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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NASA Grant # NNX16AP60G

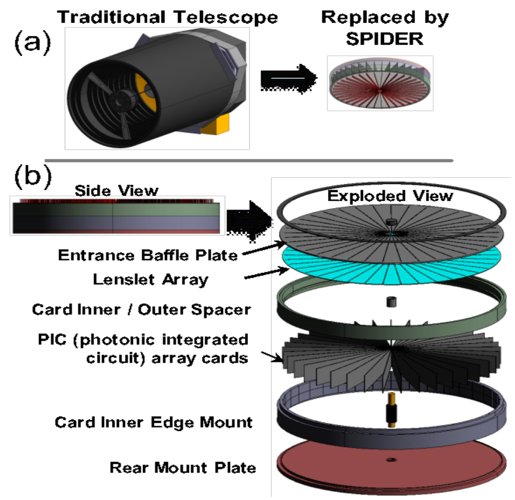
ESTO Earth Science Technology Office

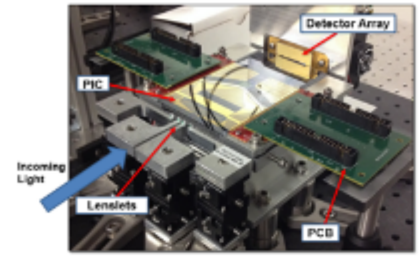
Multi-Spectral, Low-Mass, High-Resolution Integrated Photonic Land Imaging Technology

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 => TRL_{out} = 5

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Motivation

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

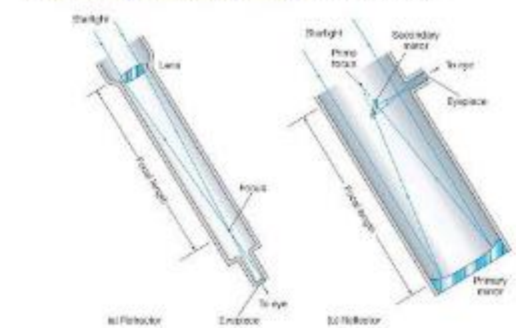
1) Aperture Size: ~2.4m in diameter
2) Volume: ~ $5m^3$
3) Weight: ~500kg
4) Power: ~ 500W

Hubble Telescope

IKONOS satellite

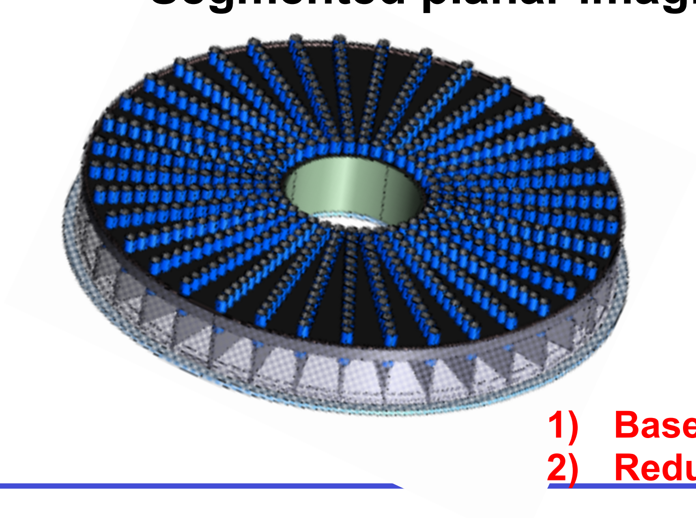
Optical Telescopes

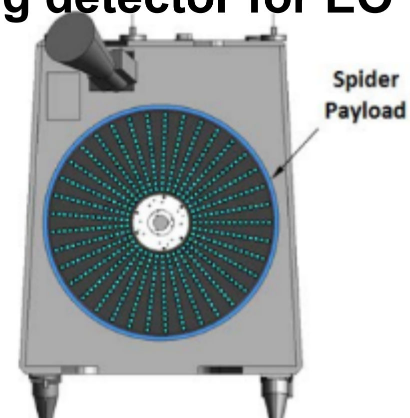
Reflecting and refracting telescopes:

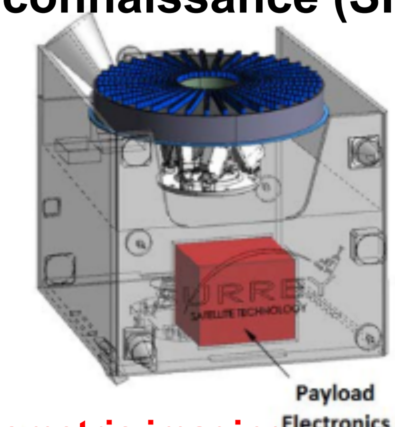


$\theta = 1.22\,\lambda/D$ $\quad L \sim D$

Segmented planar imaging detector for EO reconnaissance (SPIDER)

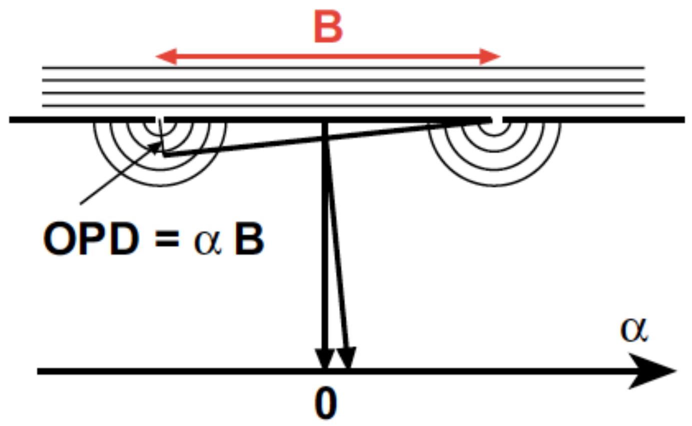






1) **Based on multi-baseline interferometric imaging**
2) **Reduce SWaP by the factor of 10~100**

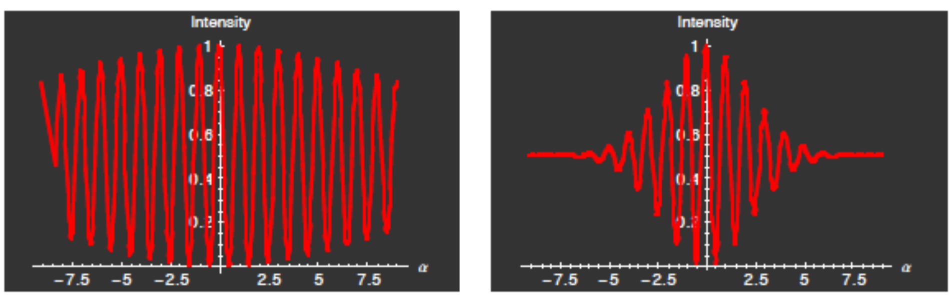
Basic Idea--Young's Two-Slit Experiment



1st Min: OPD = $\lambda/2 \Rightarrow \alpha_{min} = \lambda/(2B)$

- Light source at infinity at $\alpha = 0$
- Intensity pattern ~ 1+cos as a function of α, period length: λ/B
- OPD > coherence length $\Rightarrow$ fringes disappear

Light source at angle α_0 $\Rightarrow$ fringe pattern shifts accordingly

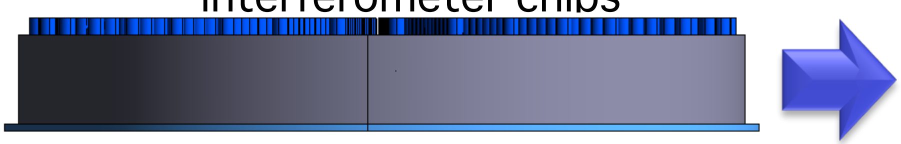


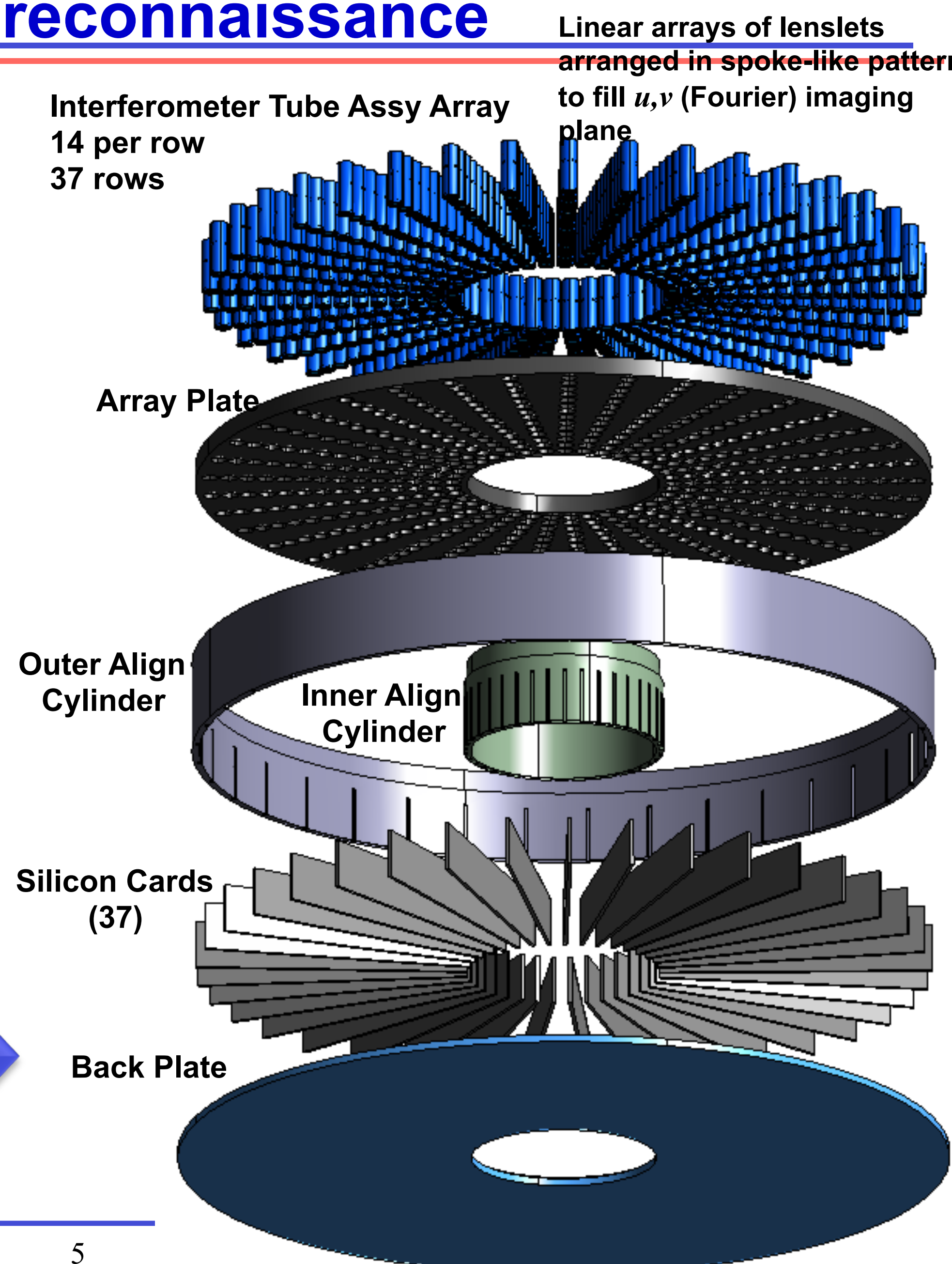
(First and last picture of a movie)

Figure Courtesy of Andreas Glindemann

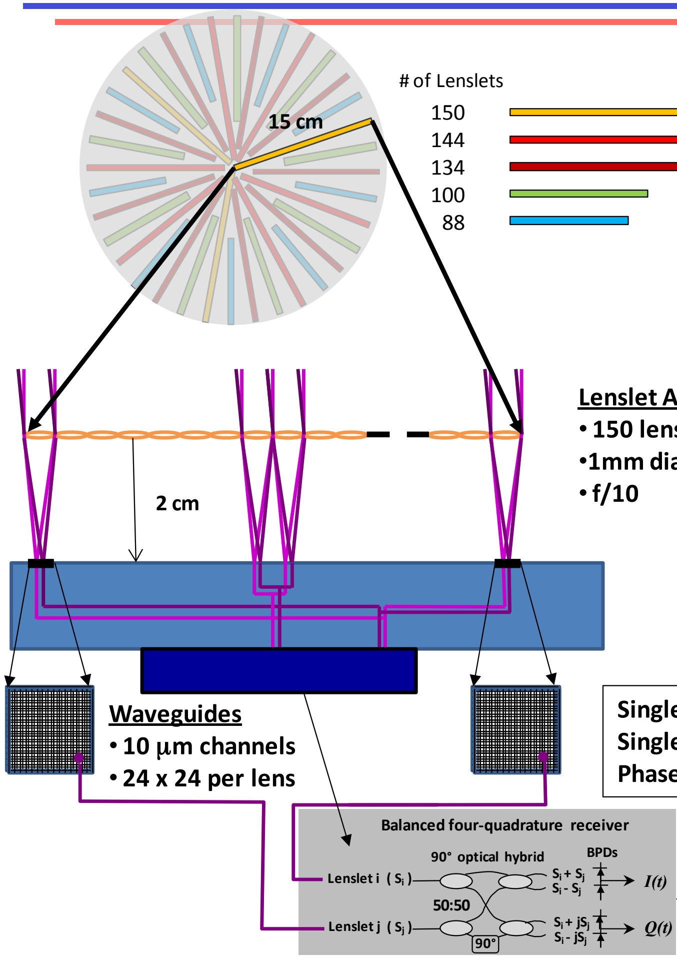
SPIDER: segmented planar imaging detector for electro-optical reconnaissance

- Objectives
  - Planar "flat panel" telescope with <u>NO</u> large optics
  - Large field of view with <u>NO</u> 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





