Prototype Photonic Integrated Circuit (ProtoPIC) Platform and Applications

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Dr. David Kharas

MIT Lincoln Laboratory

6 March 2018

Outline

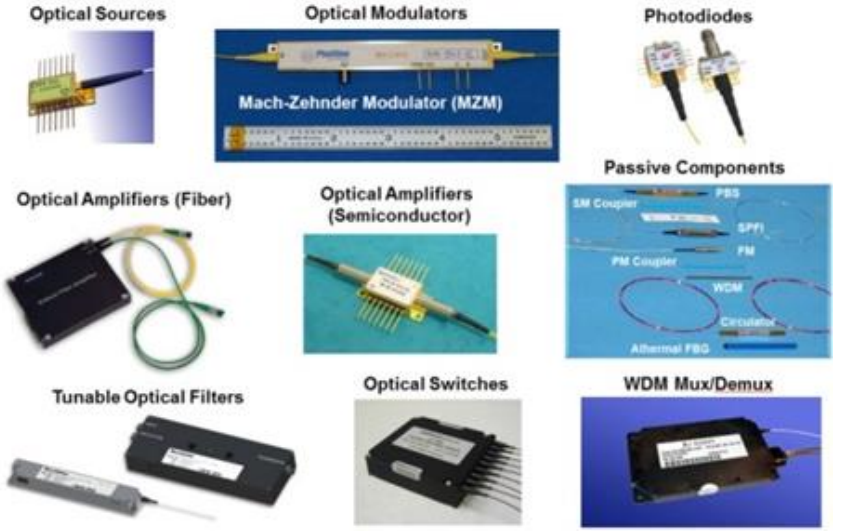
- Motivation
- Integrated Photonics Platforms at Lincoln Laboratory
- Hybrid Integration and ProtoPIC
- Applications

Photonic Integration in the Commercial Space

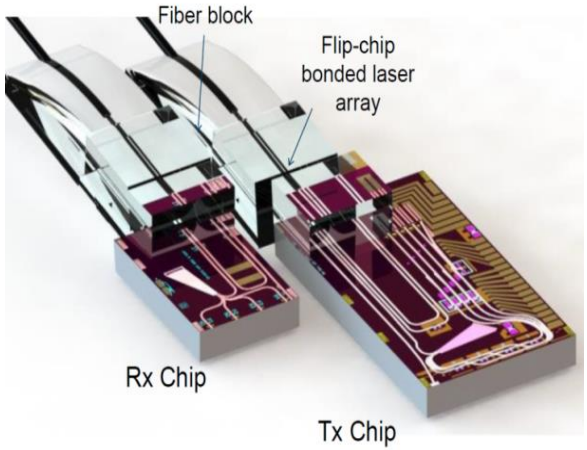
- **Light enables higher data speeds with less power consumption**

- **Photonic integrated circuits (PICs) enable manipulation of light on a chip**
  - Commercial driver: Internet/Telecom
  - Silicon photonics incorporate on-chip modulators and photodetectors, but no native light sources!
  - Challenge: Hybrid integration of III-V lasers

