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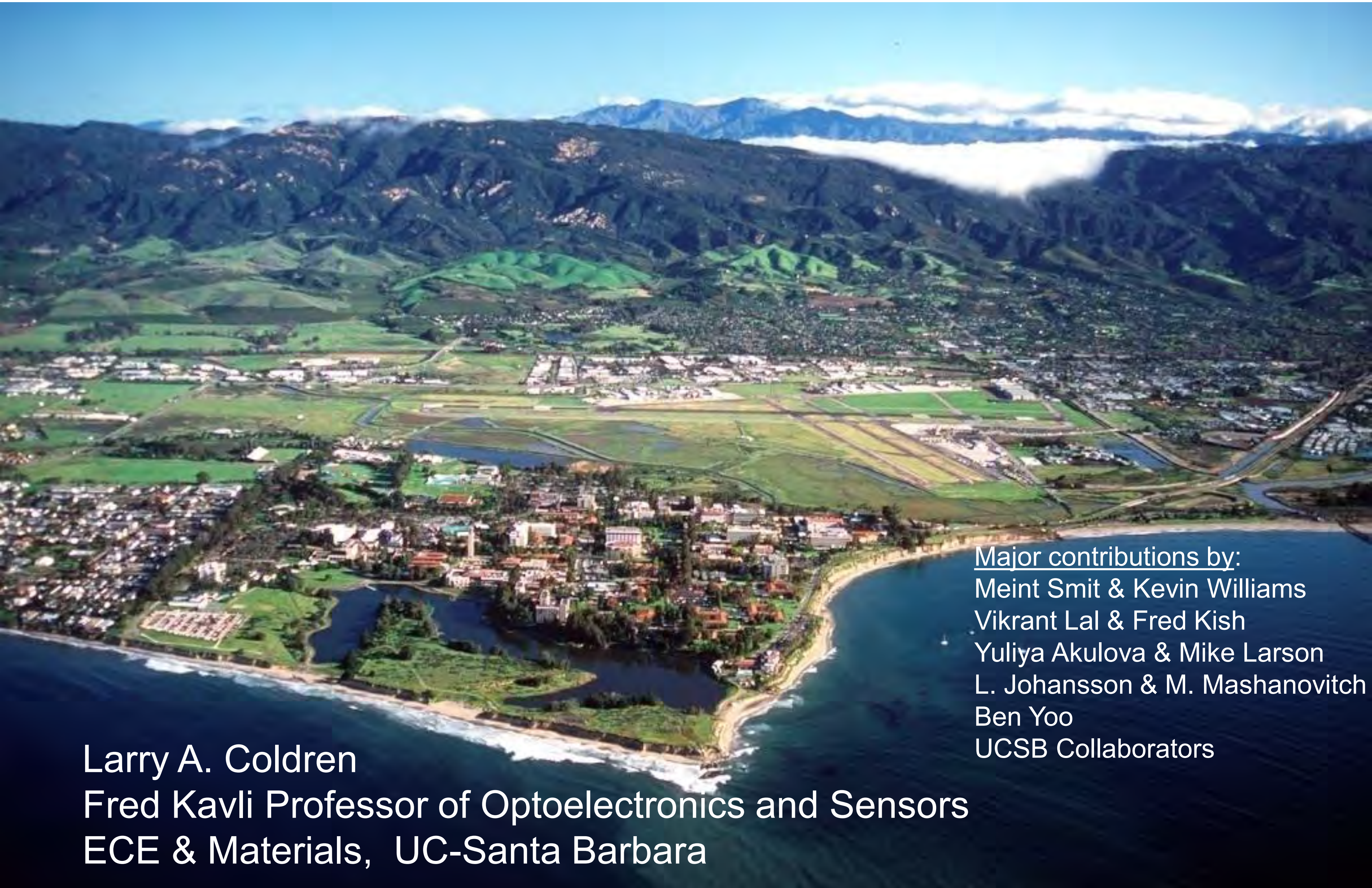
Indium-Phosphide Photonic-Integrated-Circuits



Major contributions by:
Meint Smit & Kevin Williams
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L. Johansson & M. Mashanovitch
Ben Yoo
UCSB Collaborators

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ECE & Materials, UC-Santa Barbara

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What’s the problem?

Size, Weight, Power, Cost, Performance, Reliability

Where?

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

Integration Platforms

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Indium Phosphide
- Excellent active components
- Mature technology
- Propagation losses for passive elements
- Foundries evolving

Silica on Silicon (PLC)
- Excellent passive components
- Mature technology
- Lack of active elements

Polymer Technology
- Low loss
- Passive waveguides
- Modulators
- No laser

Hybrid Solutions

Silicon Photonics
- Piggy-back on Si-CMOS technology
- Integration with electronics?
- Constantly improving performance
- No laser

"Heterogeneous Integration Technology"

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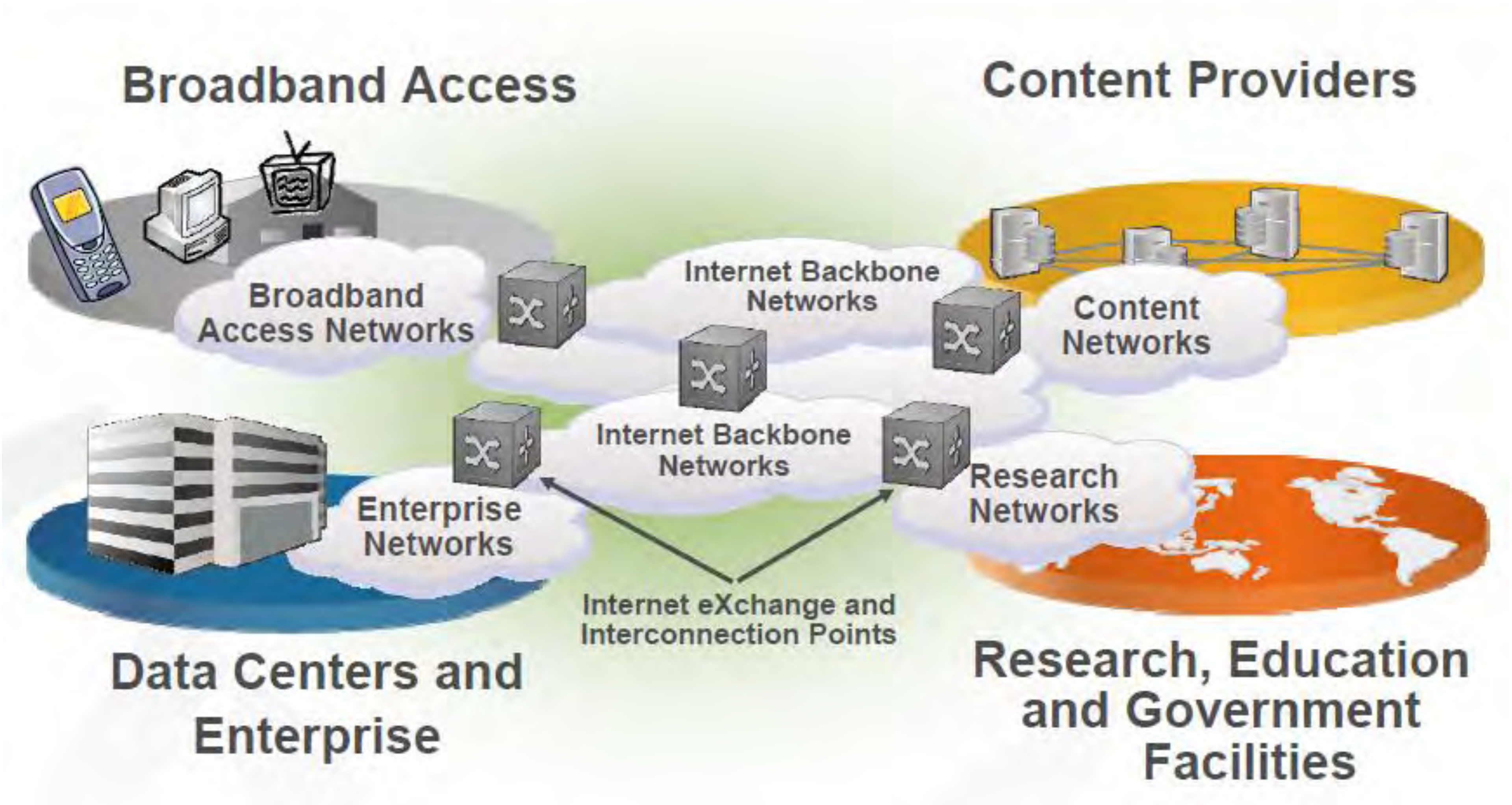
Introduction/Historical View—PICs

- 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, small-scale 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; improved VCSEL performance; heterogeneous integration approaches
- 2017 – Some delineations; InP-PICs for long-haul/metro; Si-photonics beginning to emerge in high-volume short-data/metro

Motivation

Communication Requires a Complex Network

- **The Ethernet ecosystem—it's nearly all optical (fiber)**
- **Need higher bandwidth & performance with lower SWAP-C**



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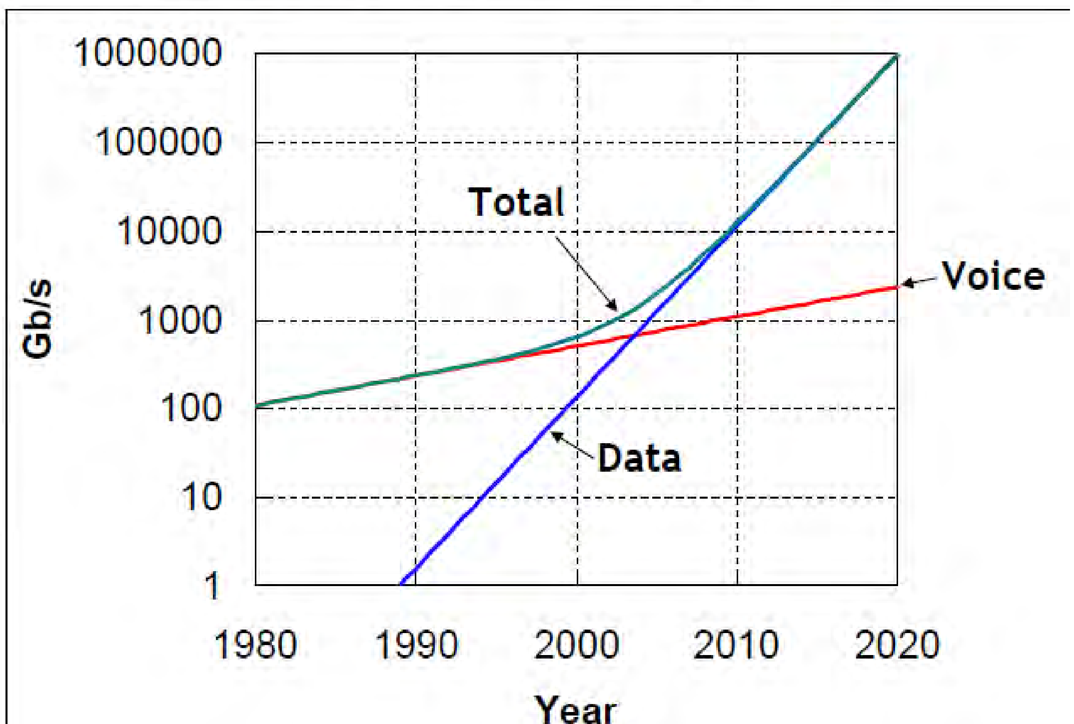
Data is King

Network Traffic (Including voice)



Exponential network traffic growth is driven by high-bandwidth digital applications

G4, Video-on-demand, HD-TV, wireless backhaul, cloud computing & services

Scaling spectral efficiency through WDM, Coherent, ?

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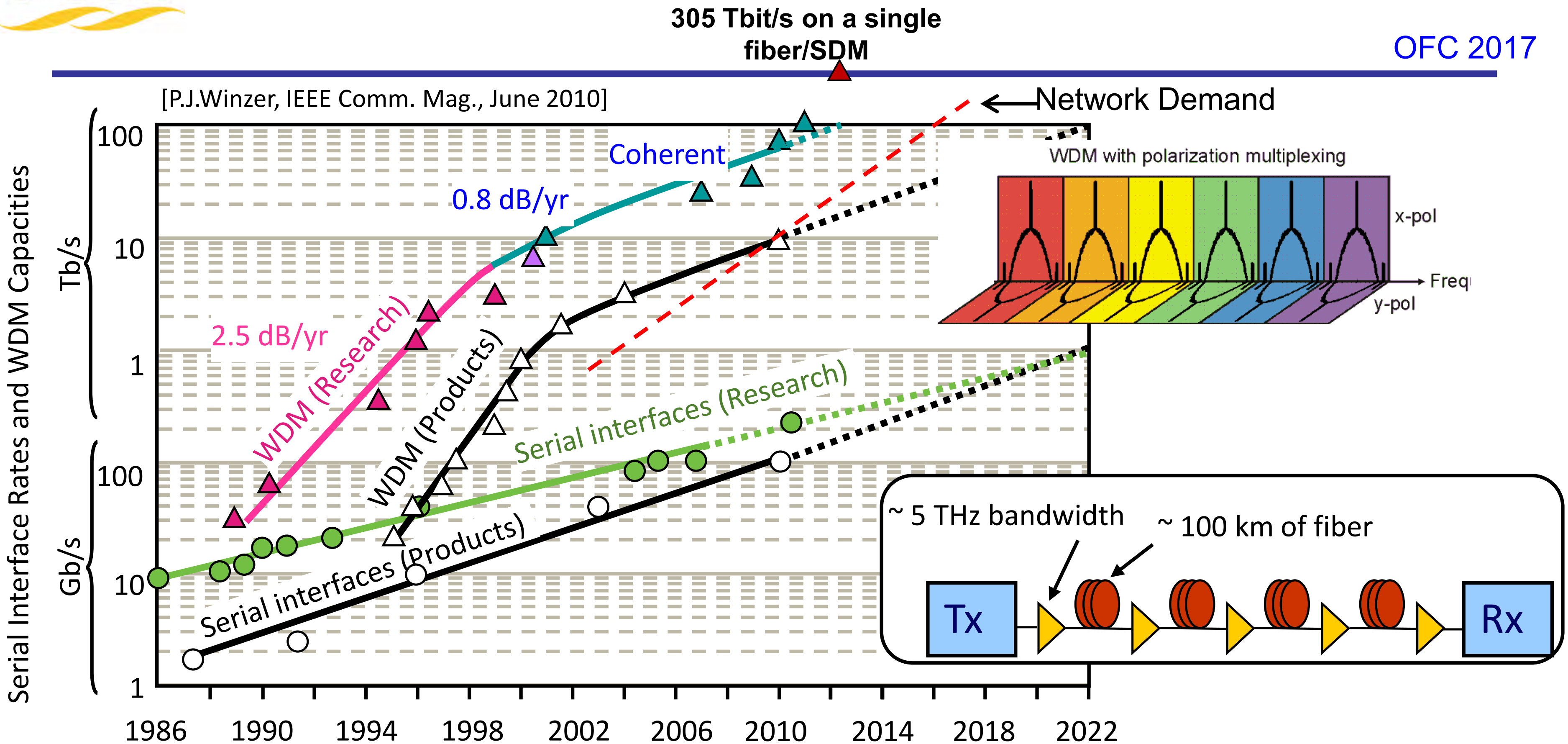

~10 Terabit/s WDM systems are now commercially available

~100+ Terabit/s WDM systems have been demonstrated in research (Coherent)

EDFA enabled WDM (wavelength division multiplexing)in 1990s

Growth of WDM system capacities has noticeably slowed down

Now “Space-Division-Multiplexing” (SDM) is being explored

Courtesy P. Winzer

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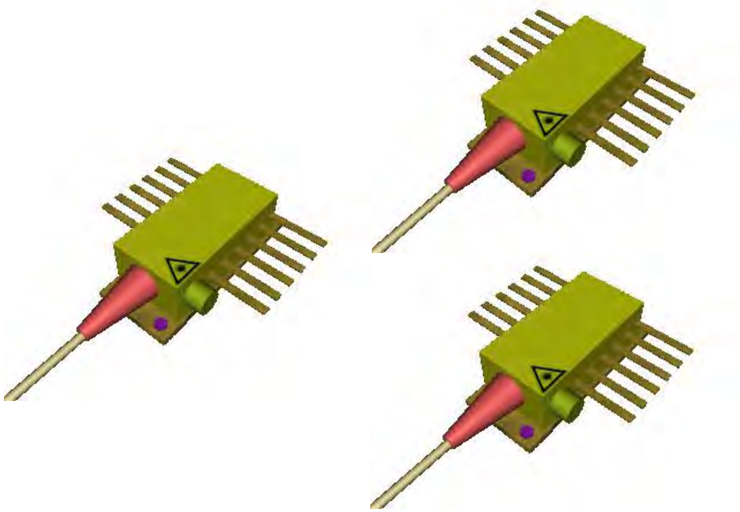
Motivation for Photonic Integration

- Reduced size, weight, power (SWAP)
- Improved <u>performance</u> (coupling losses, stability, etc.)
- Improved <u>reliability</u> (fewer pigtails, TECs, fiber alignment optics, etc…), although chip yield may not be highest
- Cost (in volume)

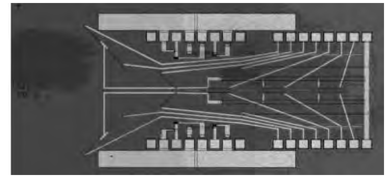


Horizontal and vertical integration possible
- <u>multiple functionality</u> and <u>arrays</u> of chips in one

After C. Joyner, infinera

Photonic integrated circuit (PIC) pros/cons

- Small footprint
  - No lenses between elements
  - Strongly confining waveguides



- Low power
  - Avoid 50-ohm lines (if close to electronics); only one cooler/PIC
- Performance
  - Cannot optimize components separately → need common design rules
  - Only one input/output coupling, but still need mode X-former or optics
  - Can usually avoid isolators on-chip, but still need at output
  - Phase delays for interference and feedback <u>stable and small</u>
- Low price (need large market to realize)
  - Fewer touch points
  - No mechanical adjustments—packaging still issue
  - Less test equipment
  - Less material

Based on C. Doerr inputs, *OFC* 2014,

InP vs Si vs PLC

	Performance		
Building block	InP	Si	TriPleX
Passive components	●	●●	●●●
Lasers	●●●	○	○
Modulators	●●●	●●	●
Switches	●●●	●●●	●
Optical amplifiers	●●●	○	○
Detectors	●●●	●●●	○

Performance	
●●●	Very good
●●	Good
●	Modest
○	Challenging

Footprint	●●	●●●	●
Chip cost	●	●●	●●
CMOS compatibility	○○	●●	●
Low cost packaging	○	○[1]/●●[2]	●●

[1] Endfire coupling (low refl.)

[2] Vertical coupling (med. refl.)

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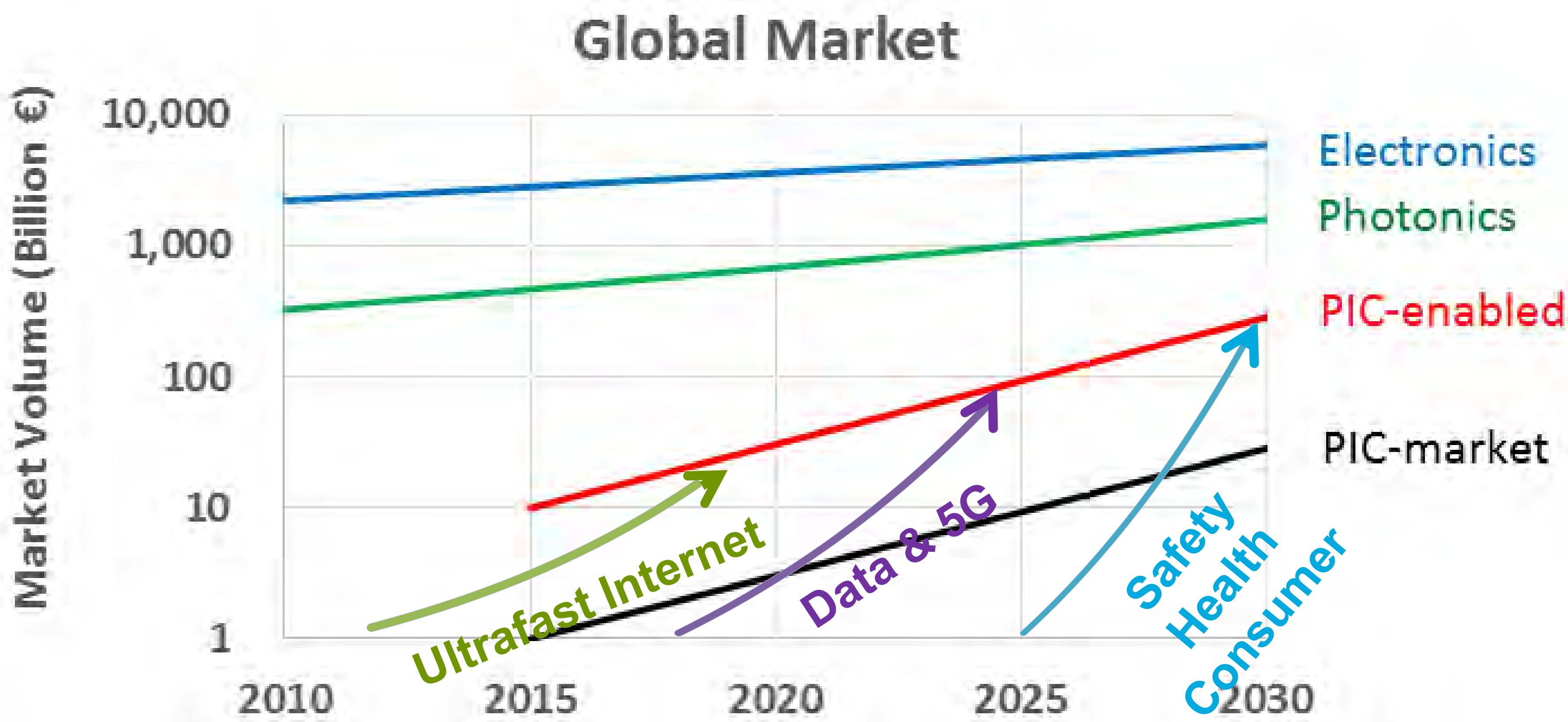
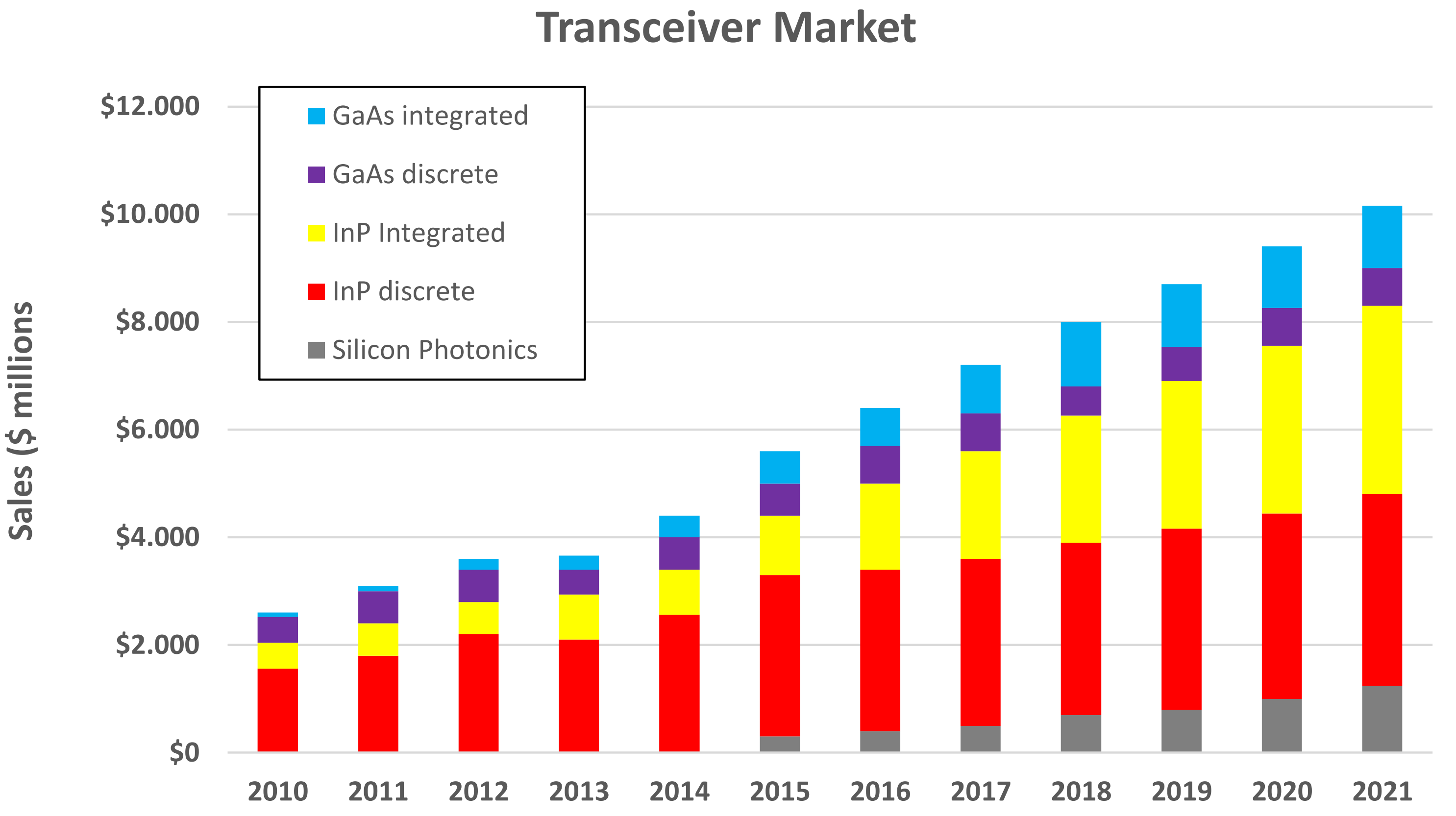
A PIC enabled revolution in Photonics



A global photonics market development **powered by integration**

TU/e Technische Universiteit Eindhoven University of Technology

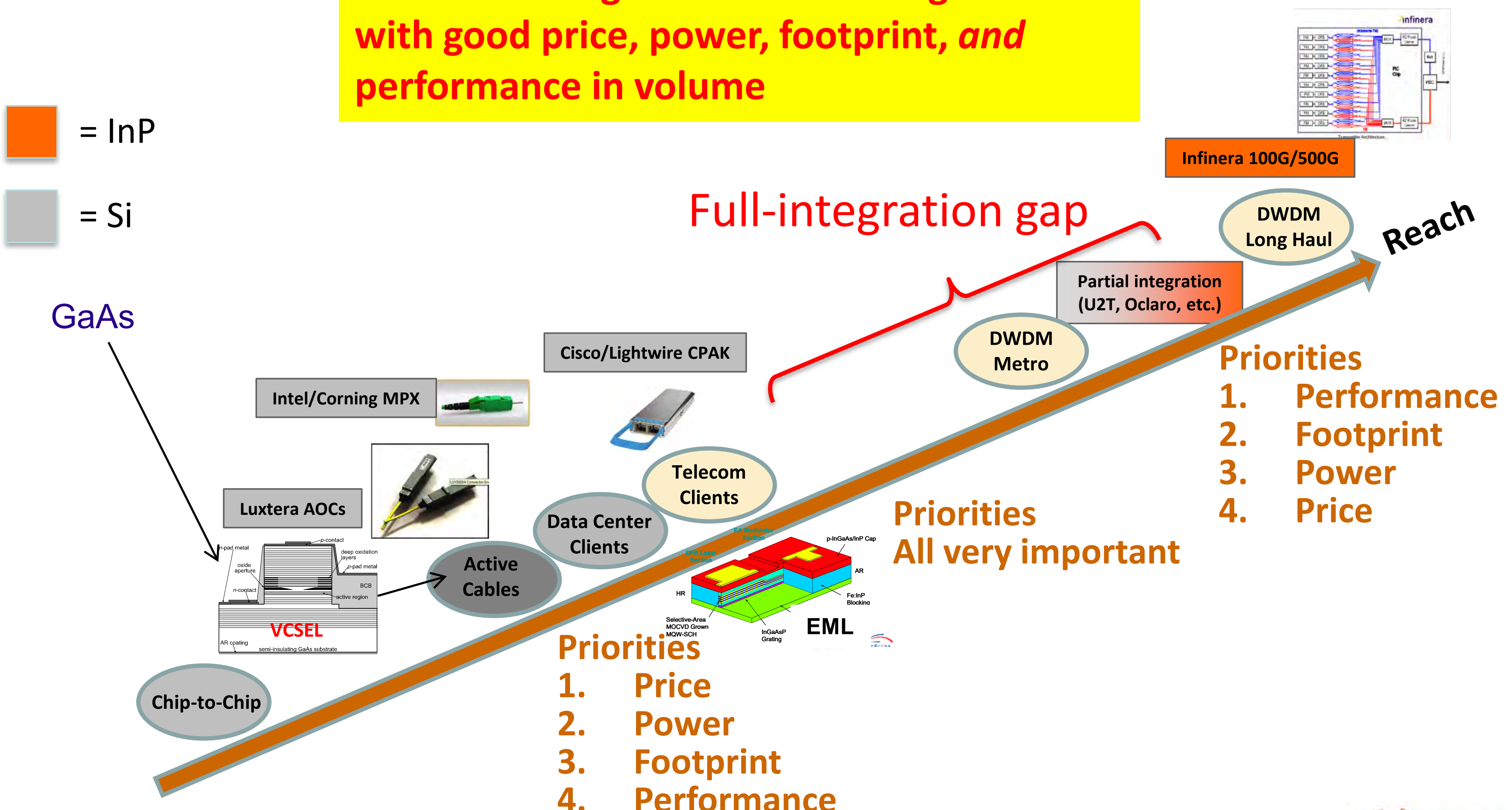
Transceiver market history and projection



Source *LightCounting*

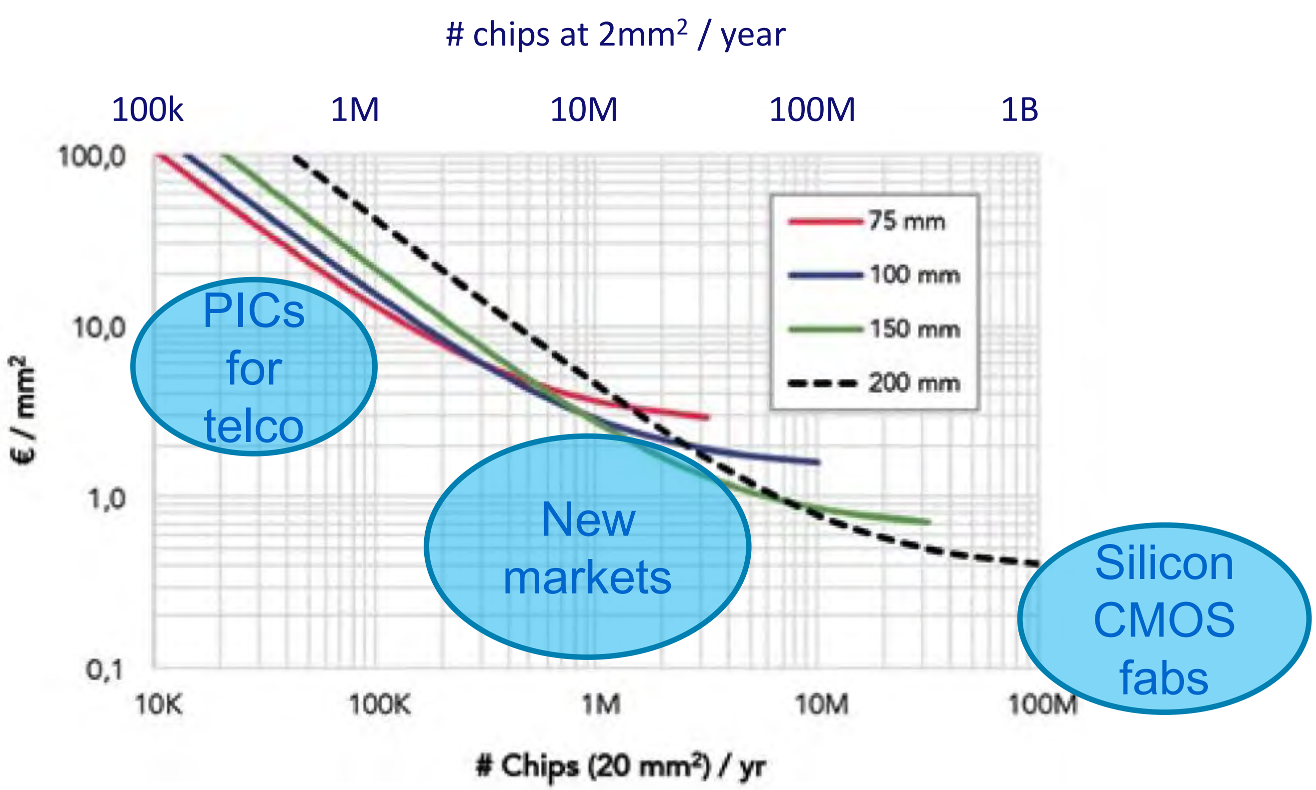
Metro Challenge

Metro challenge: deliver full integration with good price, power, footprint, *and* performance in volume



Based on C. Doerr inputs, *OFC* 2014,

Cost reductions through volumes



- The existing (large) fabs and processes for Silicon may be a disadvantage
- Need a mechanism to allow new applications to grow
- Organically scale or a step change ?