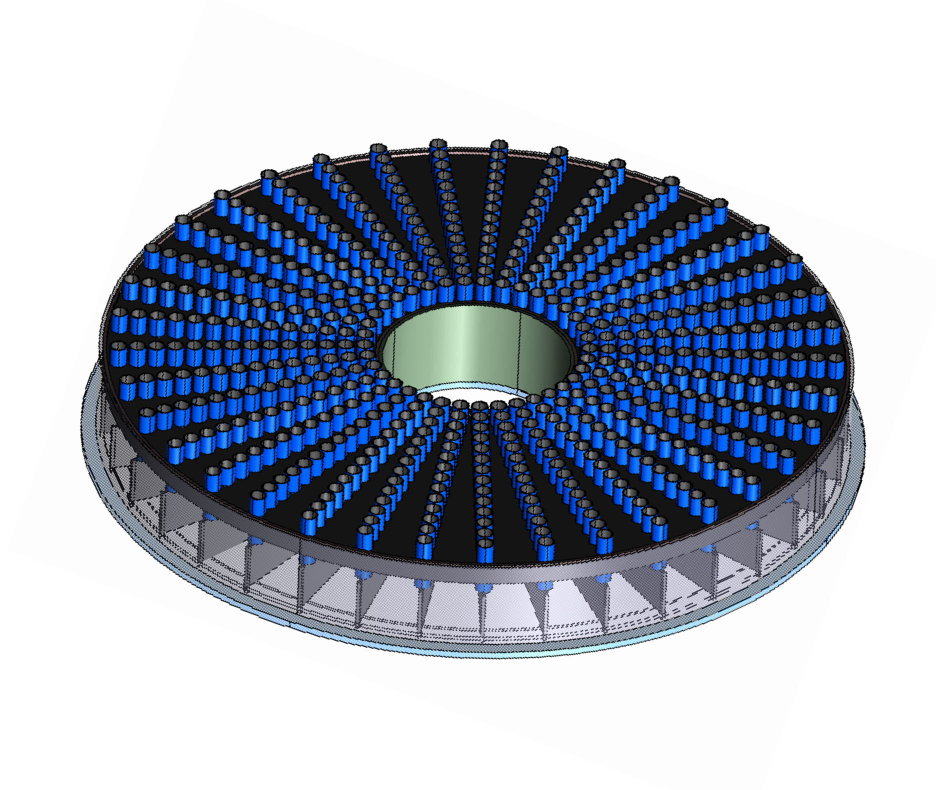
SPIDER PIIT Approach

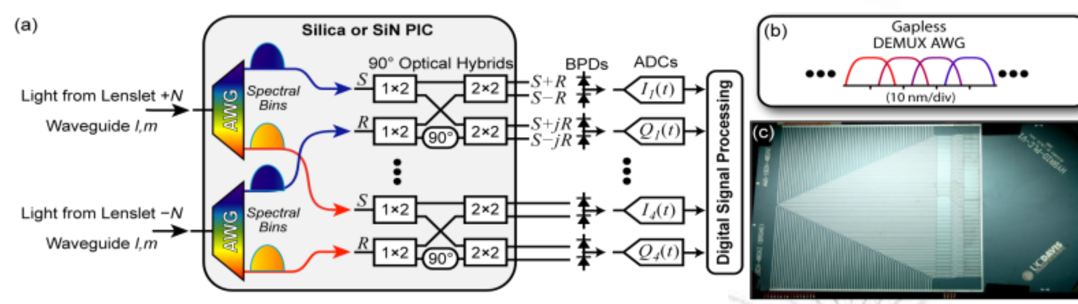


Lenslet Array
- 150 lenses
- 1mm diameter
- f/10

Waveguides
- 10 μm channels
- 24 x 24 per lens

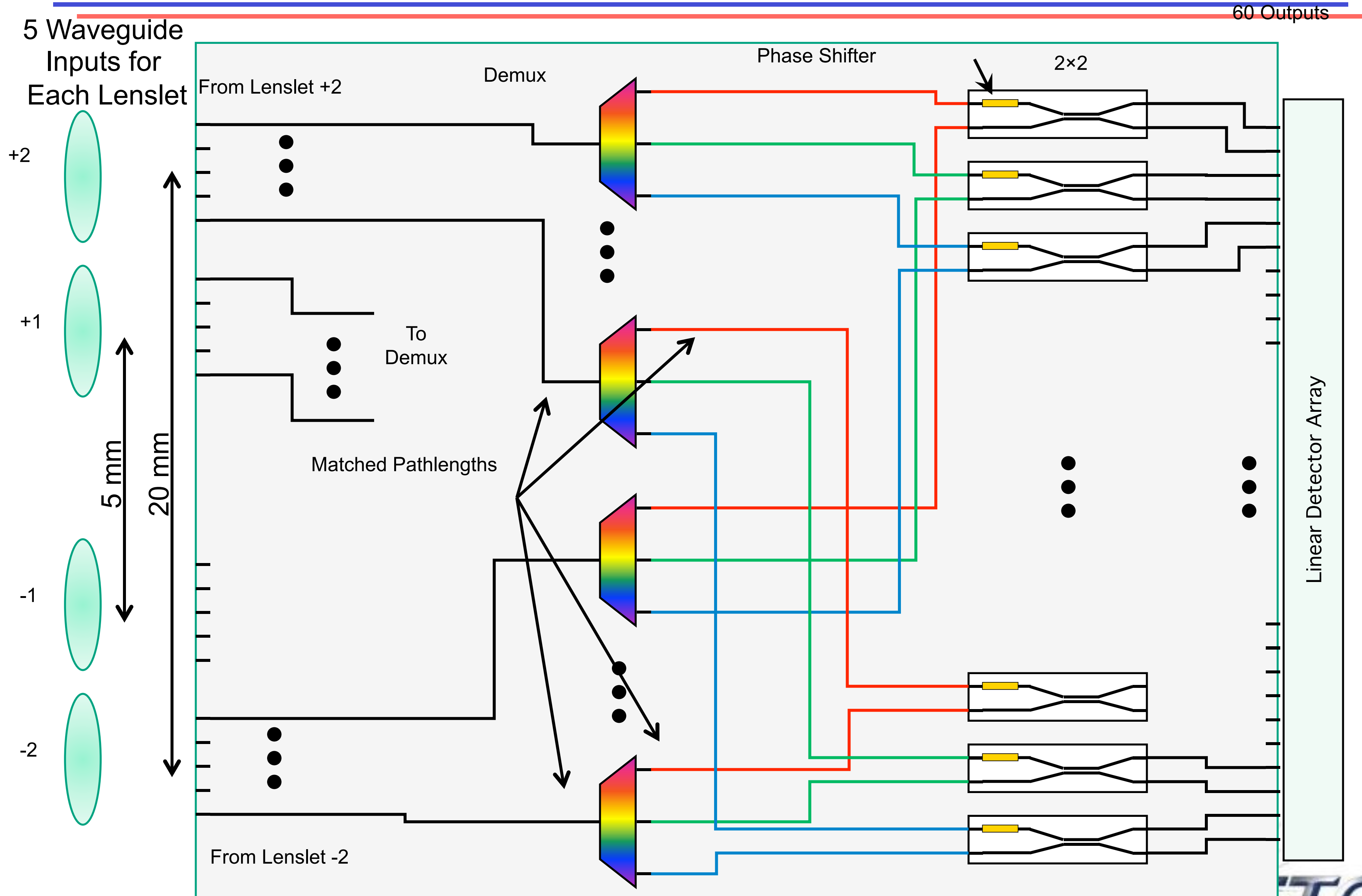
Single field point,
Single wavelength
Phase & Amplitude



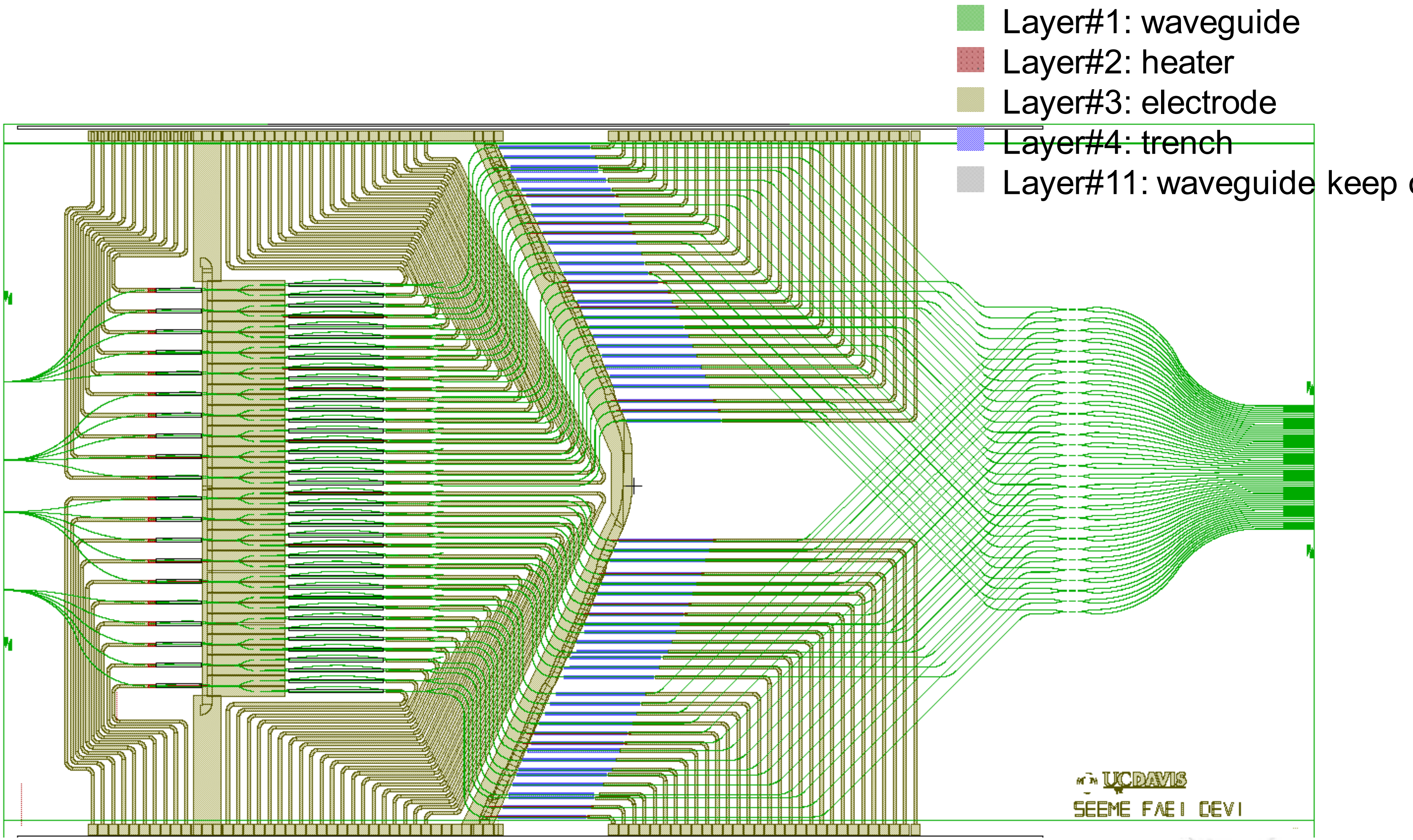


Spectrally Resolved High Resolution Interferometric Telescope

Our Previous SPIDER Photonic Integrated Circuits (NIAC I & II)
10-Spatial-Channel × 3 Spectral Band SPIDER PIC Single Layer

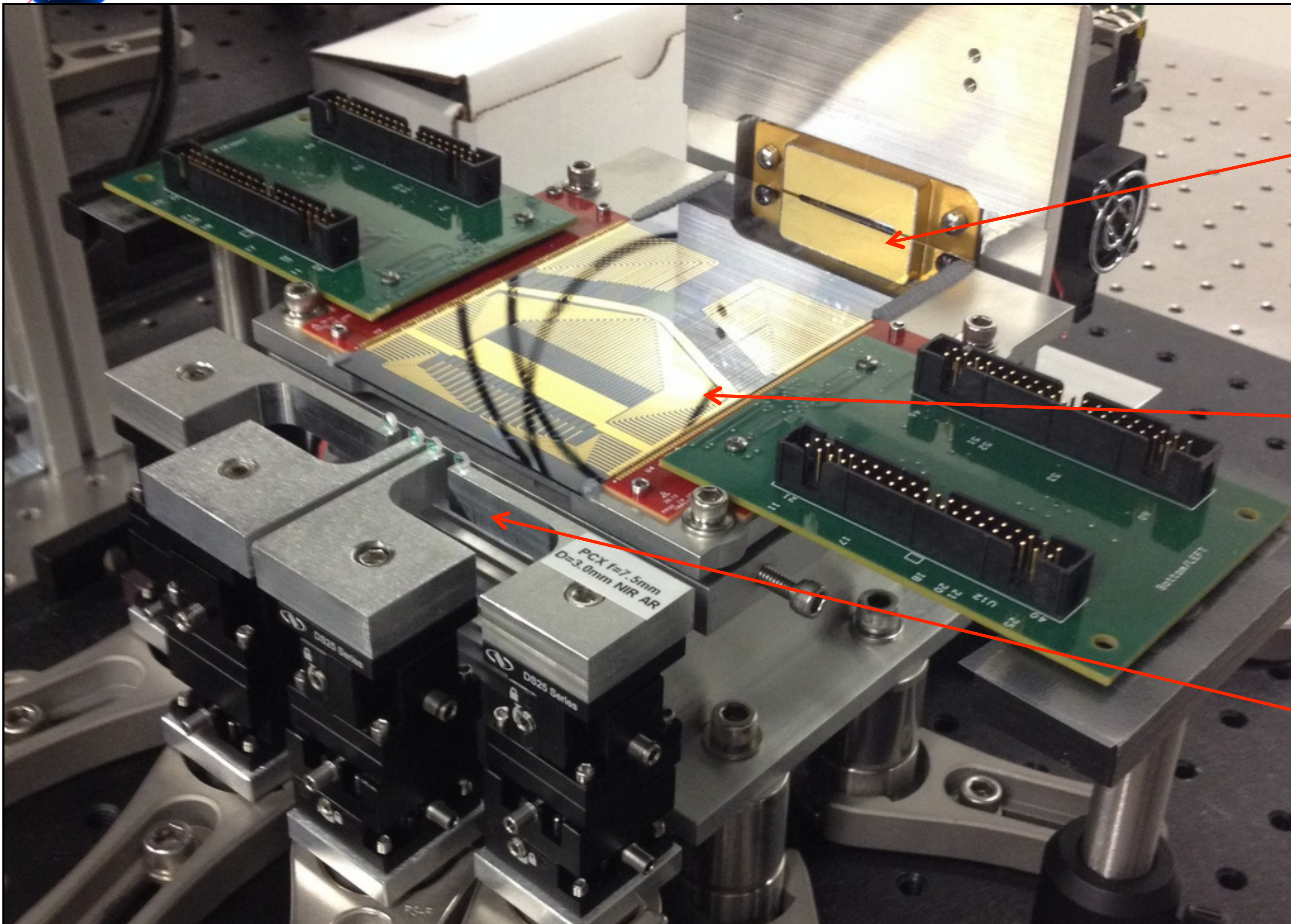


10-Spatial-Ch ×3 Spectral Band SPIDER PIC Layout



NASA NIAC and DARPA funded work

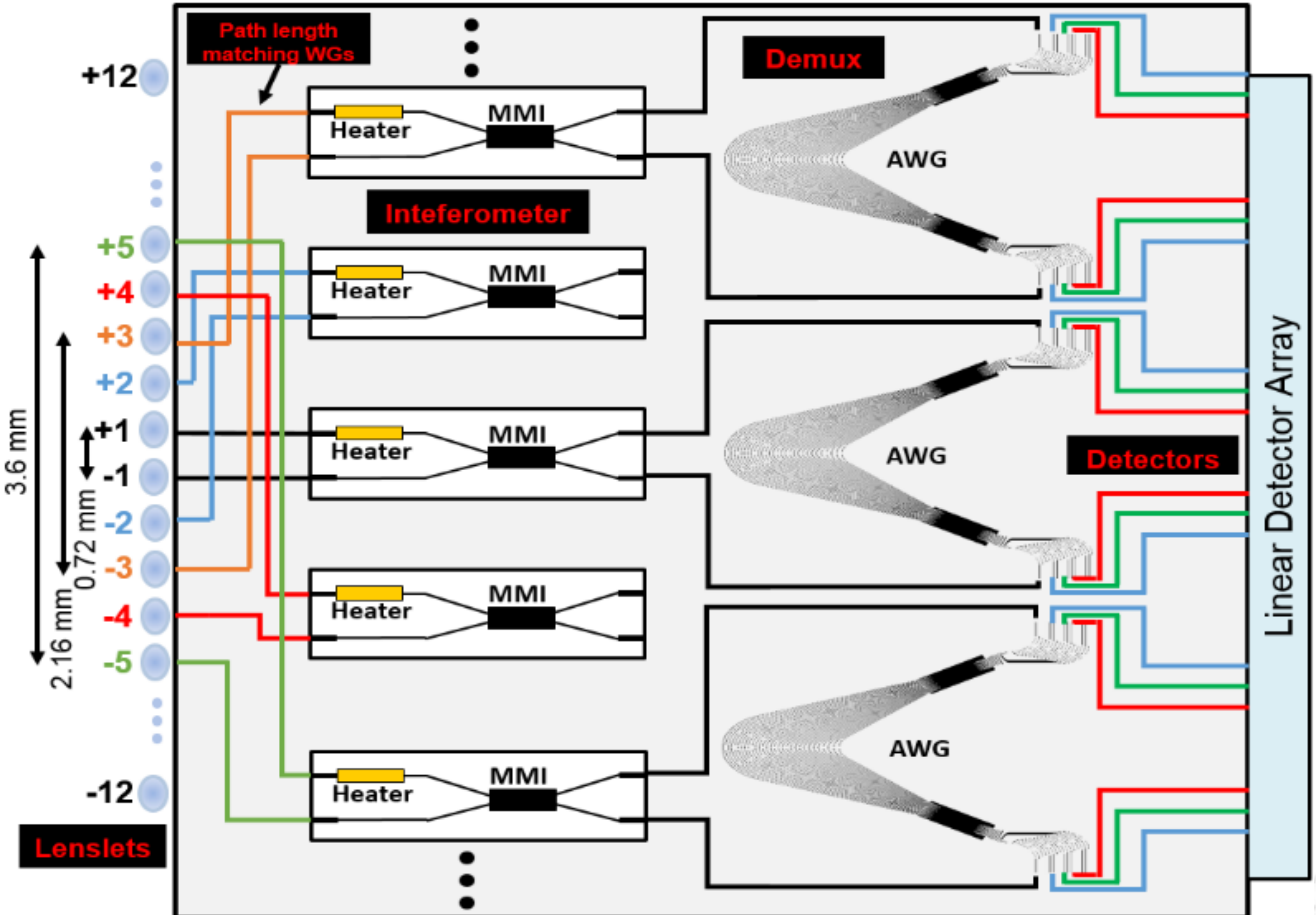
Packaged PIIT-SPIDER PIC



NASA NIAC and DARPA funded work

PIIT: Photonic Interferomic Integrated Telescope

Our New SPIDER Photonic Integrated Circuit Design



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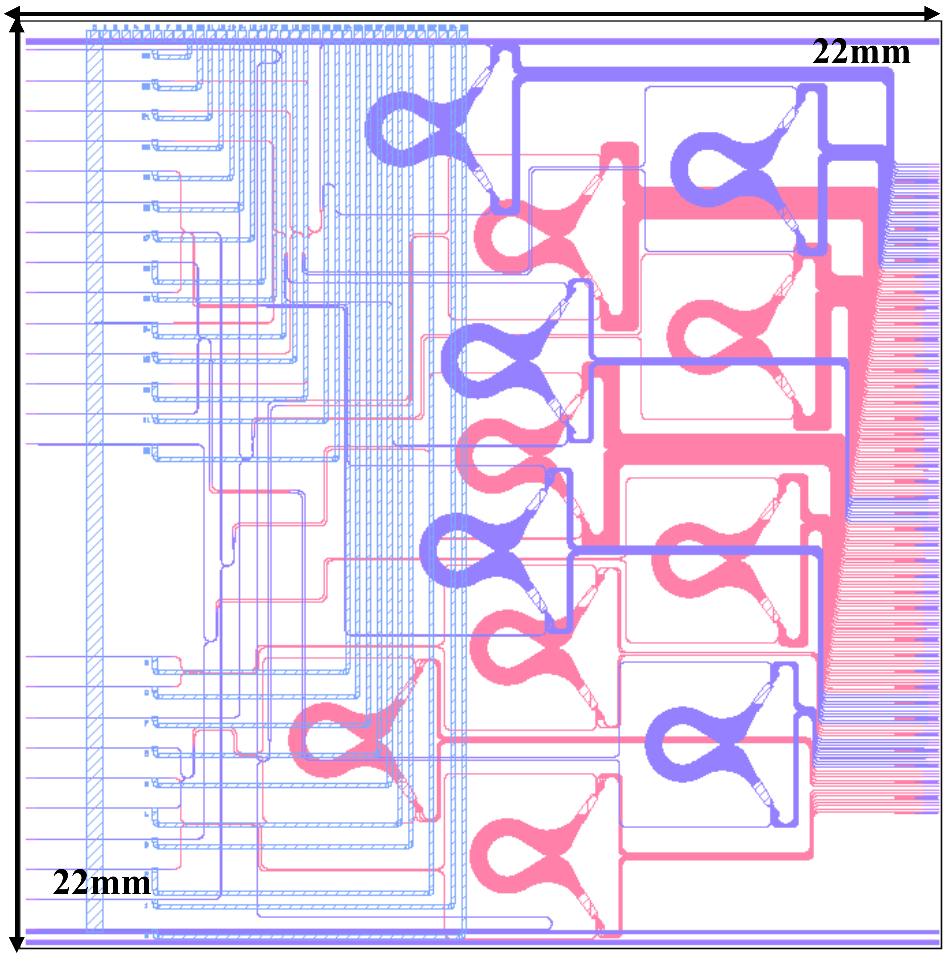
Our New Photonic Integrated Circuit Draft Plan (NASA SLIT)

Si_3N_4 PIC



- What's New:
  - Si_3N_4 instead of 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 μm instead of 1 μm)
  - Silicon CMOS compatible manufacturing platform instead of silica PLC: more ubiquitous foundry availability; possibility of integration of CMOS and detectors.