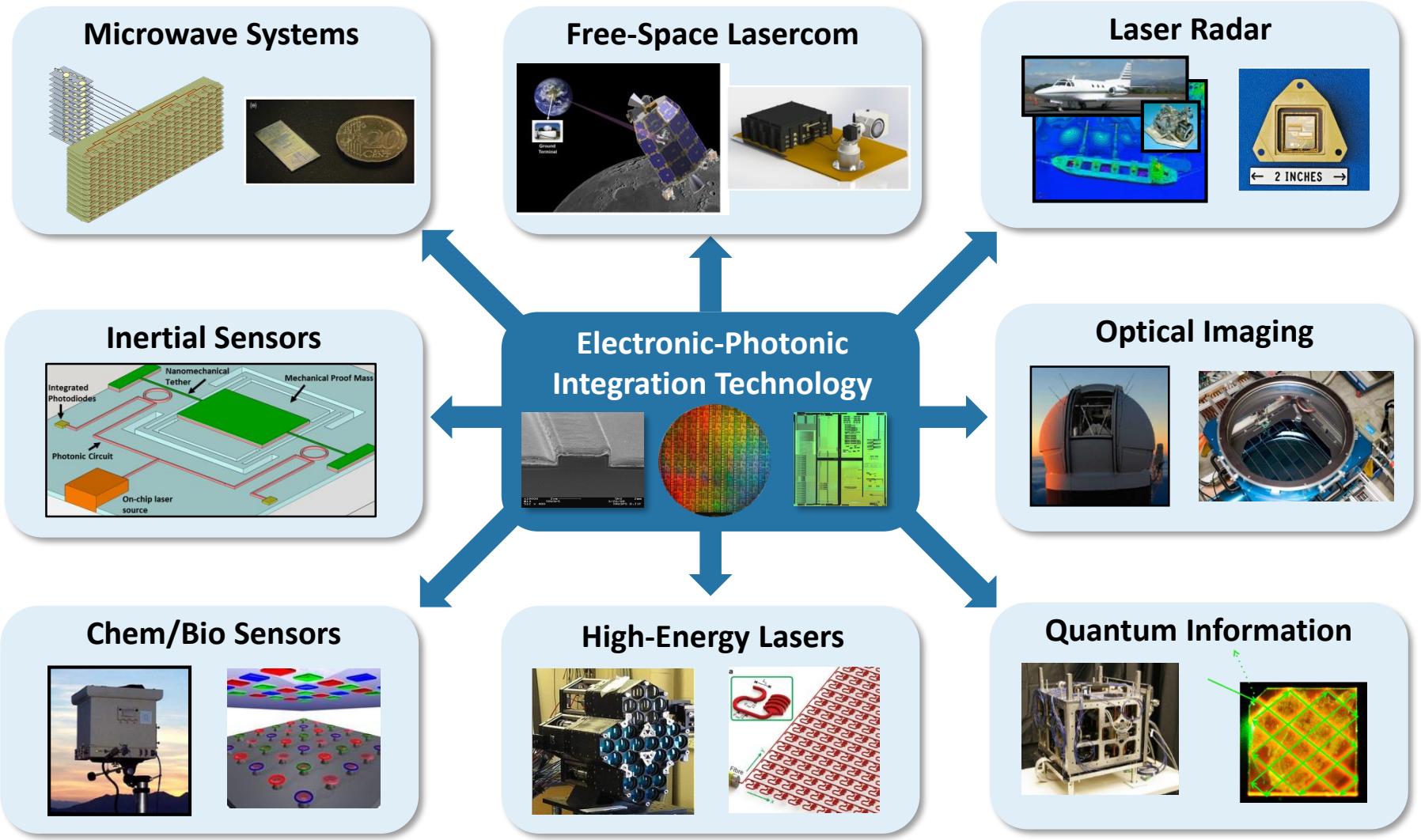
Discrete Optical Components



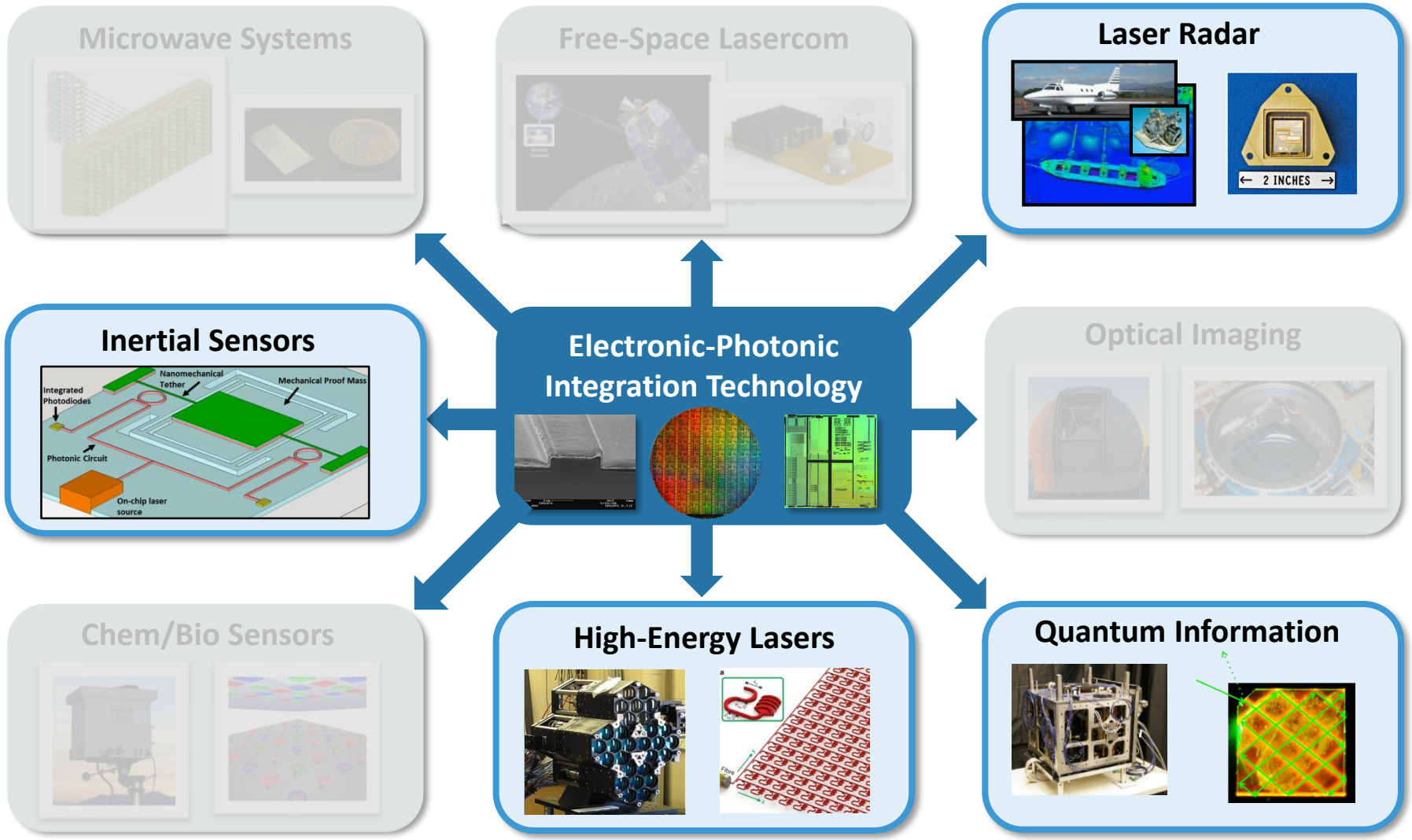
Chip-Scale Integration



Photonic Integration in Other Domains

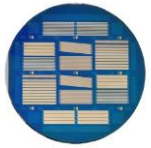


Photonic Integration in Other Domains



Electronic-Photonic Integration Development Resources at Lincoln Laboratory

InP Laser Wafer 50 mm Diameter

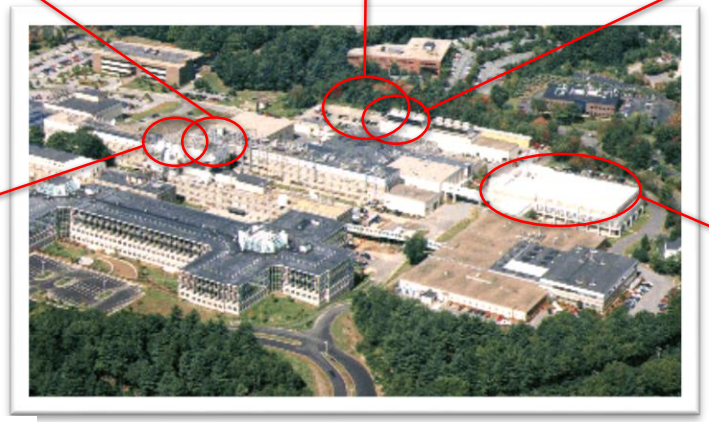


Materials Growth (III-V, Diamond)

III-V Fabrication Cleanroom

- InP, GaAs, GaN, Diamond
- Optoelectronic Components
- Emitter and Detector Arrays
- III-V Photonic Integration

Electronic-Photonic Packaging



- Precision Flip-Chip Packaging
- Laser-Welded Fiber Pigtailing
- Reliability and Lifetime Testing
- Heterogeneous Hybrid Integration

Back-end Processing Cleanroom

Microelectronics Laboratory

- 200 mm Silicon Fab Toolset
- 90 nm CMOS and Silicon and Nitride Photonics
- Wafer-Scale 3D Integration
- Multi-Project Runs

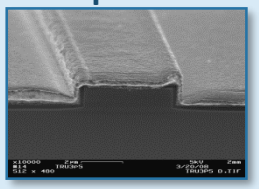
Silicon PIC Wafer 200 mm Diameter

Photonic Components at Lincoln Laboratory

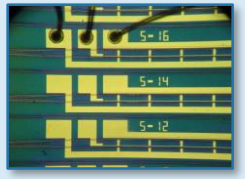
Compound Semiconductor (III-V) Photonic Integration

Materials: InP, GaAs, GaN, Diamond

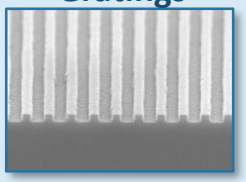
Lasers and Optical Amplifiers



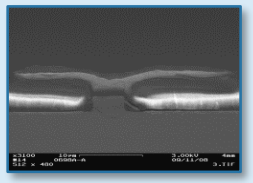
Modulators



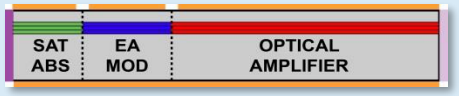
Gratings



Photodiodes

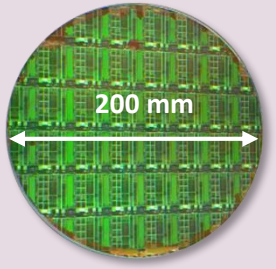


Monolithic III-V PICs

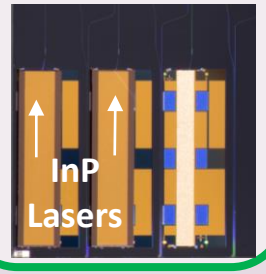


III-V to Si Hybrid Integration and Electronic-Photonic Integration

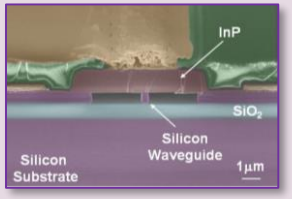
Si Photonics + CMOS



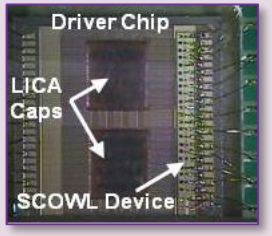
SiN Photonics + III-V Laser



Hybrid Si/III-V Wafer Bonding



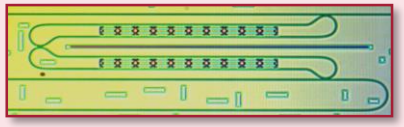
III-V Laser + CMOS Driver



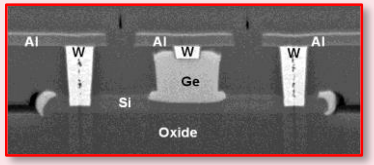
Silicon and Silicon Nitride Photonic Integration

