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

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# Future Imaging Systems with Low SWaP

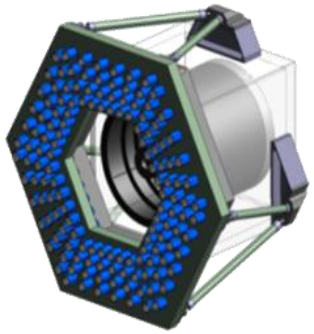
## Key to Affordability – Low SWaP

**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**

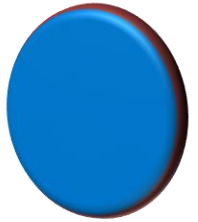


**SPIDER Ring Blade**
**Design:** Outer ring enhances resolution of conventional telescope

**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**

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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

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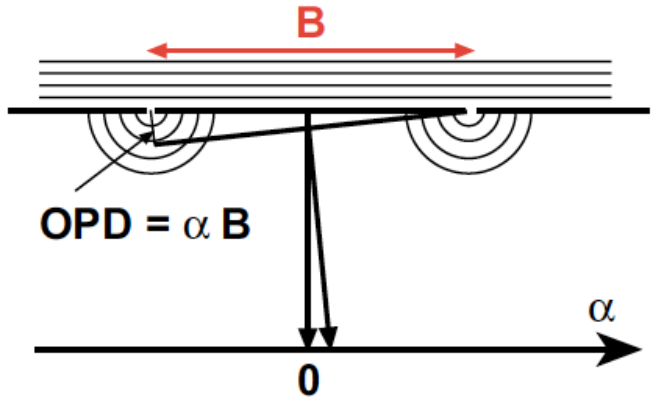
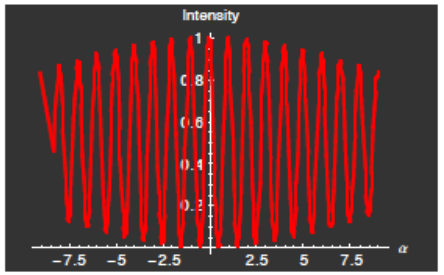
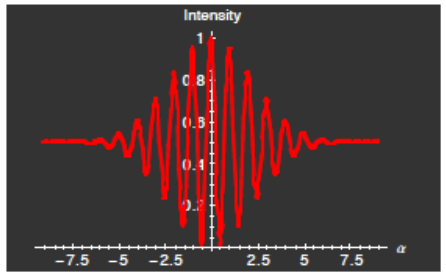
# Interferometric Imaging




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




(First and last picture of a movie)

- Light source at infinity at $\alpha = 0$
- Intensity pattern ~ 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

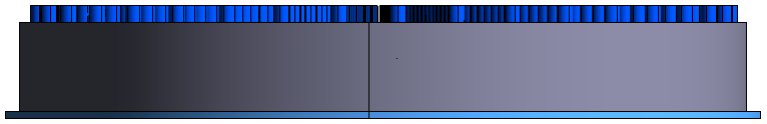
**Interferomic Telescopes**

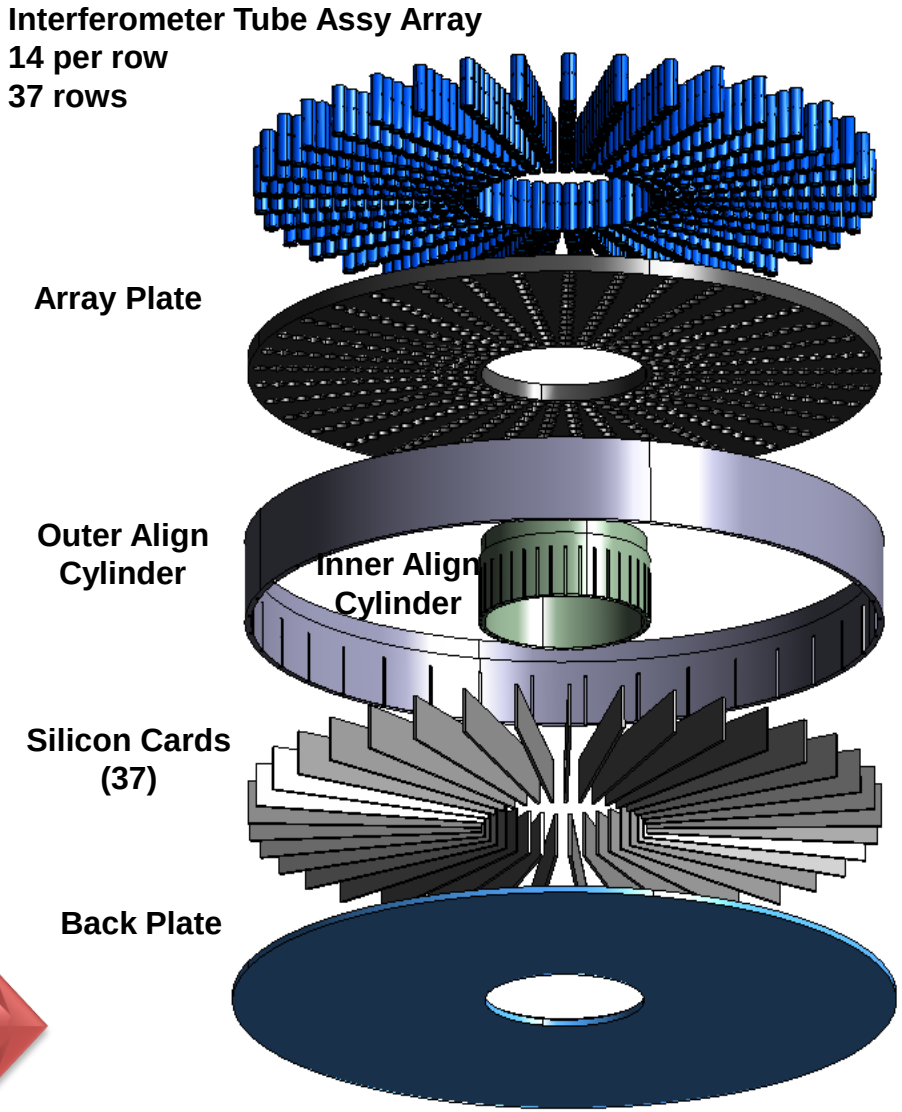
$$\Delta\theta \approx \frac{\lambda}{2B}$$

Figure Courtesy of Andreas Glindemann

# SPIDER: segmented planar imaging detector for electro-optical reconnaissance

- **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

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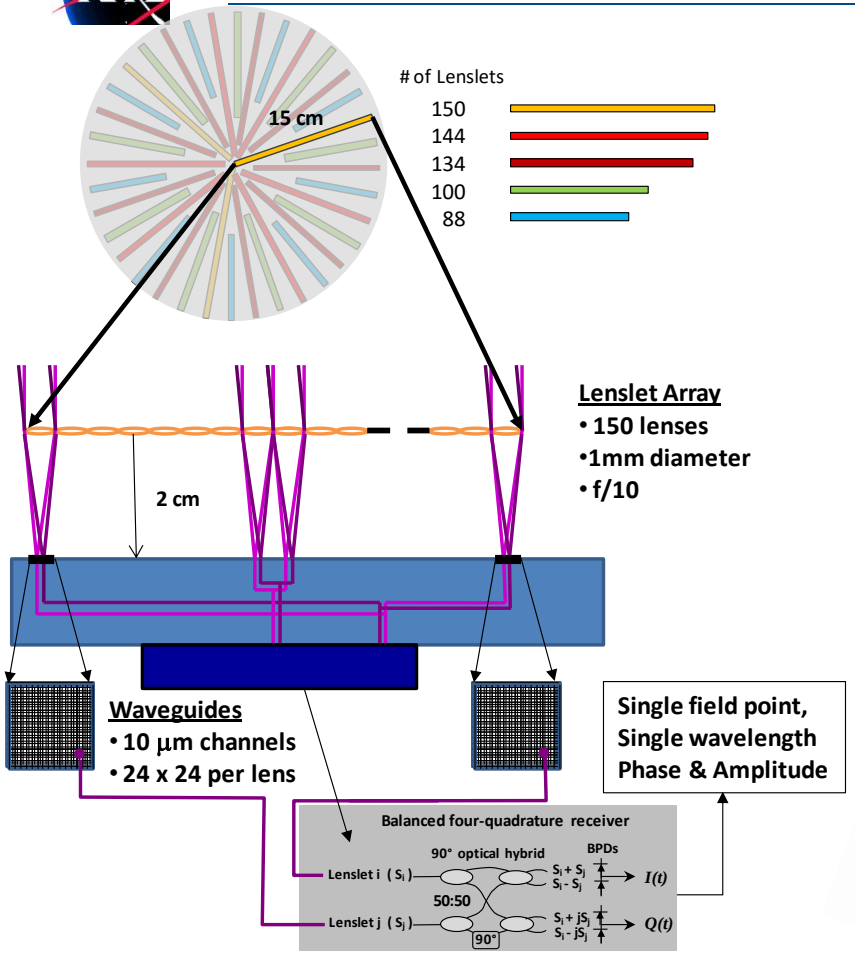
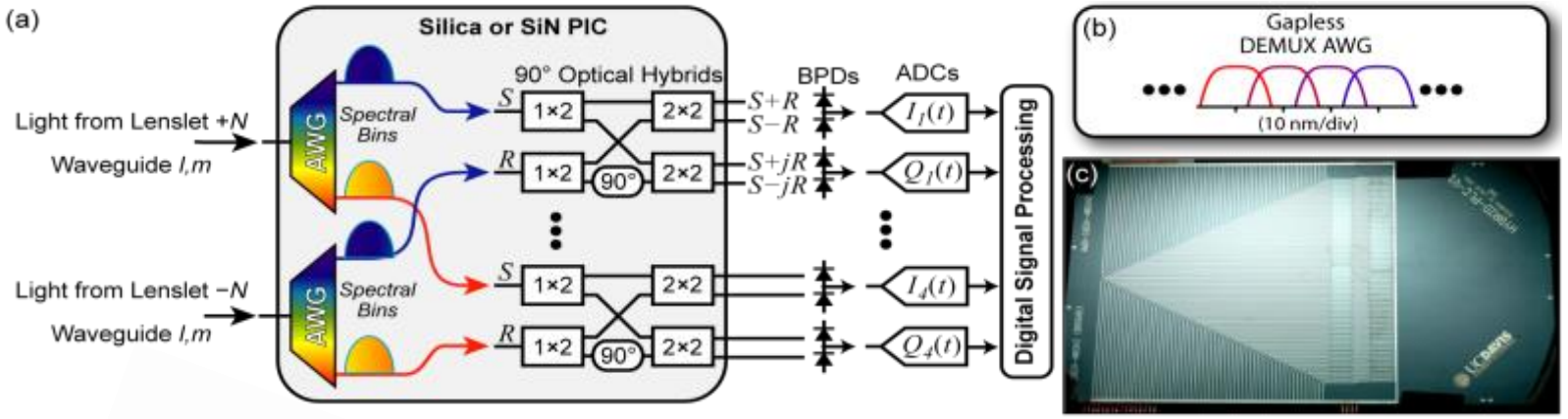
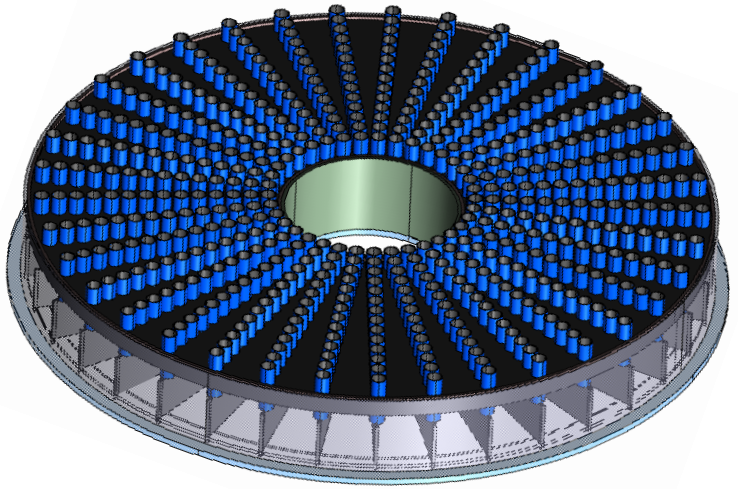
# SPIDER with PICs



Spectrally Resolved High Resolution Interferometric Telescope


"Experimental demonstration of interferometric imaging using photonic integrated circuits", Tiehui 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 Wuchenich, Chad Ogden, Guy Chriqui, Alan Duncan, Samuel T. Thurman, S B. Yoo, Tiehui Su, Weicheng Lai, Jaeyi Chun, Siwei Li, Guangyao Liu, *OSA Conference on Lasers and Electro Optics Pacific Rim (CLEO-PR),* 2017.