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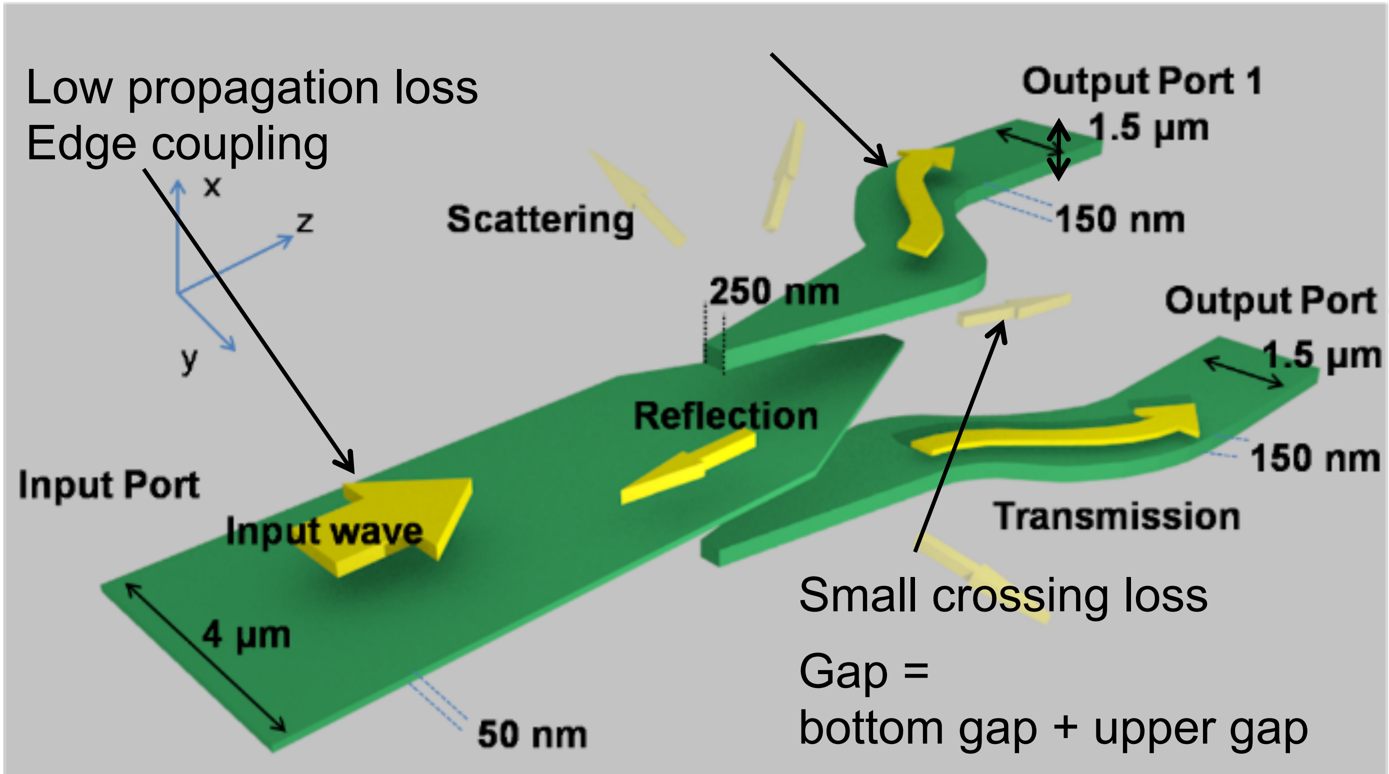
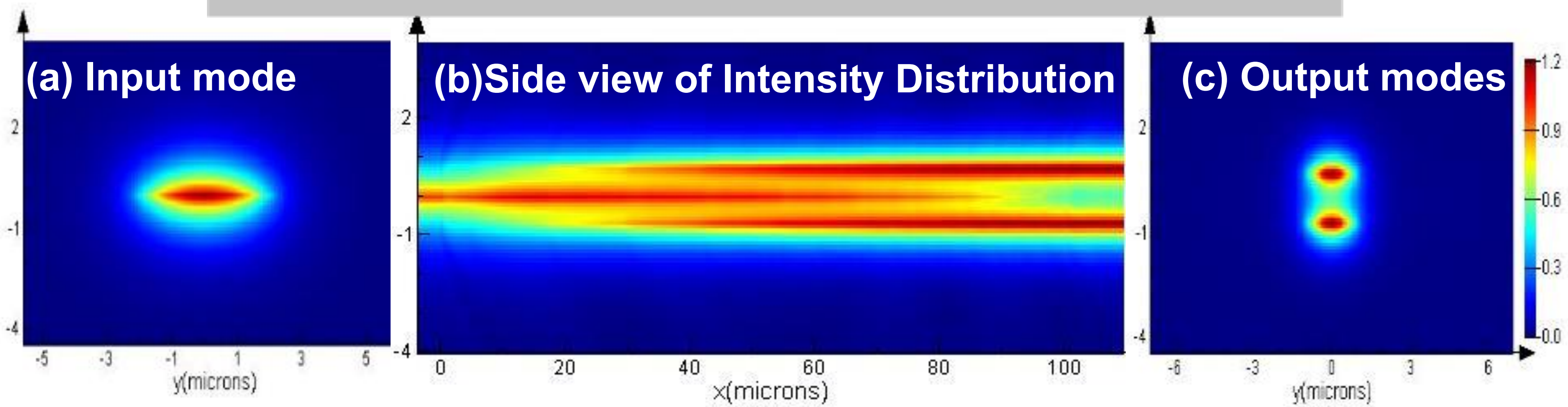
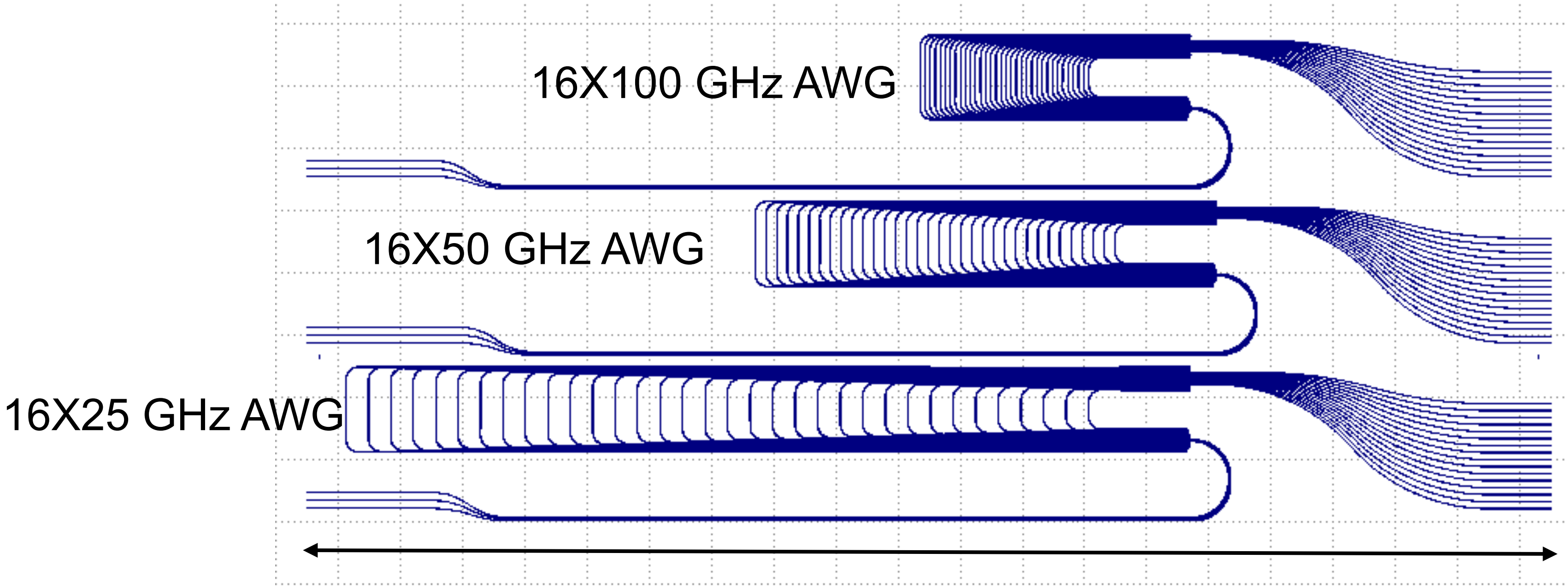
Multilayer 150nm/50nm/150nm Si_3N_4 PIC Platform for the new SPIDER PIIT Design





SiN Arrayed Waveguide Gratings - Design

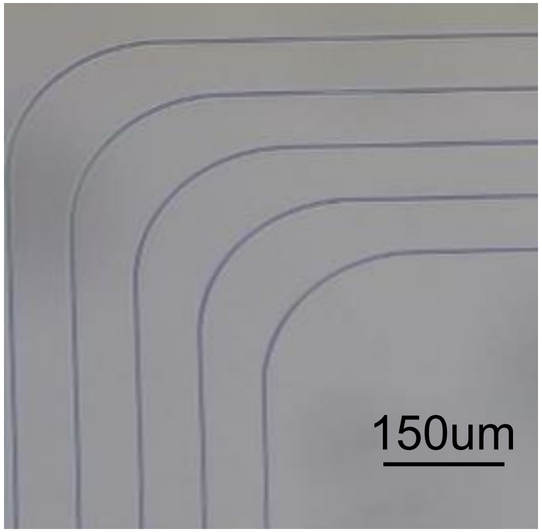
No. Channel	Channel Spacing (GHz)	No. Waveguide	FSR (THz)	Foot Print (mm^2)
16	100	34	1.8	2.2X0.7
16	50	34	0.9	3.7X0 .7
16	25	34	0.45	6.8X0.7



SiN Arrayed Waveguide Gratings – Fabricated Device Photo

16 channel X 50 GHz AWG

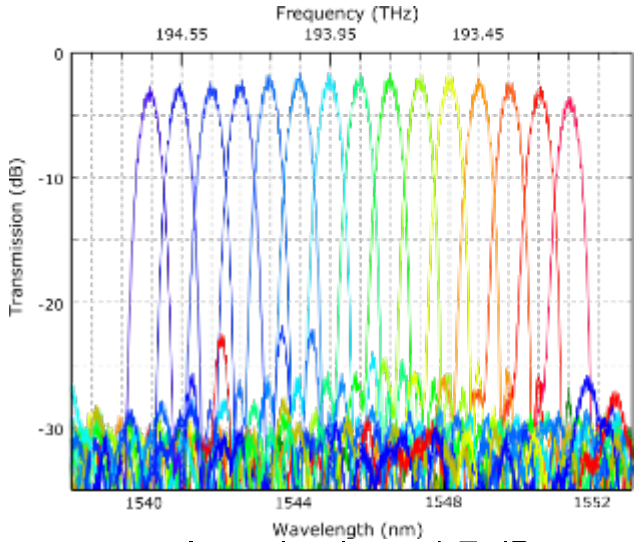
Bending



Star Coupler

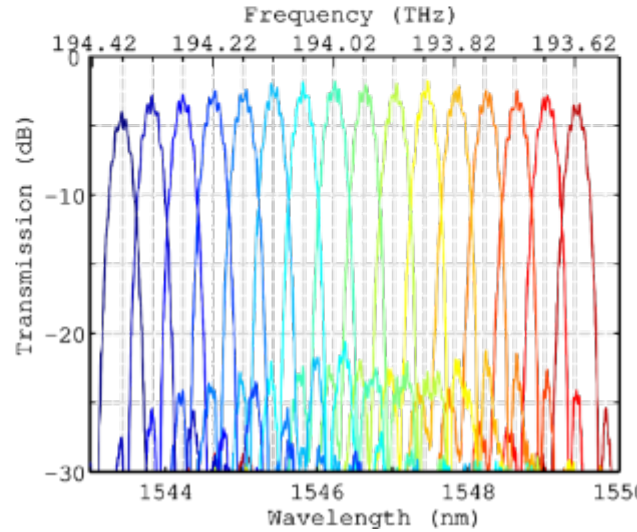
Arrayed Waveguide Gratings – Fabricated Device Transmitted Spectrum Measurements

16 ch X100 GHz AWG



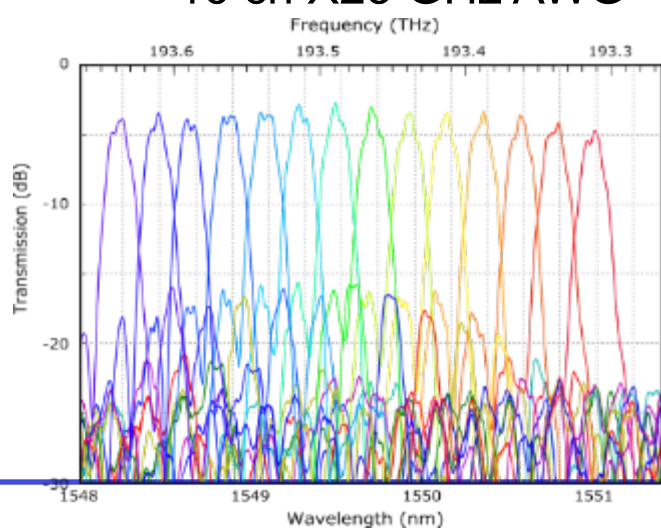
Insertion loss: 1.7 dB
Crosstalk: -21 dB

16 ch X50 GHz AWG

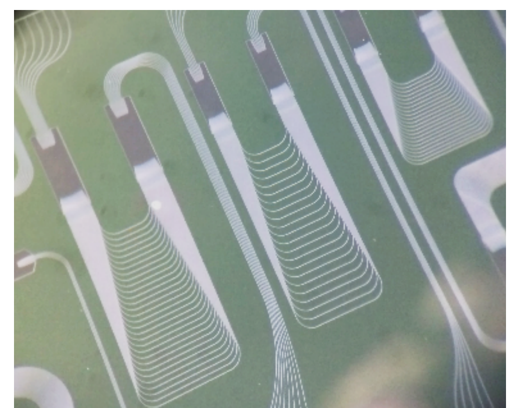


Insertion loss: 1.8 dB
Crosstalk: -20 dB

16 ch X25 GHz AWG

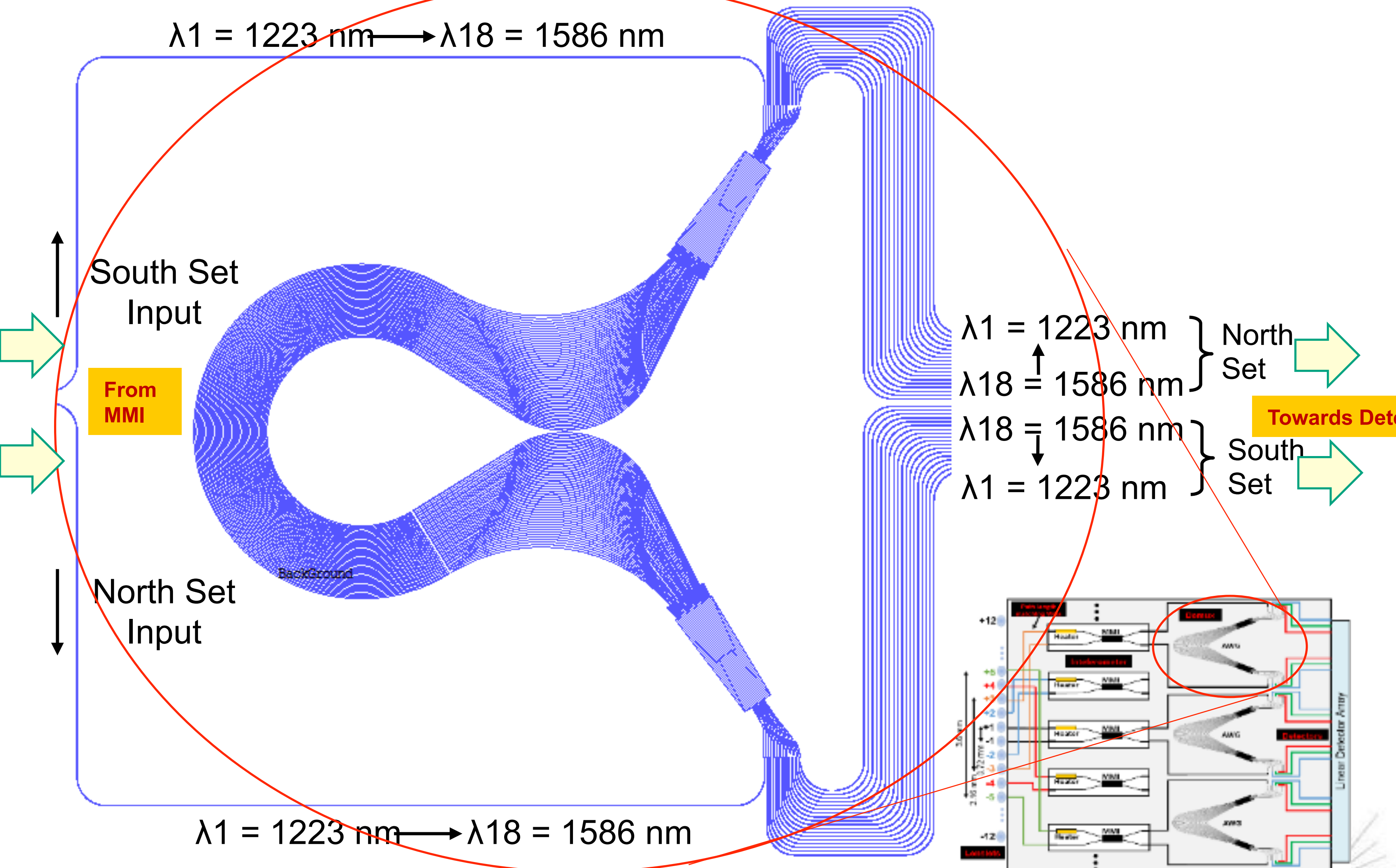


Insertion loss: 2.7 dB
Crosstalk: -13 dB



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

Symmetric Dual Arm Design for Interfacing with Mach-Zehnder Interferometer



WL (nm)
1223
1240
1257
1275
1293
1311
1331
1350
71
1392
1413
1436
1459
1483
1507
1533
1559
1586

