Photonic Integrated Circuits for Free Space Communications and Sensing

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Outline

- Integrated photonics background
- Applications and opportunities
  - Free space optical communications
  - Remote Earth science sensing
- Conclusions

Photonic Integrated Circuits (PICs)

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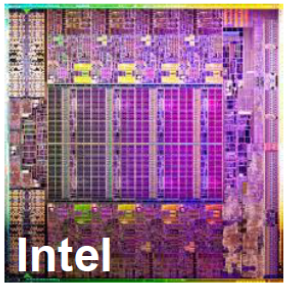
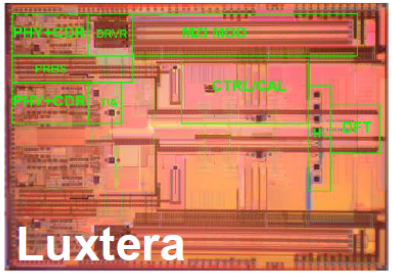
Integrated Circuit:
an electronic circuit whose components are manufactured in one flat piece of semiconductor material



Transistors
Capacitors
Resistors
Inductors

Photonic Integrated Circuit:
a photonic circuit whose components are manufactured in one flat piece of [semiconductor] material

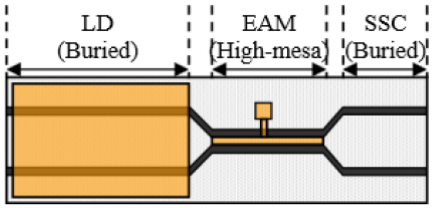


Lasers
Modulators
Photodetectors
Optical amplifiers
Control electronics
Couplers
Filters
Attenuators
Isolators
Mode converters

Photonics: generation, emission, transmission, modulation, signal processing, switching, amplification, detection and sensing of light

Photonic Integrated Circuit Complexity

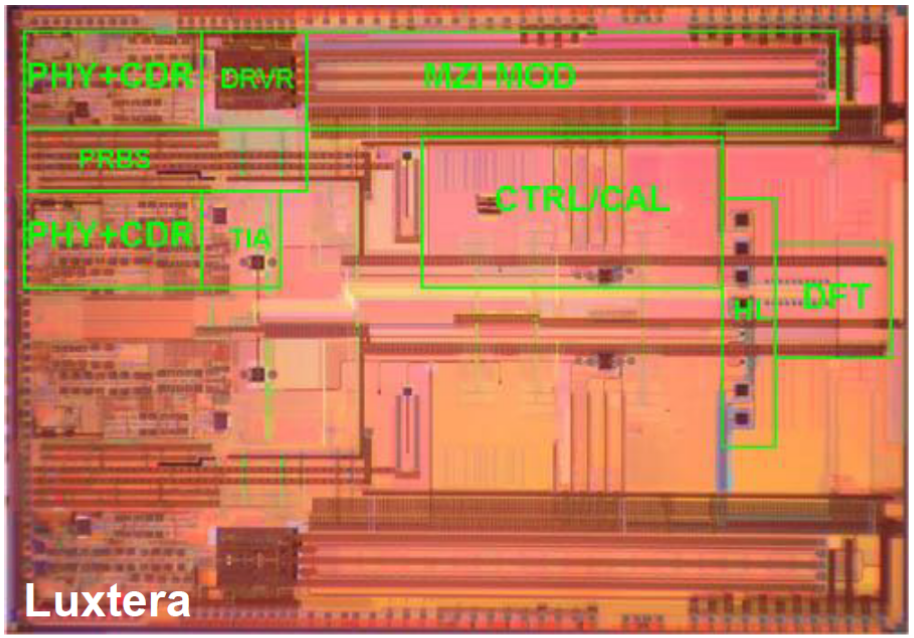
Integrated 28 Gb/s Externally Modulated Laser



Mitsubishi Electric

DFB laser and high-speed EAM

Luxtera 10 Gb/s Optical Transceiver



Optical modulators, photodetectors, integrated electro-optical signal conditioning, clock and data recovery, control and calibration circuitry

Integrated Photonics Platforms

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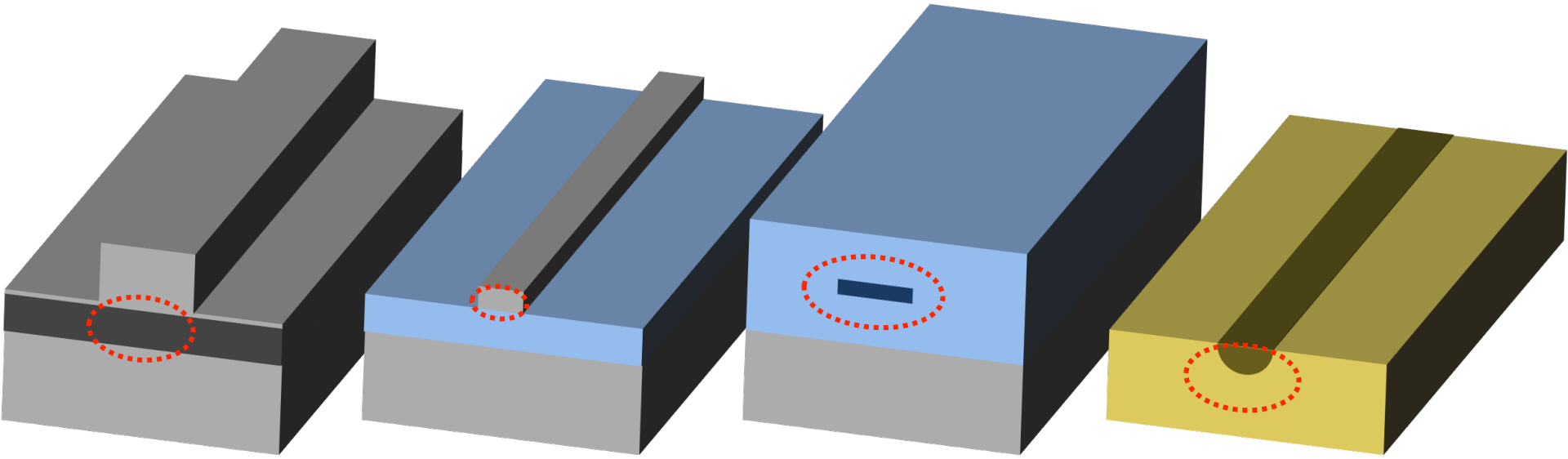


Indium phosphide (InP)

- [?] = 5-10%
- Small devices (~μm-mm)
- Lasers, modulators, SOAs, photodetectors, passives

Silicon photonics (SiPh)

- [?] = 40-45%
- Small devices (~μm)
- Modulators, photodetectors, passives

Planar lightwave circuit (PLC) [SiO_2, SiON, Si_3N_4]

- [?] = 0.5-20%
- Large devices (~mm-cm)
- Passives

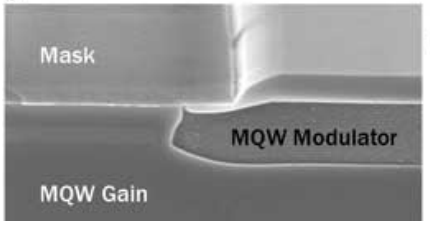
Lithium niobate (LN)

- [?] = 0.5-1%
- Large devices (~mm-cm)
- Modulators, passives

Index contrast = [?] = $(n_{core}^2 - n_{cladding}^2)/(2n_{core}^2)$

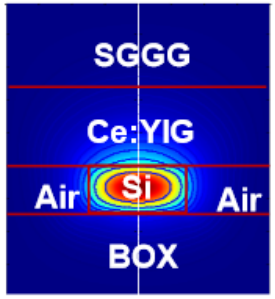
Types of Photonic Integration

- ***Monolithic***: More than one photonic component integrated on a common substrate



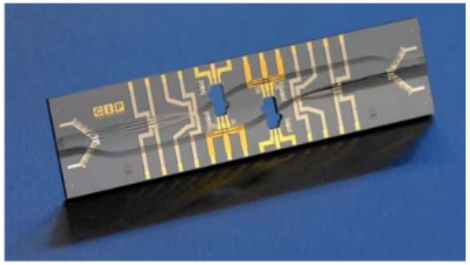
Y. Akulova, et al., Photonics Spectra, 2013

- ***Heterogeneous***: Merging traditionally incompatible photonic material systems on a common substrate to exploit unique material properties



M. –C. Tien, et al., Optics Express, 2011

- ***Hybrid***: Close integration of discrete photonic chips whereby light is coupled from one chip to the other