Materials: Si, SiN_x, Al_2O_3, Ge

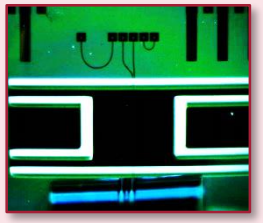
Waveguides and Optical Filters



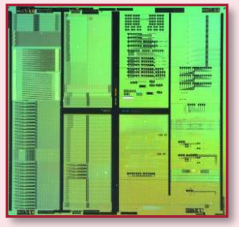
Photodiodes and Modulators



Optomechanics (MEMS + NEMS)

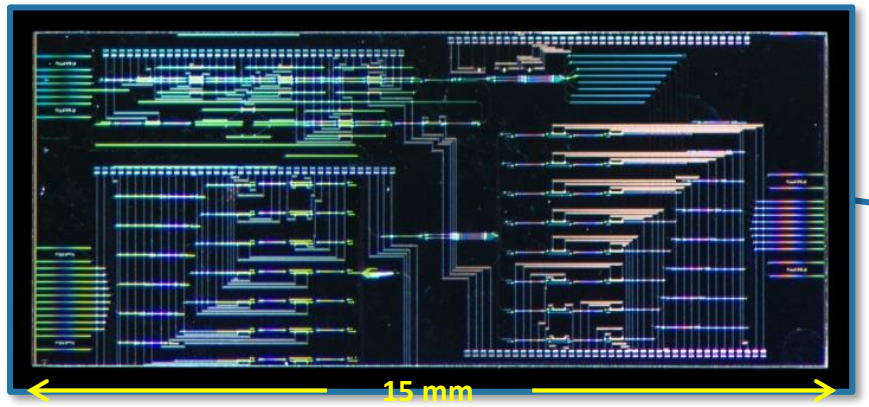


Multi-Project Fab Runs

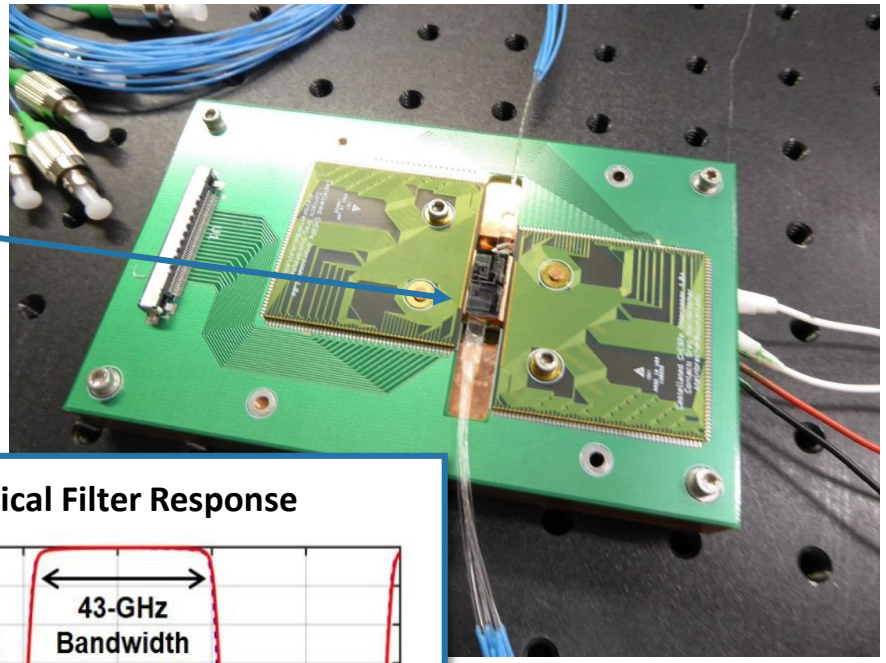


Reconfigurable Silicon Nitride (SiN_x) Photonic Integrated Circuits (PICs)

Image of SiN_x/SiO_2-on-Silicon PIC

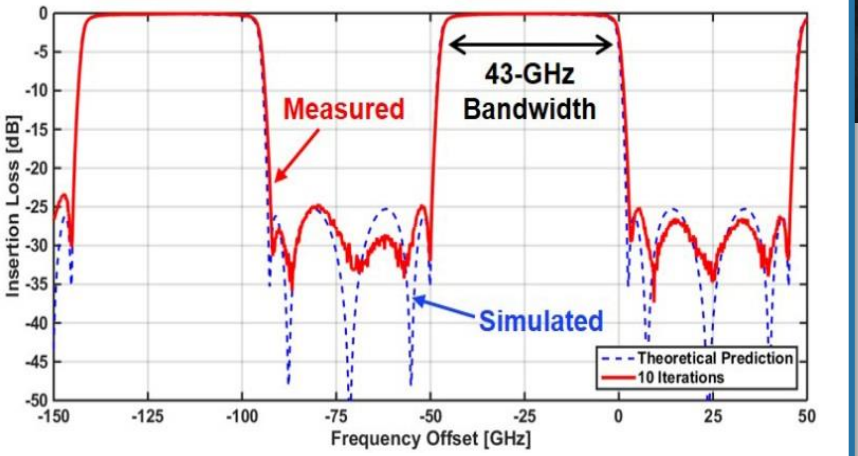


Fiber Pigtailed SiN_x PIC on Printed Circuit Interface Board



- **Operating wavelength ~1550 nm**
- **Fabricated using MIT LL's 200 mm silicon fabrication toolset**
- **SiN_x PIC contains ~80 components:**
  - **Adiabatic 3-dB couplers**
  - **1-to-N power dividers**
  - **Ring resonators**
  - **Mach-Zehnder modulators**
  - **Thermo-optic phase shifters**