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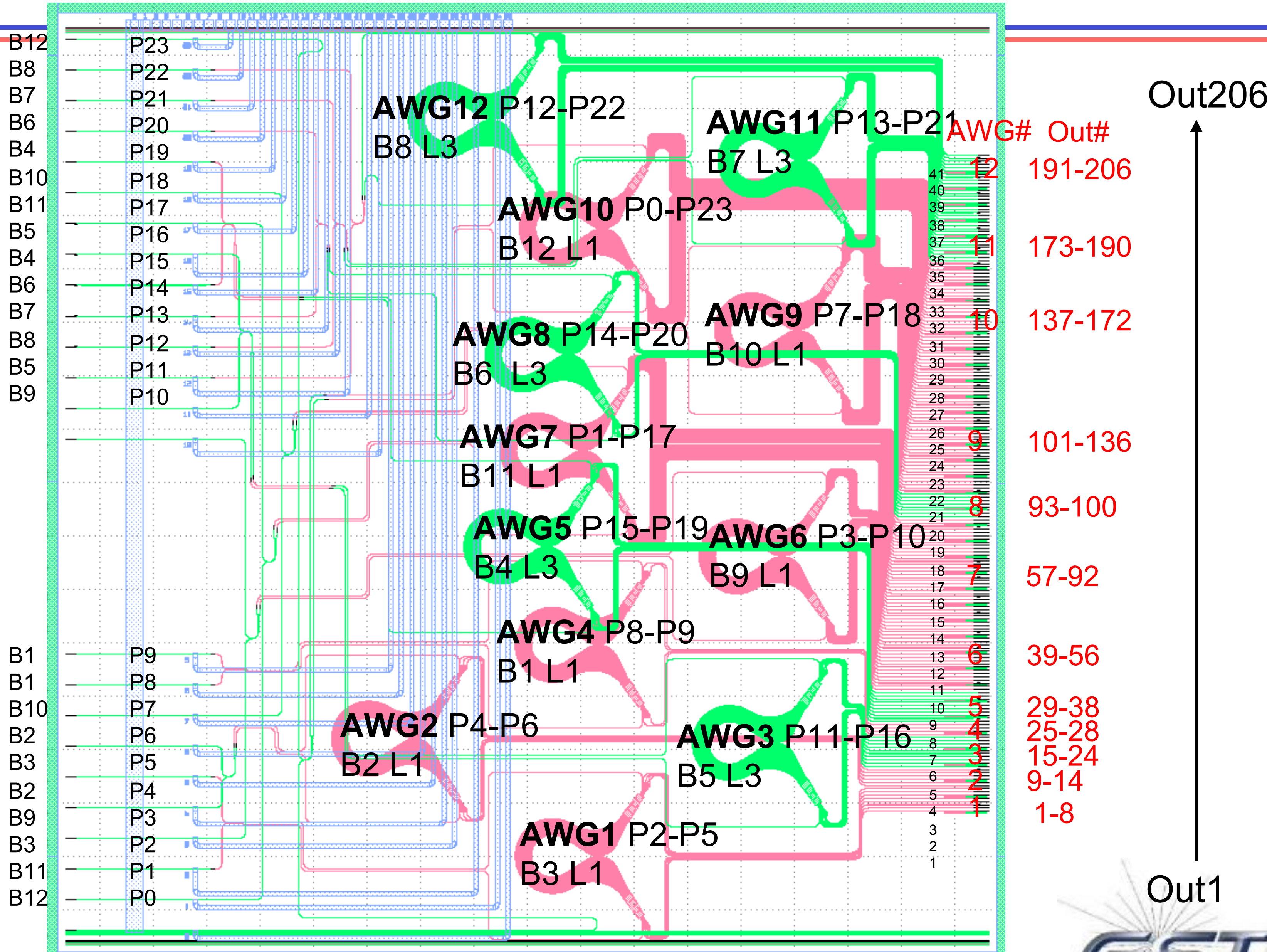
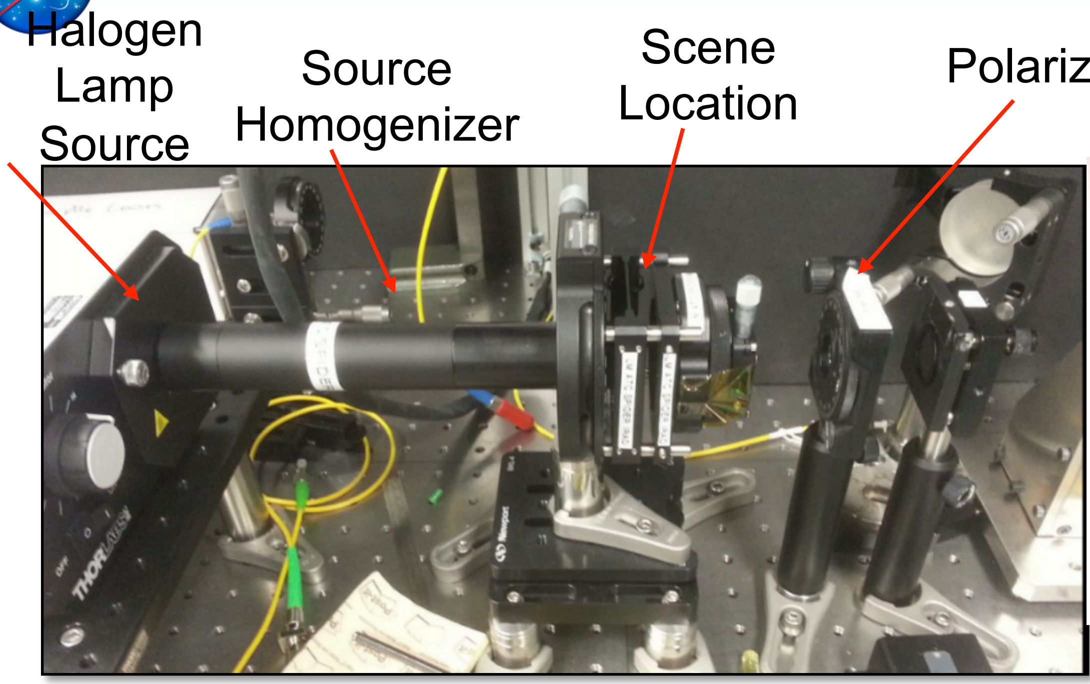
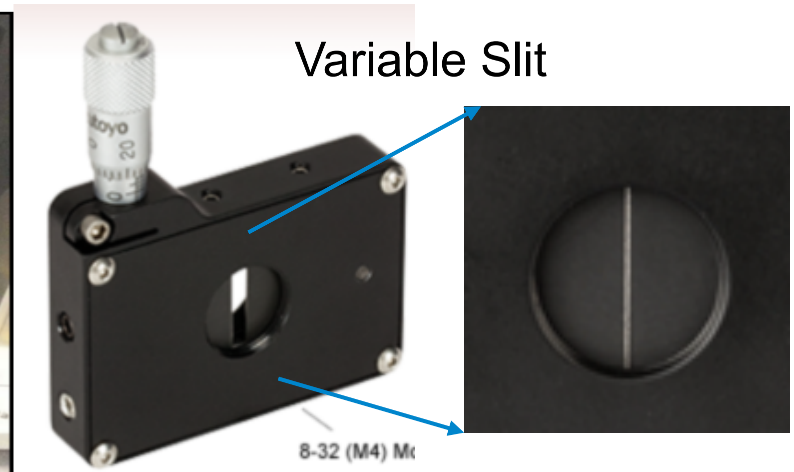
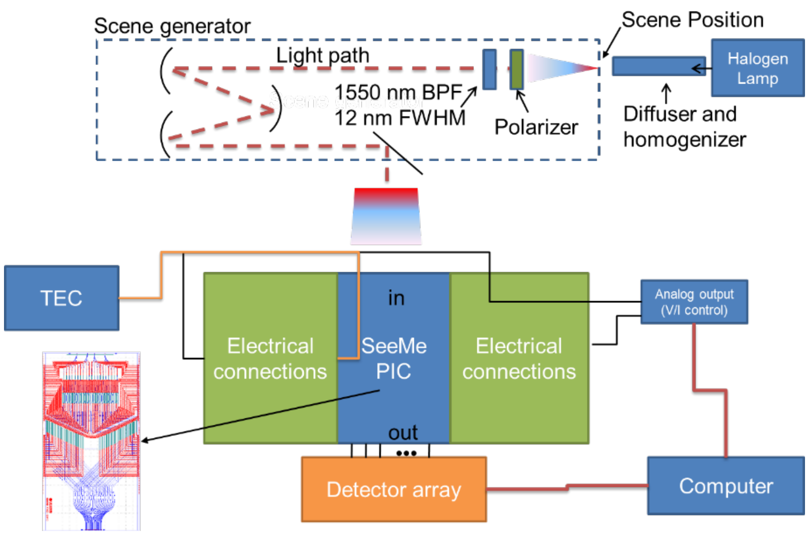
Our New SPIDER PIC Design and Layout



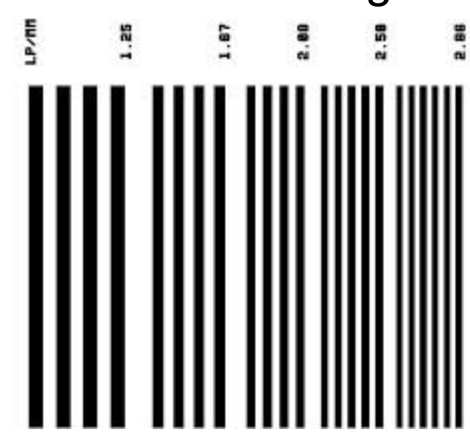
Scene Generation and Imaging Experiments





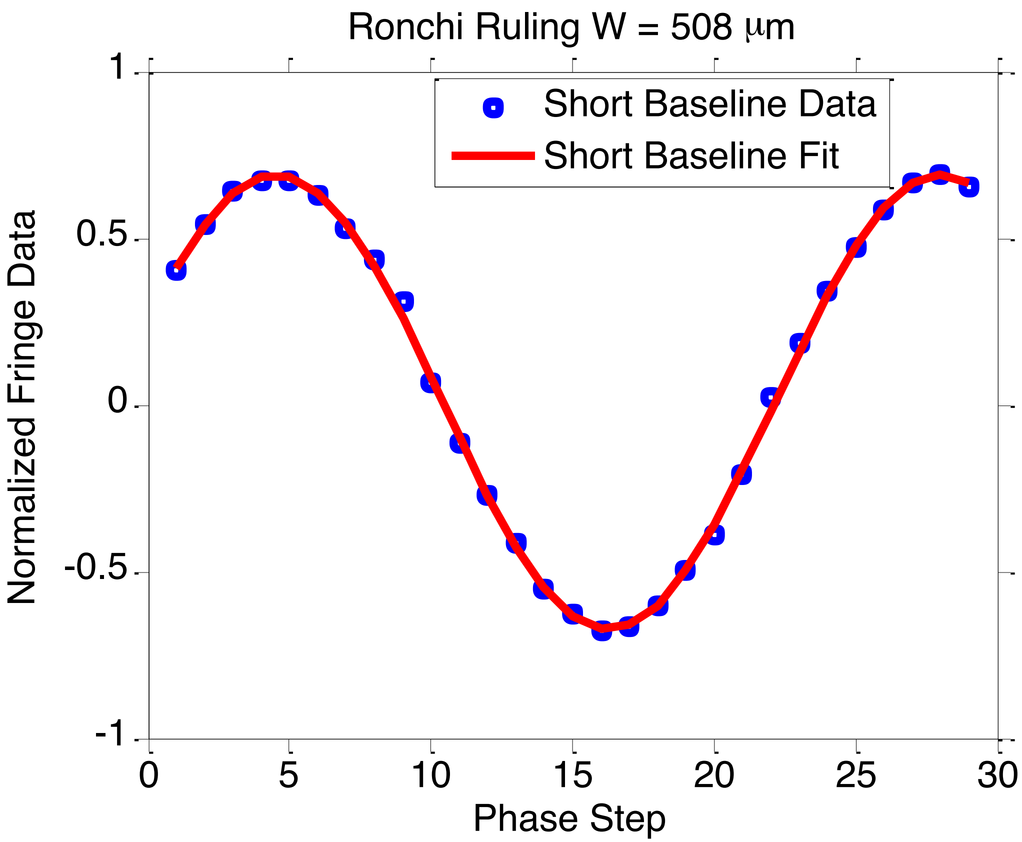


Ronchi rulings



Ronchi Ruling – 5 mm Baseline

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



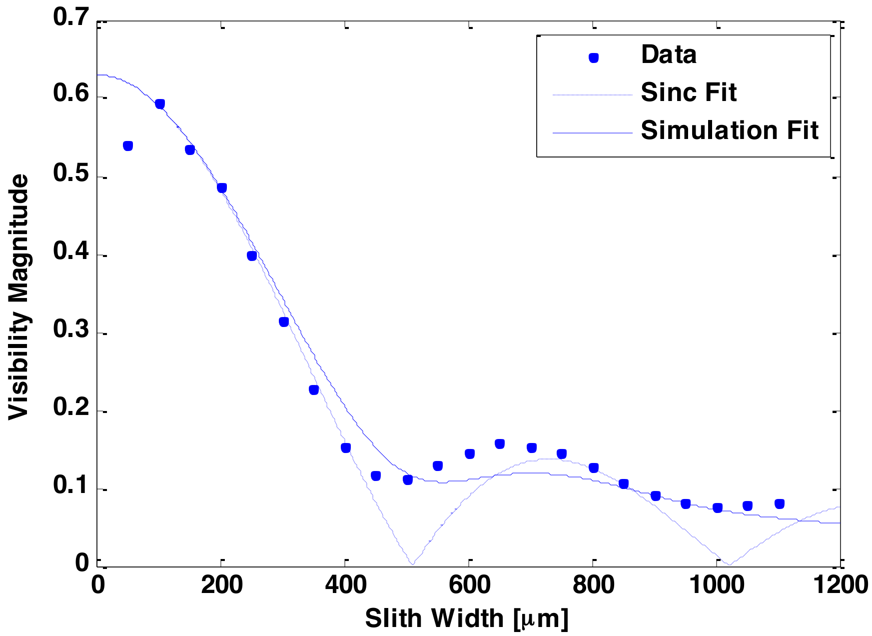
After a sinusoidal fit:

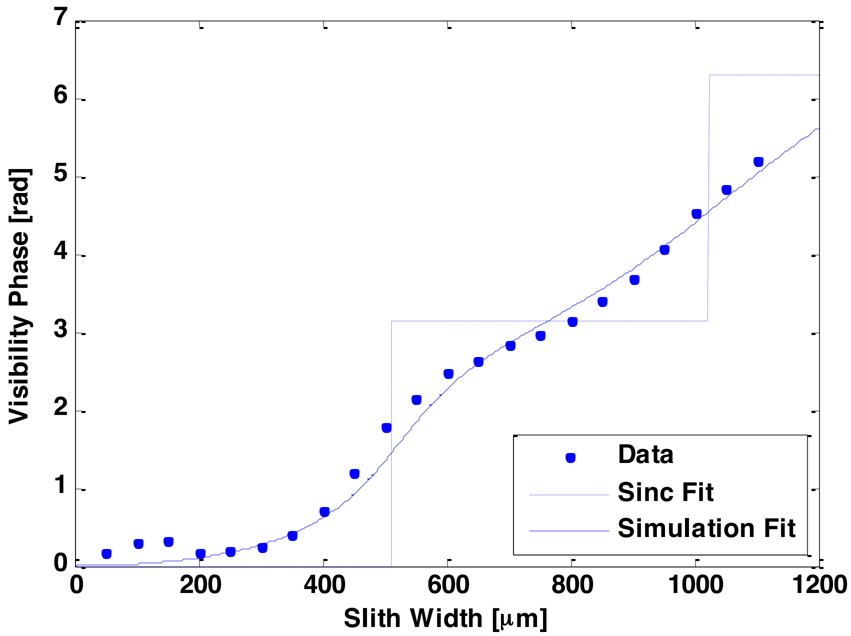
- **The amplitude is 0.75**
- **The RMSE of the fit is 0.017**
- **Estimated signal to noise ratio for a single data point is 44**
- **Estimated SNR of the amplitude would be 44×sqrt(29/4) = 118**
- **The visibility should be close to 50% for this case**

