Photonic-Integrated-Circuits for Coherent Communication and Sensing

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Fred Kish—Infinera
UCSB Collaborators

What's the problem?

Size, Weight, Power, Cost, Performance, Reliability

Where?

- Communication
  - Long haul
  - Metro, campus
  - Data centers, Supercomputers
- Sensing/instrumentation
- Computing

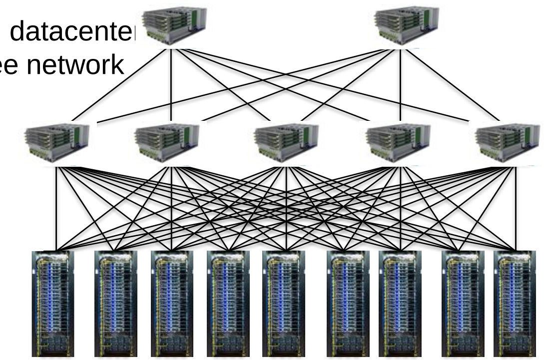
Introduction/Historical View—PICs

- **1970's - OEICs on GaAs for high-speed computing**
- **1980's – InP photonics/fiber; integration & tunables for coherent → Reach**
- **1990's – Widely-tunables, laser-mods, EDFAs; int. for WDM and cost**
- **1990's – VCSELs for datacom and optical interconnection**
- **2000 - Bubble: Explosion of strange ideas, bandwidth-demand satisfied by DWDM → crash; but bandwidth needed by 2010.**
- **2000's – InP PICs & PLCs expanded and matured; increasing use of VCSELs in high-speed datacom and computing interconnects**
- **2006+ – Emergence of Si-PICs with several different goals: low-cost OEICs; high-performance PICs; or stop Moore's-Law saturation**
- **2008+ - Use of advanced modulation formats/coherent receivers for improved Spectral Efficiency —need for integration at both ends of links**
- **2010's – Increased InP-PIC use; maturity of Si-photonics solutions; heterogeneous integration approaches; improved VCSEL link efficiency**
- **2018 – Data-center focus; coherent LIDAR/imaging; InP & Si-PICs in 'volume'**

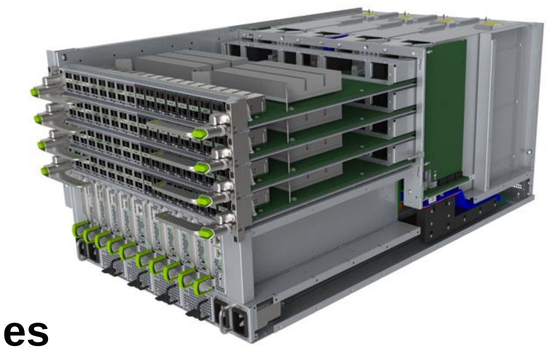
INTREPID

Intelligent Reduction of Energy through Photonic Integration for Datacenters

Typical datacenter Fat Tree network

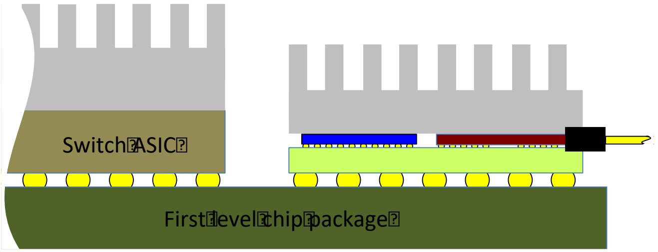


Facebook OCP "Backpack" switch



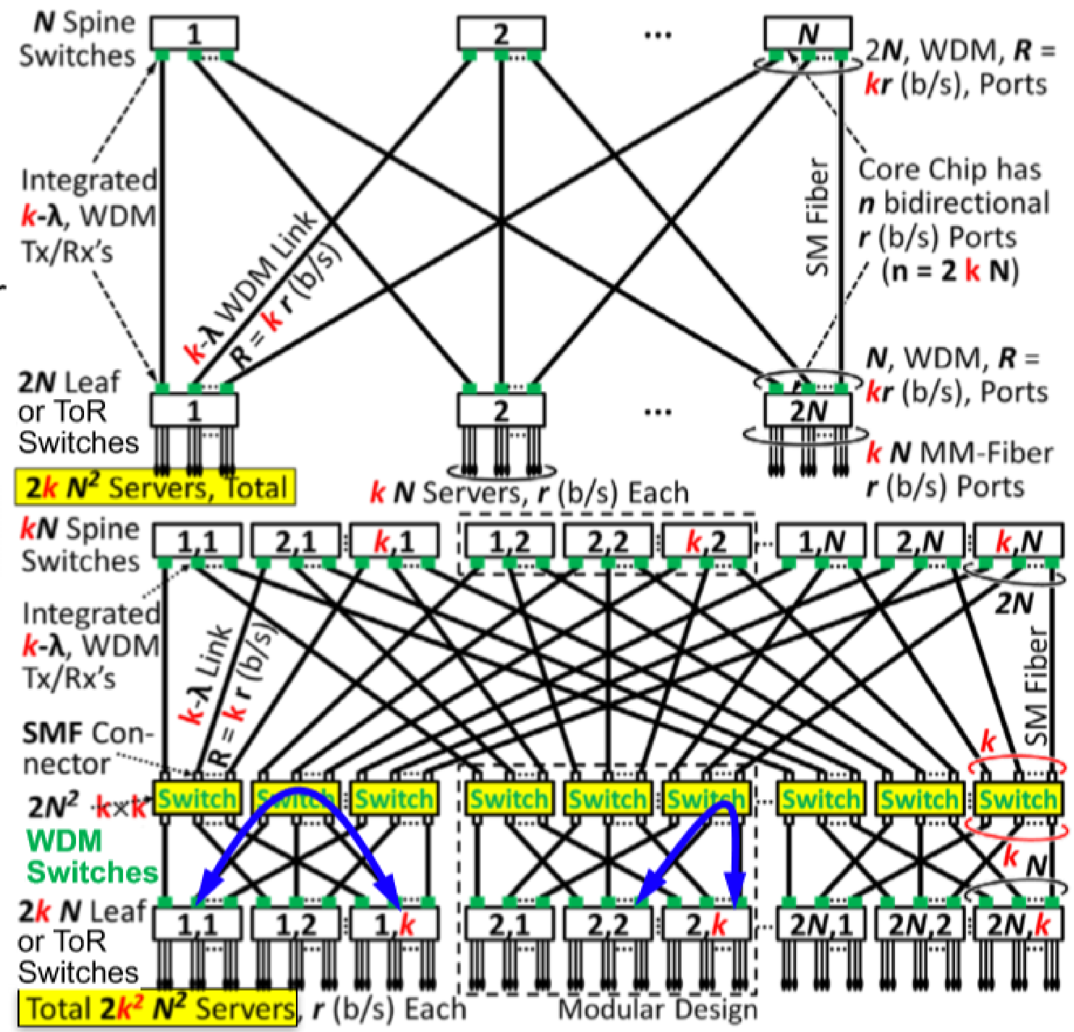
Facebook OCP Rack "Wedge" ToR switch (ToR = Top of Rack)

- **Photonics Integrated into Switch Packages**
  - Points of highest bandwidth concentration
- **Analog Coherent Links Optimized for Datacenters**
  - Large sensitivity gain → more energy efficient interconnects
  - Enabling technology for WDM, photonic routing and switching
- **Low-Power VCSEL Links**
  - Ultra-low power connections from servers to ToR or EoR switches
- **New Network Architectures**
  - Exploring wavelength routing and switching
- **Transition to Widespread Commercial Availability**
  - Technology demo in live datacenter
  - Open Compute Project (OCP), Telecom Infra Project (TIP)



Datacenter Network Architecture

- <u>**Aggressive Integration**</u>
  - Analog coherent WDM interfaces, with ***k*** = 4 to16 wavelengths
  - Integrated <u>directly</u> into high-radix electronic switch ports
  - Greatly reduced cost, latency, power
- <u>**Phase 1 Enhancements**</u>
  - Add a layer of ***k***x***k*** AWGRs[1]
  - Network scales-out by a factor of ***k***
  - *x2-4 increase in energy efficiency, compared to conventional designs*
  - Same latency and switch sizes
- <u>**Phase 2 Enhancements**</u>
  - Replace AWGRs by **WDM switches**[2]
  - Enabling network configurability, including direct optical ToR-to-ToR connections, to match workload
  - Leads to further improvements in energy efficiency and latency



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[1] Saleh, "Scaling-out Data Centers Using Photonics Technologies," PS Conference, 2014.
[2] Saleh, et al, "Elastic WDM Switching for Scalable Data Center Networks," OECC/PS Conference, 2016.

Analog Coherent: Maximizing Energy Efficiency

Direct-Modulation/Direct Detection

Detected power $\propto (P_{laser} \cdot A_{total})$

P_{laser} = laser power, A_{total} = total link attenuation

- RX sensitivity sets link budget, energy efficiency
  - Poor sensitivity = higher transmitter power
- Sensitivity directly degrades with datarate
  - Problem only getting worse

Field Modulation/Coherent Detection

Detected power $\propto \sqrt{(P_{laser} \cdot A_{total}) \cdot P_{LO}}$

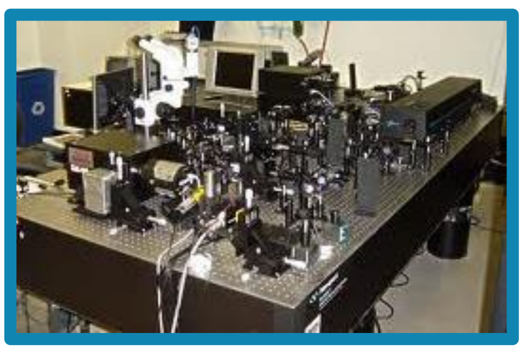
P_{LO} = Local Oscillator (LO) power

- ~20dB improvement in RX sensitivity possible
- Much greater toleranance to attenuation
  - Looser component specs for yield and cost
  - Ability to compensate for insertion loss of optical routing/switching devices

Optical Phase Locked Loop (OPLL) → Eliminating Power-Hungry DSP

Typical OPLLs prior to 2000

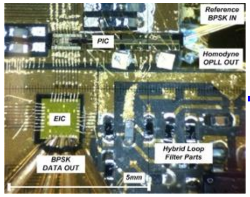
Lab-scale



<1000X size
<100X power

Prior UCSB work

Carrier-scale, single channel



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<10X power

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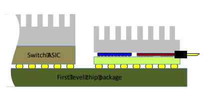
Chip-scale, WDM multi-channel

with simple mux/demux

Photonic and Electronic Integration



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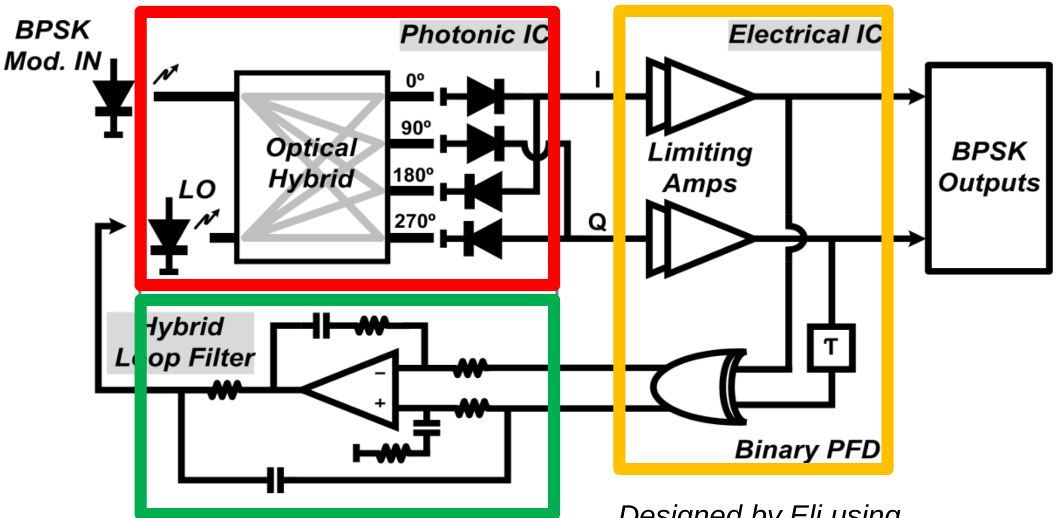
Prior Work: Phase Locked Coherent BPSK Receiver "Analog Coherent"

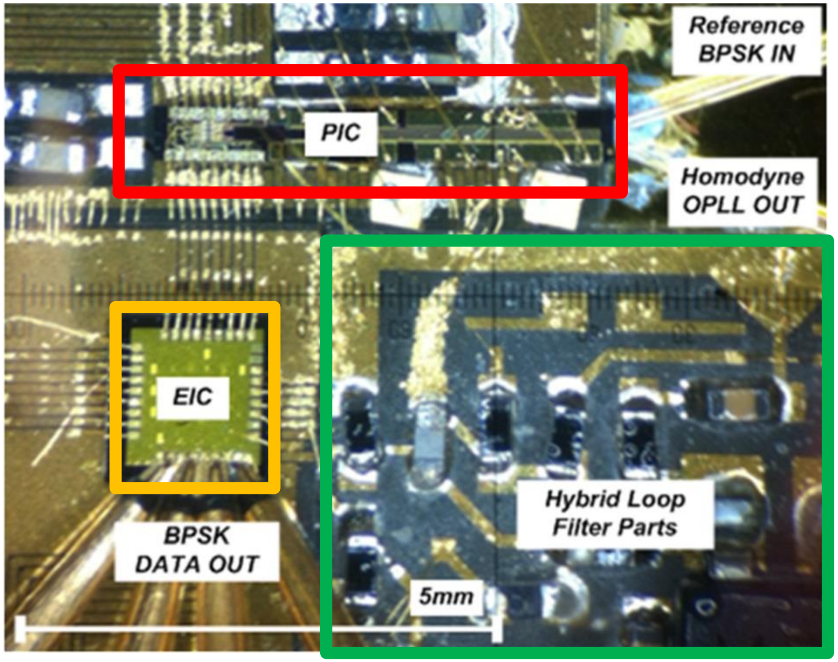
OPLL + Costas Loop → 1 cm^2 footprint

Fabricated by Mingzhi



Loop filter and system designed by Hyunchul

Designed by Eli using Teledyne 500nm HBT Process



Photonic IC: SGDBR laser, optical hybrid, and un-balanced PDs

Electronic IC: limiting amplifiers and phase & frequency detector (PFD)

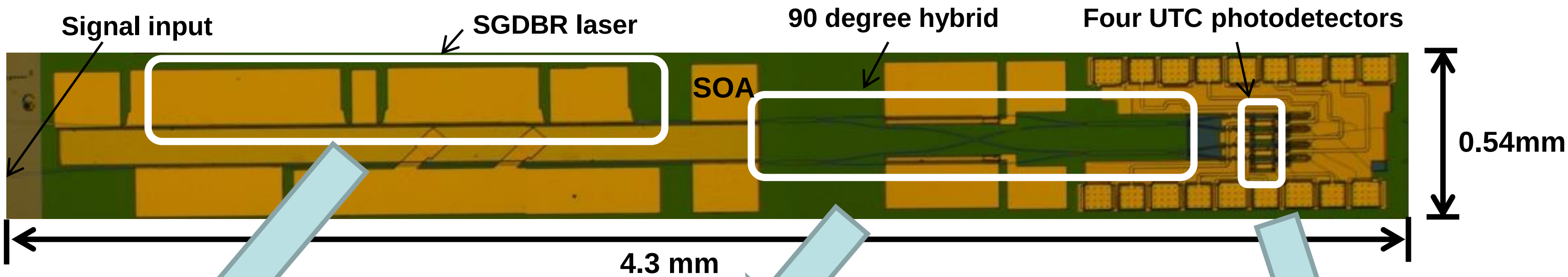
Hybrid loop filter: Feed-forward technique, op-amplifier and 0603 SMDs

Mingzhi Lu, et. al., Optics Express, Vol. 20, Issue 9, pp. 9736-9741 (2012)

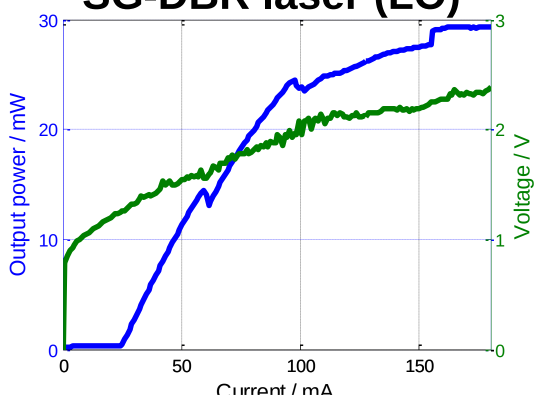
InP Widely-tunable Coherent Receiver PIC-2

(Heterodyne or Intradyne—also for Optical Synthesis)

MOC 2018



- **SG-DBR laser (LO)**

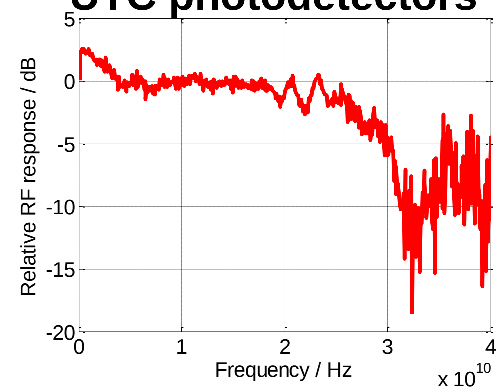


- **30 mW output power (~100 mW after SOA)**
- **40 nm tuning range**
- **25 mA threshold current**

- **90 deg hybrid**
  - ***1x2 MMI couplers***
  - ***Directional couplers***
  - ***Phase shifters***

No phase error
4% power imbalance

- **UTC photodetectors**

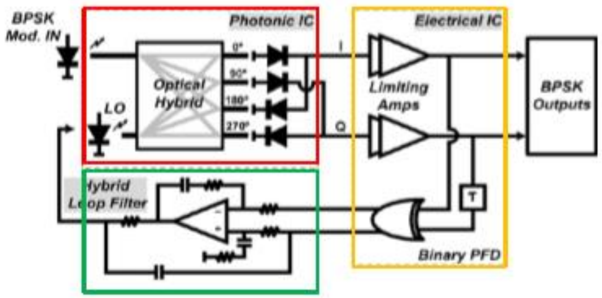


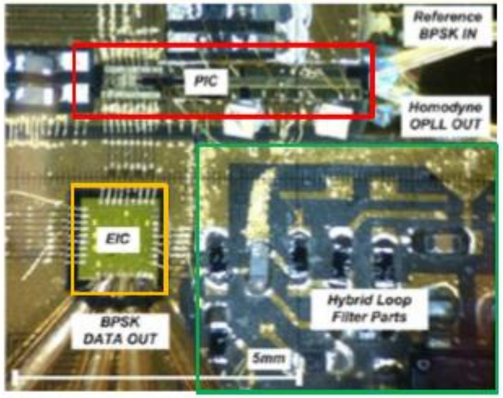
- ***29 GHz 3-dB bandwidth with -2V bias***
- ***18 mA saturation current at -5V bias.***