TU/e Technische Universiteit Eindhoven University of Technology

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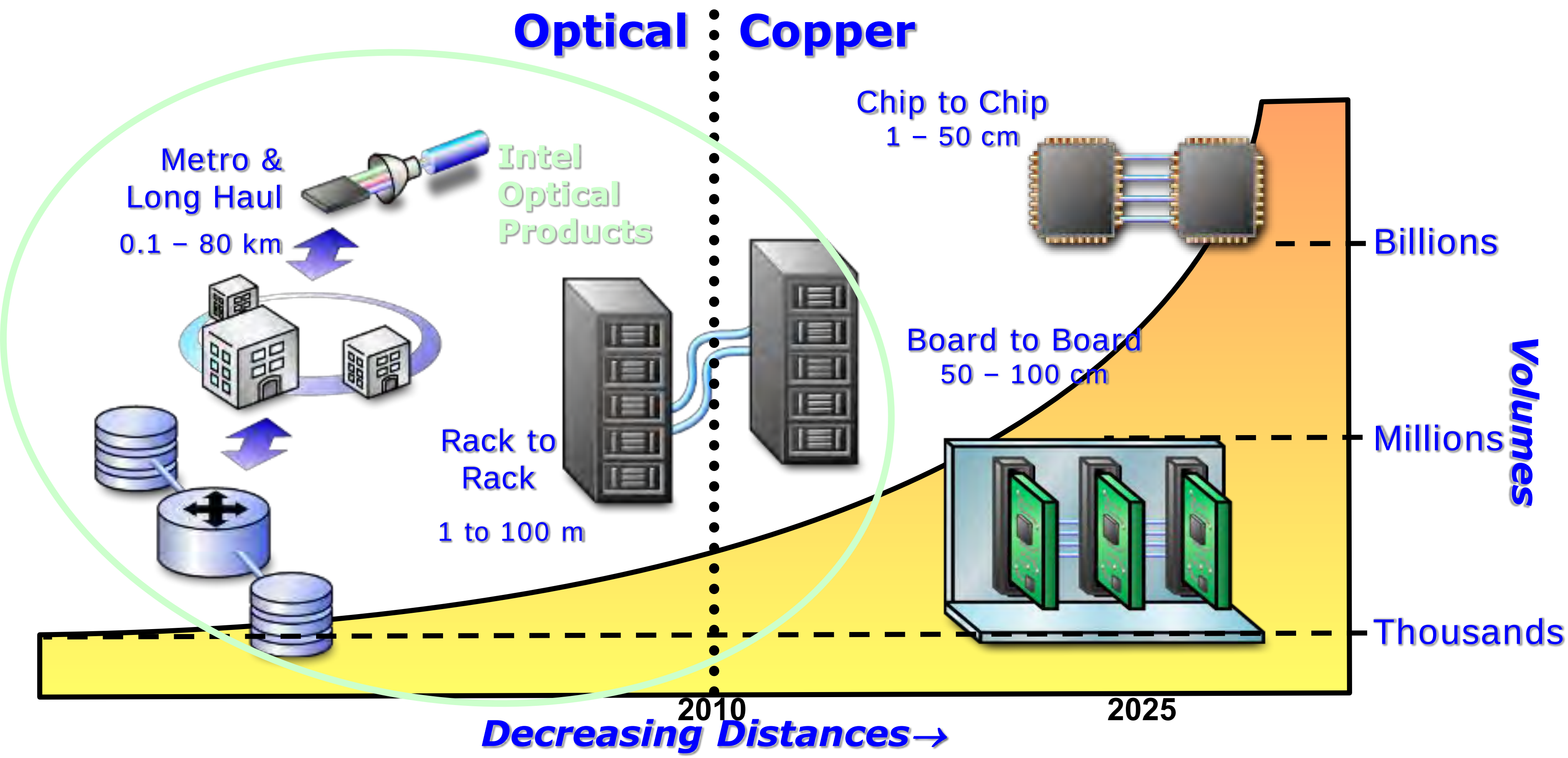
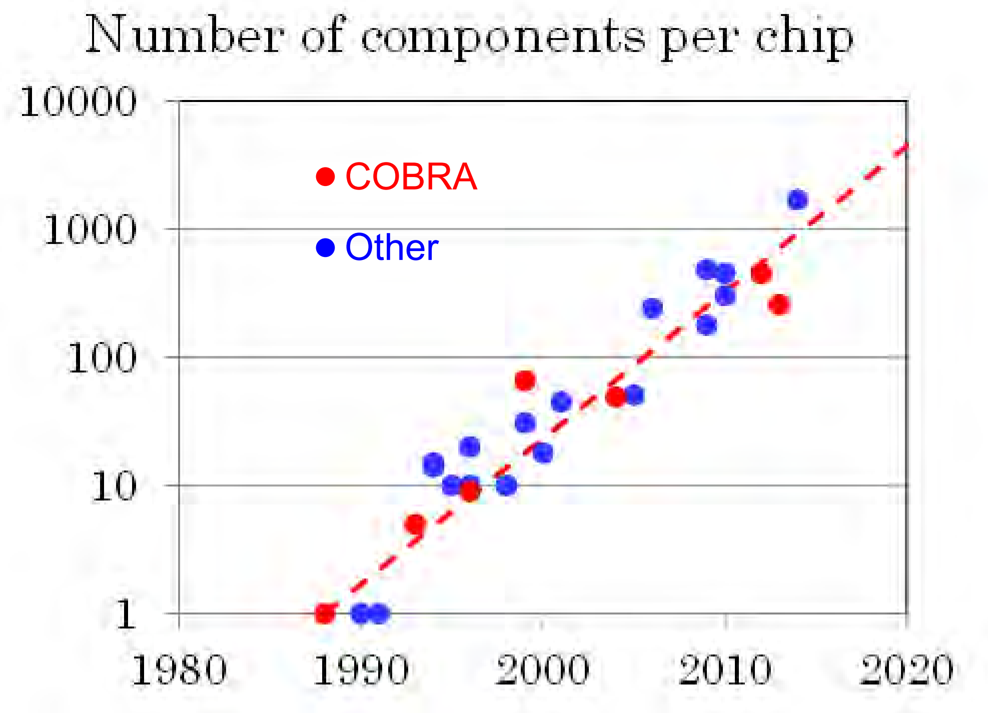
Moving to Interconnects



Drive optical to high volumes and low costs

Moore's Law for Photonics

Scaling in Photonic ICs



Photonics Research 3, 5, pp. B60-B68 (2015)

https://www.osapublishing.org/prj/abstract.cfm?uri=prj-3-5-b60

Indium Phosphide as the Materials Platform

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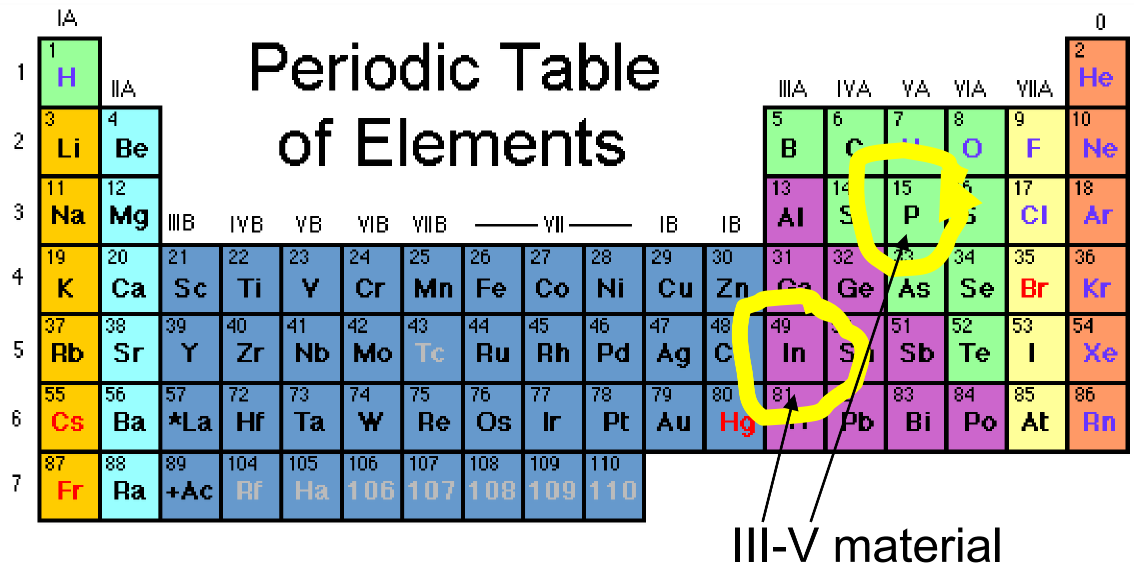
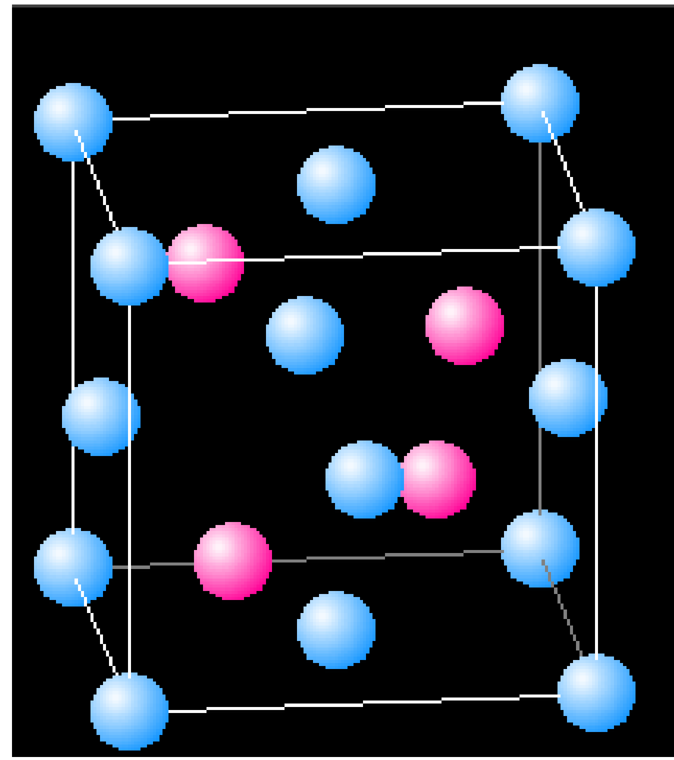
Indium Phosphide





Zincblende structure

(two intersecting FCC lattices, one for In and one for P)

Lattice constant = 5.87 A at 300K

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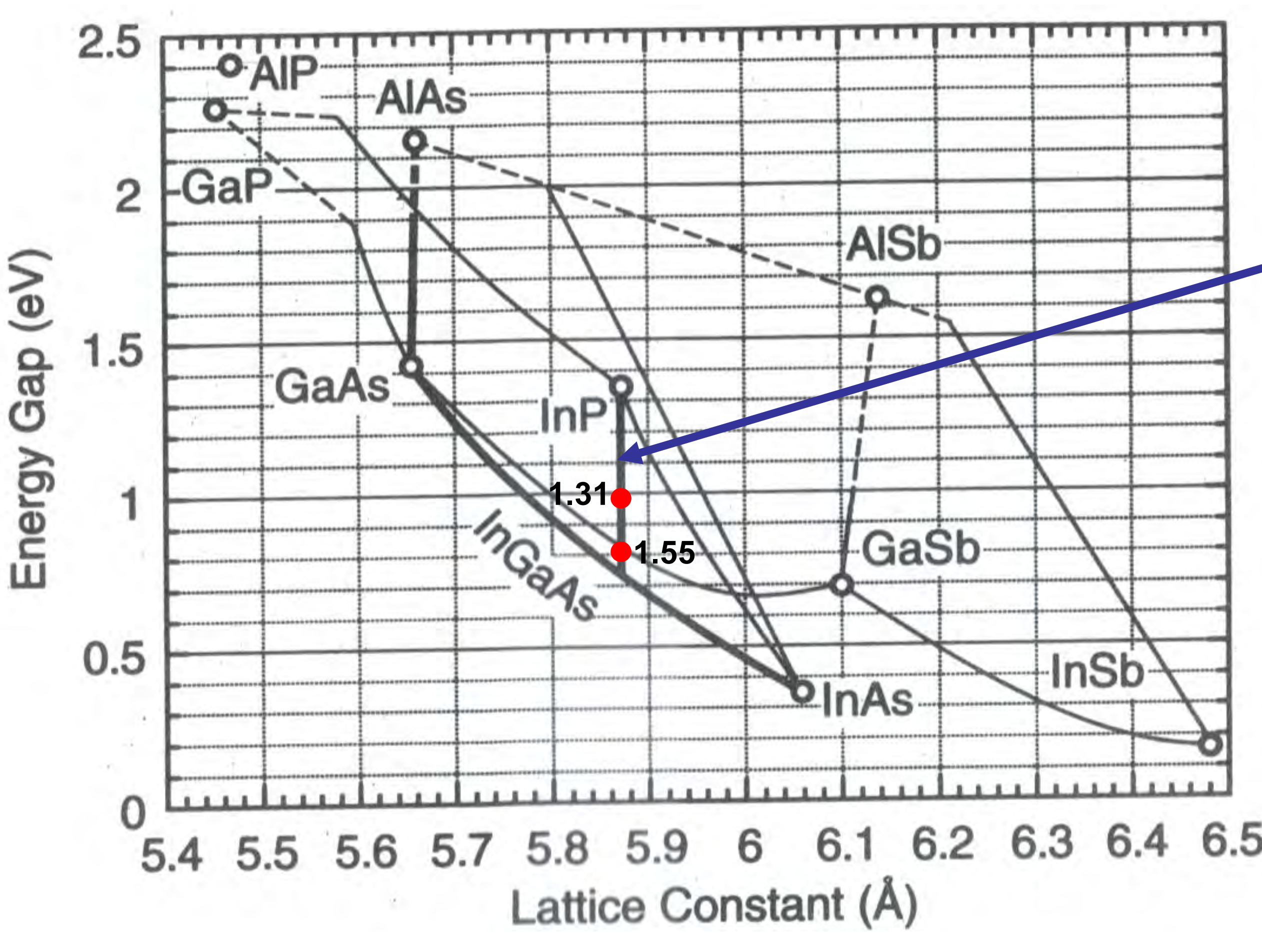
InGaAsP/InP lattice-matched alloys

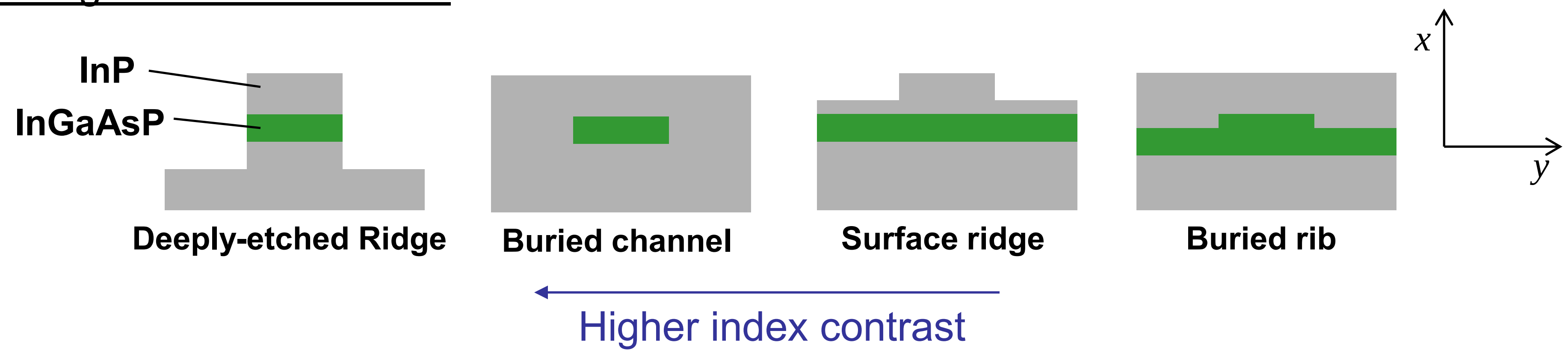


InGaAsP lattice-matched to InP

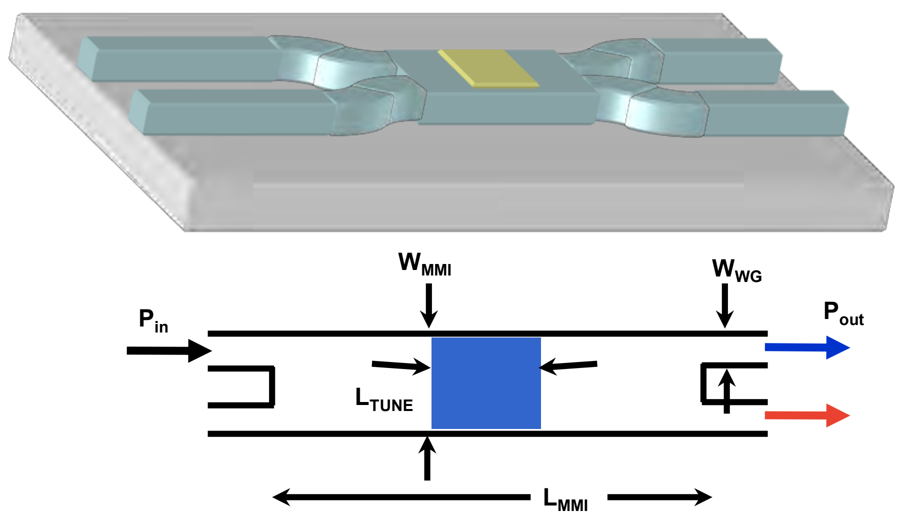
$\lambda_g(\mu m) = 1.24/\ E_g(eV)$

Integration Technology:
Lateral waveguides/couplers

Waveguide cross sections



MMI coupler



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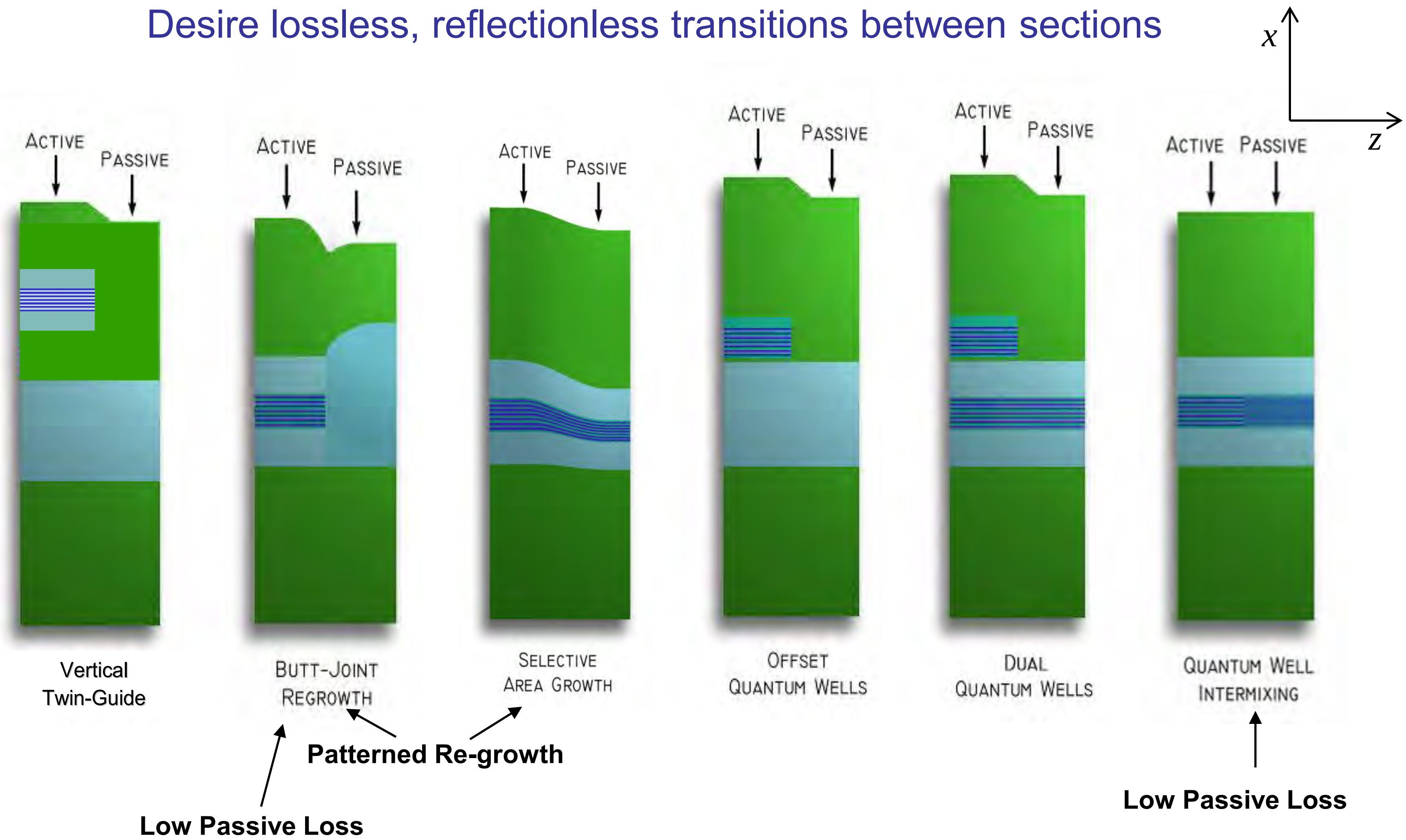
Integration Technology:
Active-Passive (axial) Integration

Desire lossless, reflectionless transitions between sections



3 Bandgaps usually desired

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Integration Technology:
Offset Quantum Well Process

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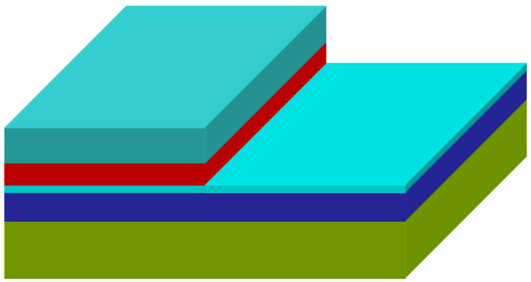
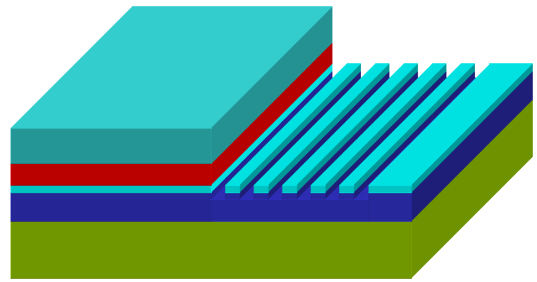
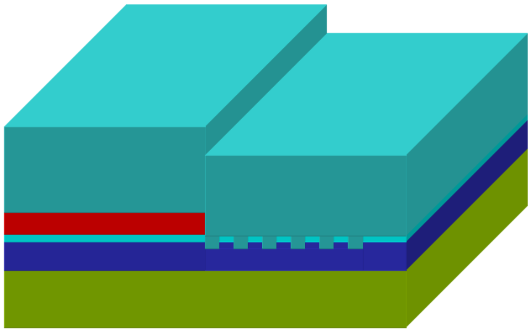
Active−Passive Region Definition



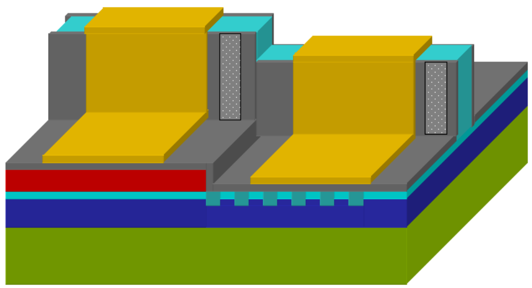
Grating Formation



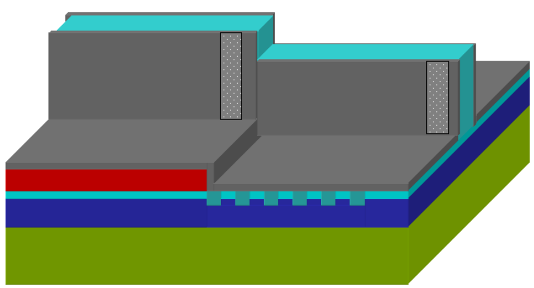
InP/InGaAs Regrowth



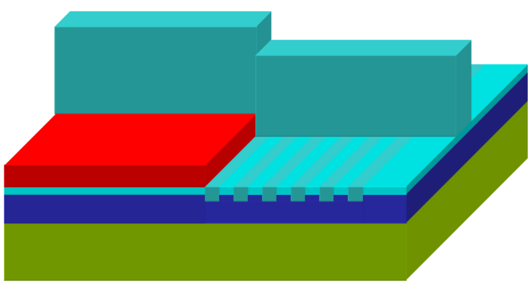
Metalization/Anneal



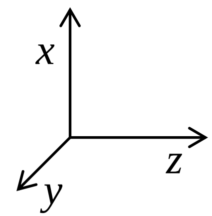
Passivation/Implant



InP Ridge Etch



- Requires Single ‘Planar’ MOCVD Regrowth
- Foundry compatible



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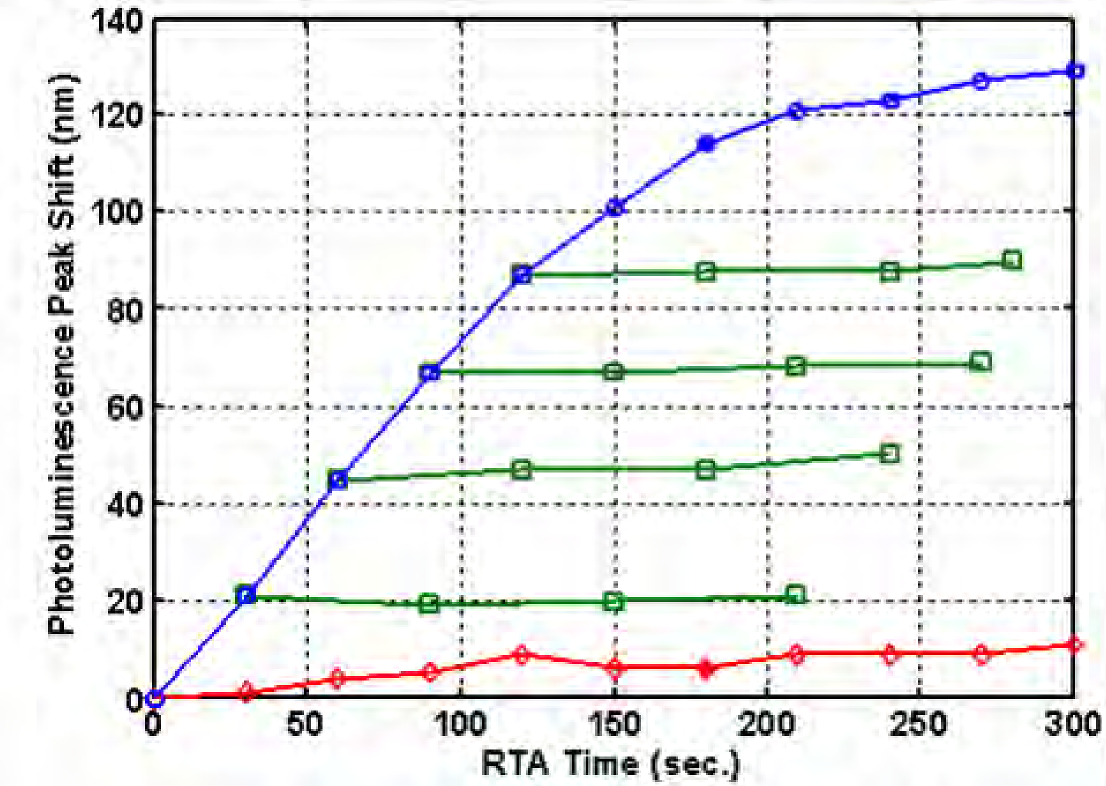
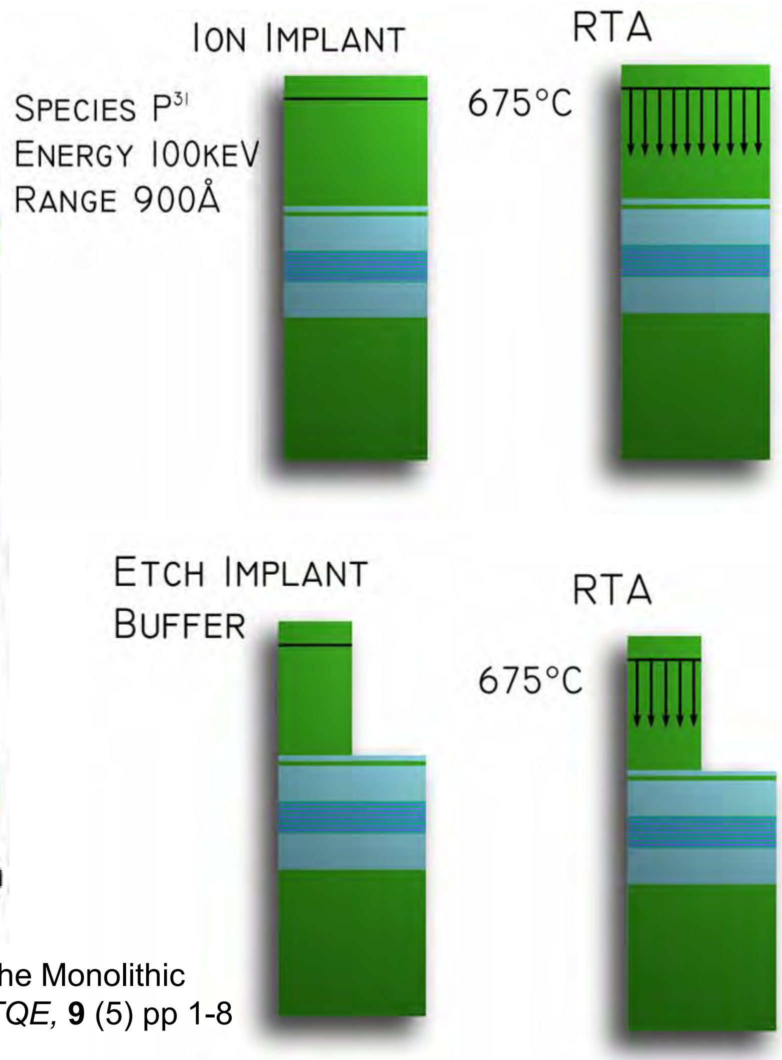
Integration Technology:
QWI For Multiple-Band Edges/Single Growth

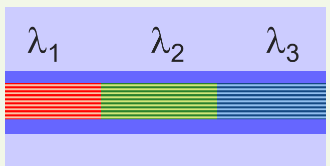
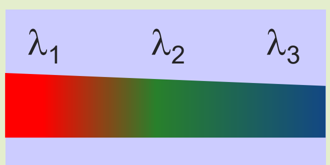
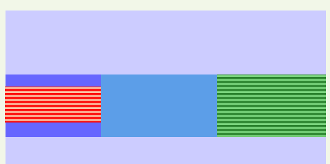
Simple/robust QWI process
- Ability to achieve multiple band edges with a single implant





E. Skogen et al, "Post-Growth Control of the Quantum-Well Band Edge for the Monolithic Integration of Widely-Tunable Lasers and Electroabsorption Modulators," *JSTQE,* **9** (5) pp 1-8 (Sept, 2003).