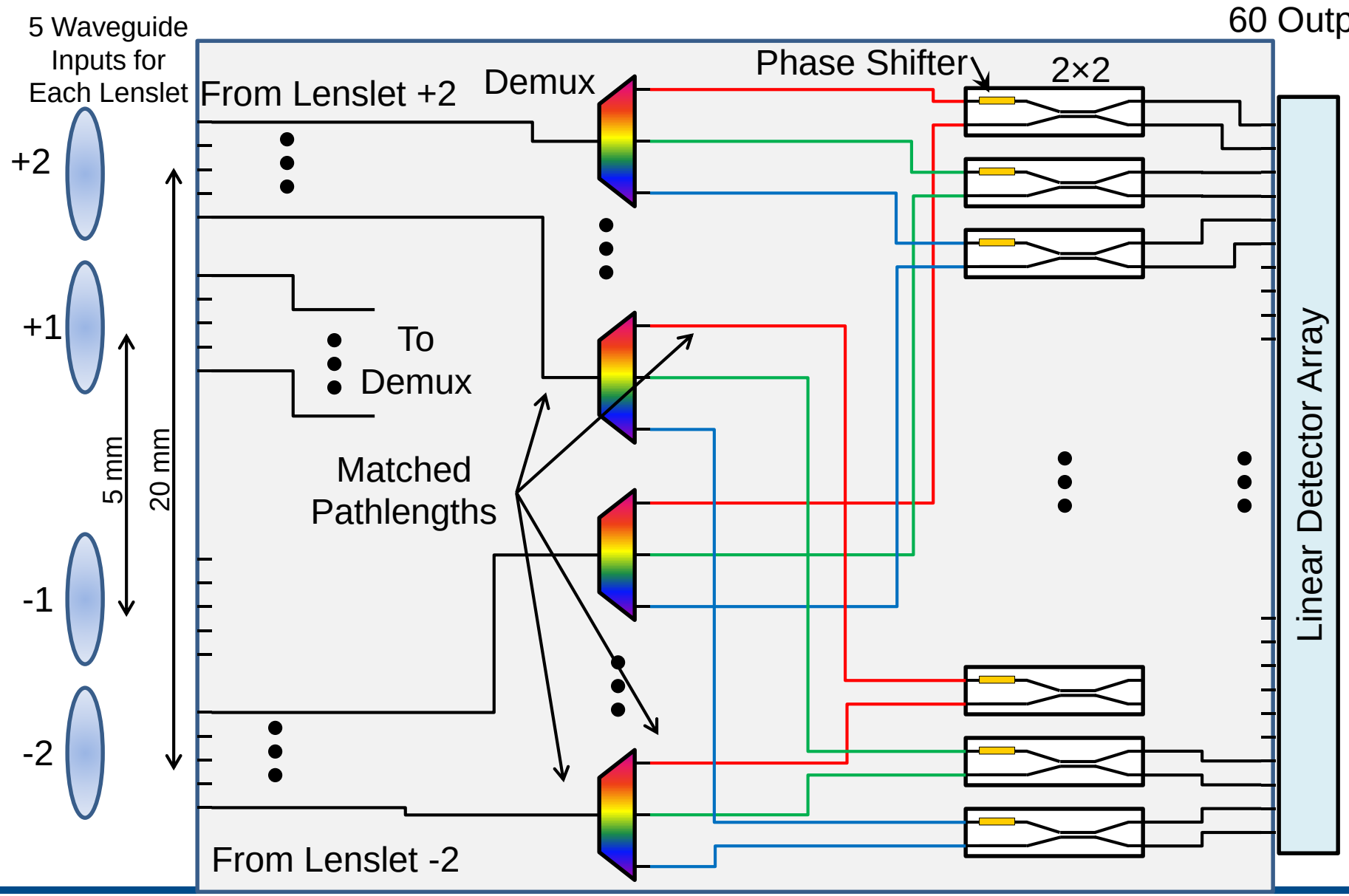
"Progress on Developing a Computational Imager Using Integrated Photonics", Samuel Thurman, Alan Duncan, Richard Kendrick, Chad Ogden, Danielle Wuchenich, Tiehui Su, Shibna Pathak, Wei-Cheng Lai, Mathias Prost, Roberto Proietti, Ryan Scott, S. J. Ben Yoo , *2016 SIAM Conference on Imaging Science,* 2016.

"SPIDER: Next Generation Chip Scale Imaging Sensor Update", Duncan, A.; Kendrick, R.; Ogde C.; Wuchenich, D.; Thurman, S.; Su, T.; Lai, W.; Chun, J.; Li, S.; Liu, G.; Yoo, S. J. B., *Proceedings Advanced Maui Optical and Space Surveillance Technologies Conference,* 2016

"Demonstration of a Photonic Integrated Circuit for Multi-baseline Interferometric Imaging", Ryan P. Scott, Tiehui Su, Chad Ogden, Samuel T. Thurman, Richard L. Kendrick, Alan Duncan, Runxiang Yu, and S. J. B. Yoo, *IEEE Photonics Conference (IPC) (Postdeadline),* October 2014.

"Flat Panel Space Based Space Surveillance Sensor", Richard L. Kendrick, Alan Duncan, Chad Ogden, Joe Wilm, David M. Stubbs, Samuel T. Thurman, Tiehui Su, Ryan P. Scott, and S. J. B. Y , *Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference* , Septembe 2013

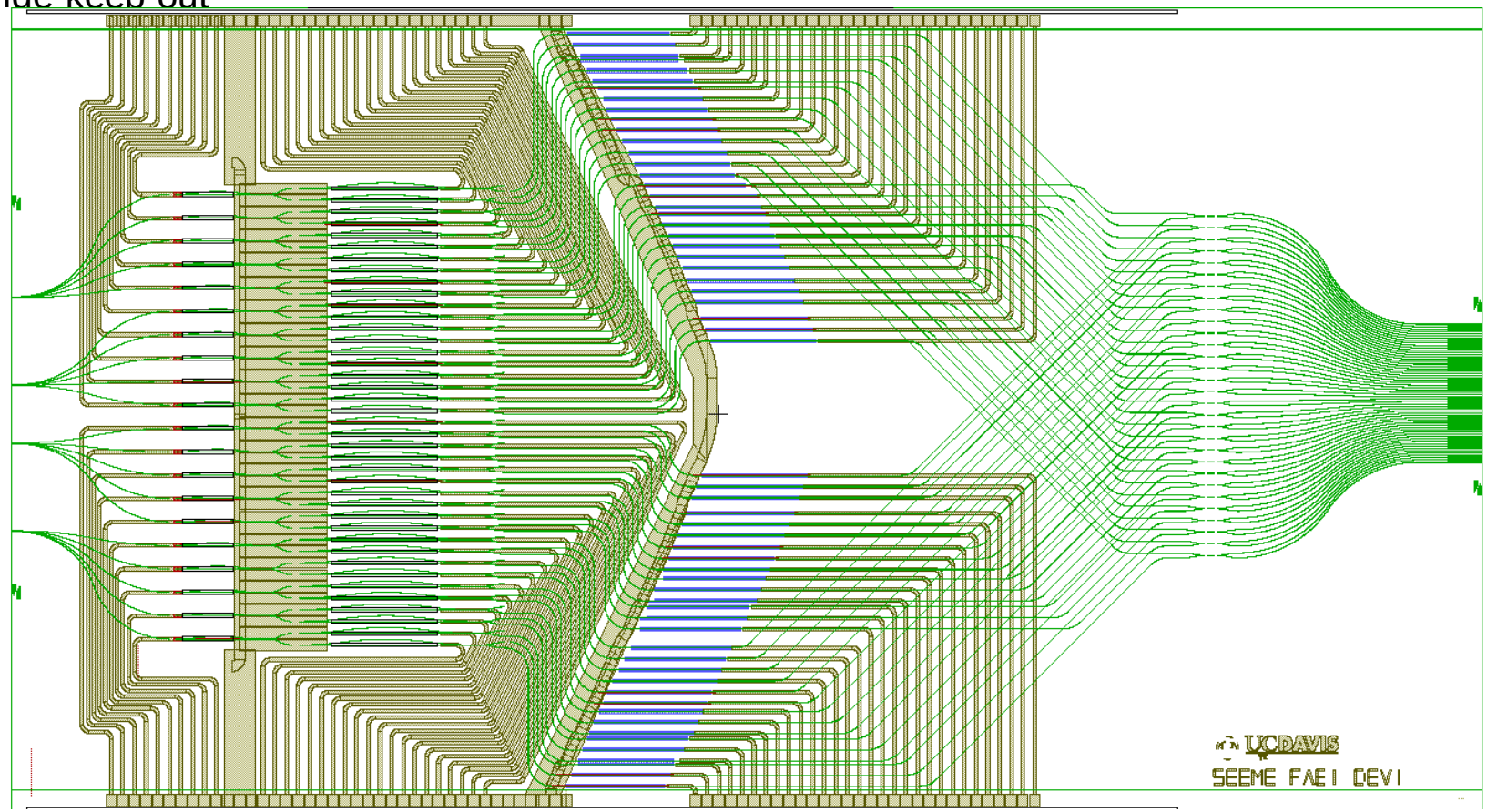
# 1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band)