- ***I* and *Q* outputs normally connected to ADC and DSP for Receiver**
- **Much lower SWaP-C Optical Phase Locked Loop (OPLL) used**

Mingzhi Lu, et. al., Optics Express, Vol. 20, Issue 9, pp. 9736-9741 (2012)

Feasibility Established: Analog Coherent OPLLs





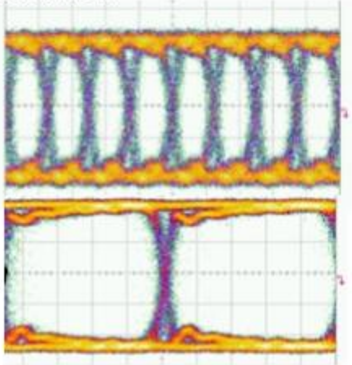
Operation at 1550nm

- **1.1GHz** closed loop bandwidth
- **120ps** loop propagation delay
- **100kHz** SGDBR-linewidth *(as ref. laser)*
- **-100dBc/Hz@above 50kHz** phase noise
- **600ns** frequency pull-in time
- **<10ns** phase lock time

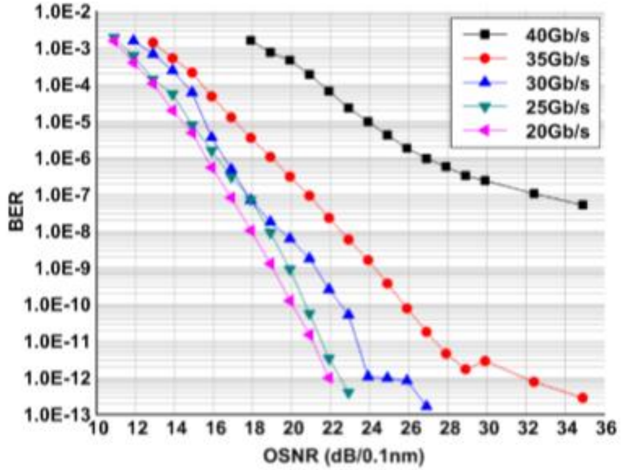
High-Speed Operation:

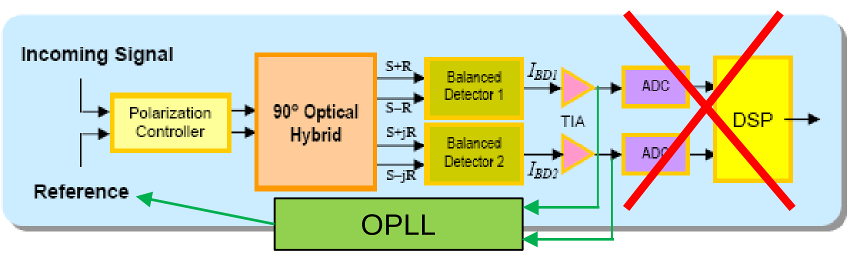
40 Gb/s *back-to-back*

10 Gb/s *25km SMF*



Error-free up to 35Gb/s:





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- S. Ristic *et. al., JLT* (2010)
- *M. Lu et. al., Optics Express, (2012)*
- P. R. A. Binetti *et. al., JQE* (2012)
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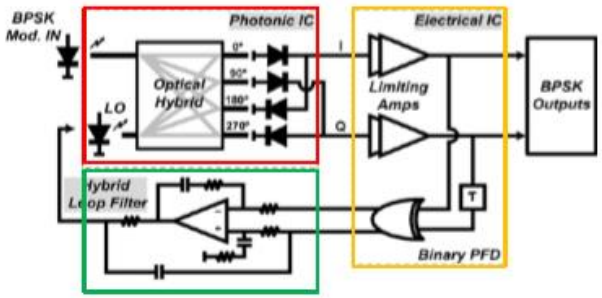

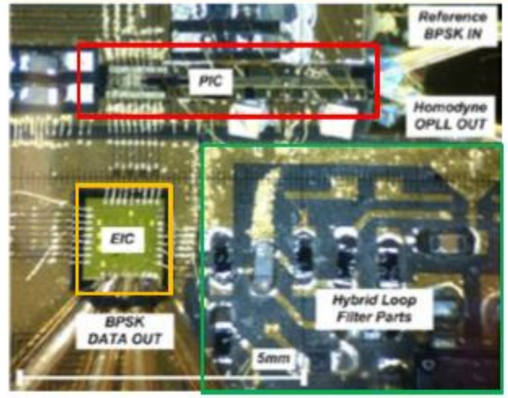

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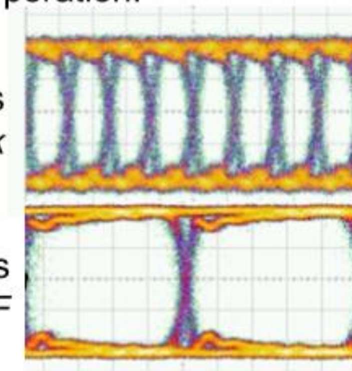

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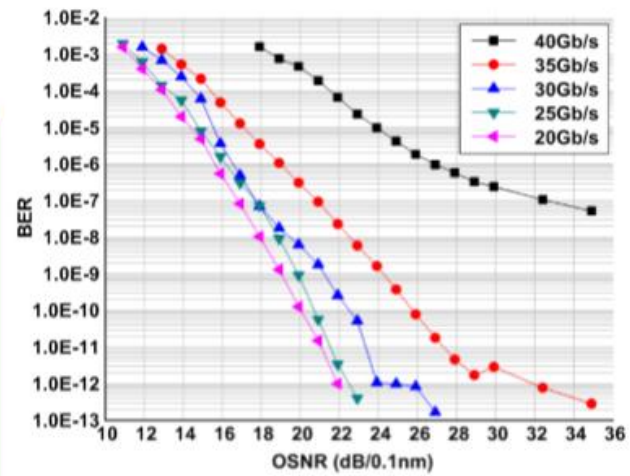

INTREPID Focus

- O-band operation at maximum energy efficiency
- Co-optimization and tighter integration of photonics and electronics
- Flip-chip packaging supporting multi-channel WDM scaling

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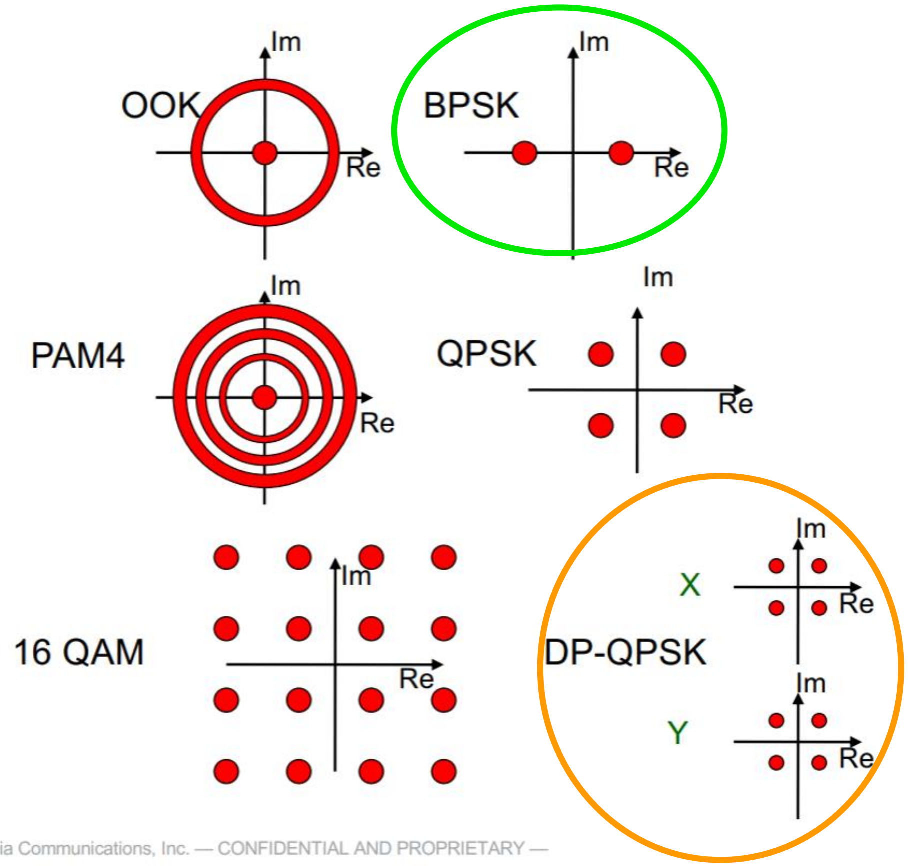
- S. Ristic *et. al.*, *JLT* (2010)
- *M. Lu et. al., Optics Express, (2012)*
- P. R. A. Binetti *et. al.*, *JQE* (2012)
- M. Lu *et. al.*, *JLT* (2013)

From Chris Doerr--Acacia

For coherent use Vector modulation:

Modulation formats

Tu2E.5.pdf



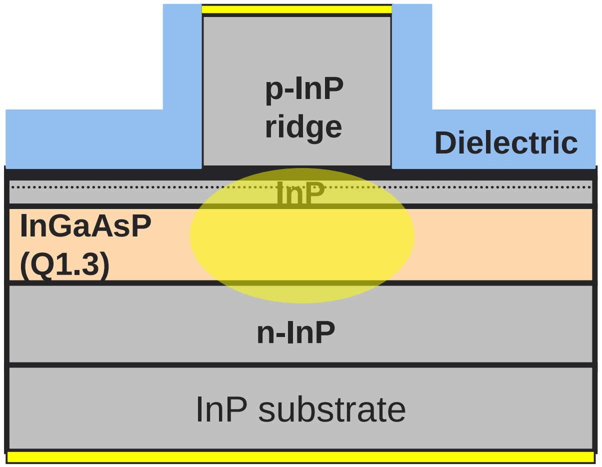
b/baud = 1

b/baud = 2

b/baud = 4

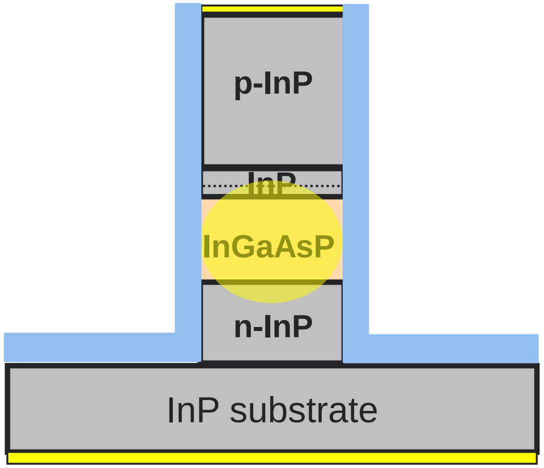
Waveguides: InP vs SiP (Lumentum Slides—M. Larson)

InP Shallow Ridge Waveguide



- Ridge width ~2um
- Core thickness 200-300nm
- Moderate index step (3.4 <-> 3.17) $\Delta n \sim 0.2$

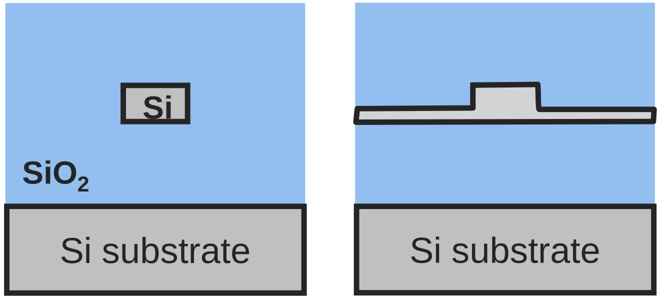
Deep Ridge Waveguide



- Ridge width ~1.2-1.8um
- Core thickness 200-300nm
- Moderate vertical index step
- Large lateral index step (3.3 <-> 1.45) $\Delta n \sim 2$

Si nanowire waveguide

channel rib



- 450 x 220nm typical
- Large index step vertical & lateral (3.5 <-> 1.45) $\Delta n \sim 2$

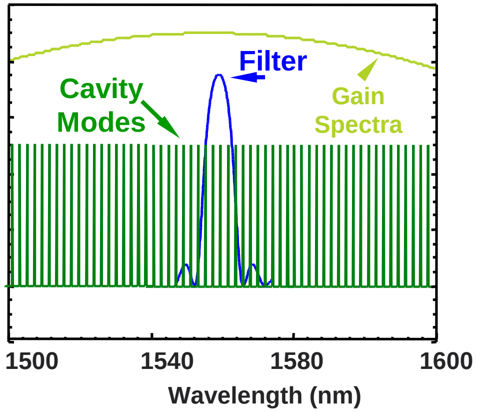
- Waveguides in both systems are polarization sensitive

Passive PIC Elements

Passive Element	InP	SiP
Power Splitter/Combiner	Multimode Interference Couplers (MMIs)	MMIs Directional Couplers Adiabatic Couplers Y Junctions
90 degree hybrid co-mixer	2x4 MMI cascaded 2x2 couplers	2x4 MMI cascaded 2x2 couplers
Off-chip coupling	Cleaved Facet Spot size converter (vertical/lateral taper)	Spot size converter to SiNx Grating coupler
Polarization diversity	hybrid	Polarization Beam Splitter/Rotator (PBSR)
Isolator	hybrid	hybrid

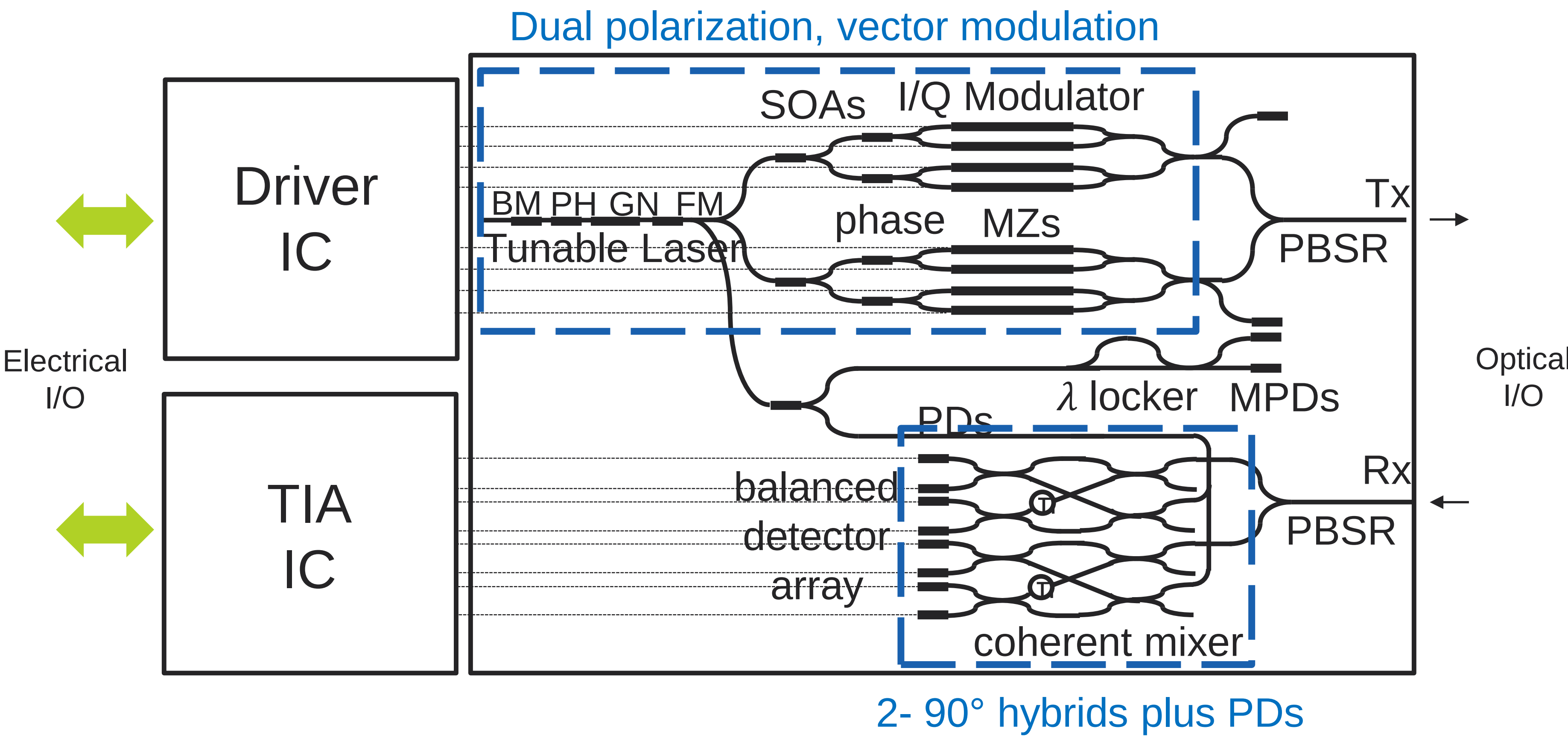
Laser Building Blocks

- Laser source required for transmitter and local oscillator
- Narrow linewidth, high power, full C-band tunable
- Vernier tuning architecture with 2 or more filters to overcome refractive index tuning limitations
- Laser must be temperature stabilized or suffer environmentally-induced frequency drift



	InP	SiP
Optical Gain Medium	InGaAsP or InGaAlAs quantum wells	hybrid or heterogeneous
Filters / Mirrors	Vertically-etched gratings in InGaAsP waveguide Microring resonators	Micro-ring resonators; Laterally-patterned gratings
Tuning mechanism	Carrier injection or thermal (microheater)	Thermal (microheater)

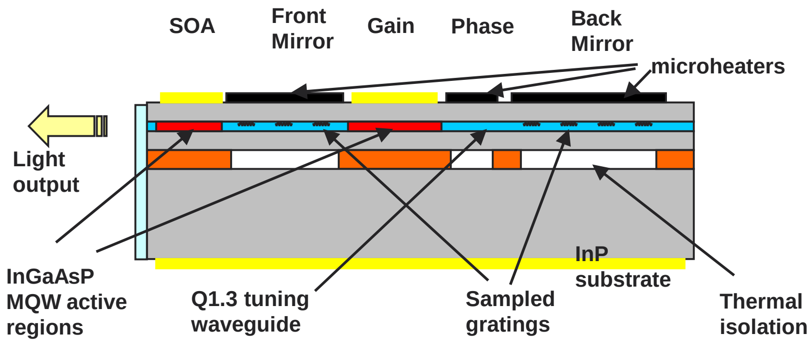
Single or Multiple PICs?
InP Practical View (Lumentum)