Reconfigurable Optical Filter Response

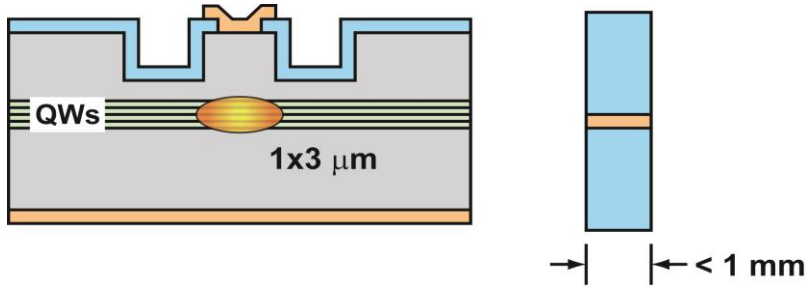


Semiconductor Waveguide Optical Gain Media

Semiconductor Optical Amplifiers (SOA) and Lasers

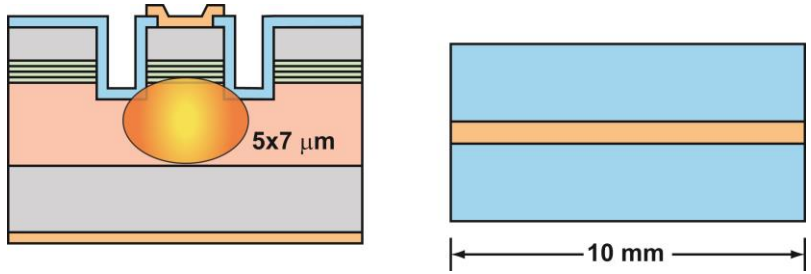
- III-V compound semiconductor p-i-n diode structures that use quantum wells (QW)
- Can act as an optical amplifier or an emitter source
- Optical mode is confined by a sandwich of lower refractive index materials

Standard Rib Waveguide



- **High gain (30 dB)**
- **Mode propagation in QW layer leads to high loss and limits power to <100 mW**
- **Small mode 1 × 3 μm size complicates optical coupling**

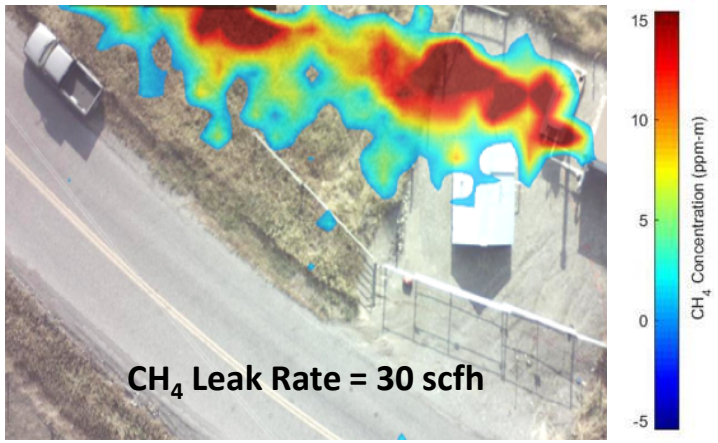
Slab-Coupled Optical Waveguide Amplifier (SCOWA)



- **Moderate gain (15 dB)**
- **Propagation in slab with low loss – higher power >1 W**
- **Large mode 5 × 5 μm improves coupling tolerance**

Field Demonstration of SCOWA Emitter Technology

Methane-Emission Mapping Demonstration (September 2017)



Methane (CH_4) Concentration Map

Integrated 3D Lidar and Gas Sensor

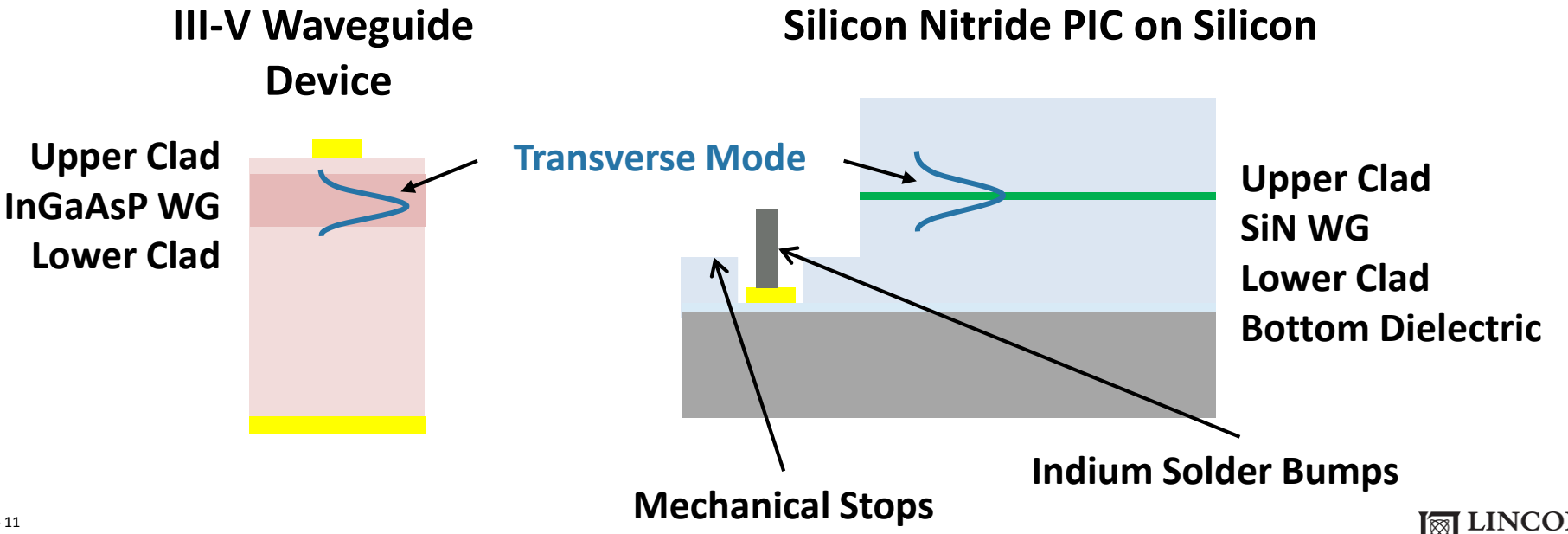
Lincoln Laboratory SCOWA technology has been flight tested

Prototype Photonic Integrated Circuit (ProtoPIC)

Goal: Create a platform for hybrid integration of III-V components with SiN photonics

Concept:

- **Create a SiN PIC with a recess to receive a III-V device**
- **Flip chip (FC) bond III-V die with indium bumps**
- **Vertical alignment with mechanical stops**
- **Fiducials to enable sub-micron lateral alignment**



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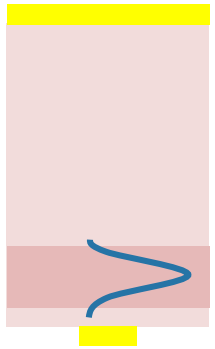
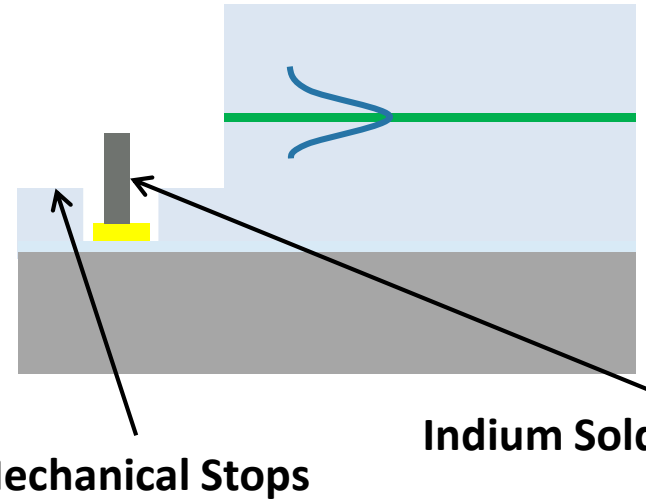
III-V Waveguide Device