A. Poustie, IPNRA, 2007

UCSB Facilities for Integrated Photonics

UCSB Nanotech

- 13,000 sq. ft. shared cleanroom for nanofabrication

incubator

California NanoSystems Institute

- Cleanroom facility, microscopy, space

Materials Research Laboratory

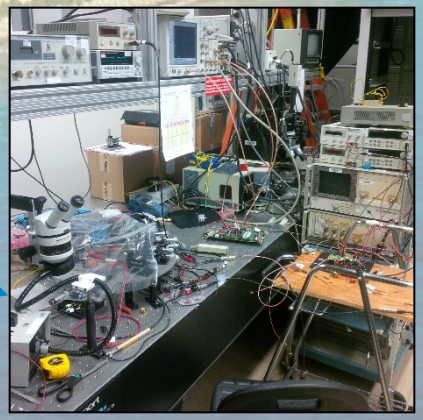
- Microscopy, spectroscopy

MOCVD Laboratory

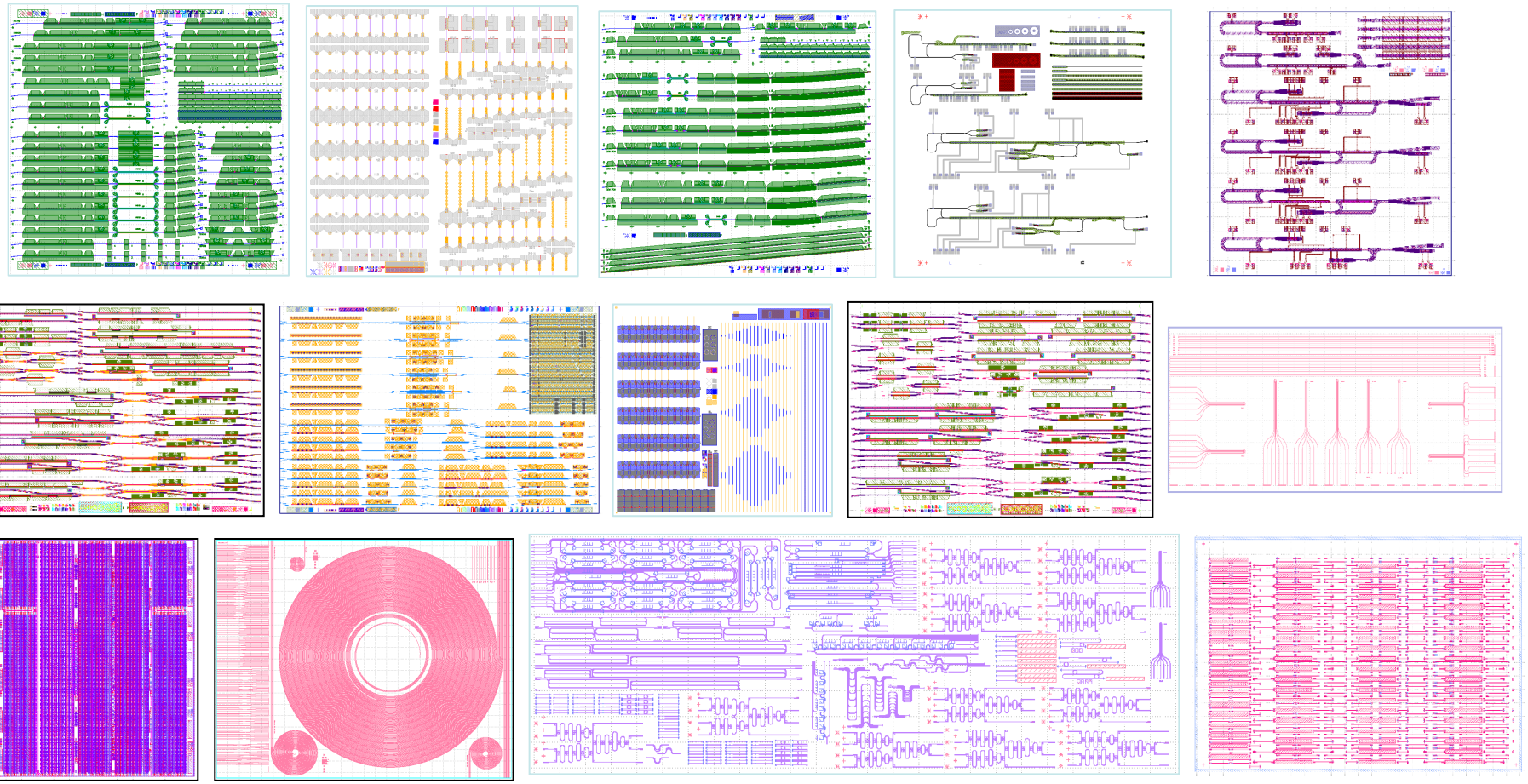
- InP and GaAs crystal growth

Integrated Photonics Laboratory

- Backend processing, packaging, high-speed testing

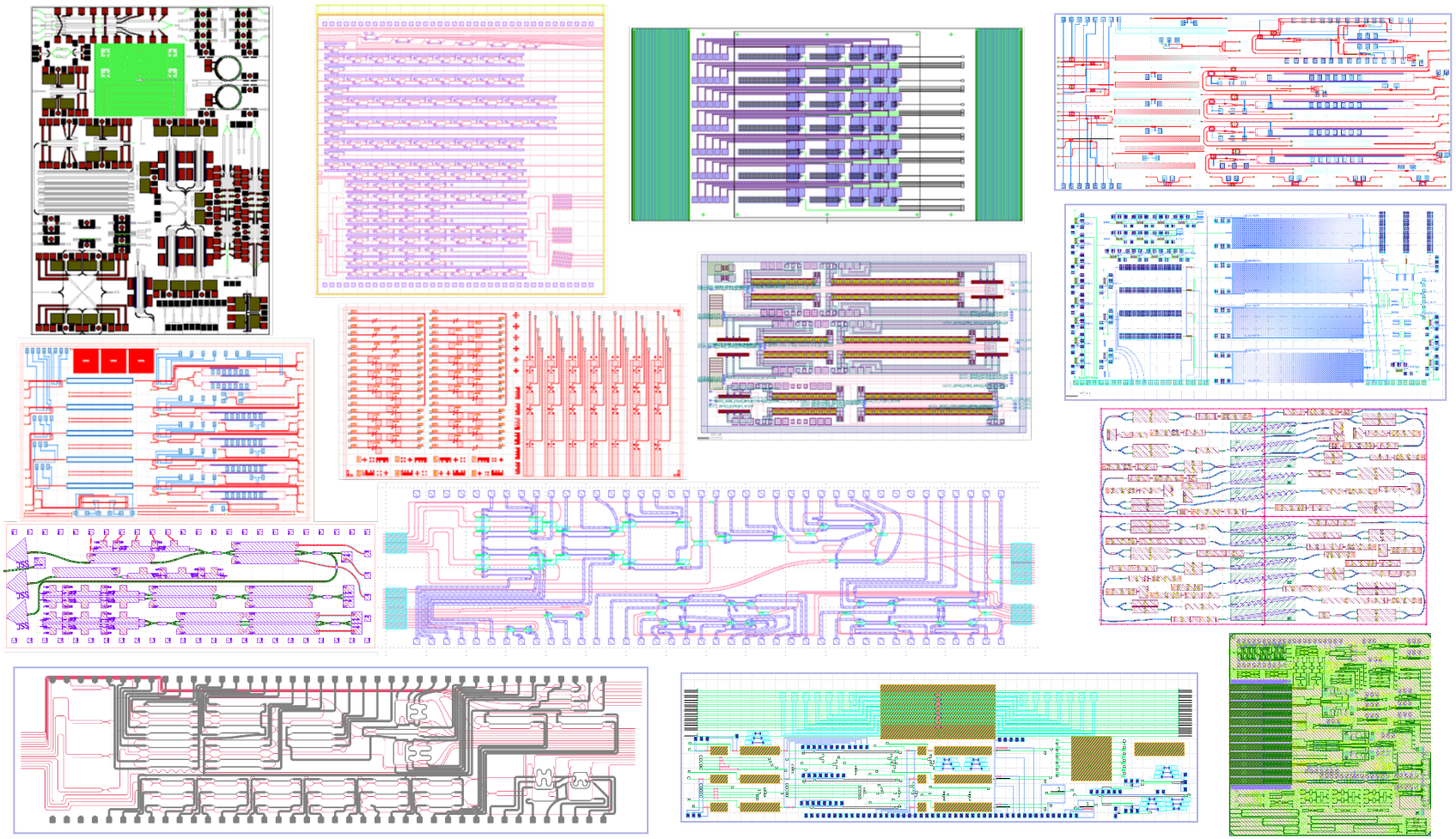


In-House Integrated Photonics Runs



- **Platforms**: indium phosphide, silicon photonics, silicon nitride
- **Full vertical integration**: materials growth, simulation, design, fabrication, packaging, test, subsystems

Tapeouts with External Foundries



- Our group has participated in ~50 external photonics tapeouts.
- UCSB is west coast hub of AIM Photonics (American Institute for Manufacturing Integrated Photonics).

Large-Scale Integration

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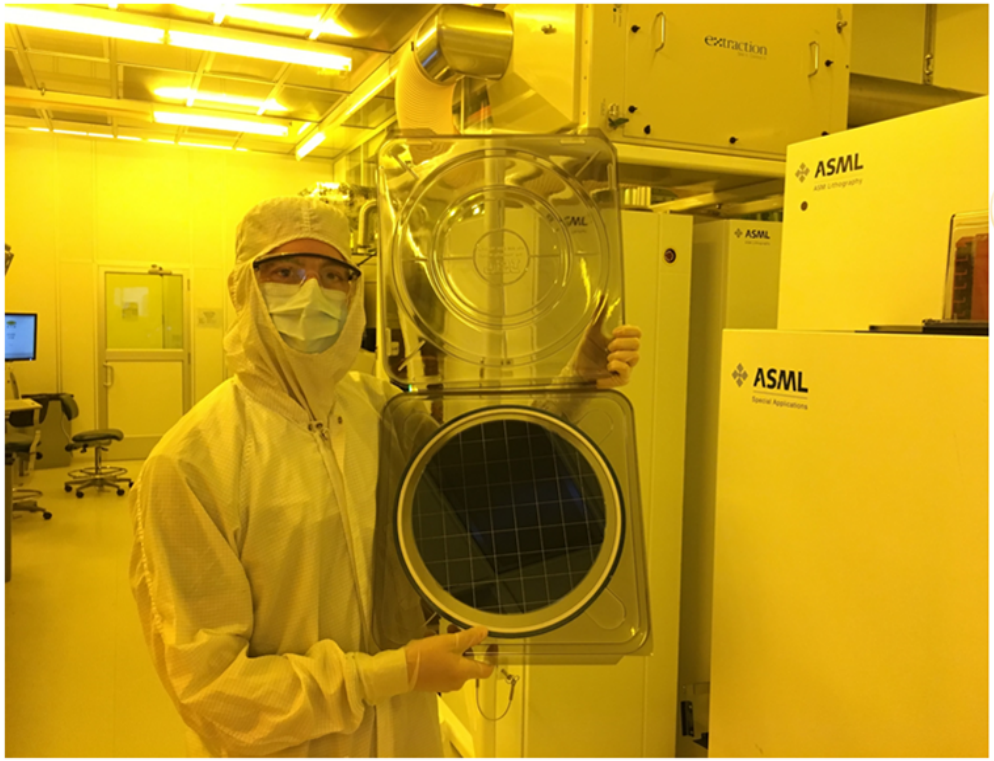
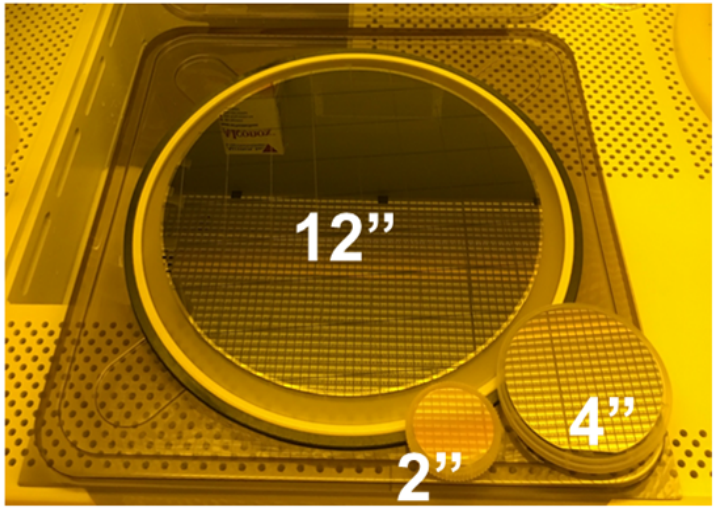