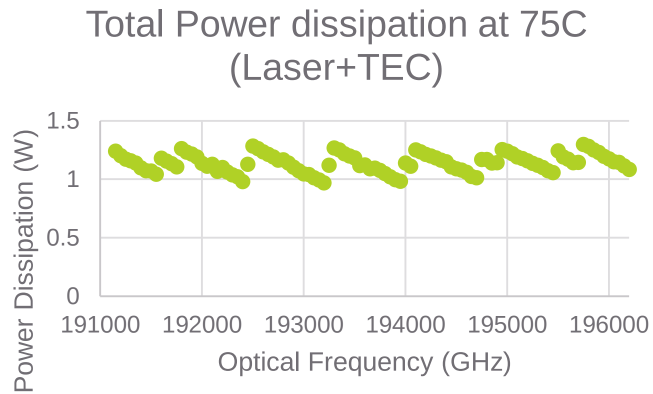


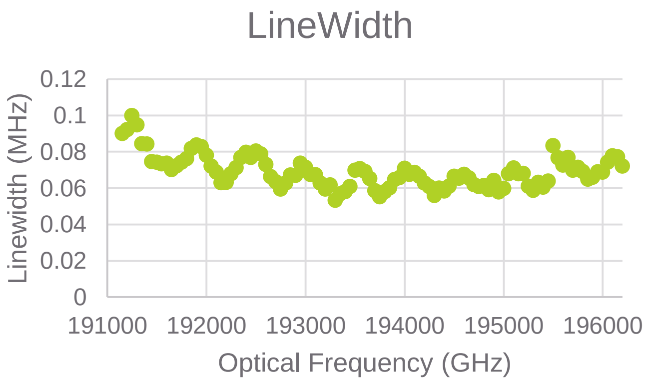
- Separate Tx and Rx PIC for thermal considerations
  – Laser + Modulator must be temperature controlled; Receiver is uncooled

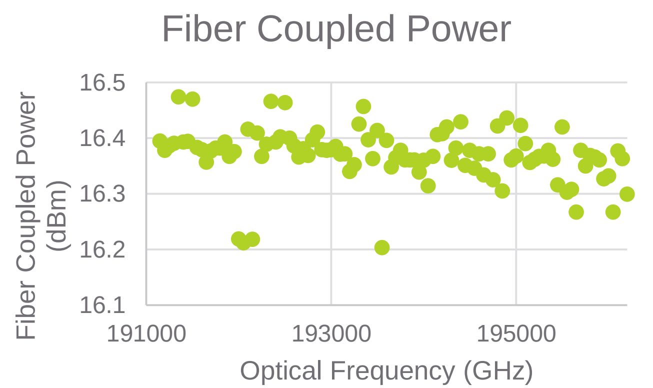
Narrow linewidth thermally tuned Sampled Grating DBR laser in InP (Lumentum)

- Vernier-tuned SGDBR Laser, comb spacing ~700GHz
- +16dBm output power, 100kHz linewidth
- <1.4W Pdiss at 75C (laser TEC at 52C)



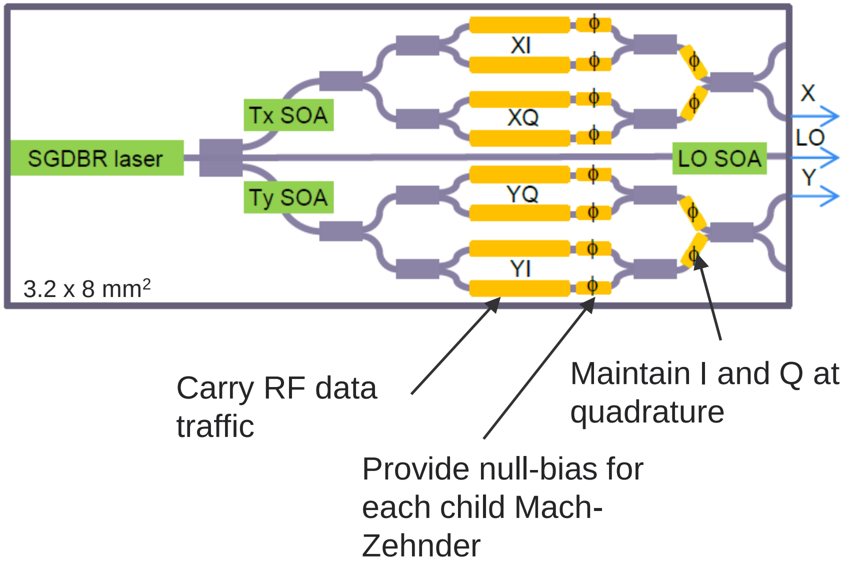


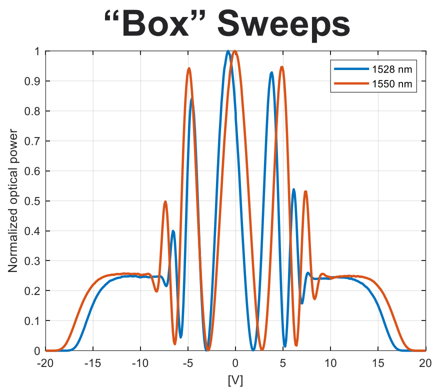


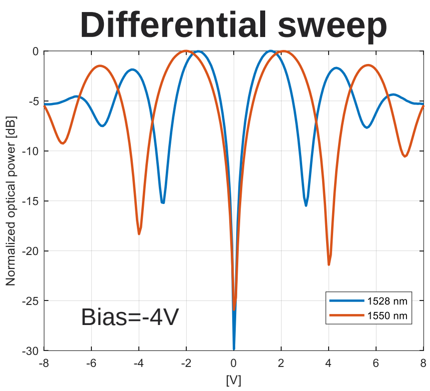


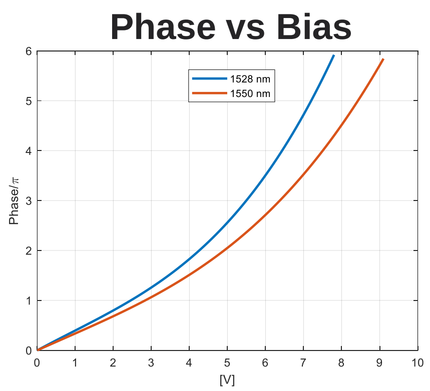
InP Coherent Tx PIC

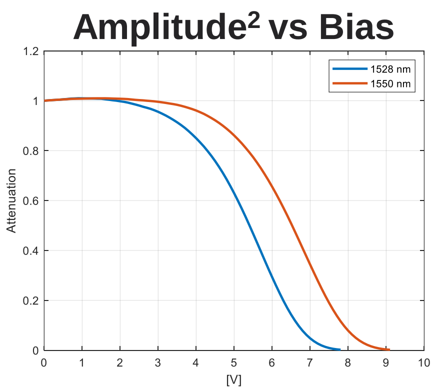
- Integrated Narrow Linewidth Tunable Laser with Dual Polarization IQ modulator and LO Output





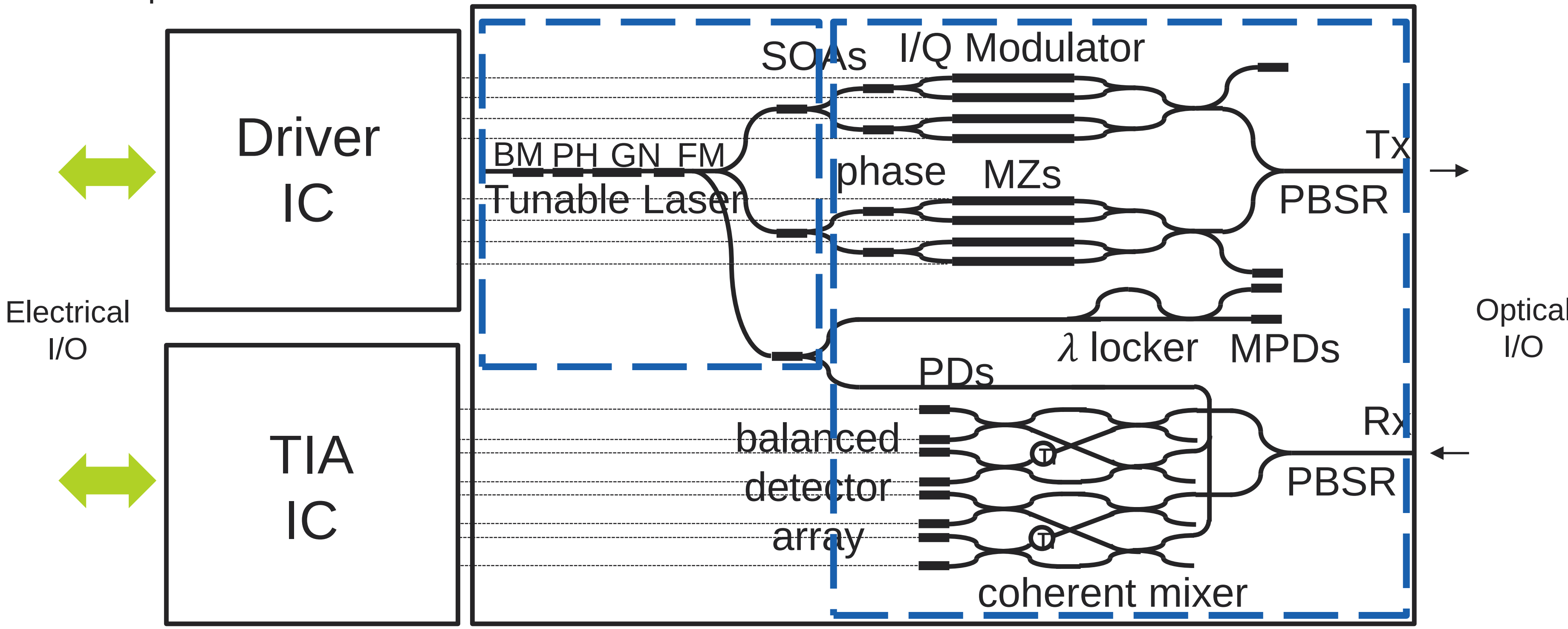






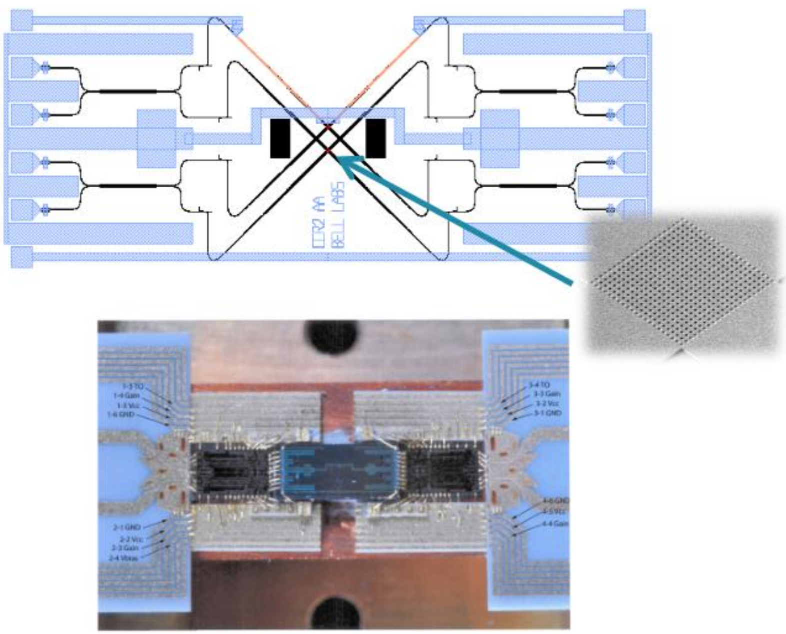
Single or Multiple PICs?
SiP Preferred View (Acacia, NTT)

- Separate Tunable Laser PIC from Modulator+Receiver PIC for thermal considerations



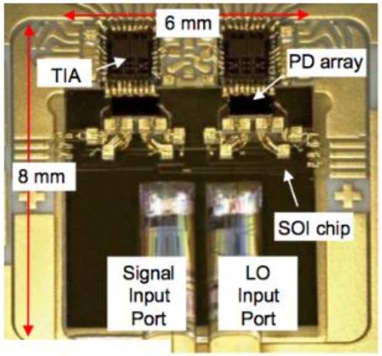
C. Doerr et al., OFC 2016
K. Kikuchi et al., Compound Semiconductor Integrated Circuit Symposium (CSICS), 2017

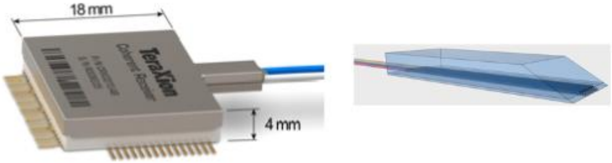
Early SiPh coherent receivers



C. R. Doerr, et al., J. Lightwave Tech., vol. 28, pp. 520-525, 2010.
C. R. Doerr, et al., IEEE PTL, 2011.

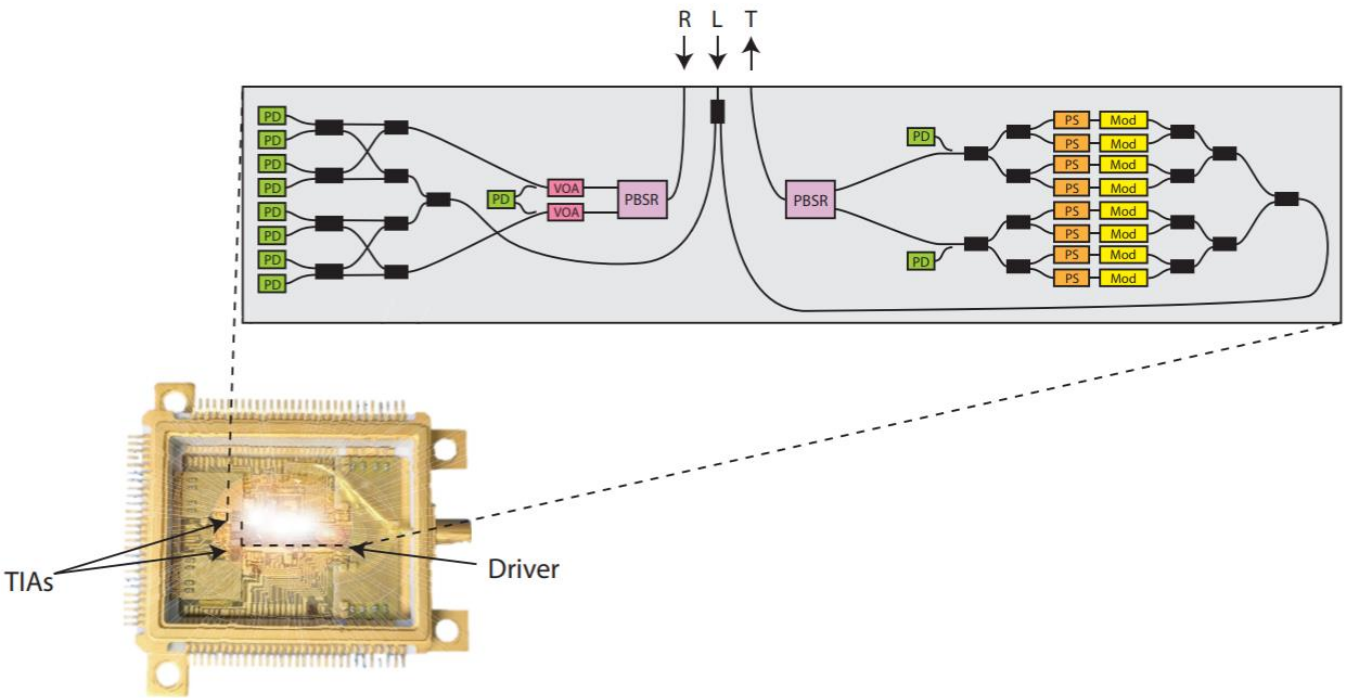
Si + InP





Y. Painchaud, et al., 2013.

Single-chip coherent transceiver



Power consumption = 4.3 W

C. Doerr, et al., OFC, Th5C.4, 2016.

ASIC-PIC co-packaging

Improved heat dissipation

Tu2E.5.pdf

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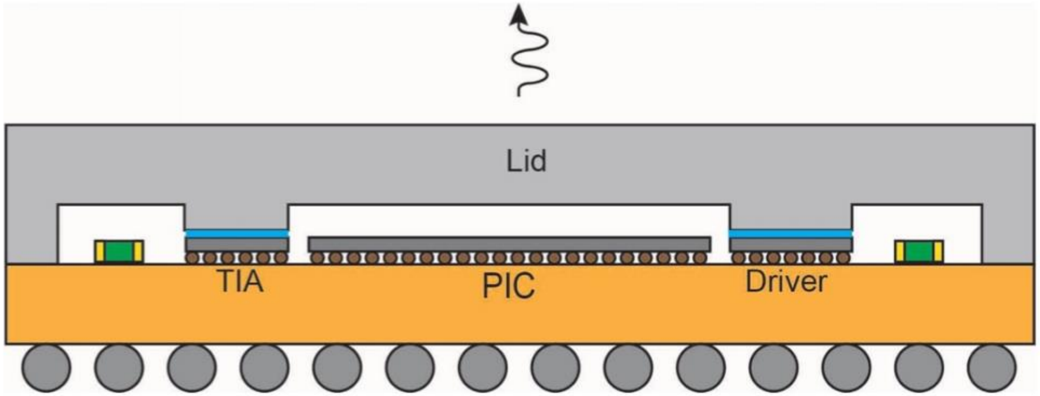
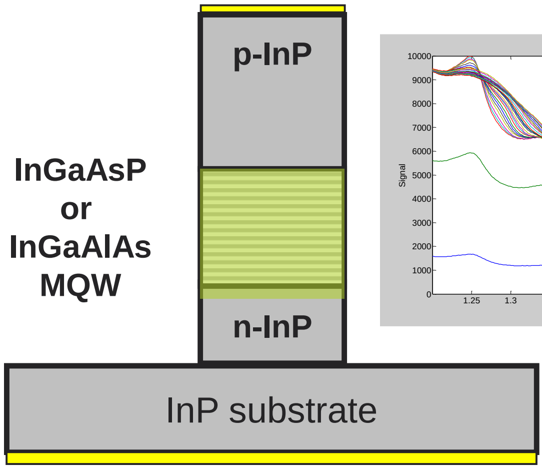
- Heat flows directly from die backside to lid