Developed under
NASA NIAC
Phase I & II
DARPA TTO
SeeMe

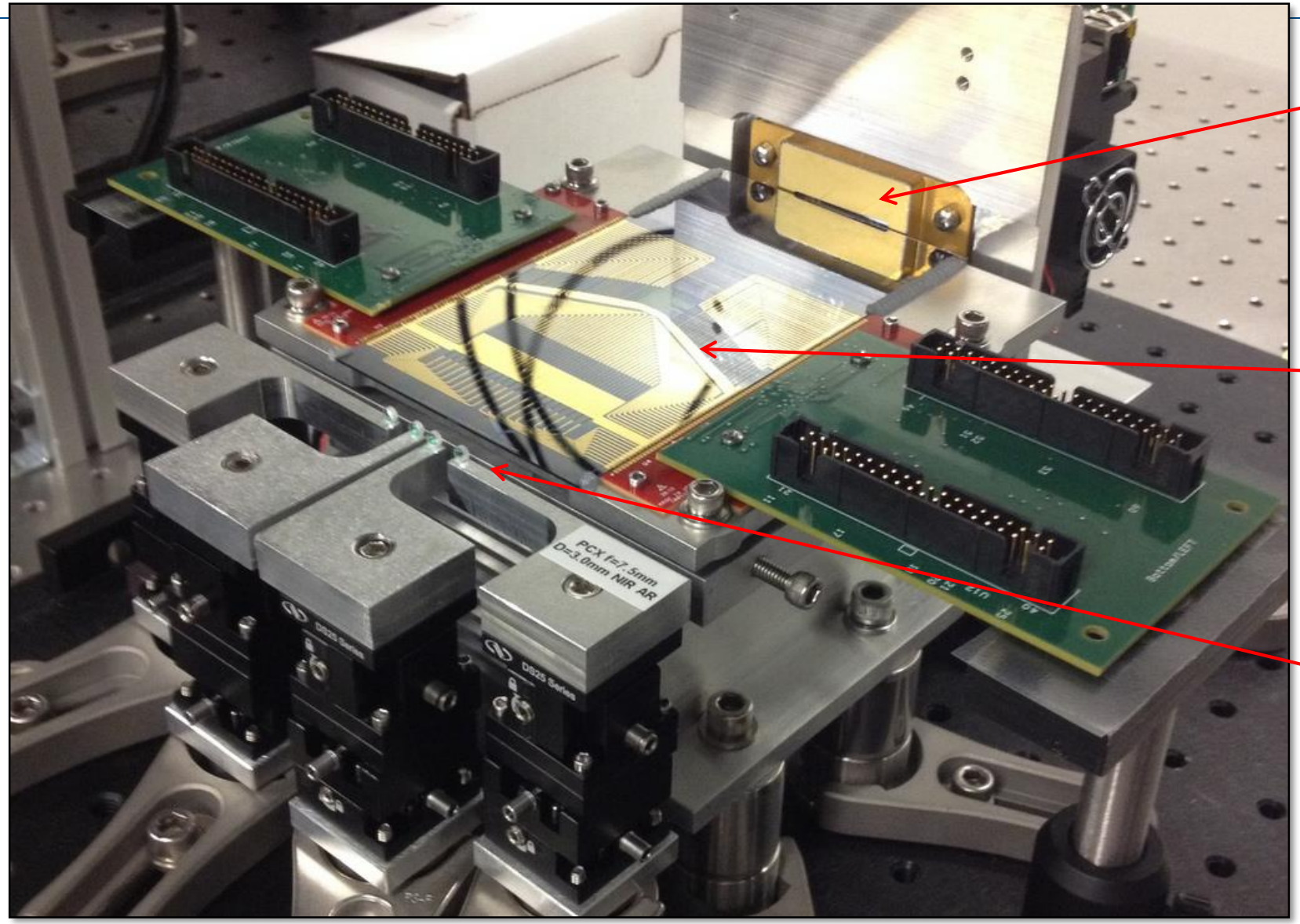
# 1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band)

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




DARPA funded work

# 1st Gen SPIDER PIC



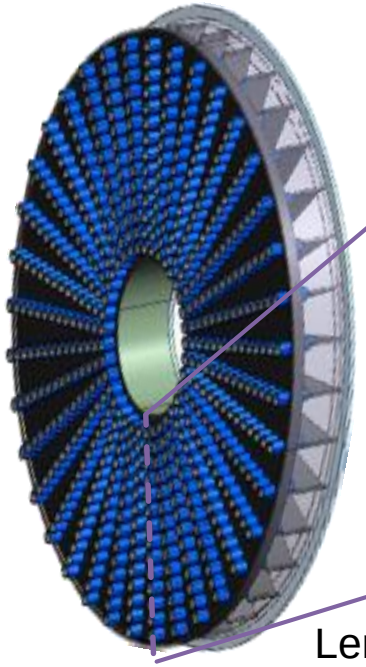

DARPA funded work

PIIT: Photonic Interferomic Integrated Telescope

# 2nd Gen SPIDER Concept Design – Interferometry

## 2D Interferometer Array

37 Blade SPIDER concept



Scene light

Lenslets couple light into PIC waveguides → Interferometric beam combination on PIC → Output waveguides with fringe information imaged onto detector → Coherence function estimate from fringe intensity data → Image reconstruction

## Planar Photonic Integrated Circuit (PIC)




Lenslets couple light into Waveguides

Electrodes for adjusting interferometer OPD

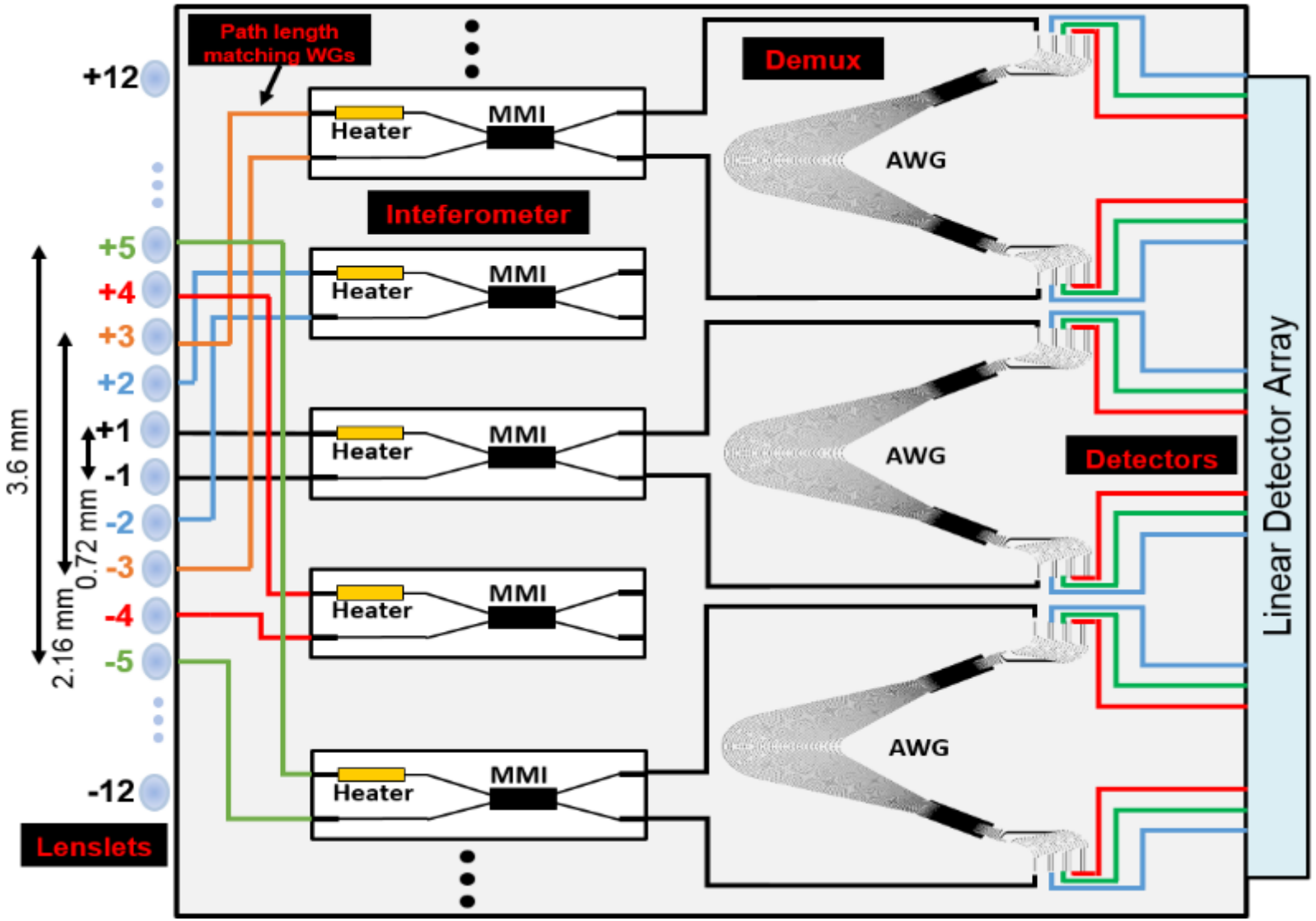
2x2 Beam Combiner

Arrayed Waveguide Grating (AWG) disperses light among narrowband spectral channels

Observe interference of light collected for each baseline and spectral channel

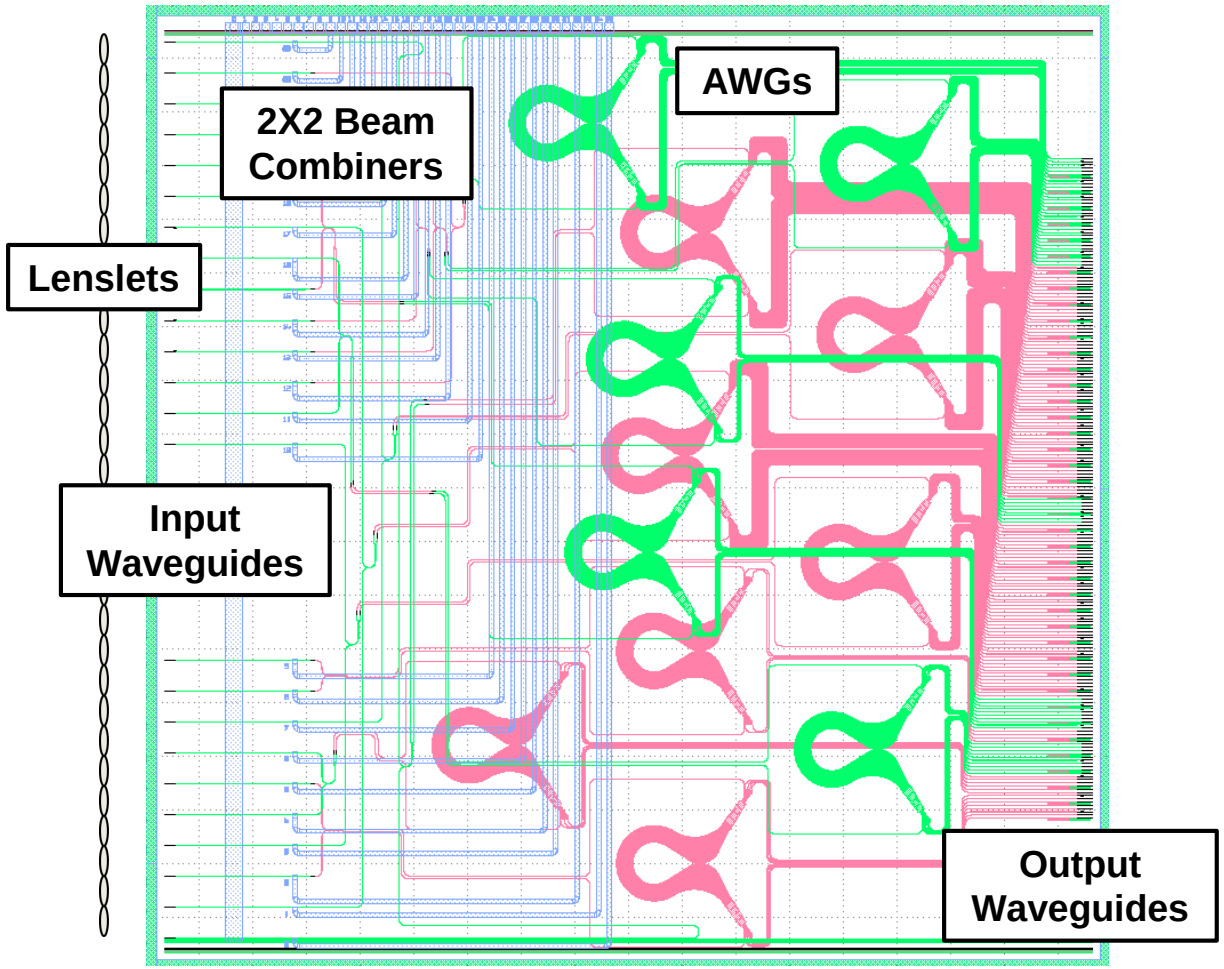
$$\text{FOV} = 2.44\frac{\lambda}{d_{lenslet}}$$

