Multi-Spectral and Low-Mass Photonic Integrated Interferometric Telescopes

S. J. Ben Yoo

Guangyao Liu[1,*], Yichi Zhang[1], Yu Zhang[1], Tiehui Su[1], Siwei Li[1], Weicheng Lai[1], Katherine E. Badham[2], Samuel T. Thurman[3], Richard L. Kendrick[2], Danielle Wuchenich[2], Chad Ogden[2], Guy Chriqui[2], Greg Feller[2], Kate Newcomer[2], Alan Duncan[2], David Theil[2]

[1] Dept. of Electrical and Computer Engineering, University of California, One Shields Ave, Davis, California, 95616, USA

[2] Lockheed Martin ATC, 3251 Hanover Street, Palo Alto, California, 94304, USA

3 Lockheed Martin Coherent Technologies, 135 S. Taylor Ave., Louisville, Colorado, 80027, USA

sbyoo@ucdavis.edu

http://sierra.ece.ucdavis.edu

In collaboration with

Lockheed Martin Advanced Technology Center, Palo Alto, CA, 94304 USA

UCDAVIS
UNIVERSITY OF CALIFORNIA

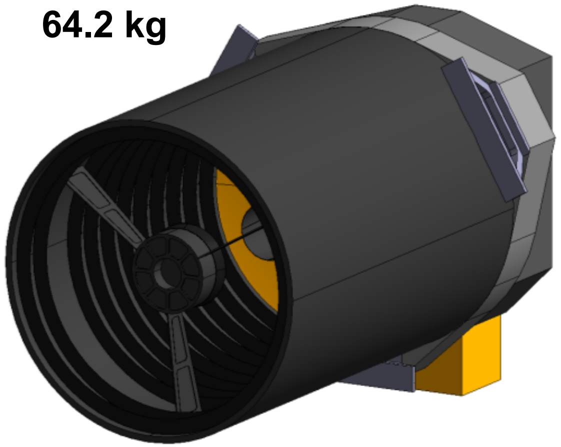
1990 STS-31 Mission (Shuttle Discovery)

Future Imaging Systems with Low SWaP

Key to Affordability – Low SWaP

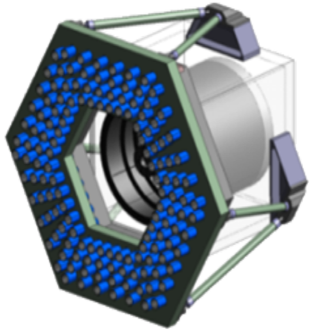
Orders of Magnitude SWaP Reduction Achievable

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



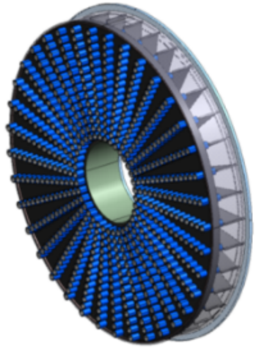
Conventional Telescope and focal plane

Estimate
0.5m x 0.5 m
~ 30kg



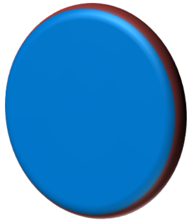
SPIDER Ring Blade Design: Outer ring enhances resolution of conventional telescope

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



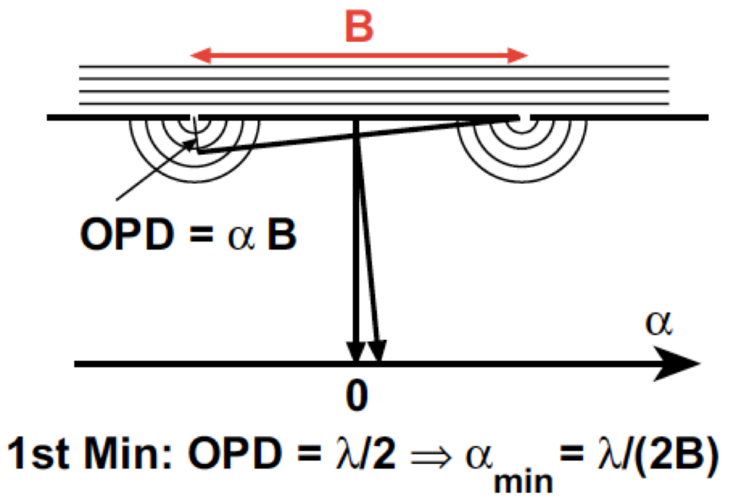
SPIDER Single Chip Design

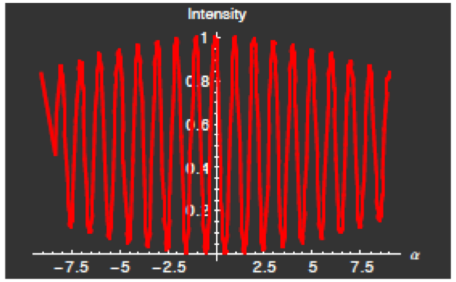
LOCKHEED MARTIN

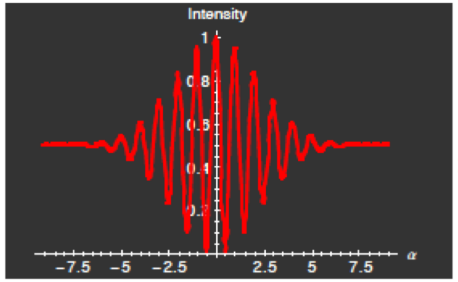
Link to review article on emerging large scale silicon photonics / CMOS integration for optical system applications
http://www.osa-opn.org/home/articles/volume_24/september_2013/features/the_road_to_affordable,_large-scale_silicon_photon/

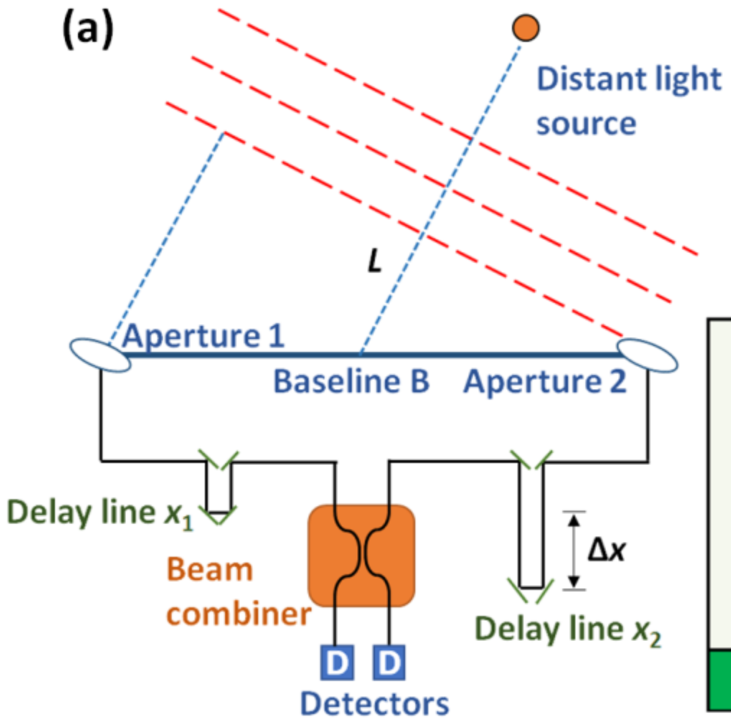
SPIDER: segmented planar imaging detector for electro-optical reconnaissance

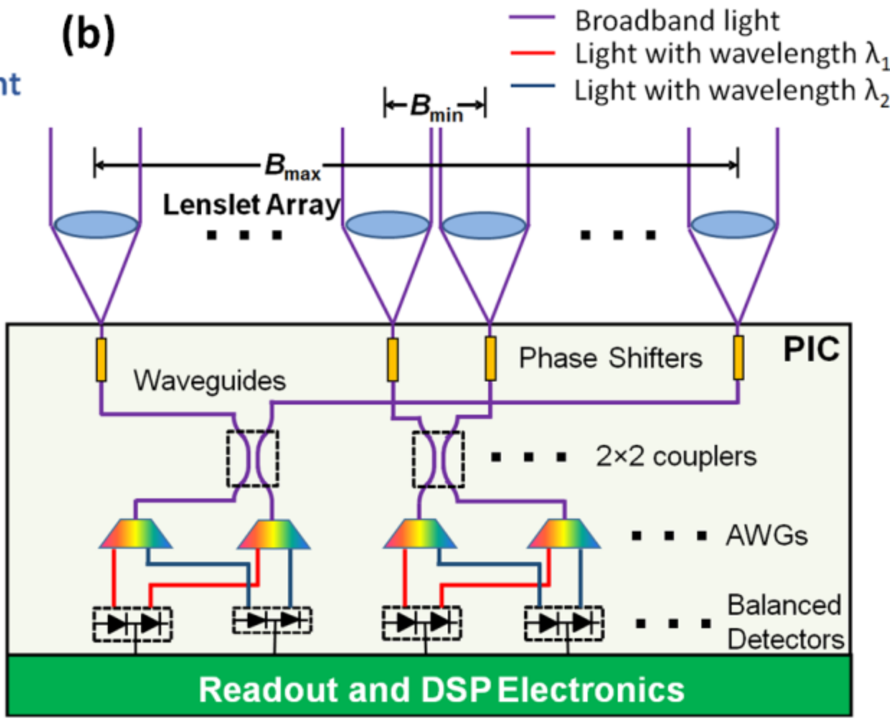
Basic Idea--Young's Two-Slit Experiment in PICs