WEST COAST HEADQUARTERS OF
AIM PHOTONICS
AMERICAN INSTITUTE FOR MANUFACTURING INTEGRATED PHOTONICS
UC SANTA BARBARA



- AIM Photonics established from the National Network for Manufacturing Innovation (NNMI) initiative
- Mission is to advance PIC manufacturing and provide access to state-of-art fabrication, packaging, testing

PIC Examples and Applications

PICs for Free Space Optics

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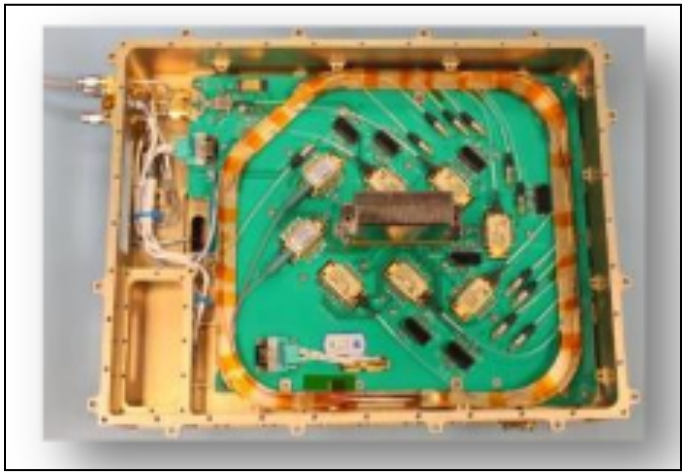
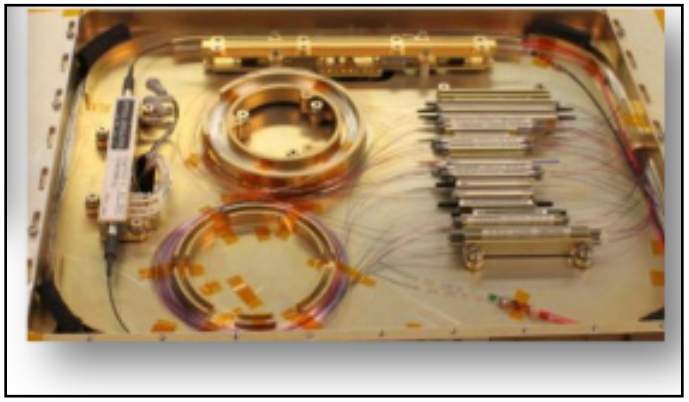
Transceiver with Discrete Components

— 1 inch

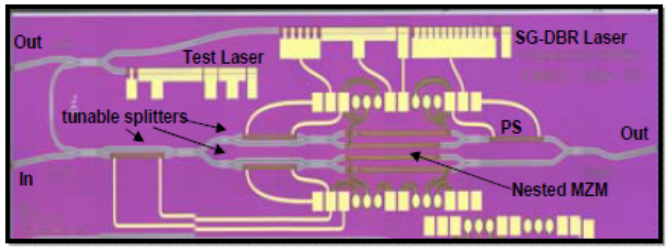




*NASA Lunar Laser Communication Demonstration

PIC Transceiver

6 mm



Lower Cost, Size, Weight and Power (CSWaP)

PPM Transmitter Demonstration

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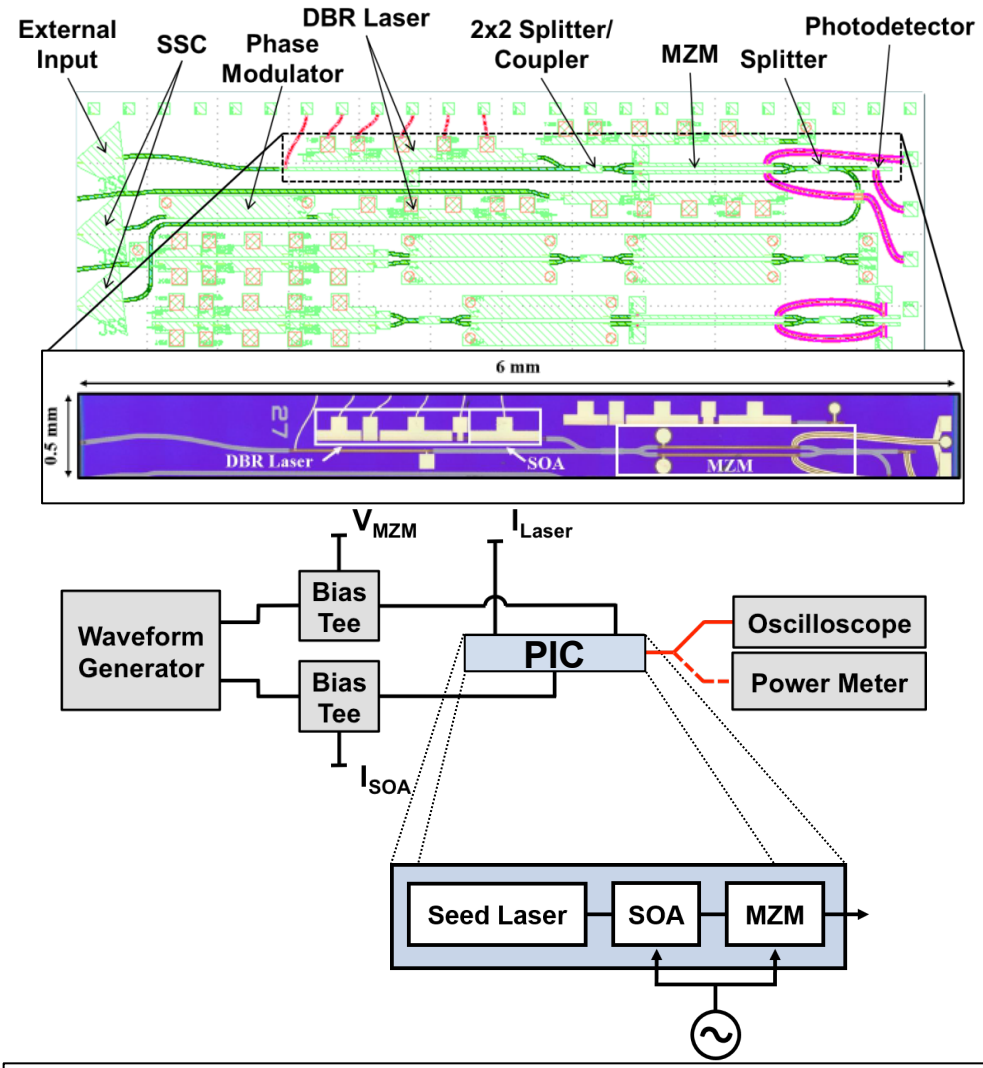
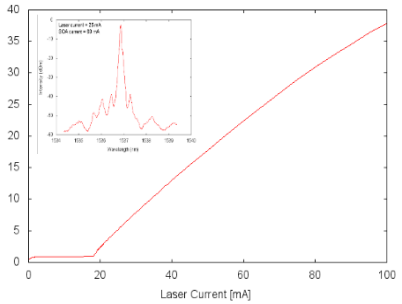
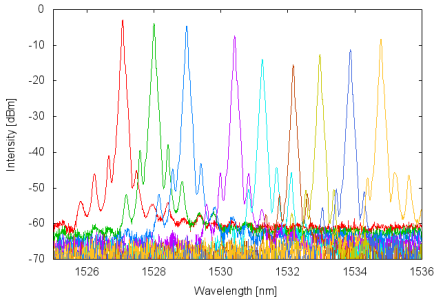
PIC Transmitter Frontend

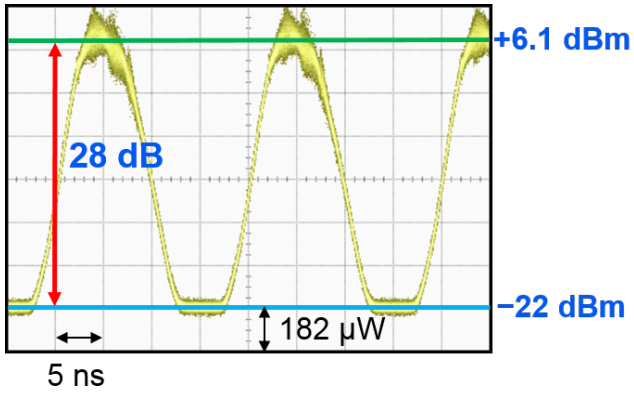


DBR laser characteristics





- >30 mW laser power
- ~7 nm tuning range; >35 dB SMSR
- PPM demonstration with SOA-MZM for high extinction ratio (ER)
  - >28 dB extinction
  - Suitable for 12.5 Mbps 16-ary PPM



*Developed under NASA Deep Space Laser Transmitter program

Free Space PIC Transmitter

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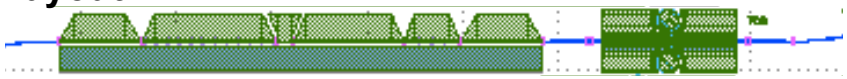
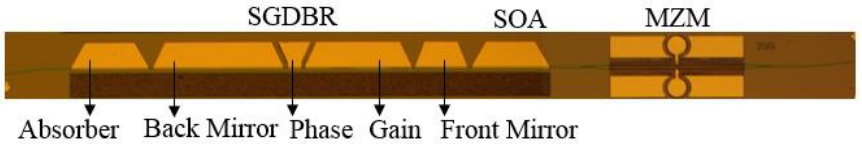
Sampled Grating DBR (SGDBR) Laser TX