# 2nd Gen SPIDER Photonic Integrated Circuit Design

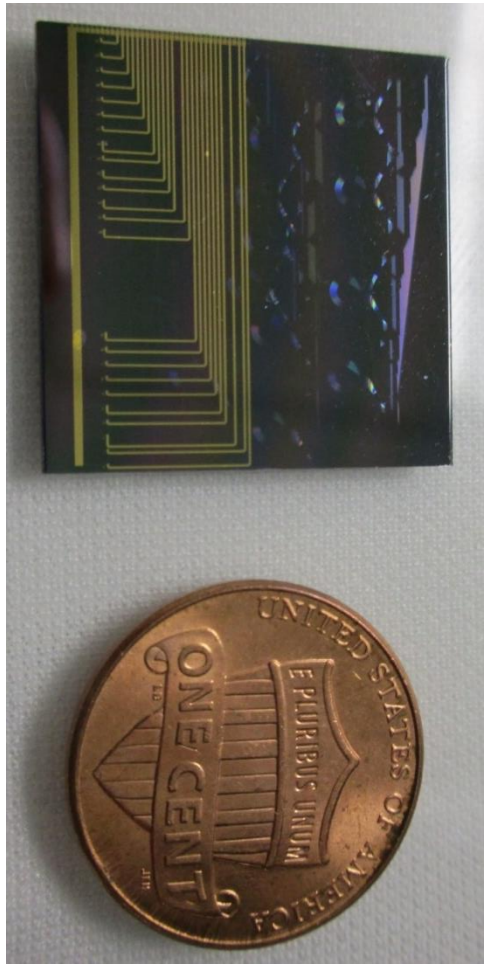


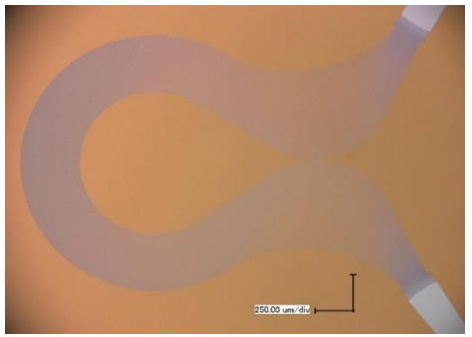
# 2nd Gen SPIDER PIC (12 baseline, 18 spectral bin) fabricated w/ CMOS Compatible Process @ UC Davis

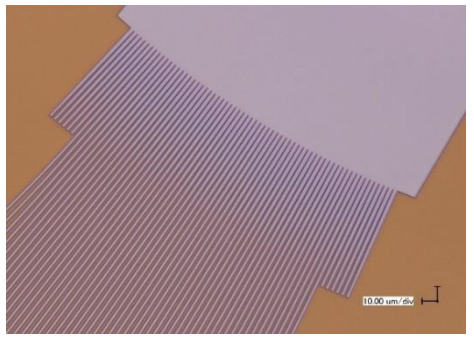
## Lithography Layout

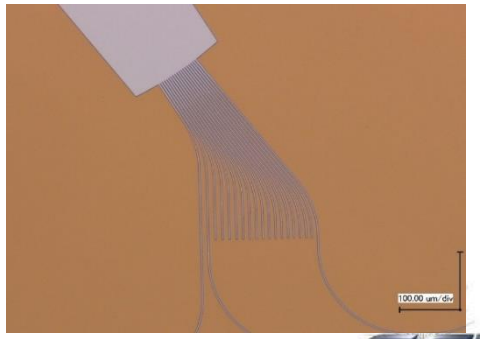



## Photograph







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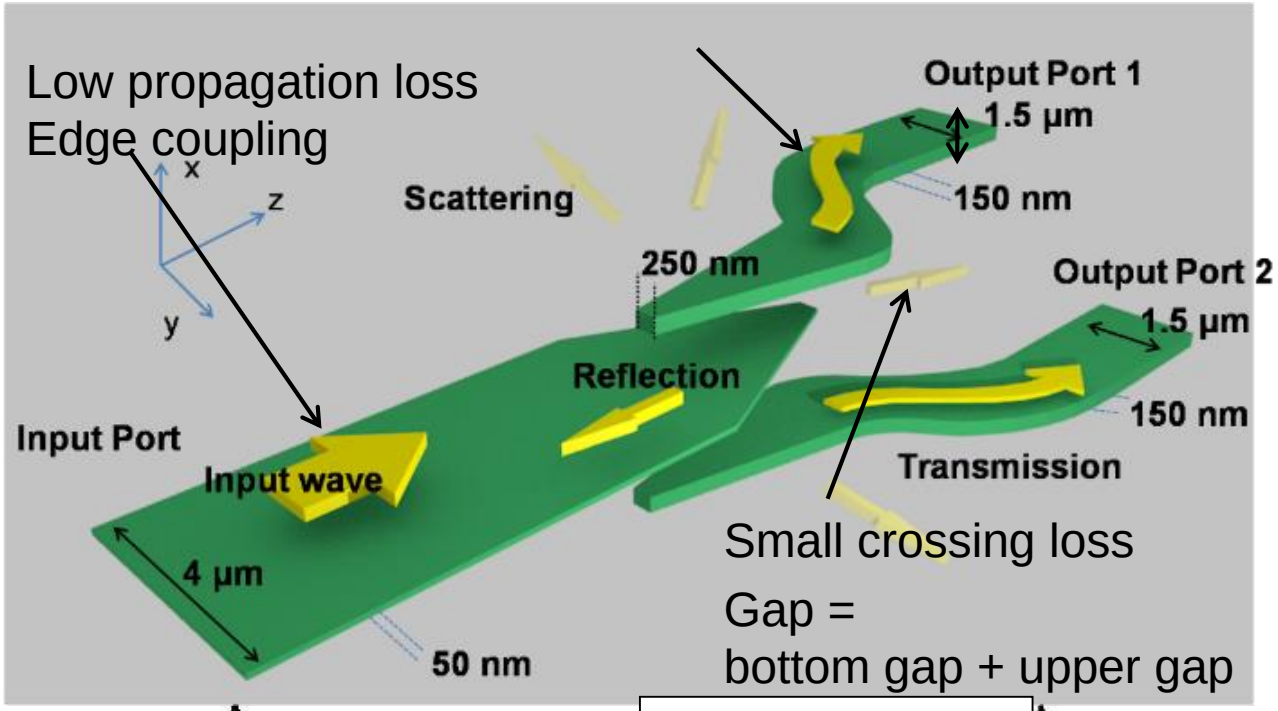
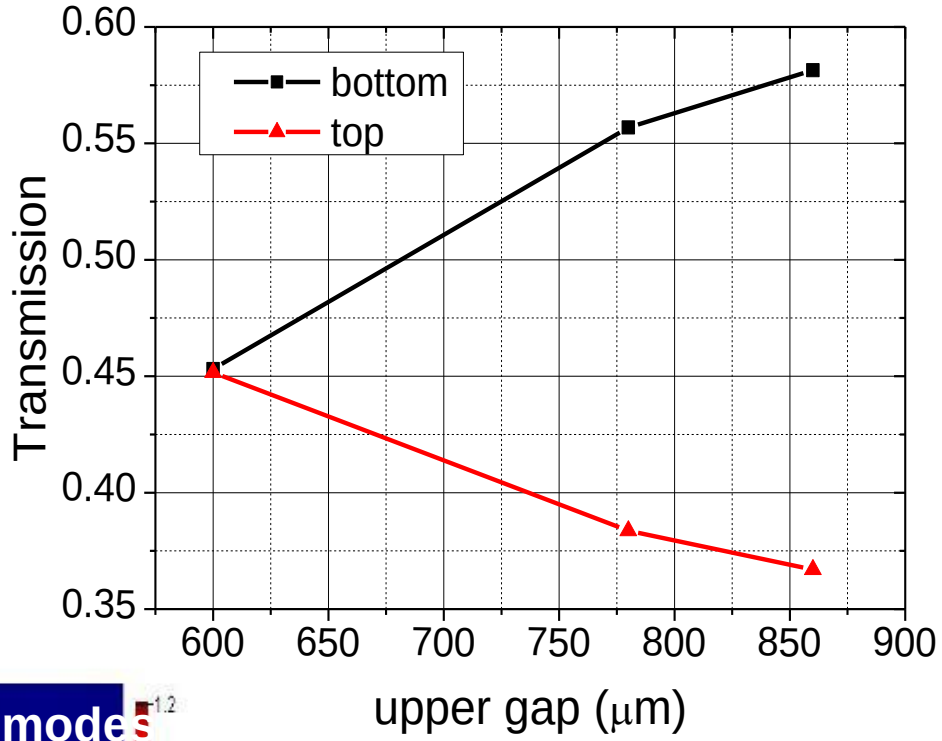
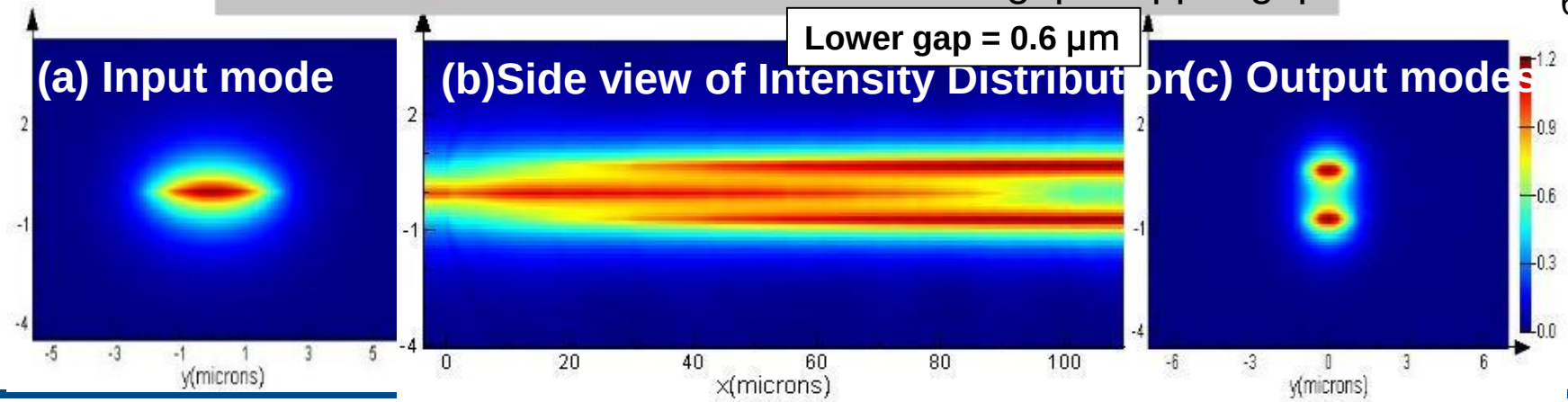
# Multilayer 150nm/50nm/150nm $Si_3N_4$ PIC Platform for the 2nd Gen SPIDER Design