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

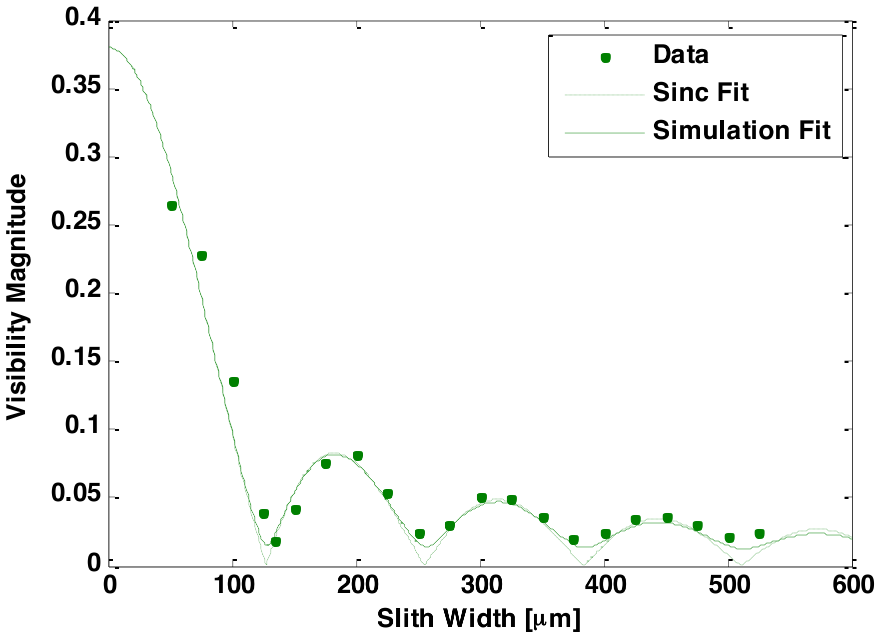
- **Curve Fit shows Offset = 300 μm (Suspect there is an additional offset between the individual lenslet FOV's)**
- **In the future, measure photometric signal levels for individual lenslets to obtain direct information about offset**





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



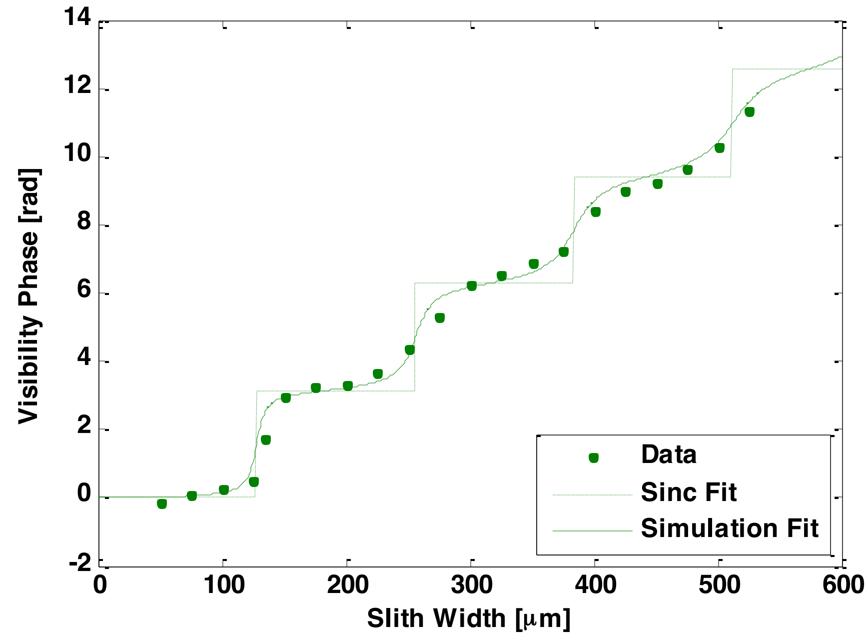
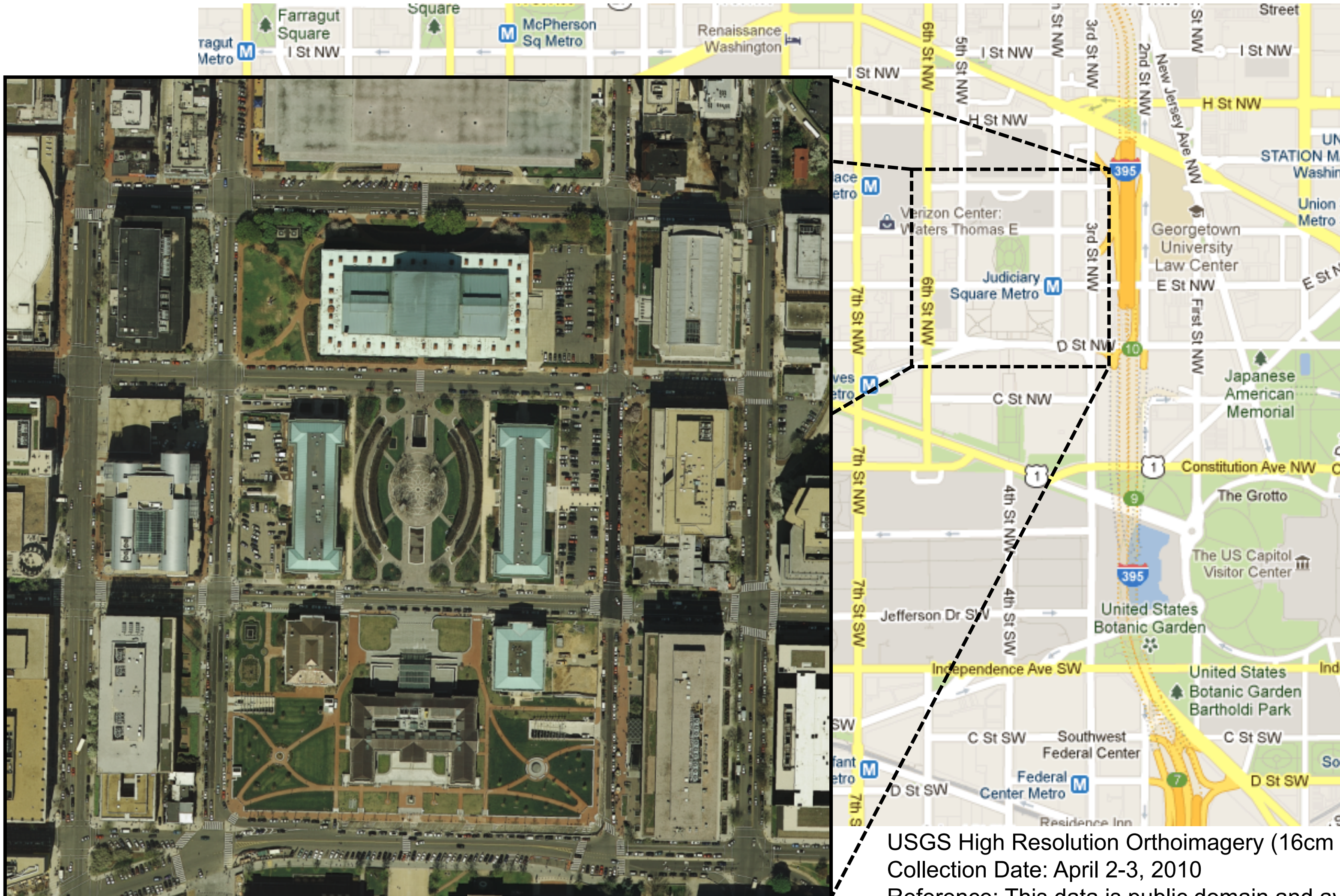


Image Reconstruction Simulations: Scene Data used for Imager Simulations

Judiciary Square, Washington, D.C.

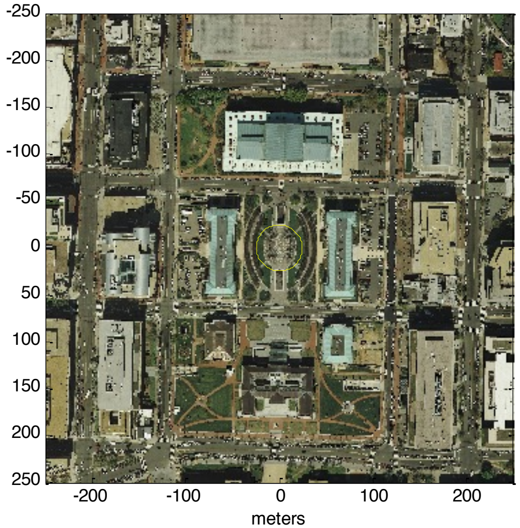


USGS High Resolution Orthoimagery (16cm GSD)
Collection Date: April 2-3, 2010
Reference: This data is public domain and available from the United States Geological Survey through http://nationalmap.gov.

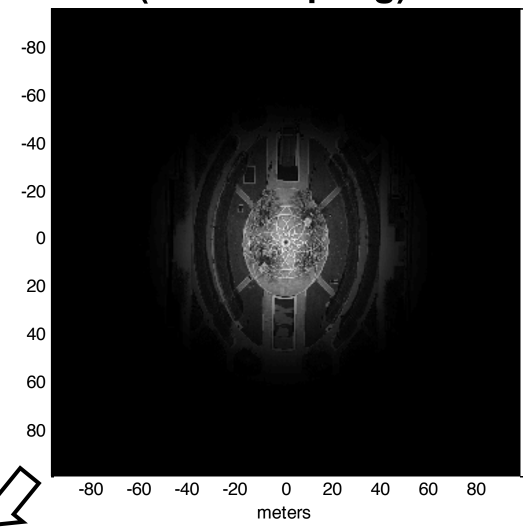
Lockheed Martin IRAD work

Simulation for a Single Sub-Image

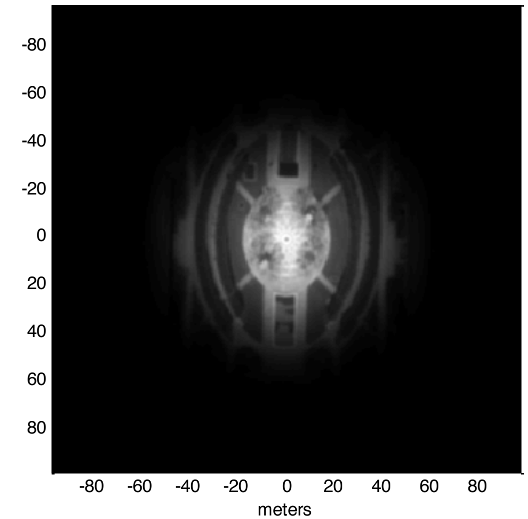
1. User selects FOV for sub-image



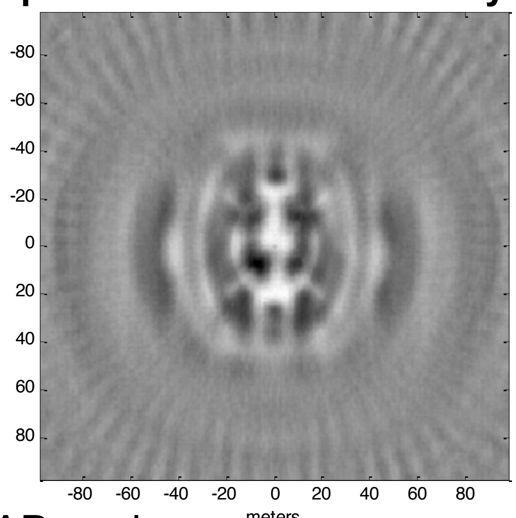
2. Crop scene and apodize (fiber coupling)



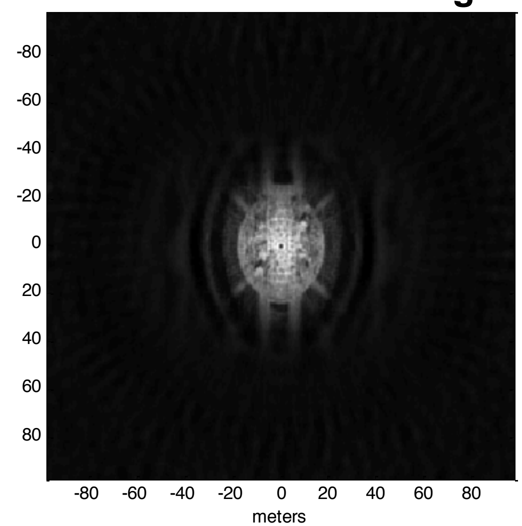
3. Make a conventional comparison sub-image