Flip Device for Flip Chip Bonding



Silicon Nitride PIC on Silicon



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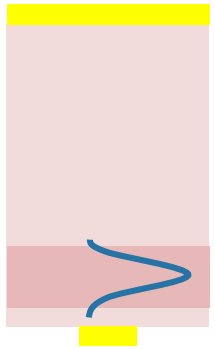
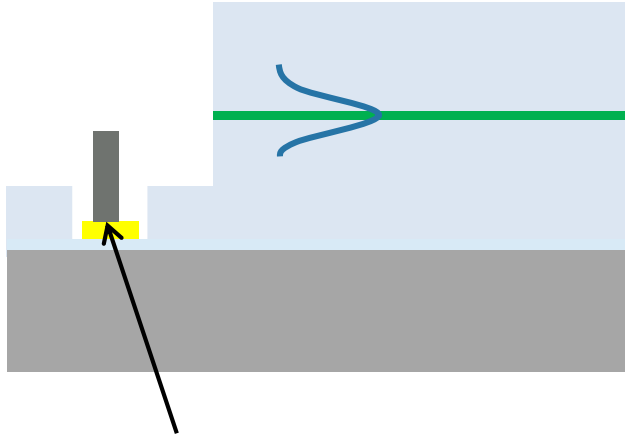
III-V Waveguide Device

Flip Device for Flip Chip Bonding



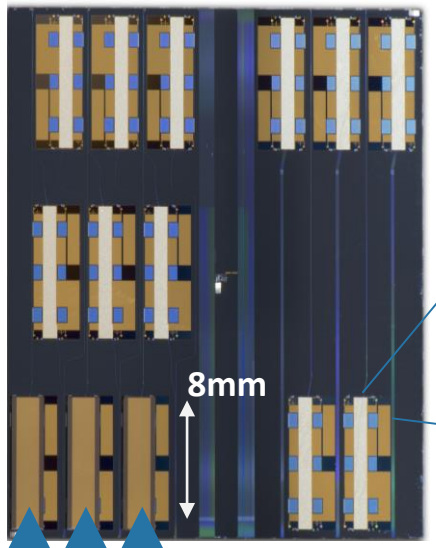
Silicon Nitride PIC on Silicon

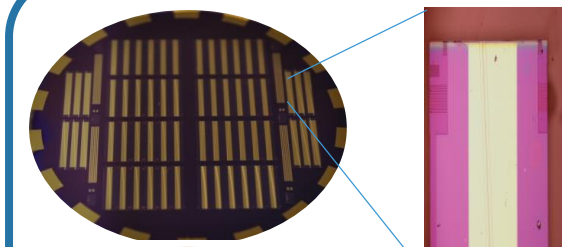


ProtoPIC Hybrid Integration Submount

ProtoPIC Submount

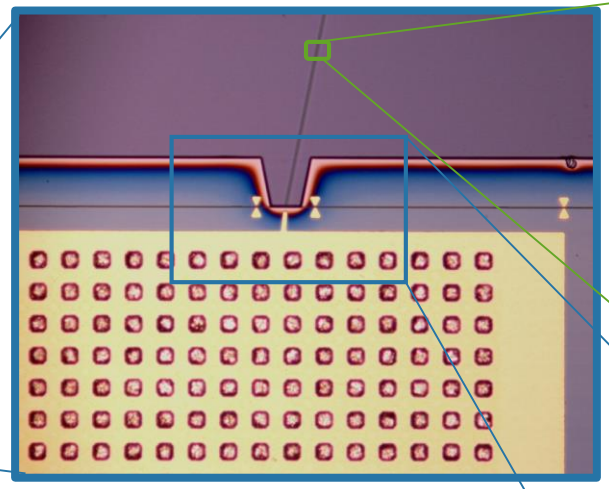
14 Insert Slots



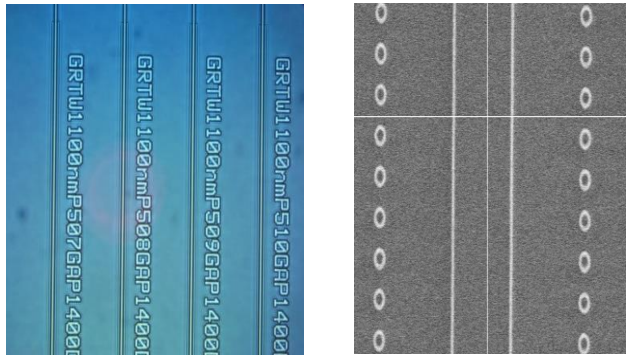


InP SCOWA Insert Devices

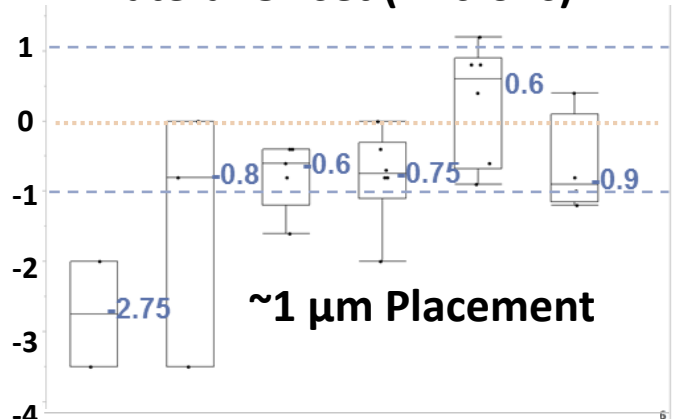
Silicon Nitride PIC on Silicon



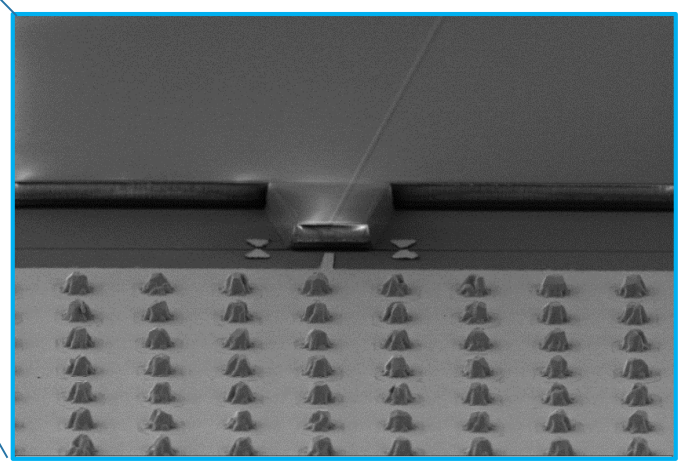
Bragg Gratings



Lateral Offset (Microns)