InP integration platforms

Integration Technology		Design constraints	Other advantages/issues
Dual waveguides (offset quantum wells)		Gain/mode overlap Carrier injection into the laser	Coupling loss
QW intermixing		Number of QWs and doping is shared between all functional sections	- QW width is not optimum for laser and/or modulator; - detuning control is difficult; - shape of the QWs is affected by intermixing => modulator efficiency degradation
Selective Area Growth (SAG)		Number of QWs and doping is shared between all functional sections	- QW width is not optimum for the laser/or modulator; - transition regions; - detuning control is difficult
Regrowth		None	Regrowth can be combined with SAG to tailor waveguide thickness further (ex. spot size converter)

- Regrowth integration is robust integration platform with ultimate design flexibility:
  - ✓ Optimization of material composition, number and width of the quantum wells, and doping

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Early Active PICs—InP

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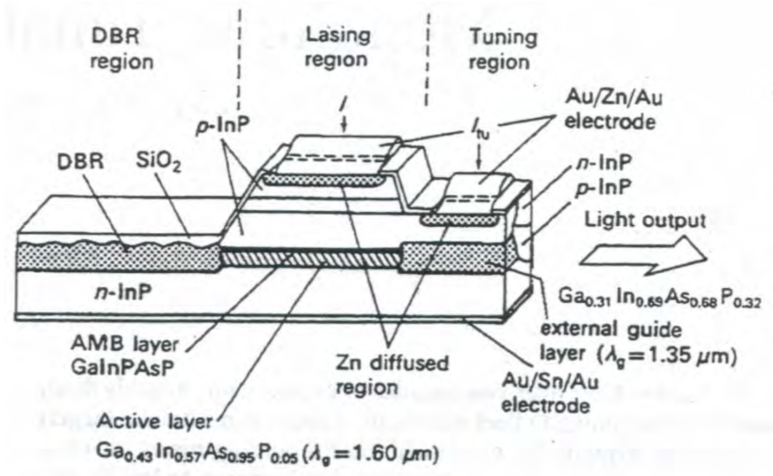
Partially transmissive mirrors (couplers) and active-passive integration needed

→ DBR gratings and vertical couplers

- Tunable single frequency
- Combined integration technologies

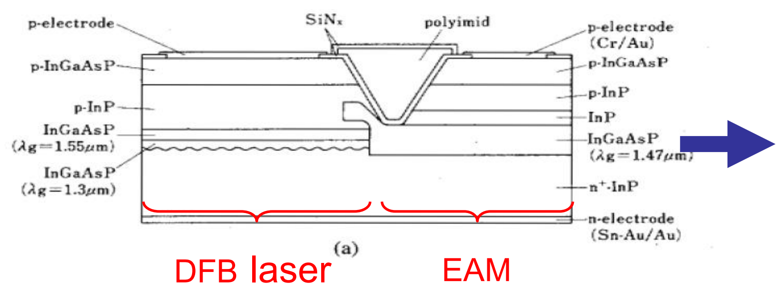
Y. Tohmori, Y. Suematsu, Y. Tushima, and S. Arai, "Wavelength tuning of GaInAsP/InP integrated laser with butt-jointed built-in DBR," *Electron. Lett.*, 19 (17) 656-7 (1983).



→**EML =** electroabsorption-modulated laser

- Still in production today

M. Suzuki, et al., *J. Lightwave Technol.*, **LT-5**, pp. 1277-1285, 1987.



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Coherent Communication Motivated Photonic Integration

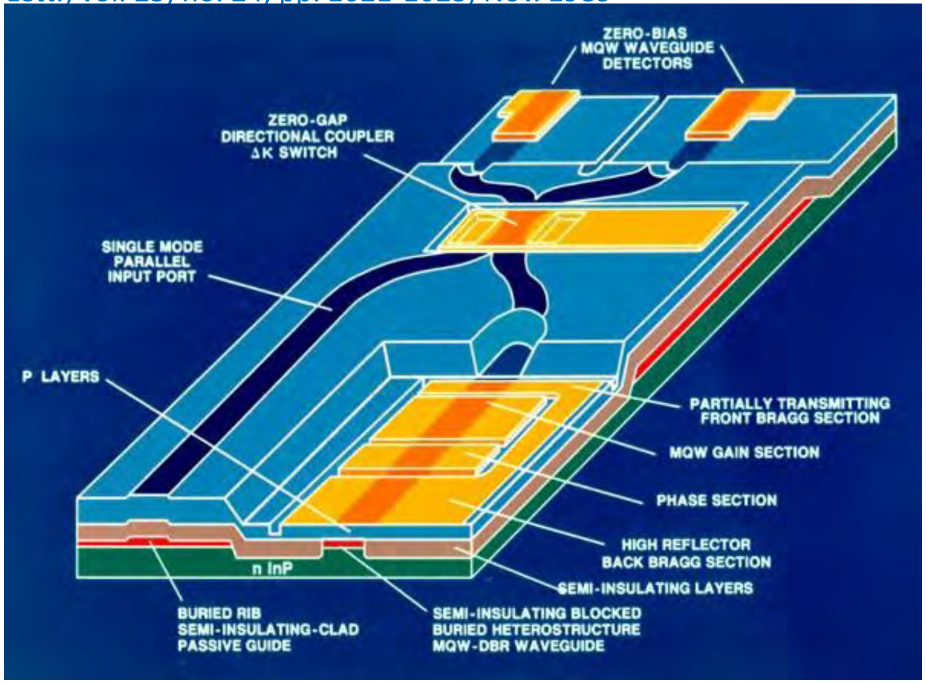
- In the 1980's coherent communication was widely investigated to increase receiver sensitivity and repeater spacing. It was also seen as a means of expanding WDM approaches because optical filters would not be so critical.

Y. Yamamoto and T. Kimura, "Coherent optical fiber transmission systems," *IEEE J. Quantum Electron*, vol. 17, no. 6, pp. 919-925, Jun. 1981.

- This early coherent work drove early photonic integration efforts—Stability; enabled phase-locking

T. L. Koch, U. Koren, R. P. Gnall, F. S. Choa, F. Hernandez-Gil, C. A. Burrus, M. G. Young, M. Oron, and B. I. Miller, "GaInAs/GaInAsP multiple-quantum-well integrated heterodyne receiver," *Electron. Lett.*, vol. 25, no. 24, pp. 1621-1623, Nov. 1989

Integrated Coherent Receiver
(Koch, et al)



- The EDFA enabled simple WDM repeaters
- (just amplifiers) and coherent was put on the shelf
- But, some aspects of Photonic Integration continued → e.g., Tunable Lasers

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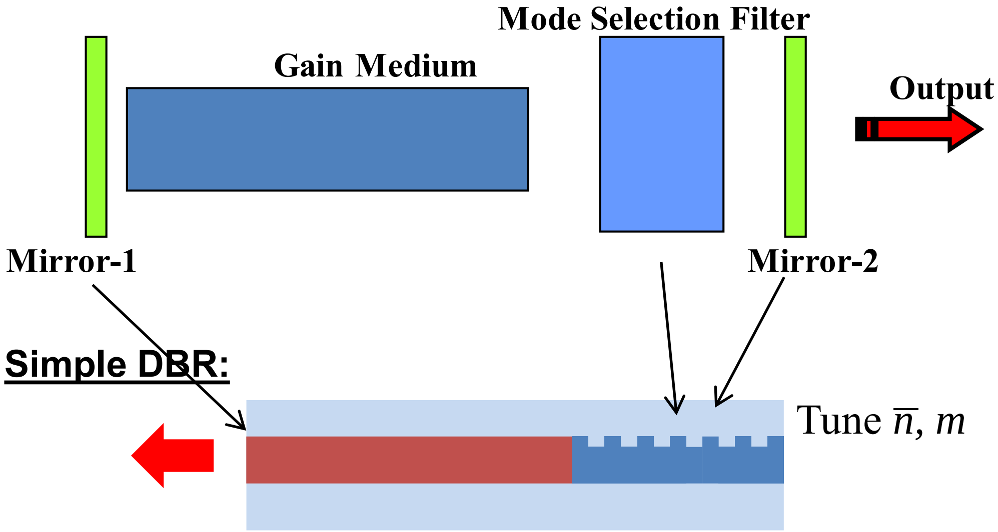
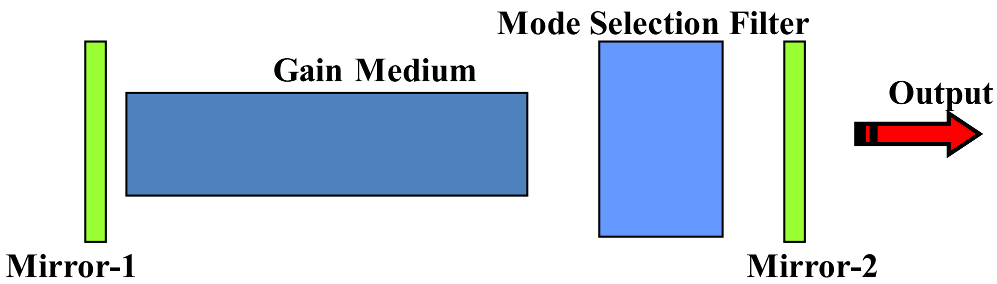
Tunable Lasers



$$m\lambda/2 = \bar{n}L$$

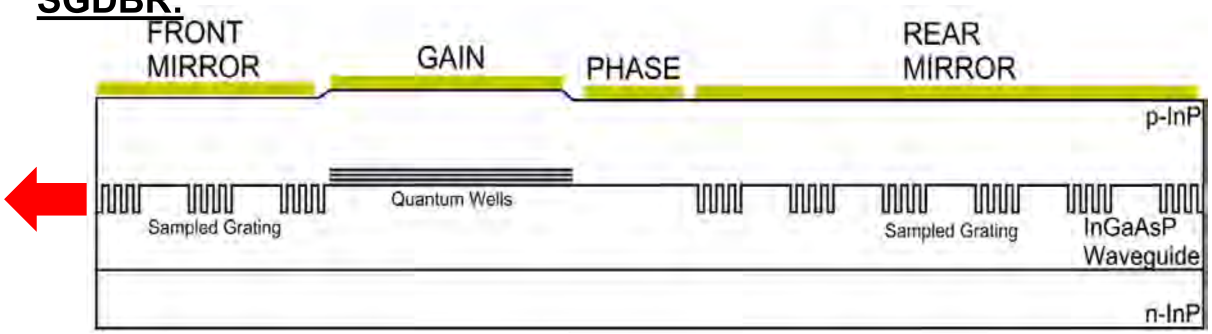
Tunable DBR Lasers→ SGDBR



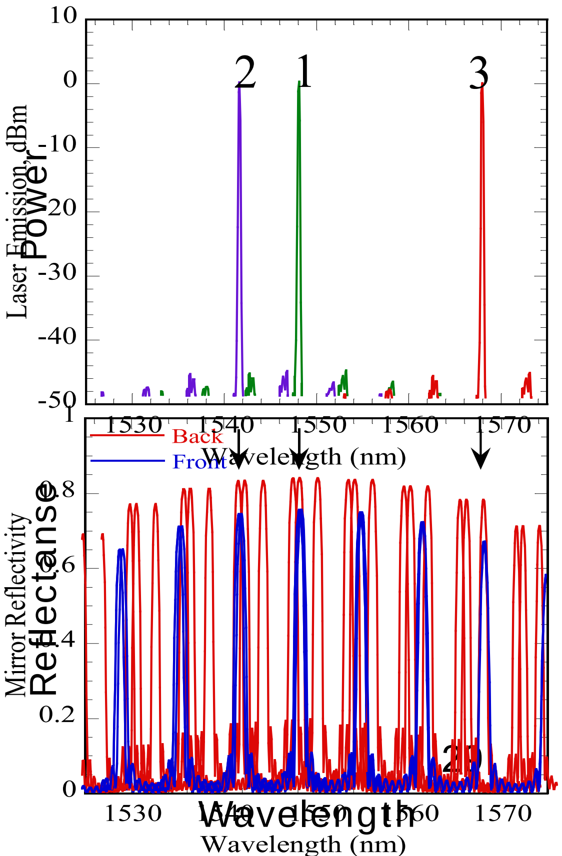
$m\lambda/2 = \bar{n}L$

Simple DBR:

SGDBR:



Supermode (multiband) tuning



- Uses vernier effect for multiband tuning
- $\Delta\lambda/\lambda$ = N x $\Delta n/n$ by differential mirror tuning

Tunable Lasers:
Sampled-Grating DBR: Monolithic and Integrable

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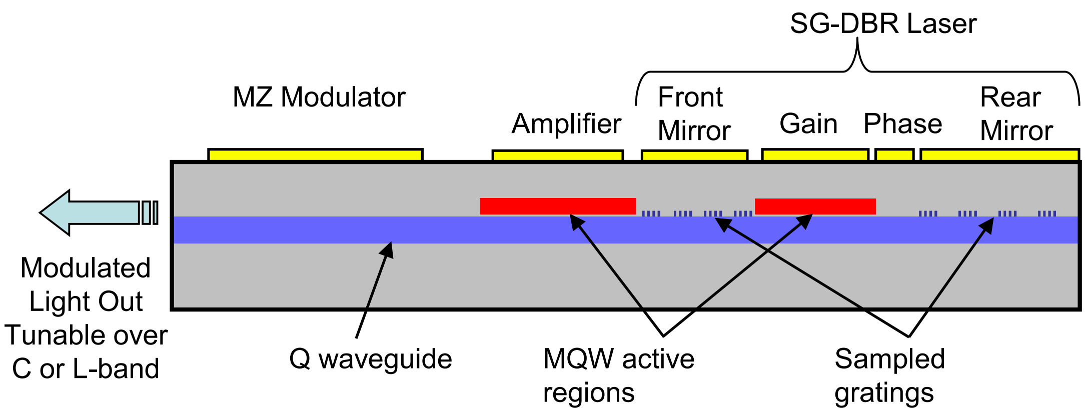
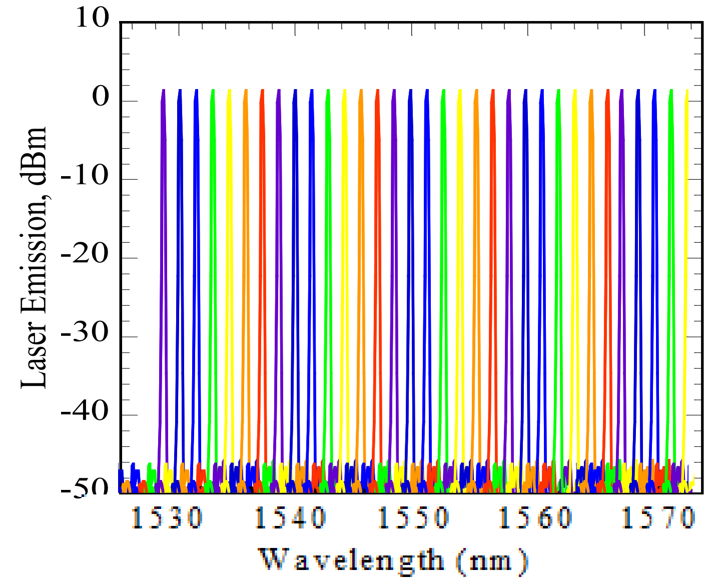
SGDBR+X widely-tunable transmitter:

- Foundation of PIC work at UCSB

(UCSB'90-- → Agility'99-'05 → JDSU'05→ Lumentum'15)

"Multi-Section Tunable Laser with Differing Multi-Element Mirrors," US Patent # 4,896,325 (January 1990)



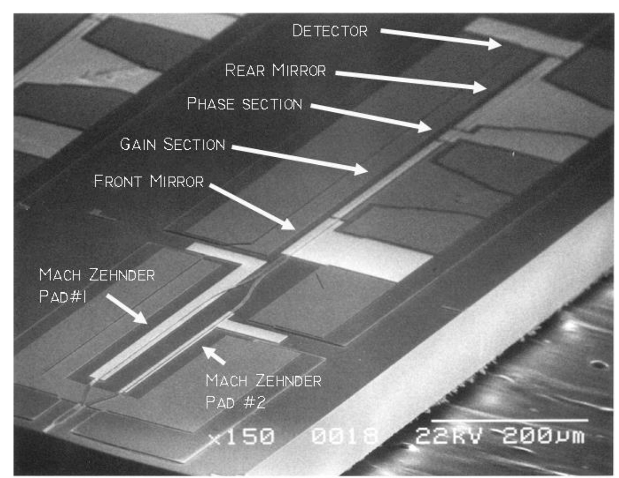


- Vernier tuning over 40+nm near 1550nm
- SOA external to cavity provides power control
- Currently used in many new DWDM systems (variations)
- Integration technology for much more complex PICs

ILMZ TOSA (~ 18mm)

JDSU 2008

6 section InP chip



J. S. Barton, et al,," *ISLC,* TuB3, Garmish, (Sept, 2002)

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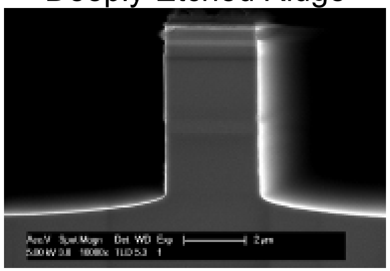
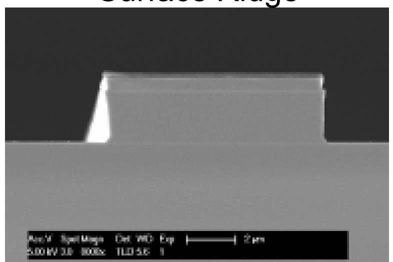
Integration Example: 8 x 8 MOTOR Chip: (40 Gb/s per channel)

- SOA – Mach-Zehnder Wavelength Converters
- Quantum-well intermixing (QWI) to shift bandedge for low absorption in passive regions
- Three different lateral waveguide structures for different curve/loss requirements
- Single 'blanket' regrowth

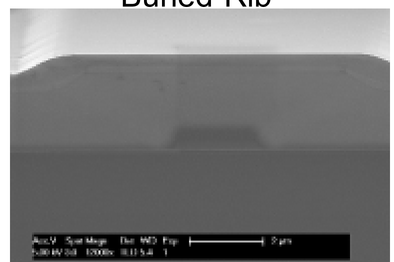
Deeply-Etched Ridge



Surface Ridge

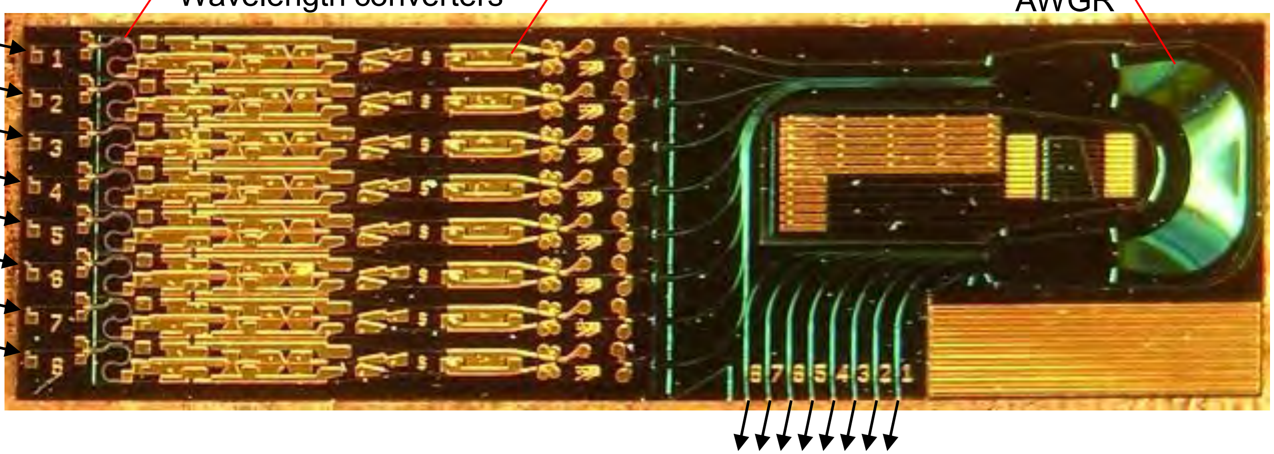


Buried-Rib



Wavelength converters

AWGR



Monolithic Tunable Optical Router

QWI for active-passive integration interfaces

See S. Nicholes, et al, "Novel application of quantum-well intermixing implant buffer layer to enable high-density photonic integrated circuits in InP," *IPRM '09*, paper WB1.2, Newport Beach (May, 2009)

Commercial PIC Examples

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Widely Deployed Commercial "WDM" PICs
(~2009)

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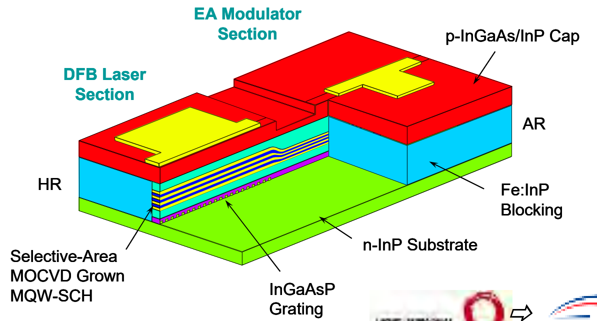
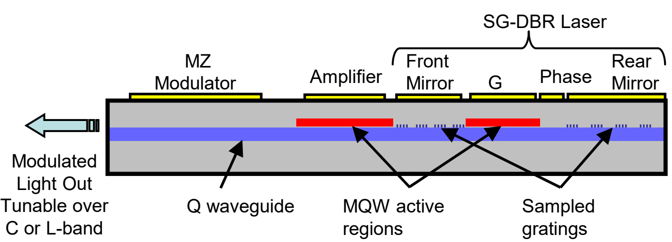
EML's:

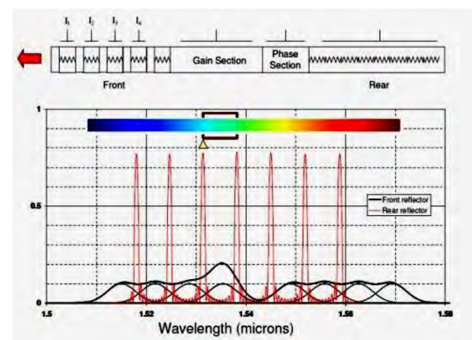


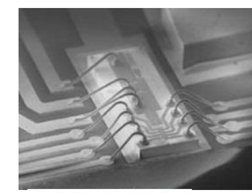
into XFP transceivers, etc.

Tunables & Selectable Arrays:

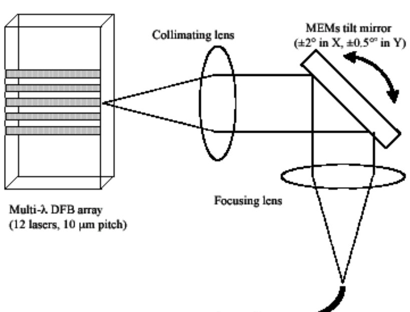


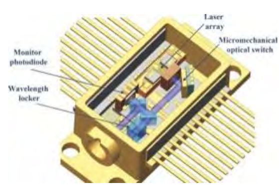
UCSB ⇨ AGILITY ⇨ JDSU



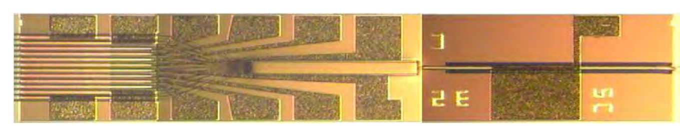


Bookham ⇨ oclaro

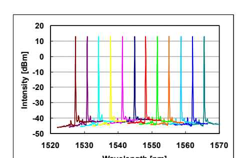




Santur Corporation



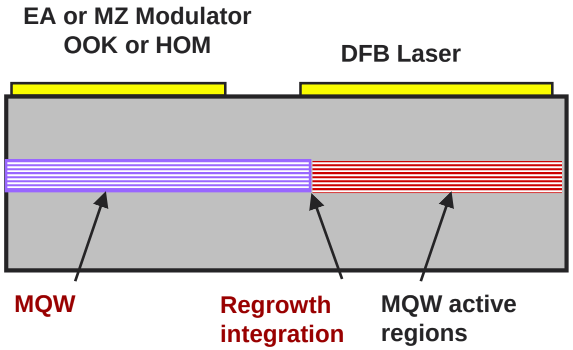
1 x 12 DFB S-Bent MMI SOA

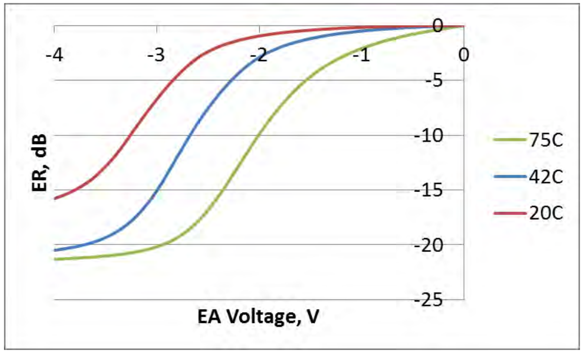


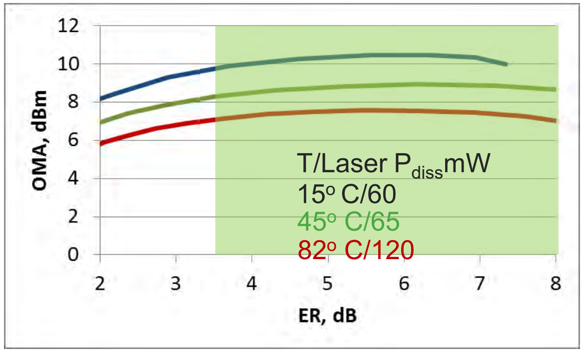
FURUKAWA ELECTRIC

courtesy of T. Koch

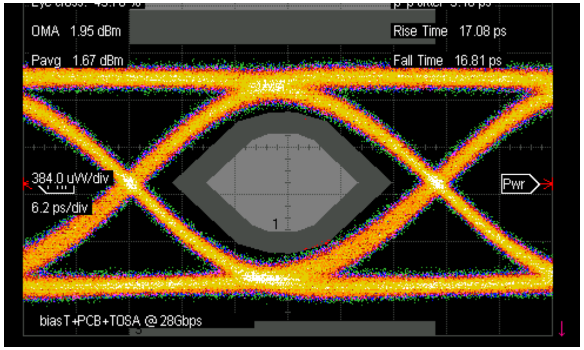
InP PICs for datacenter transceivers



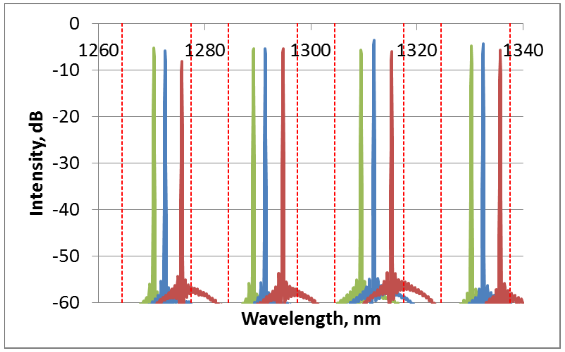




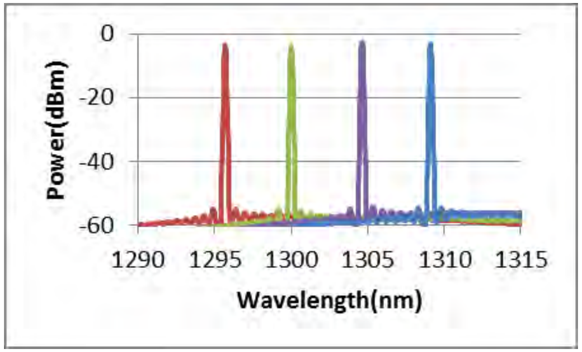
100G TOSA @ 28Gb/s
ER>5dB, MM>40%, Vpp=1.2V