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



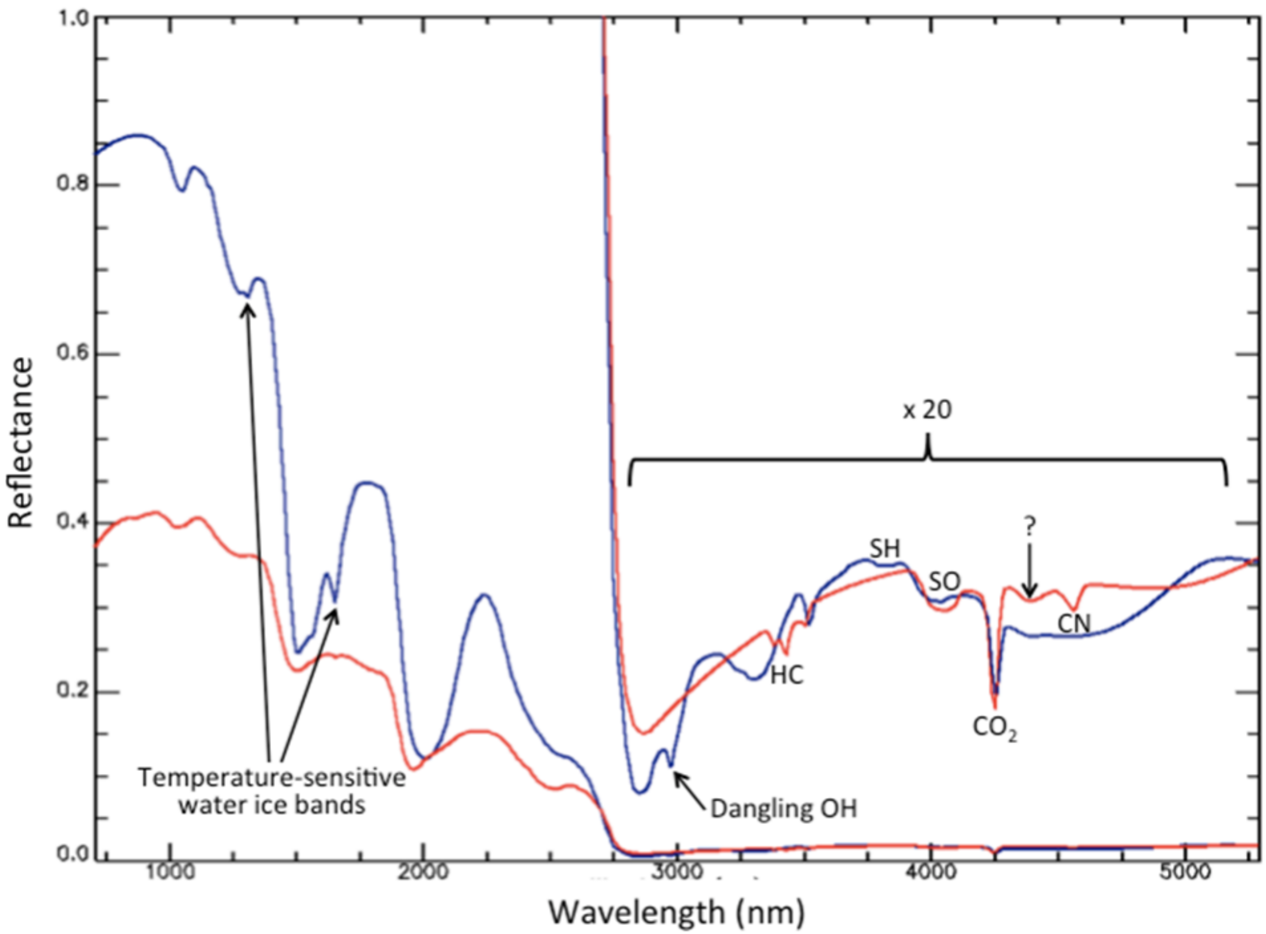
5. Reconstruct sub-image



Lockheed IRAD work

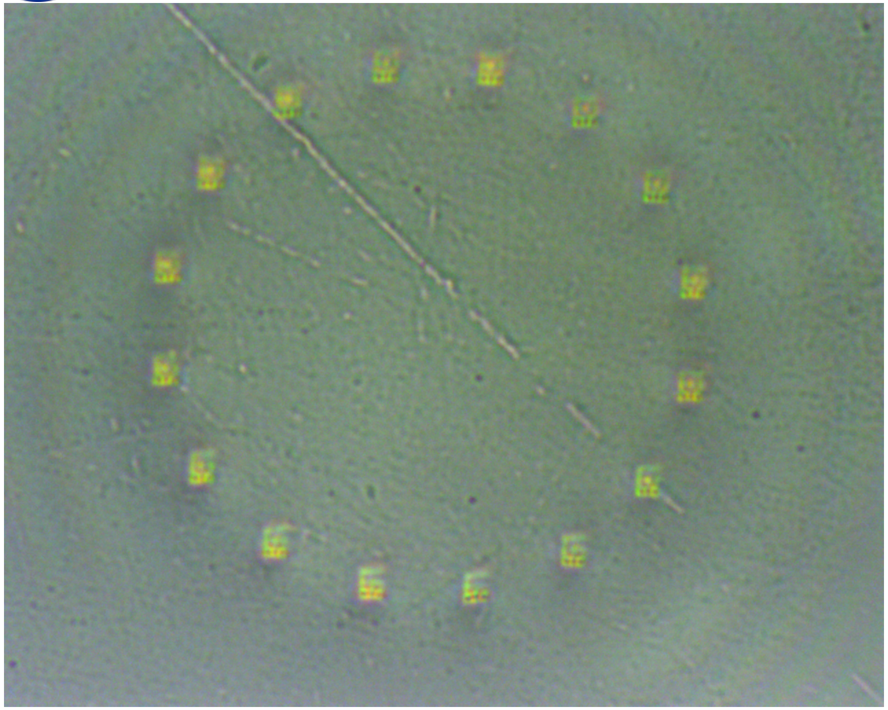
Motivation for MWIR and LWIR

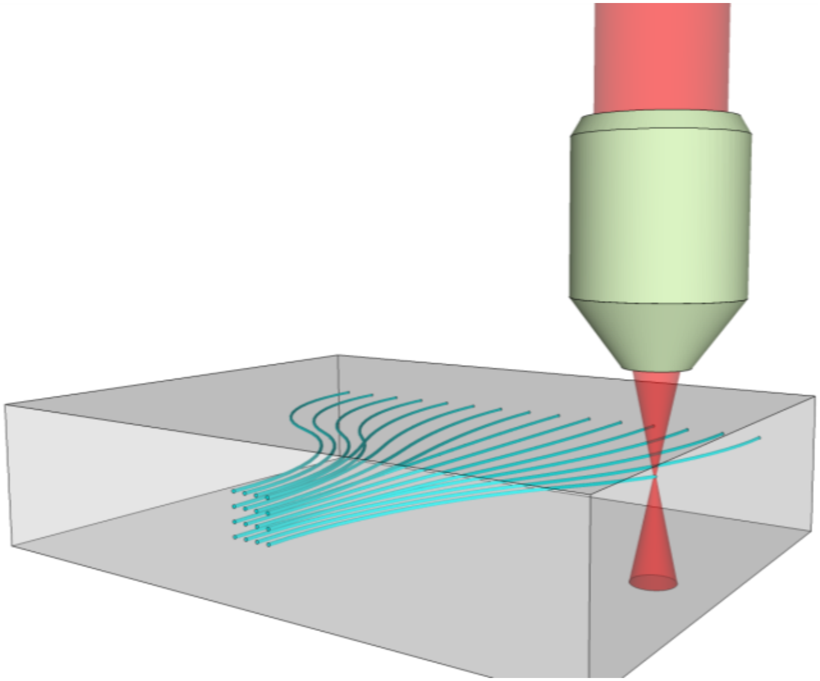
"Notional reflectance spectra for ice-rich regions (blue curves) and ice-poor regions (red curves) on Europa … in the 1–5 μm spectral range."

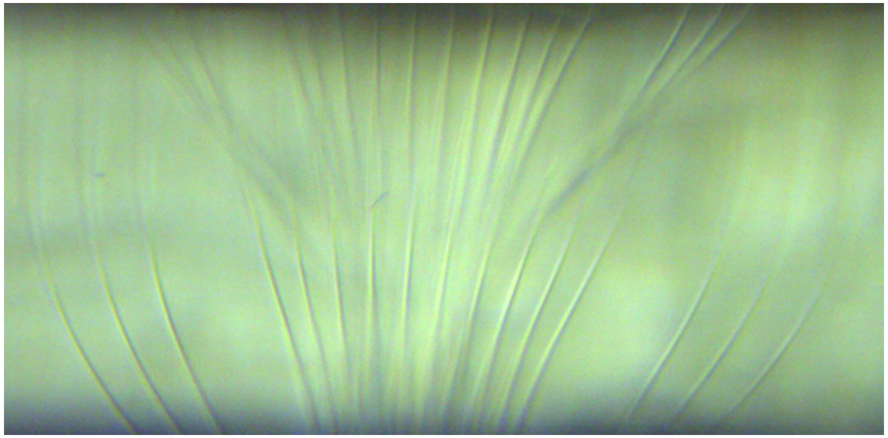


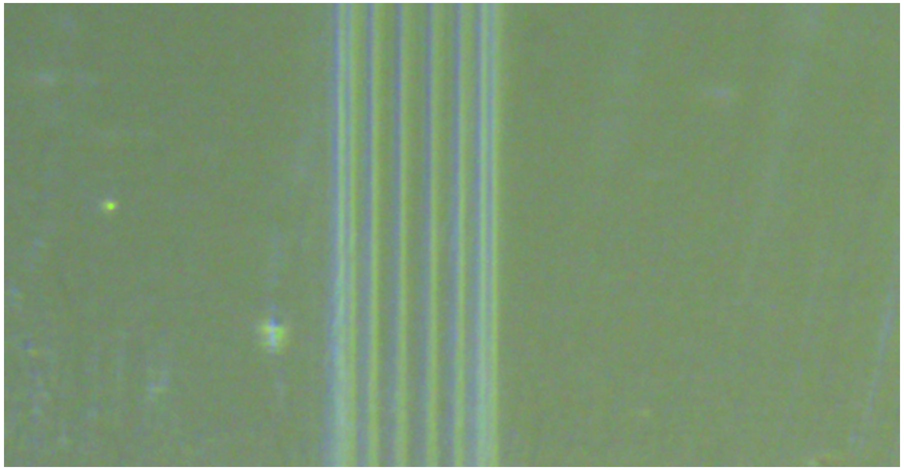
Europa Study 2012 Report – Europa Multiple Flyby Mission, JPL D-71990 (2012)

3D Integrated Photonics by Ultrafast Laser Inscription

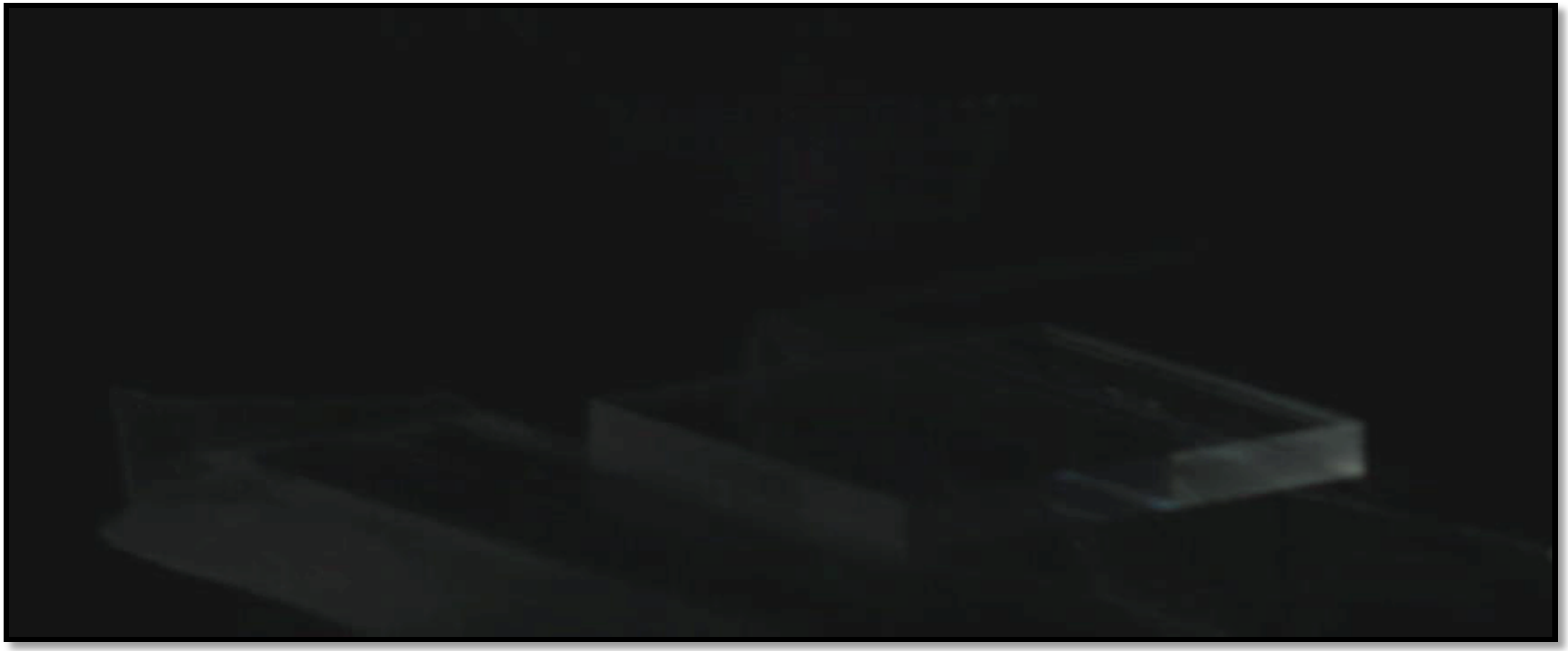








3D Waveguide Writing at UC Davis

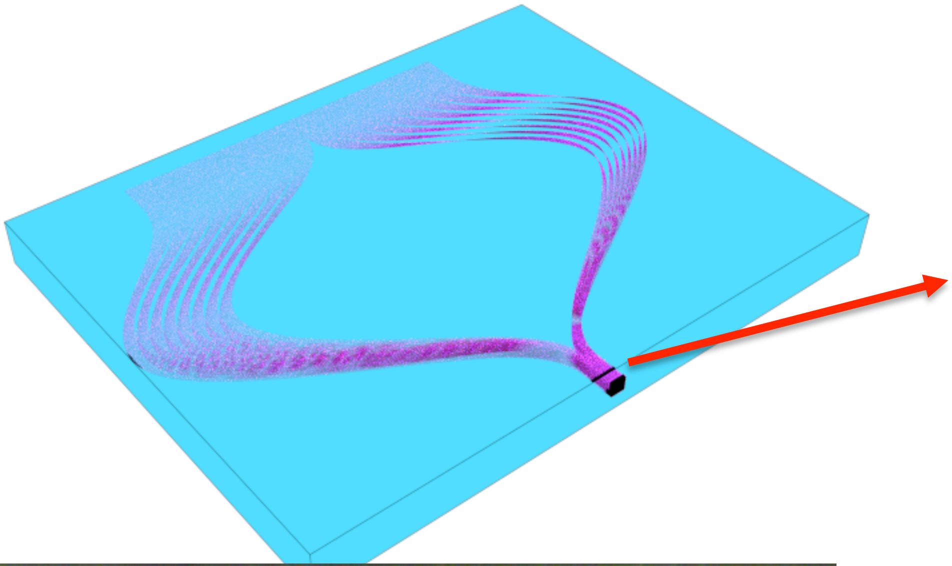


~150 mm/s writing speed

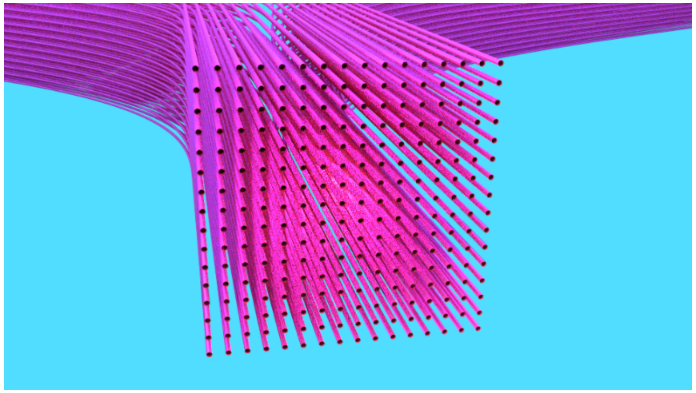
Precision and Low Loss 3D waveguide Fabrication by fs Laser Inscription