•

•

•

Figure Courtesy of Andreas Glindemann

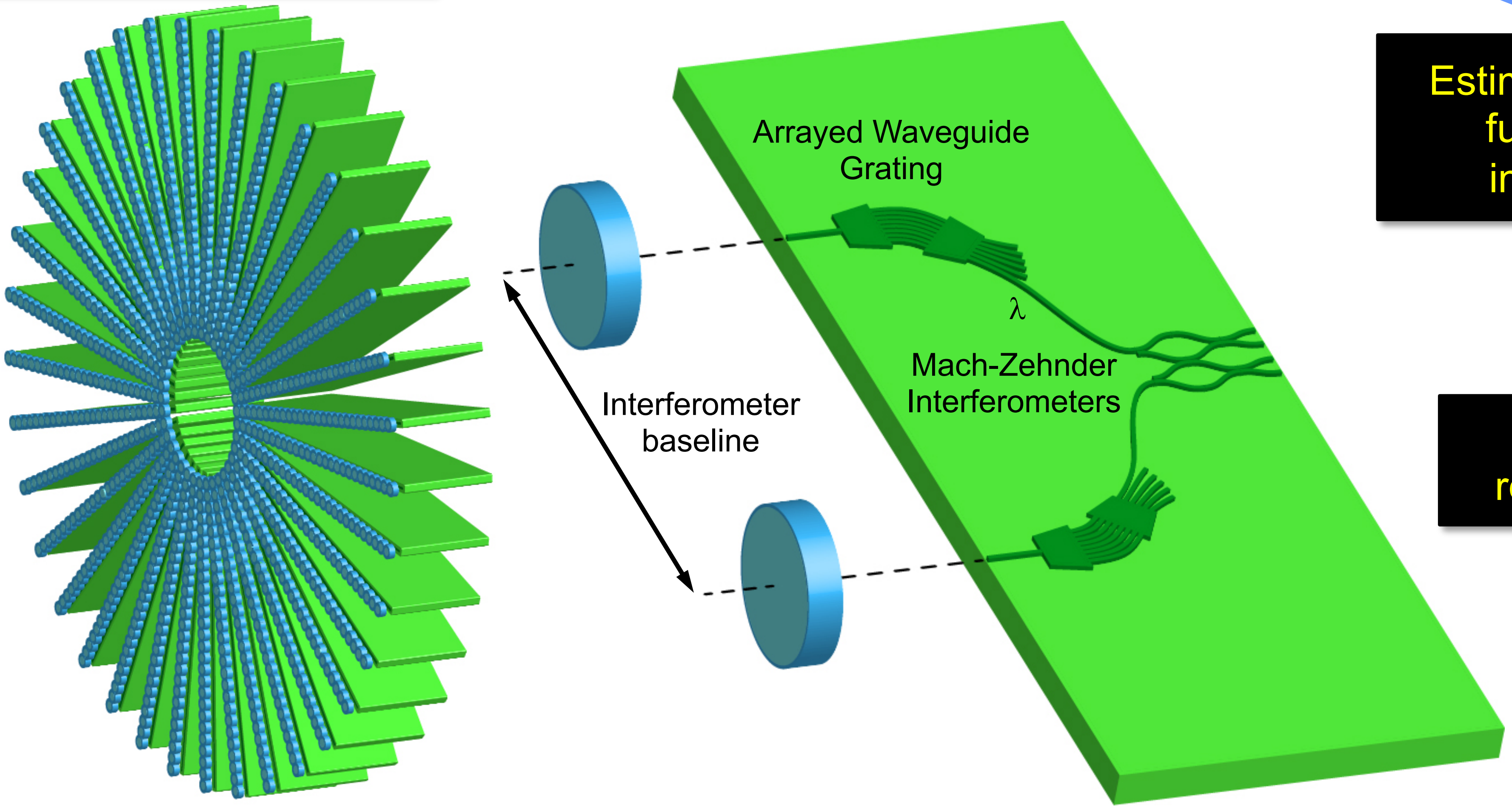
SPIDER Imager

Lenslets couple light into PIC waveguides

Interferometric beam combination performed on PIC

Estimate coherence function from intensity data

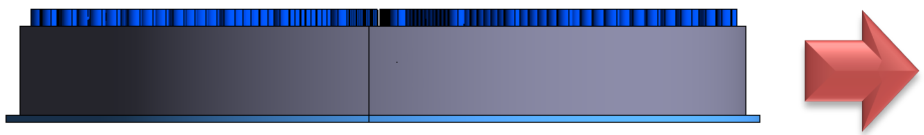
Image reconstruction

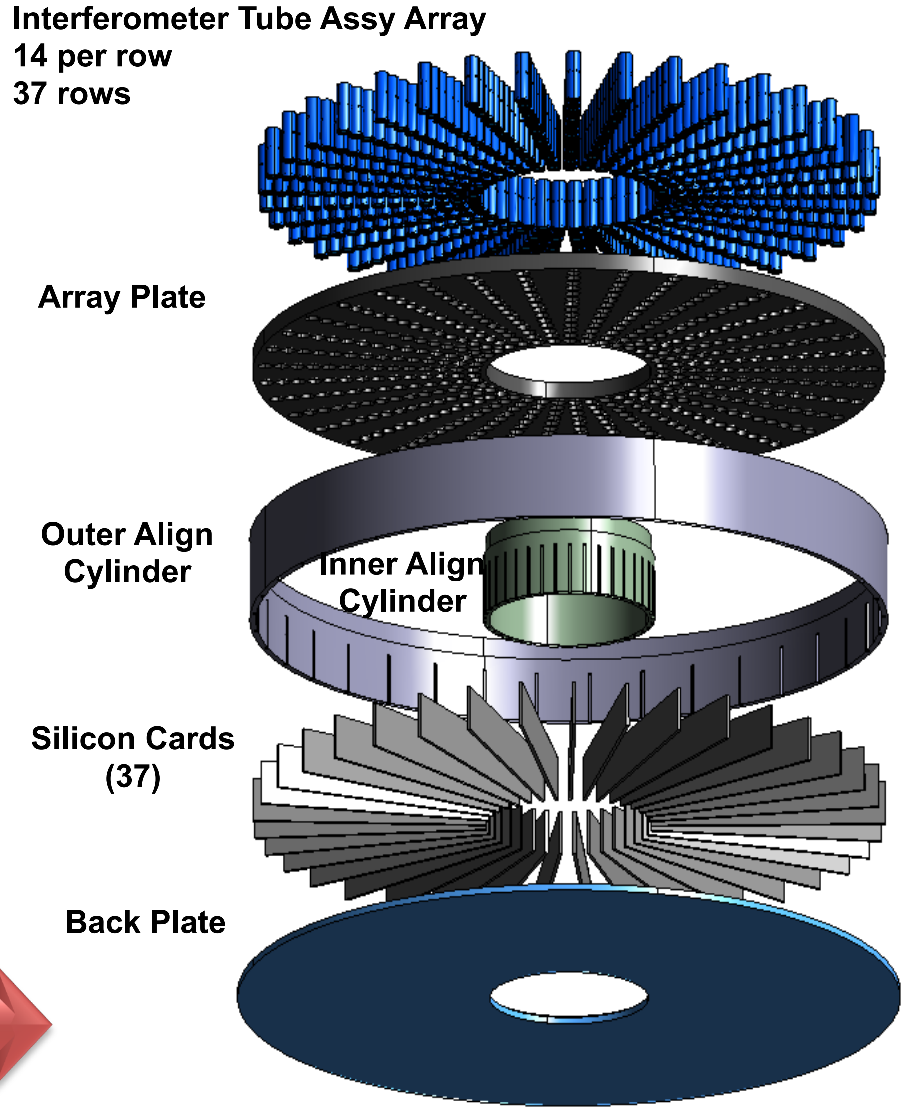


Photonic circuits are used to create a dense imaging interferometer

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

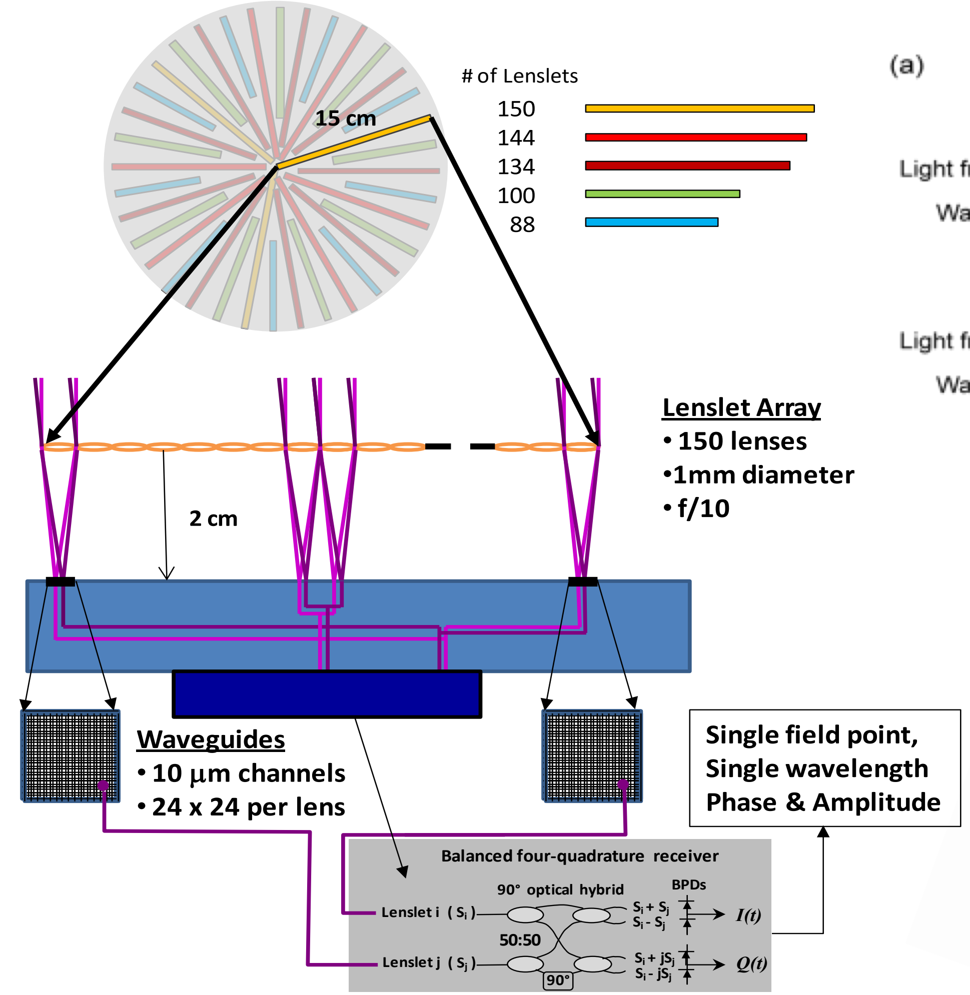




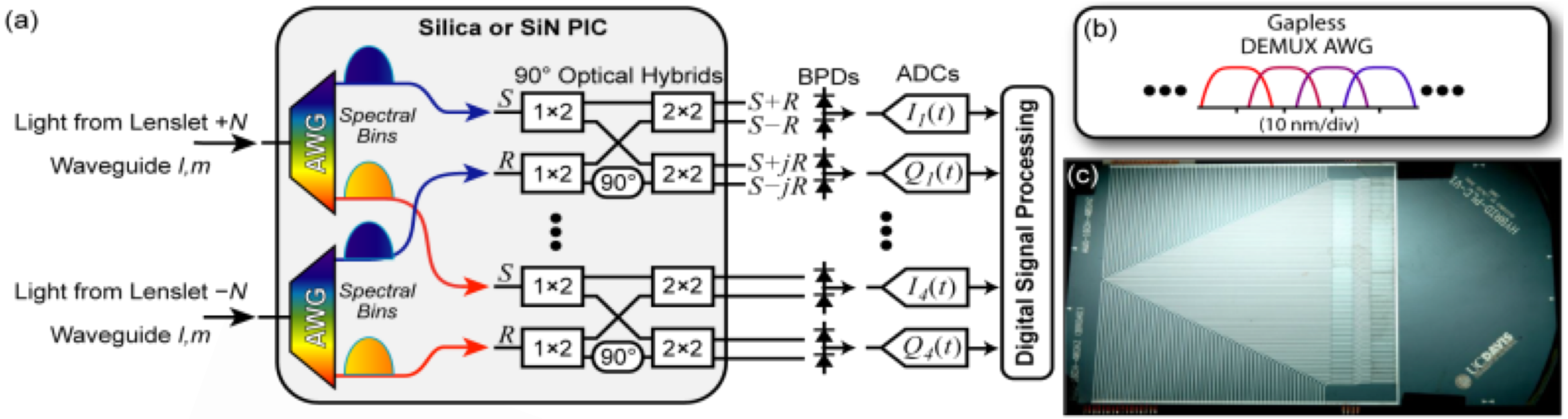
Linear arrays of lenslets arranged in spoke-like pattern to fill u,v (Fourier) imaging plane

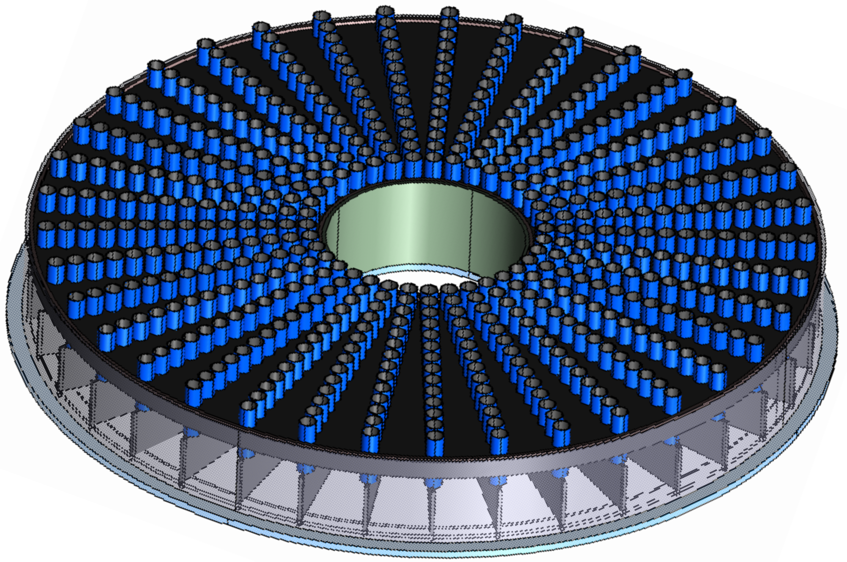
LOCKHEED MARTIN

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. J. B. Yoo, Tiehui Su, Weicheng Lai, Jaeyi Chun, Siwei Li, Guangyao Liu, *OSA Conference on Lasers and Electro Optics Pacific Rim (CLEO-PR)*, 2017.

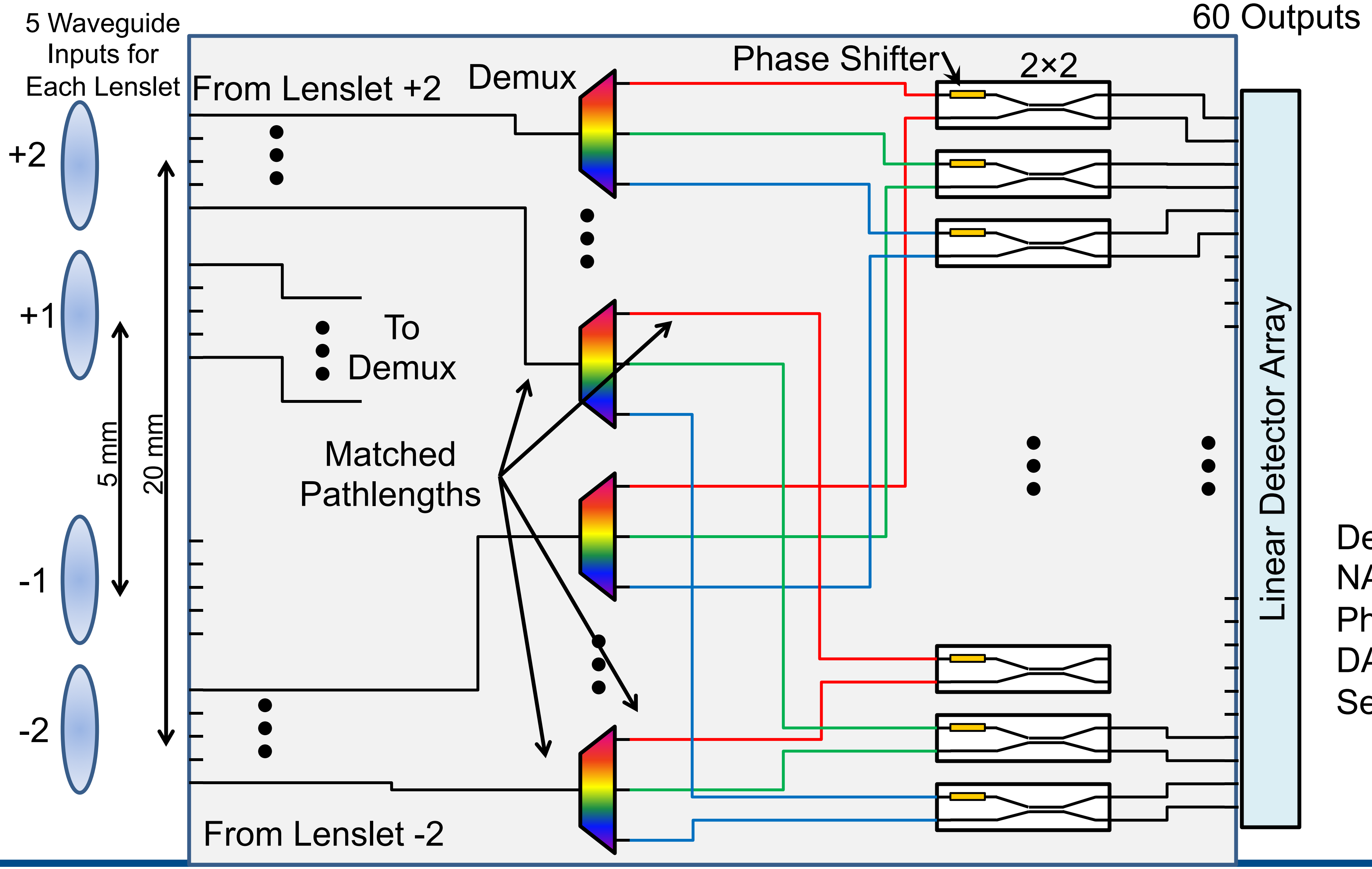
"Progress on Developing a Computational Imager Using Integrated Photonics", Samuel Thurman, Alan Duncan, Richard Kendrick, Chad Ogden, Danielle Wuchenich, Tiehui Su, Shibnat Pathak, Wei-Cheng Lai, Mathias Prost, Roberto Proietti, Ryan Scott, S. J. Ben Yoo , *2016 SIAM Conference on Imaging Science*,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

"SPIDER: Next Generation Chip Scale Imaging Sensor Update", Duncan, A.; Kendrick, R.; Ogden, C.; Wuchenich, D.; Thurman, S.; Su, T.; Lai, W.; Chun, J.; Li, S.; Liu, G.; Yoo, S. J. B., *Proceedings o 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.