CWDM4



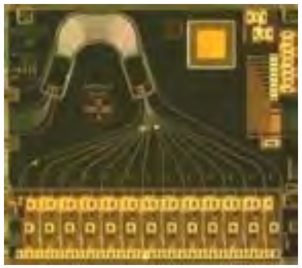
LR4

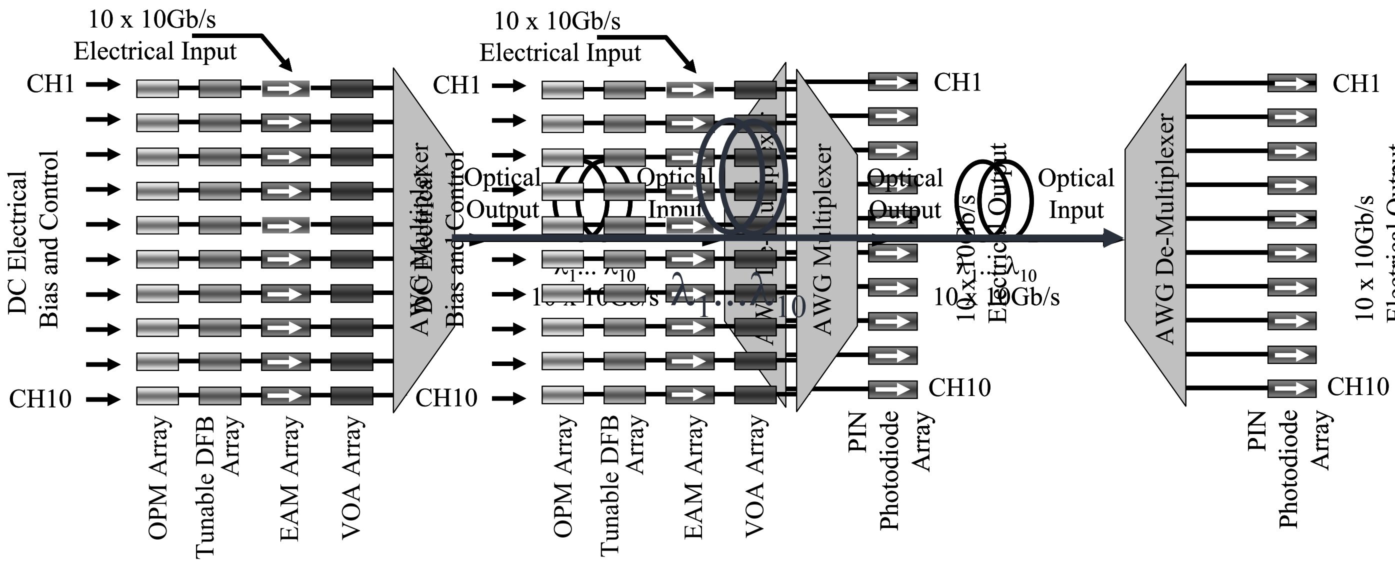


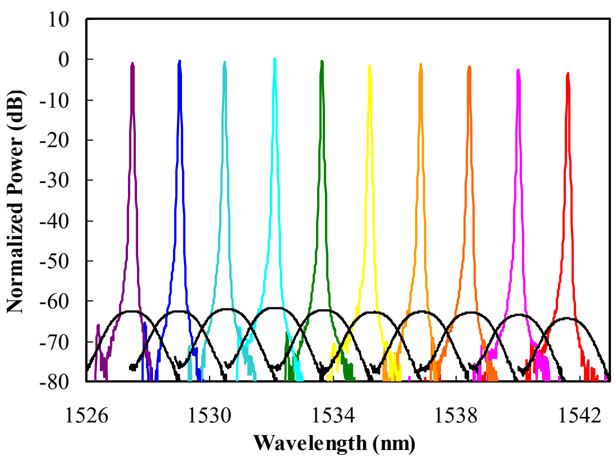
- InP PIC technology enabled 100Gb/s QSFP28 CWDM4 and LR4 transceivers
- Lossless integration of lasers with high efficiency modulators delivers high OMA and ER with low modulation voltage and low power dissipation
- => continues to be technology choice for 28 and 53Gbaud PAM4 400 Gb/s transceivers

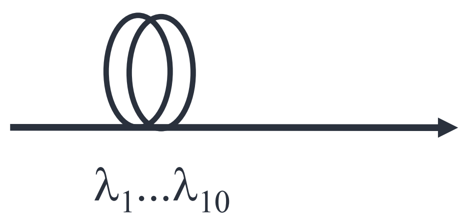
2004: First Commercial Large-Scale InP-Based PICs

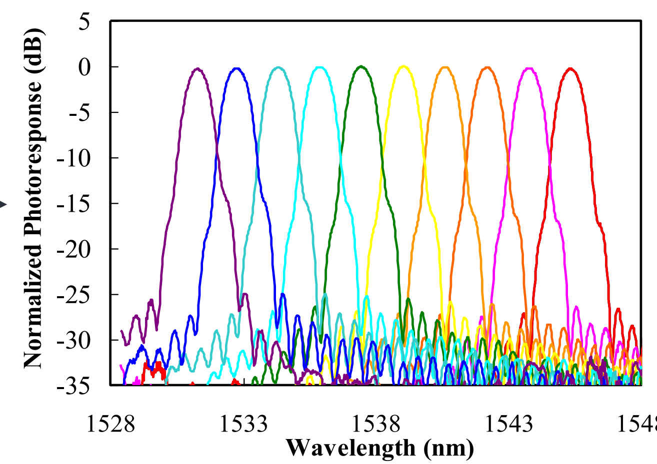
100 Gb/s (10 x 10Gb/s) Transmitter and Receiver PIC











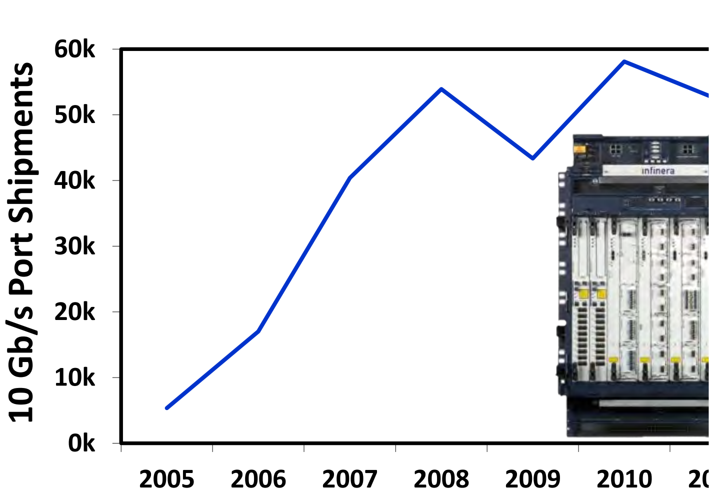
infinera

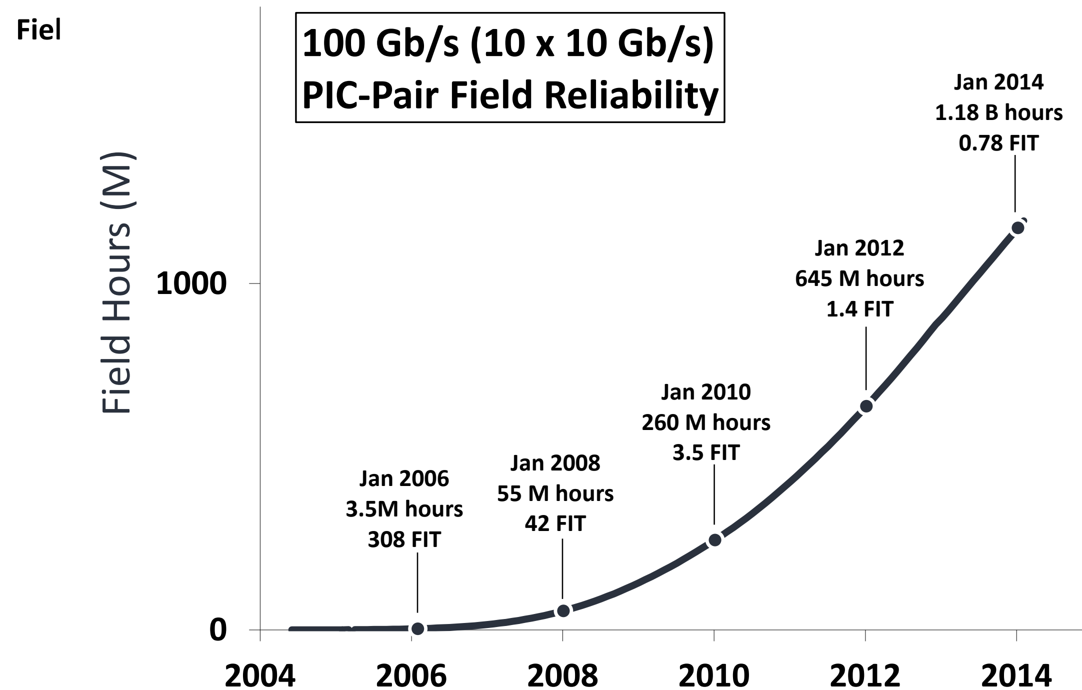
100Gb/s InP PIC-Based Systems Lead Market

2007 – 2011 Infinera PICs capture 45% of All LH 10G ports*

>1B Field Hours Without A Failure (100 Gb/s PIC Pairs: Tx+Rx)

100Gb/s (10 x 10Gb/s) PIC-Based Optical Trans

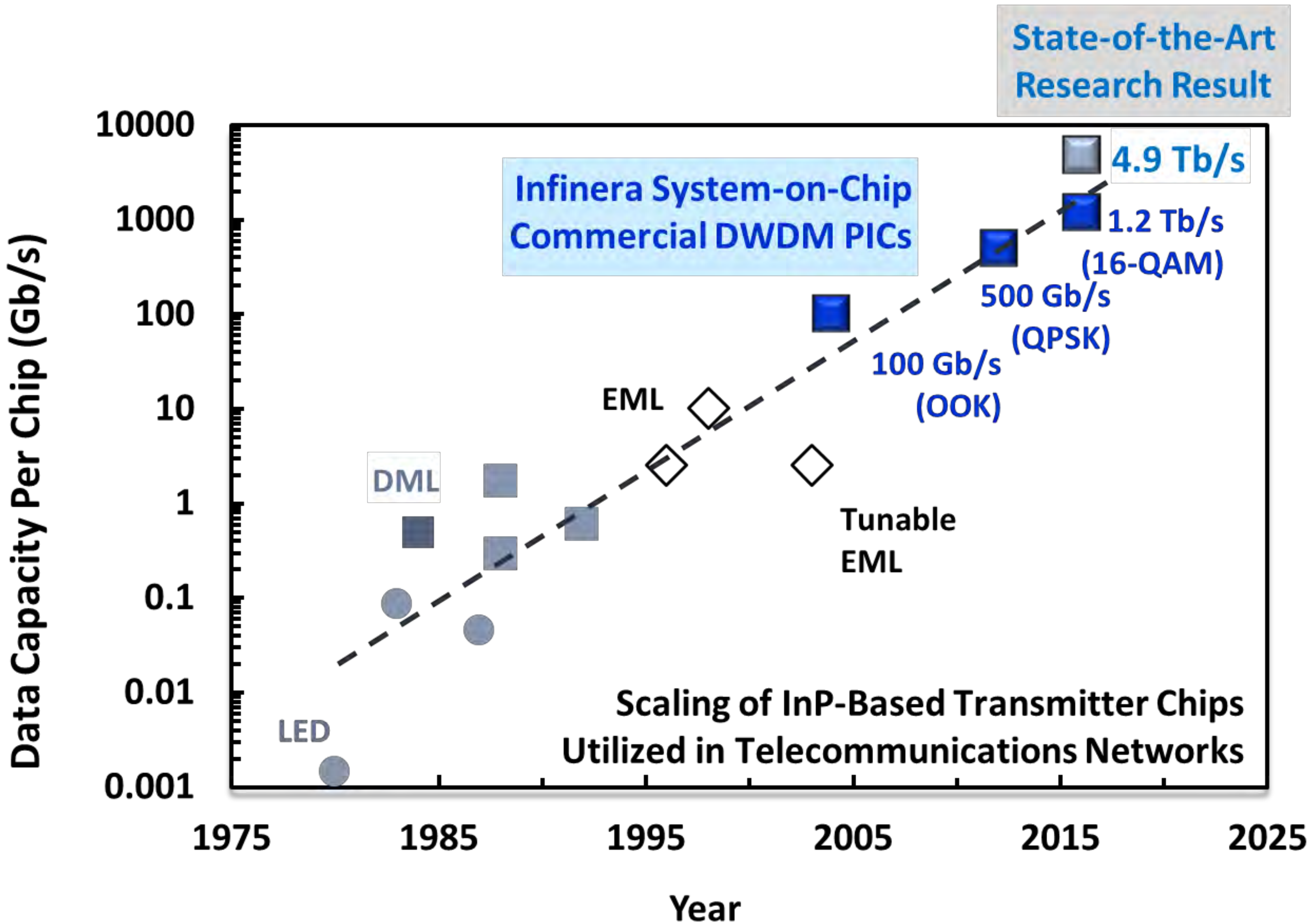




Large-Scale PICs Enable:
- **100 Gb/s per card (slot)**
- **Integrated Switching for digital bandwidth management**

infinera

Data Capacity Scaling in The Network

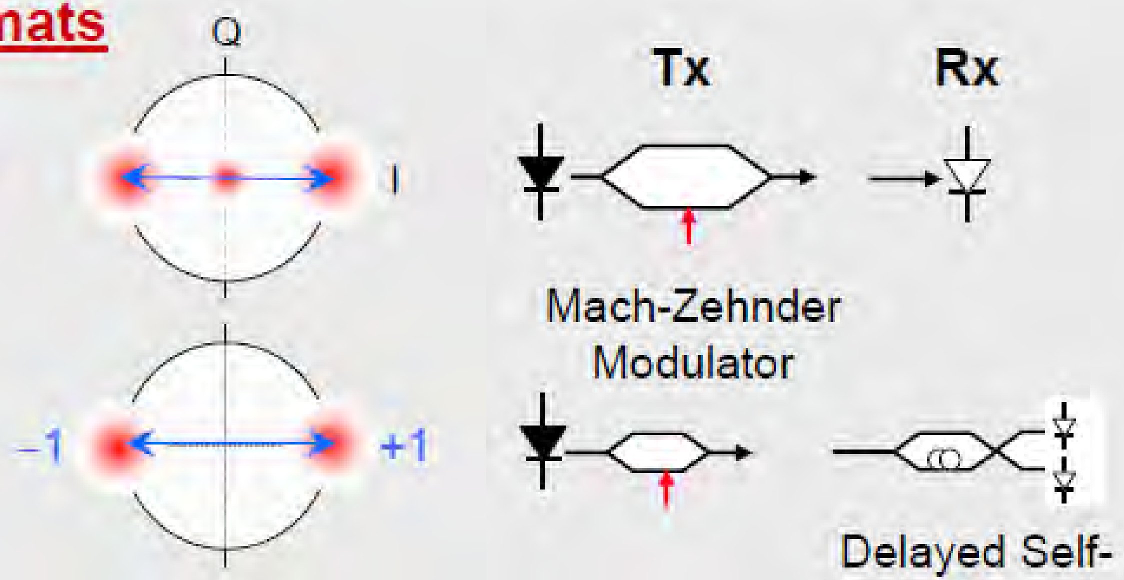


UCSB

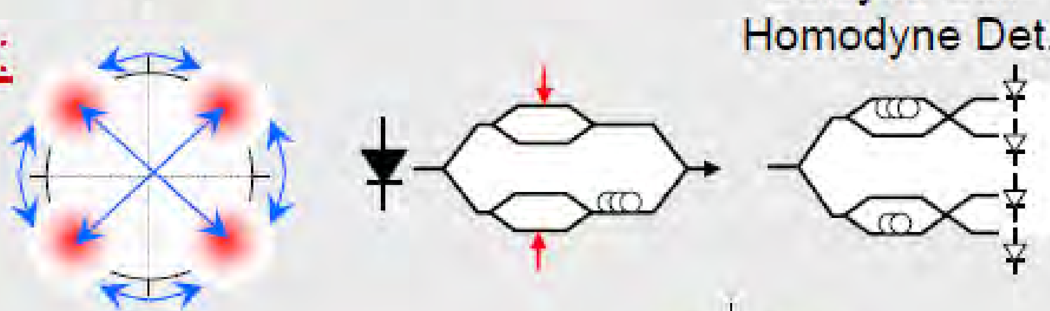
Advanced Modulation Formats & Coherent Detection to increase Spectral Efficiency

OFC 2017

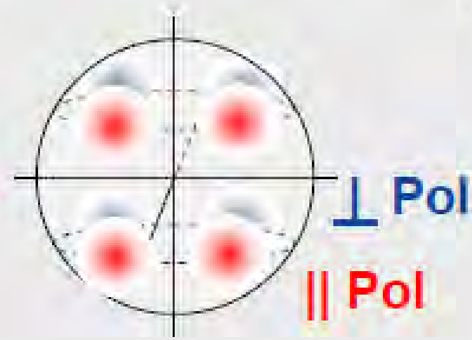
- **Binary modulation formats** (1 bit/symbol):
  - Optical duobinary / PSBT
  - NRZ- / RZ-DPSK ("bipolar" ASK)



- **Quaternary** (2 bits/symbol):
  - NRZ- / RZ-DQPSK

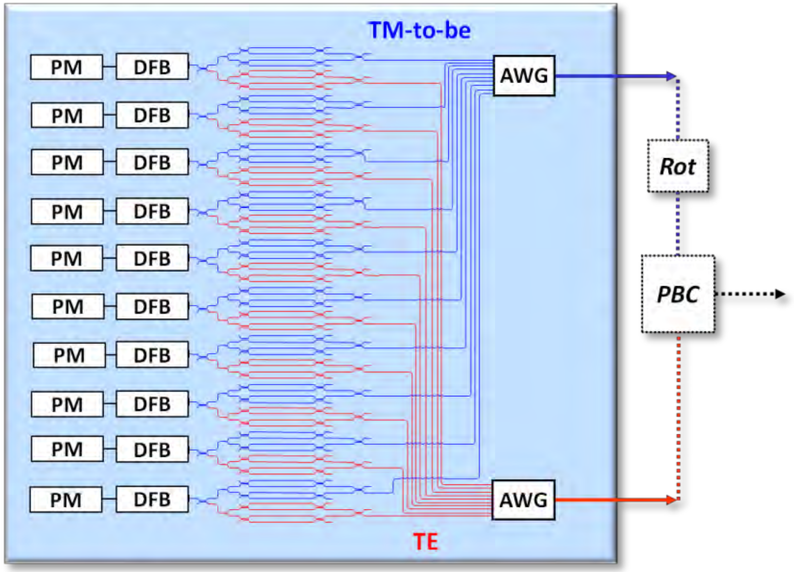


- **Polarization-multiplexed QPSK** (4 bits/symbol):
  - Dual-Polarization QPSK

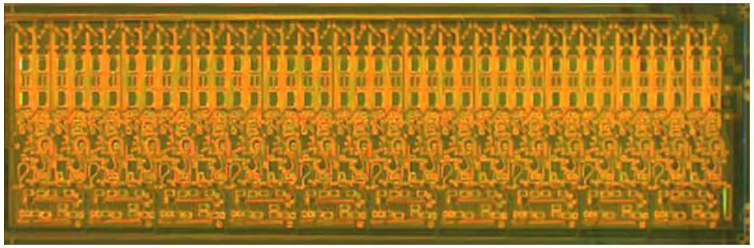


2011: 500 Gb/s PM-QPSK Coherent PICs

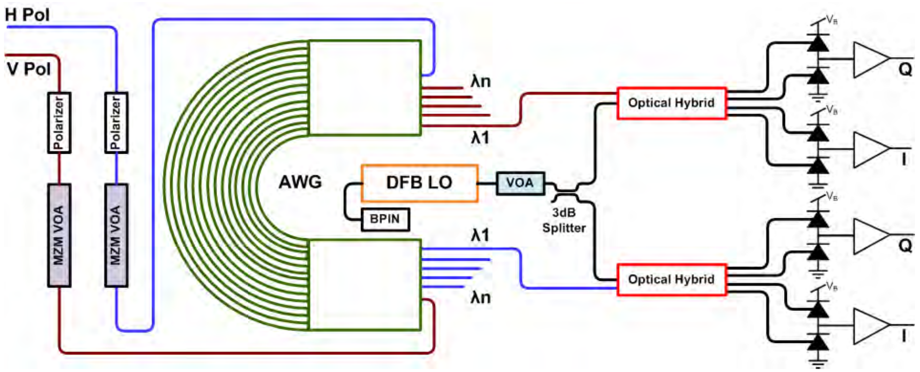
Tx PIC Architecture (5 x 114 Gb/s)



- > 450 Integrated Functions
- 8 Different Integrated Functions



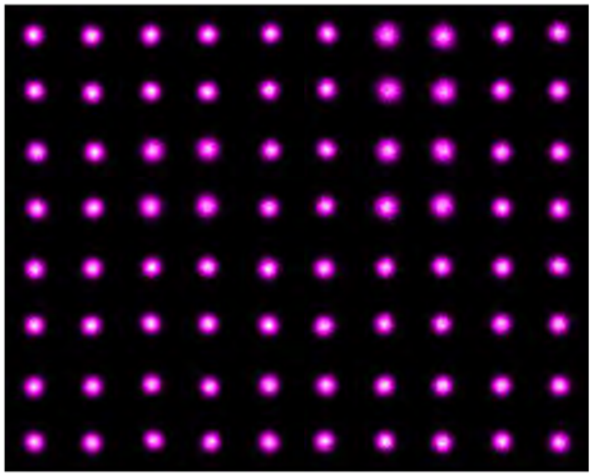
Rx PIC Architecture (5x 114Gb/s)



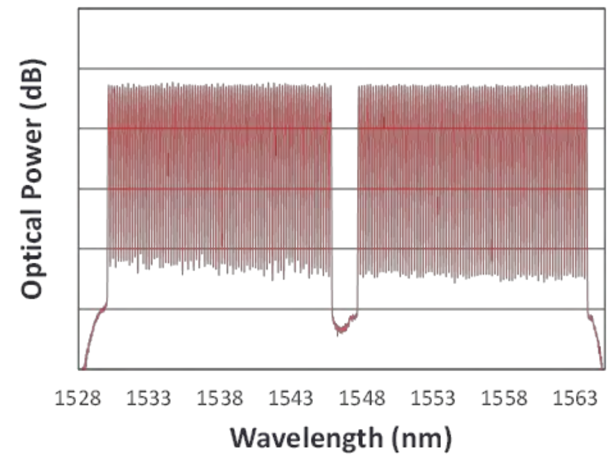
- > 150 Integrated Functions
- 7 Different Integrated Functions

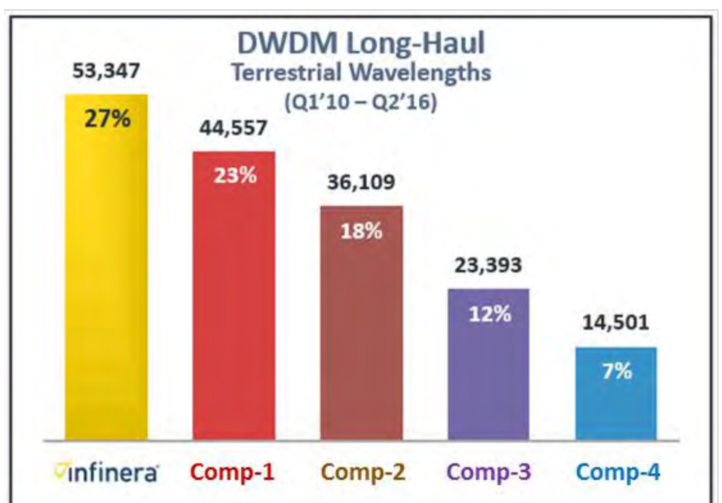
500 Gb/s PM-QPSK Coherent PICs

500 Gb/s Tx→Rx Contiguous Super-Channel



500Gb/s PIC-based Transport / Switching System

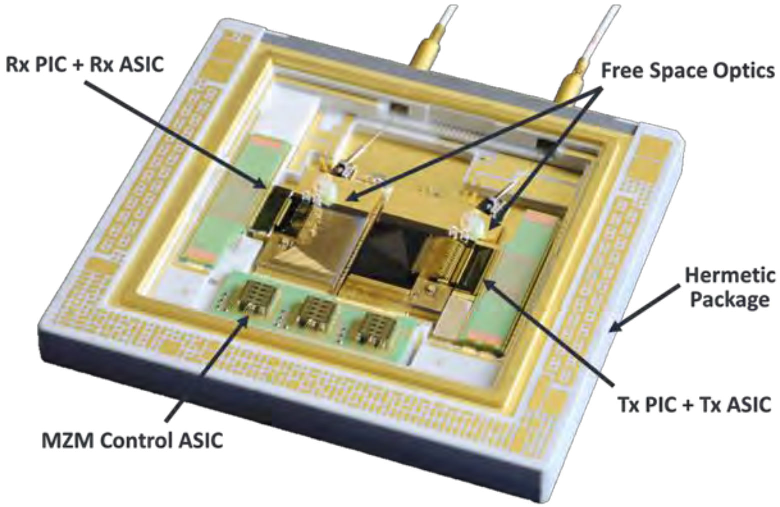


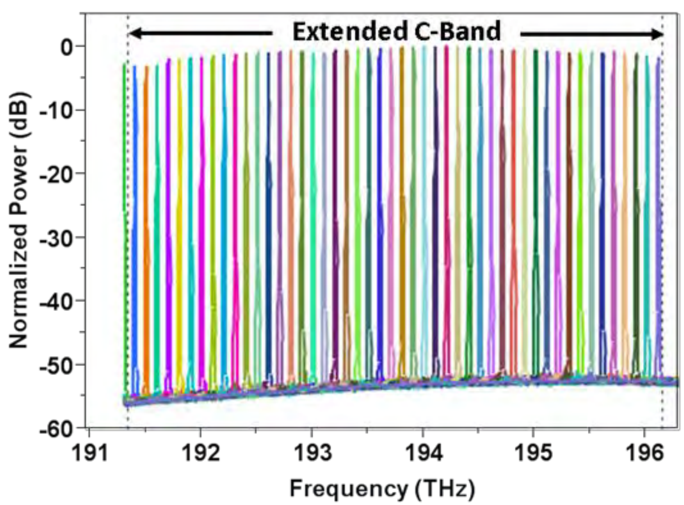


#1 in 100G Long-haul

Infinera has 28% of all 100G LH wavelengths sold since Q1-2010, excluding china

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

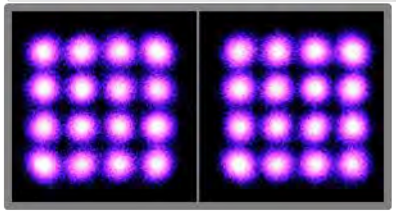




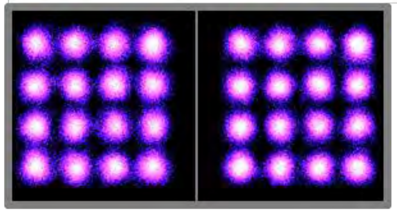
Typical laser output spectrum

- 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

33GBaud, 16-QAM



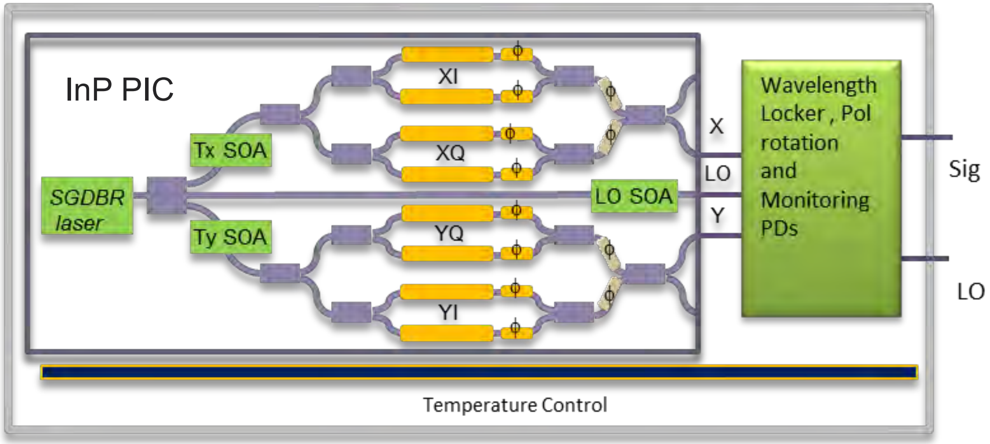
44GBaud, 16-QAM

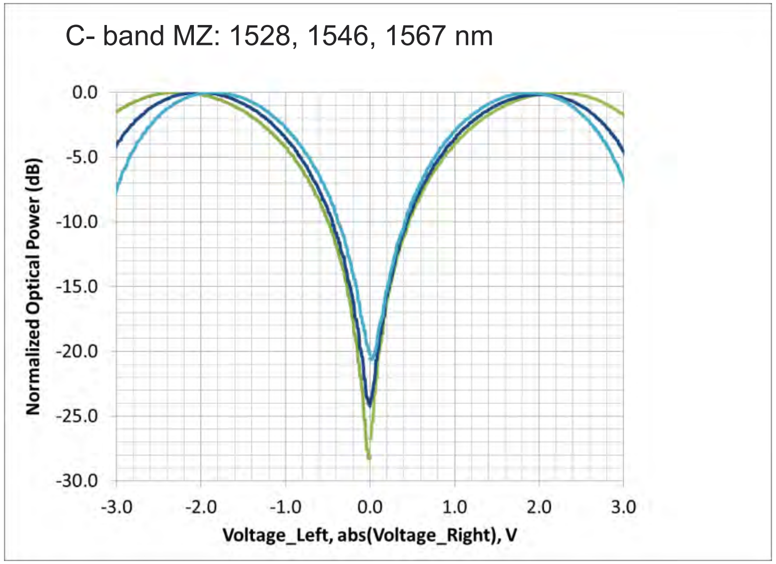


B2B Constellations

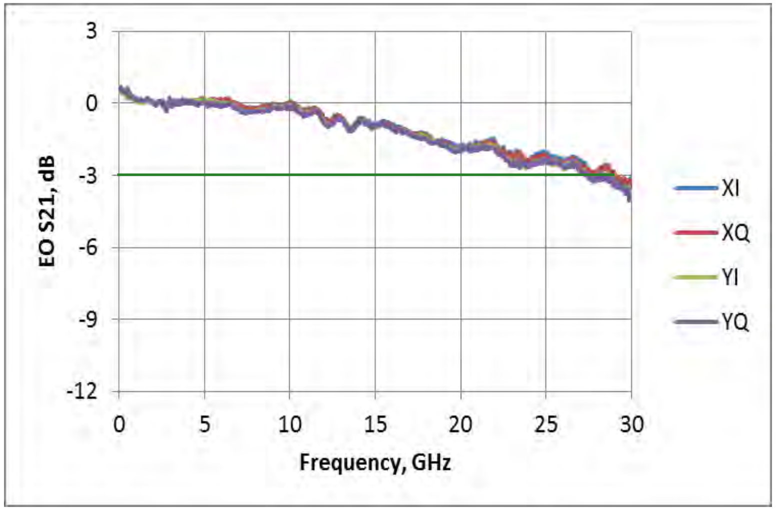
infinera®

C-band Tunable Integrated Coherent Transmitter PIC



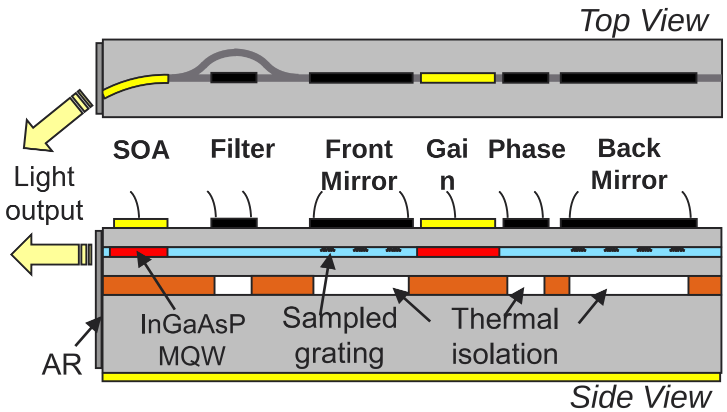


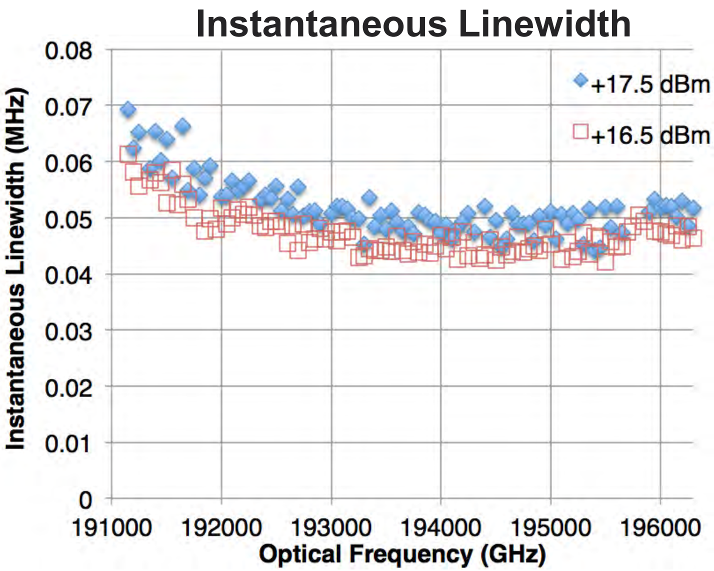
- Narrow Linewidth Sampled-Grating DBR laser
- Two quadrature Mach-Zehnder modulators
- High power LO output
- 3 SOAs
  - Independent power control for LO and each Tx polarization
  - VOAs
- InP PIC technology is employed for 32 Gbaud 100 and 200 Gb/s coherent pluggable modules