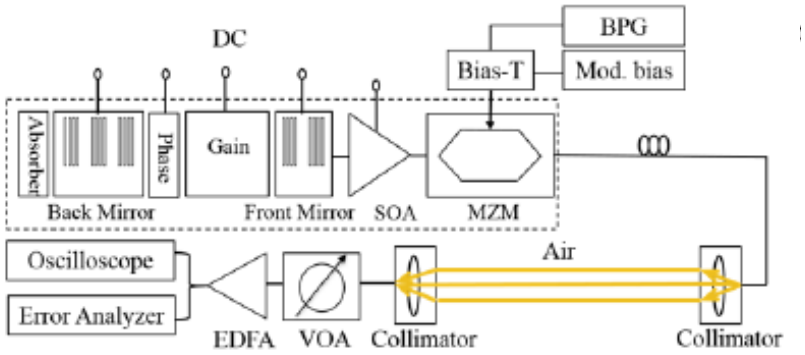
Layout



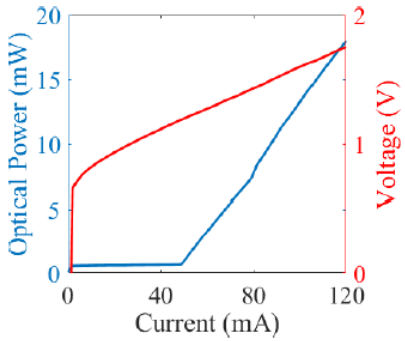
Fabricated device

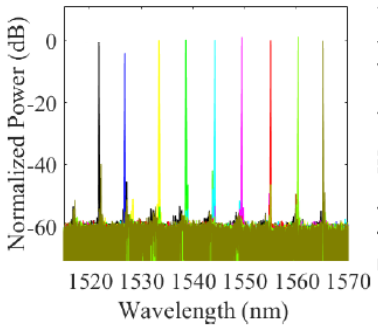


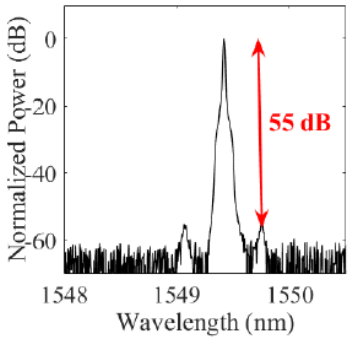
- >15 mW laser power (>60 mW with output SOA)
- ~45 nm tuning range; >50 dB SMSR
- Up to 7 Gb/s modulation (50 Gb/s possible)
- Free space link at 1 Gb/s demonstrated
  - BER < 1e-9 for ~20 dB attenuation (120 m distance)
  - < 1 dB power penalty compared to 10 Gb/s LN modulator

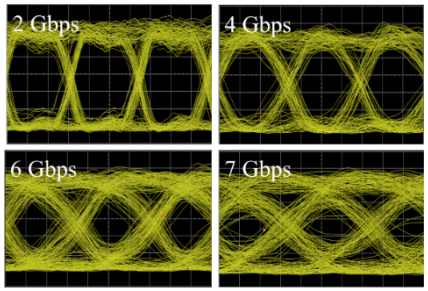


*Developed under NASA FSOC program

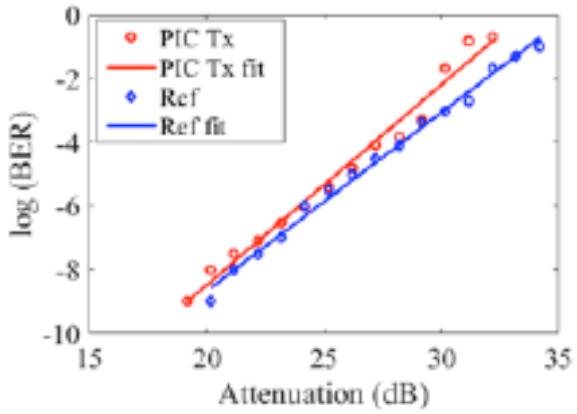








Free space link performance



RZ-DPSK PIC Transmitter

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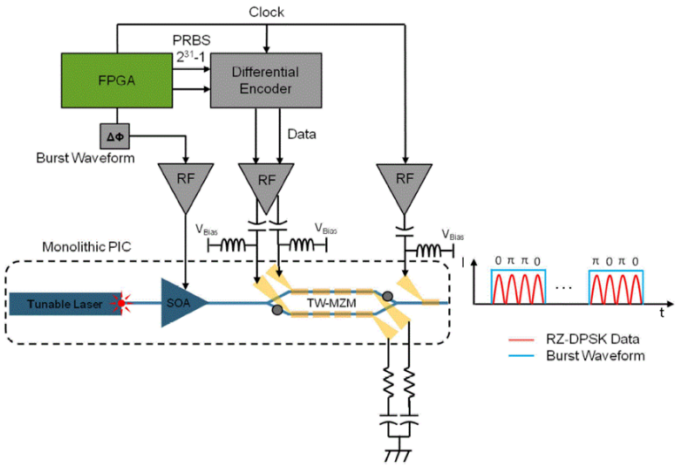
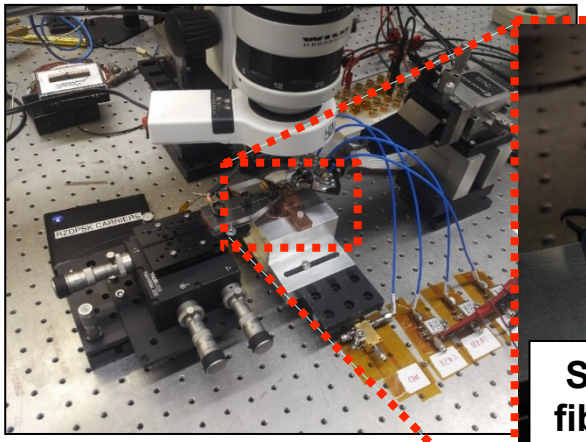
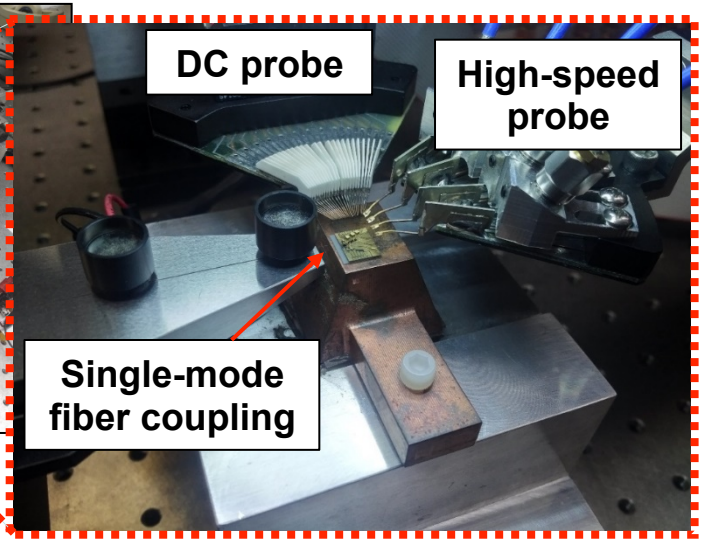
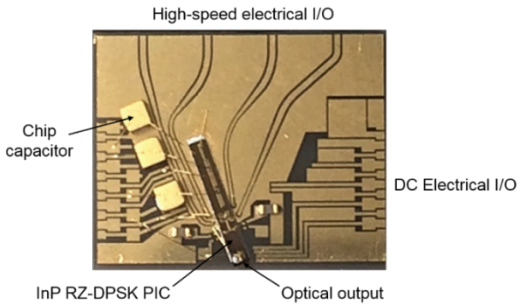






PIC on carrier



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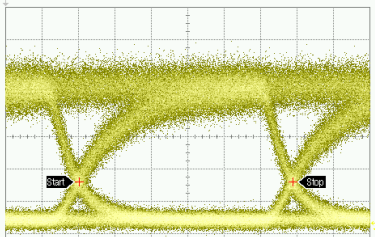
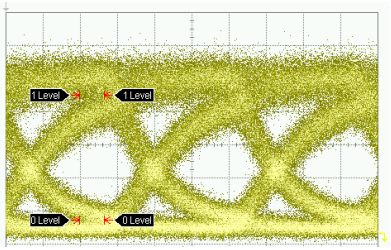
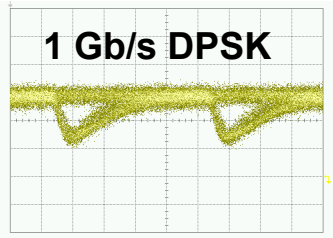
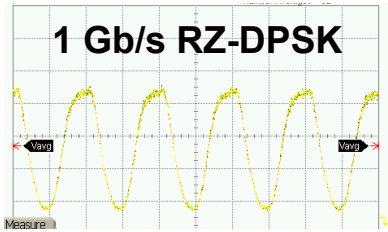


BR = 1 Gb/s; ER = 15.6 dB



BR = 3 Gb/s; ER = 10.3 dB





- PIC transmitter with SGDBR laser, SOA, dual-drive MZM and EAM RZ-pulse carver
- Up to 3 Gb/s OOZ demonstrated with high extinction ratio
- RZ-DPSK demonstration at 1 Gb/s