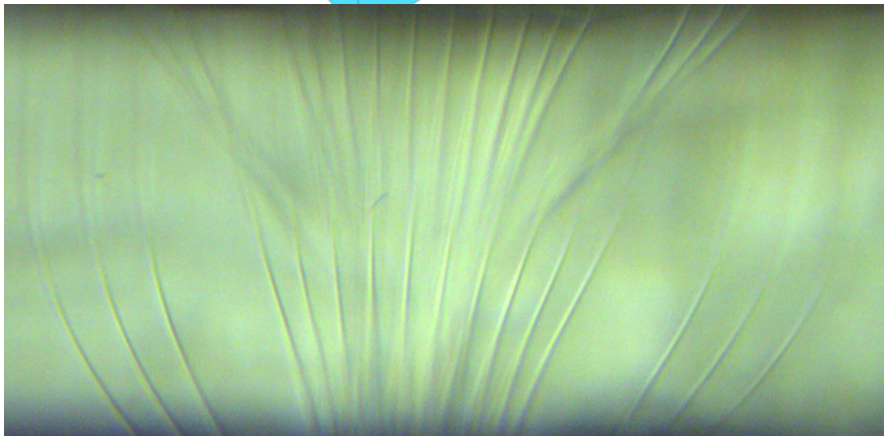
3D waveguides CAD Design

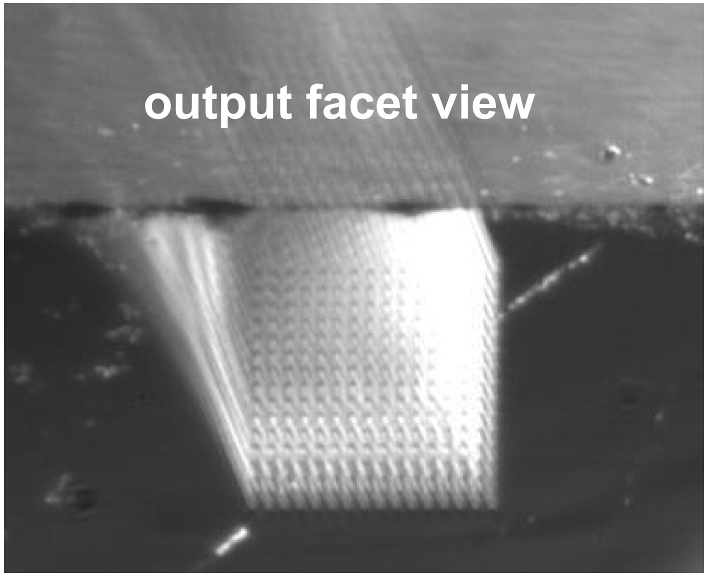
Accuracy at 10 ppb



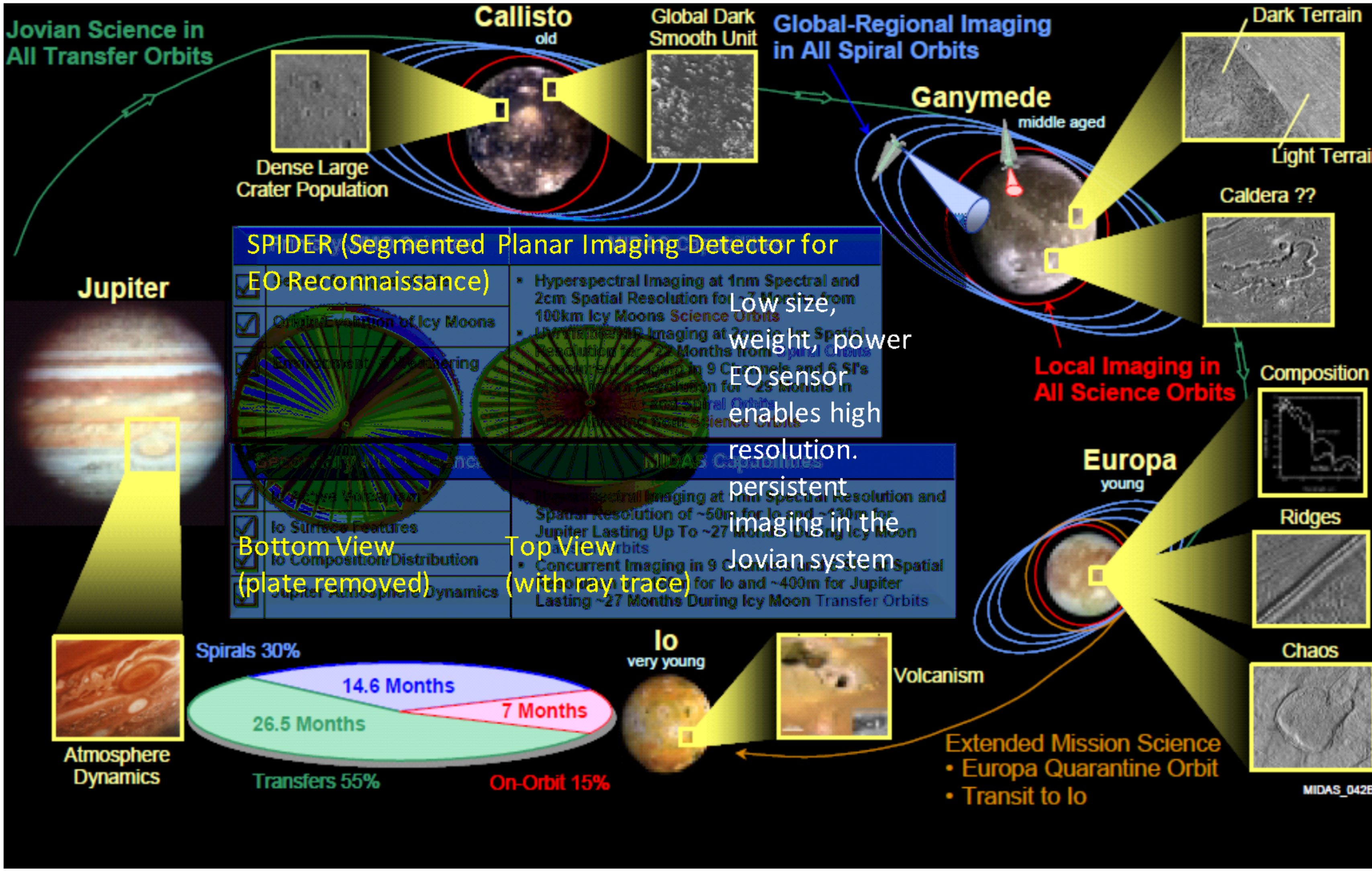
3D waveguides output pattern





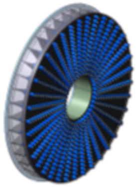


Possible Impacts on SLI-T
Ref: Jupiter Icy Moons Orbiter Reference Mission

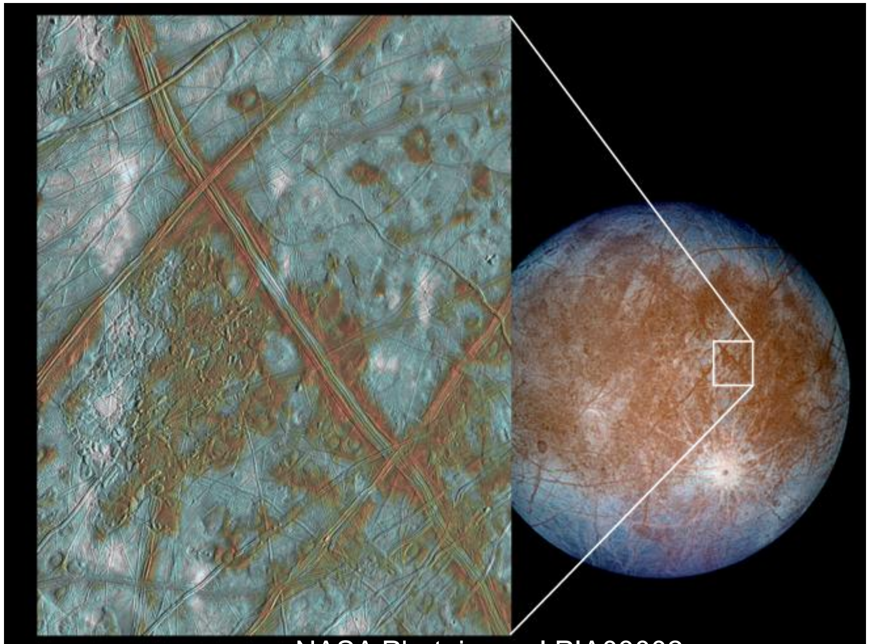


Possible Impacts on SLI-T
Ref: SPIDER-based Topographical Imager (TI)

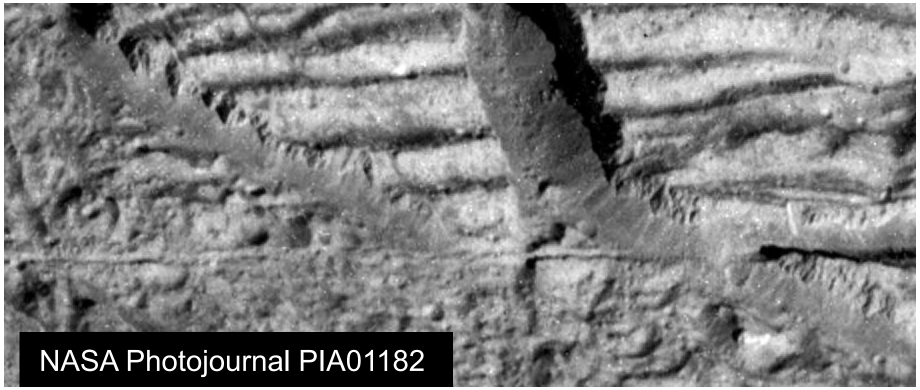
- **SPIDER Topographical Imager**
  - **4 cm diameter aperture (same enclosure)**
  - **15 µrad IFOV → 1.5 m Ground-Sampled-Distance (GSD) at 100 km**
  - **10 Mpixel area, 150-ms integration time**



For the same enclosure, SPIDER could collect 10× the area on ground with 17× the resolution


NASA Photojournal PIA03002

NASA Photojournal PIA00589


NASA Photojournal PIA01182

Possible Impacts on SLI-T
Ref: Traditional Topographical Imager

Europa Study 2012 Report – Europa Multiple Flyby Mission, JPL D-71990 (2012)

- **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**

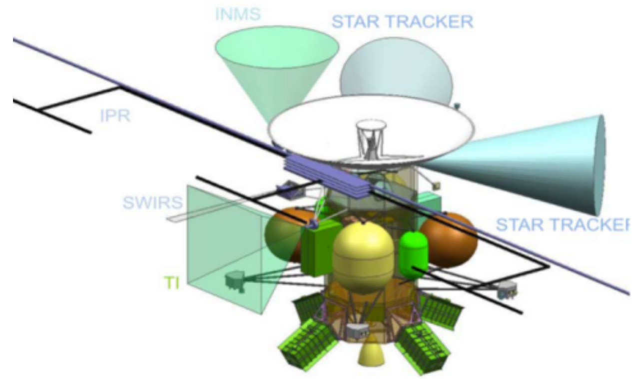
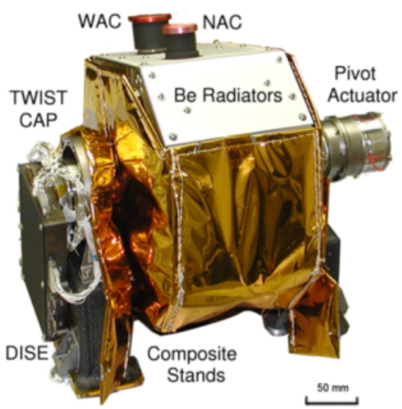
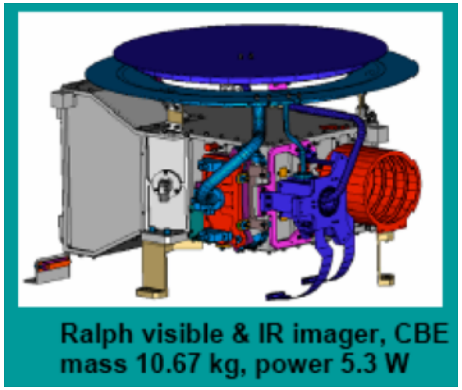


Figure C.2.2-1. Notional model payload accommodation and fields of view.

Similar Imagers

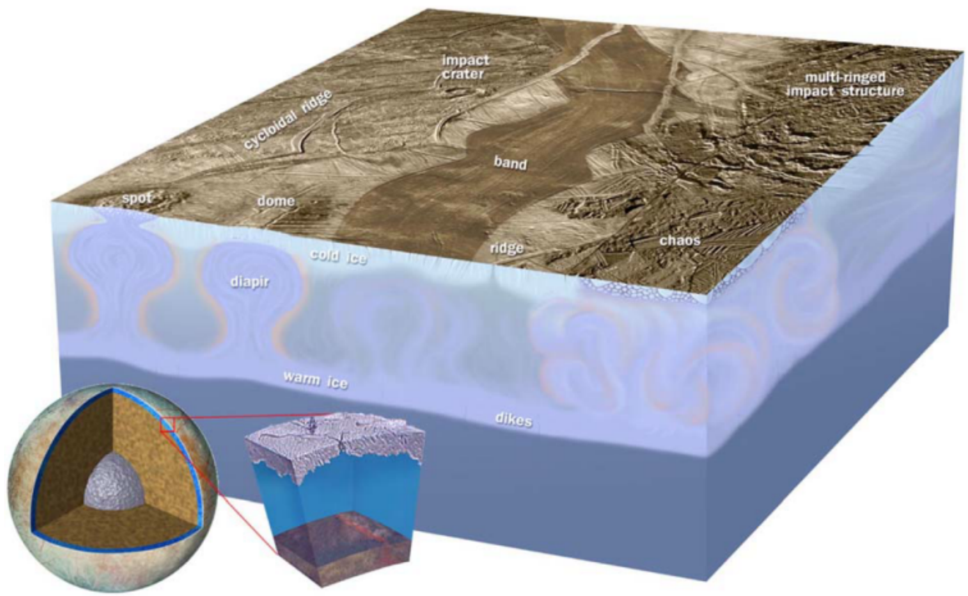


MRO Mars Color Imager (MARCI)



New Horizons Multi-spectral Visible Imaging Camera (MVIC)