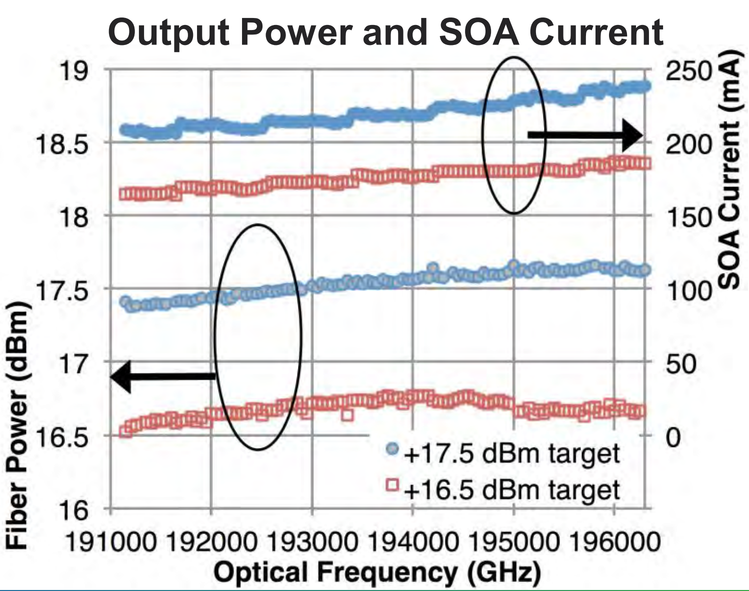


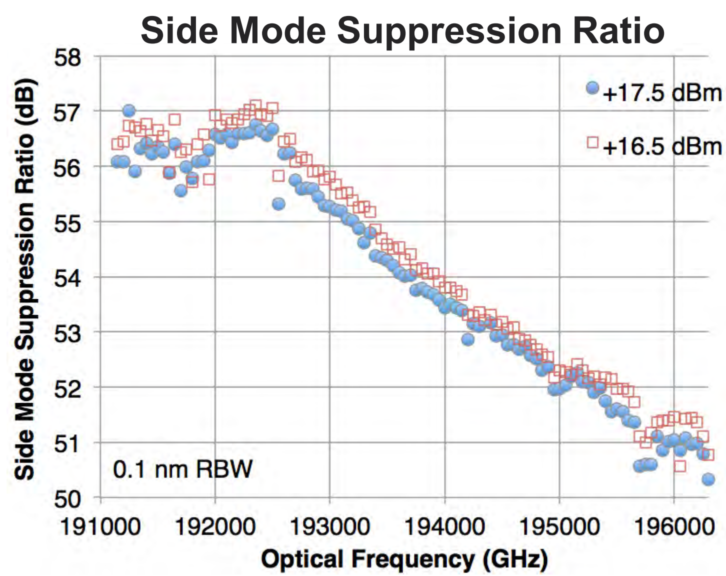
Narrow linewidth thermally-tuned SGDBR Laser

- 70kHz linewidth and 50dB SMSR at +17dBm fiber power over 41nm range in C-band



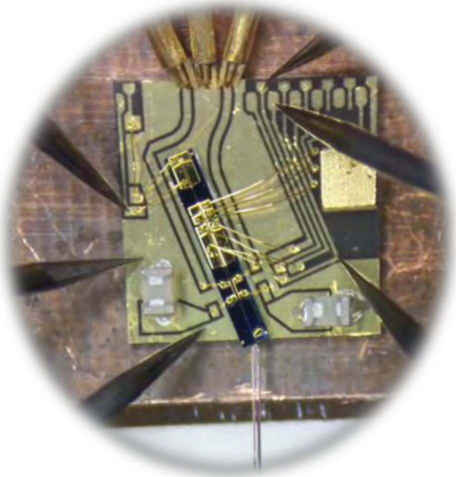


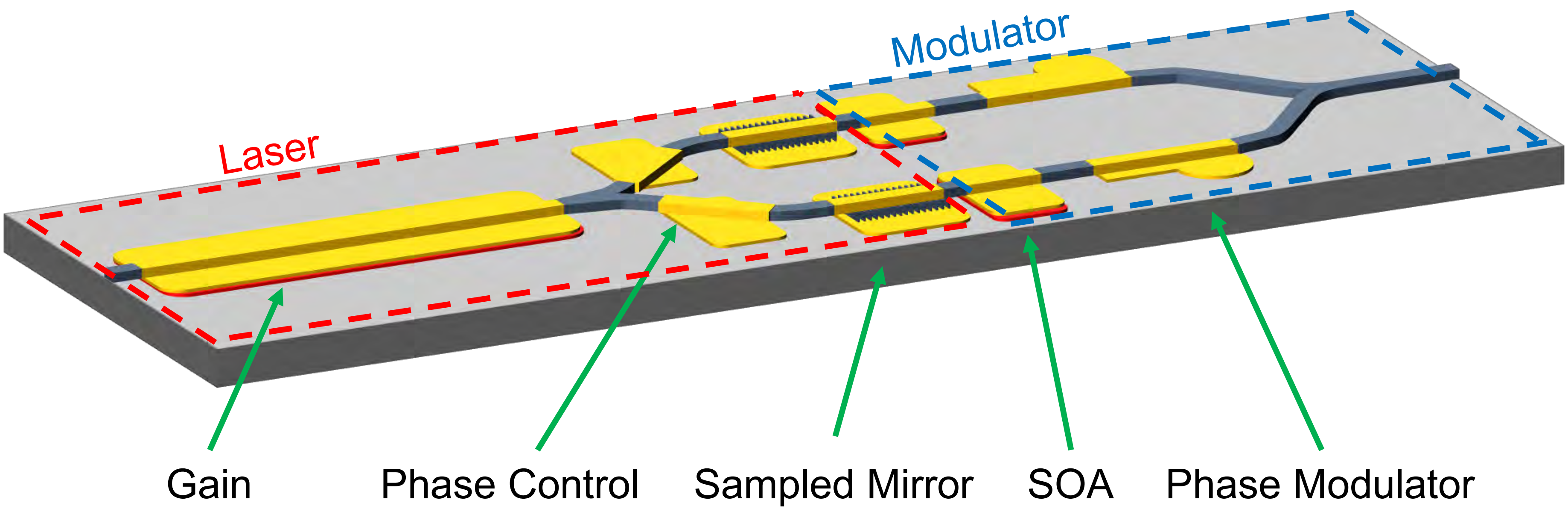




Tunable Interferometric Transmitter

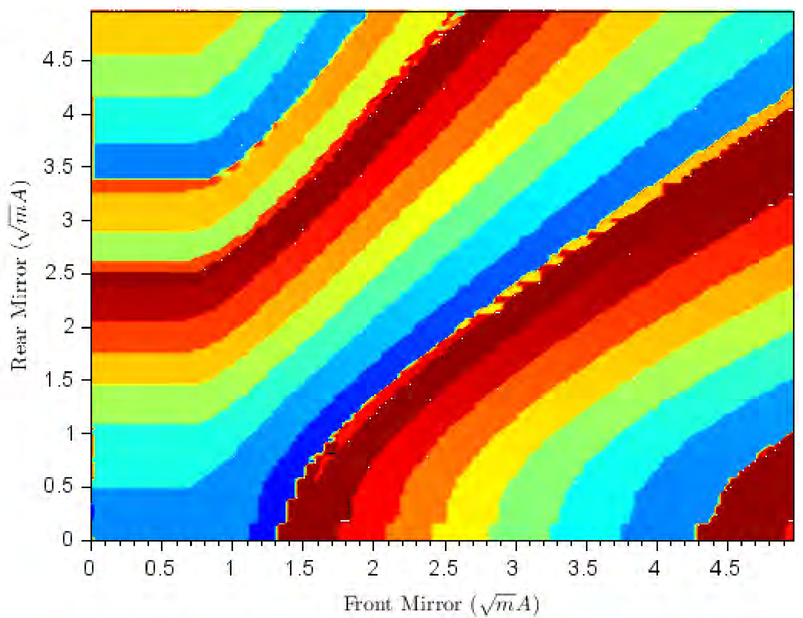
- Compact cavity (broadband HR back mirror used)
- Dual output laser – natural fit for interferometric modulation
- Lumped or traveling wave modulators
- (Optional) SOAs for power balancing

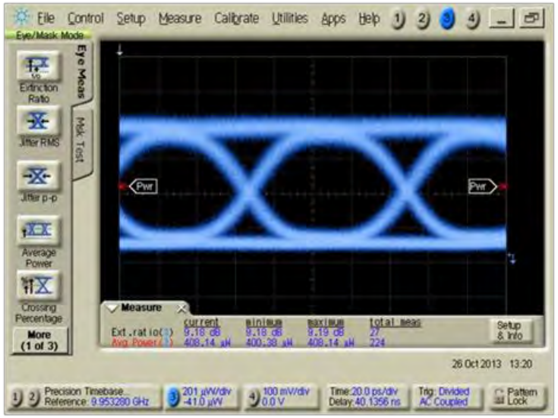




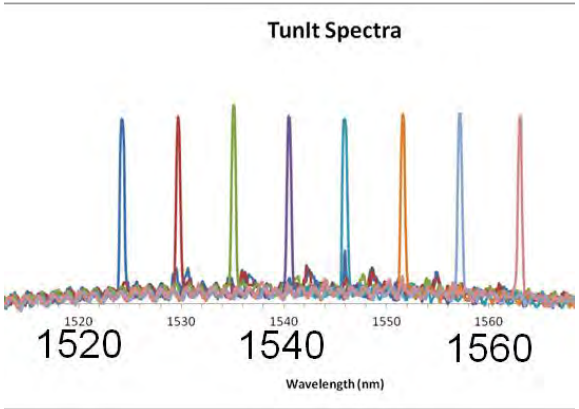
1550 nm Widely Tunable Interferometric Transmitter

- 50 dB SMSR
- 50 nm tuning range
- 12.5 Gbps operation
  - 25 Gbps in development
- Chirp control
- 80+ km reach in SMF-28 fiber

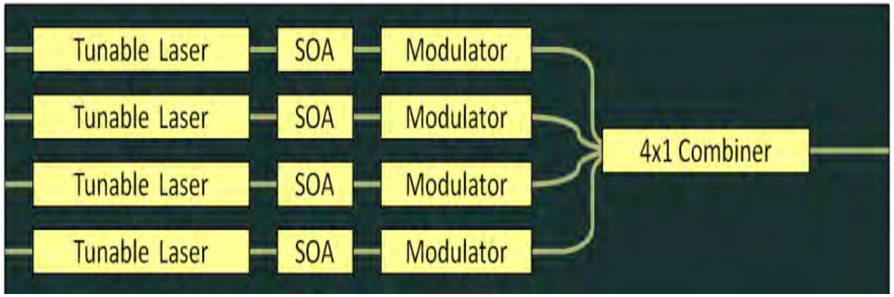


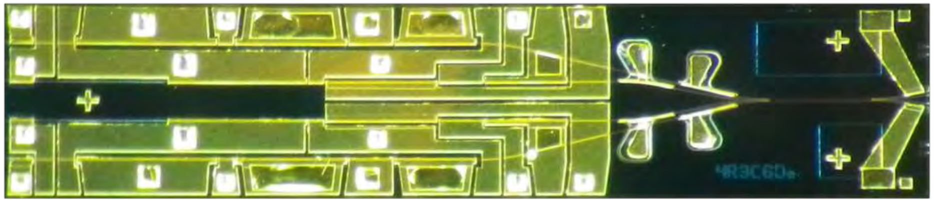


12.5 Gbps

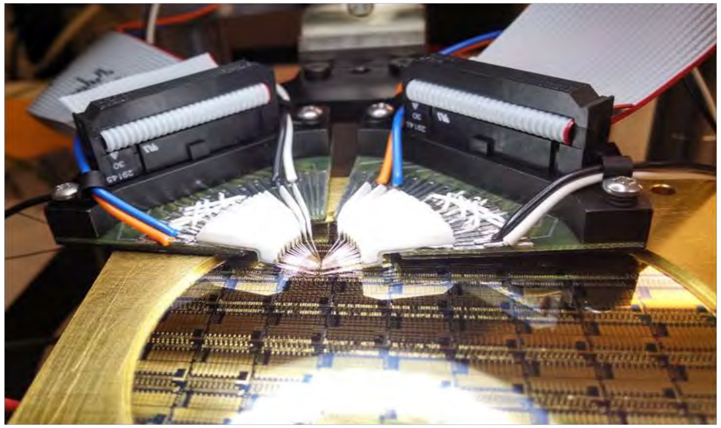


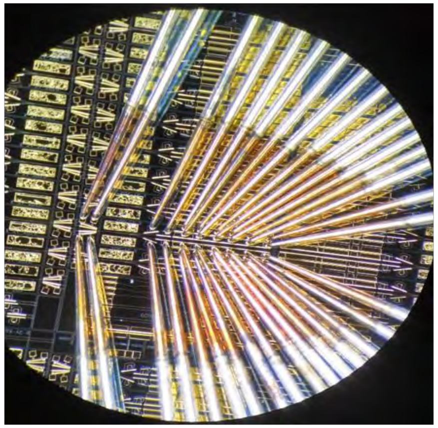
Quad Transmitter- Butt Joint Platform



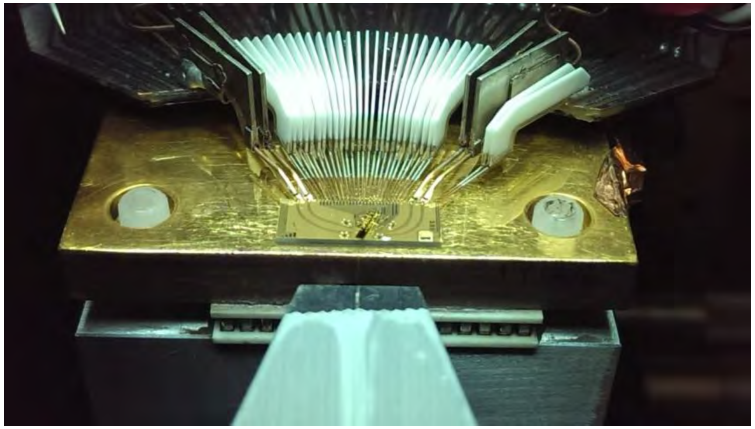


- Monolithic InP QUAD C-Band tunable Tx PIC with single output waveguide
- PIC operates at 55°C for reduced power consumption of TEC
- Individual SOAs amplify output power and enable VOA and blanking
- 12.5Gbps Electro-absorption modulators



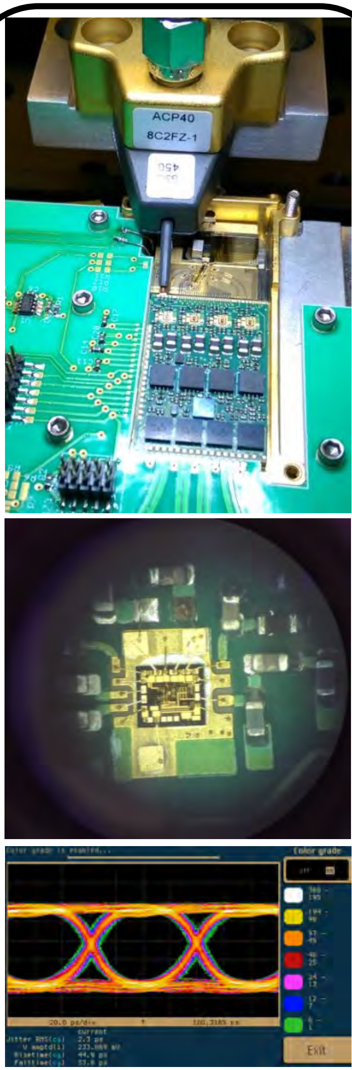


Wafer-Level Electrical and Optical Measurements



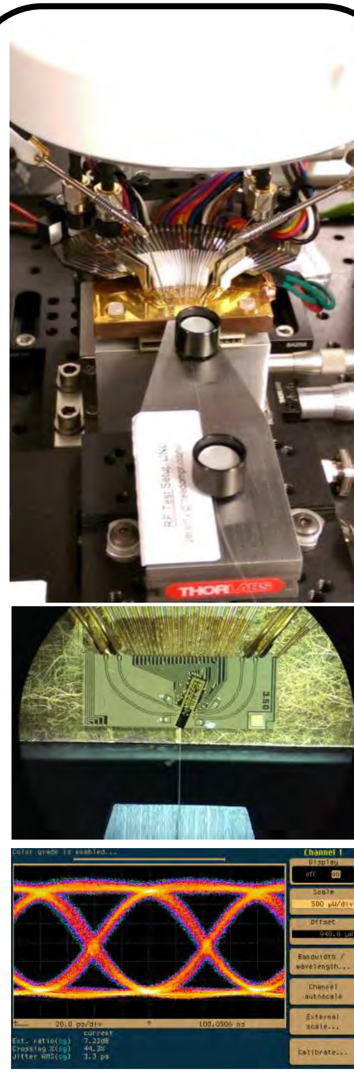
CoC CW and RF Testing

Quad Transmitter– RF Performance



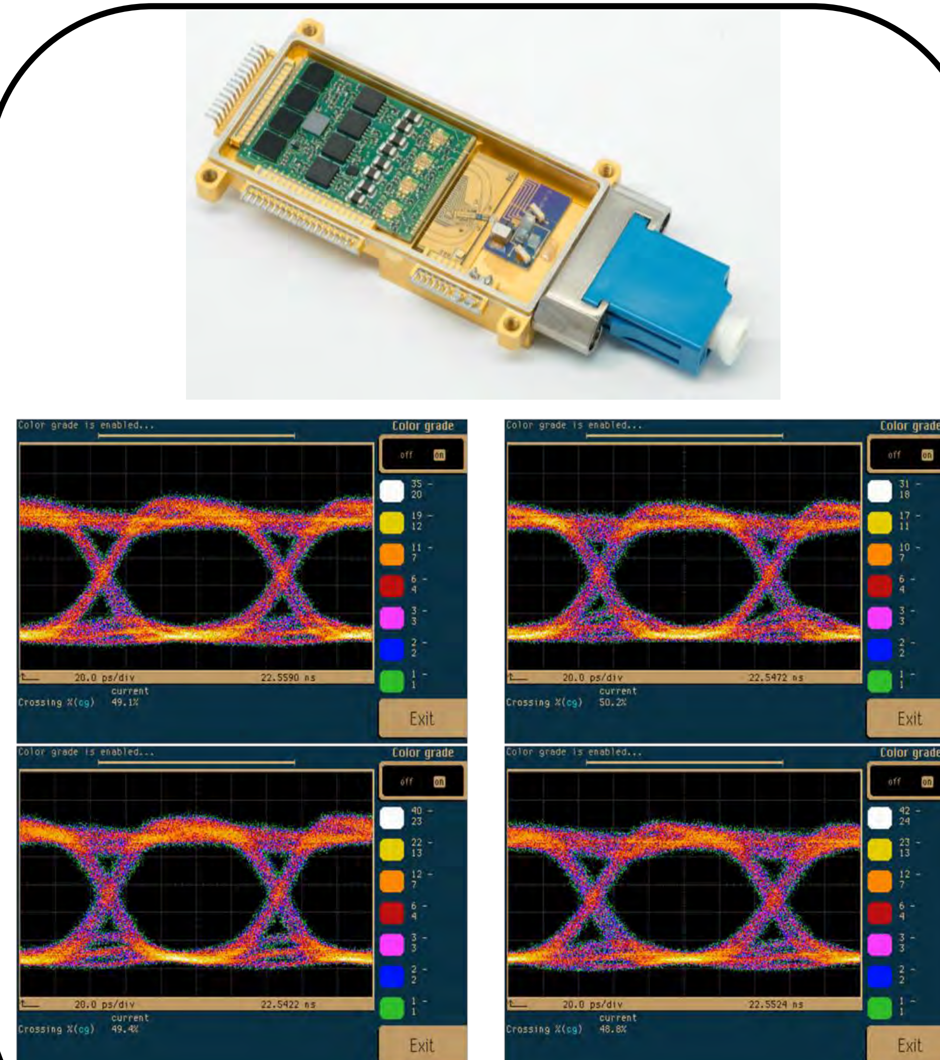
Driver E-E

12.5Gbps



CoC E-O

12.5Gbps



TOSA E-O, all Transmitters

(Non-optimized impedance of driver -> CoC transition) 10Gbps

Research Examples

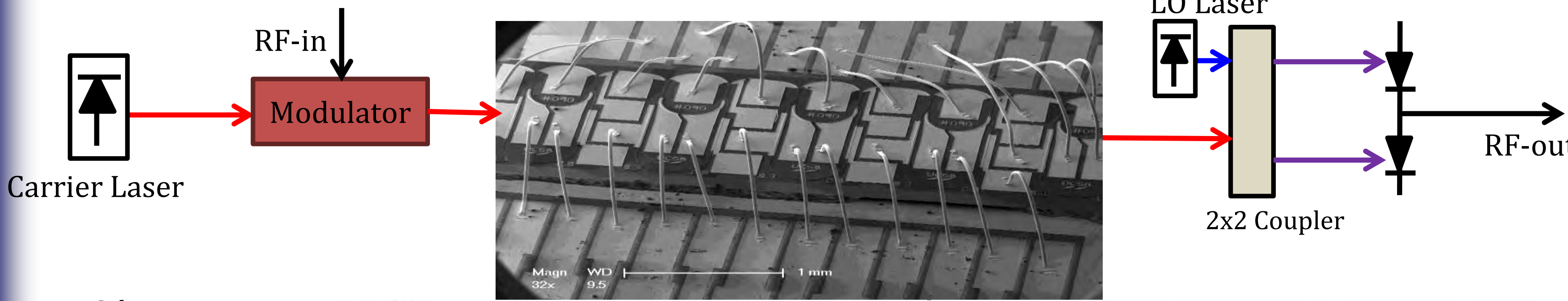
Background:

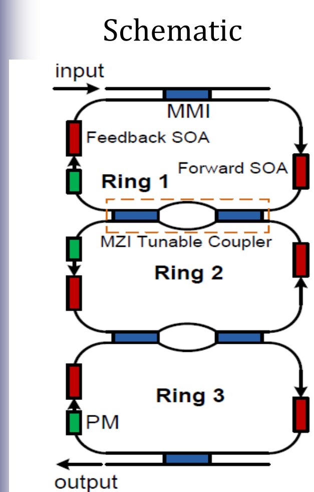
Microwave Filtering - with Integrated Photonics

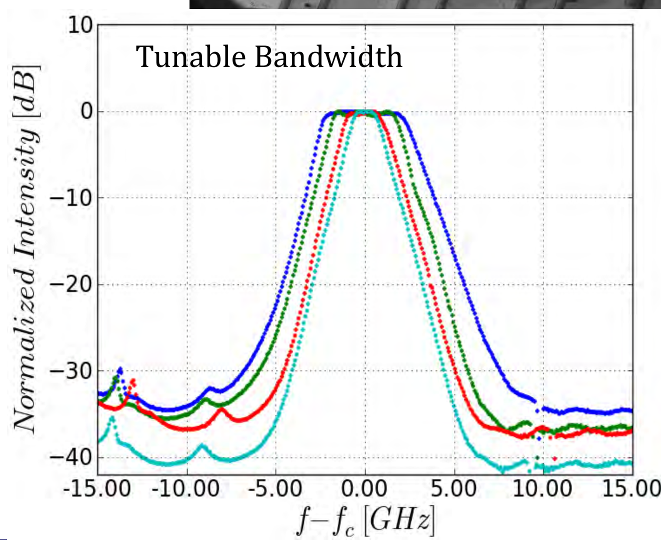
Demonstrated reconfigurable photonic filter - using an active InGaAsP platform and deeply etched waveguides

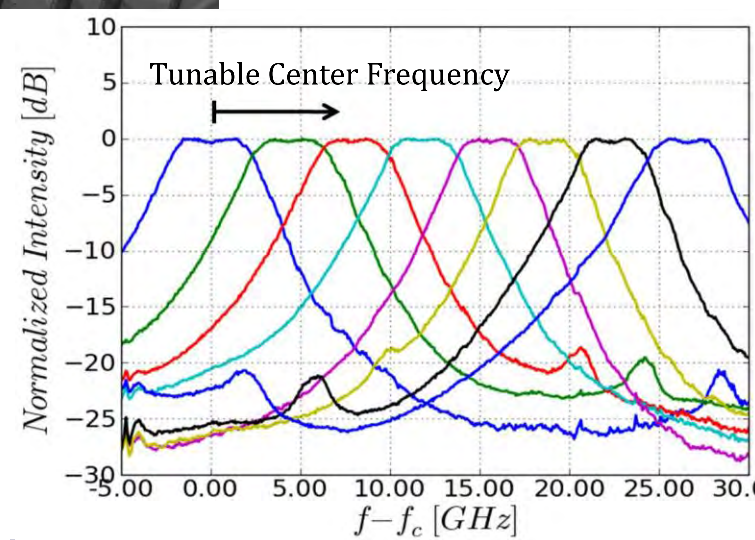
→ Novel filter characteristics – unmatched by electrical RF filters!

