$ overcladding

Ring resonator with 250nm wide waveguide

Blue shift
$-11.3$ pm/°C ($+1.41$ GHz/°C)

Blue shift
$-1.60$ pm/°C ($+0.20$ GHz/°C)
Identifying Compounds on Europa

“Notional reflectance spectra for ice-rich regions (blue curves) and ice-poor regions (red curves) on Europa … in the 1–5 µm spectral range.”
Transmission Range of Selected Materials

<table>
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<th>Material</th>
<th>Transmission Range (µm)</th>
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<tr>
<td>Fused Silica</td>
<td>2.6 - 3.6</td>
</tr>
<tr>
<td>BaF₂</td>
<td>2.8 - 3.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>3.1 - 5.0</td>
</tr>
<tr>
<td>Silicon Nitride</td>
<td>7.5</td>
</tr>
<tr>
<td>MgF₂</td>
<td>8.0</td>
</tr>
<tr>
<td>CaF₂</td>
<td>8.5</td>
</tr>
<tr>
<td>Silicon</td>
<td>7.5</td>
</tr>
<tr>
<td>GaAs</td>
<td>15.0</td>
</tr>
<tr>
<td>Germanium</td>
<td>20.0</td>
</tr>
<tr>
<td>Sapphire</td>
<td>6.0</td>
</tr>
<tr>
<td>InP</td>
<td>13.0</td>
</tr>
<tr>
<td>ZBLAN</td>
<td>7.0</td>
</tr>
<tr>
<td>GLS</td>
<td>8.5</td>
</tr>
<tr>
<td>Zinc Selenide</td>
<td>20.0</td>
</tr>
<tr>
<td>Lithium Niobate</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Wavelength (µm)
Thank you for support
<table>
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<th>Objective</th>
<th>Benefit</th>
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<tr>
<td>1</td>
<td>Develop radiometry model of Europa</td>
<td>Provide input data to address required integration times for a realistic mission scenario (Europa Clipper).</td>
<td>Anchor results to a specific mission of interest (relevant to a broad class of “icy moons” type missions).</td>
</tr>
<tr>
<td>2</td>
<td>Develop SPIDER design</td>
<td>Tailor our design for the Europa Clipper reference mission to show potential and identify key technologies.</td>
<td>Showcase low cost and SWaP.</td>
</tr>
<tr>
<td>3</td>
<td>Evaluate various PIC material platforms and architectures</td>
<td>Provide data on waveguide coupling efficiencies and device losses to improve SPIDER model.</td>
<td>Quantifies performance limitations due to current technology constraints.</td>
</tr>
<tr>
<td>4</td>
<td>Develop image reconstruction algorithm</td>
<td>Adapt existing algorithms to optimize performance for Europa reference mission.</td>
<td>Increases fidelity of critical algorithm required to generate science products.</td>
</tr>
<tr>
<td>5</td>
<td>Develop SPIDER model (predict raw signal characteristics including SNR)</td>
<td>Provide realistic data to enable high fidelity predictions of sensor performance.</td>
<td>Addresses performance limitations due to fundamental physics constraints.</td>
</tr>
<tr>
<td>6</td>
<td>Perform image simulations and evaluate predicted performance</td>
<td>Provide quantitative performance predictions to assess feasibility of meeting science goals.</td>
<td>Forms the basis for scaling design and performance to a broad class of imaging missions.</td>
</tr>
<tr>
<td>7</td>
<td>Develop a technology roadmap</td>
<td>Identify technology needs and provide a roadmap to guide further investigation and to show where there is significant leverage of existing technology.</td>
<td>Minimize development cost by leveraging Lockheed Martin IRAD, commercial industry and DARPA investments.</td>
</tr>
</tbody>
</table>