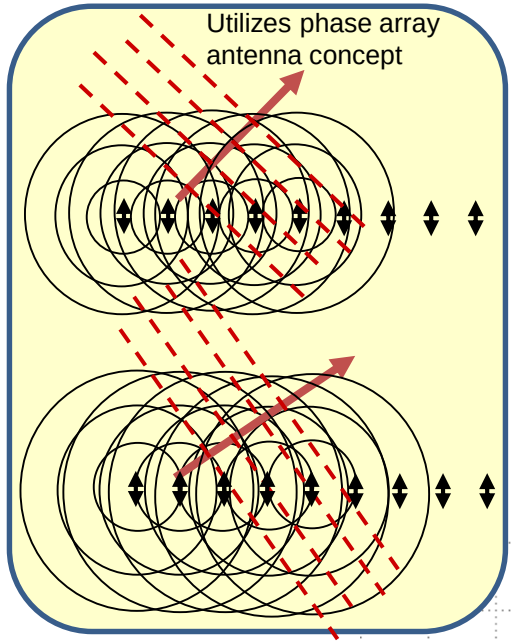


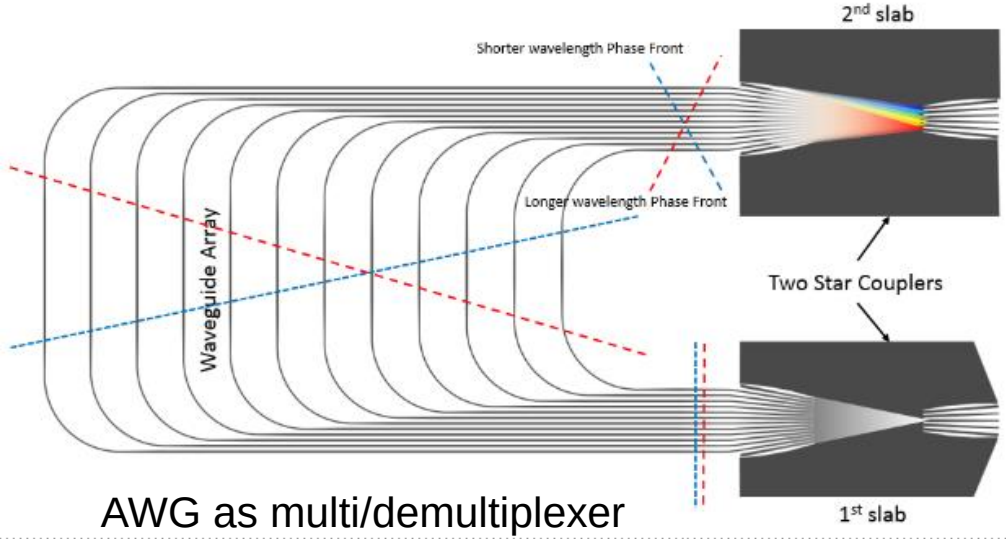




**Lower gap = 0.6 μm**



# On-Chip Spectrometers: Arrayed Waveguide Gratings



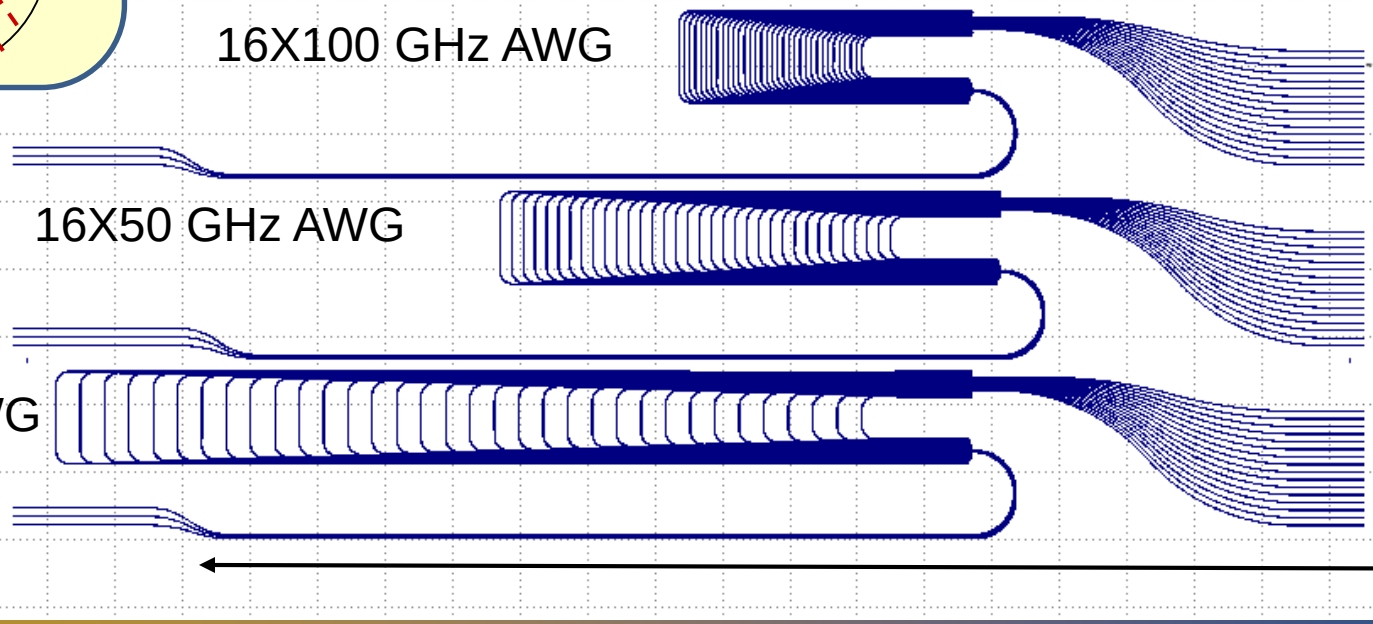




AWG as multi/demultiplexer

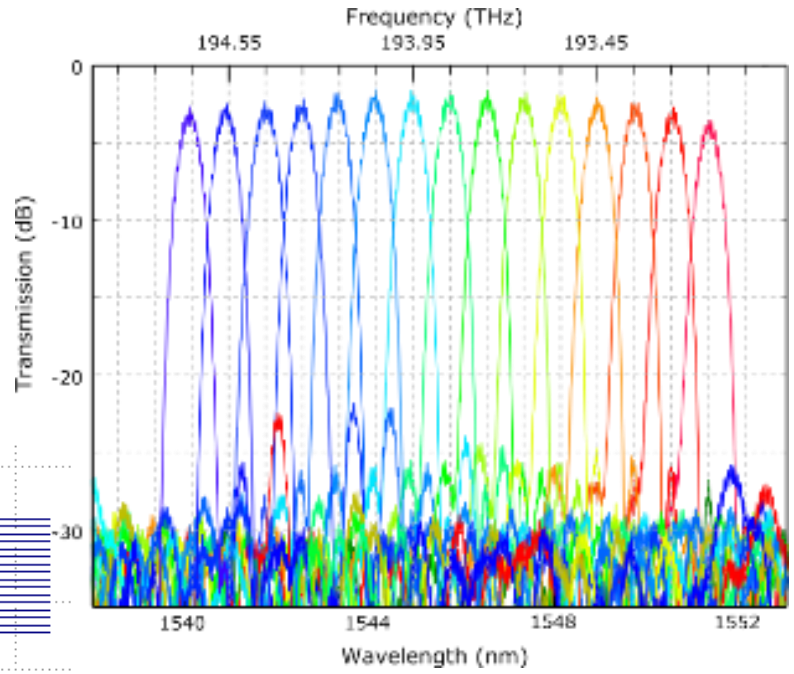
16X100 GHz AWG

16X50 GHz AWG

16X25 GHz AWG



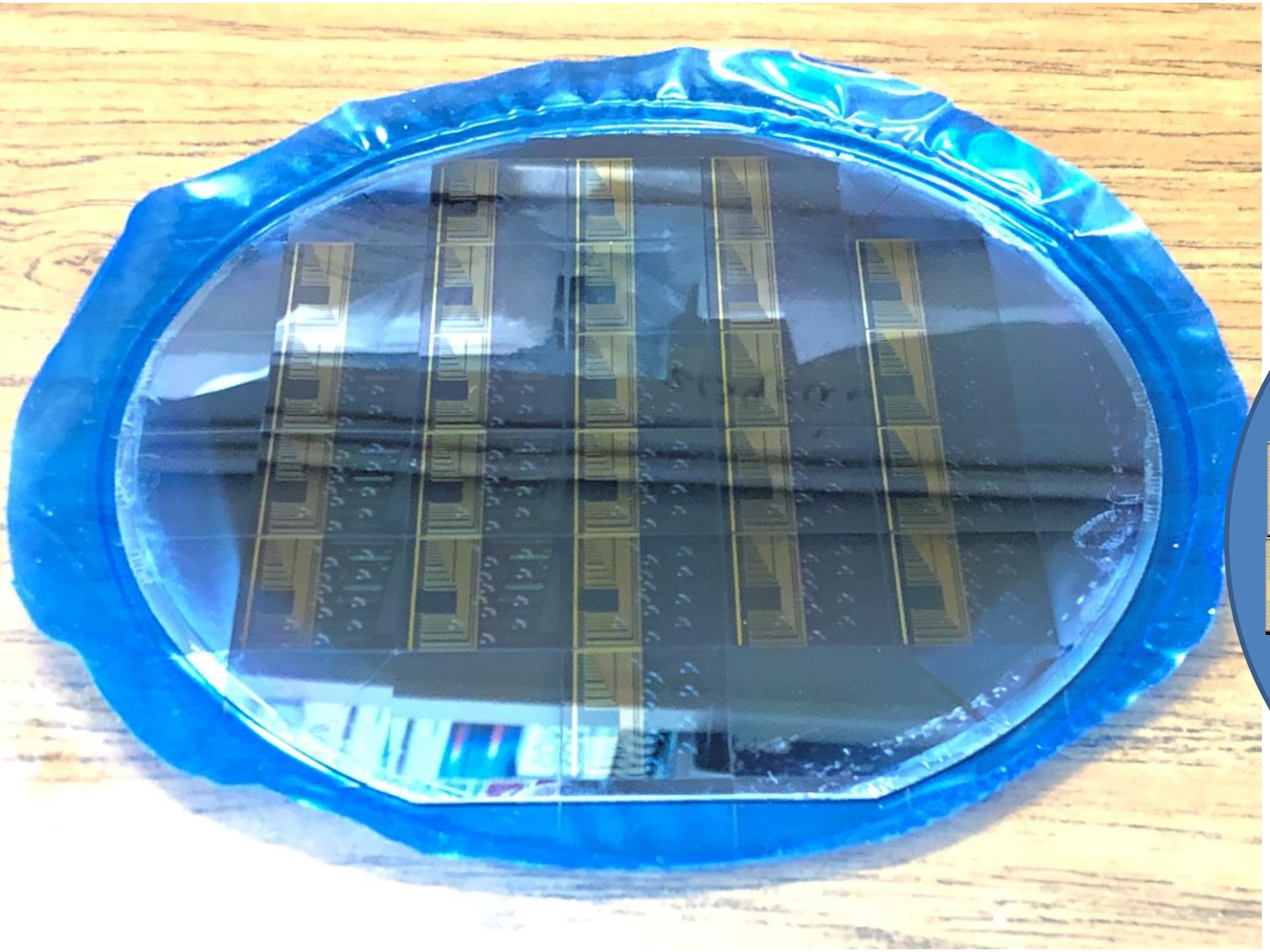
16 ch X100 GHz AWG



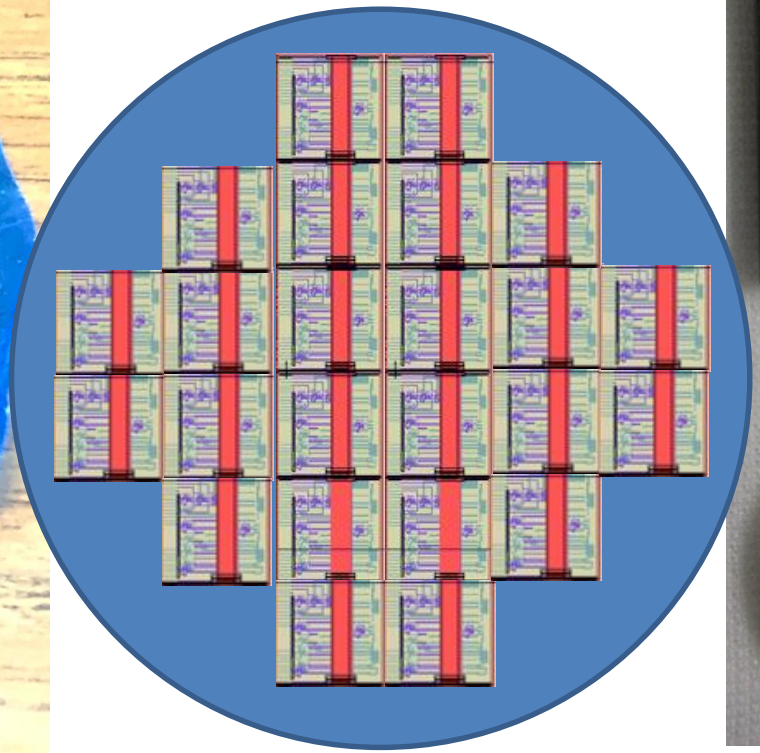