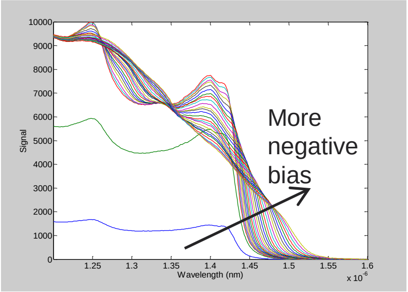
Very high bandwidth connections



Modulator Material Physics

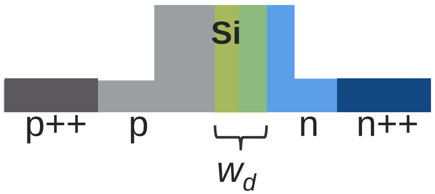
- InP: Quantum Confined Stark Effect
  - Applied reverse bias causes a redshift of the multiple quantum well excitonic absorption edge
  - $\Delta n \propto V, V^2$





D.A.B Miller, et al., Phys. Rev. Lett., 53 (1984) p. 2174

- SiP: plasma dispersion effect
  - $\Delta n \propto$ carrier concentration $\Delta N, \Delta P$.
  - Carrier concentration is a non-linear function of applied V



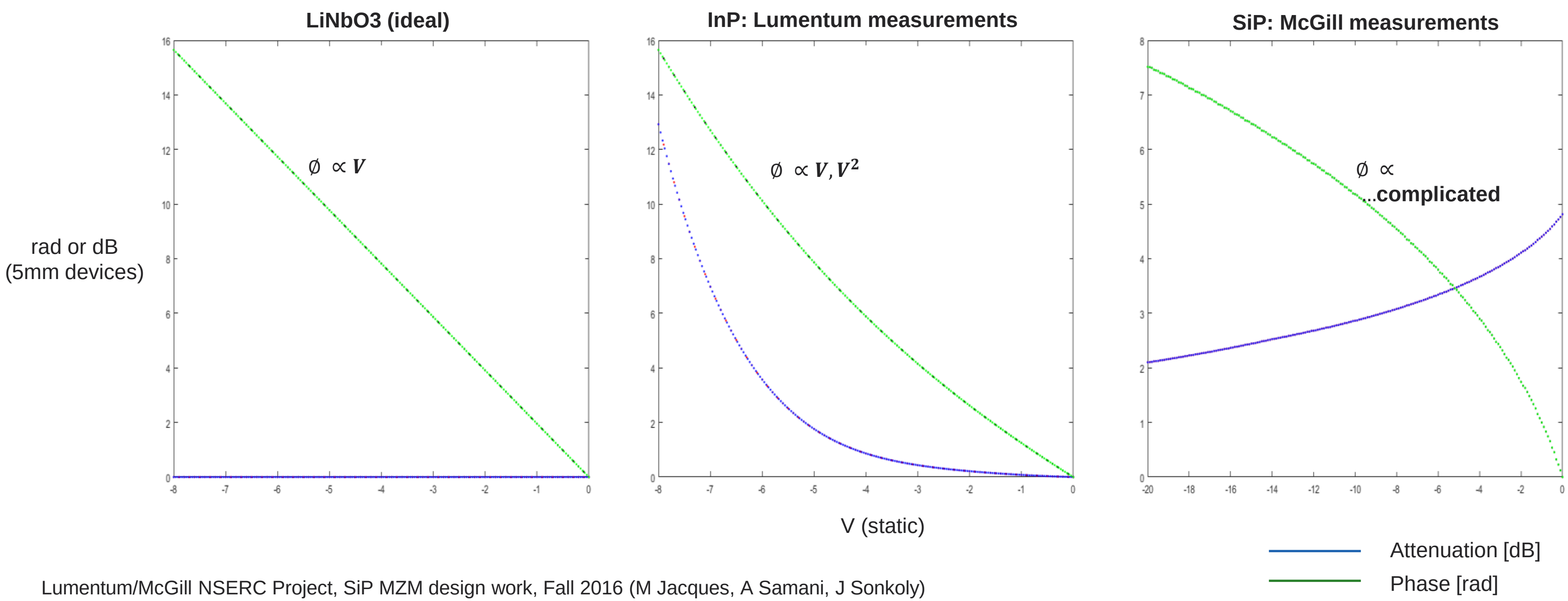
$$\Delta n(\lambda) = -3.64 \times 10^{-10}\lambda^2 \Delta N - 3.51 \times 10^{-6}\lambda^2 \Delta P^{0.8}$$

'Soref' equation. Fitting parameters are empirical

Soref and Bennett. IEEE JQE 23.1 (1987): 123-129.

Phase Shifter Transfer Functions

- Phase & attenuation vs applied voltage for 3 modulator materials
  - InP: nonlinear phase and attenuation (electro-absorption) with increasing reverse bias
  - SiP: complicated phase and attenuation; notice: vertical scale range is ½, horizontal scale (V) is 2.5X



Lumentum/McGill NSERC Project, SiP MZM design work, Fall 2016 (M Jacques, A Samani, J Sonkoly)

Power Dissipation Budget Comparison:
64 Gbaud DP-16QAM IC-TROSA component level estimate

- Conservative estimates for budgetary purpose
- InP PIC + TEC is 3.3W vs. 2.3W for SiP + External Laser: 1W SiP advantage
- SiP solution is disadvantaged by high Vpp => high driver power dissipation

Power dissipation Item (max)	**InP IC-TROSA Tx PIC + Rx PIC**	**SiP IC-TROSA TxRx PIC + Laser PIC**	**Notes**
Tx PIC active load (W)	0.9	0.1	InP case includes laser
Tx TEC (W)	2.4	0	
External Laser + TEC (W)	0	2.2	SiP case only
Driver (W)	1.9	3.5	
TIA (W)	1.1	1.1	
Total (W)	**6.3**	**6.9**	maximum

Summary

- As long as laser is temperature sensitive and requires TEC, single PIC solution is unlikely the lowest power dissipation
  - At 1310 may be able to use uncooled laser

- High Vpi of SiP modulator is a challenge for driver power dissipation and scaling to higher baud rates
  - SiP modulators may not be good choices within data centers

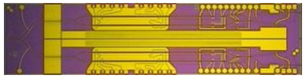
InP Modulator Integration Evolution

2008 2013 2014 2015 2016 2017 2018 2019 2020

20 Gbaud
QPSK MZ

Multi-MZ
PIC

32 Gbaud
MZ-SOA

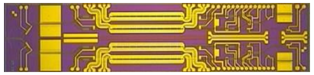


SOA
integration

AlQ
materials

100/200G Coherent Transmission

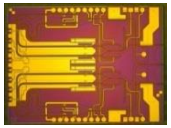
64 Gbaud
MZ-SOA



High bandwidth
Design
SI wafer process

100/200G ULH and 600G Metro/Edge

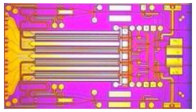
43 Gbaud
fold MZ-SOA



200G Low power compact

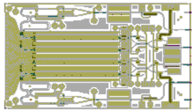
Folded
architecture

64 Gbaud
fold MZ-SOA



400G CDM

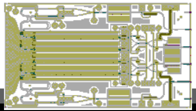
High-temp
Low-dissipation



400G Low Power

100Gbaud
wafer process

100 Gbaud
fold MZ-SOA



1T single λ

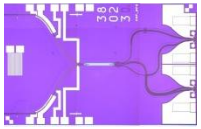
Accelerating InP modulator PIC development

- Increasing integration and functionality
- Higher modulation rates
- Low cost optics architecture
- Efficiency improvements

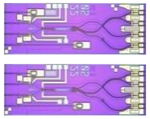
InP Receiver PIC Integration Evolution

2011 2013 2014 2015 2016 2017 2018 2019 2020

20Gbaud QPSK Rx



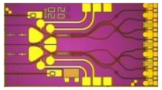
32Gbaud Rx



100/200G Coherent Receiver

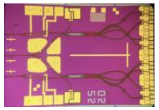
Miniaturisation

64 Gbaud Dual-Rx



100-600G Coherent Receiver

Integration

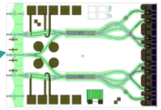


100-400G Compact

Integrated VOA

100 Gbaud Rx

100Gbaud wafer process



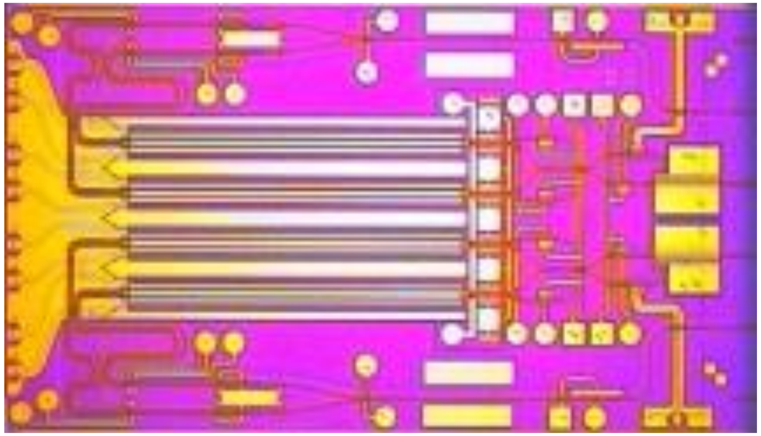
1T single λ

Accelerating InP modulator PIC development

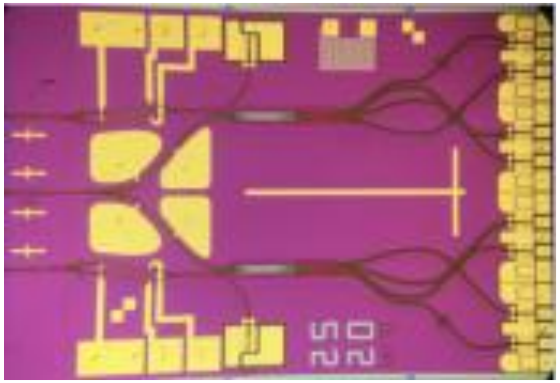
- Increasing integration and functionality
- Higher modulation rates
- Low cost optics architecture

64 Gbaud Tx & Rx dual channel 400G today

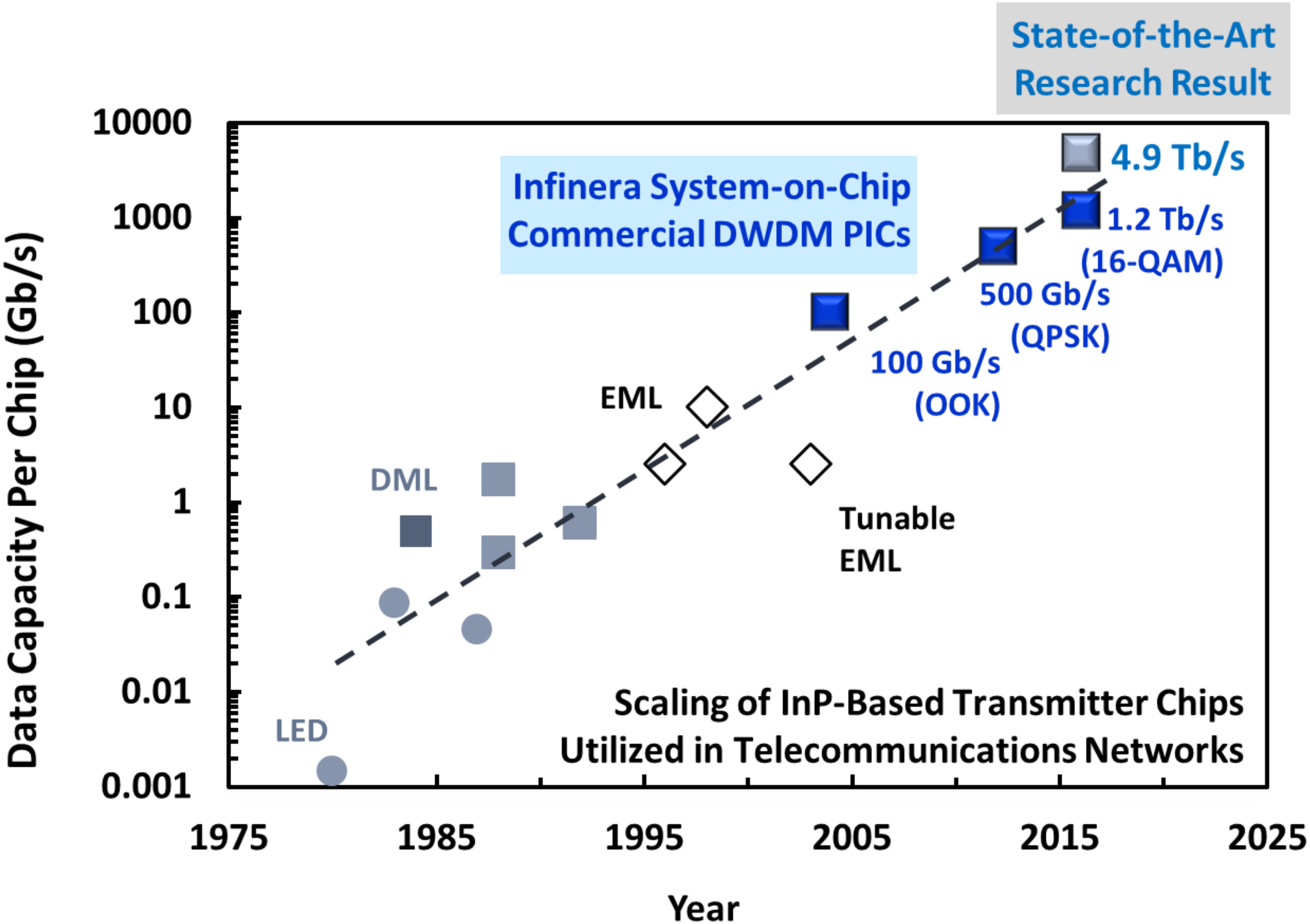
Folded MZ-SOA Tx



Integrated Compact
Rx/VOA



Data Capacity Scaling in The Network



Photonic Module Evolution

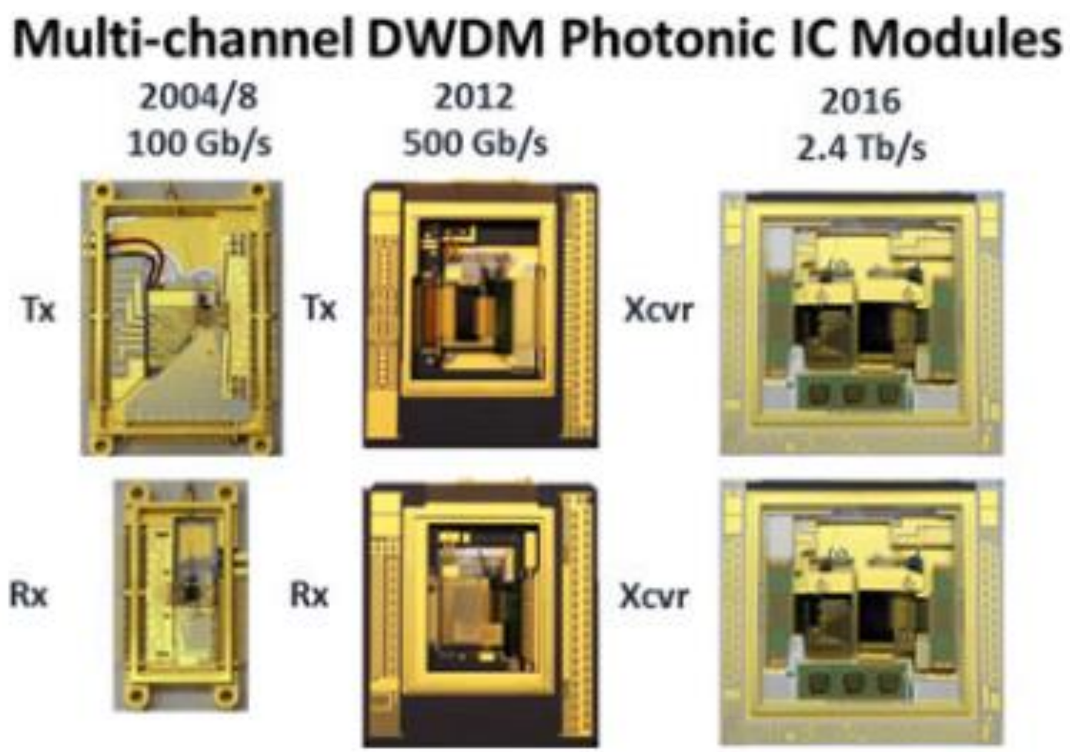
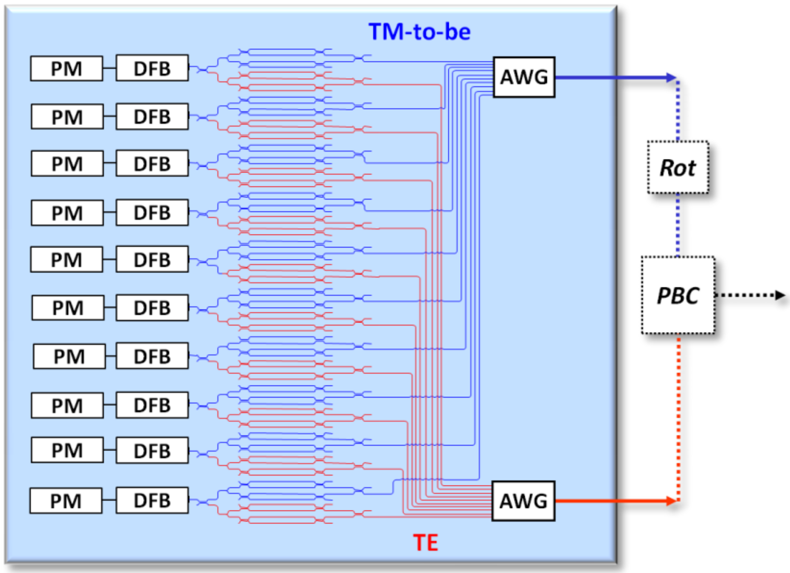


Fig. 21. Scaling of four generations of multi-channel DWDM SOC photonic IC modules. From their first commercial deployment in 2004 to 2016 (12 years), the data capacity of these modules has scaled 24x in roughly the same footprint (images shown to scale).