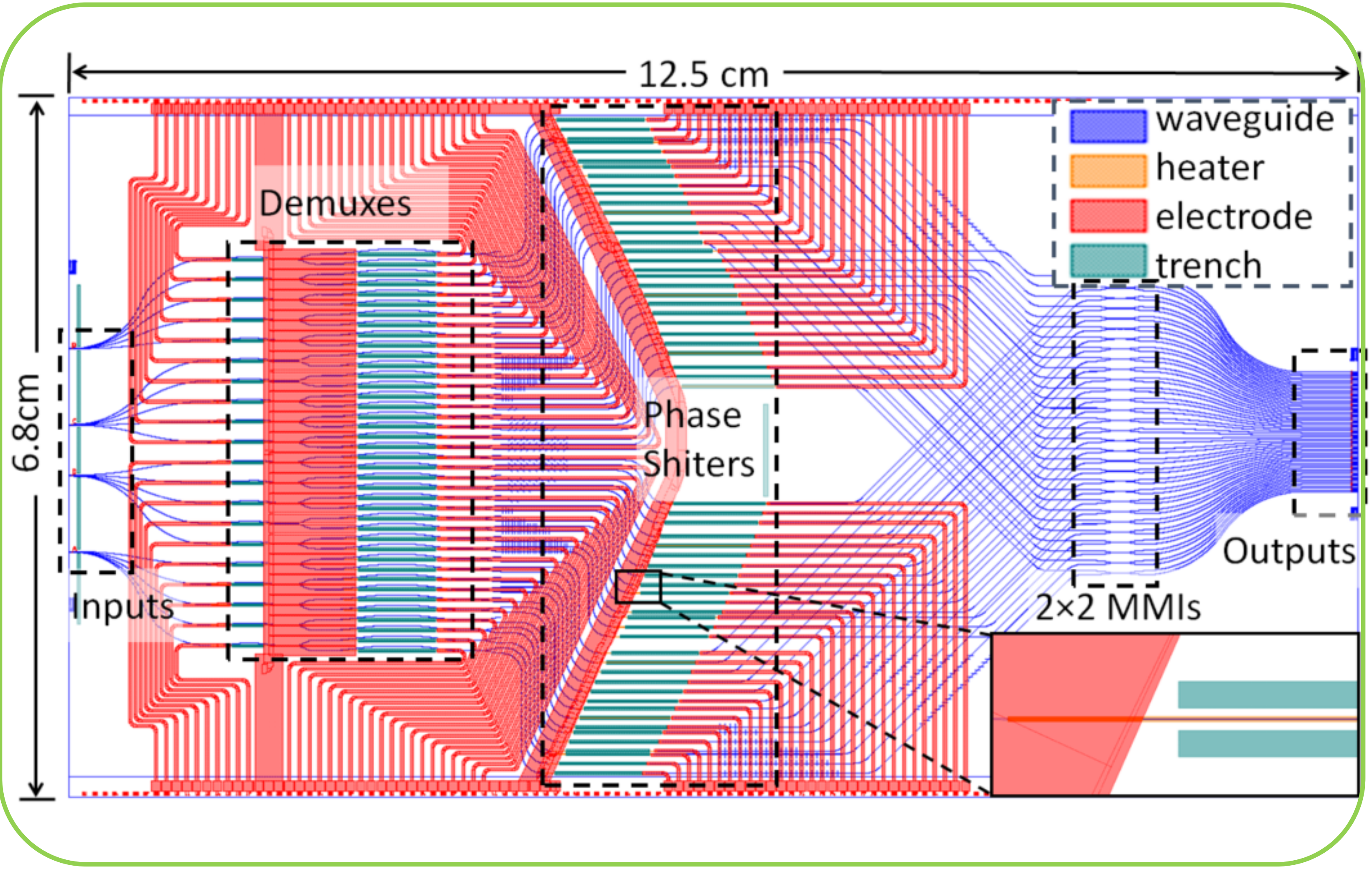
"Flat Panel Space Based Space Surveillance Sensor", Richard L. Kendrick, Alan Duncan, Chad Ogden, Joe Wilm, David M. Stubbs, Samuel T. Thurman, Tiehui Su, Ryan P. Scott, and S. J. B. Yo , *Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference* , September 2013

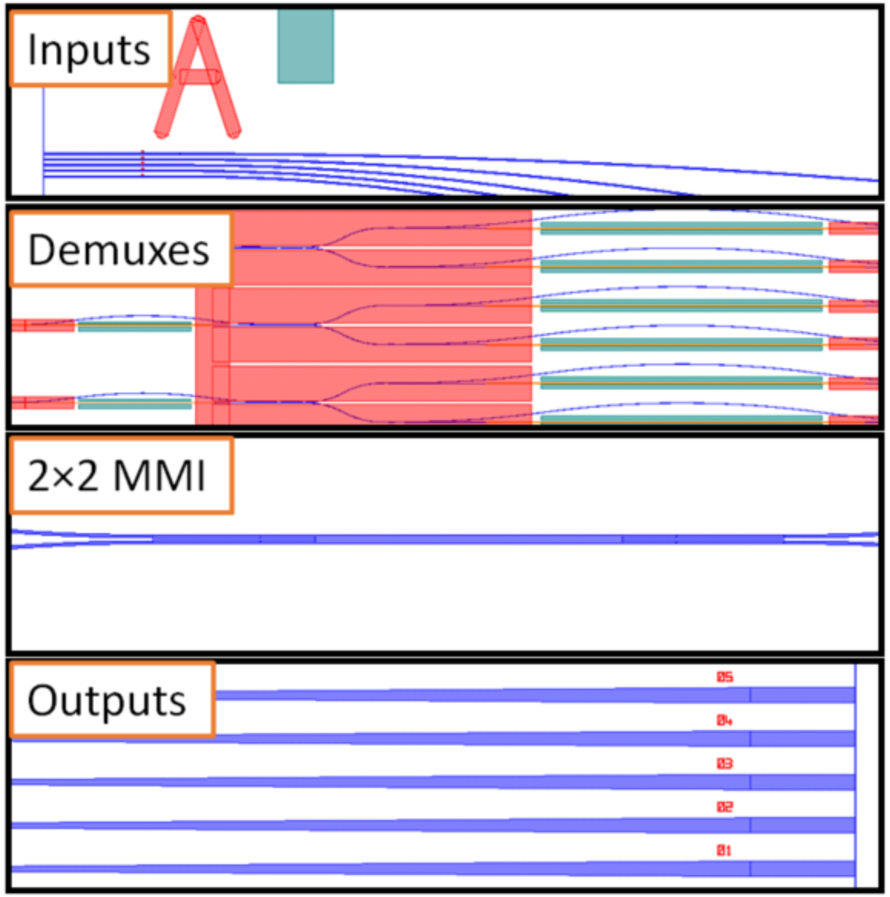
1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band)



Developed under NASA NIAC Phase I & II
DARPA TTO SeeMe

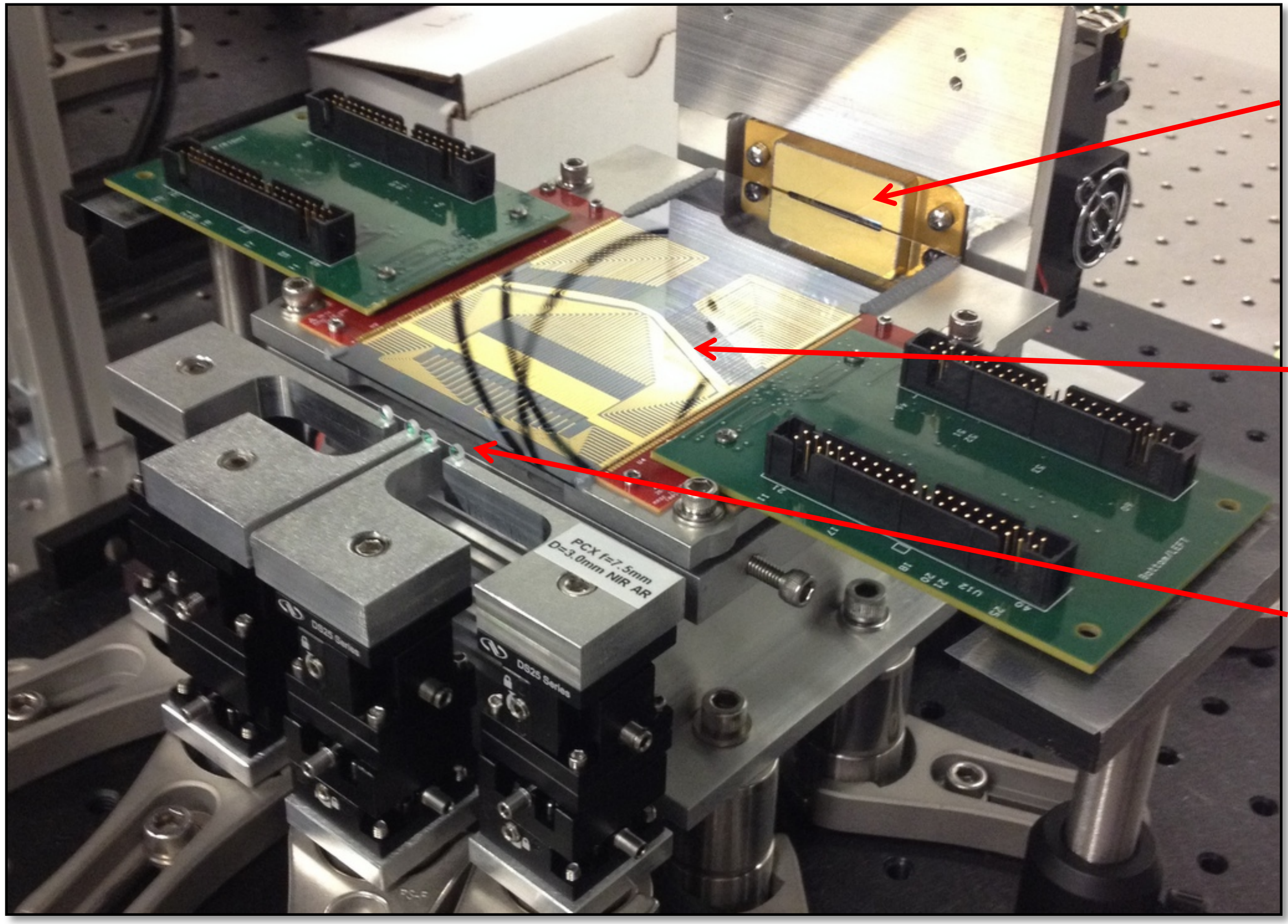
1st Gen SPIDER PIC (10-Spatial-Channel × 3 Spectral Band) Layout



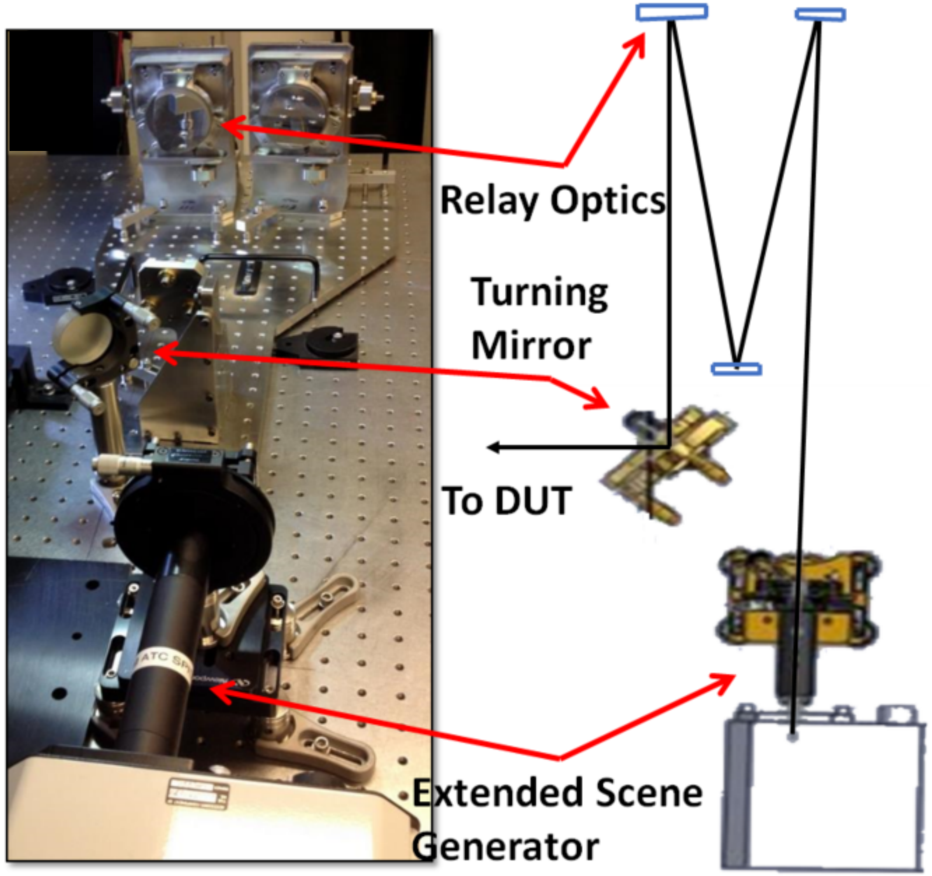


DARPA funded work

1^{st} Gen SPIDER PIC

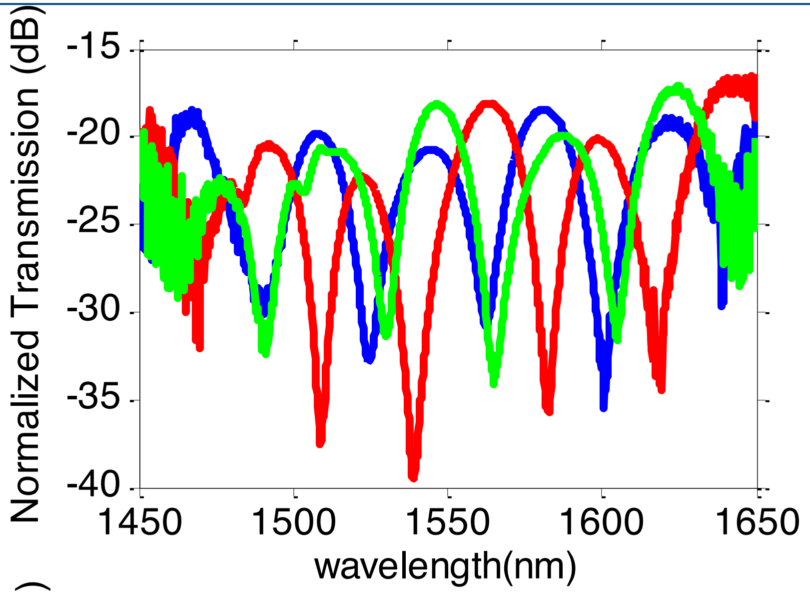


DARPA SeeMe funded work

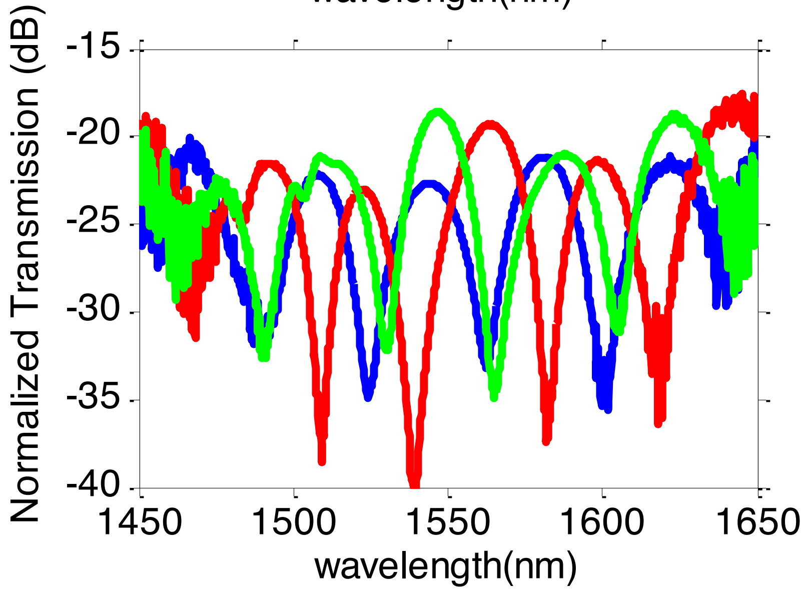


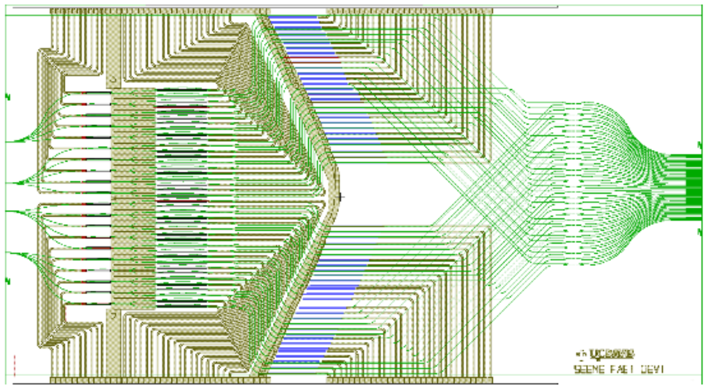
Spectrometer Response measurement

a)



b)





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.