*Developed with Freedom Photonics

Photonic Integrated Circuits for Free Space Communications and Sensing

Optical Beamforming for Millimeter Wave Communications and Phased Arrays

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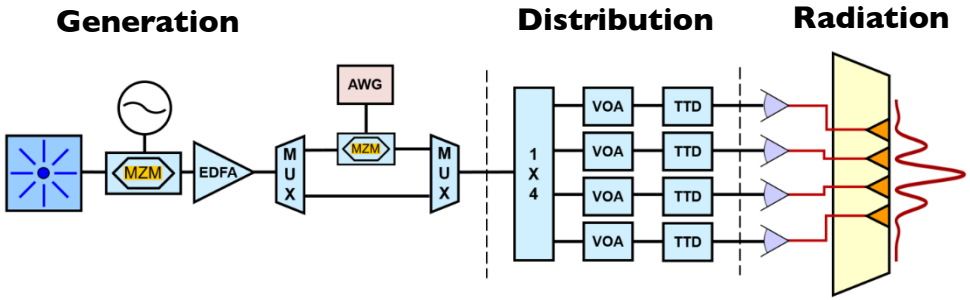
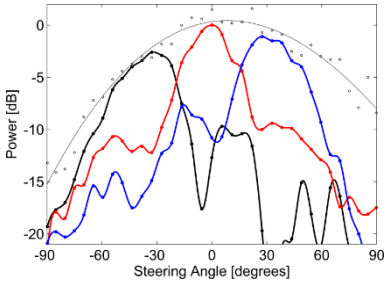
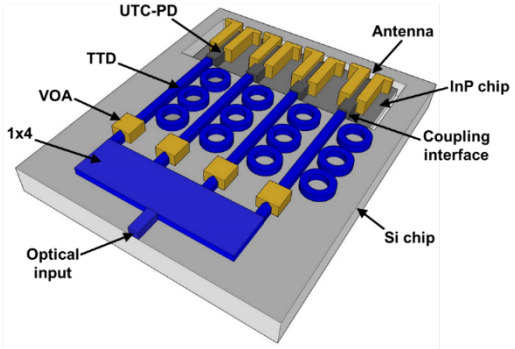
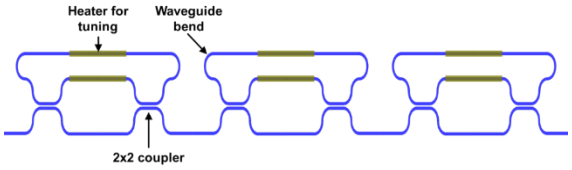
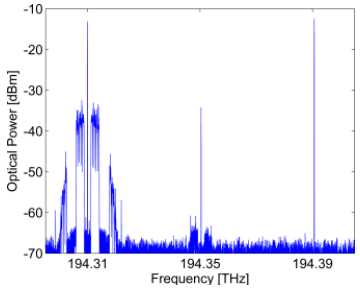


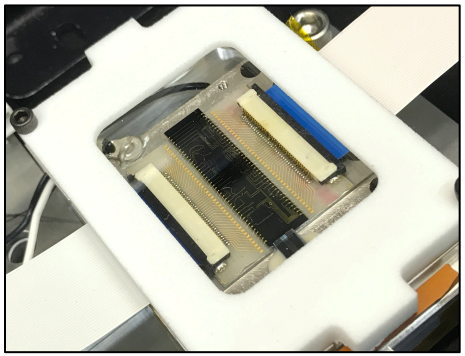


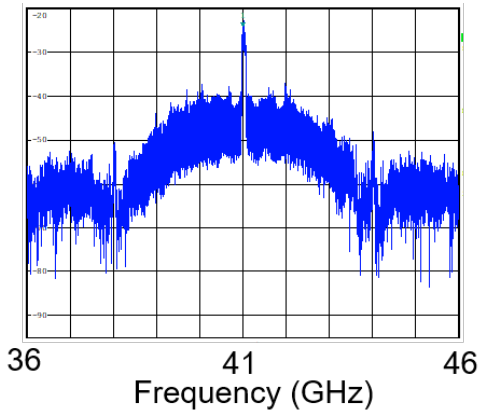


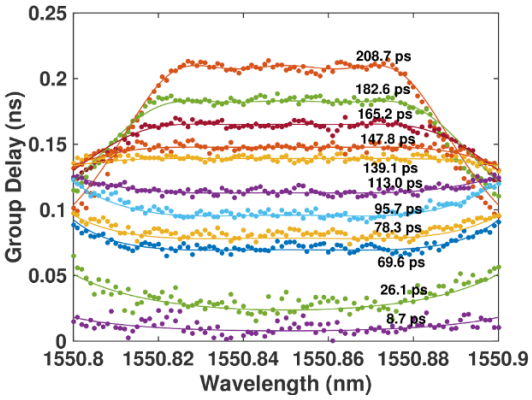


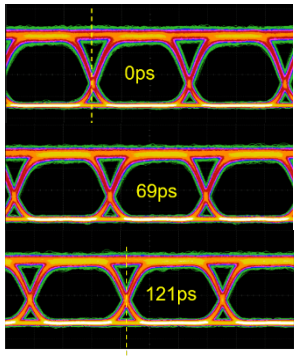


- True time delay (TTD) technology for squint-free beamforming
- Ring resonators for continuous tuning
- Applications include high-frequency communications and sensing









*Developed with JHU/APL and under NASA EHF program

T. McKenna et al., PTL 26(14), 2014
Y. Liu et al., JSTQE 24(4), 2018

PICs for Remote Sensing Lidar

PICs for Remote Sensing Lidar

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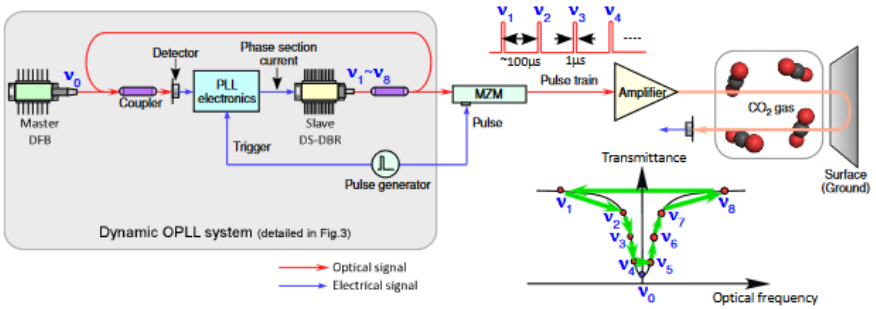
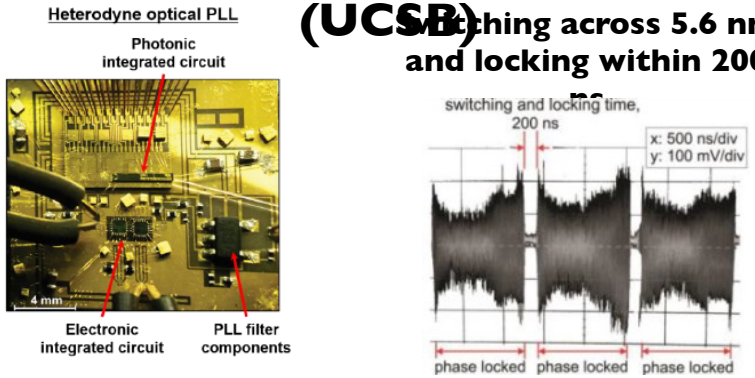
CO_2 Lidar (NASA GSFC)



K. Numata, et al., Optics Express, 2012

Integrated OPLL (UCSB)

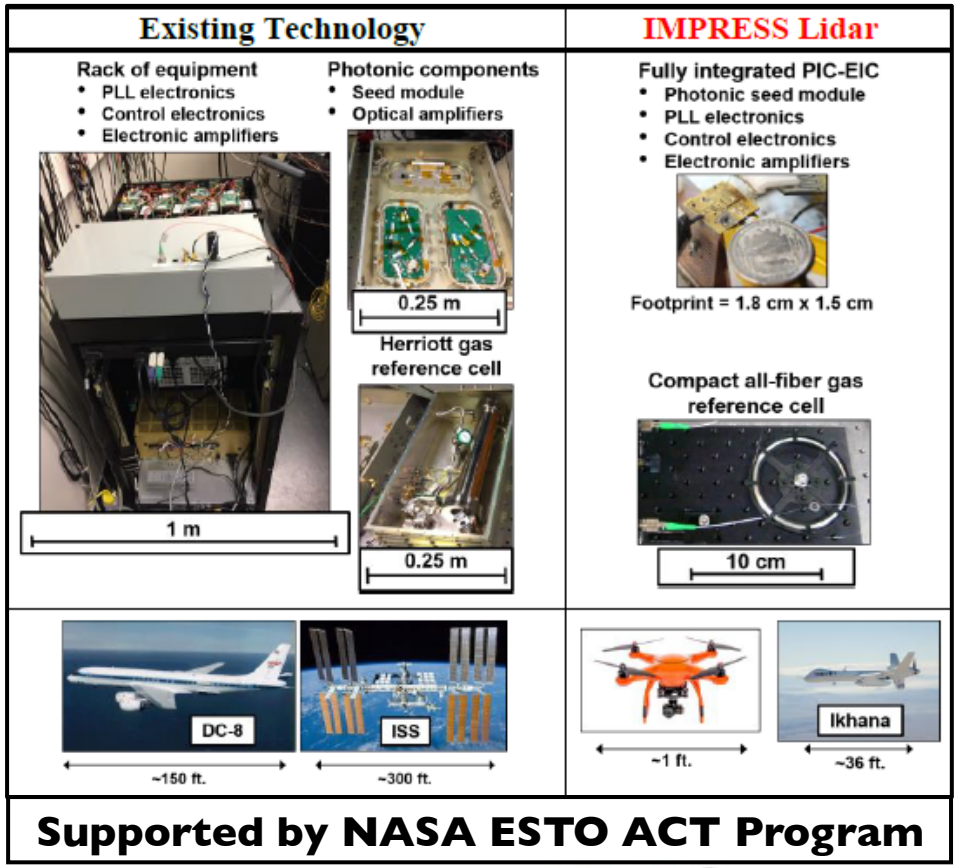
Switching across 5.6 nm and locking within 200 ns



S. Arafin, et al., Optics Express, 2017

IMPRESS Lidar: Integrated Microphotonics for Remote Earth Science Sensing Lidar

Fully integrated Lidar sensor based on optical phase locked loop for fast switching/locking