(Optimum NF @ SOA gains to give near zero net filter insertion loss)







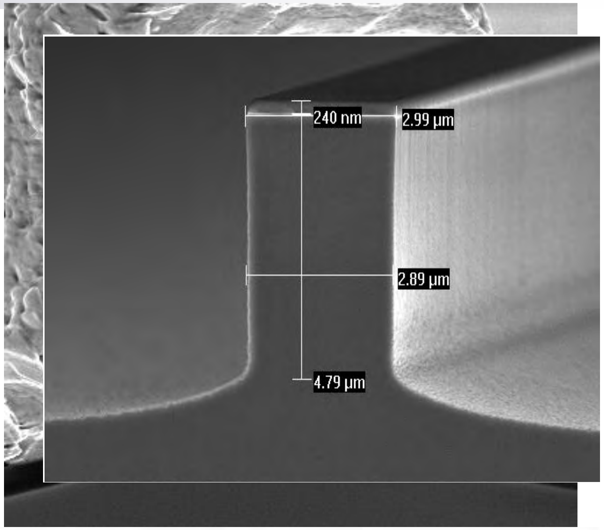


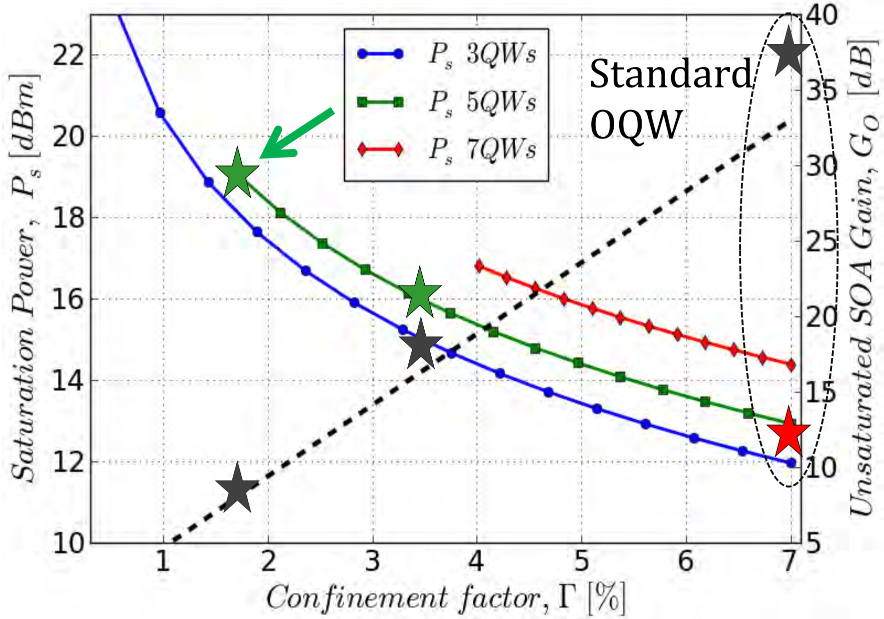
*E J. Norberg, R S. Guzzon, J S. Parker, L A. Johansson and L A. Coldren, "Programmable Photonic Microwave Filters Monolithically Integrated in InP/InGaAsP", J. Lightwave Technol, vol. 29, no. 11, 2011

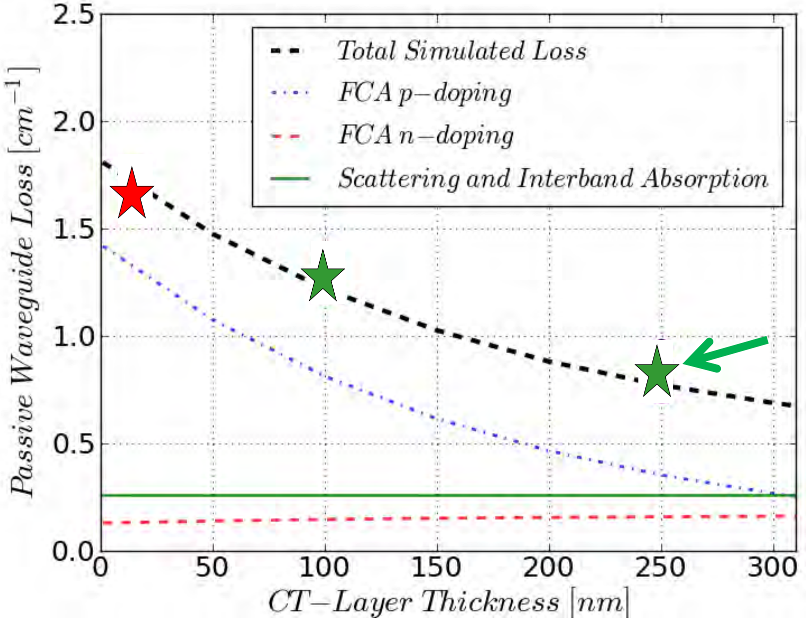
Erik Norberg

Integration Platform – Saturation and Loss

- Passive loss reduces with increased CT-Layer thickness
  - **0.35 dB/mm** passive waveguide loss using deeply etched waveguides (of which scattering loss 0.12 dB/mm)
- Saturation power of **19 dBm** (78 dB/cm gain)
  - Highest P_s reported for ridge width ≤3 µm

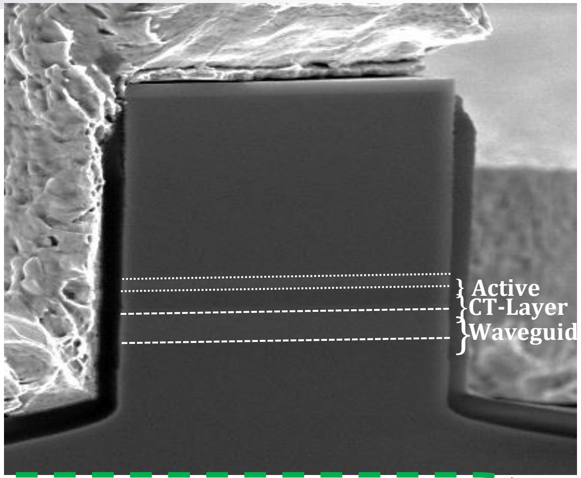


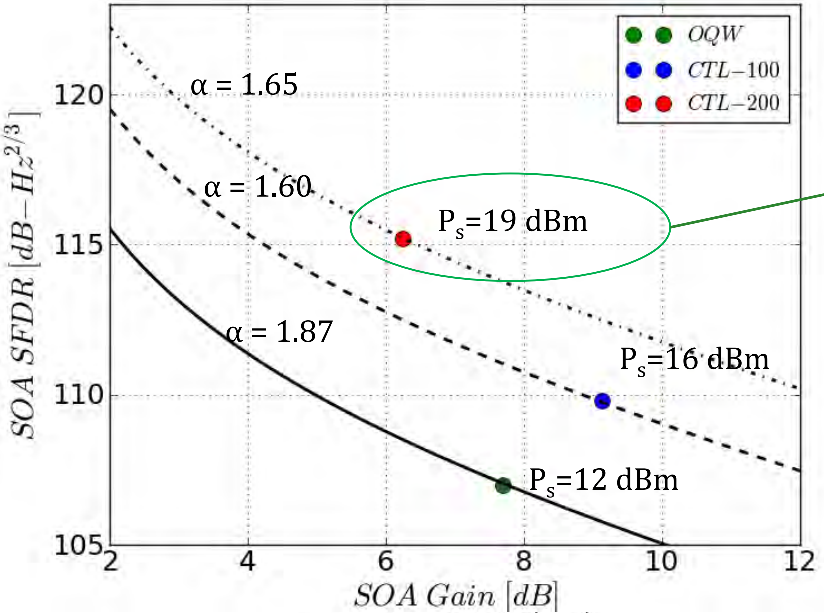




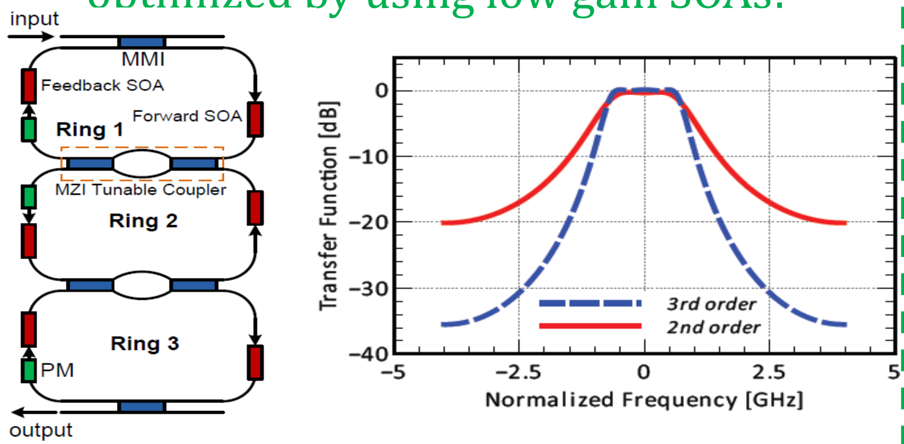
Integration Platform – RF-linearity results

- RF-linearity improves with lower confinement material platform
  - Best RF-linearity reported for SOAs
- SOAs demonstate ~4 dB noise figure (w\o coupling loss)
- SOA demonstrates useful SFDR performance!
  - Design devices with short SOAs (G small)





SFDR of integrated tunable filter can be optimized by using low gain SOAs!**



Device **SFDR >115dB-Hz$^{2/3}$** is predicted!**

Robert S. Guzzon, Erik J. Norberg, and Larry A. Coldren,"Spurious-Free Dynamic Range in Photonic Integrated Circuit Filters with Semiconductor Optical Amplifiers", *JQE*, **48 (2) p269-278 (2012)

 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 32, NO. 20, OCTOBER 15, 2014
W4G.1.pdf OFC 2017 © OSA 2017

A Photonic Temporal Integrator With an Ultra-Long Integration Time Window Based on an InP-InGaAsP Integrated Ring Resonator

OFC 2017

Weilin Liu, *Student Member, IEEE*, Ming Li, *Member, IEEE*, Robert S. Guzzon, Erik J. Norberg, John S. Parker, Larry A. Coldren, *Life Fellow, IEEE, Fellow, OSA*, and Jianping Yao, *Fellow, IEEE, Fellow, OSA*

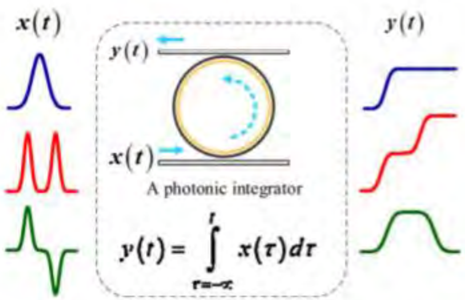


Fig. 1. The schematic diagram of a photonic temporal integrator based on a microring resonator.

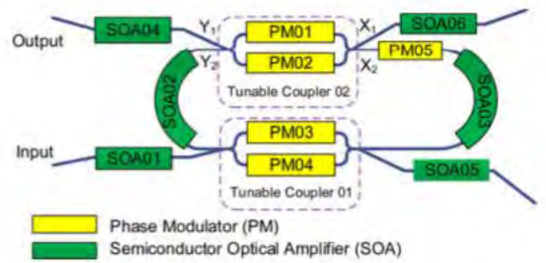


Fig. 2. The schematic of the proposed on-chip photonic temporal integrator based on a microring resonator.

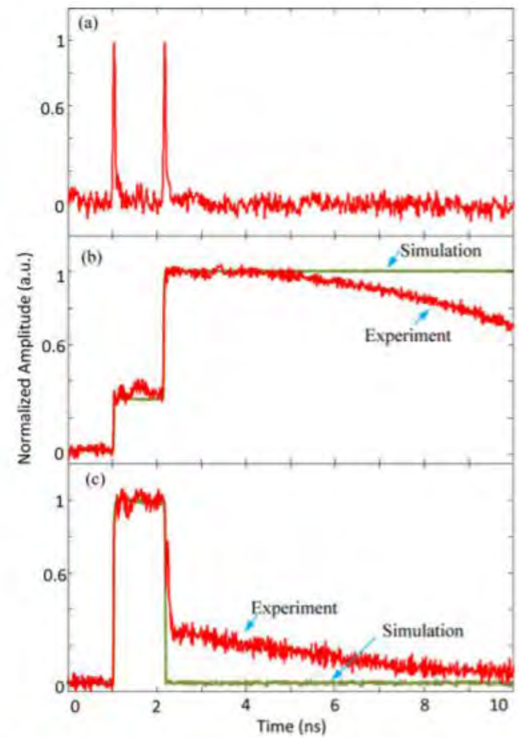


Fig. 8. The experimental results. (a) The input in-phase doublet pulse, (b) the integral of the in-phase doublet pulse, and (c) the integral of the out-of-phase doublet pulse.

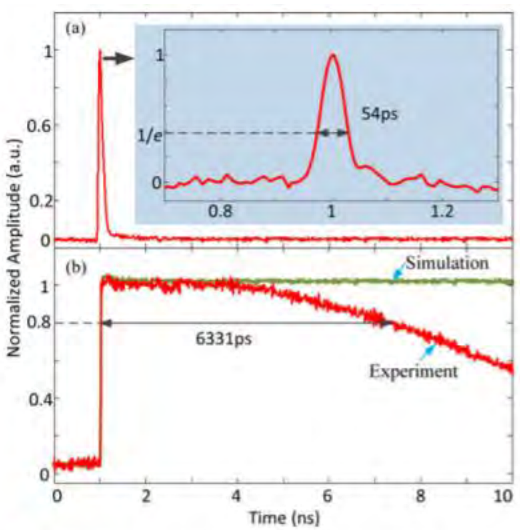
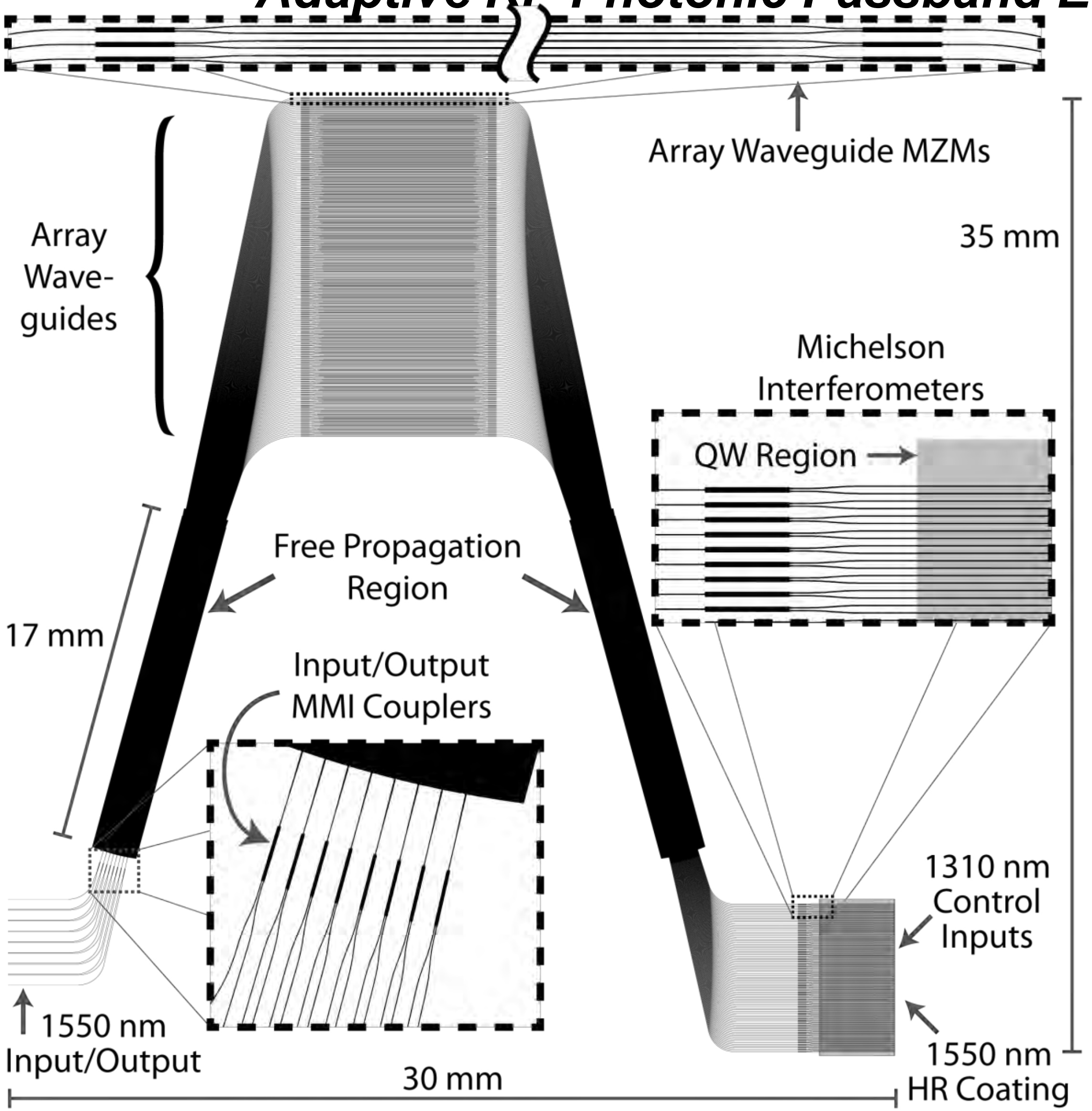


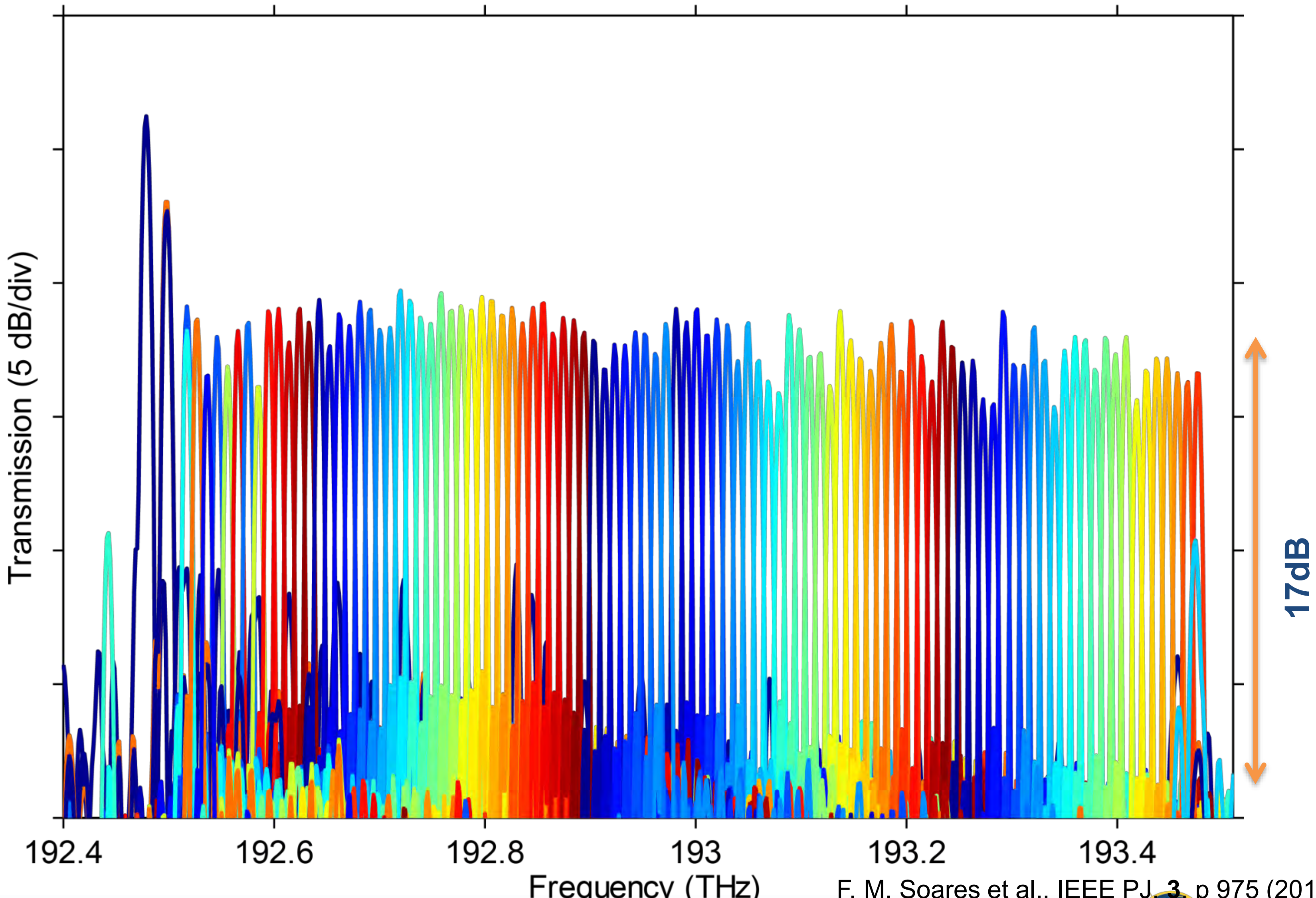
Fig. 7. The experimental results. (a) The input Gaussian pulse with a temporal width of 54 ps. (b) The integral of the Gaussian pulse with an integration time window of 6331 ps.

1 THz, 100×10 GHz monolithically integrated InP OAWG with Built-in Adaptive RF-Photonic Passband Engineering



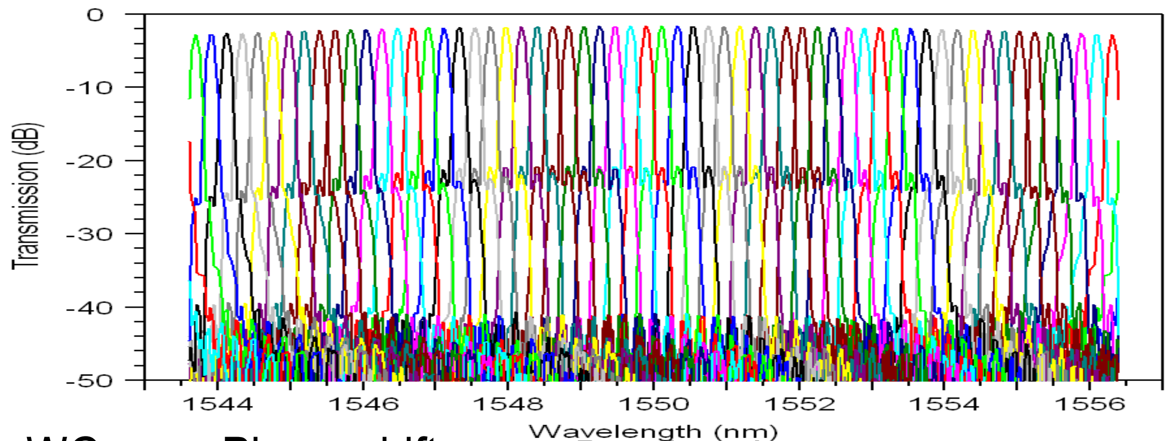
F. M. Soares et al., IEEE PJ, **3**, p 975 (2011)

100ch x 10 GHz AWG Output Spectrum After Phase-Error Correction

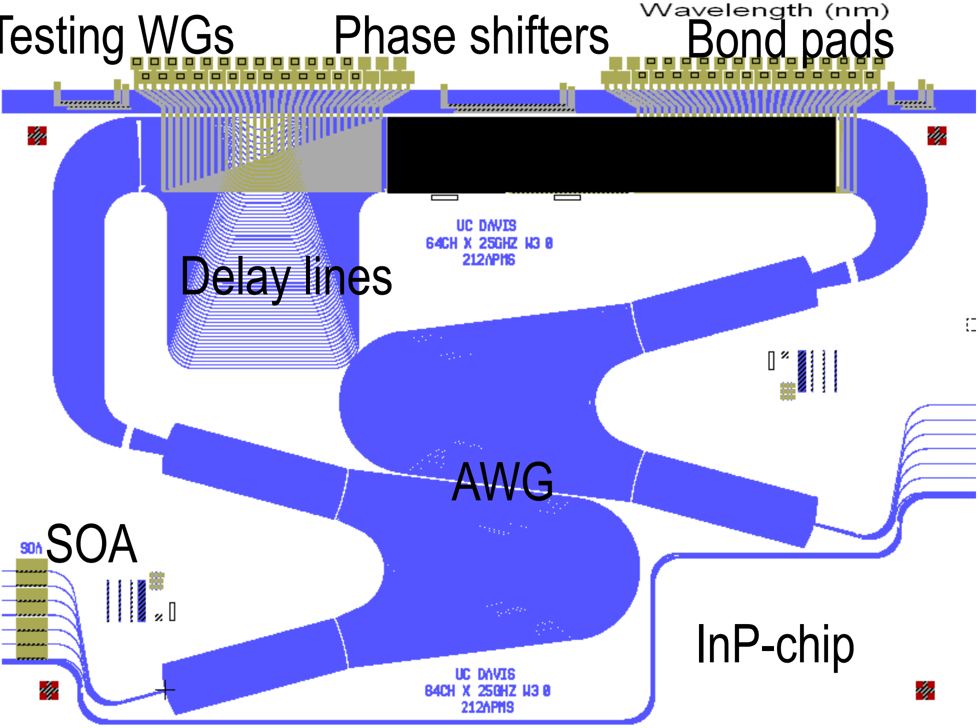


F. M. Soares et al., IEEE PJ, **3**, p 975 (2011)

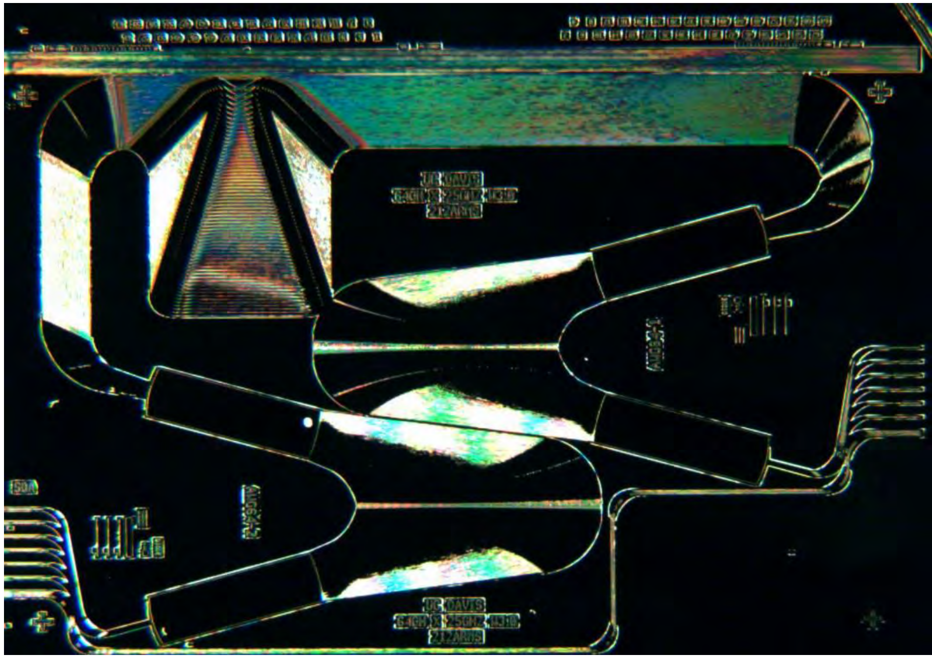
64 channel O-CDMA encoder/decoder



64 channel
25 GHz spacing
16.8x11.4 mm^2



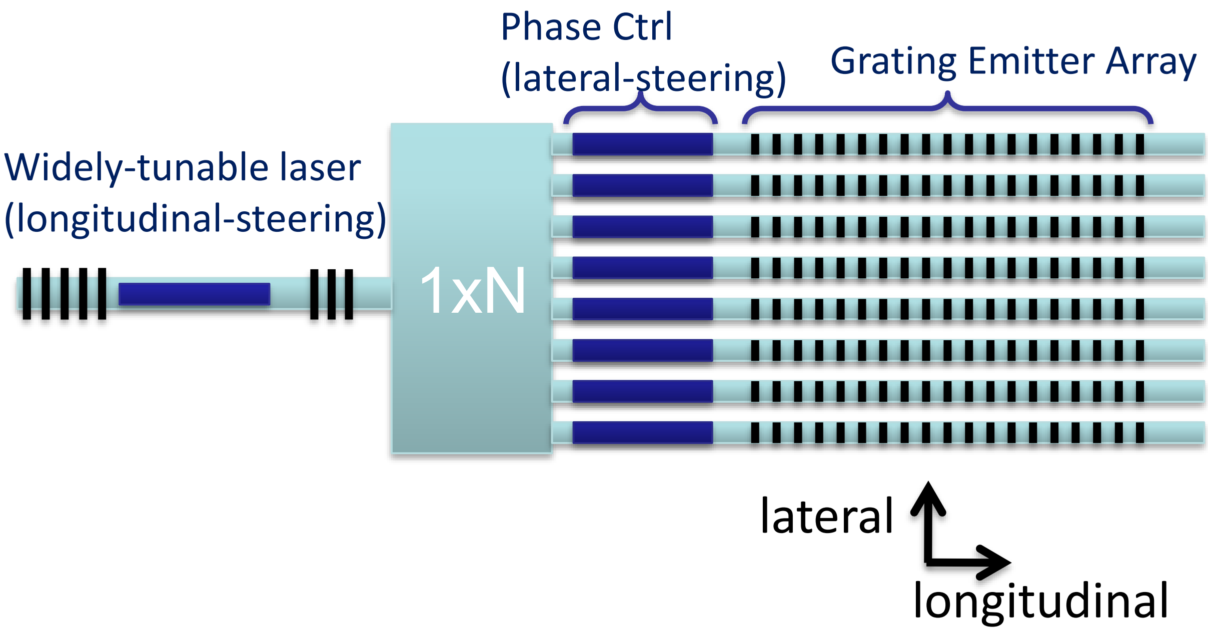
16.8 x 11.4 mm^2

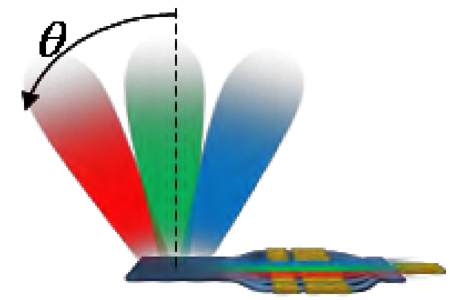


UCSB

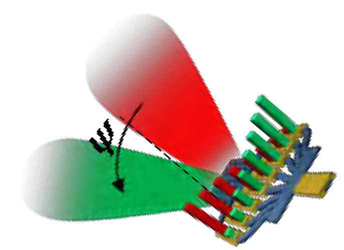
2D-Beam Sweeping

- **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**

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

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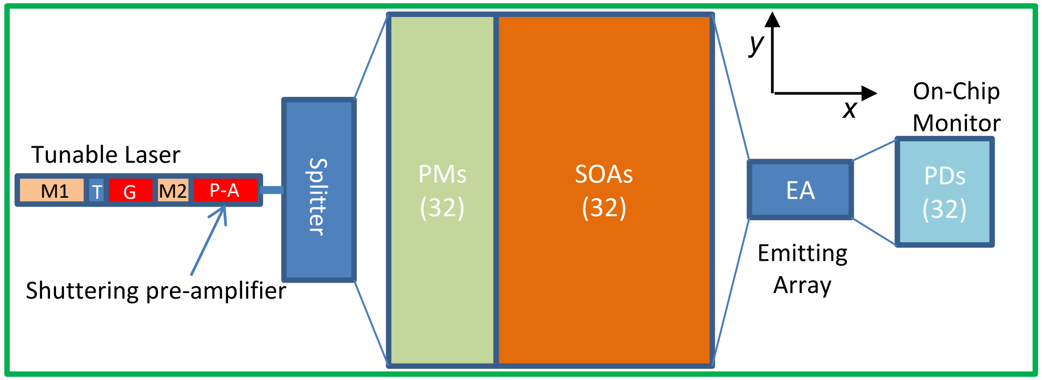
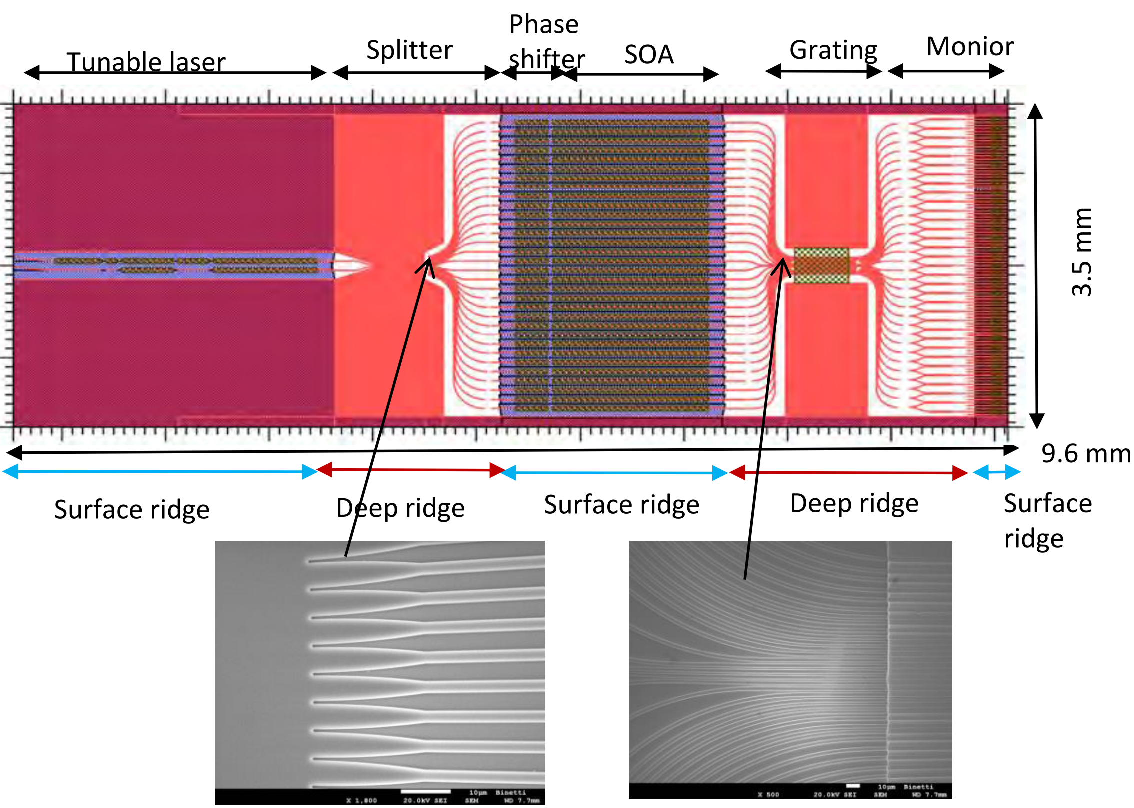
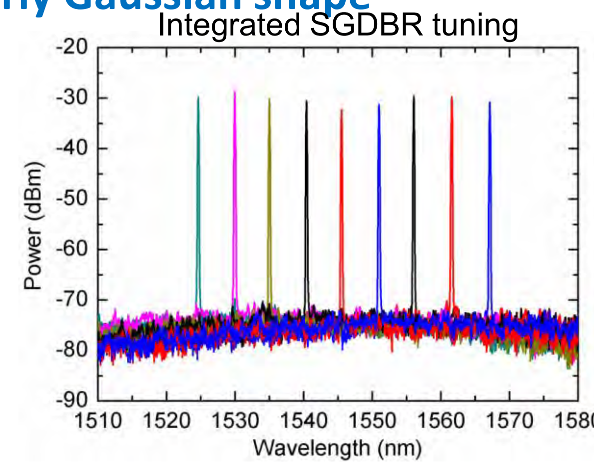
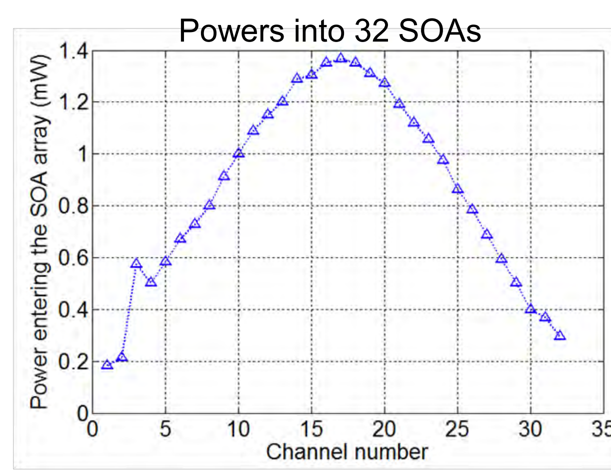