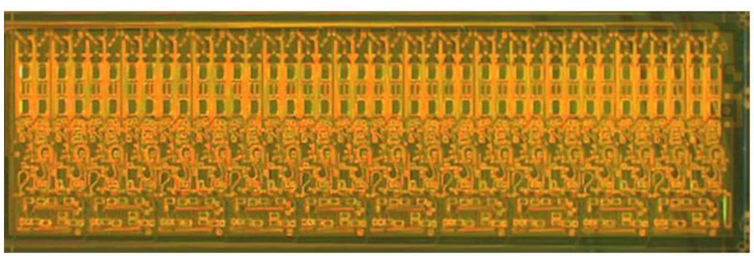
 F. Kish, et al, *JSTQE*, **24** (1) 2018

2011: 500 Gb/s PM-QPSK Coherent PICs

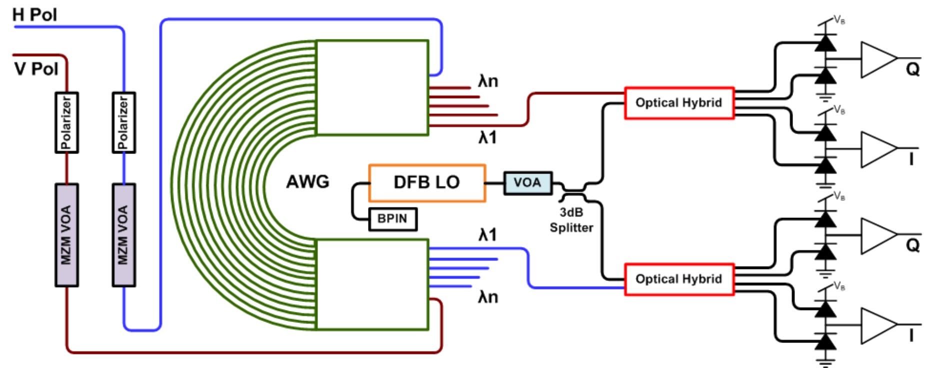
Tx PIC Architecture (5 x 114 Gb/s)



- > 450 Integrated Functions
- 8 Different Integrated Functions

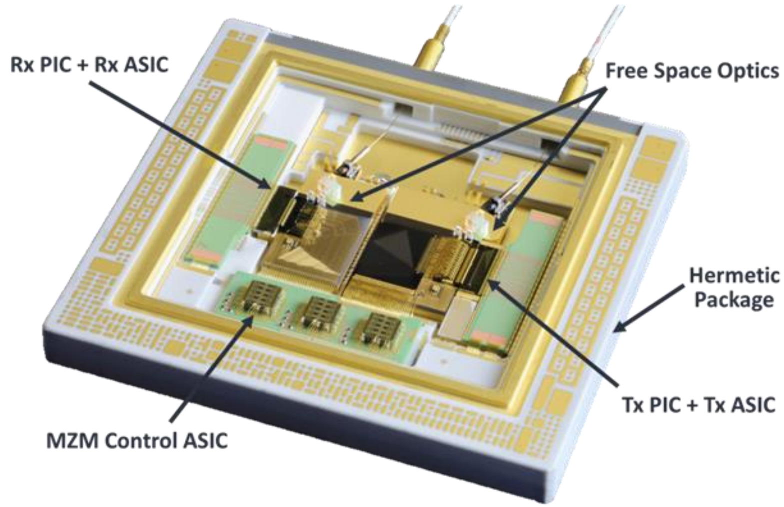


Rx PIC Architecture (5x 114Gb/s)

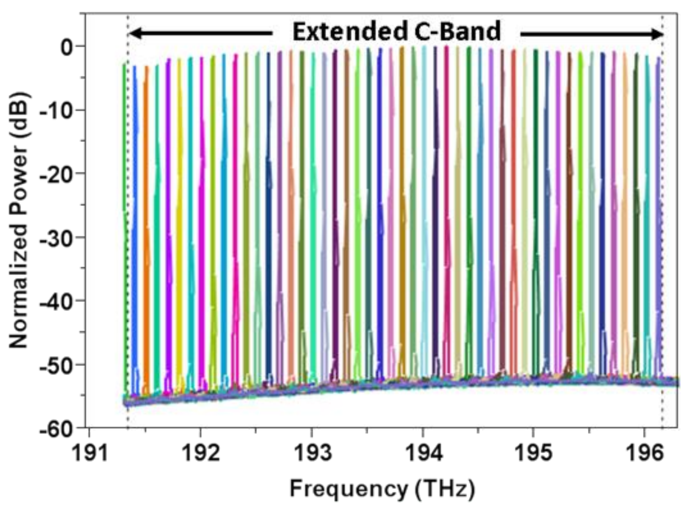


- > 150 Integrated Functions
- 7 Different Integrated Functions

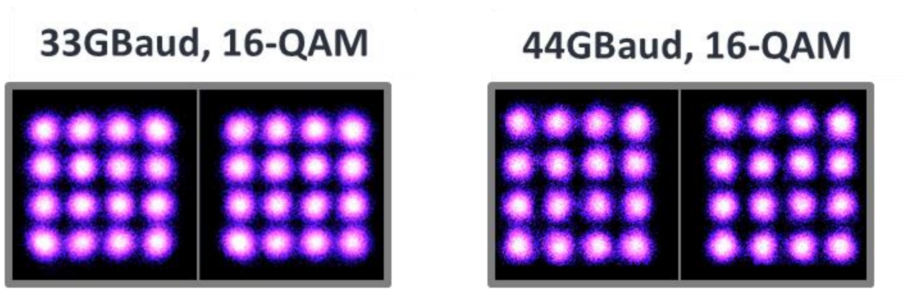
2016 : 1.2Tbps Extended C-Band tunable coherent 32GBaud/16-QAM coherent Transceiver



- **1.2 Tbps, 6-Channel transmitter and receiver PICs in single Module**
- **Independent extended C-Band tunable channels**
- **200Gbps per channel (33GBaud/16QAM) capable to 1500km Reach.**
- **44GBaud data rate demonstrated**



Typical laser output spectrum



B2B Constellations

infinera

Back-to-back transmitter constellations on PIC with potential capacity of 4.9 Tb/s

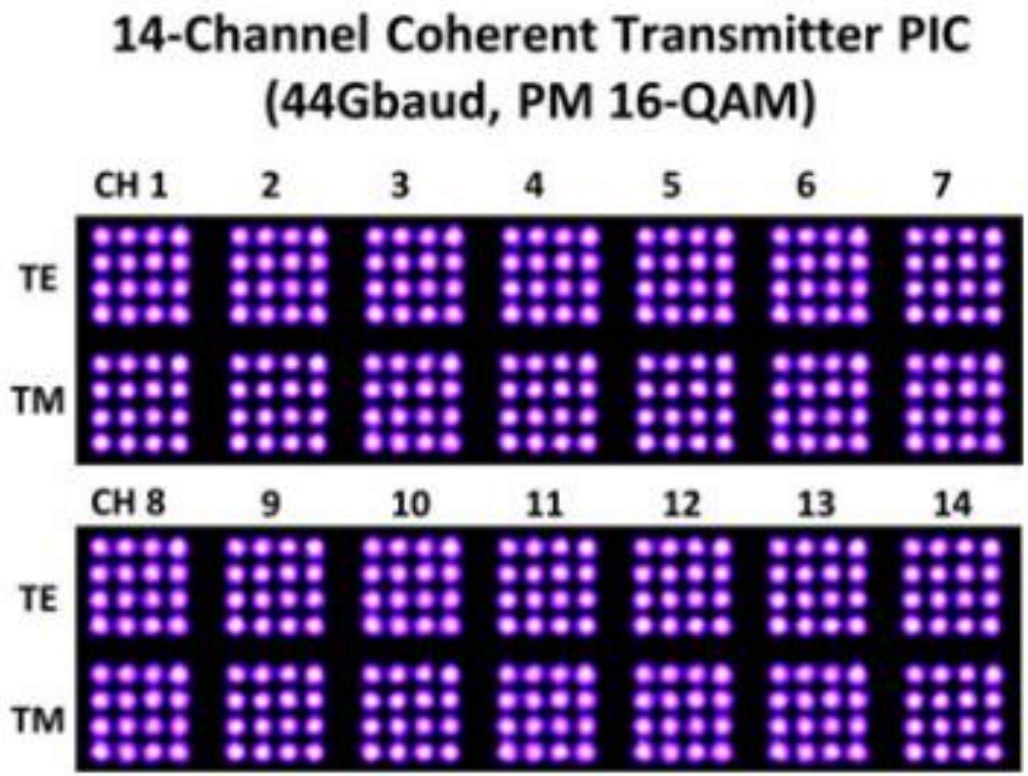
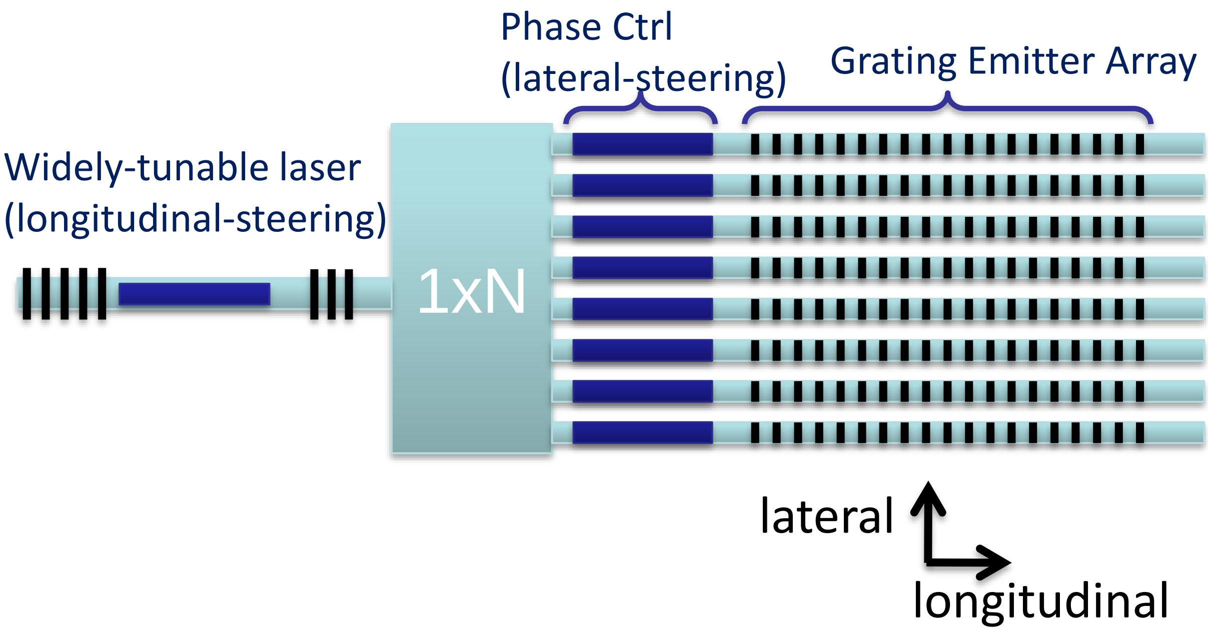


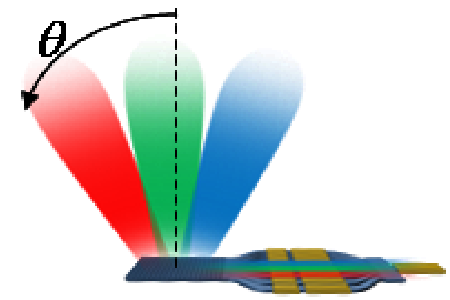
Fig. 19. Back-to-back 44 Gbaud constellations for PM 16-QAM modulation for all 14 channels on a SOC DWDM coherent transmitter PIC (measured using a companion widely tunable multi-channel receiver PIC). The figure shows only the outermost sub-carrier on each polarization for a dual-pol 16-QAM signal. The total capacity of this photonic IC is >4.9 Tb/s.

F. Kish, et al, *JSTQE*, **24** (1) 2018

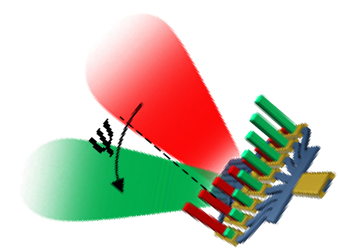
2D-Beam Sweeping

- **Our approach: 1D array + grating**
- **Scaling as N + 1, not N^2**





1 (wavelength)



N (number of waveguides)

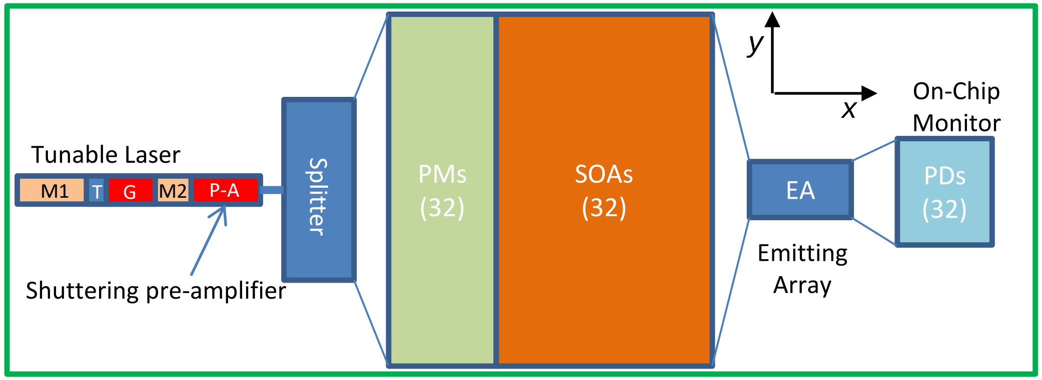
- **Lateral beam-steering via phase-shifter array, *ψ***
- **Longitudinal beam-steering via wavelength-tuned grating diffraction, θ**

W. Guo, et al, OFC '13, Mar. 21, 2013

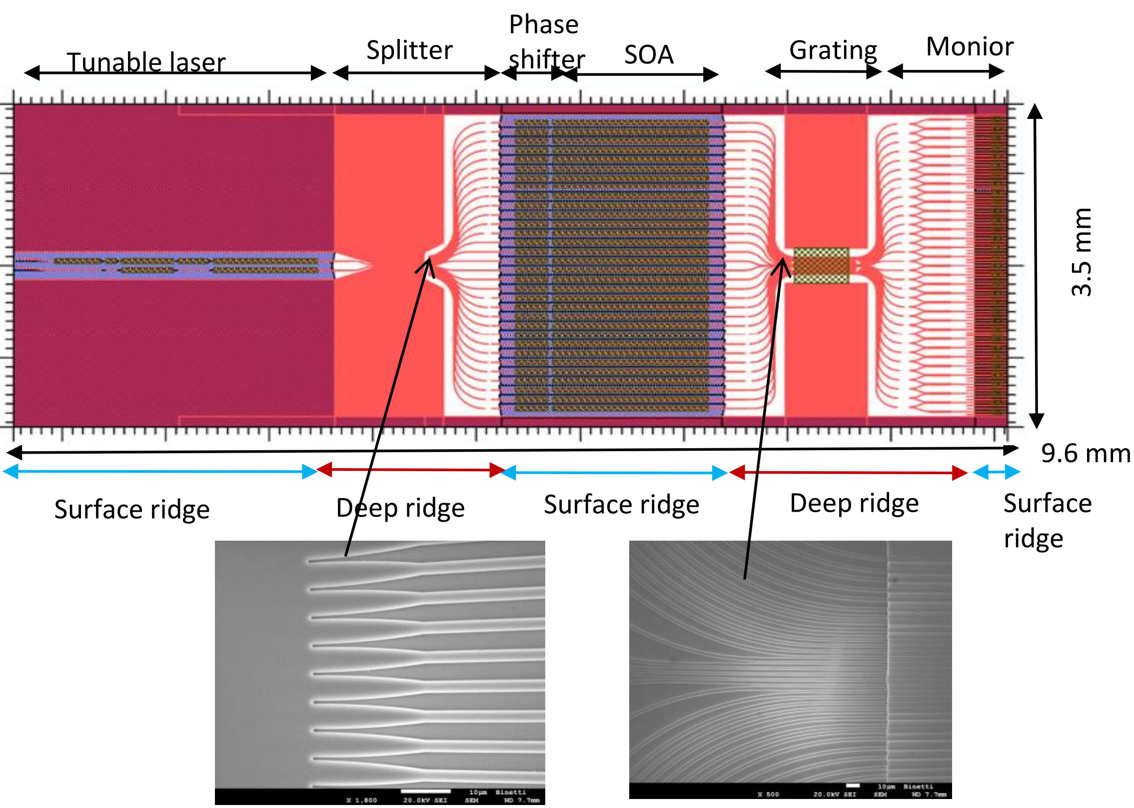
32 x N: Surface-emitting grating phased-array Optical Beam SWEEPER—InP-PIC

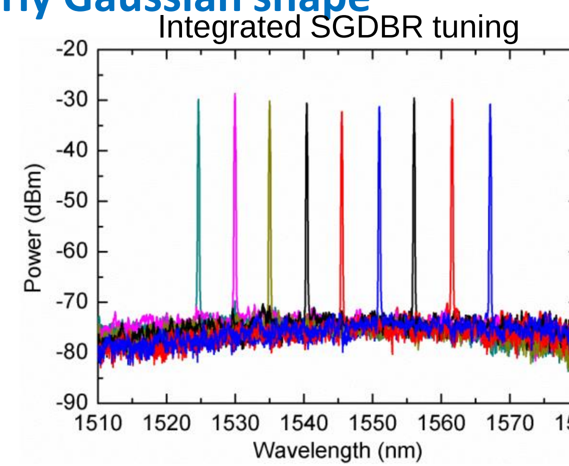
UCSB

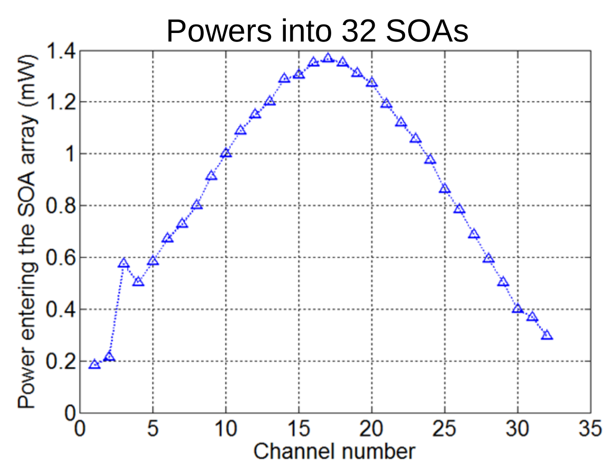
MOC 2018



- **Waveguide spacing varied to suppress lateral side lobes.**
- **Grating duty-factor weighted to extend effective length**
- **Nearly Gaussian shape**





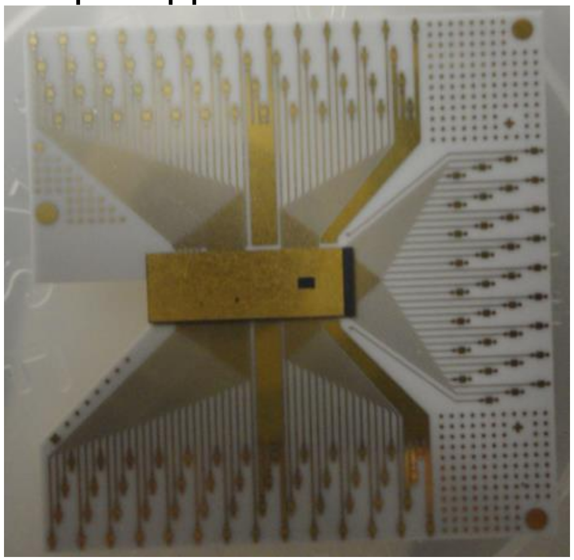


2D Beam Sweeping results (32 x N)