Supported by NASA ESTO ACT Program

NASA Goddard SPACE FLIGHT CENTER

Technical Areas and Status

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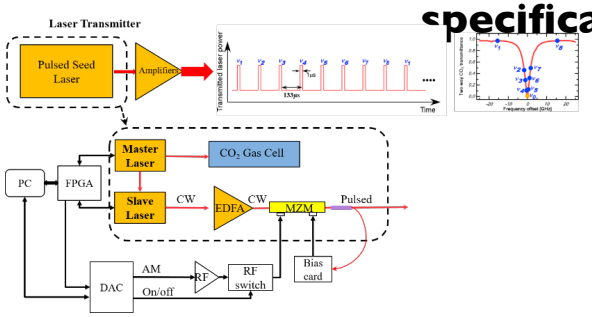
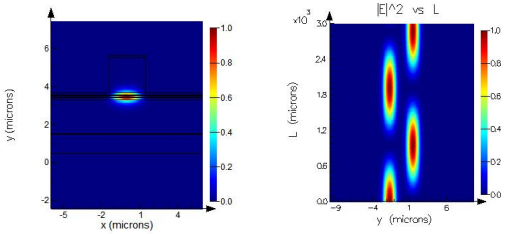
Architecture and component specifications



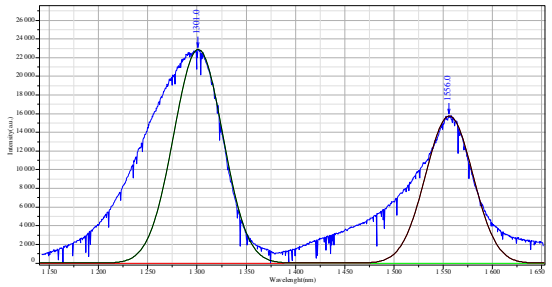
Component		
Master laser	Type	SG-DBR / DFB
	Center Wavelength	1572.335 nm
	Tuning range desired	~10-40 nm
	Frequency noise	
	-3 dB Linewidth (SGDBR)	3 – 10 MHz
	-3 dB Linewidth (DFB)	200 kHz – 1 MHz
	SMSR	40 dB
	RIN @ CW 100M < f < 10G	-140 dB/Hz

Component		
Slave Laser	Type	SG-DBR
	Center Wavelength	1572.335 nm
	Tuning range	~10-40 nm
	Mode-hop free tuning with phase	>40 GHz
	Frequency Noise	
	-3 dB Linewidth	2 MHz
	SMSR	40 dB
	RIN @ CW 100M < f < 10G	-140 dB/Hz
MZM	Type	
	Efficiency (Vpi)	< 6 V
	DC bias voltage	-1 V
	Speed	10 GHz
	Insertion loss	< 4 dB
	Extinction Ratio	20 dB

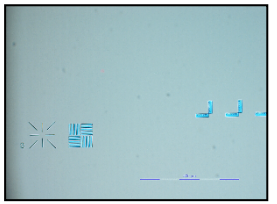
Simulations and design

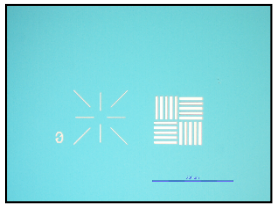


Materials design and growth

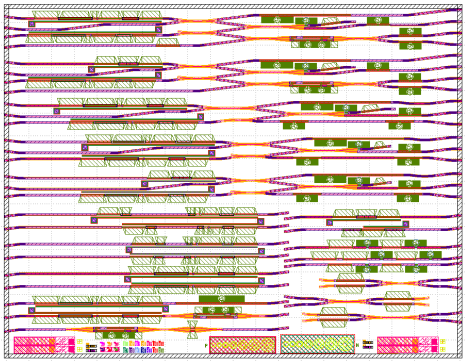


Fabrication

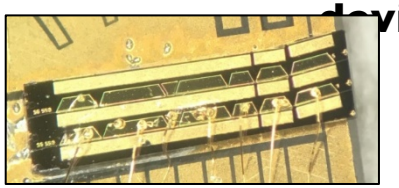


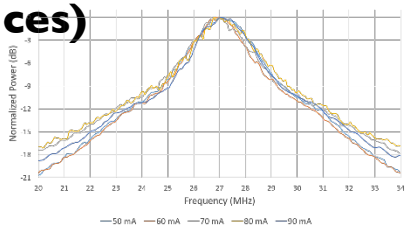


Layout



Characterization (with existing devices)





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Architecture and Integration Platform

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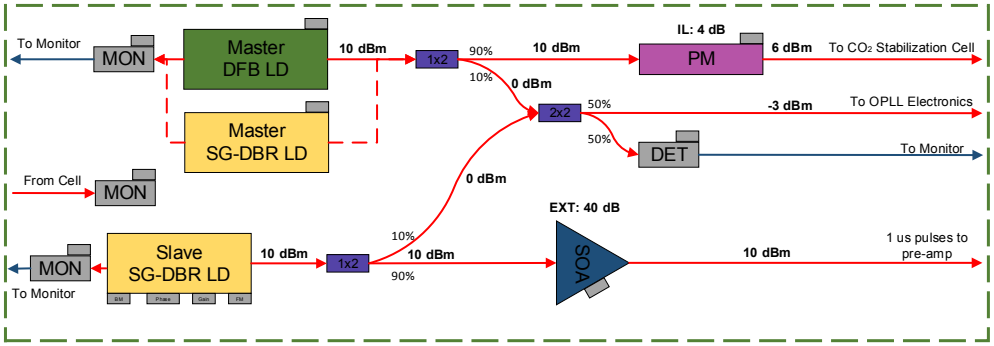
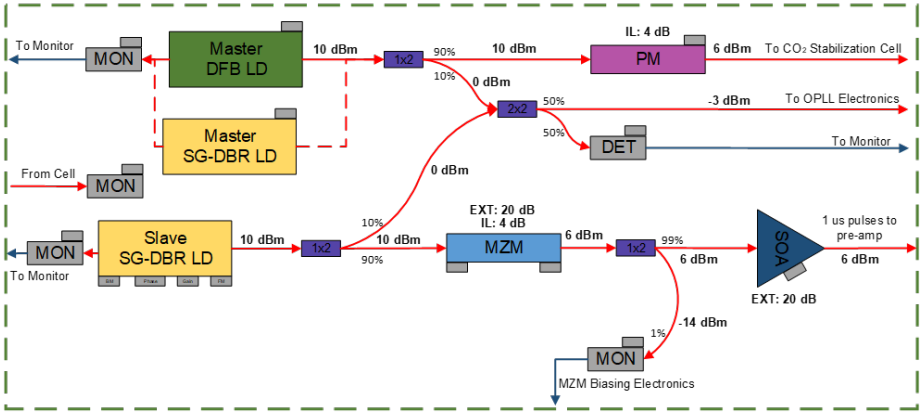
PIC A: SOA for pulse generation

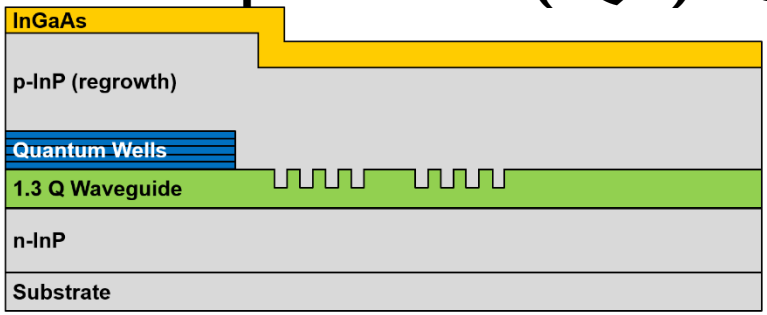


PIC B: MZM for pulse generation



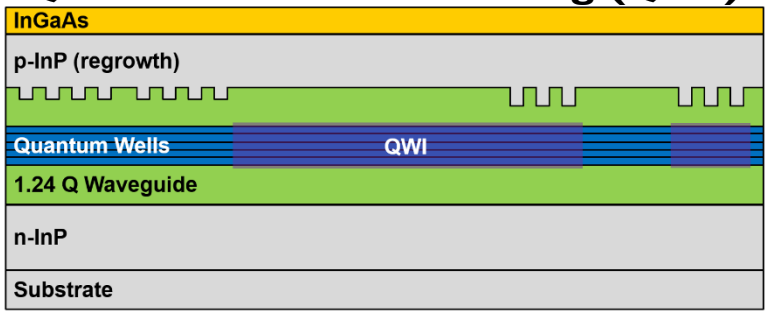
Active/passive integration

Offset quantum well (OQW)



- Simple growth and fabrication
- DBR lasers

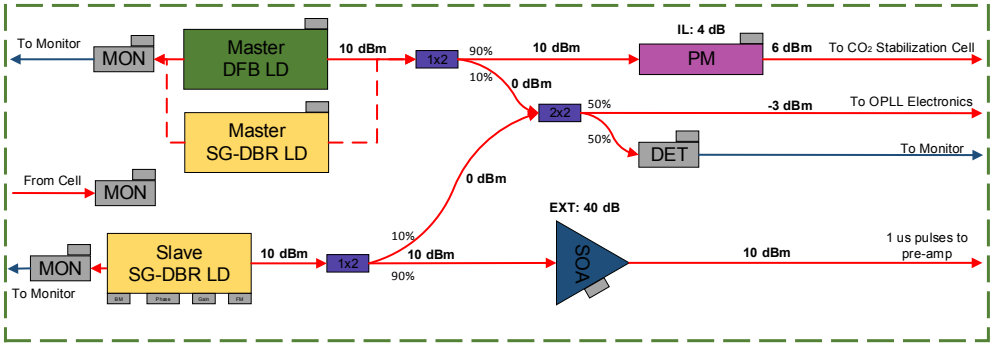
Quantum well intermixing (QWI)



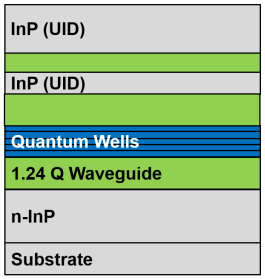
- Simple growth, moderate fabrication
- Both DBR and DFB lasers