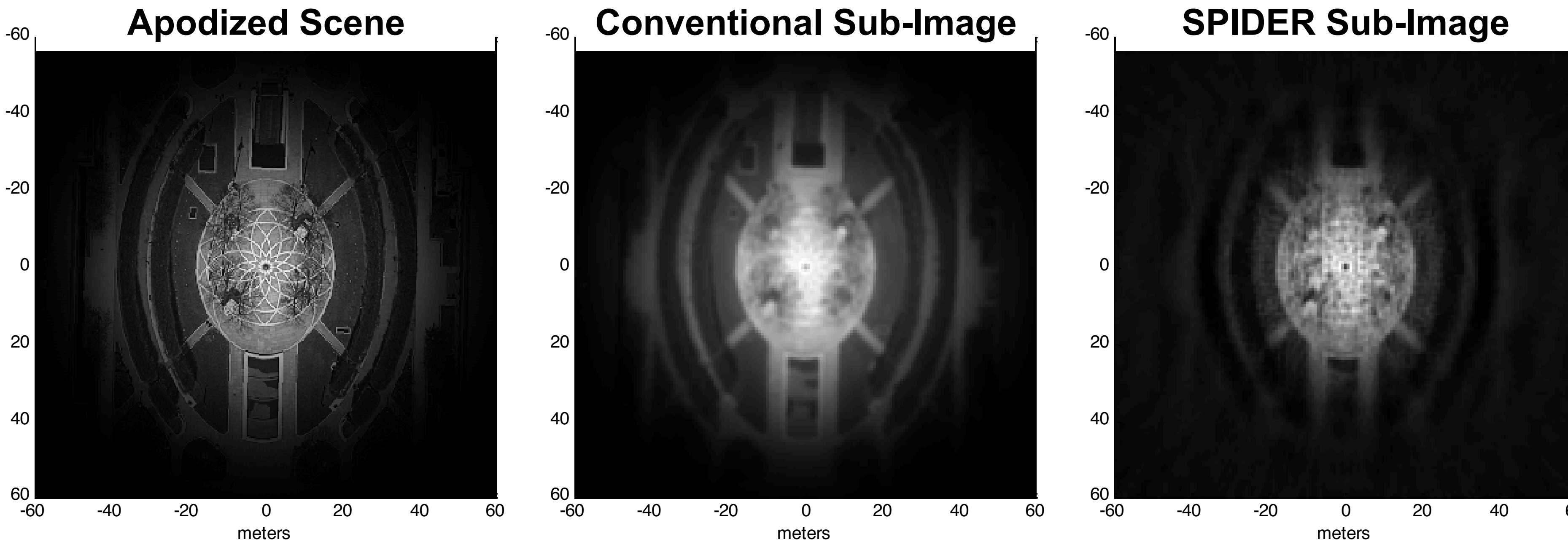
Diagram of Europa's ice shell



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



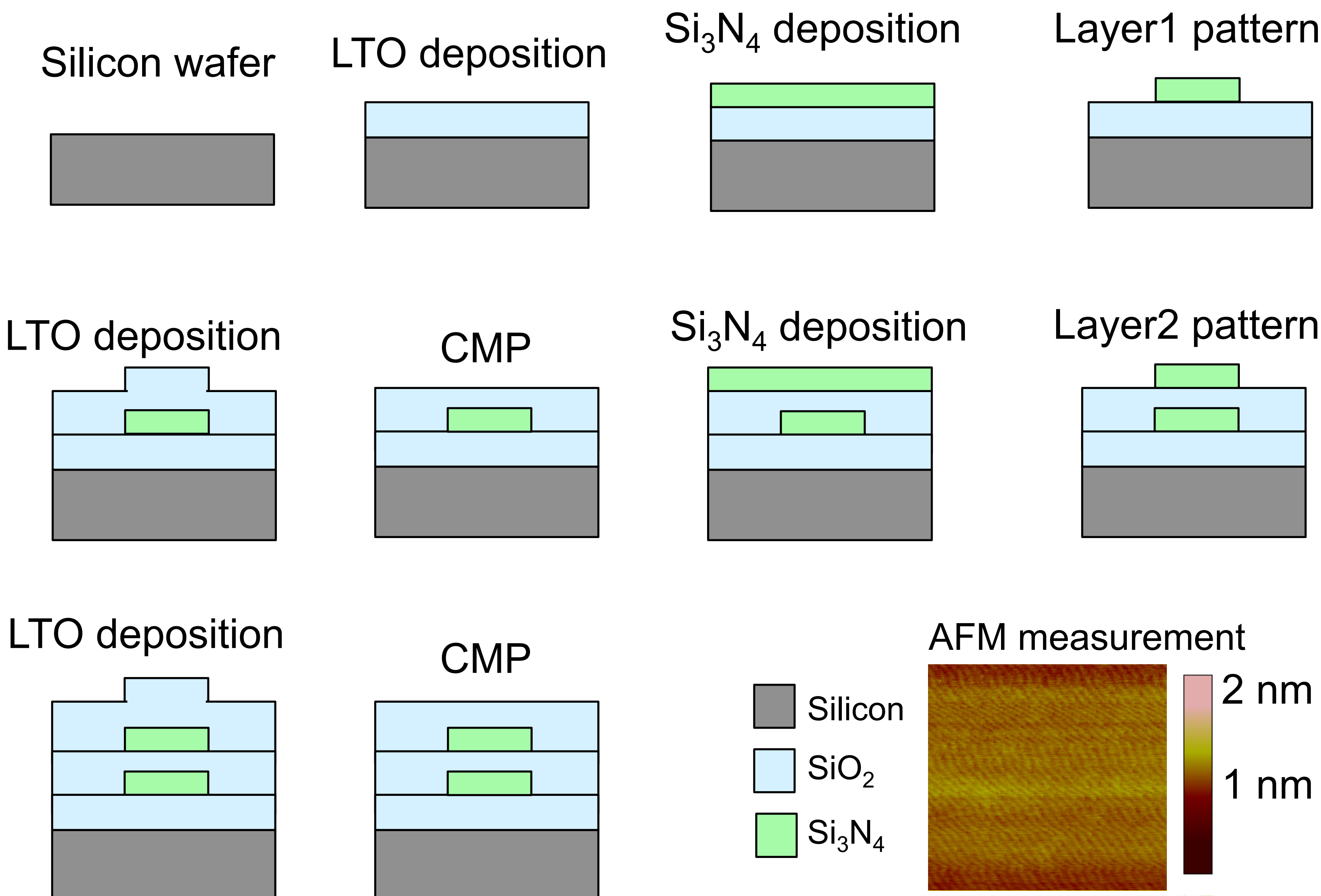
*No Wiener filter applied

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

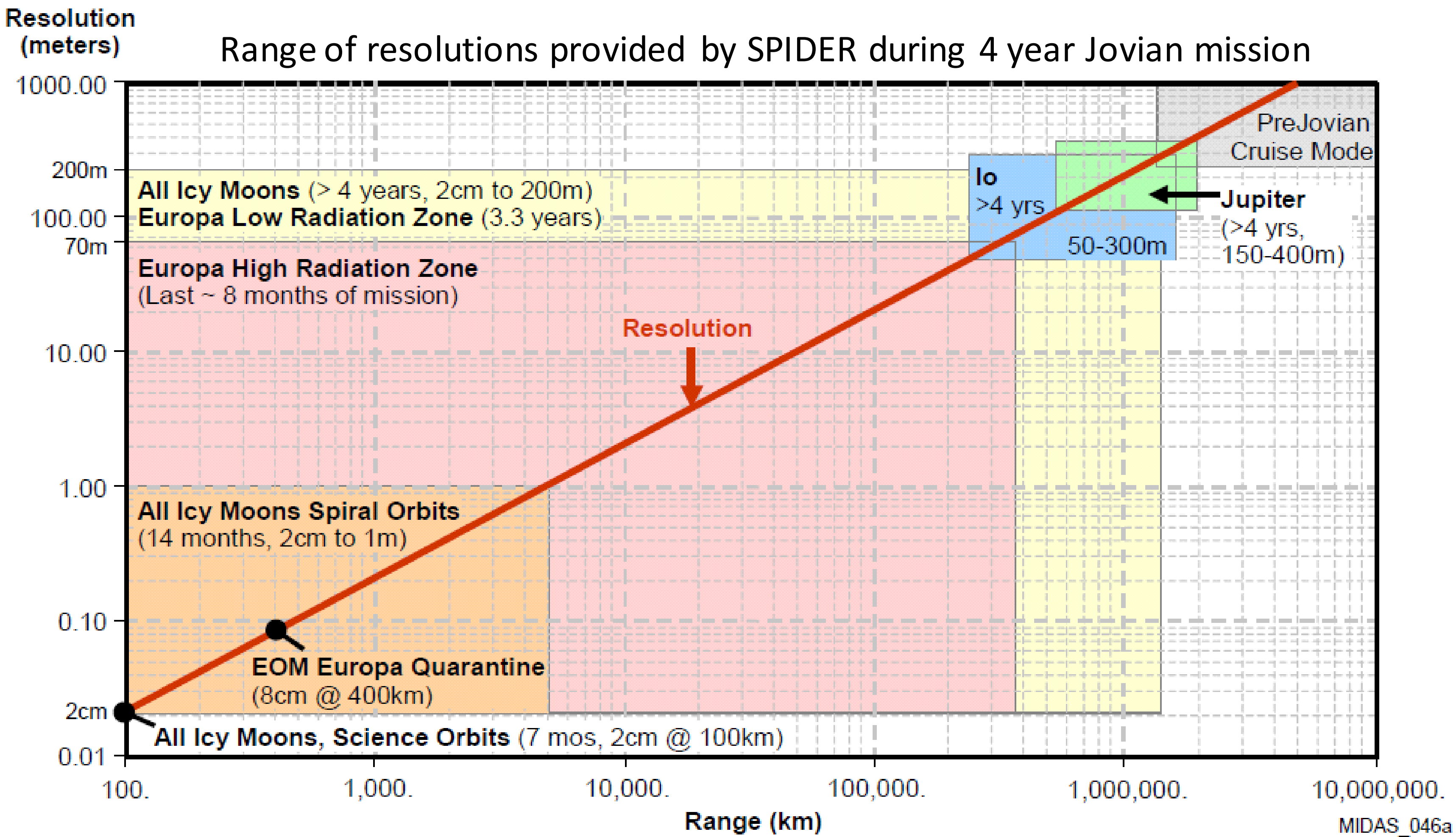
Lockheed Martin IRAD work

Multilayer 200nm Si_3N_4 PIC Platform – Fabrication Process



SPIDER Provides High Resolution Capability

1.5 m diameter aperture SPIDER

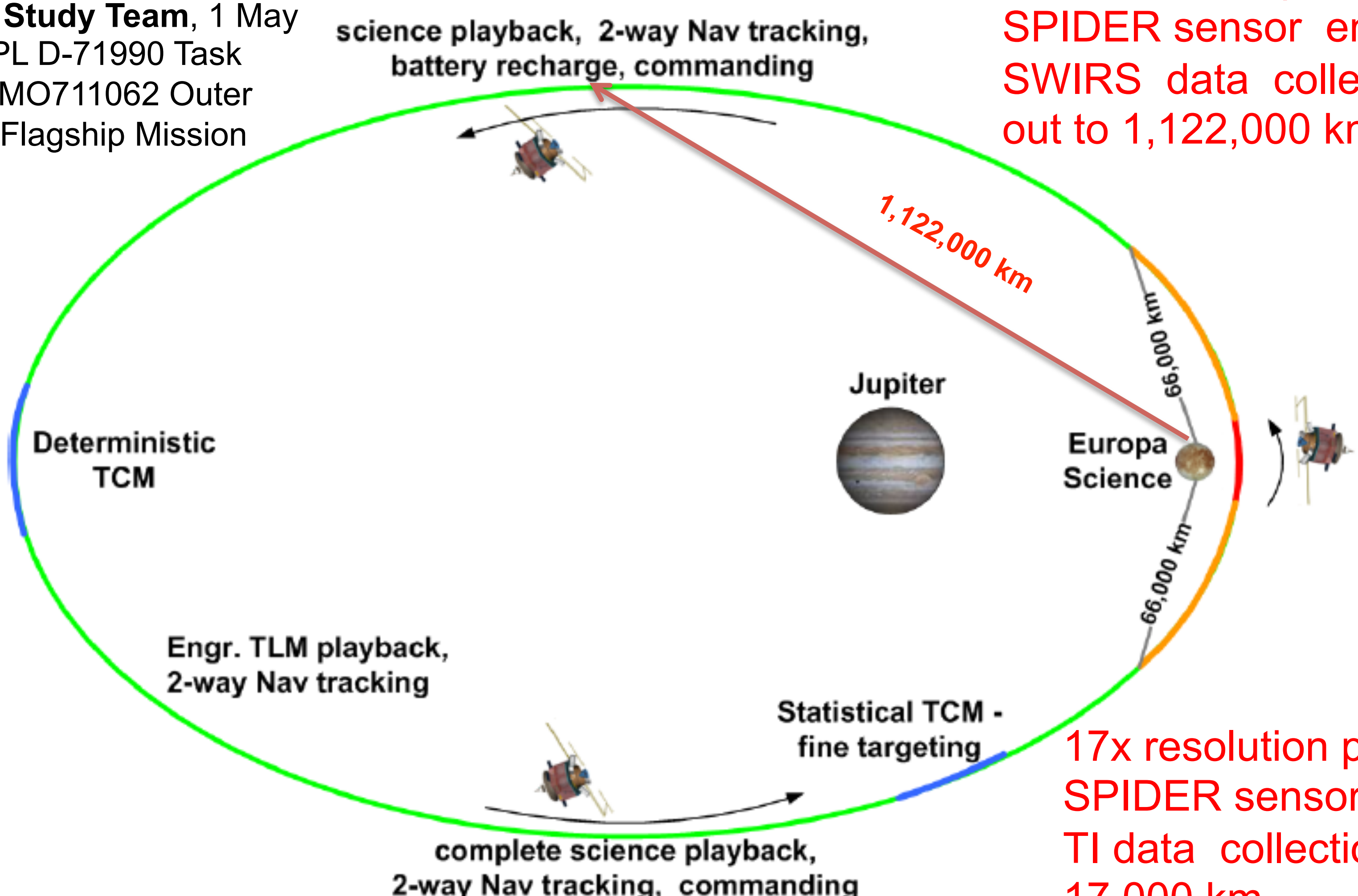


Europa Flyby Orbit

EUROPA STUDY 2012 REPORT — EUROPA MULTIPLE-FLYBY MISSION

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

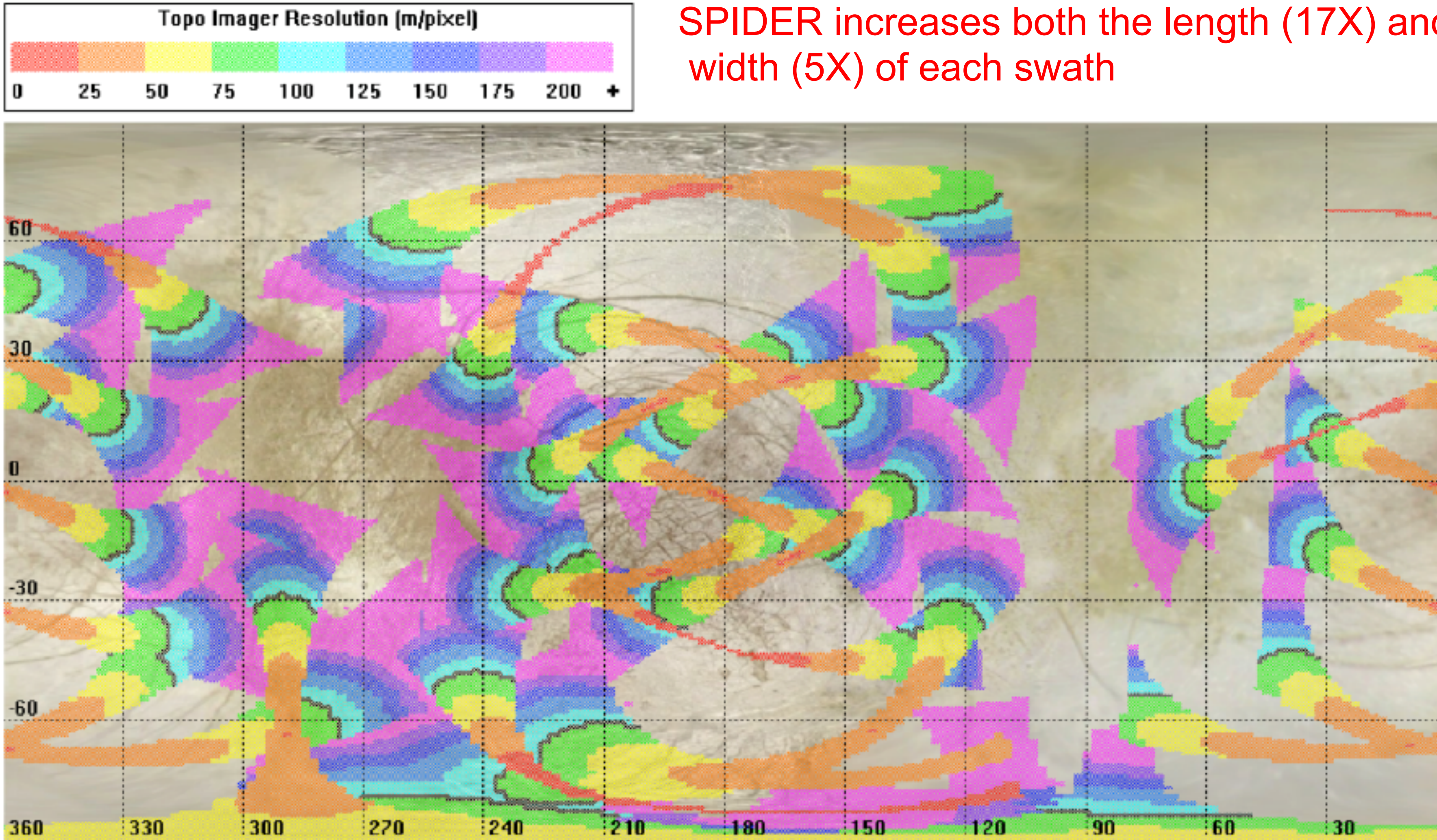
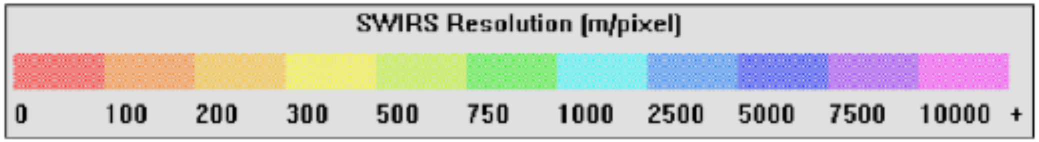


Figure C.2.5-6. TI instrument coverage.

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



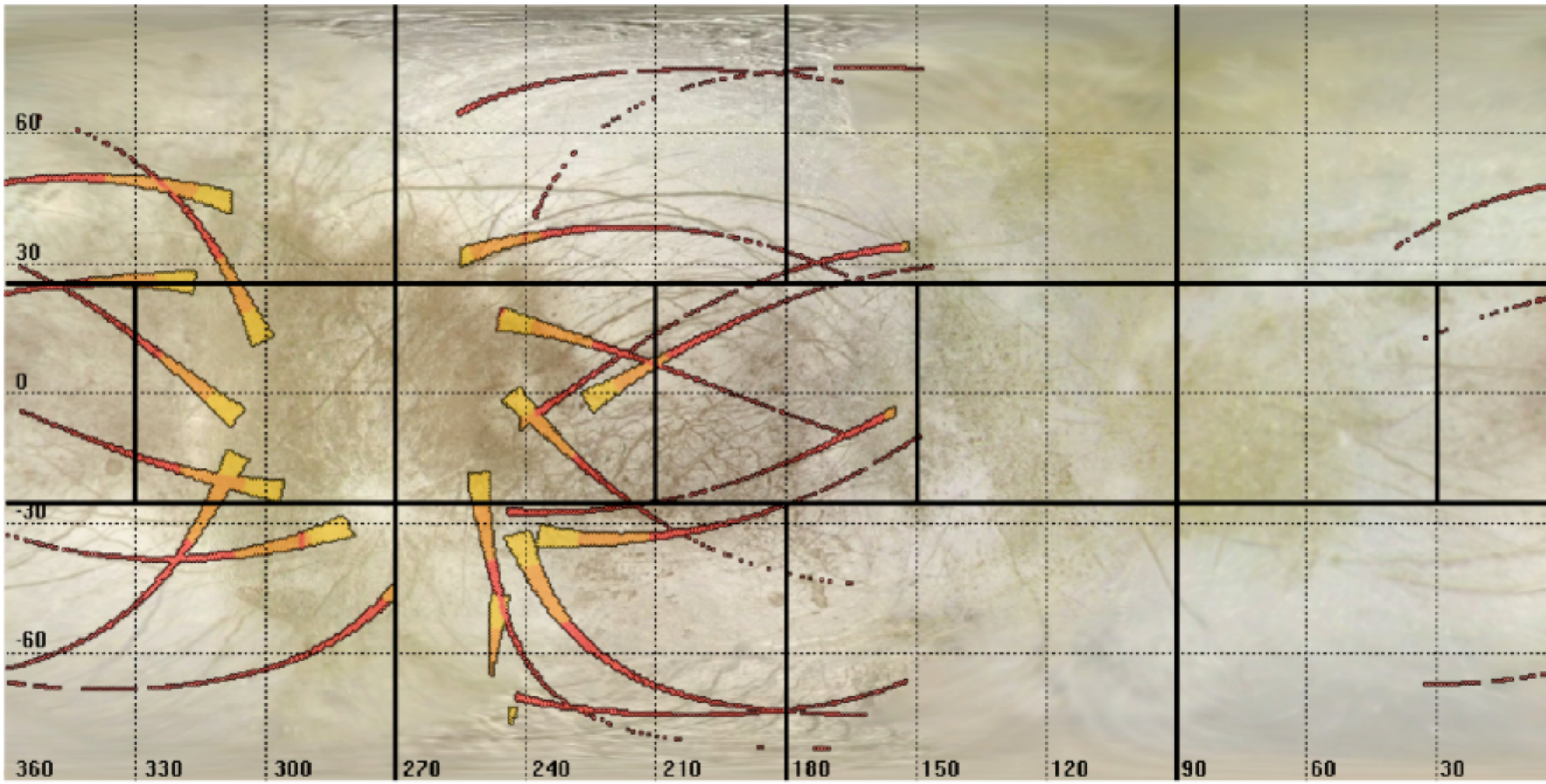
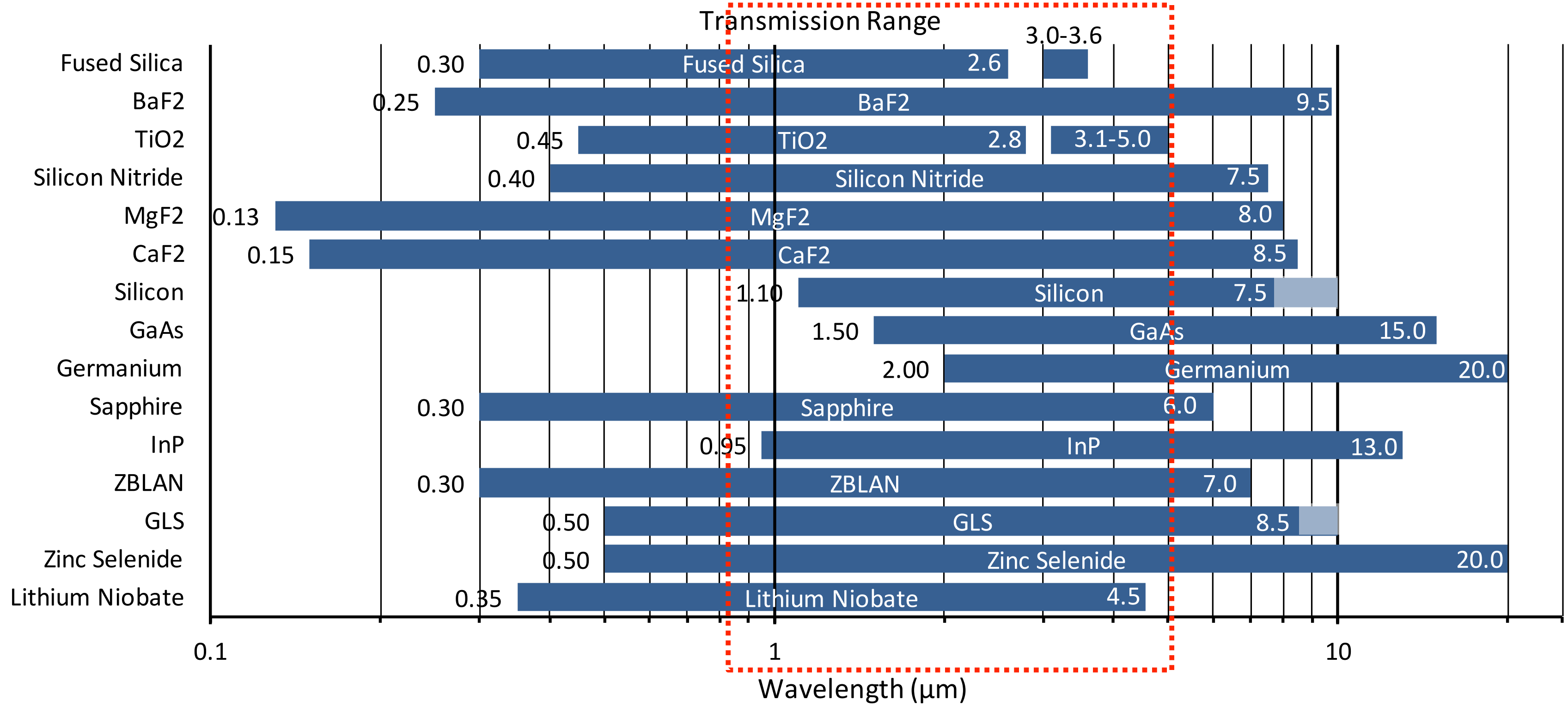


Figure C.2.5-4. SWIRS high-resolution coverage (under 2,000 km altitude).

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

Transmission Range of Selected Materials



Demonstrated Silicon/Silicon Nitride waveguides and InP/InGaAsP waveguides at 4.6 micron in Phase I