- Waveguide spacing varied to suppress lateral side lobes.
- Grating duty-factor weighted to extend effective length
- Nearly Gaussian shape



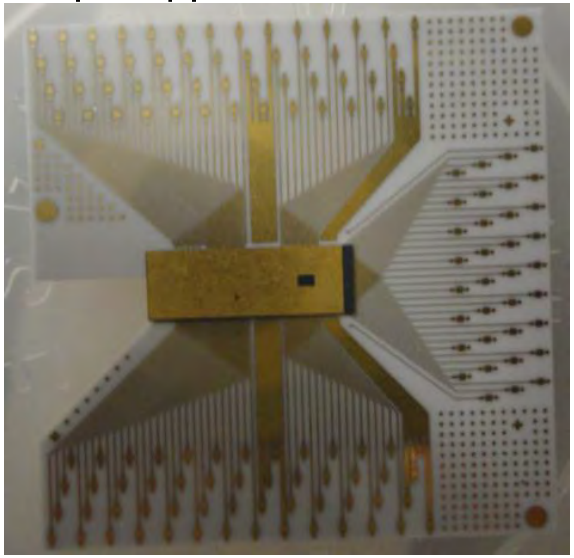




2D Beam Sweeping results (32 x N)

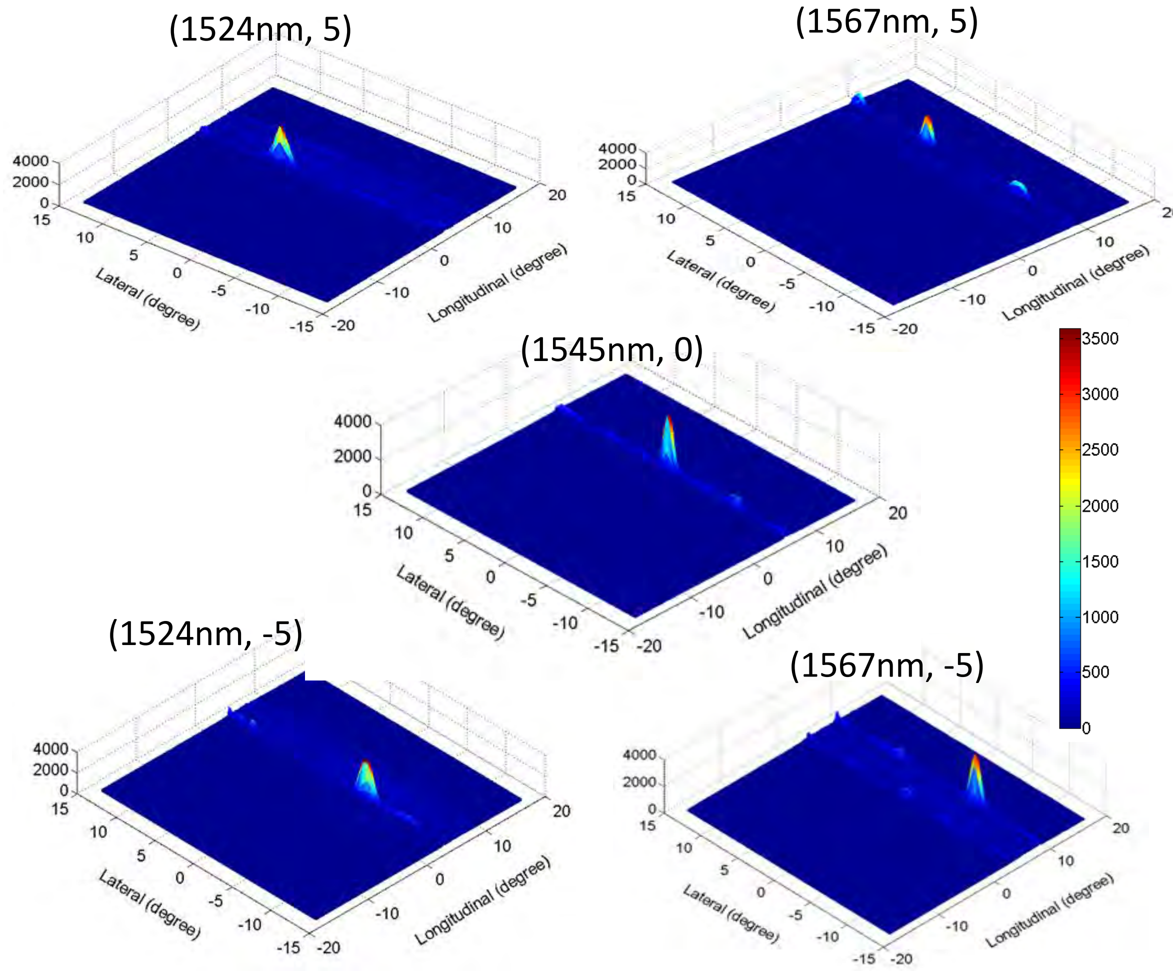
W4G.1.pdf OFC 2017 © OSA 2017

Flip-chipped PIC-on-carrier

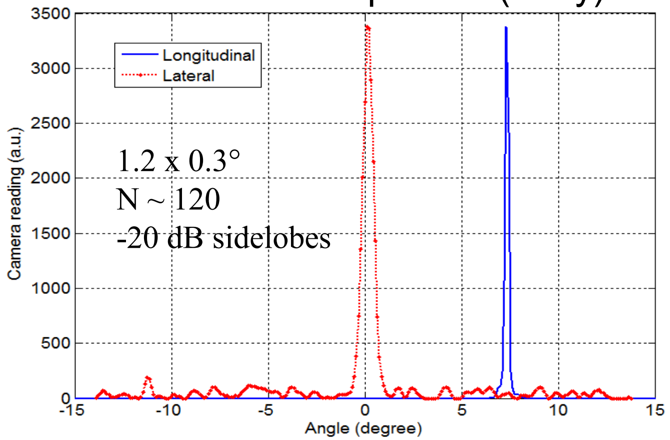


110 good contacts

- 2D beam steering demonstrated

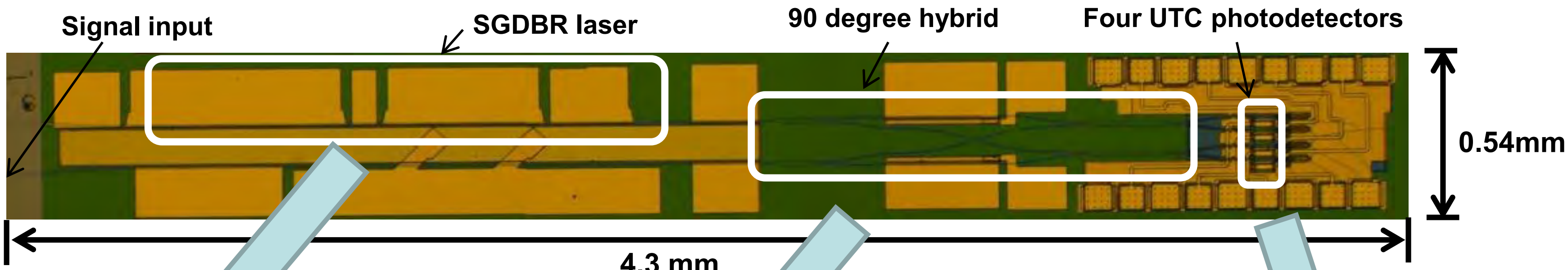


Far-field beam profiles (x & y)

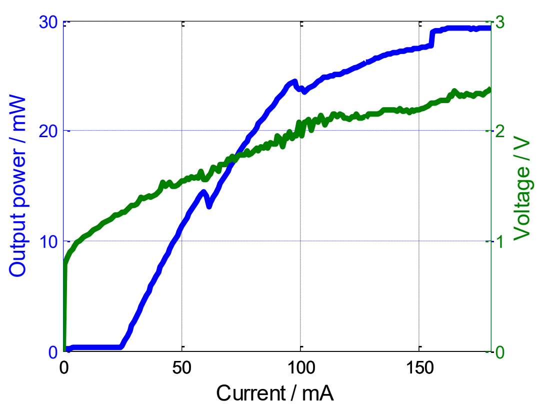


InP Widely-tunable Coherent Receiver PIC

(Phase-locked or Intradyne—also for Optical Synthesis)



- **SG-DBR laser**

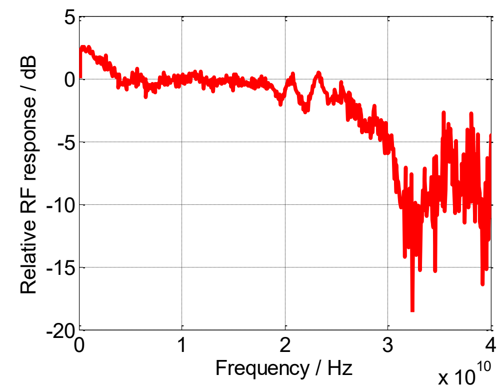


- **30 mW output power**
- **40 nm tuning range**
- **25 mA threshold current**

- **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.***

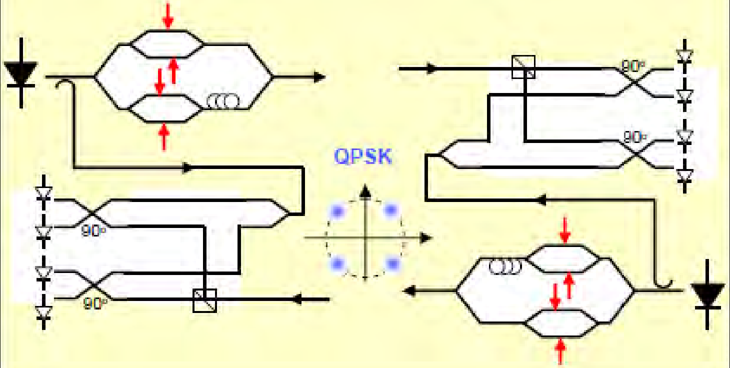
Mingzhi Lu, et. al., Optics Express, Vol. 20, Issue 9, pp. 9736-9741 (2012)

Intradyne or Phase-locked Receivers for generic sensor, instrumentation, or short-reach communication application?

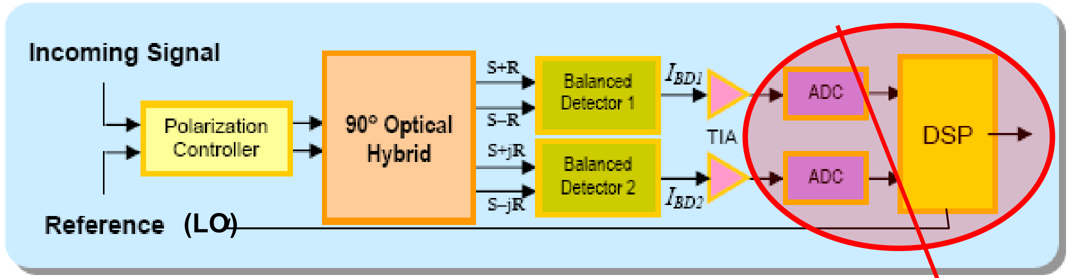
UCSB

Intradyne Coherent Detection

- Phase and polarization diversity
- Frequency-locked local oscillator
- Digital signal processing of received electrical signals
  - Electronic CD compensation
  - Electronic polarization demultiplex
  - Adaptive PMD compensation



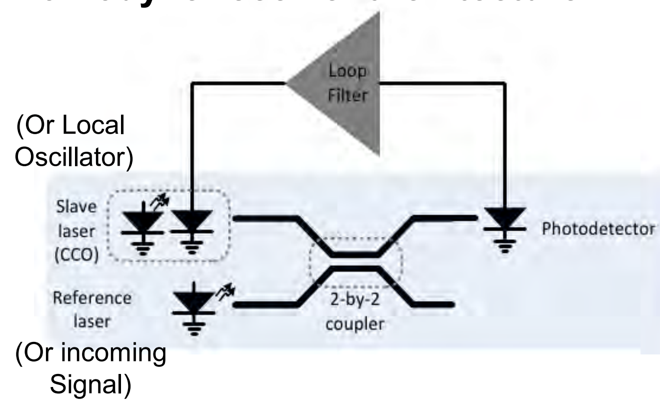
Typical Intradyne receiver architecture



But for short-modest reach:

"Analog Coherent"

Homodyne receiver architecture



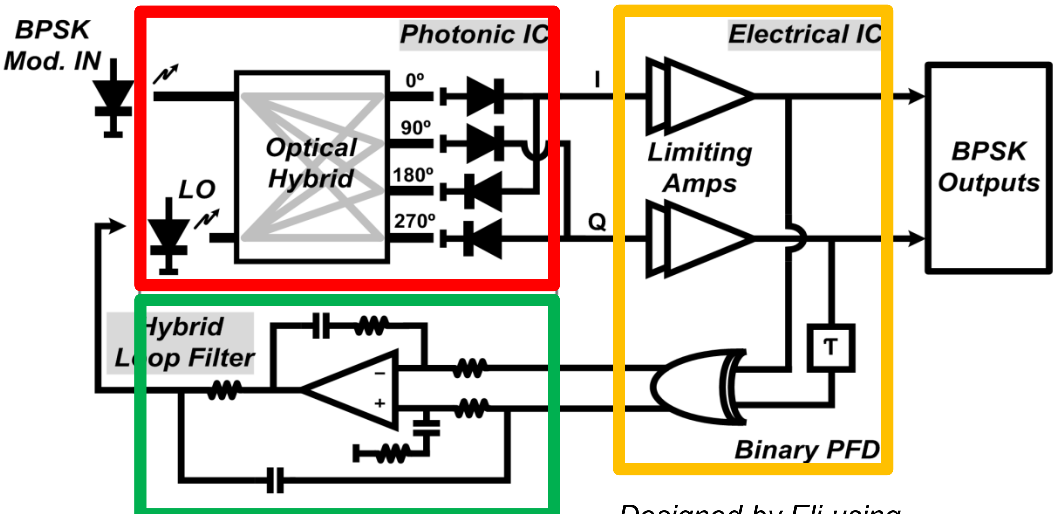
❖ **Use Phase-locked detection instead of power-hungry and costly Intradyne/ADC-DSP?**

- **Integrated Costa's loop receivers with widely-tunable LOs have been explored**
- **High-speed A/Ds & DSPs require lots of power and are expensive to design, especially as data rate increases**
- **Short feedback loops narrow LO linewidth and enable rapid and robust phase locking.**
- **Some impairments can be removed with much slower, lower-power, lower-cost signal-processing.**

Phase Locked Coherent BPSK Receiver "Analog Coherent"

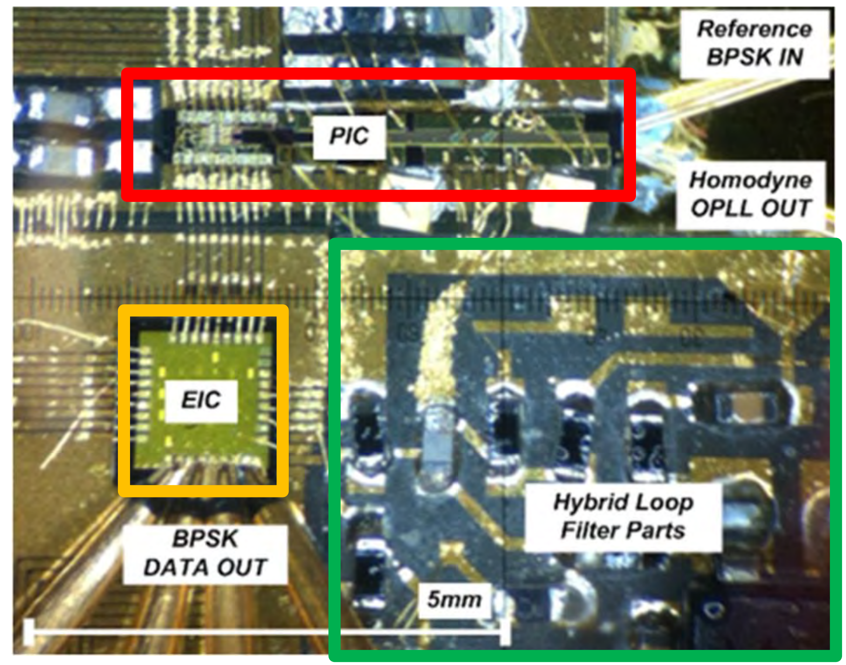
OPLL + Costas Loop → 1 cm^2 footprint

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)

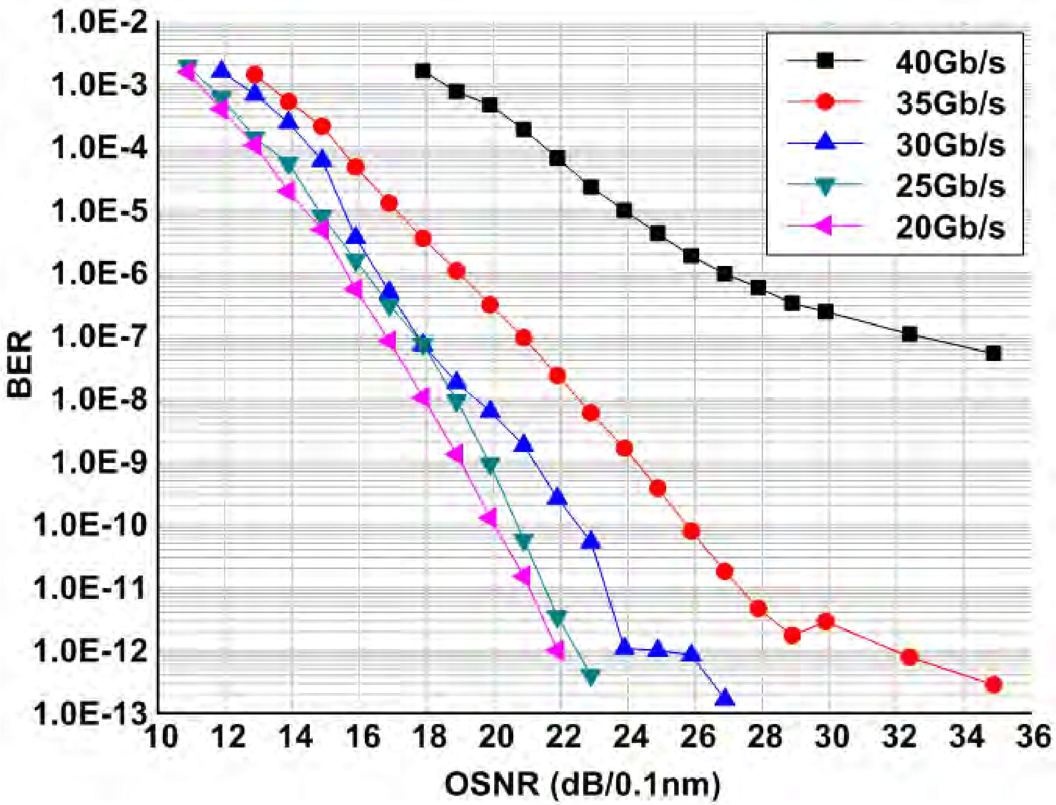
Hybrid loop filter: Feed-forward technique, op-amplifier and 0603 SMDs

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

BPSK Data Reception—BERs
"Analog Coherent"

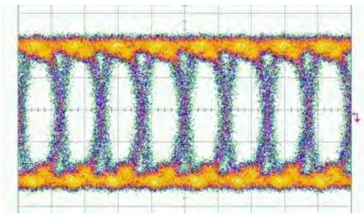
BER vs. OSNR (20Gb/s to 40Gb/s)

Error-free up to 35Gb/s , < 1.0E-7 @ 40Gb/s

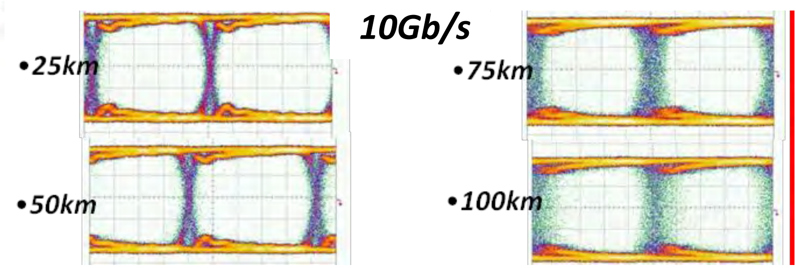


- **1.1GHz** closed loop bandwidth
- **120ps** loop propagation delay
- **100kHz** SGDBR-linewidth *(as ref. laser)*
- **-100dBc/Hz@above 50kHz** phase noise
- **600ns** frequency pull-in time
- **<10ns** phase lock time

40Gb/s Back-to-back



10Gb/s



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

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Reduced-Linewidth Rapidly-Tunable Laser

Optical Frequency Locked Loop

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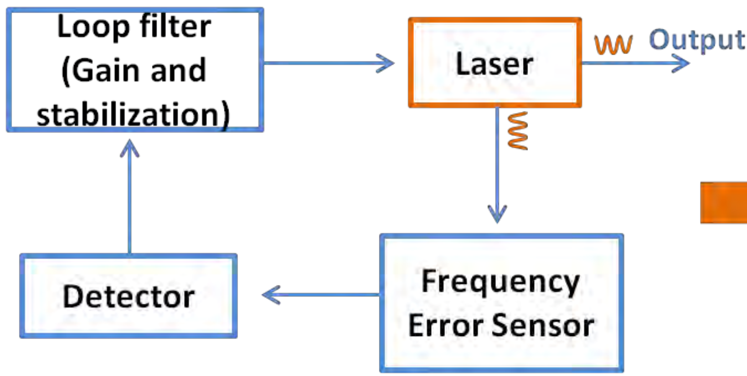
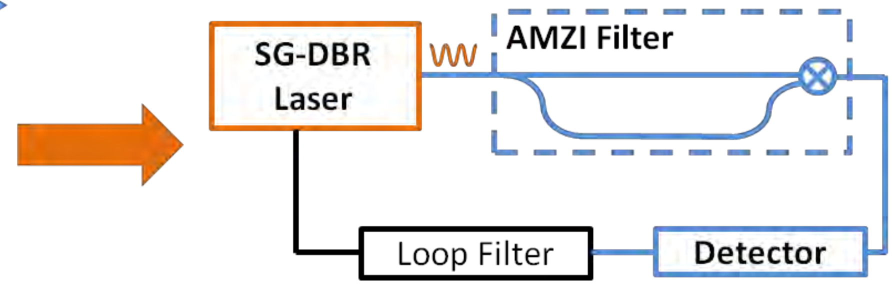
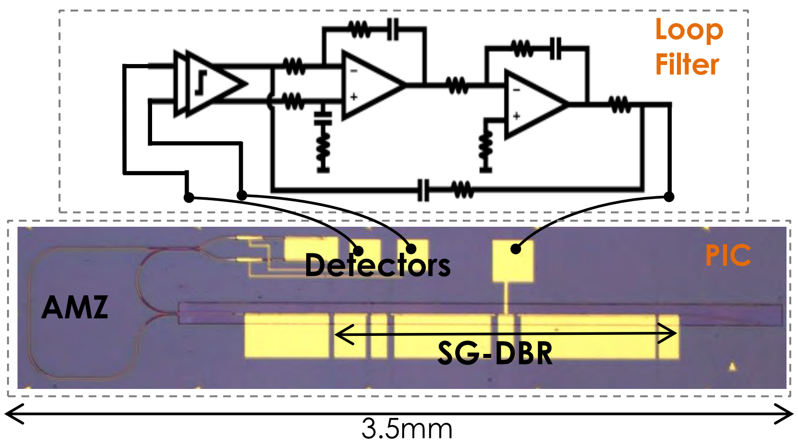
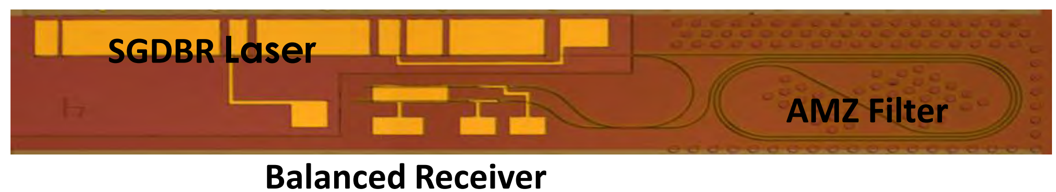
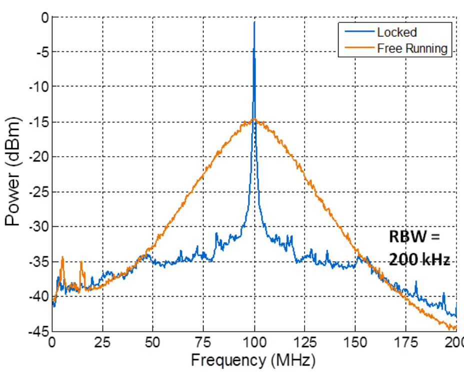


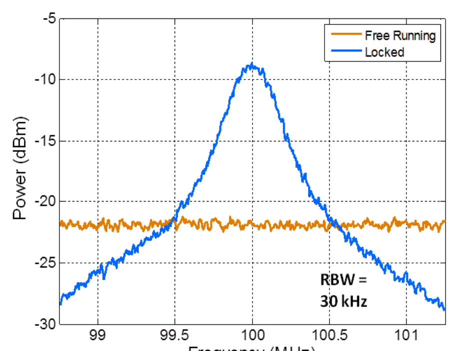






- Laser – SGDBR (40 nm tunability)
- Frequency Error Sensor – Asymmetric MZI
- Filter FSR = 10 GHz



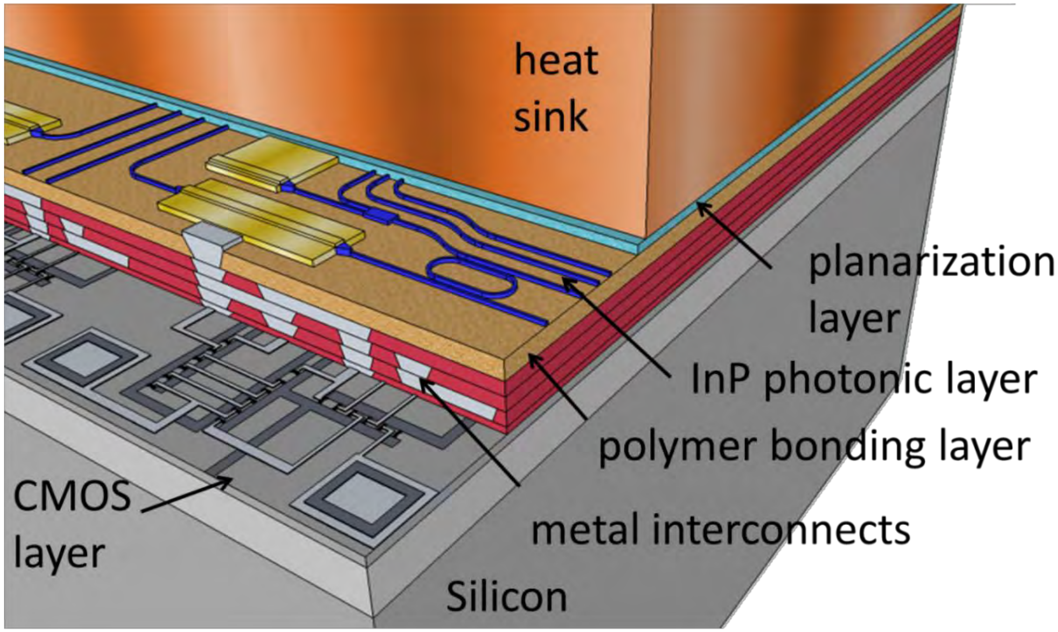


- Open loop→ > 5MHz linewidth
- Closed loop →150 kHz linewidth

A. Sivananthan, et al, OFC, 2013

Electronic-Photonic Integration

- **Single-chip vs 2.5 or 3-D integration?**



Horizon 2020
2016-2018
wipe.jeppix.eu

Connecting high performance foundry Silicon Electronics to
high performance foundry InP photonic ICs