UCSB

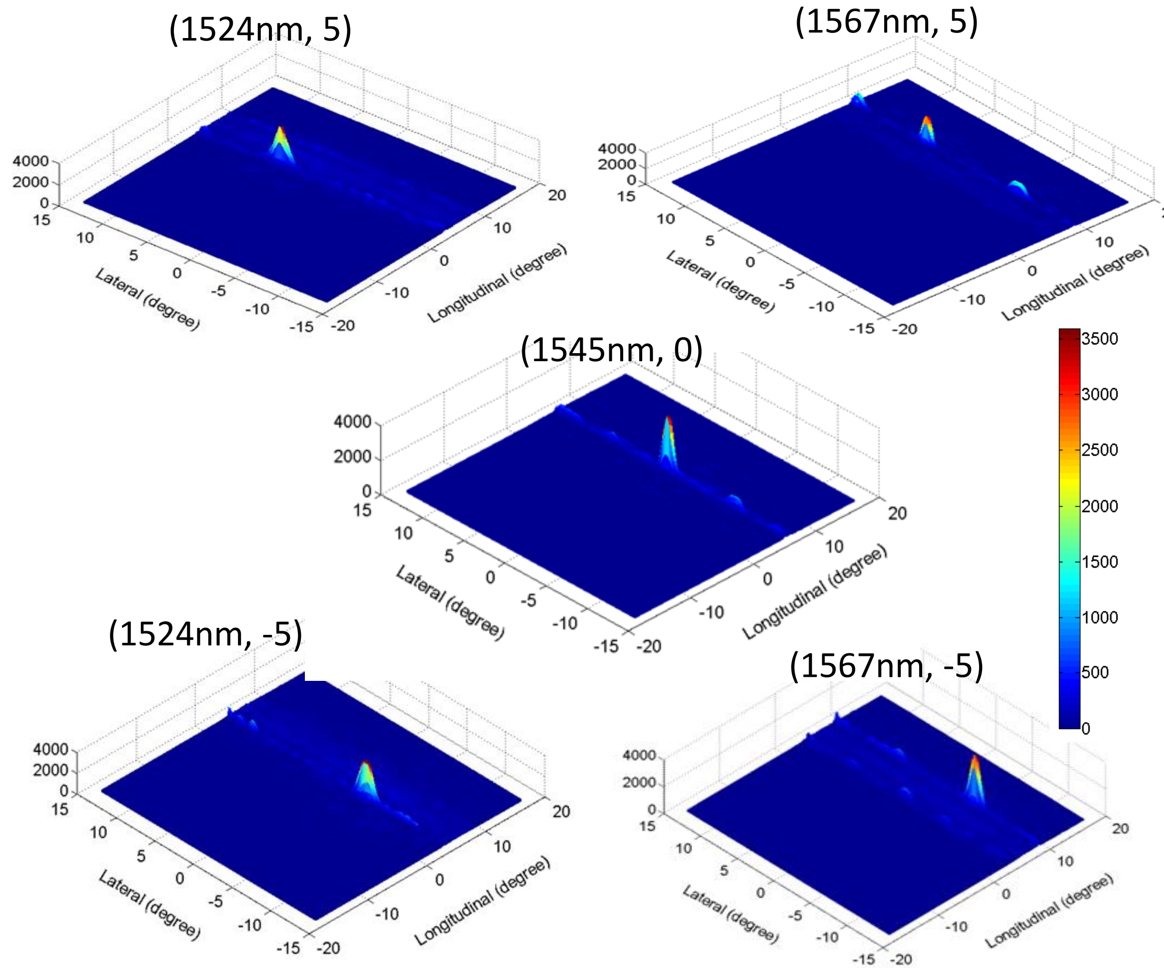
MOC 2018

Flip-chipped PIC-on-carrier

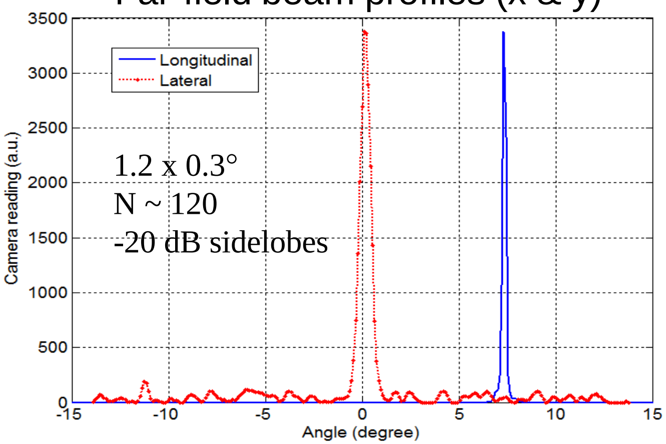


110 good contacts

• 2D beam steering demonstrated



Far-field beam profiles (x & y)



W. Guo, et al, *OFC '13*, Mar., 2013

MOABB LIDAR Project (2016→)

Similar sweeping concept, but wider angles & larger arrays + LIDAR

Phase 1 Cell

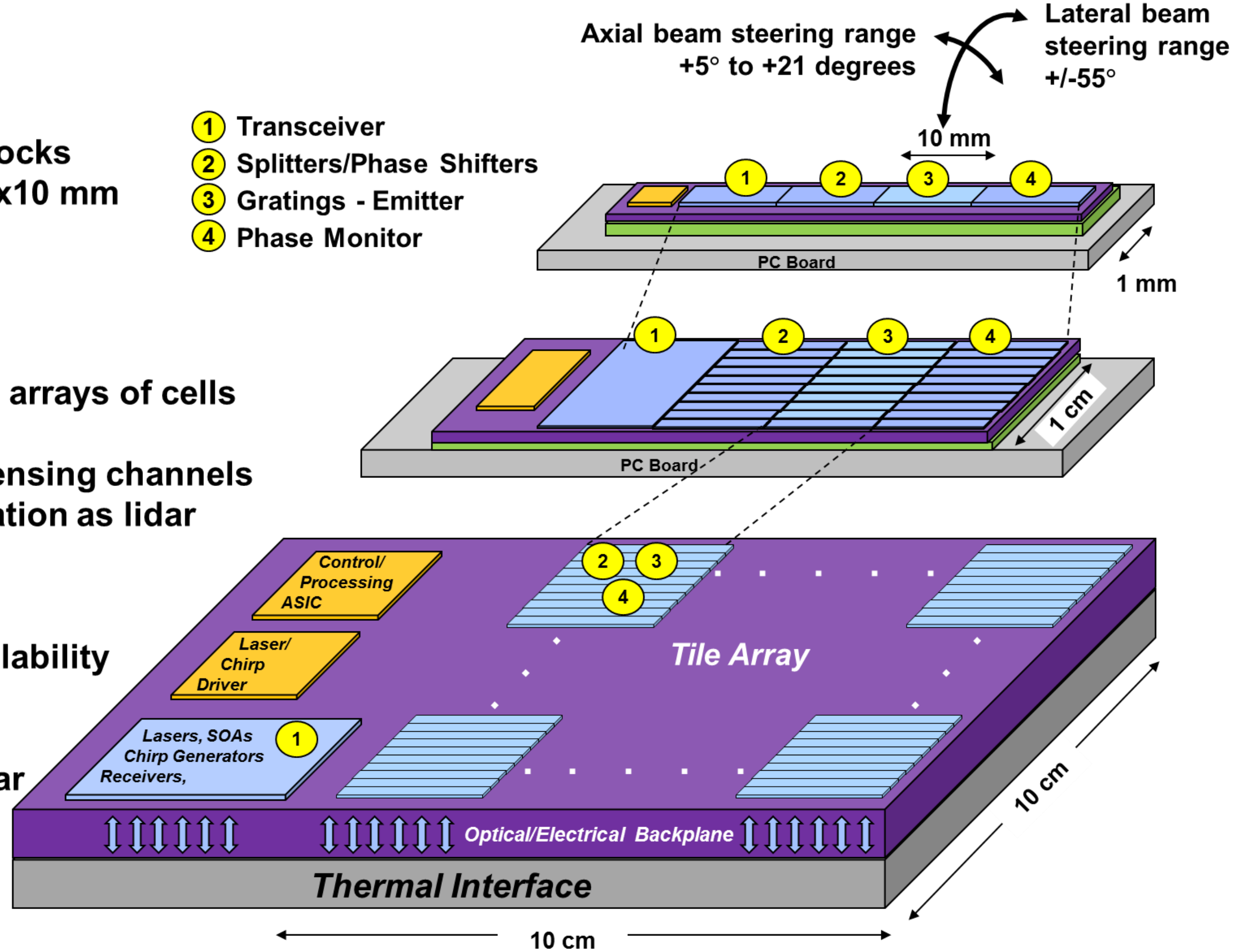
Demonstrates all key building blocks
Demonstrates full operation of 1x10 mm emission aperture cell

Phase 2 Tile

Demonstrates ability to generate arrays of cells operating as coherent apertures
Demonstrates 16 independent sensing channels
Demonstrates Phase 1 cell operation as lidar

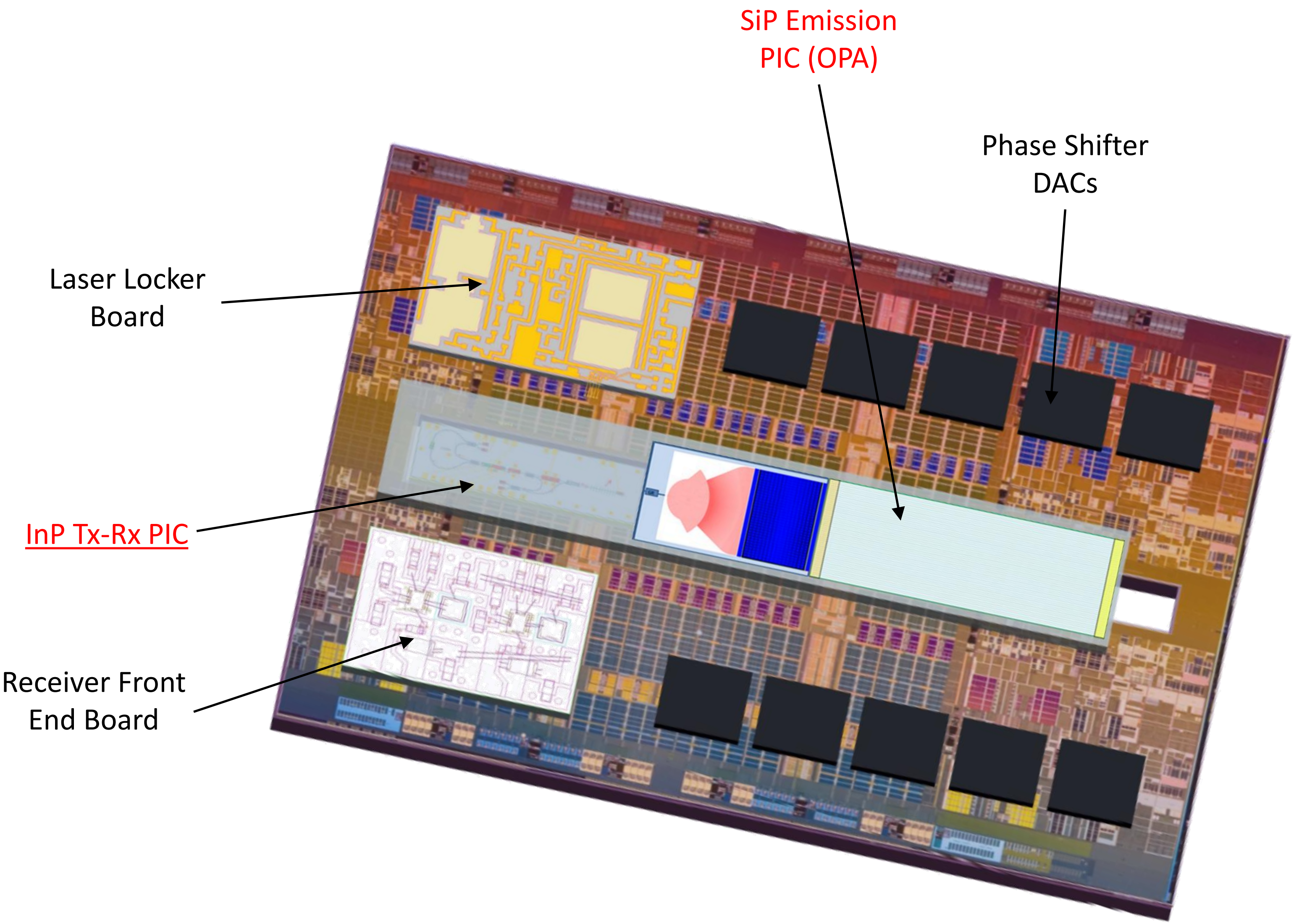
Phase 3 Multi-Tile

Demonstrates large aperture scalability
Stacks PIC layers 2-4 vertically
Integrates PICs, ASICS in 3D
Demonstrates Phase 2 tile as lidar



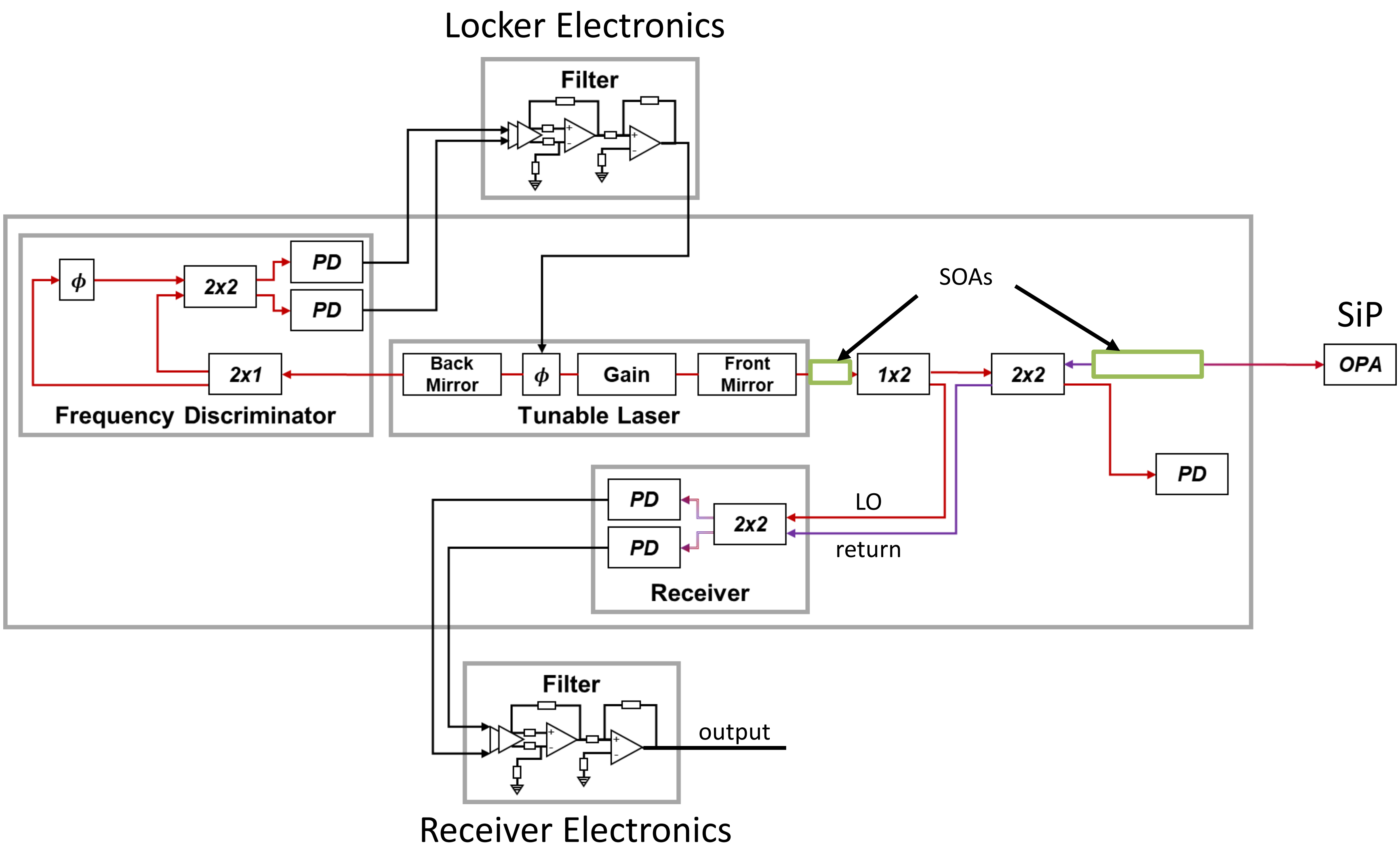
MOABB Mock-up Showing InP and SiP PICs

Phase 1:



Schematic of InP Transceiver PIC

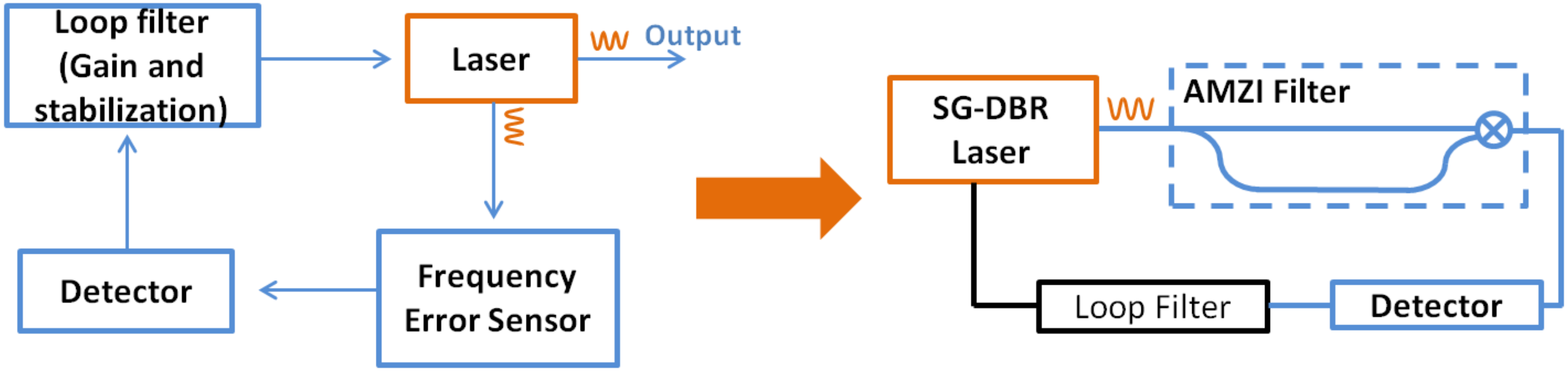
FMCW LIDAR Transceiver

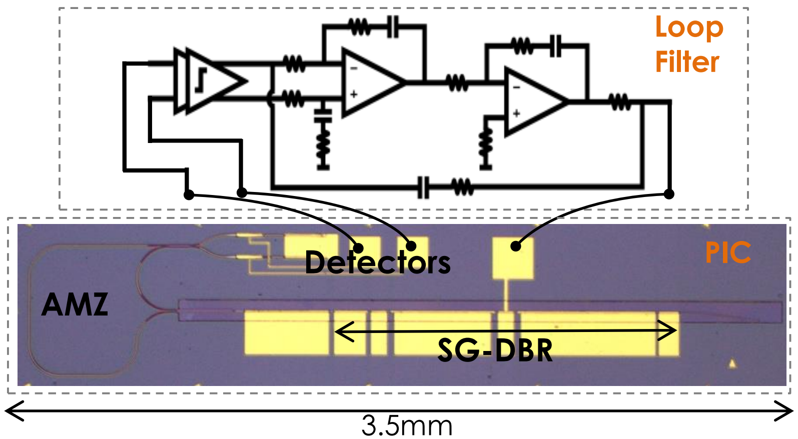


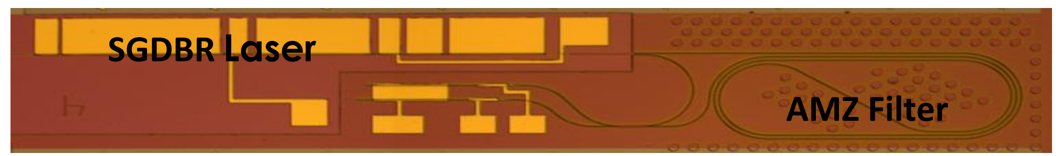
Prior work showing linewidth reduction with optical frequency locked loop

UCSB

MOC 2018

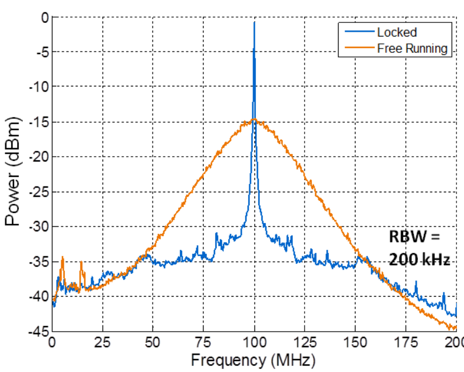


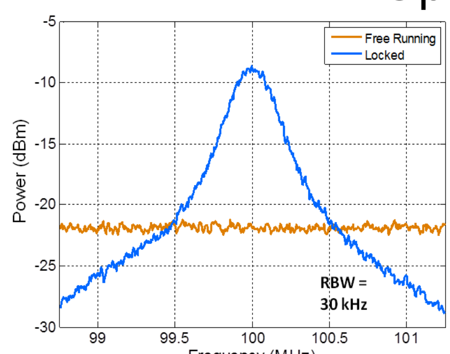




Balanced Receiver

- Laser – SGDBR (40 nm tunability)
- Frequency Error Sensor – Asymmetric MZI
- Filter FSR = 10 GHz
- Open loop tuning-to-lock in 30 ns

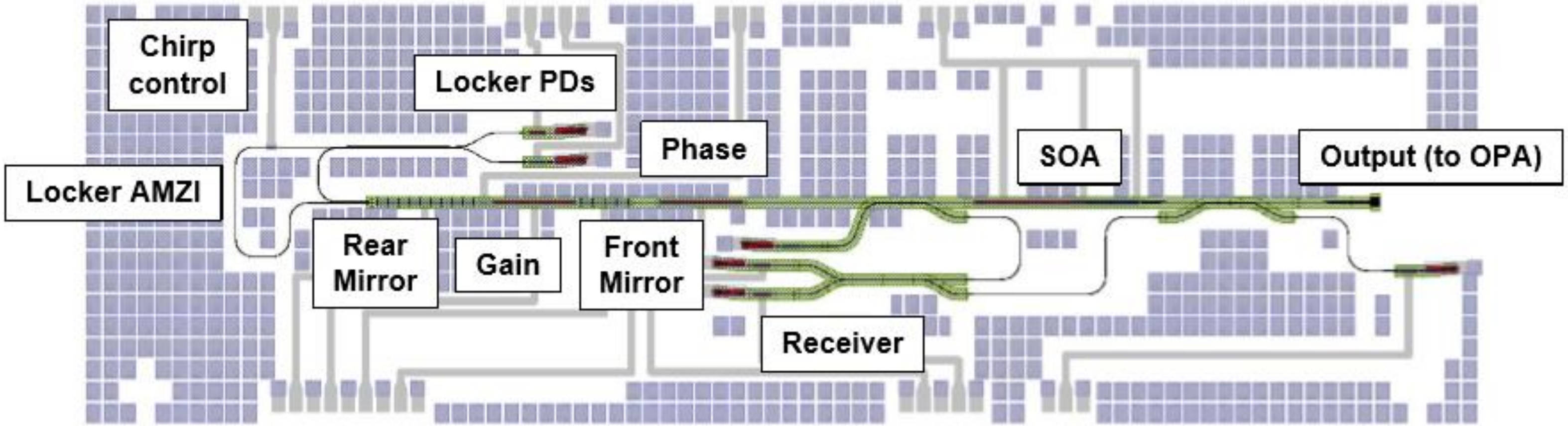




- Open loop→ > 5MHz linewidth
- Closed loop →150 kHz linewidth

A. Sivananthan, et al, OFC, 2013

InP Transceiver Mask Layout



Design features

✓ **Fully integrated frontend transceiver**
- Maximizes coupling between sections, avoids optical isolators

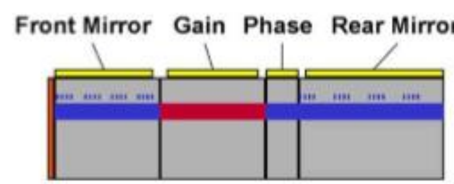
✓ **Sampled Grating DBR laser (SGDBR)**
- Proven widely tunable laser technology

✓ **Dual use laser for transmitter and LO**
- Balanced detection for common mode rejection

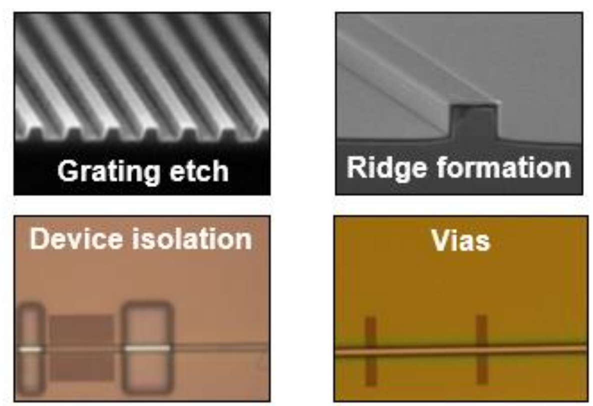
✓ **Asymmetric Mach-Zehnder interferometer (AMZI) locker**
- Stabilizes wavelength and provides stable chirp for laser

✓ **Integrated semiconductor optical amplifiers (SOAs)**
- In-situ monitoring, power amplifier, blanking during wavelength tuning, diode-based temperature sensor

Sampled Grating DBR laser



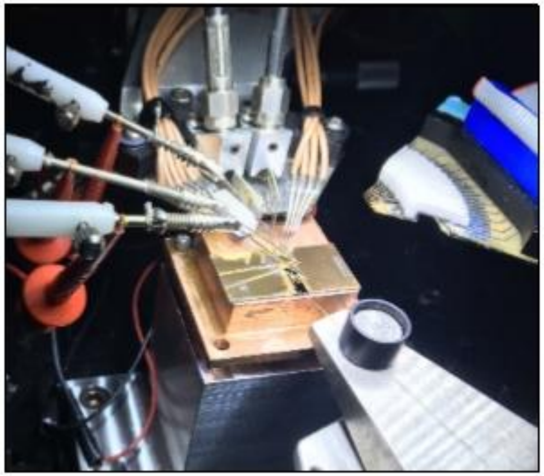
Critical Fabrication steps



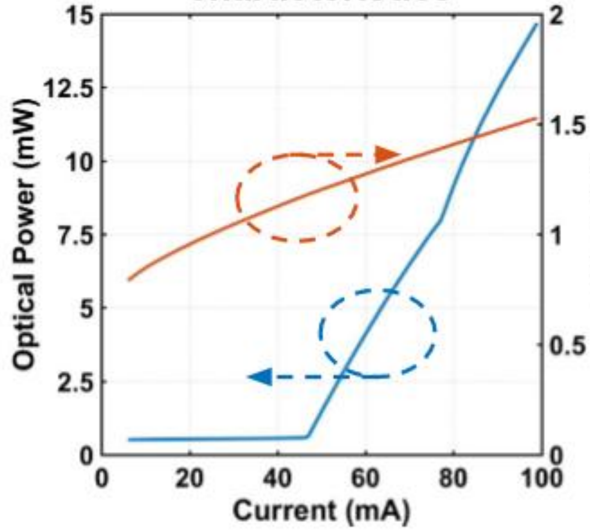
SGDBR Laser Performance

LOCKHEED MARTIN

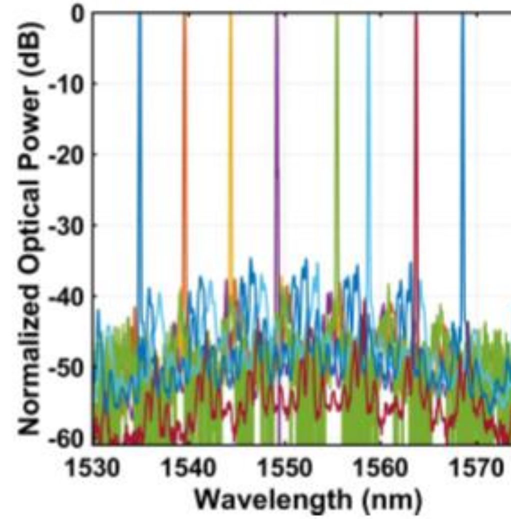
PIC on carrier under test



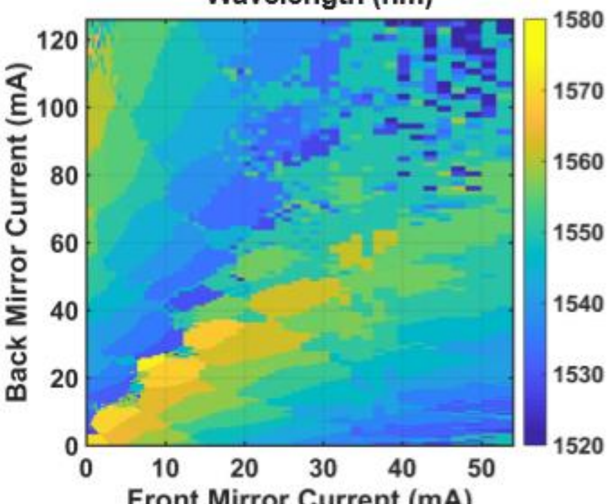
Light-current-voltage characteristics



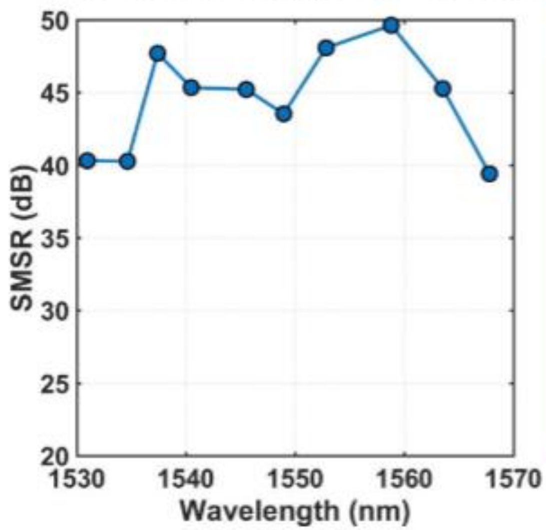
Overlaid lasing spectra



Wavelength tuning map



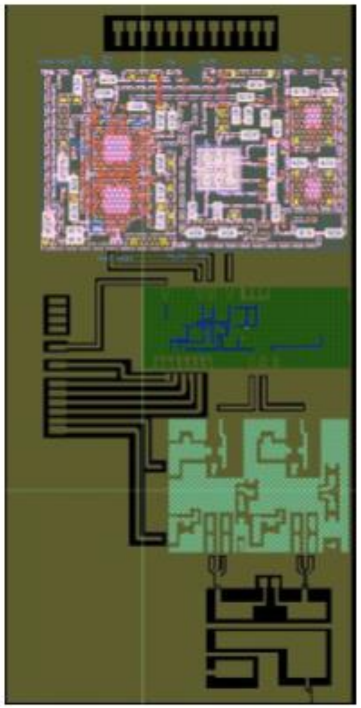
Side-mode suppression ratio



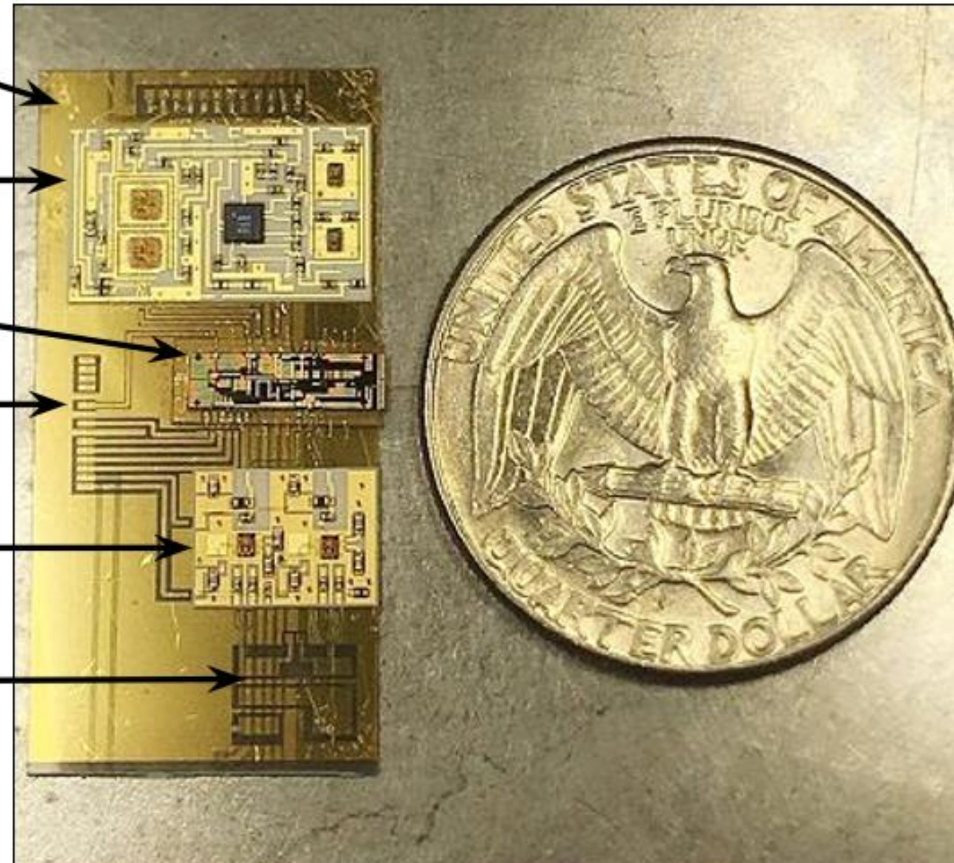
- Custom automated testbeds built for all measurements
- Typical laser performance:
  - Threshold current ~45-70 mA
  - Output power ~15 mW at 100 mA
  - Tuning range ~40 nm
  - SMSR ~40-50 dB
- Maps can provide lookup table for laser tuning

Transceiver with Locker and Receiver Circuits

Layout



Fabricated Module



InP transceiver PIC mounted on AlN PIC subcarrier, then mounted on supercarrier with locker and receiver circuits/boards

Locker and Receiver PD outputs

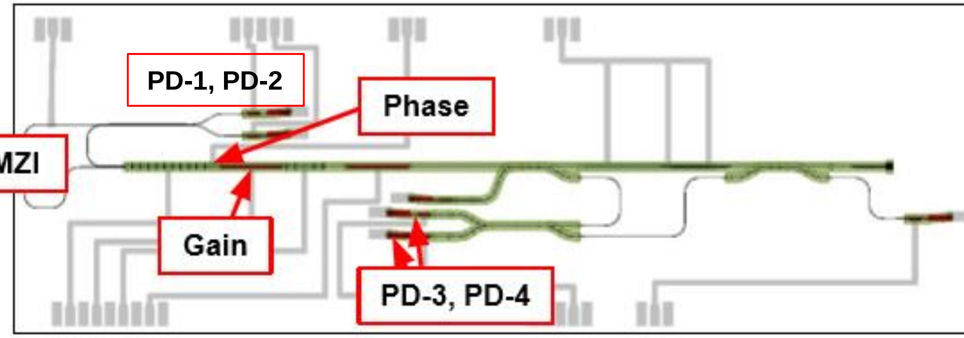
Test 1: Laser and PIC DC characteristics
- SOA-1 used to measure laser LI characteristics
- PD-1 and PD-2 used to measure AMZI response

Test 2: Locking functionality (Tune laser)
- DC bias the laser
- Sweep phase section and measure AMZI response

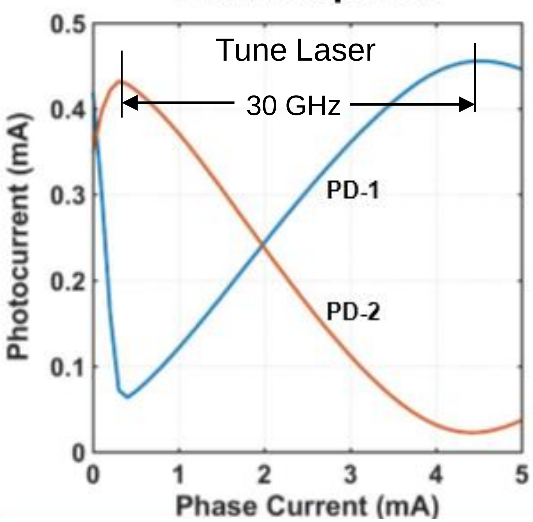
Test 3: Chirp control (Tune filter)
- Sweep chirp control current
- Measure chirp response with PD-1 and PD-2

Test 4: Receiver functionality
- DC bias the laser and sweep phase
- Measure receiver response with PD-3, PD-4