Insertion loss: 1.7 dB
Crosstalk: -21 dB

# *Wafer-scale fabrication of 2ND Gen SPIDER PIC*

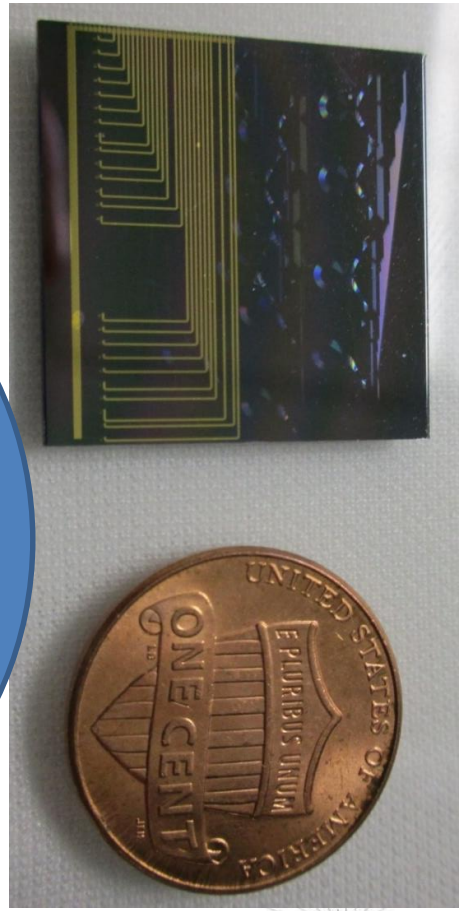
**150 mm wafer-scale fabrication**



22 x 22 mm dies



**22 mmx 22 mm die**

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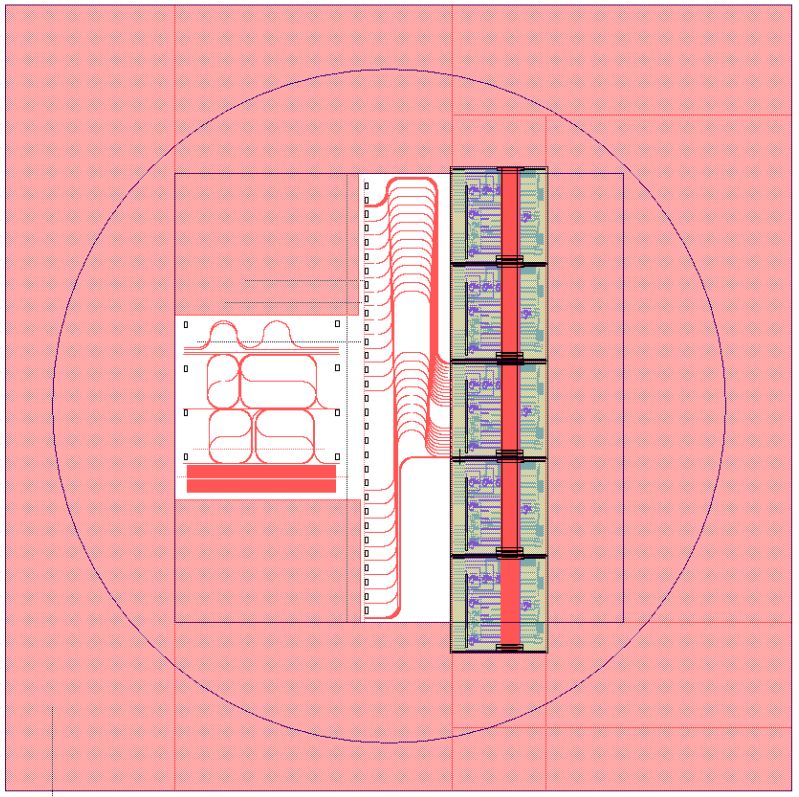
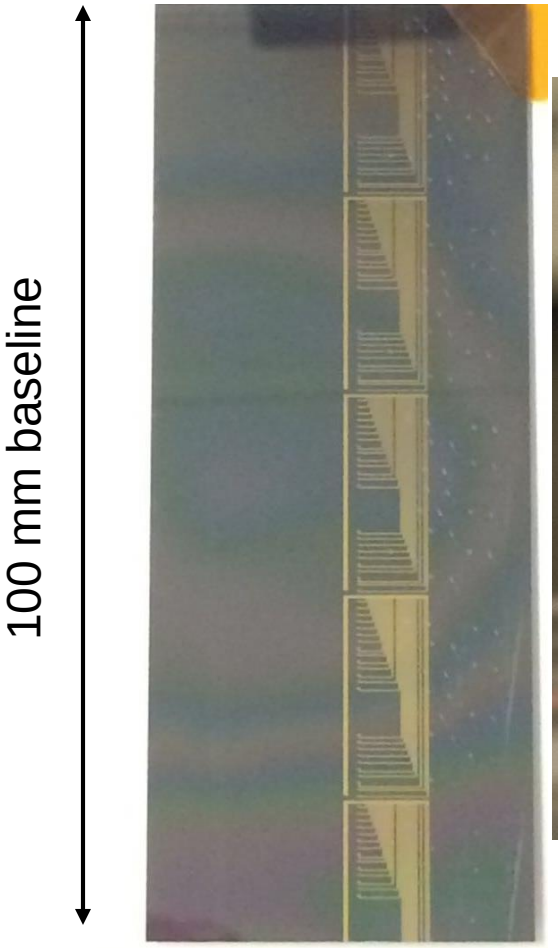
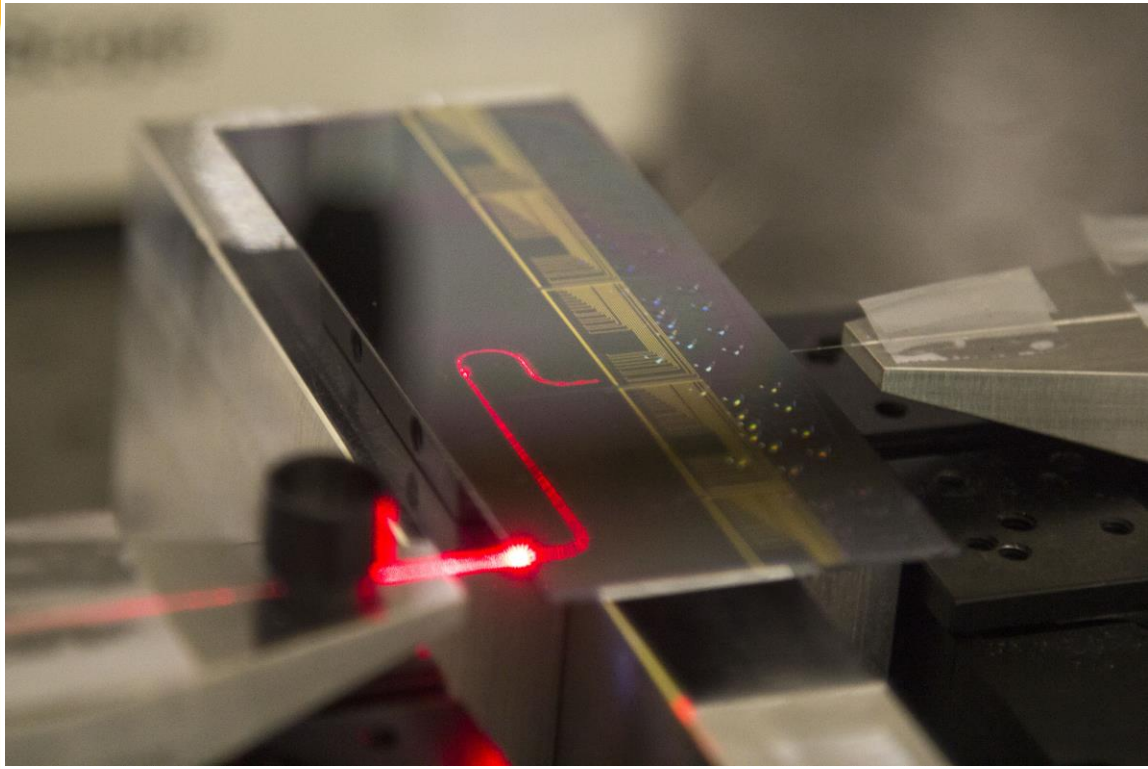
# High-Resolution 2ND Gen SPIDER PIC