PIC Design and Layout

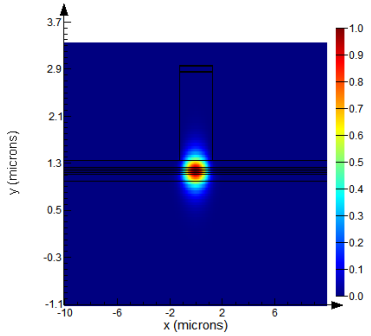
PIC A: SOA for pulse generation



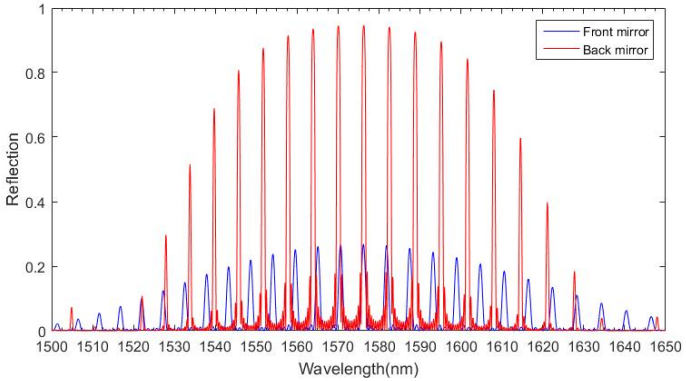
Epi-layer design



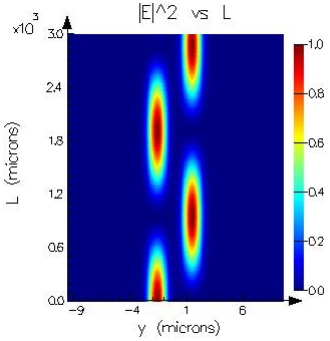
Mode simulations

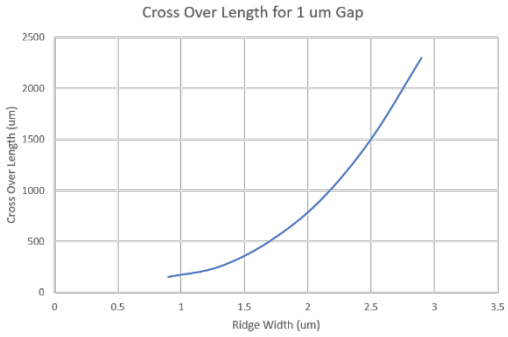


Laser design

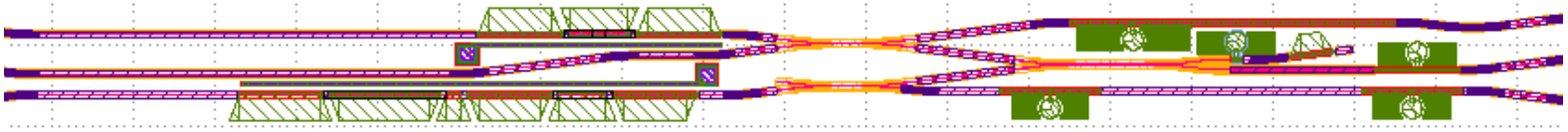


Coupler design





PIC layout



Characterization

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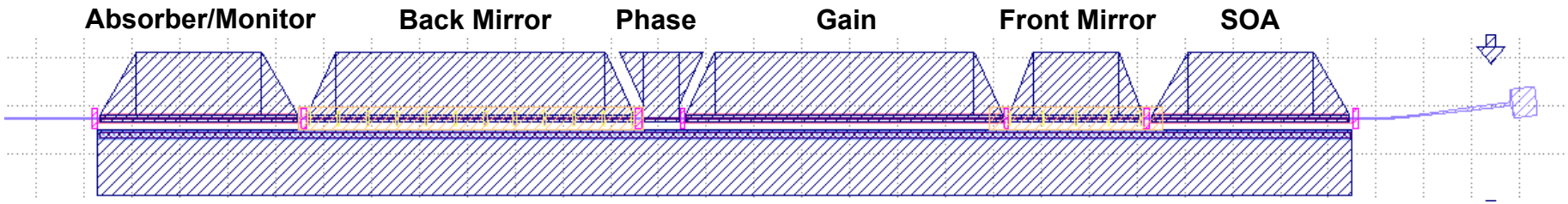
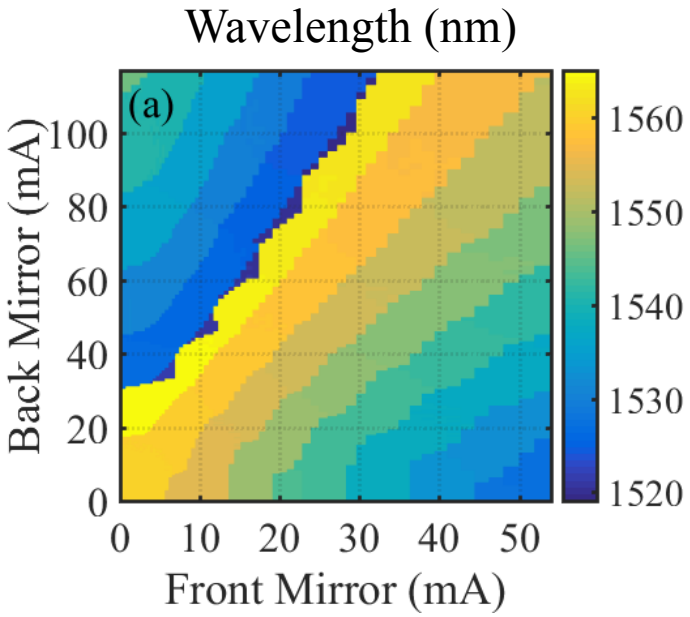
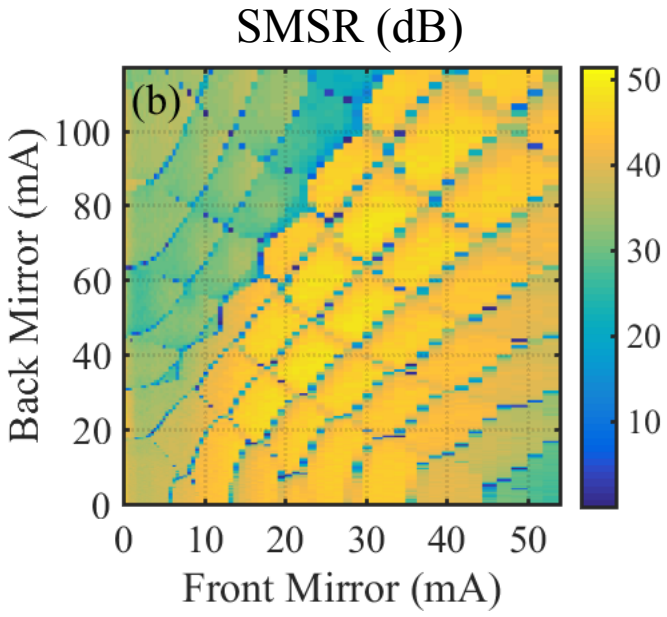
Multi-Section Widely Tunable Sampled Grating DBR (SGDBR) Laser







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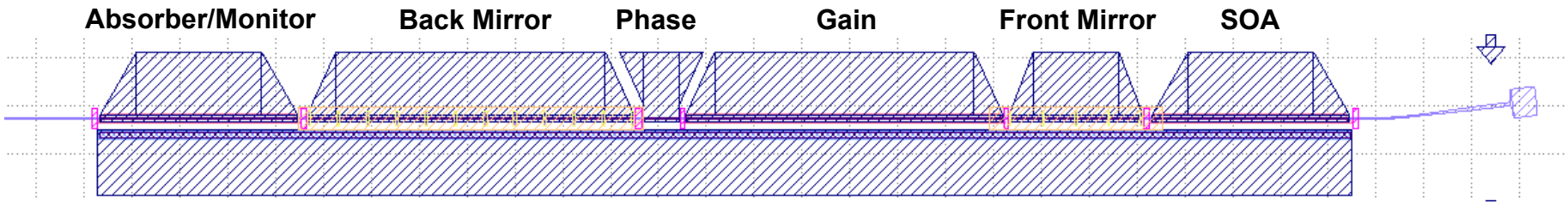
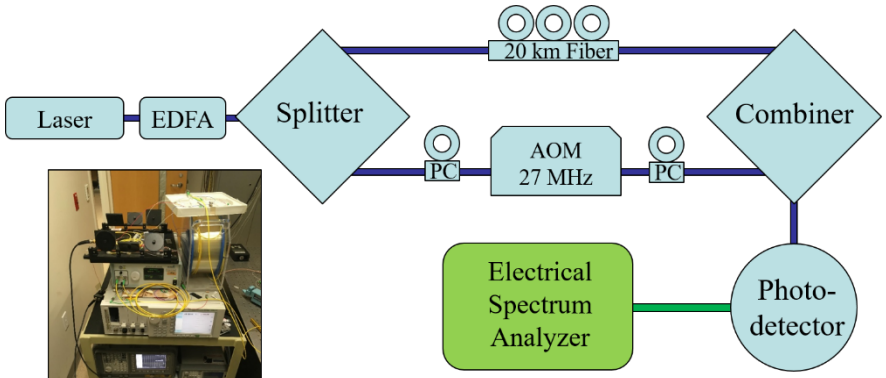
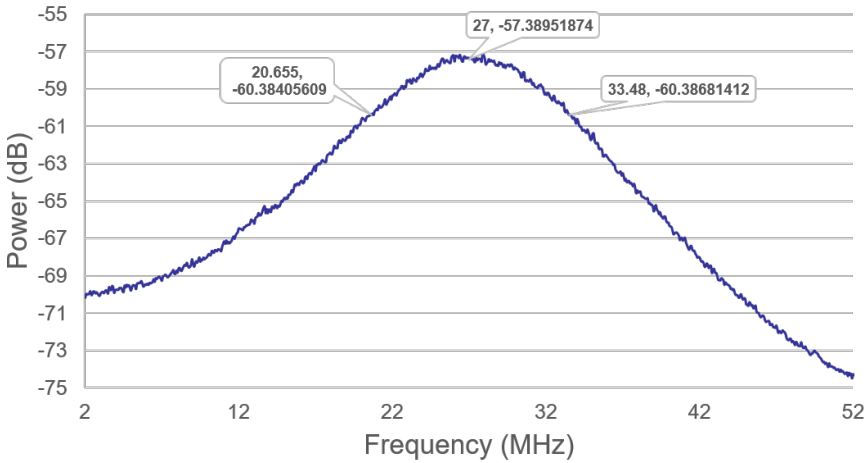
Characterization