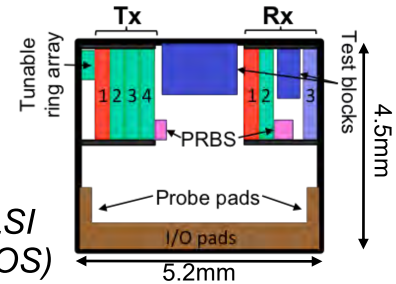
Minimizing interconnects for speed and energy efficiency

Simplifying assembly

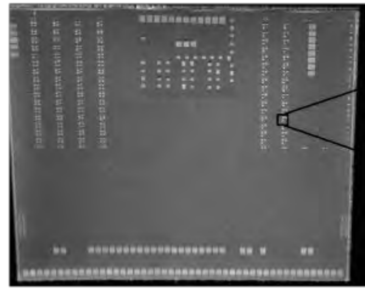
Technische Universiteit Eindhoven University of Technology

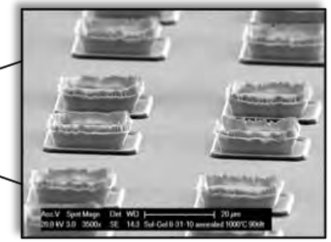
Hybrid integration technology

VLSI chip

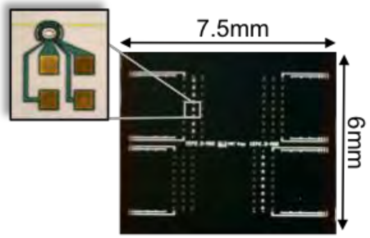


Oracle VLSI (40nm CMOS)

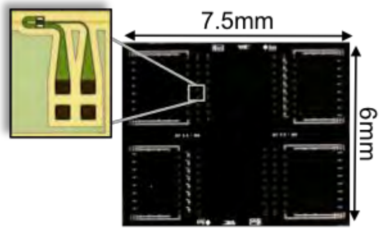




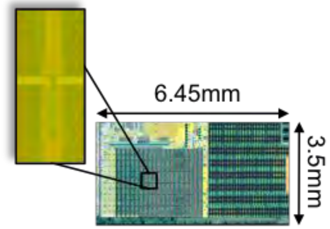
Photonic chip



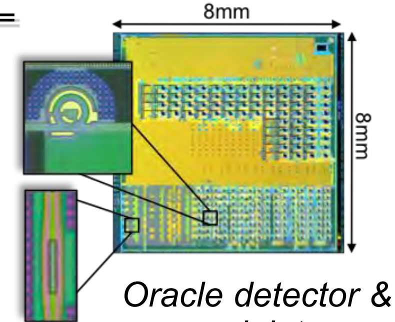
Kotura modulator



Kotura detector



Luxtera detector

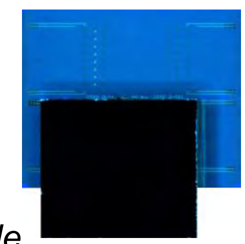


Oracle detector & modulator

Hybrids

Tx

Kotura-Oracle

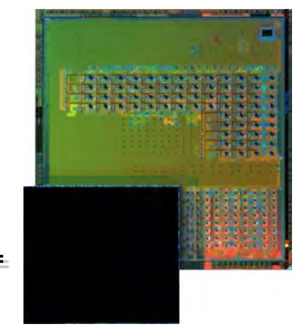


Rx

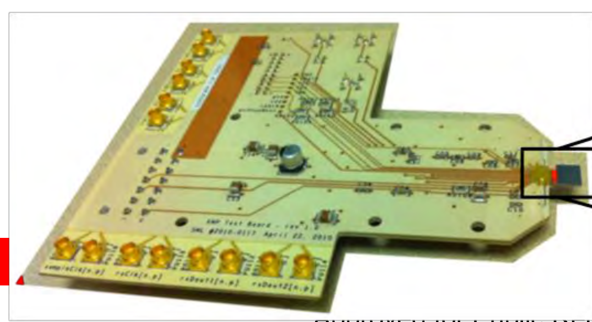
Luxtera-Oracle

Tx-Rx

Oracle

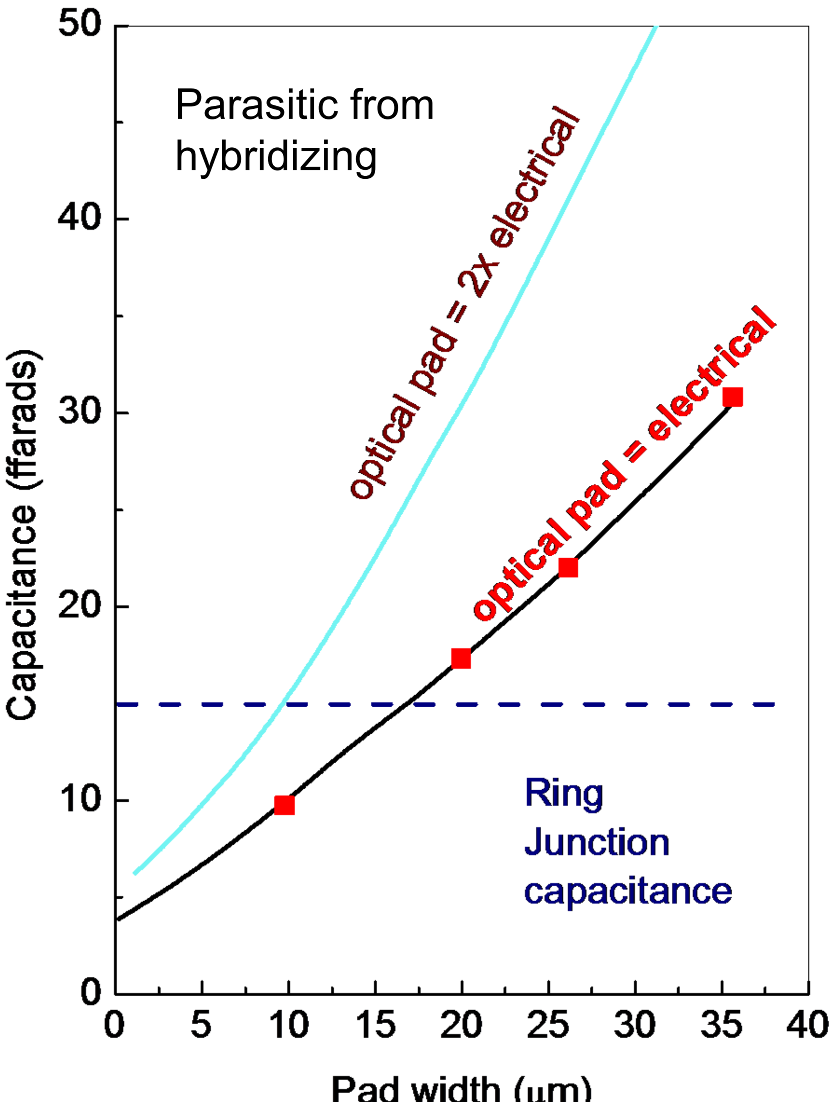


Assembled test vehicle



H.Thacker et al ,ECTC 2011, pp. 240-246, 2011.

Hybrid integration scaling



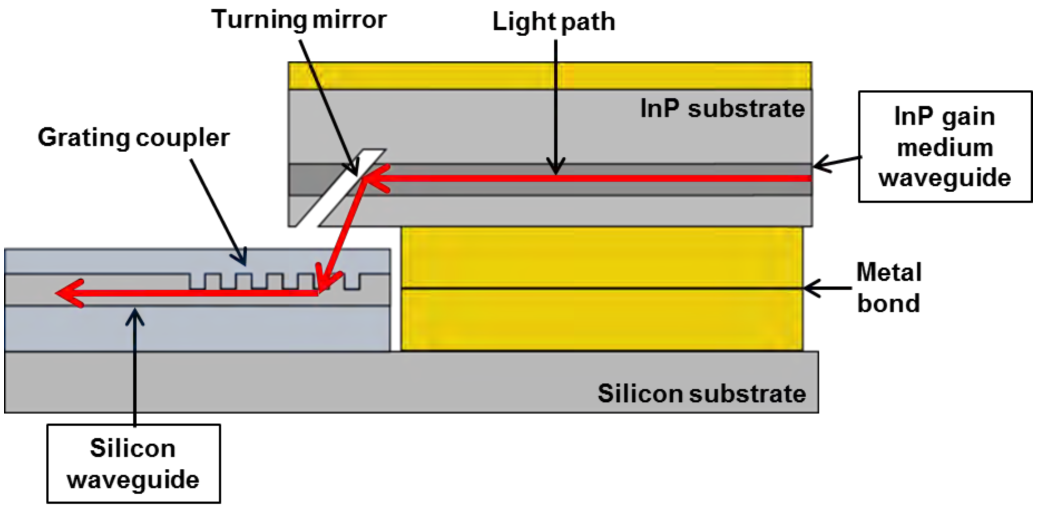
Hybrid approach parasitics become smaller than device junction as pad shrinks

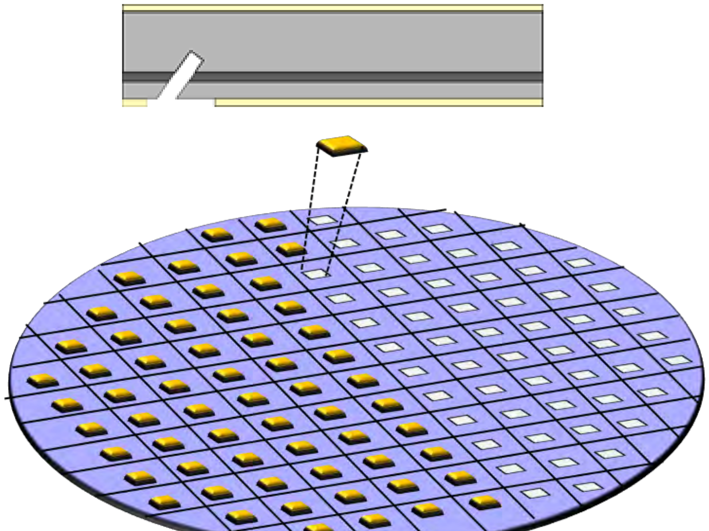
Hybrid can outperform (monolithic) in speed, power, density, and TTM

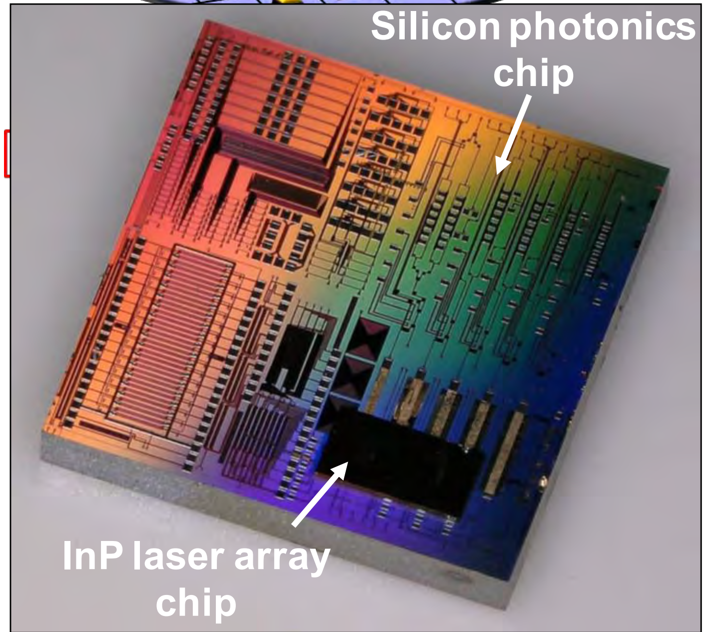
Optimization enables/requires electronics-photonics co-design

3D (or Heterogeneous) integration → Integration

3D Hybrid Integration (Klamkin group)





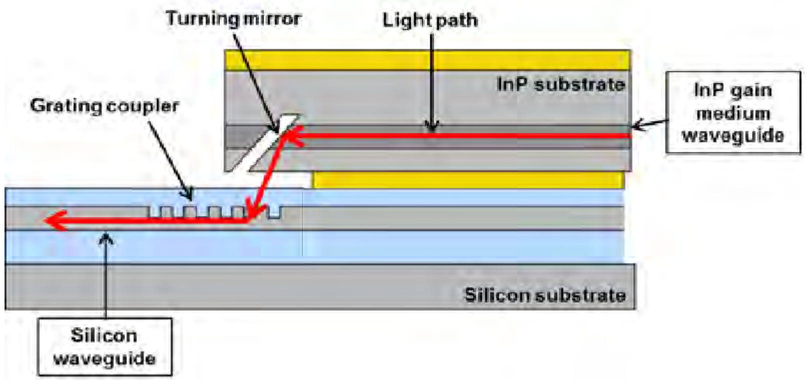


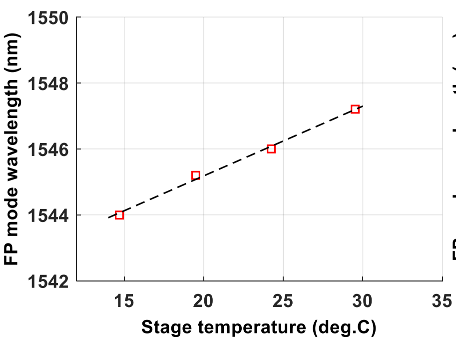
- **InP laser or PIC with integrated total internal reflection (TIR) turning mirror coupled to Si with grating coupler**
- **Chips attached with standard IC bonding**
- **Could be carried out at wafer level in backend step**
- **P-side down bond to Si substrate for heat removal**

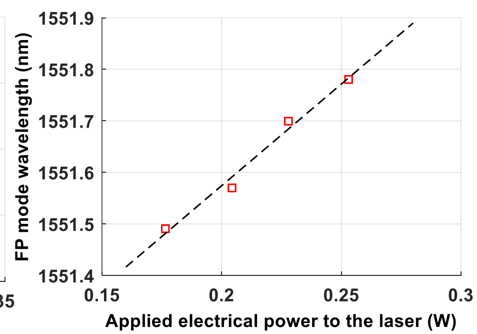
B. Song, et al., ECOC 2015
B. Song, et al., Optics Express 2016

Thermal Impedance Demonstration

Laser bonded to oxide

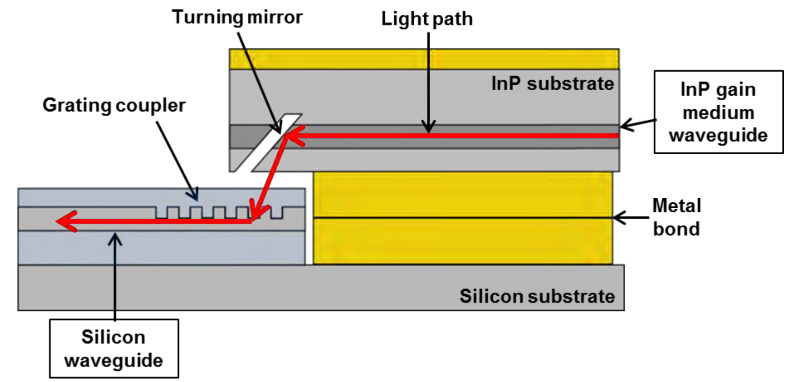


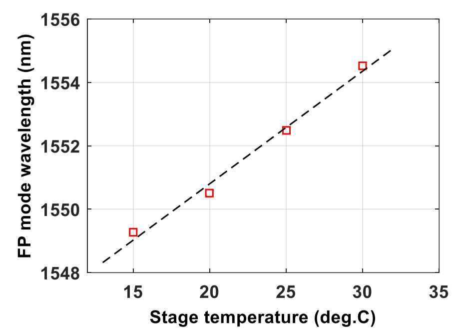


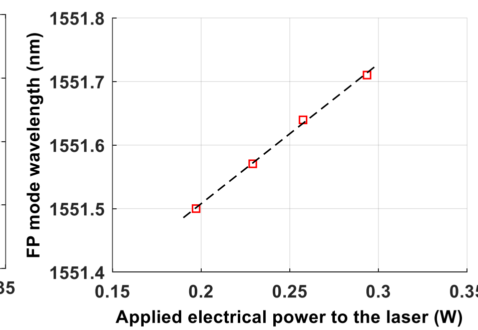


Thermal impedance = 18.63 °C/W

Laser bonded to substrate







Thermal impedance = 6.19 °C/W

Factor of 3 improvement in thermal impedance

Thermal impedance extraction as in: M. N. Sysak, et al., JSTQE, 2011

Foundry/Fabrication Services

UCSB

Example InP-PIC Foundry/Fabrication Orgs.

Foundries/PDK

- JePPIX* (broker: www.jeppix.eu)
  - HHI
  - Smart Photonics
- AIM Photonics (via Infinera—available 2018—RF only)

Custom Foundries/no PDK

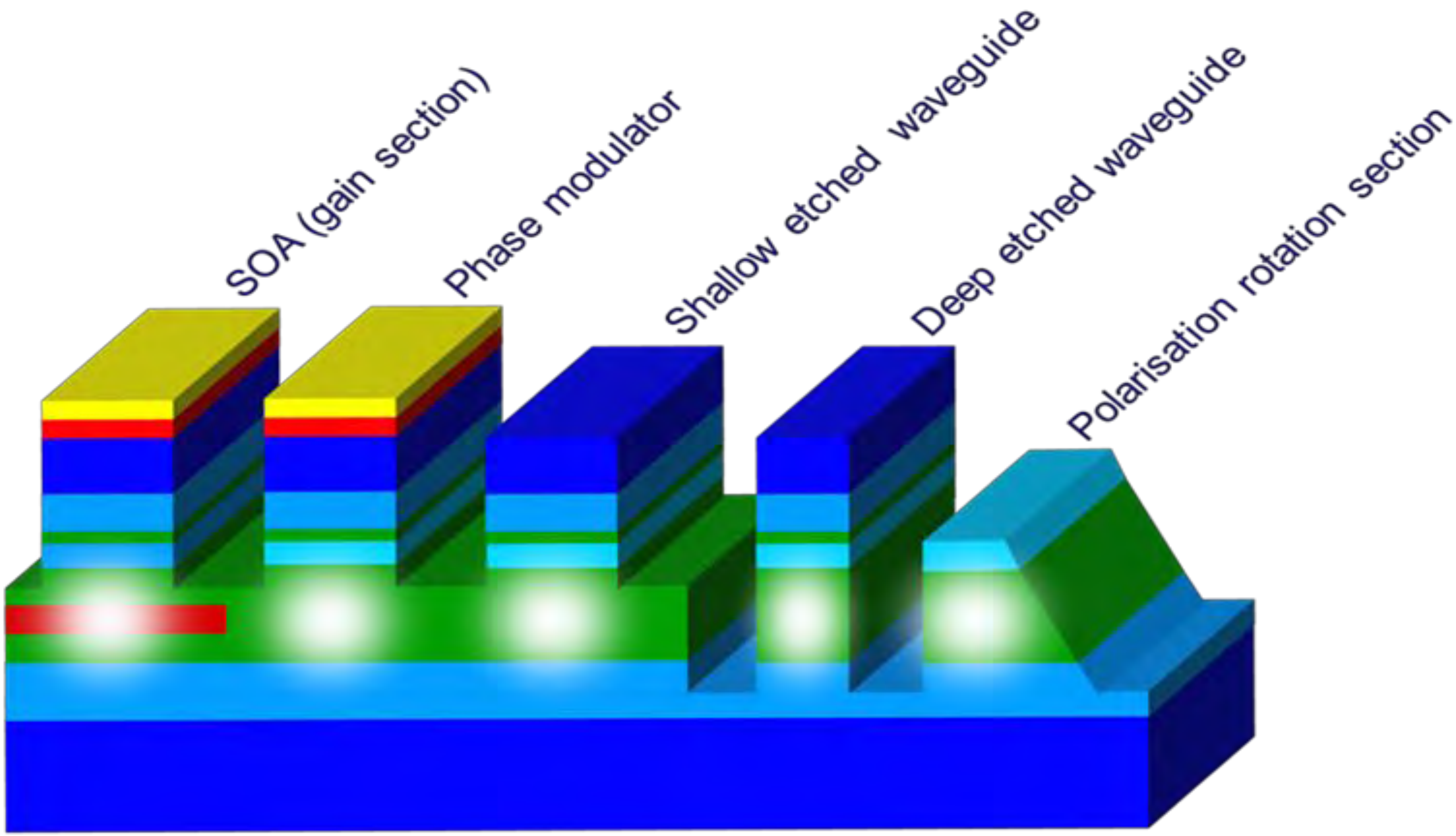
- Canadian Photonics Fabrication Centre
- Global Communications Semiconductors

Design/Fabrication Services

- Freedom Photonics (design/fab/test)
- Bright Photonics (design only)
- UCSB (research fabrication facility only)

*For more information, see:
http://iopscience.iop.org/article/10.1088/0268-1242/29/8/083001

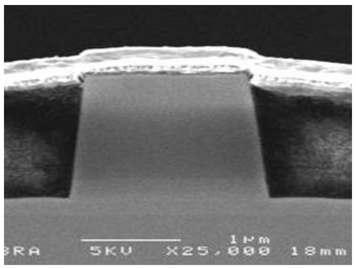
Generic Integration

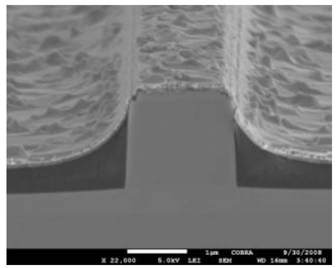


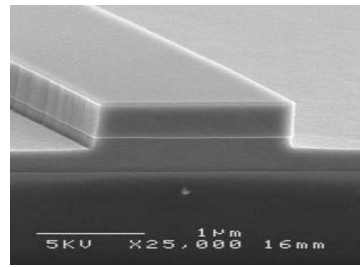
Scanning Electron Microscope Images

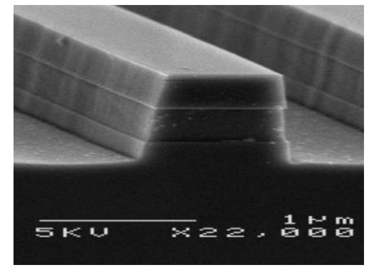
Phase Modulator

Deep etched waveguide



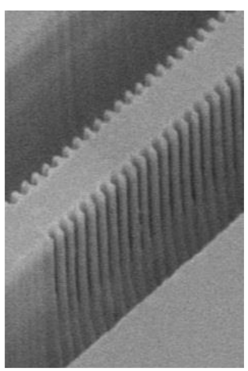




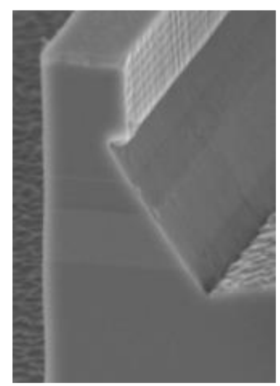


Amplifier

Shallow etched waveguide



Tunable
DBR grating



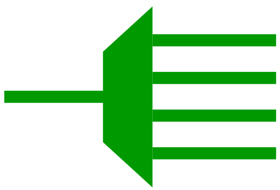
Polarization
converter

Technische Universiteit Eindhoven University of Technology

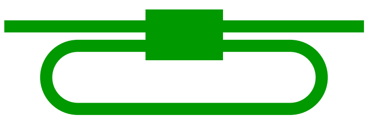
Creating interferometers

MMI-couplers and filters

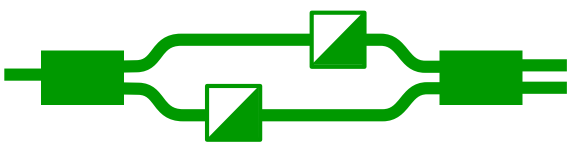
MMI-reflectors



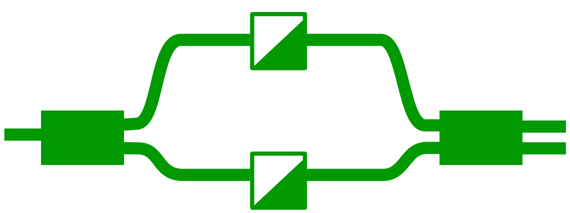
AWG-demux



ring filters



polarisation splitters
polarisation combiners

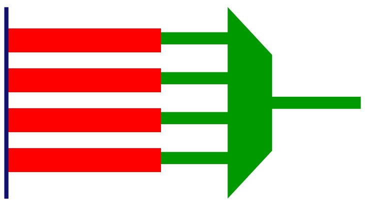


polarisation independent
differential delay lines

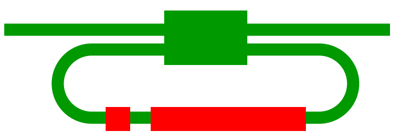
Lasers cavities

Fabry-Perot lasers

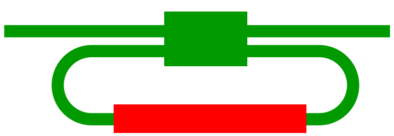
tunable DBR lasers



multiwavelength lasers



picosecond pulse laser



ring lasers

> 25 mW output power
< 100 kHz line width
< 1 ps pulse width
…

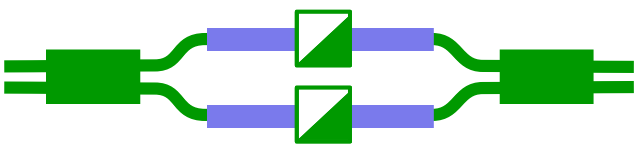
Modulators and ROADMs

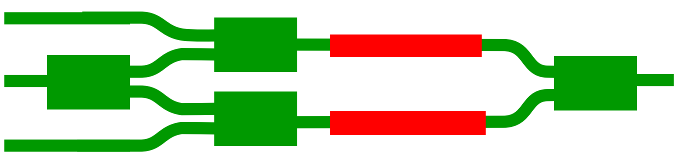
> 40 GHz bandwidth
> 50deg/V.mm

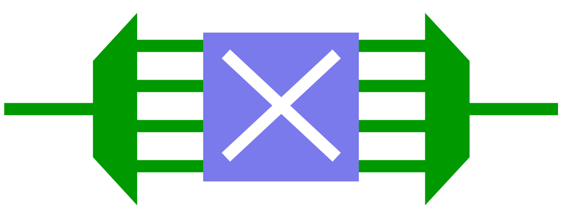

phase modulator


amplitude modulator


fast space switch


polarisation independent 2x2 switch

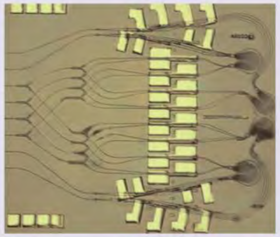

ultrafast switch


WDM crossconnect
WDM add-drop

Application Specific Photonic ICs—JePPIX

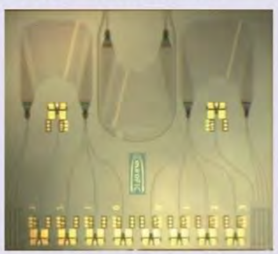
W4G.1.pdf OFC 2017 © OSA 2017

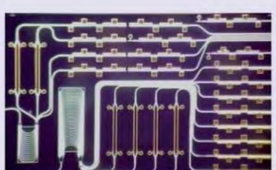
Optical switching


4x4 space and wavelength selective switch

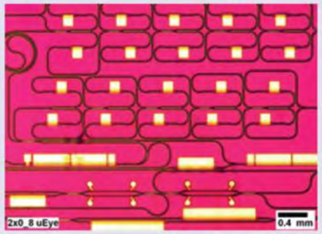

Fast optical switch matrix

Fiber to the home

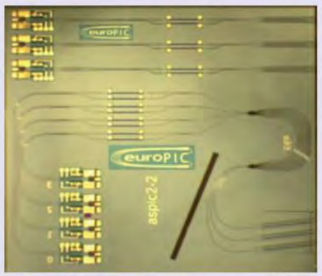

WDM receiver


WDM transmitter

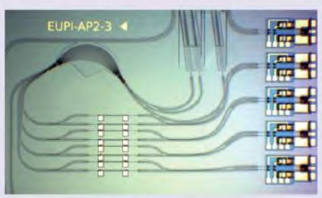
Fiber sensor readout



Brillouin strain sensor readout

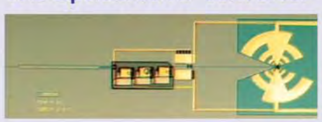


Fiber Bragg Grating readout

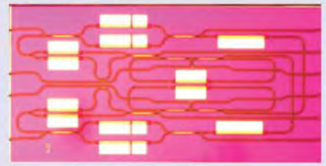


Fiber Bragg Grating readout

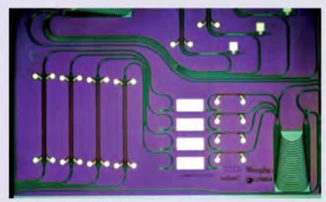
THz Optical to RF converter



Variety of lasers


Widely tunable ring laser

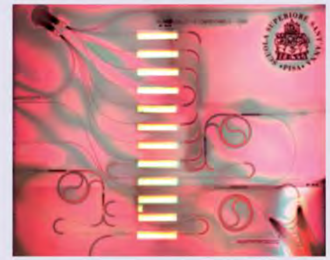

Variable repetition rate pulse laser


Filtered-feedback multi-wavelength laser

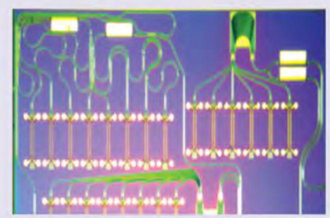

tunable laser with integrated MZI modulator

QPSK receiver

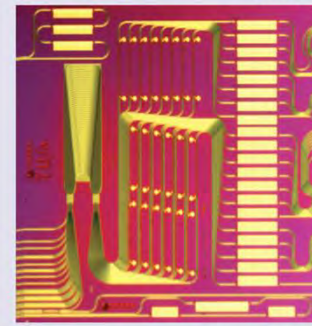
Optical data handling


All-optical regenerator for constant envelope WDM signals


WDM to TDM Trans-Multiplexer


Pulse serialiser

Medical and bio-imaging


Pulse shaper for bio-imaging


Integrated tunable laser for optical coherence tomography

TU/e Technische Universiteit Eindhoven University of Technology

Take-Aways

- PICs are desirable for modest to high volume communication, sensing and instrumentation functions, 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.
- InP-PICs currently lead the market for Long-Haul and Metro communications; 'heterogeneous integration,' & Si-photonics expanding in datacom and metro.
- For Electronic-Photonic integration, single-crystal (e.g. CMOS) integration may not be as desirable as heterogeneous (3D, 2.5D) integration (unless very high volume).