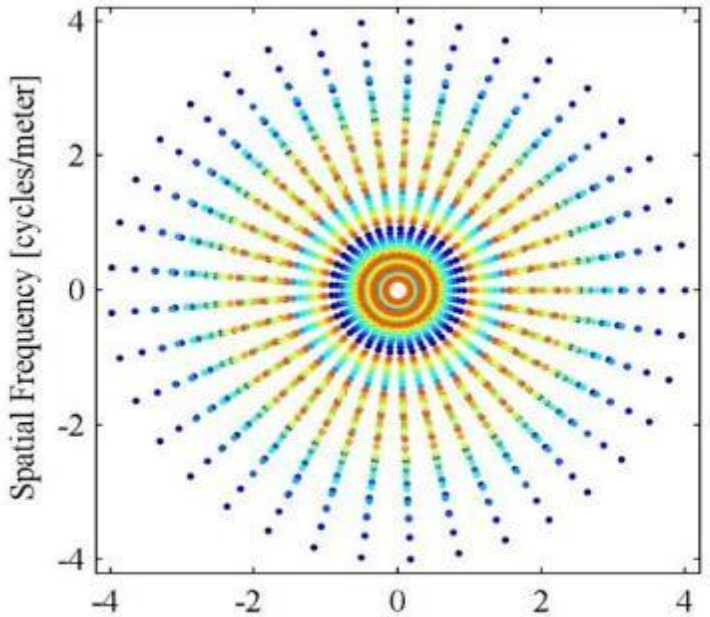



# SPIDER Imaging Simulation Example

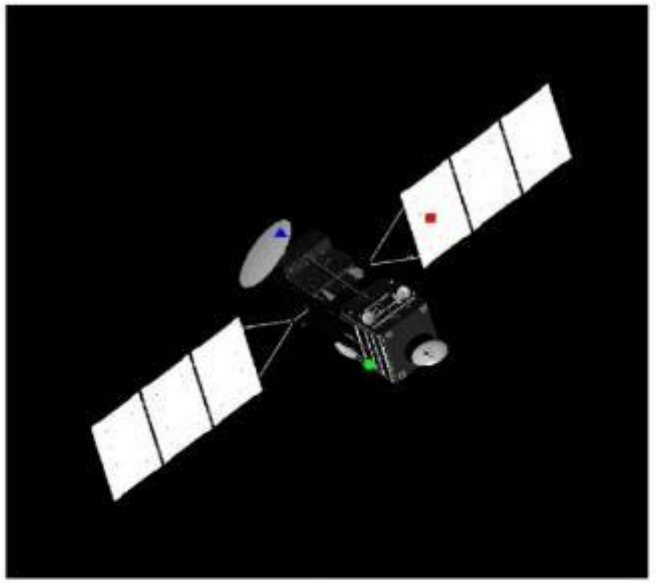
**Simulation Parameters**

| Parameter | Value |
|---|---|
| Waveband | $\lambda$ = 0.5-0.9 μm |
| Object distance | $R$ = 60 km |
| Longest baseline | $B_{max}$= 120 mm |
| Lenslet diameter | $D_{lenslet}$ = 5 mm |
| Lenslets per PIC Card | 14 |
| PIC cards | 37 |
| Number of spectral channels | $K$ = 10 ($\Delta\lambda$ = 40 nm) |
| Detector quantum efficiency | $\eta$ = 0.7 e$^-$/photon |
| Detector read noise | $\sigma_0$ = 8 e$^-$ |
| Integration time | $\tau$ = 1 sec |

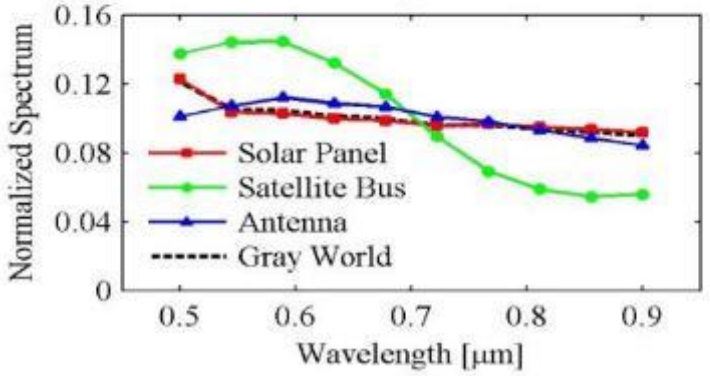
**Spatial Domain Sampling**




**Imaging Object**



(a)

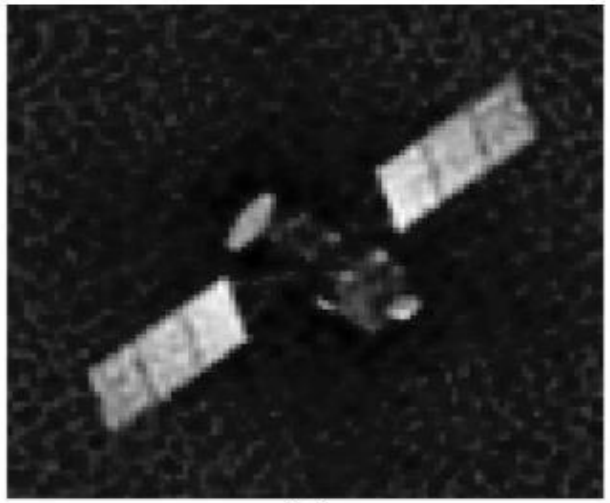



(b)

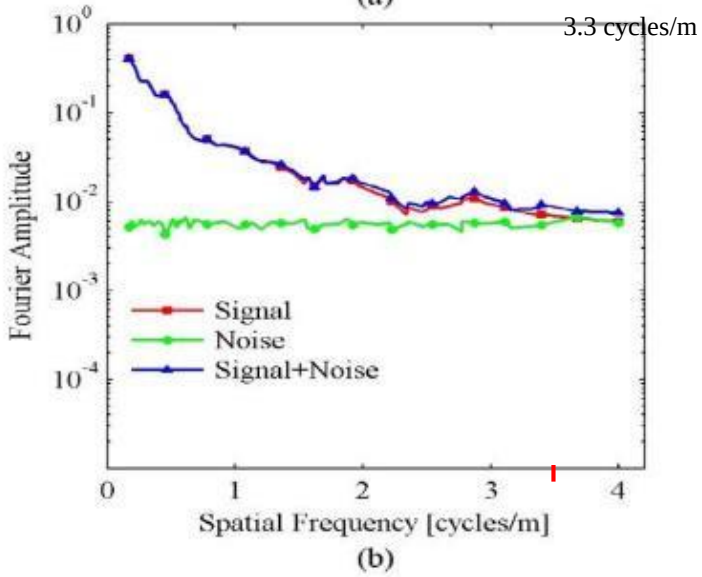
Provided by Lockheed Martin

# Simulation Result

**SPIDER simulation Result**

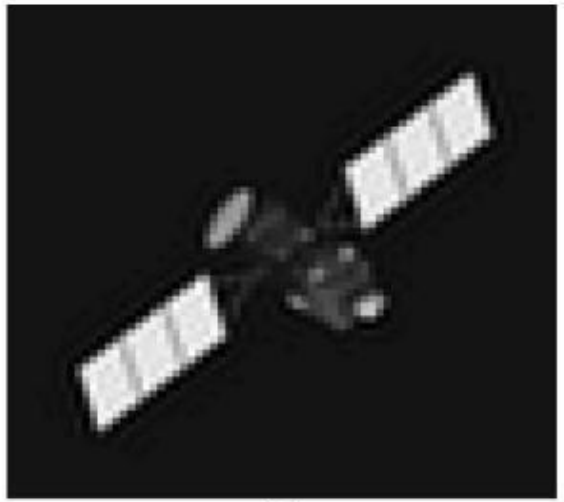


(a)

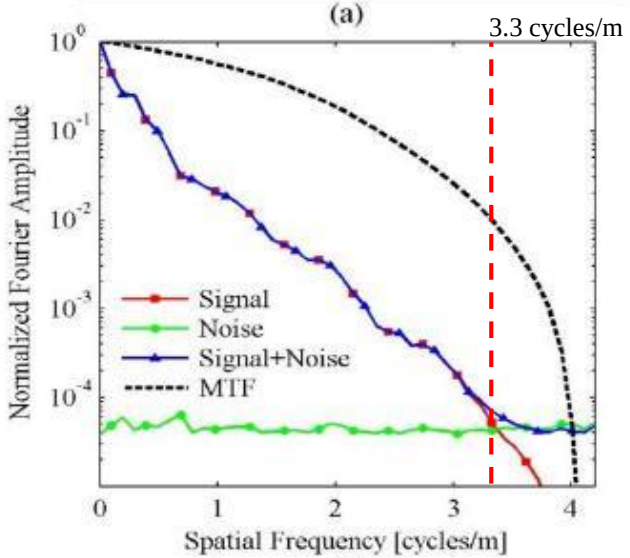



(b)

**Panchromatic Imager simulation Result**



(a)

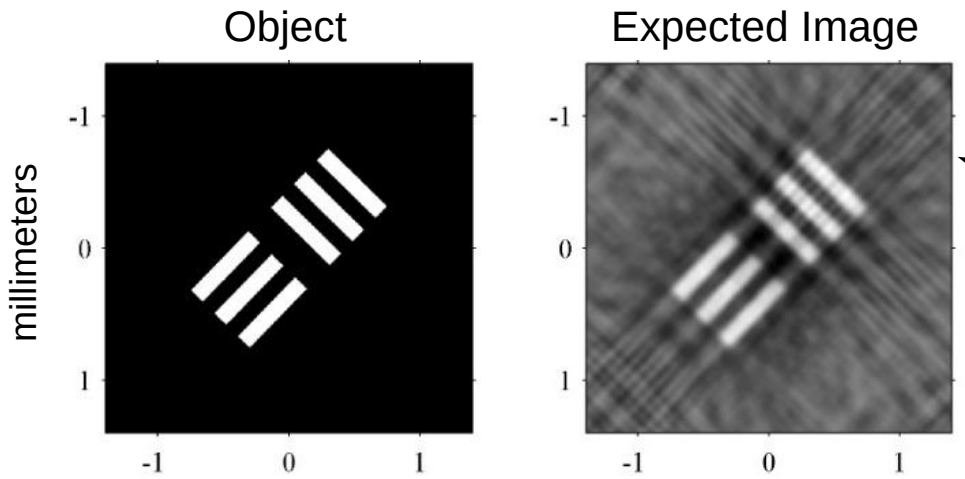



(b)

Provided by Lockheed Martin

# Experimental Results for USAF Bar Target

- Computer simulation of experiment




Sparse Fourier sampling artifacts
(polar sampling is $\Delta\theta$ = 10 deg)