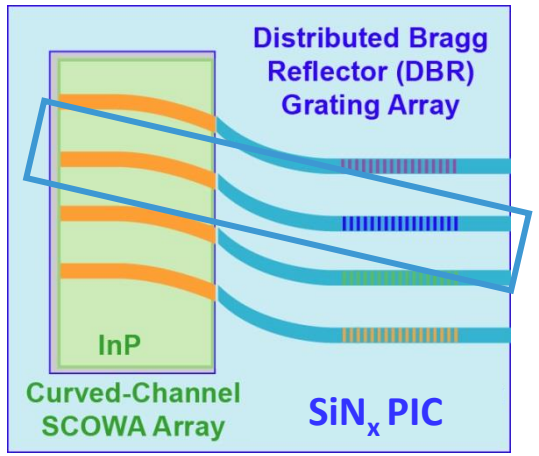


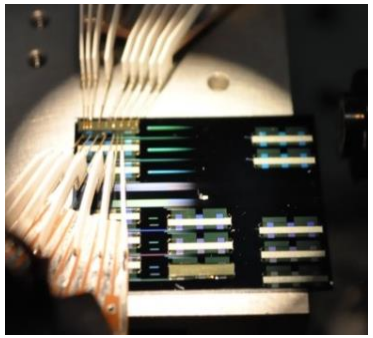
SEM Image of Input Facet

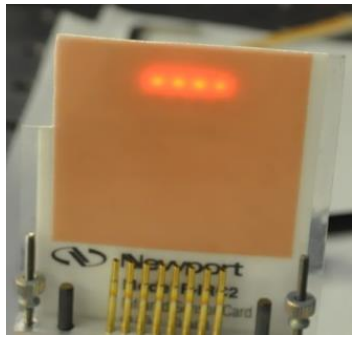


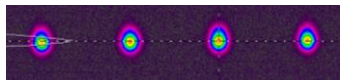
ProtoPIC Hybrid Laser with Narrow Line Width

Hybrid Laser Array (Top View)

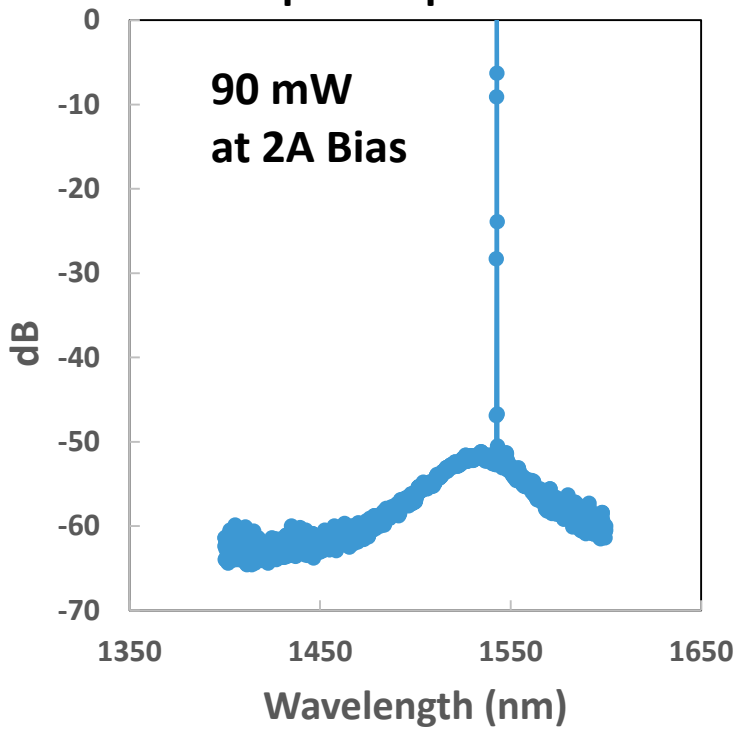




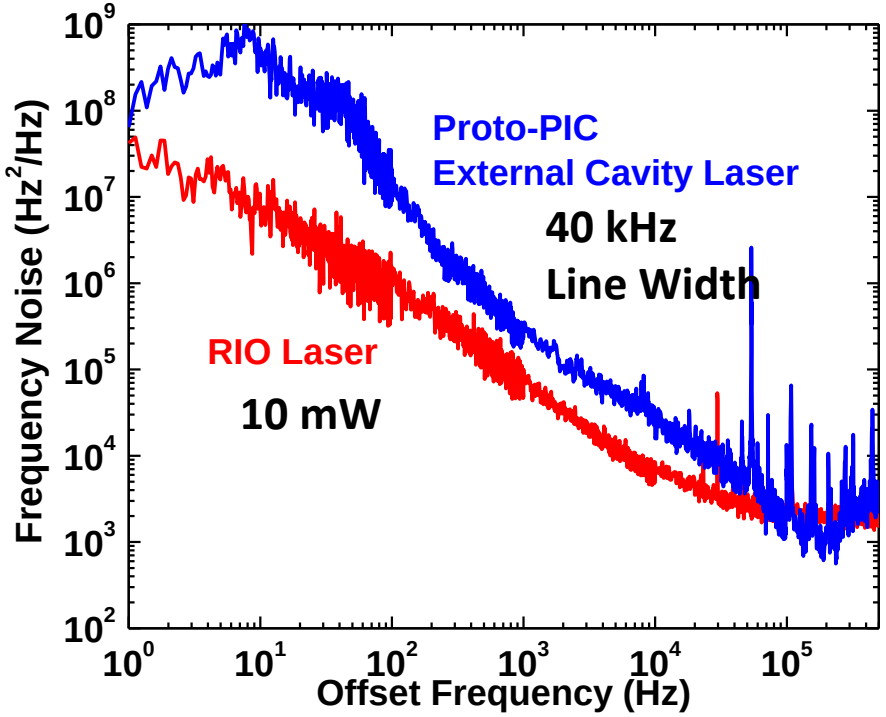




ProtoPIC Hybrid Laser Optical Spectrum

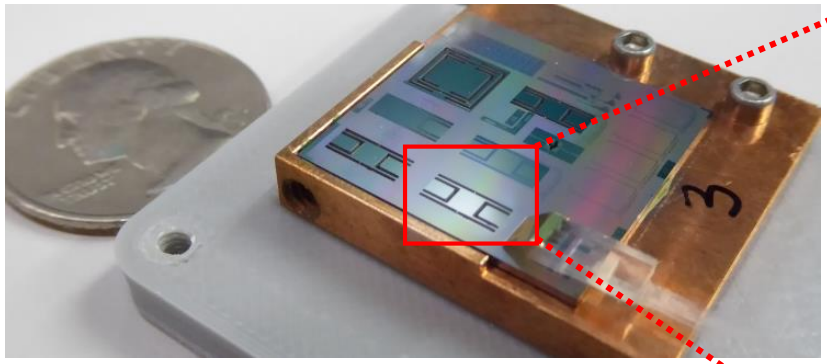


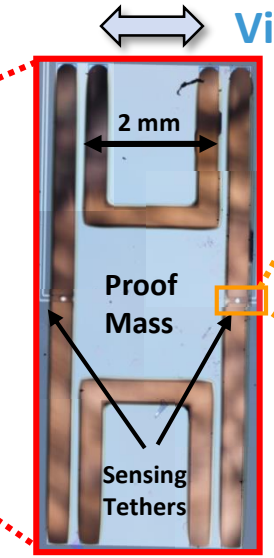
Line Width Measurement

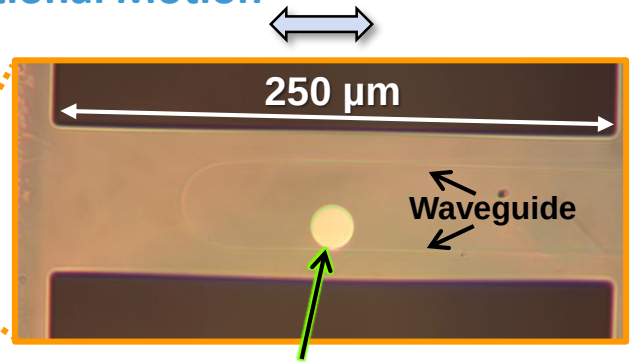


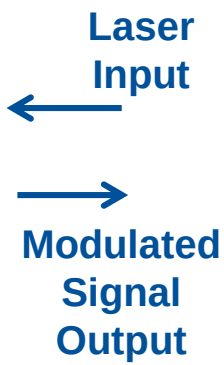
Line width on par with commercial laser but with 9× higher power