PIC Schematic

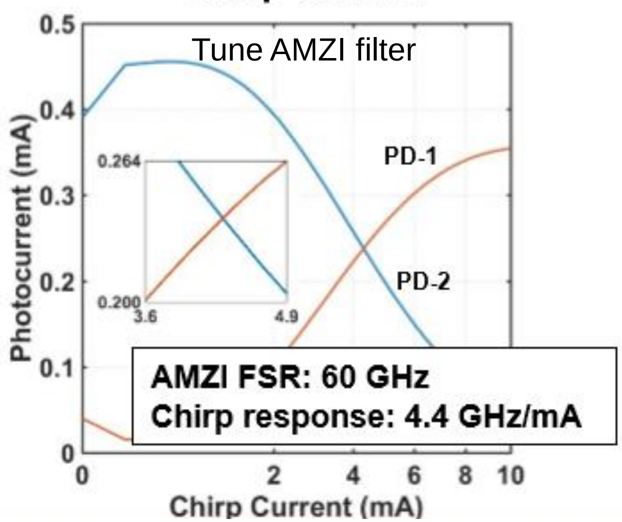


AMZI response



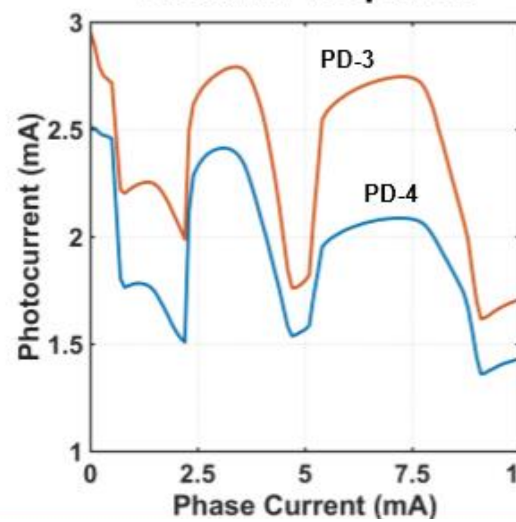
Laser frequency →
(Mode spacing= 45 GHz)

Chirp control



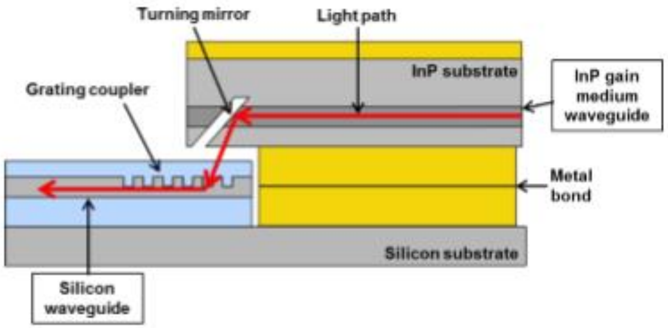
AMZI frequency →

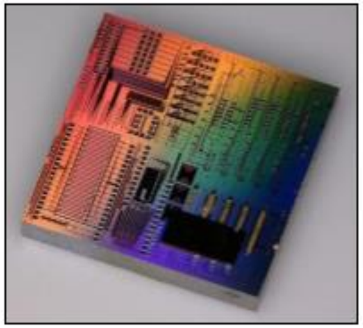
Receiver response

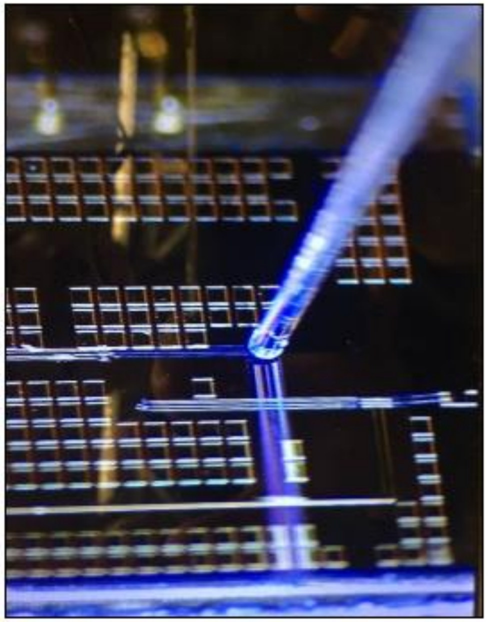


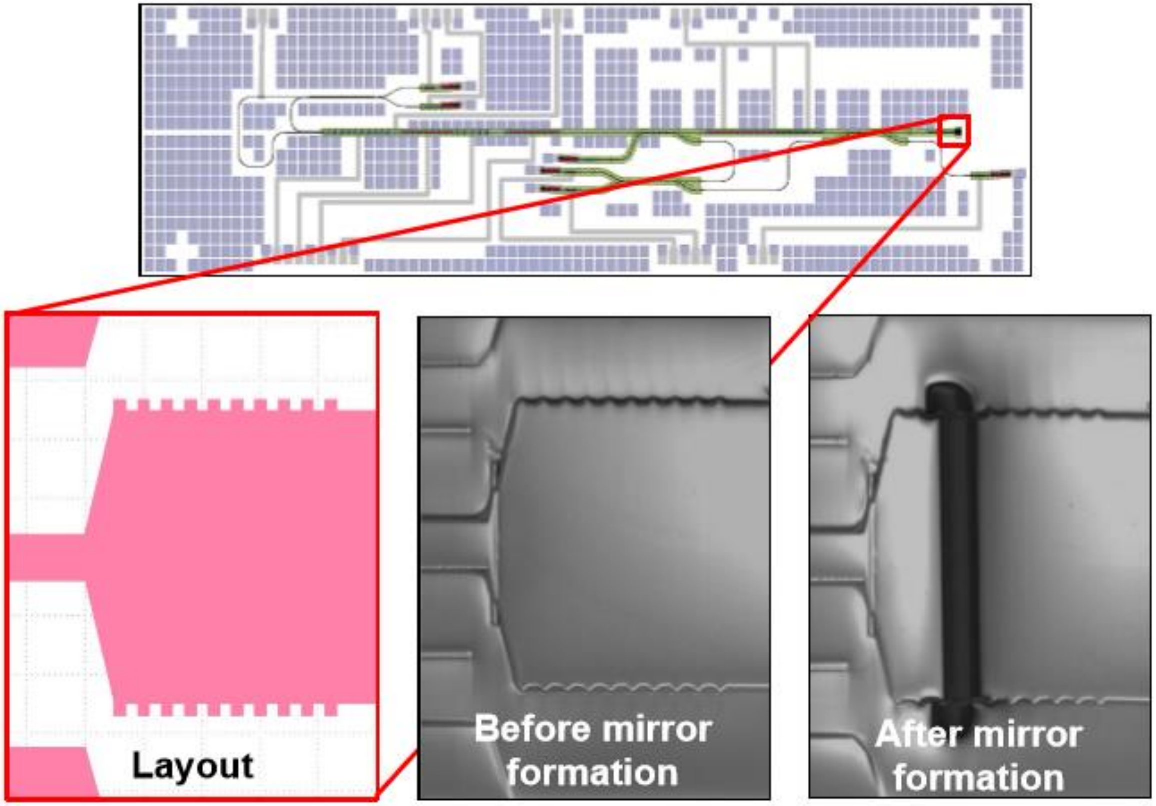
Laser frequency →

Output coupling to SiP emitter PIC

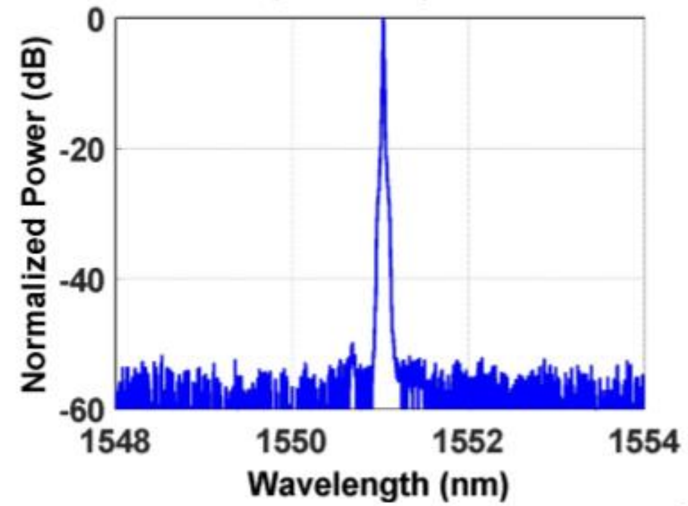






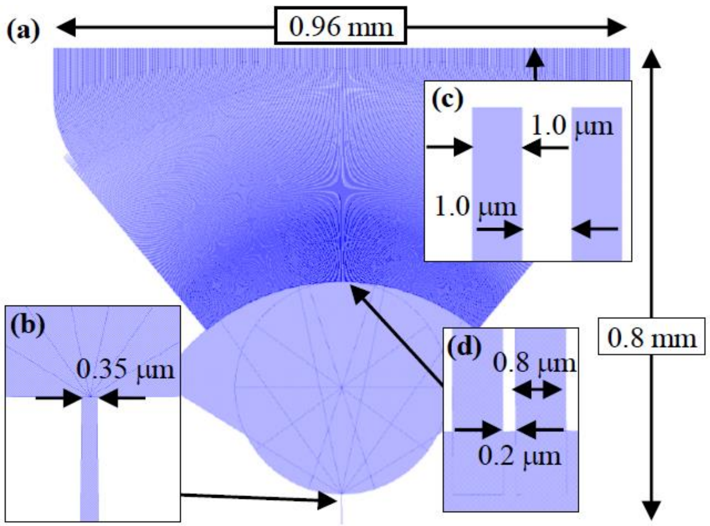


Laser signal coupled to fiber

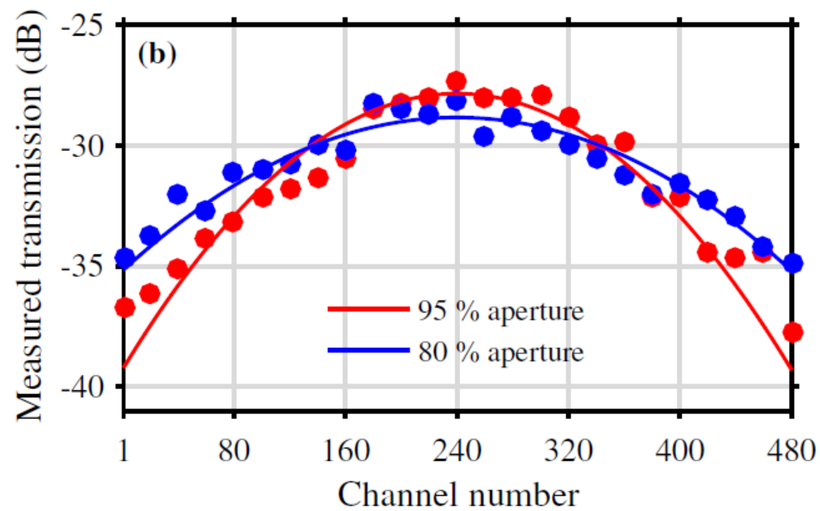


SiP—STAR Coupler

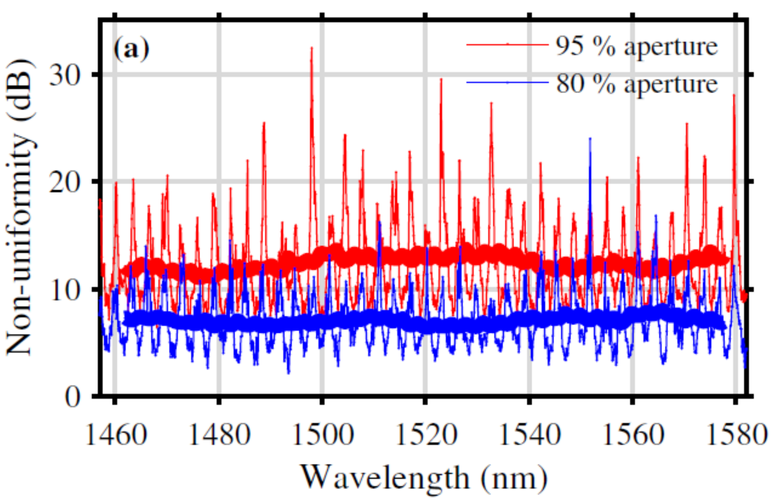
Design



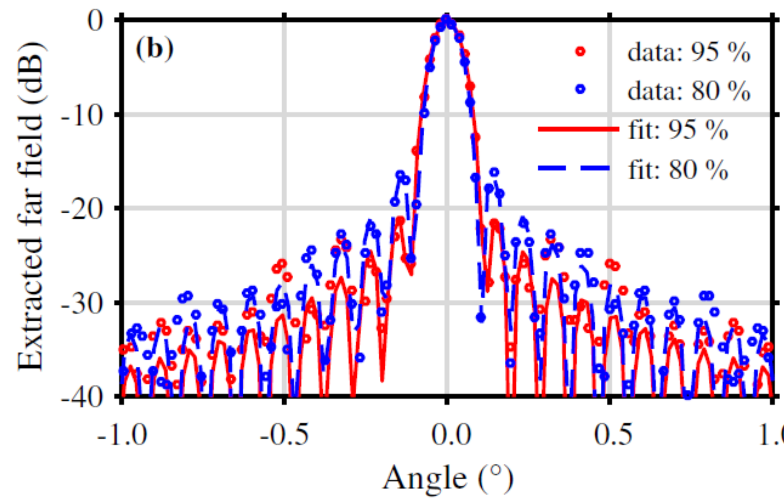
Power Distribution



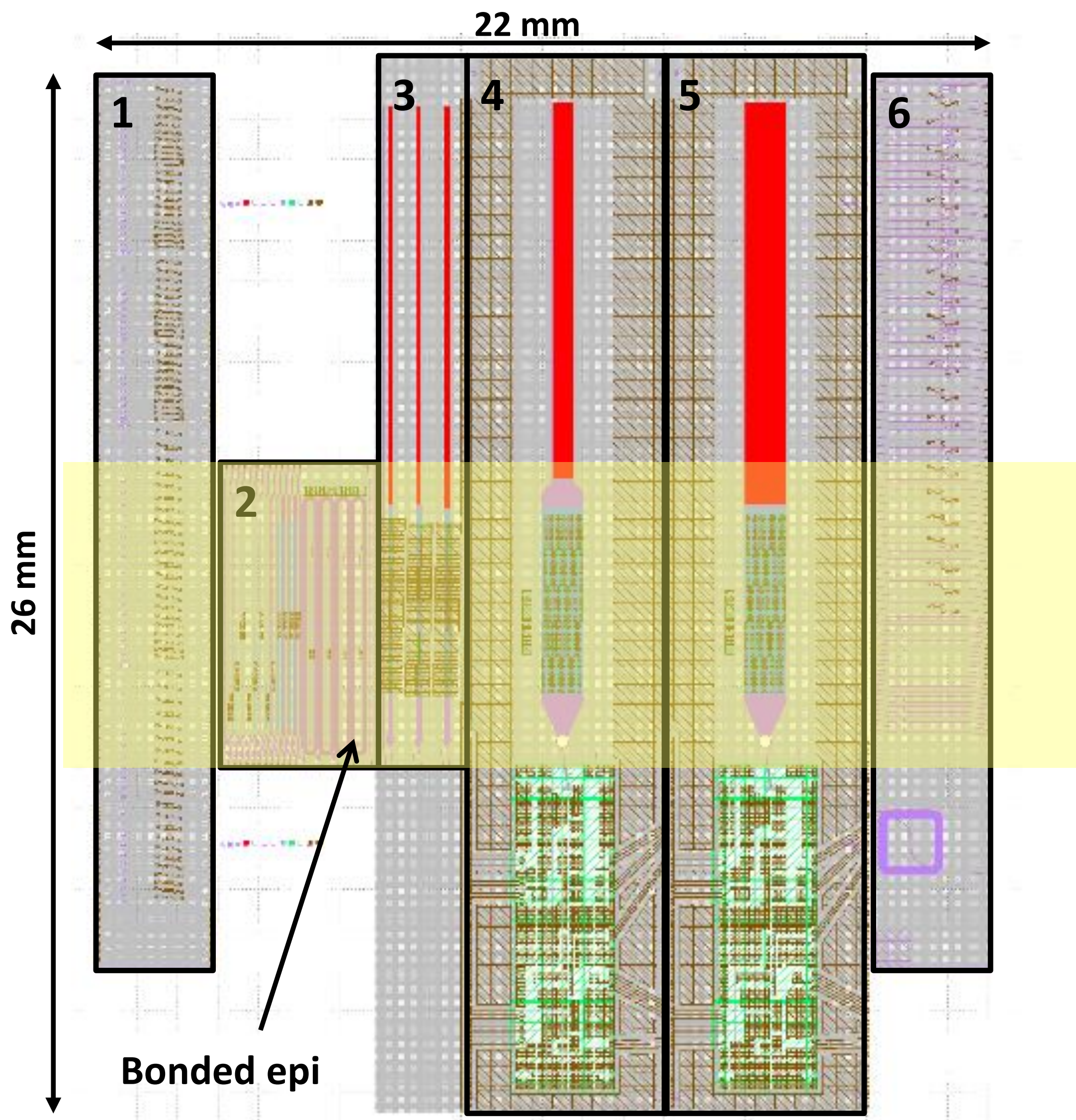
Wavelength Uniformity



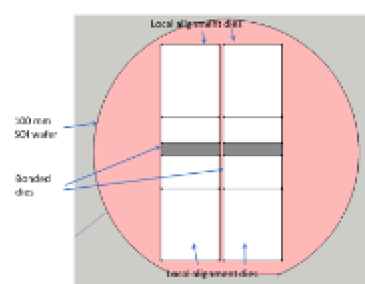
Far-Field Power Distribution



SiP-OPA full-run PIC



1. Deep etch: Directional couplers, ring resonators and loop mirrors test structures
2. Modulator test structures (MZI, loss spiral)
3. 32-channel devices (can be probed)
4. Reduced pitch 240-channel full device (to be bonded to interposer)
5. Standard pitch 240-channel full device (to be bonded to interposer)
6. Shallow etch: Directional couplers, ring resonators and loop mirrors test structures + loss spirals (both etch depths)



6 dies per 4 inch (100 mm) wafer

UCSB

Take-Aways

MOC 2018

- PICs are desirable for modest to high volume communication and sensing applications, where size, weight, power and cost (SWAP-C) reductions are desired.
- PICs are important because of the inherently stable phase relationships and possibly seamless interfaces between elements.
- PICs generally bring better reliability once properly designed; yield and some aspects of performance may be compromised, although other aspects can be improved.
- Although InP-PICs are currently being produced in higher volume, the use of SiP-PICs is growing more rapidly.