- Experimental results

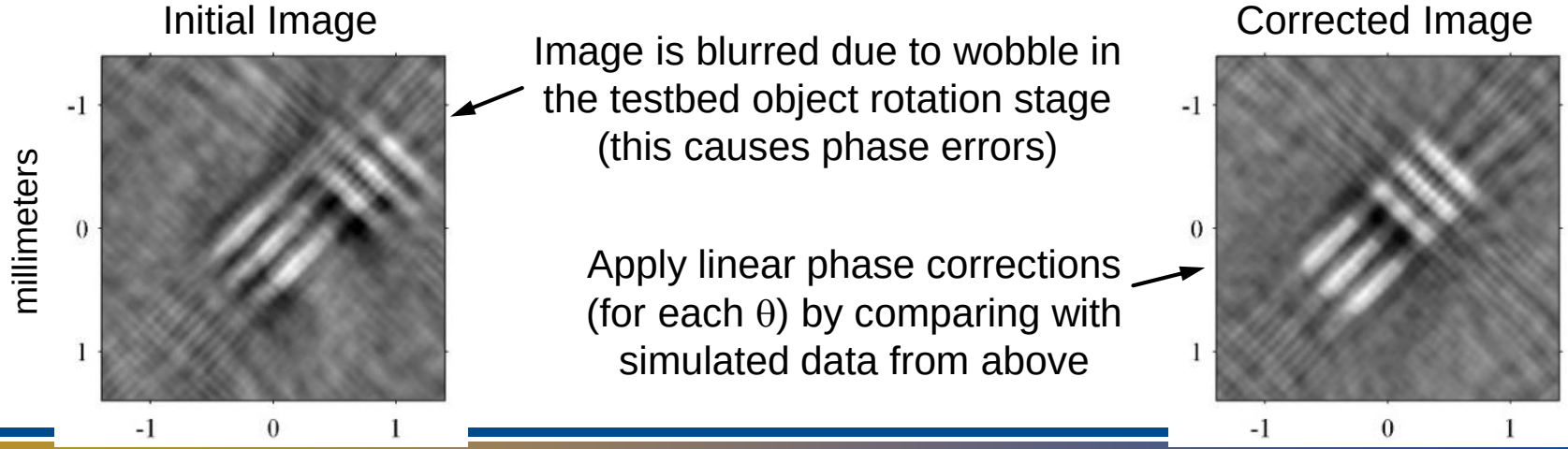
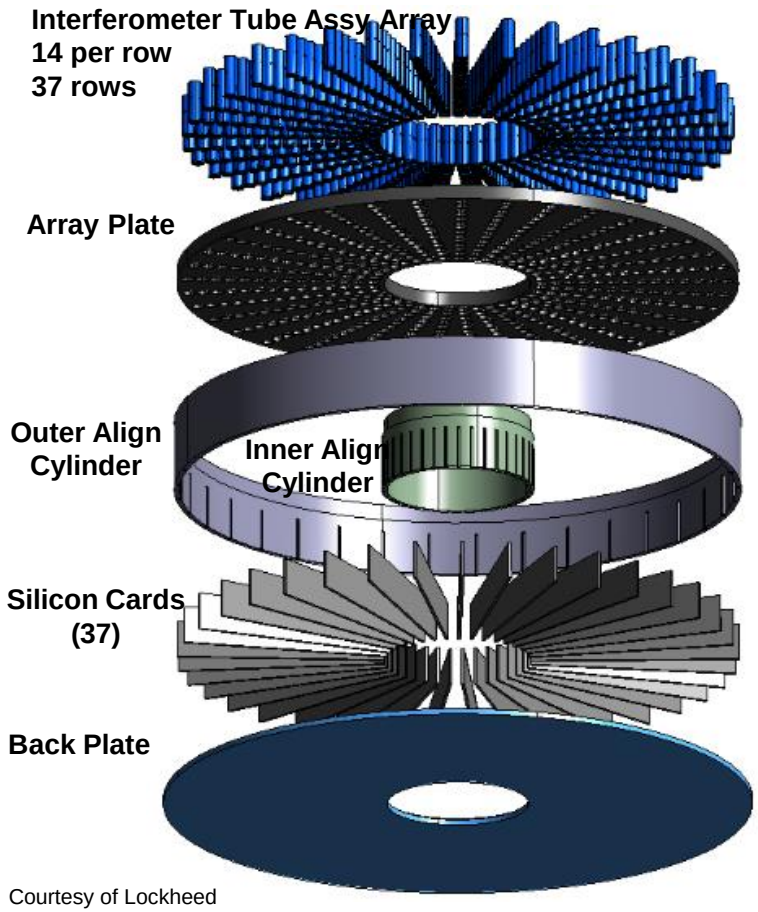


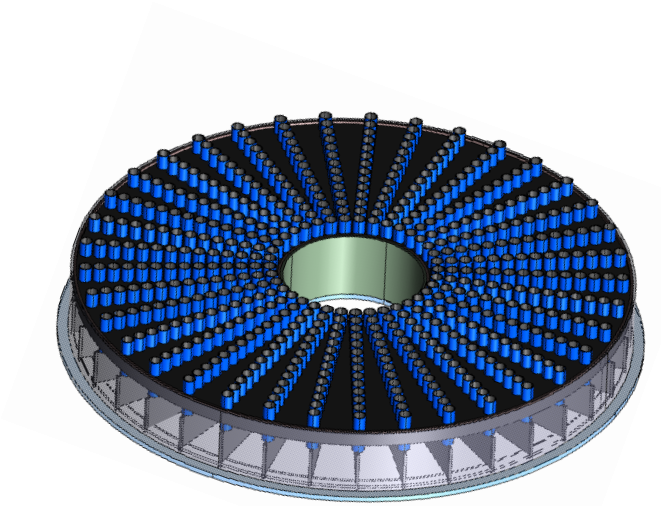

Image is blurred due to wobble in the testbed object rotation stage (this causes phase errors)

Apply linear phase corrections (for each $\theta$) by comparing with simulated data from above

Provided by Lockheed Martin

# Next Steps for 2nd Gen SPIDER PIIT



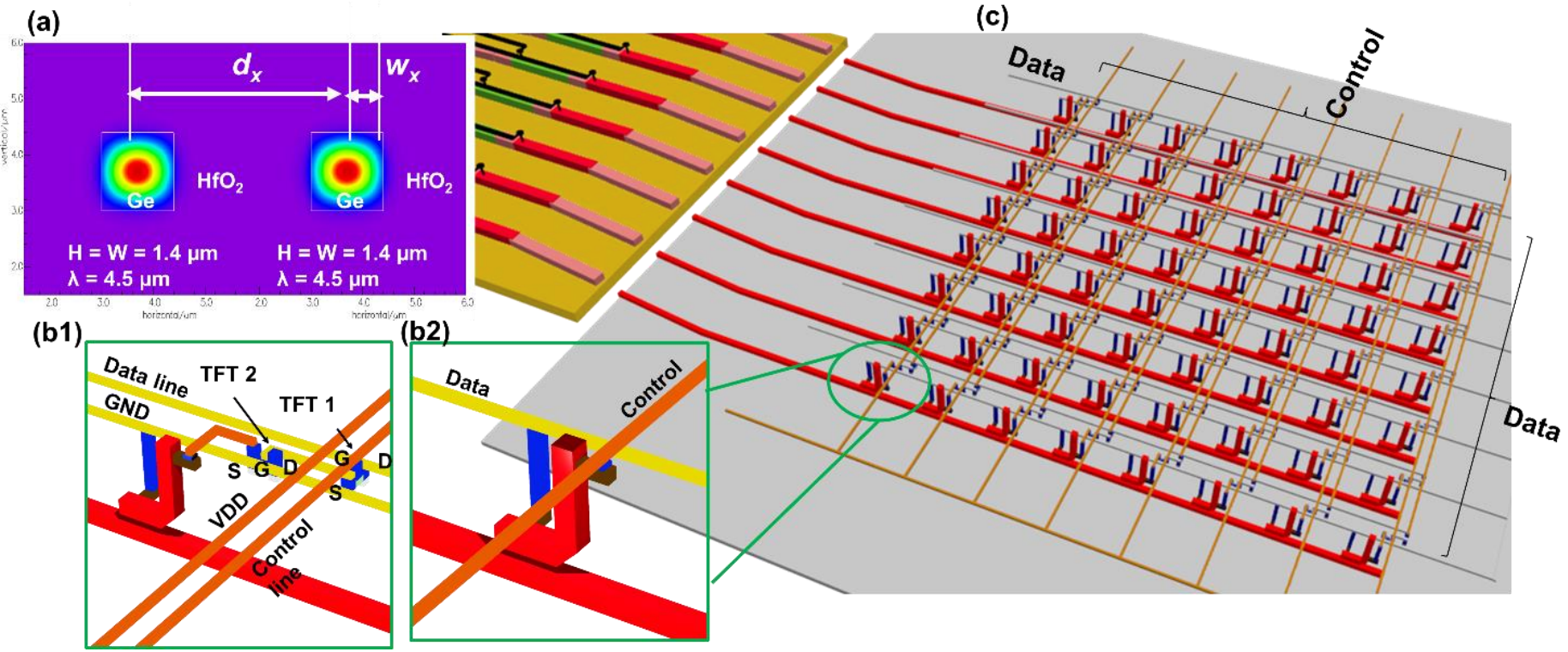



Courtesy of Lockheed Martin

Systems Integration with ~37 SPIDER PICs into SPIDER PIIT (Photonic Integrated Interferometric Telescope)

# 3rd Generation SPIDER PIIT ?

## 3D Photonic-Electronic-Integrated Circuits



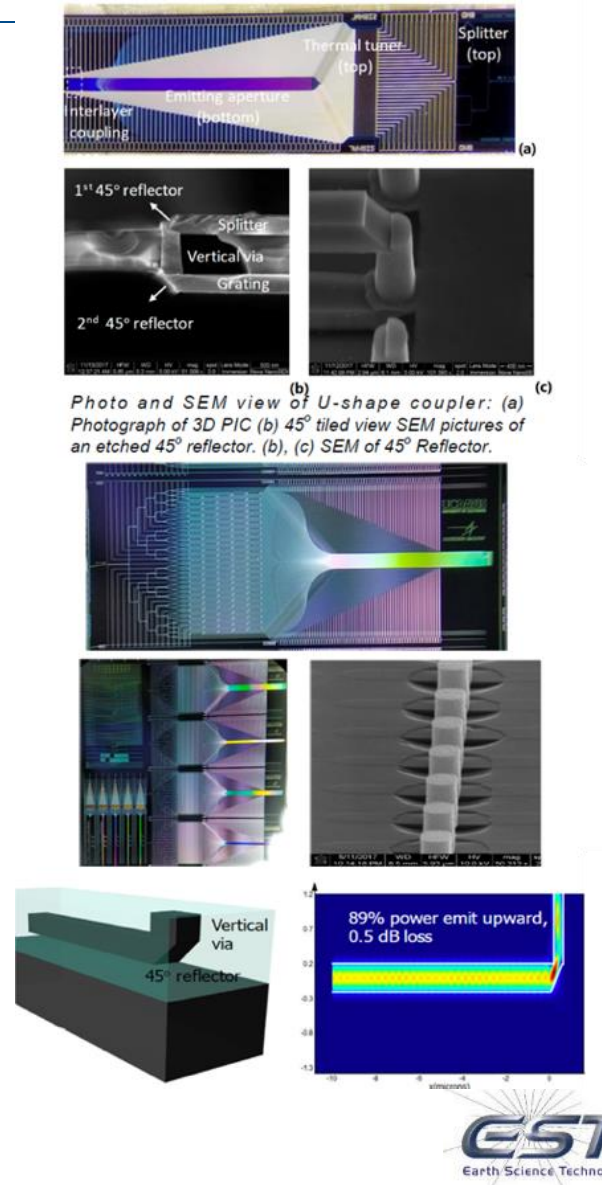




*Photo and SEM view of U-shape coupler: (a) Photograph of 3D PIC (b) 45° tiled view SEM pictures of an etched 45° reflector. (b), (c) SEM of 45° Reflector.*

# Summary

- Design, Simulations, and Demonstration of SPIDER PIIT
- Multi-Layer CMOS Compatible SPIDER PICs with 18 spectral bin 12 baseline interferometers consisting of
  - Interlayer coupler with various splitting ratios  and low loss
  - Dual arm AWG interferometric operation
  - MMI for interferometric imaging.
- Reduction of Size, Weight, Power by 100x-1000x
- Concept Scalable to Very Large-Scale Astronomical Observatories
- Possibility of Transition to Commercial Systems
- Future generations of SPIDER PICs in concept developments involving 3D Electronic-Photonic-Integrated Circuits