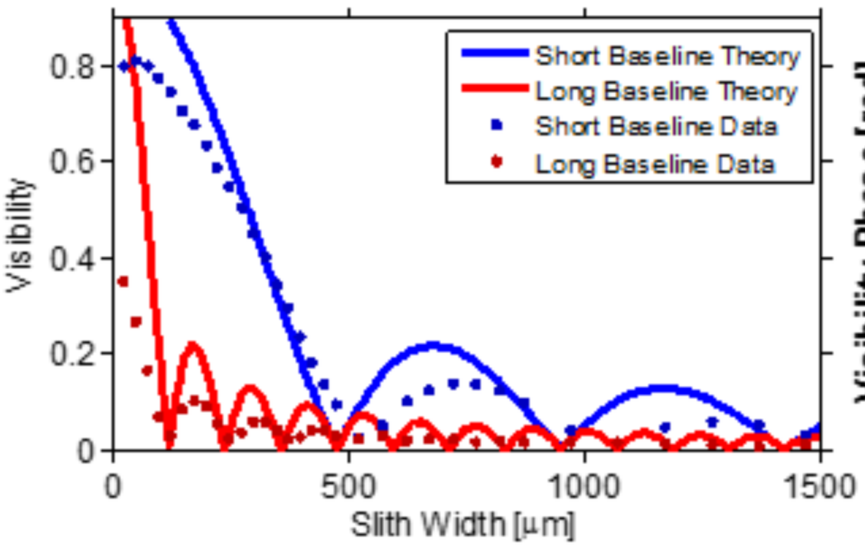
Figure a): the three wavelength channels from the first 2x2 MMI output branches.

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

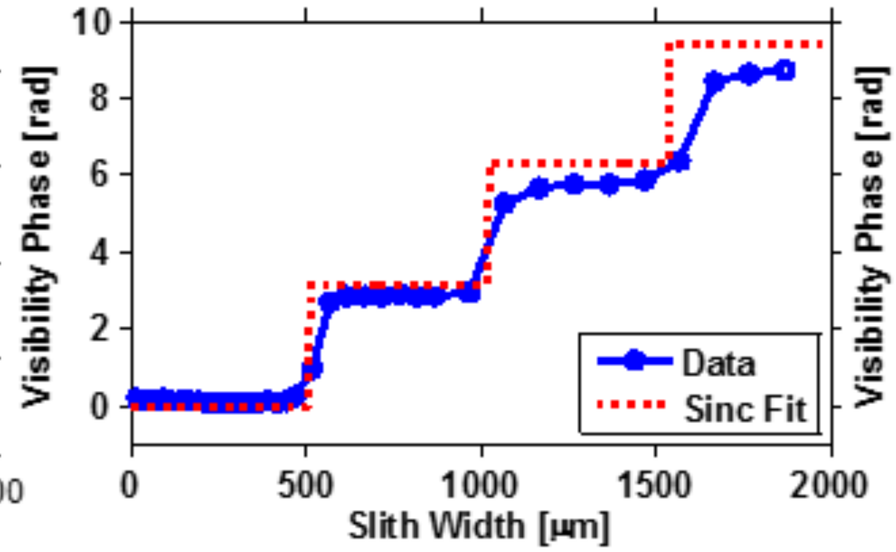
*Slight color distortion and slight misbalance observed, but the PIC expected to work

Measurement and Curve Fit on 5 mm & 20 mm Baselines

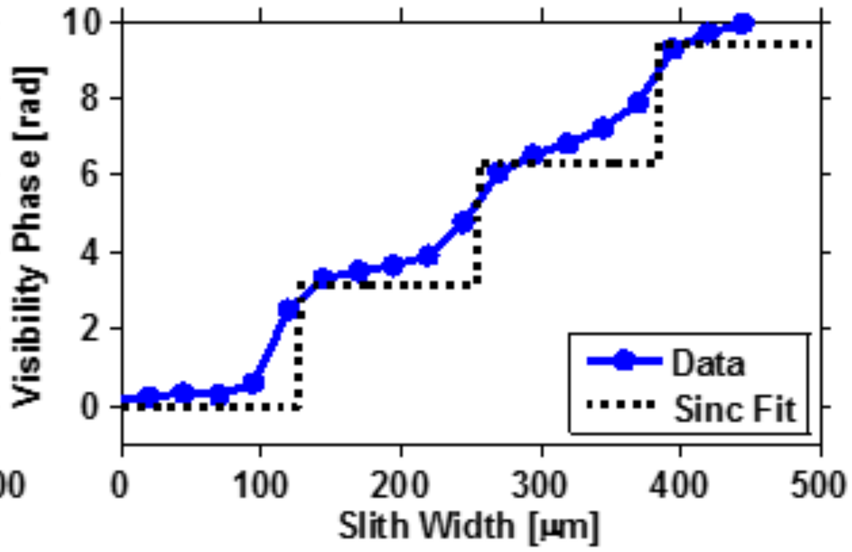
5 mm & 20 mm Baseline



5 mm Baseline



20 mm Baseline



(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

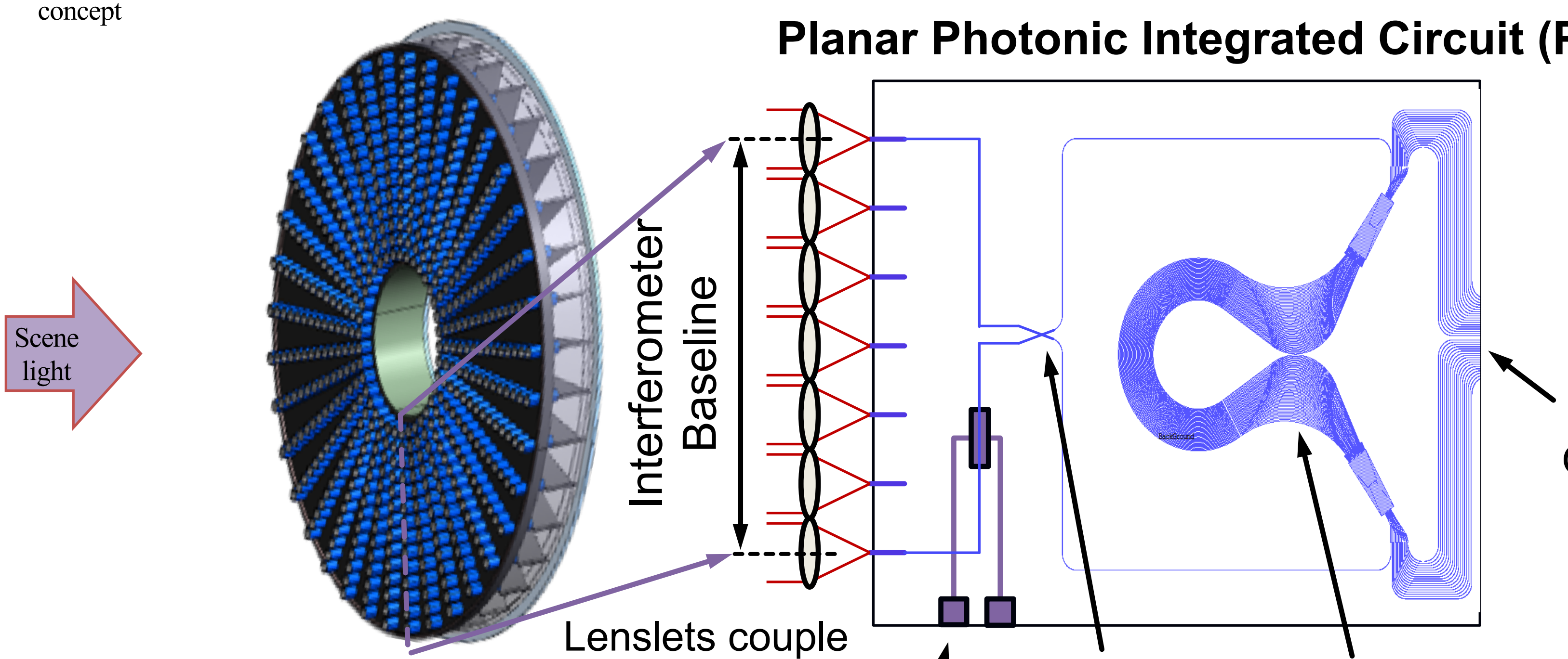
2nd Gen SPIDER Concept Design – Interferometry

2D Interferometer Array

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

37 Blade SPIDER concept

Planar Photonic Integrated Circuit (PIC)



Observe interference of light collected for each baseline and spectral channel

Lenslets couple light into Waveguides

2x2 Beam Combiner

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

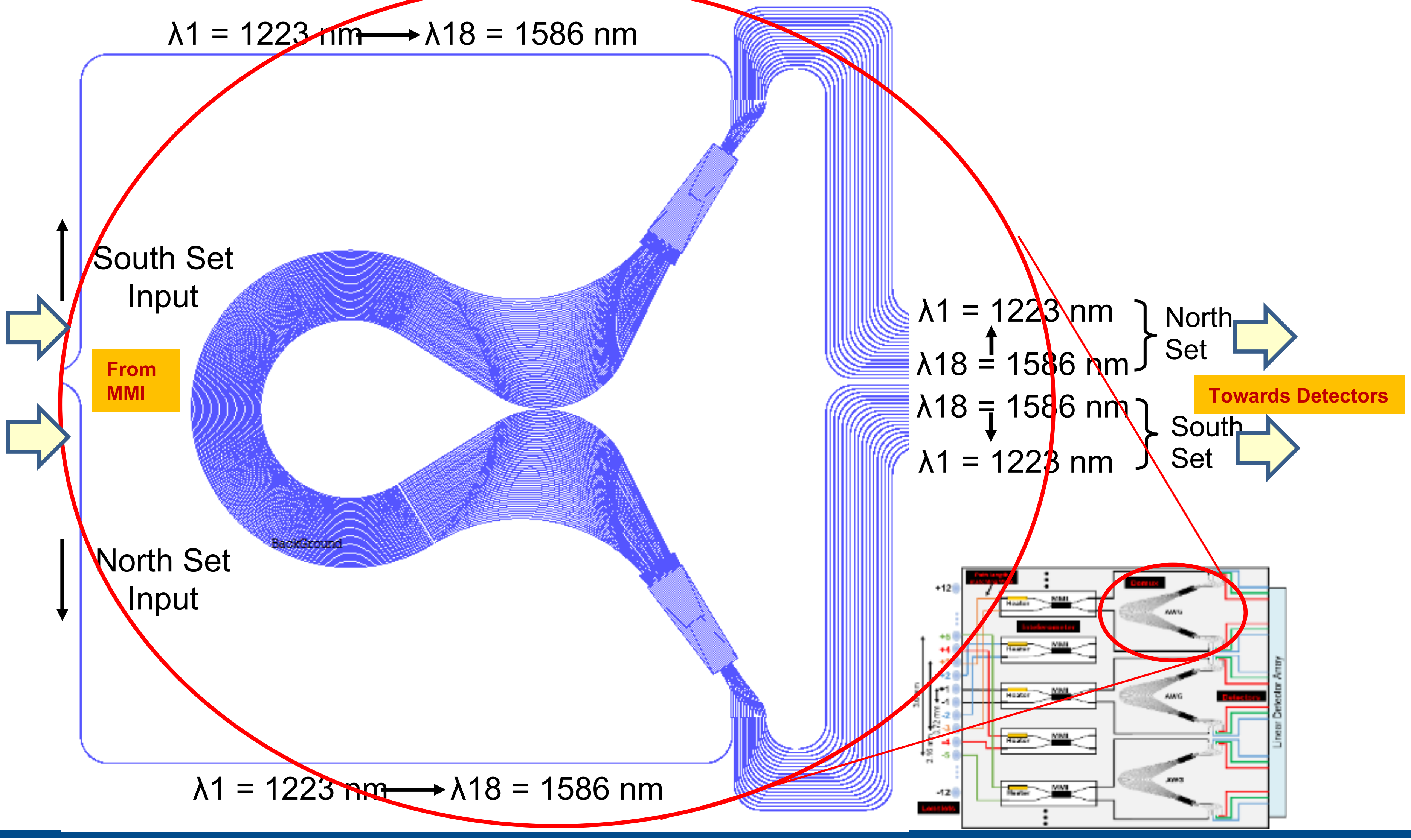
Electrodes for adjusting interferometer OPD

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

[redacted]

Spectrometer Design for the 2nd Gen SPIDER: 18 Ch (3.3THz) Arrayed Waveguide Gratings

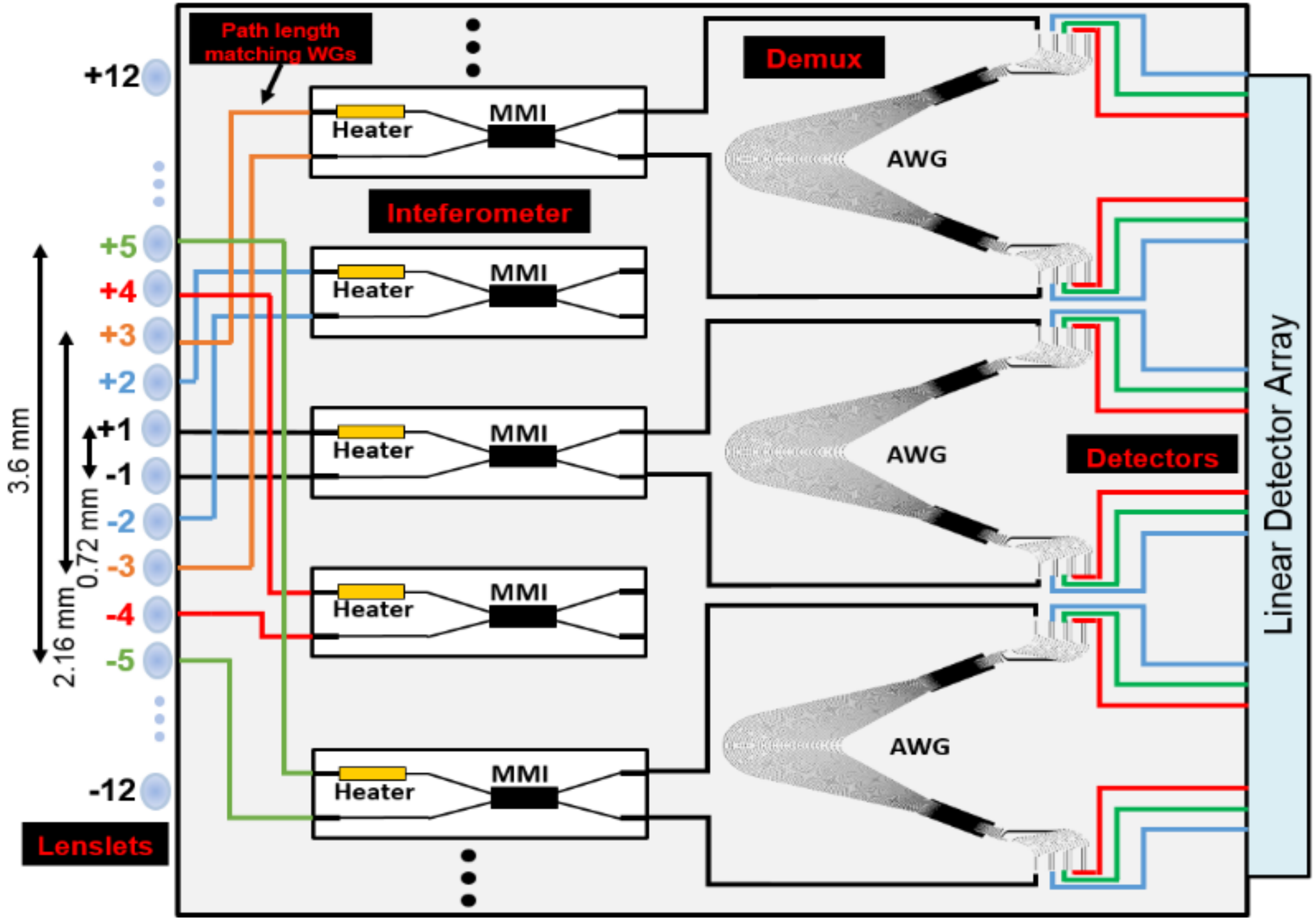
Symmetric Dual Arm Design for Interfacing with Mach-Zehnder Interferometer