Photonic Integrated Resonant Accelerometer (PIRA)

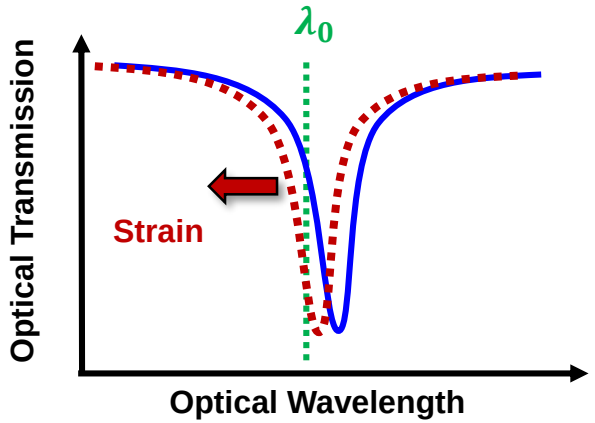








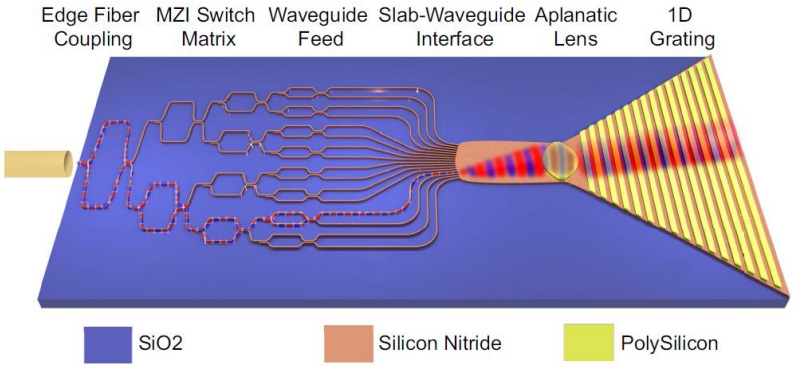
Schematic Transmission-Spectra of Microresonator

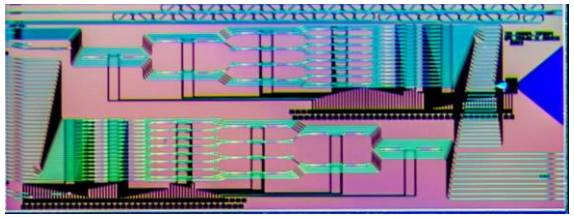


- **Integration of mm-scale proof mass + micron-scale tether + silicon photonics**
- **Present performance is on par with compact commercial accelerometers: Measured ~3 µg/√Hz sensitivity**
- **Path to <100 ng/√Hz – best compact accelerometer**

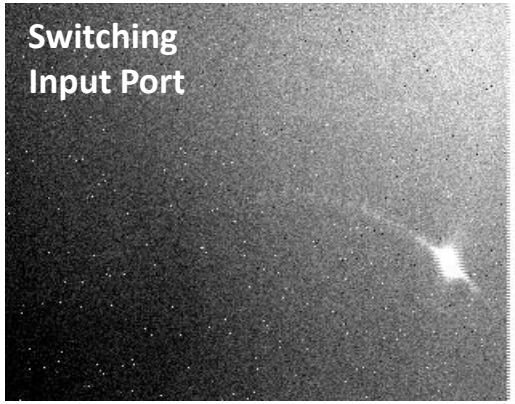
Non-Mechanical Optical Beam-Steering for Compact 3D Lidar Imaging

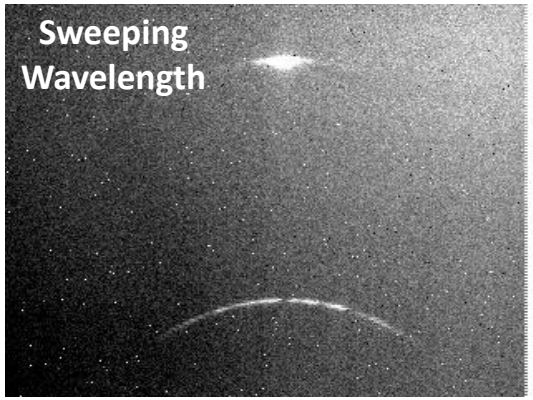
Integrated Beam-Steering System

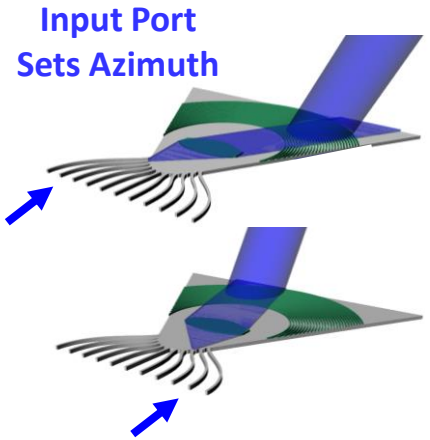




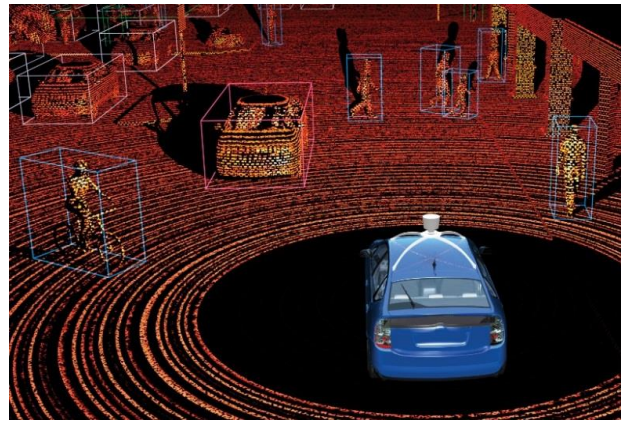
Initial Demo of 16-Channel Planar-Lens Element