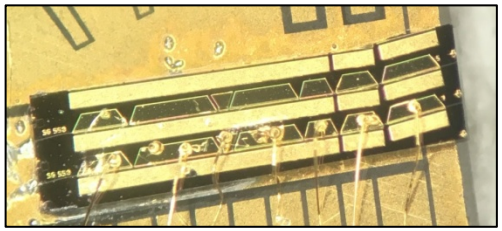
UCSB

Multi-Section Widely Tunable Sampled Grating DBR (SGDBR) Laser









Linewidth = 6.4 MHz

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Characterization

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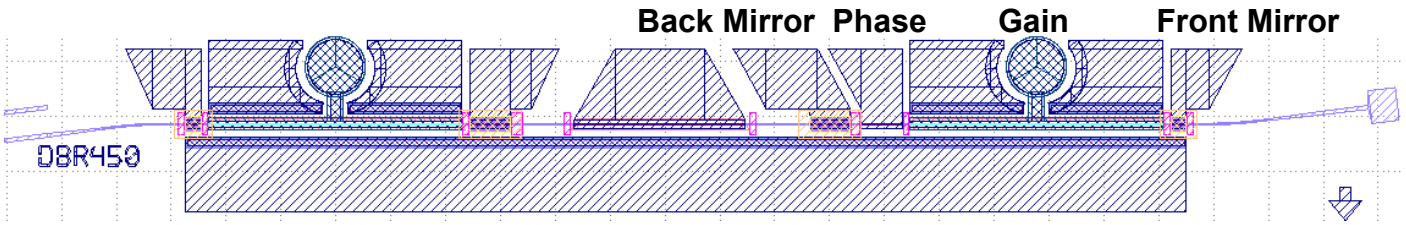
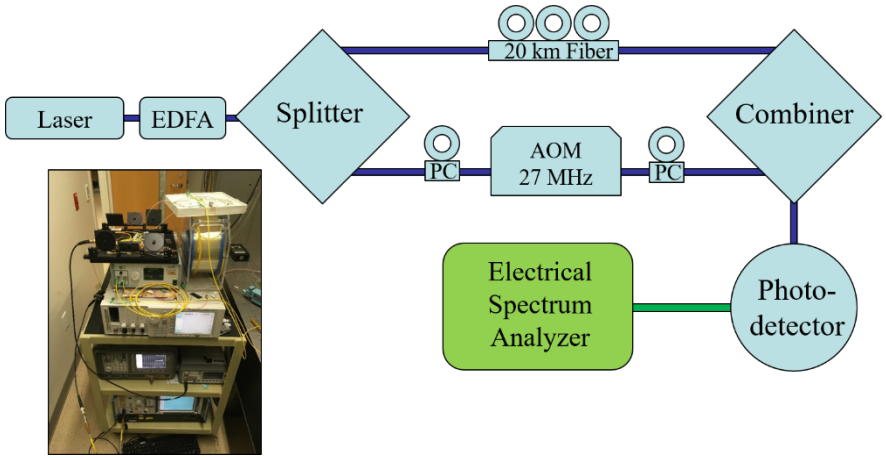
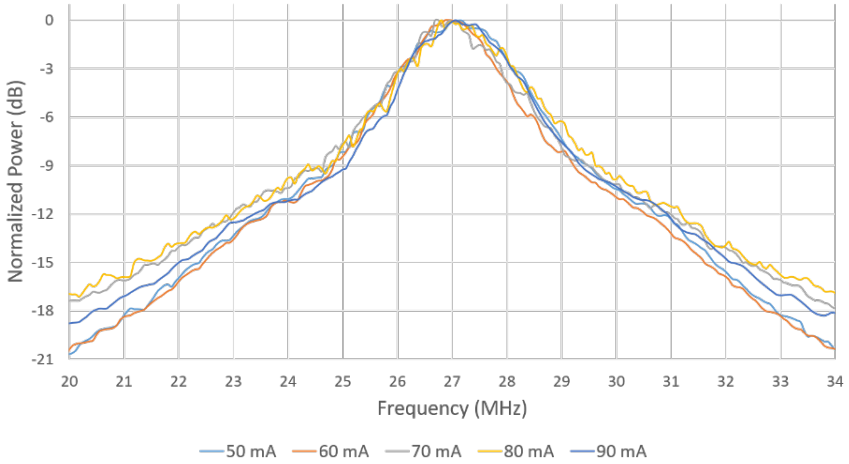
Multi-Section Widely Tunable Sampled Grating DBR (SGDBR) Laser







Linewidth = 900 kHz

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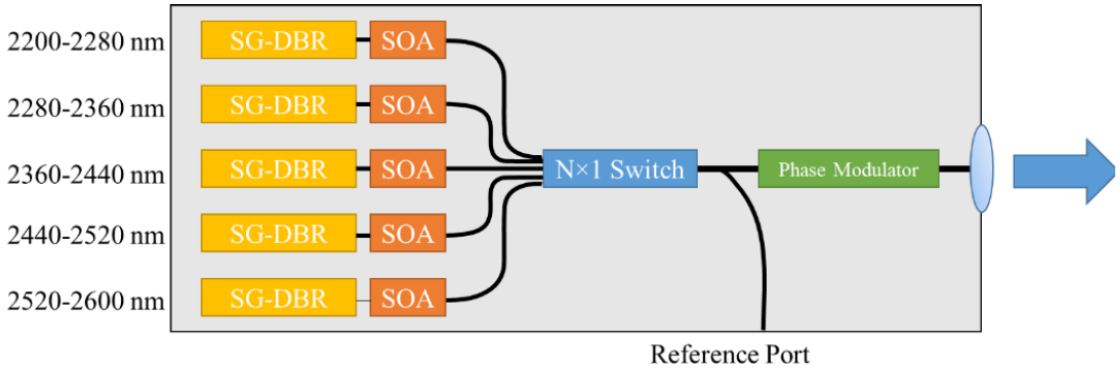
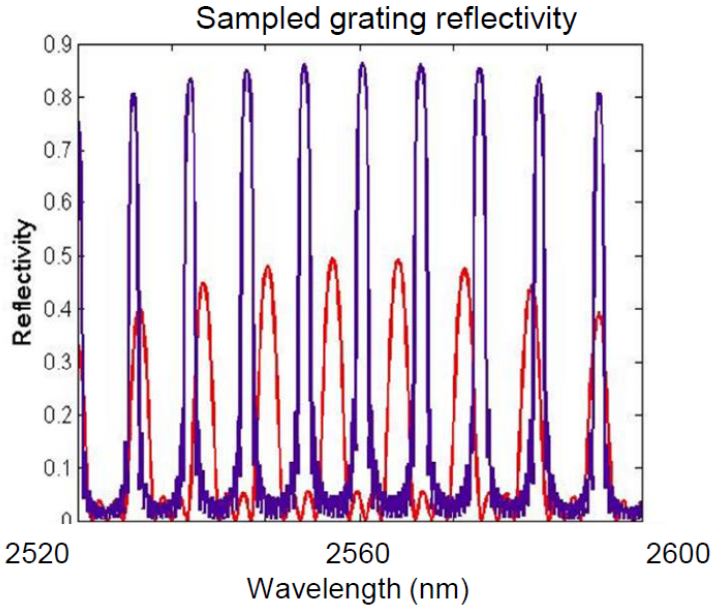
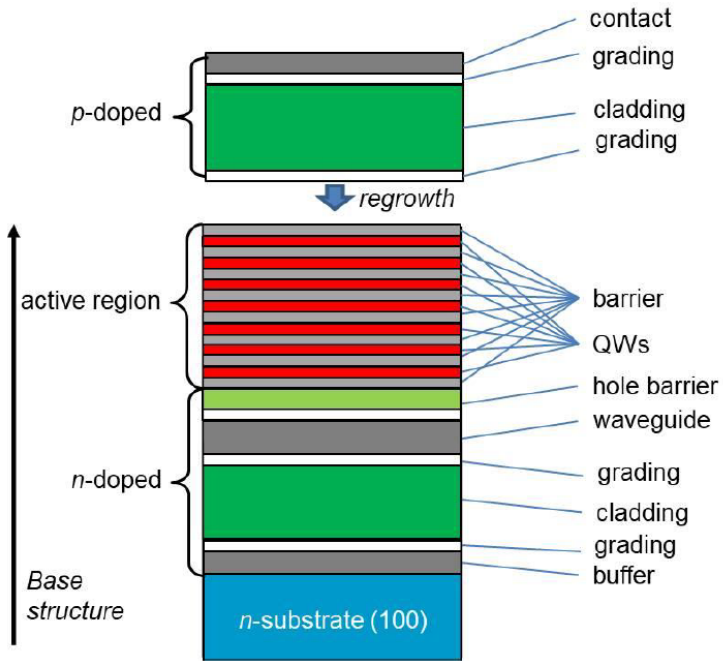
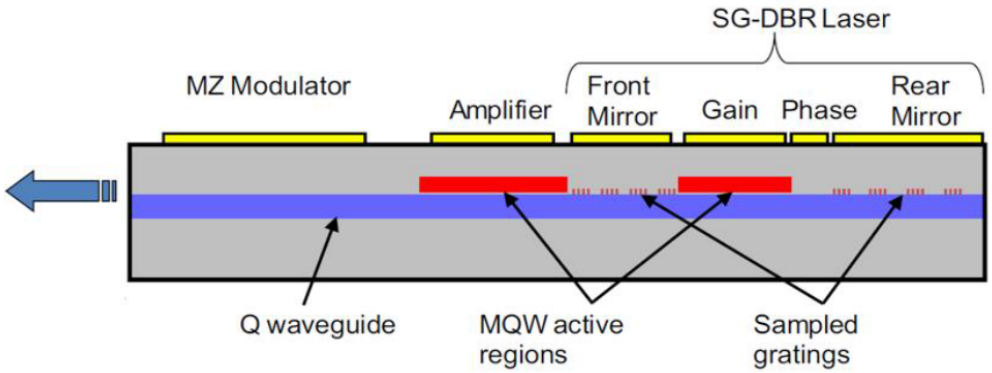
Transferability









*Work of Larry Coldren, UCSB

Conclusions

- **Integrated photonics an enabling technology for reducing system *cost, size, weight and power***
- **Various technologies and platforms available**
  - **Selected indium phosphide for IMPRESS Lidar**
- **Next steps:**
  - **PIC fabrication and testing**
  - **Driver and control circuit design**
  - **Subsystem integration and demonstrations**