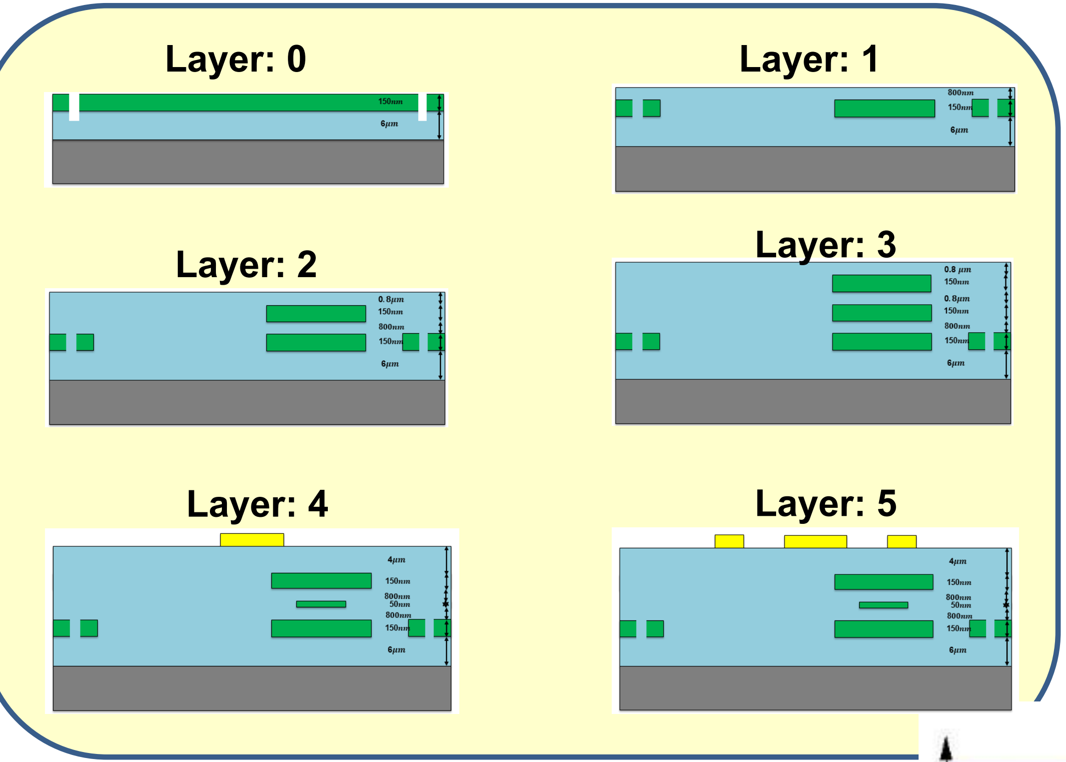
WL (nm)
1223
1240
1257
1275
1293
1311
1331
1350
1371
1392
1413
1436
1459
1483
1507
1533
1559
1586

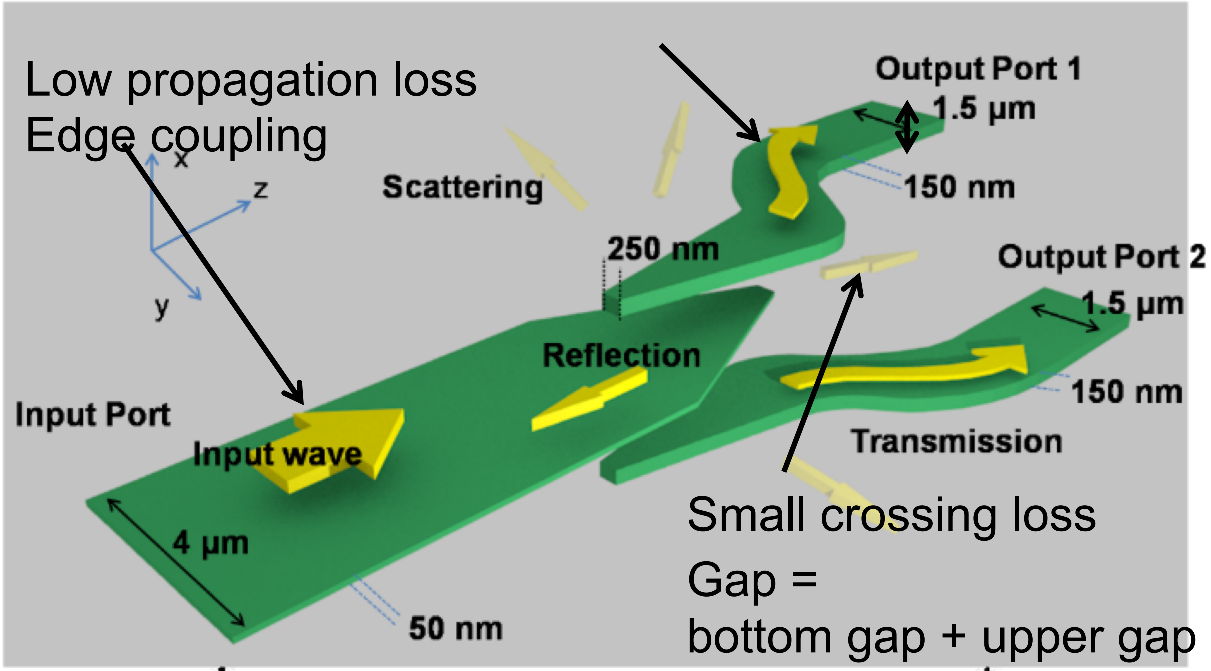
2nd Gen SPIDER Photonic Integrated Circuit Design

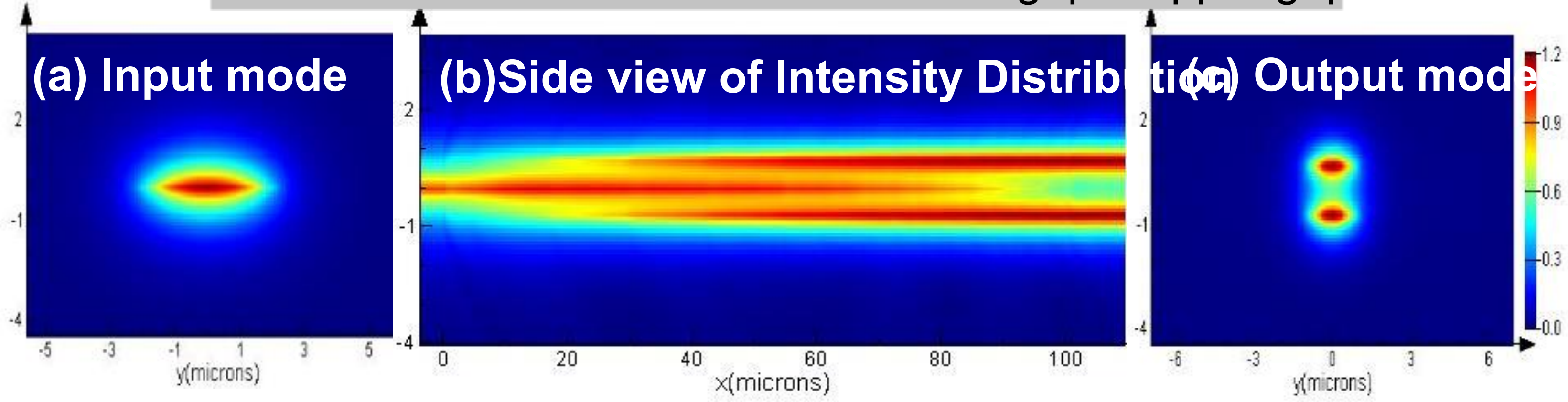
12 baselines, 18 spectral bins, multi-layer Si_3N_4/SiO_2 PICs



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

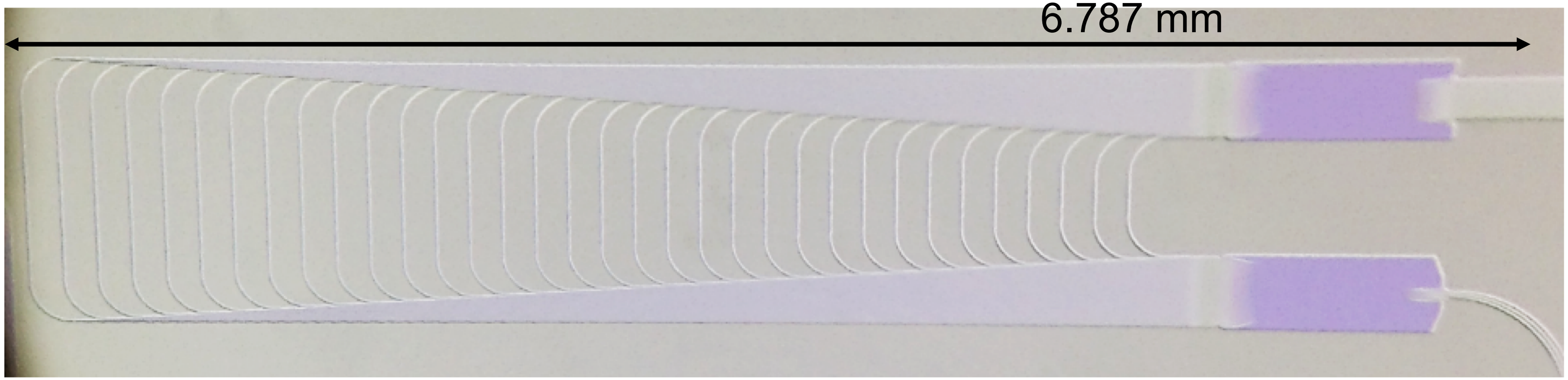




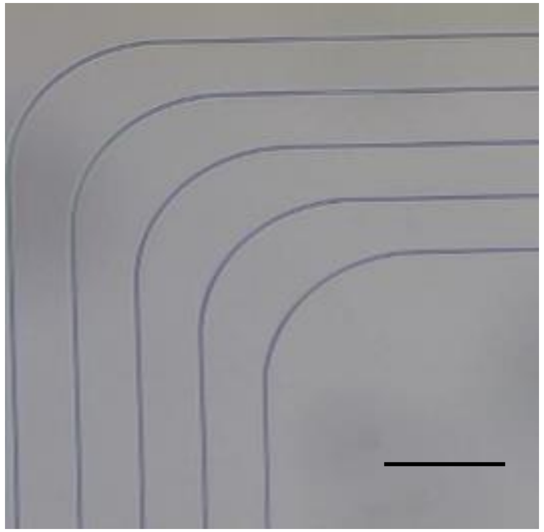


SiN Arrayed Waveguide Gratings

16 channel X 50 GHz AWG

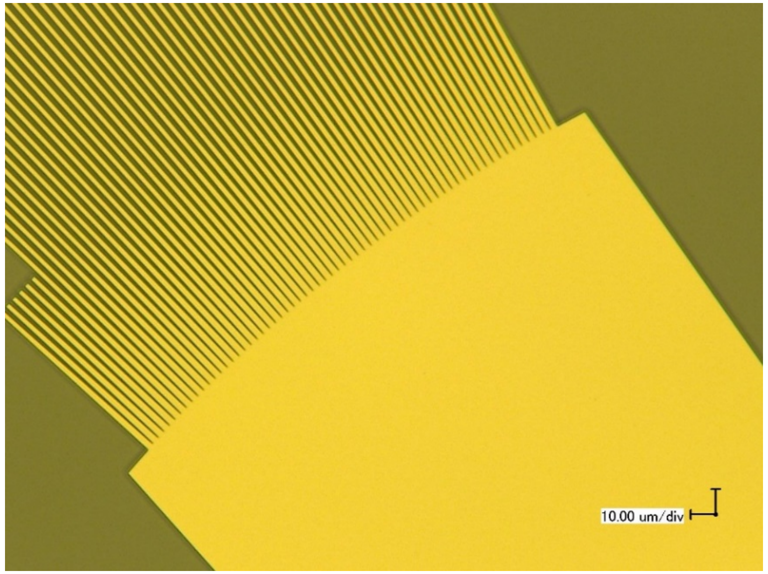


Bending



150um

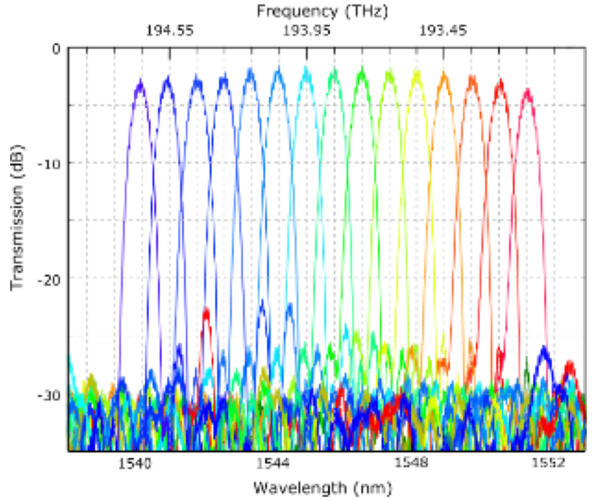
Star Coupler



10um

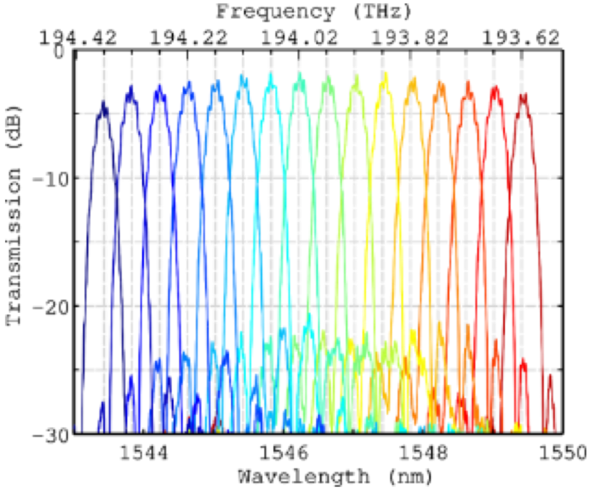
Arrayed Waveguide Gratings – Fabricated Device Transmitted Spectrum Measurements