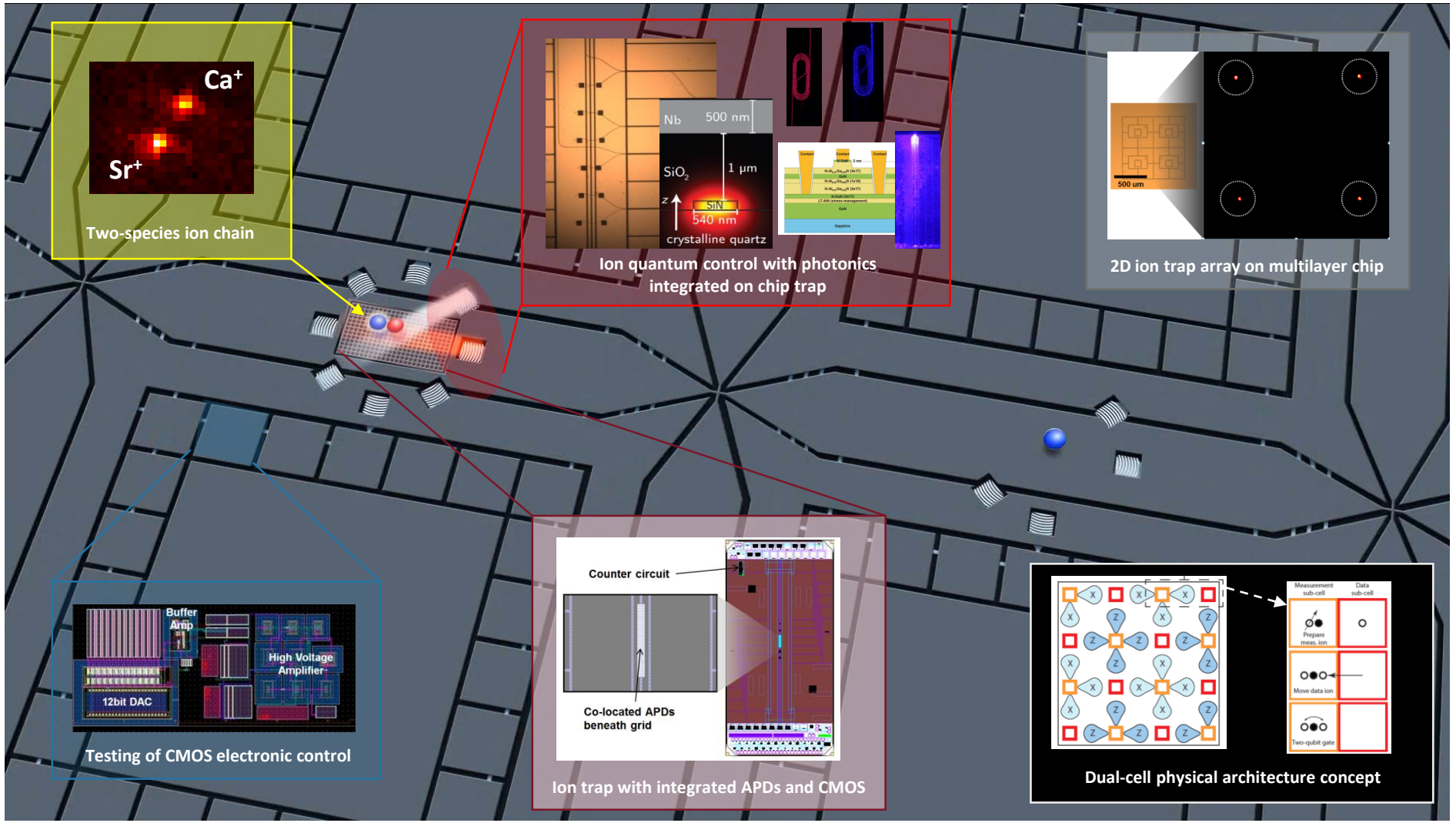


Low-Cost Lidar for Self-Driving Cars



Nanolidar for Ultra-Small Platforms

Future Direction: Trapped Ion Quantum Computing



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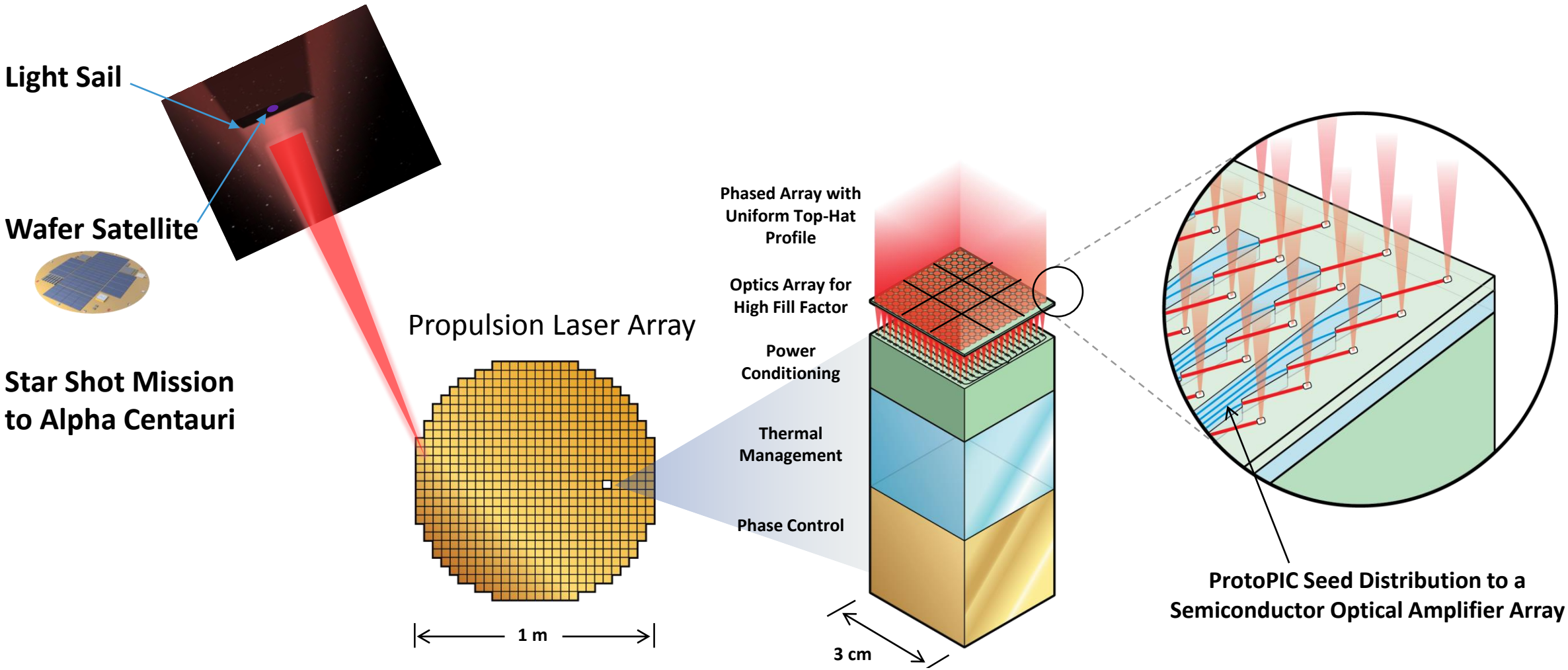
Future Direction: Laser Light Sources for Wafer Satellite Propulsion



Summary

- MIT Lincoln Laboratory has developed a library of photonic component technologies
  - SiN and silicon photonics, waveguides, splitters, modulators, thermal tuners, and filter architectures
  - III-V SCOWA amplifiers, lasers, photodiodes, modulators
- Recently developed a flexible hybrid integration platform ProtoPIC that can be used to combine a variety of III-V devices with our SiN PICs
  - Flip chip III-V attach with ~1 µm placement capability
  - Initial applications of the technology have been applied to demonstrate an extended cavity hybrid laser with narrow line width 40 kHz and 90 mW optical power
- The technology is amenable to adoption for a wide variety of applications