16 ch X100 GHz AWG



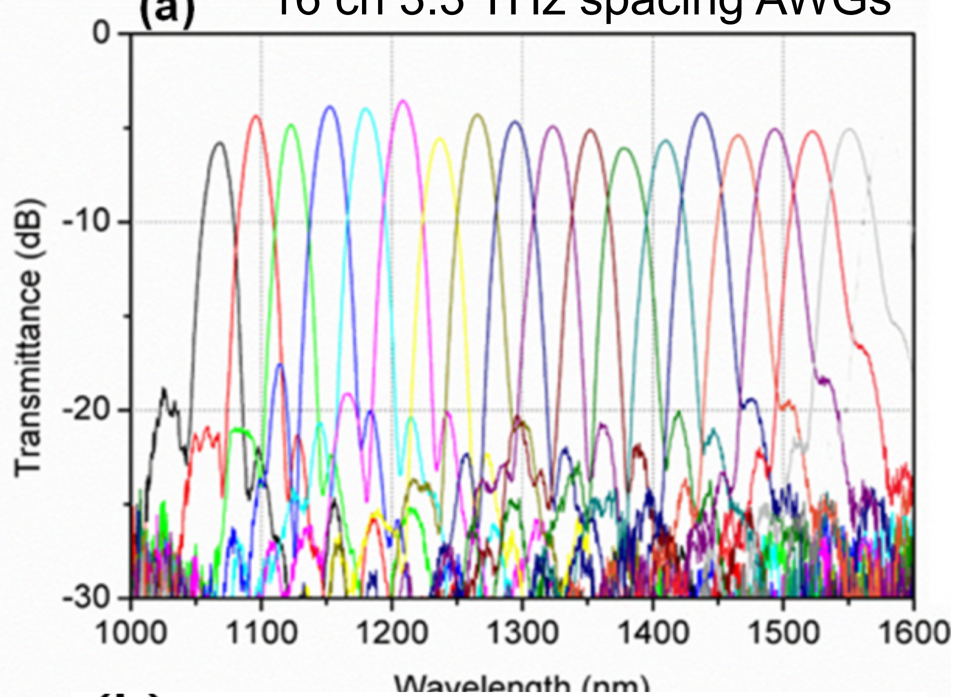
Insertion loss: 1.7 dB
Crosstalk: -21 dB

16 ch X50 GHz AWG

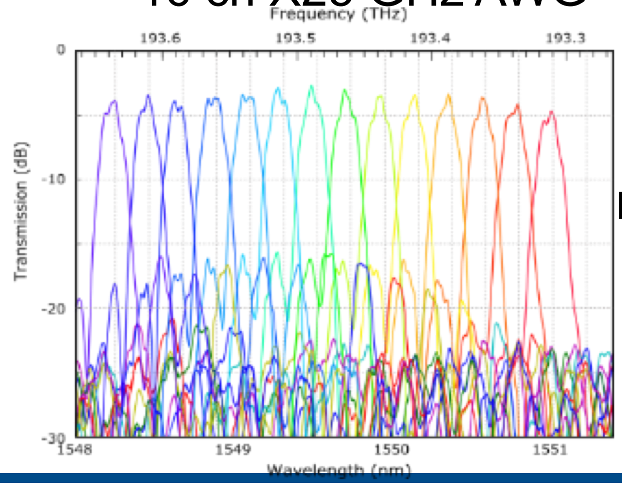


Insertion loss: 1.8 dB
Crosstalk: -20 dB

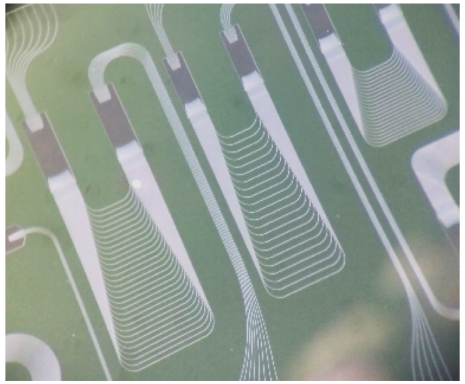
16 ch 3.3 THz spacing AWGs



16 ch X25 GHz AWG



Insertion loss: 2.7 dB
Crosstalk: -13 dB

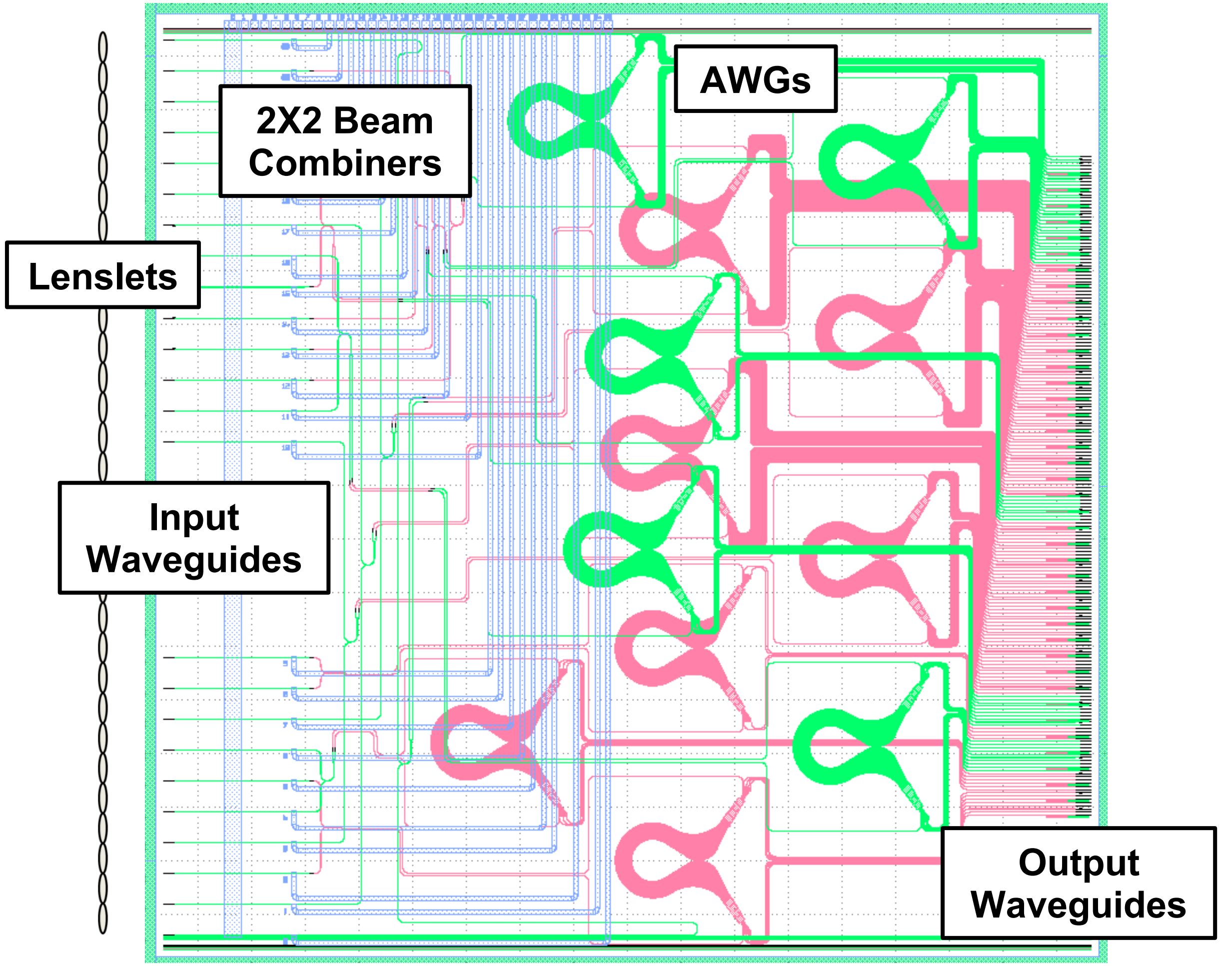


(b)

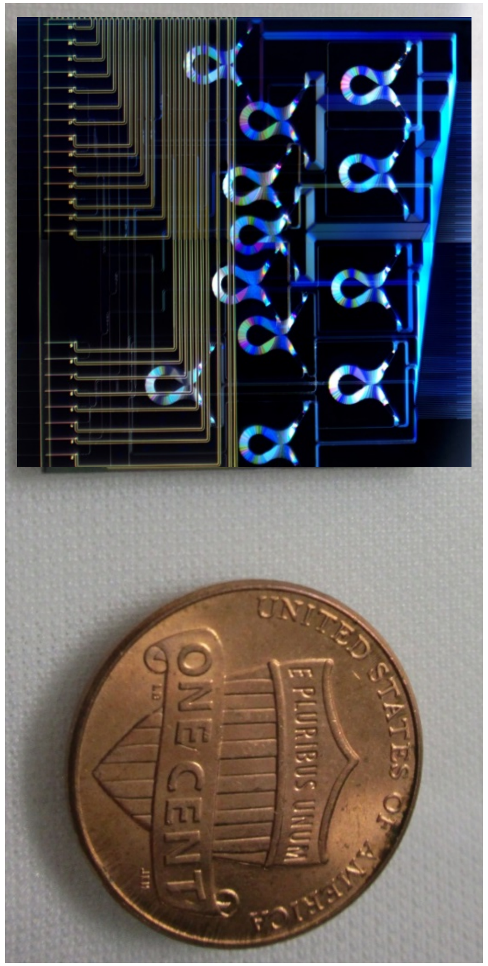
Output	λ (nm)	Output	λ (nm)
1	1065	10	1322
2	1094	11	1351
3	1123	12	1378
4	1151	13	1409
5	1180	14	1437
6	1208	15	1465
7	1237	16	1494
8	1265	17	1520
9	1296	18	1550

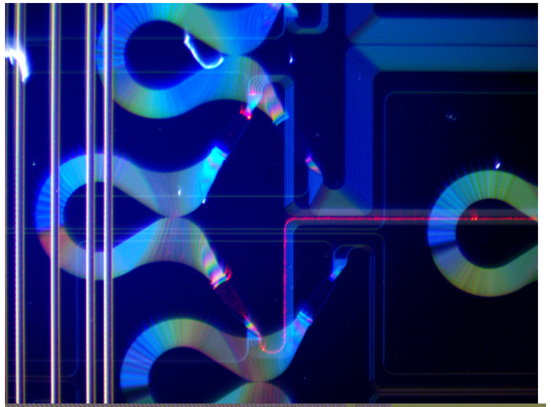
2nd Gen SPIDER PIC (12 baseline, 18 spectral bin) fabricated w/ CMOS Compatible Process @ UC Davis

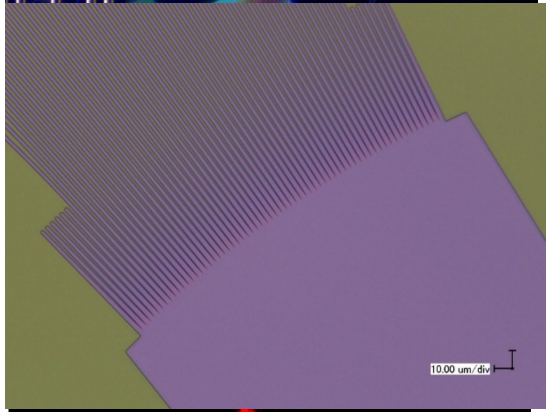
Lithography Layout

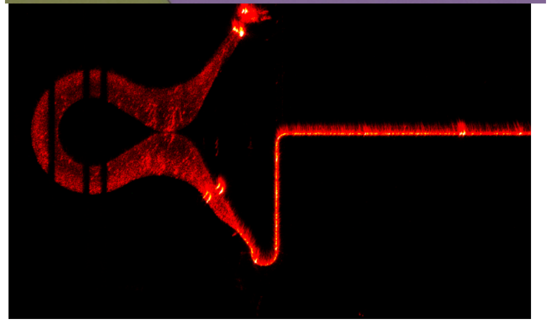


Photograph



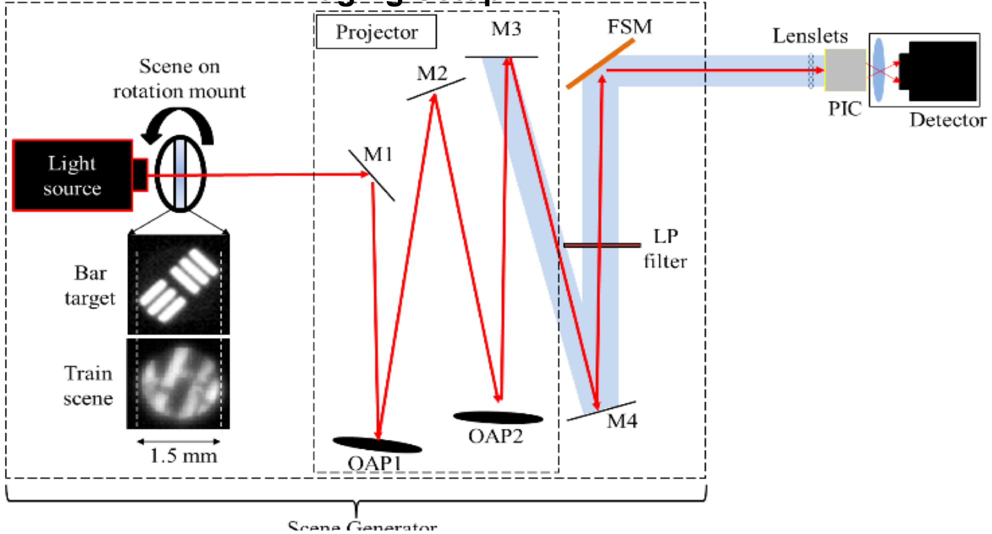




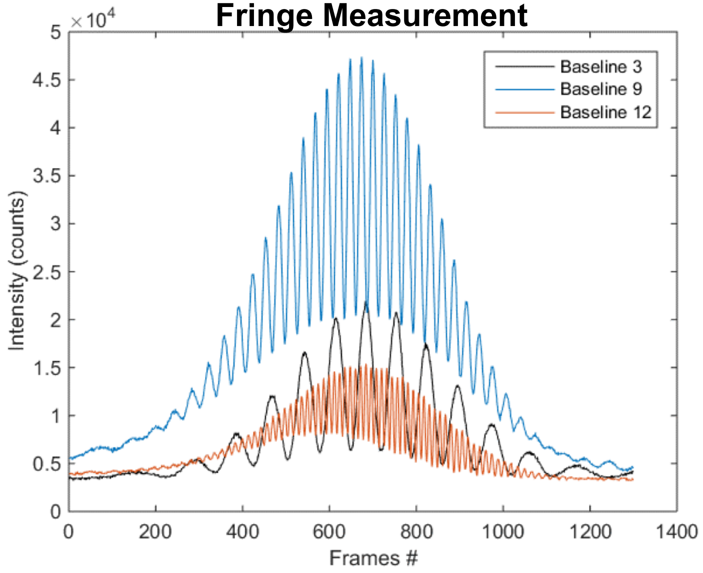


Imaging Reconstruction Experiments – Results

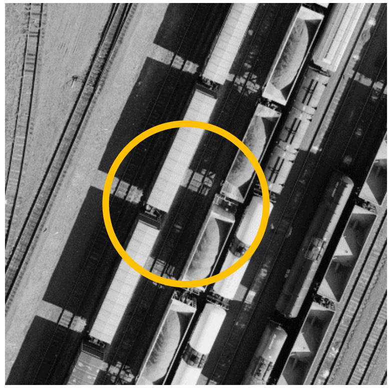
Imaging Setup



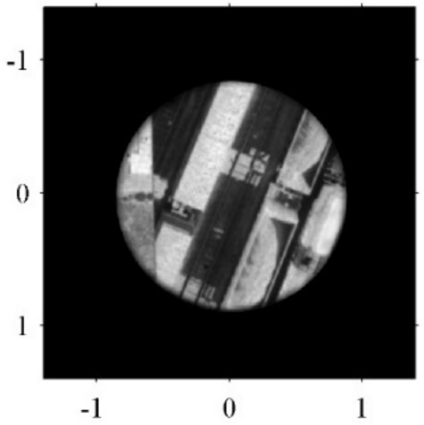
Fringe Measurement



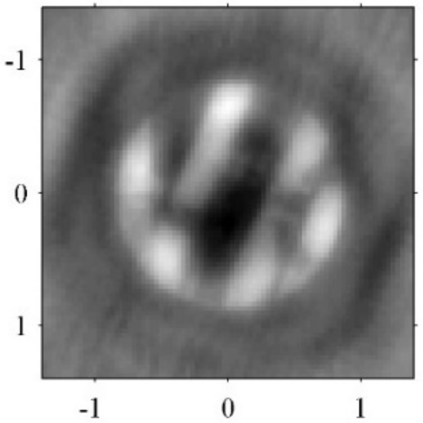
Chrome-on-glass mask



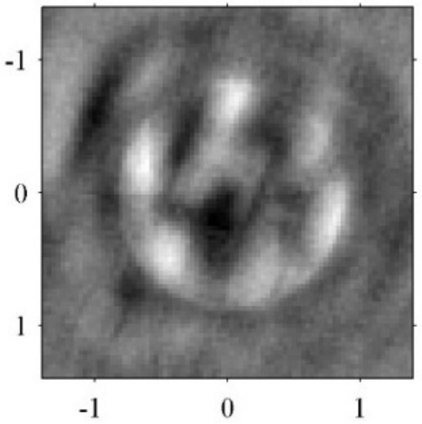
Object Image



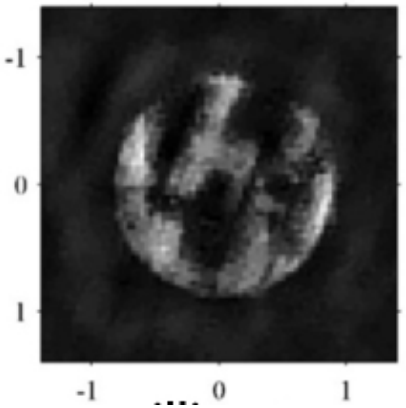
Simulated Image



Reconstructed Image

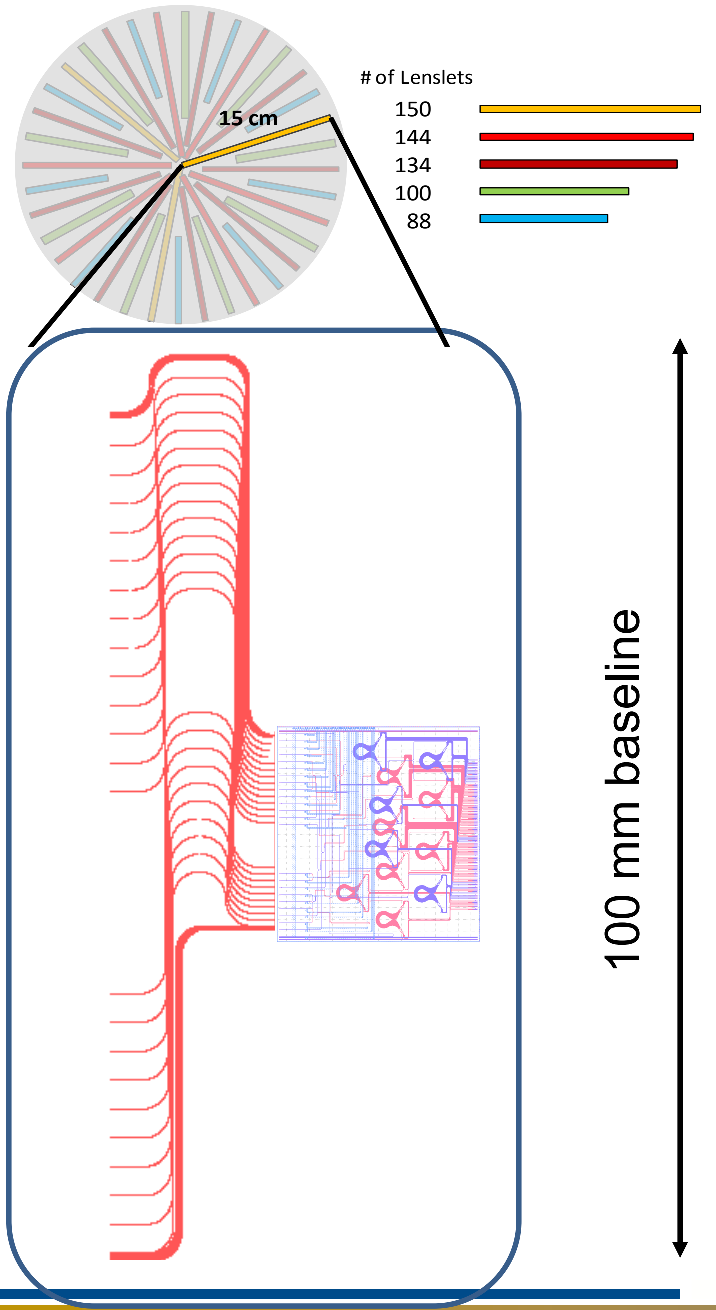


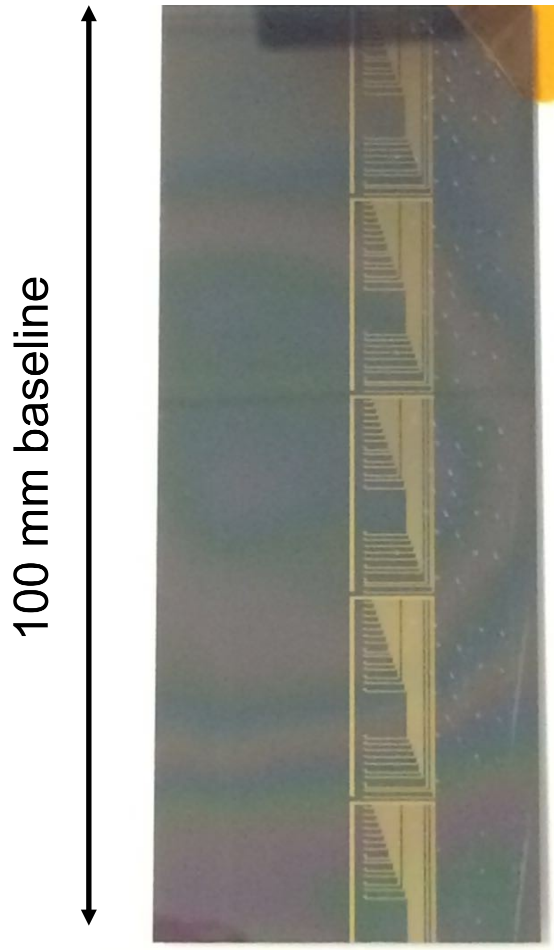
After iterative reconstruction

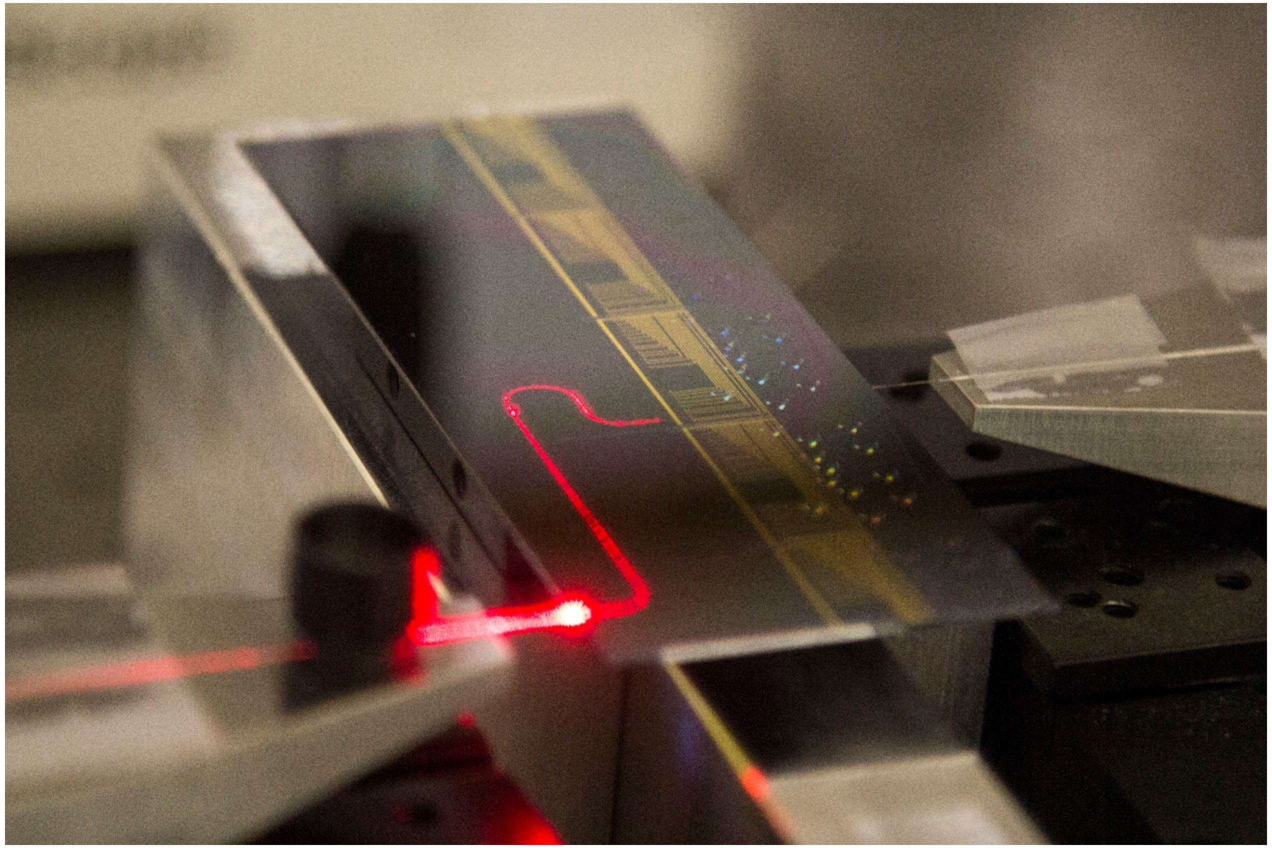


Provided by Lockheed Martin

Multi-resolution 2^{ND} Gen SPIDER PIC

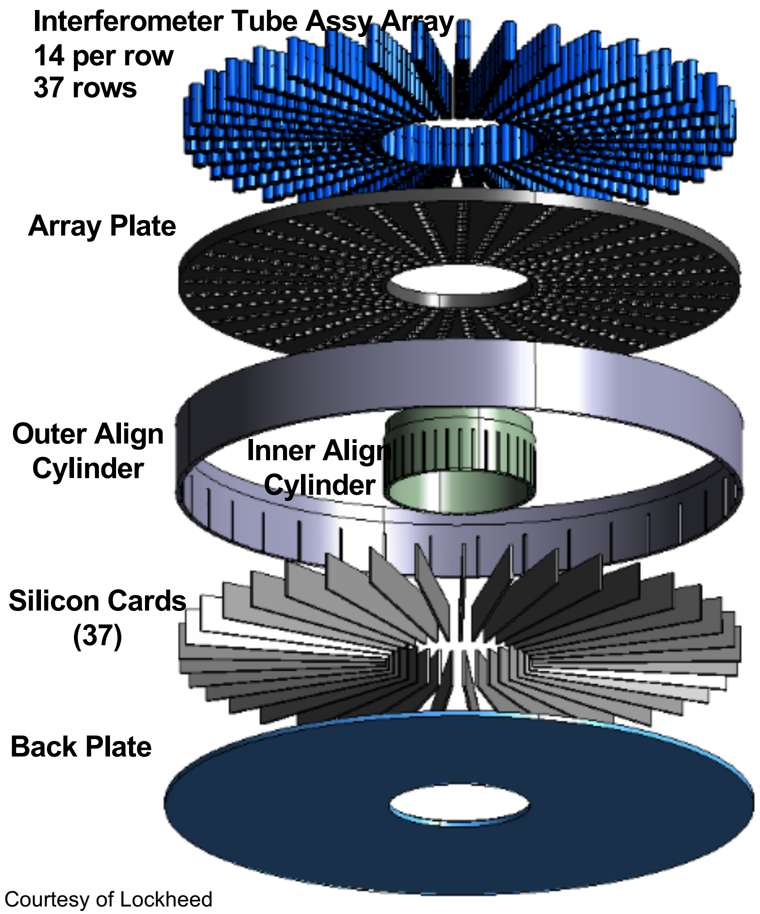




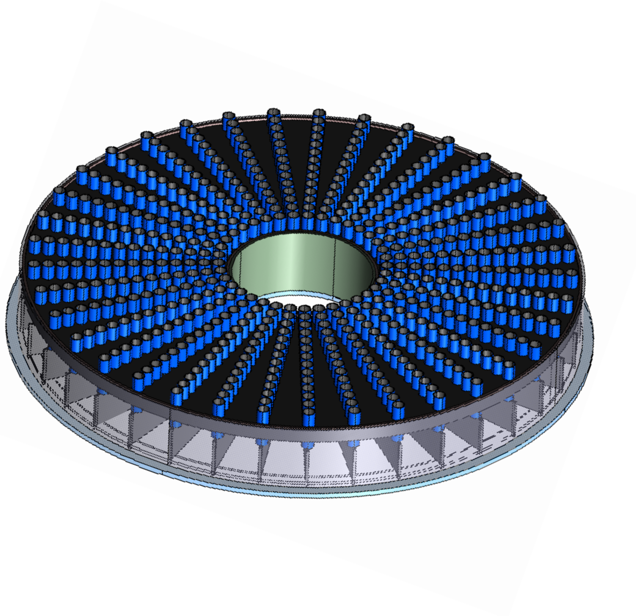


2^{nd} Gen SPIDER PIIT integration

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



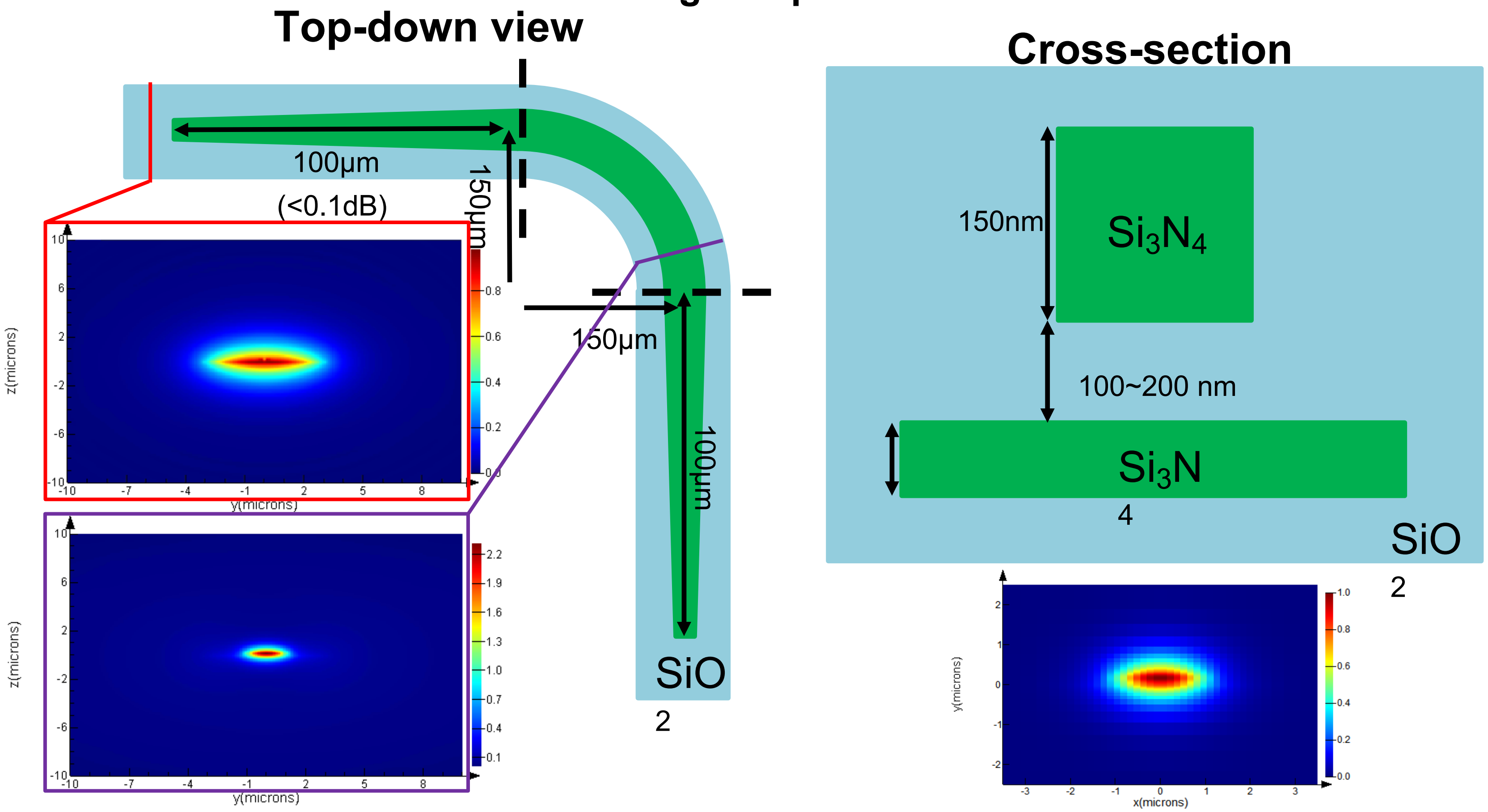
Courtesy of Lockheed Martin

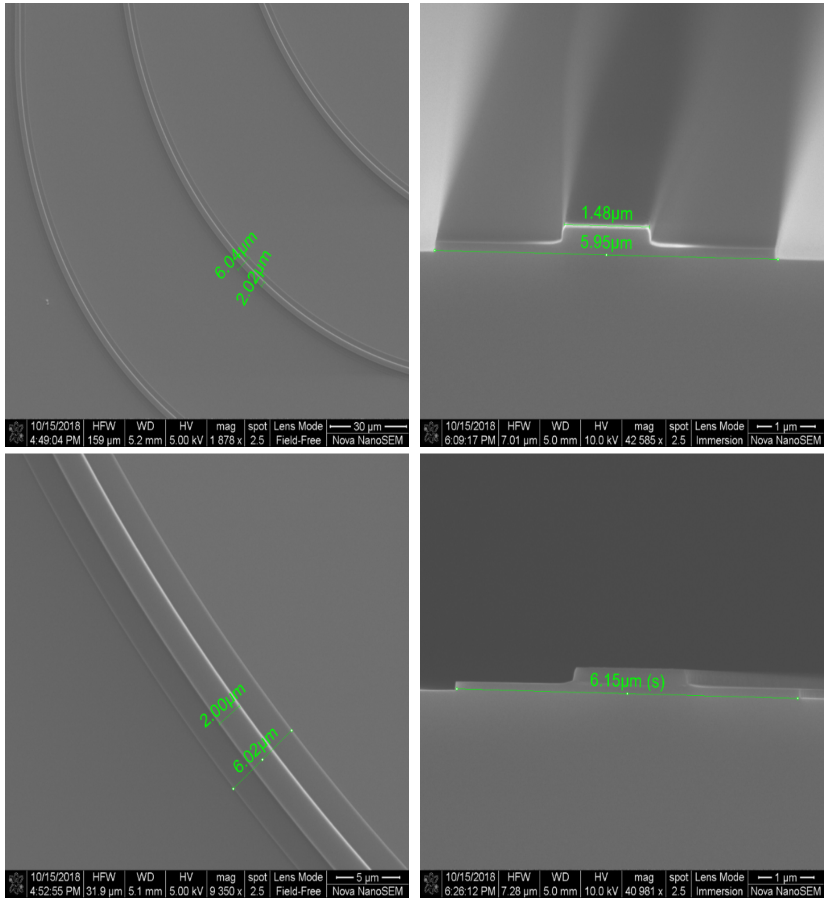


Systems Integration with ~37 SPIDER PICs into SPIDER PIIT (Photonic Integrated Interferometric Telescope)

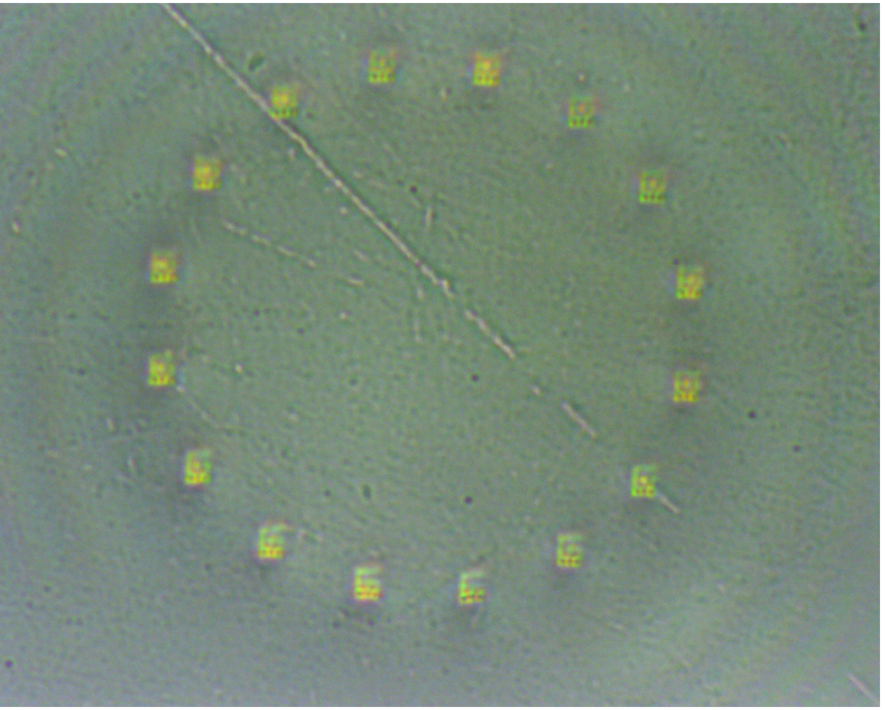
Enhancing Density and Functionality by Introducing Double-Stripe Waveguide Platform

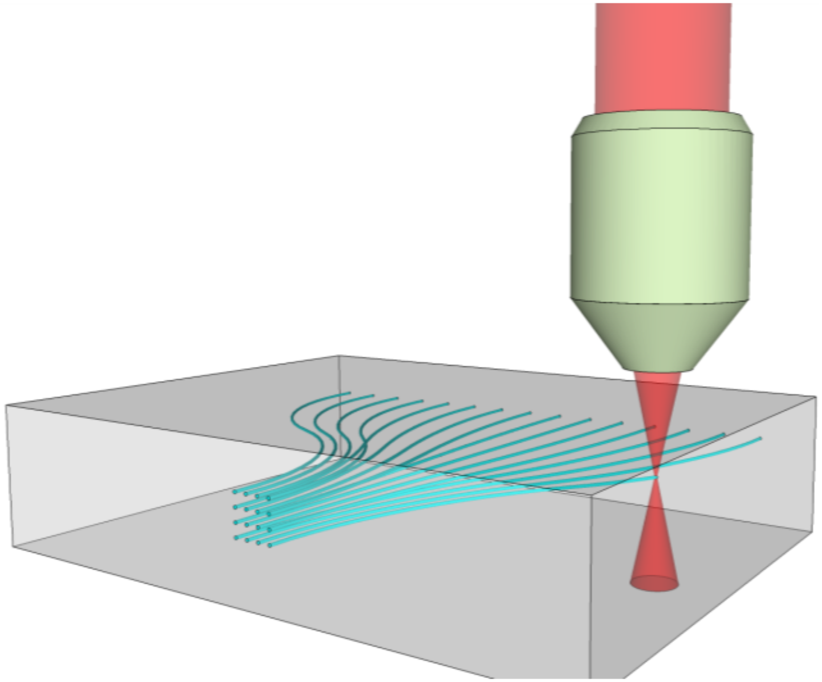
To overcome the large bending radius problem of ultra-low loss Si_3N_4 waveguide platform

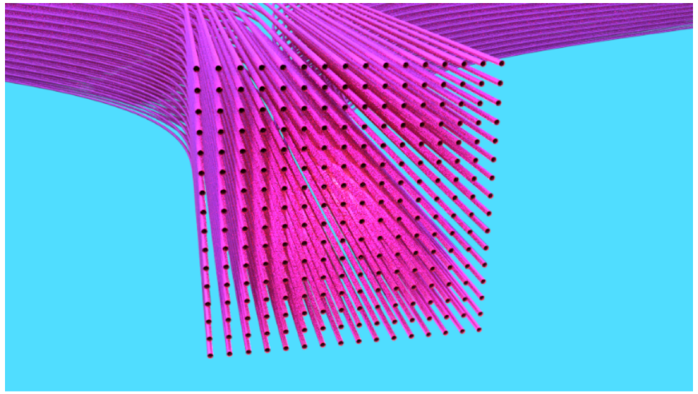


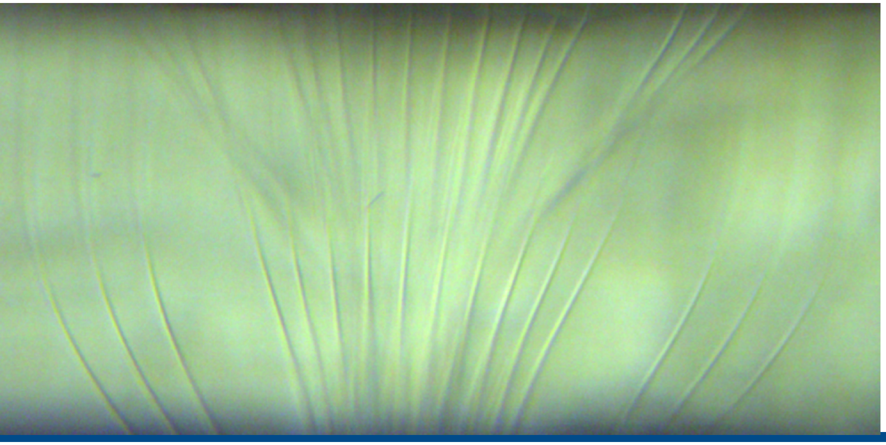


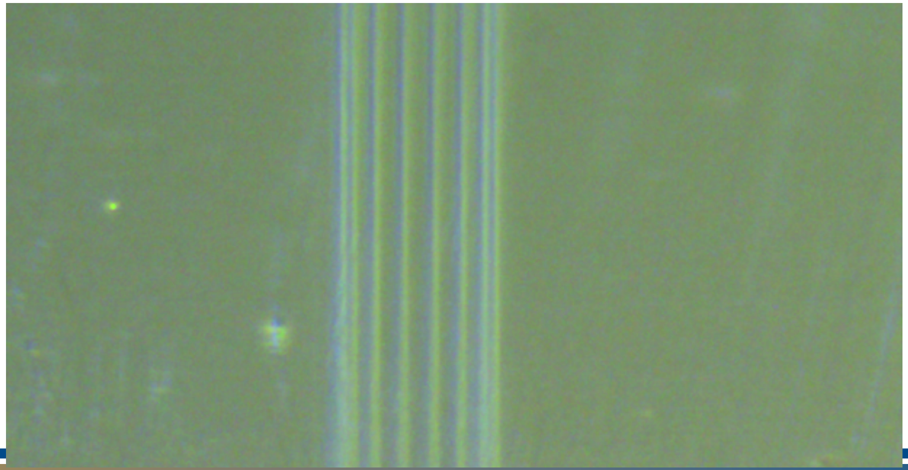
3D Integrated Photonics by Ultrafast Laser Inscription

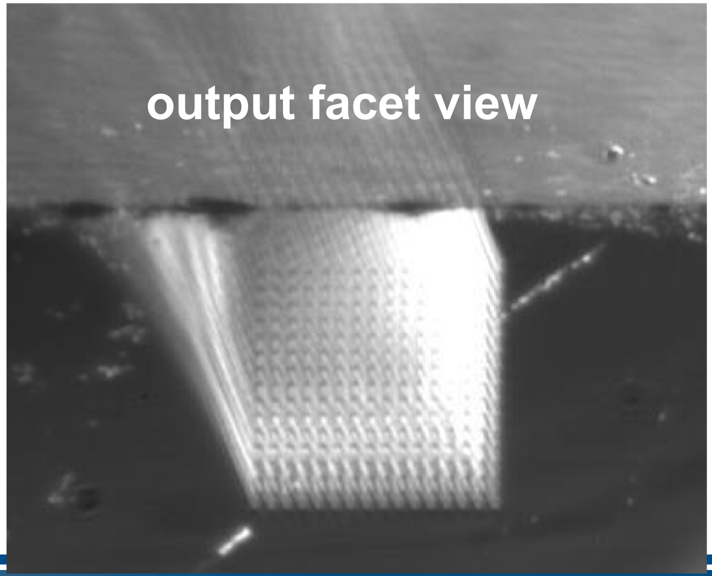






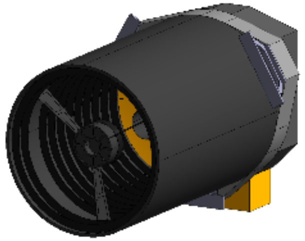






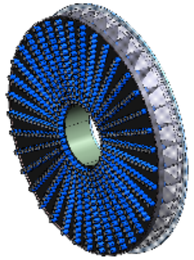
Summary

- 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



Conventional EO Sensor

DOD + commercial industry investment



SPIDER
Segmented Planar Imaging Detector for EO Reconnaissance

SPIDER Single Chip Design