High-Performance Photonic Integrated Circuits (PICs)

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OFC Tutorial
OWD1

March 24, 2010

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Outline/Contents

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- Motivation/the Demand for Data
- An Example Complex PIC: a single-chip router
- Integration Platforms/Technology
  - Indium Phosphide
- Serial & Parallel Integration Approaches
  - Transmitters/Receivers/Wavelength Converters
- Improved Spectral Efficiency Issues
  - Advanced modulation formats
  - Coherent techniques/Optical phase locked loops
- Summary

Communication Requires a Complex Network

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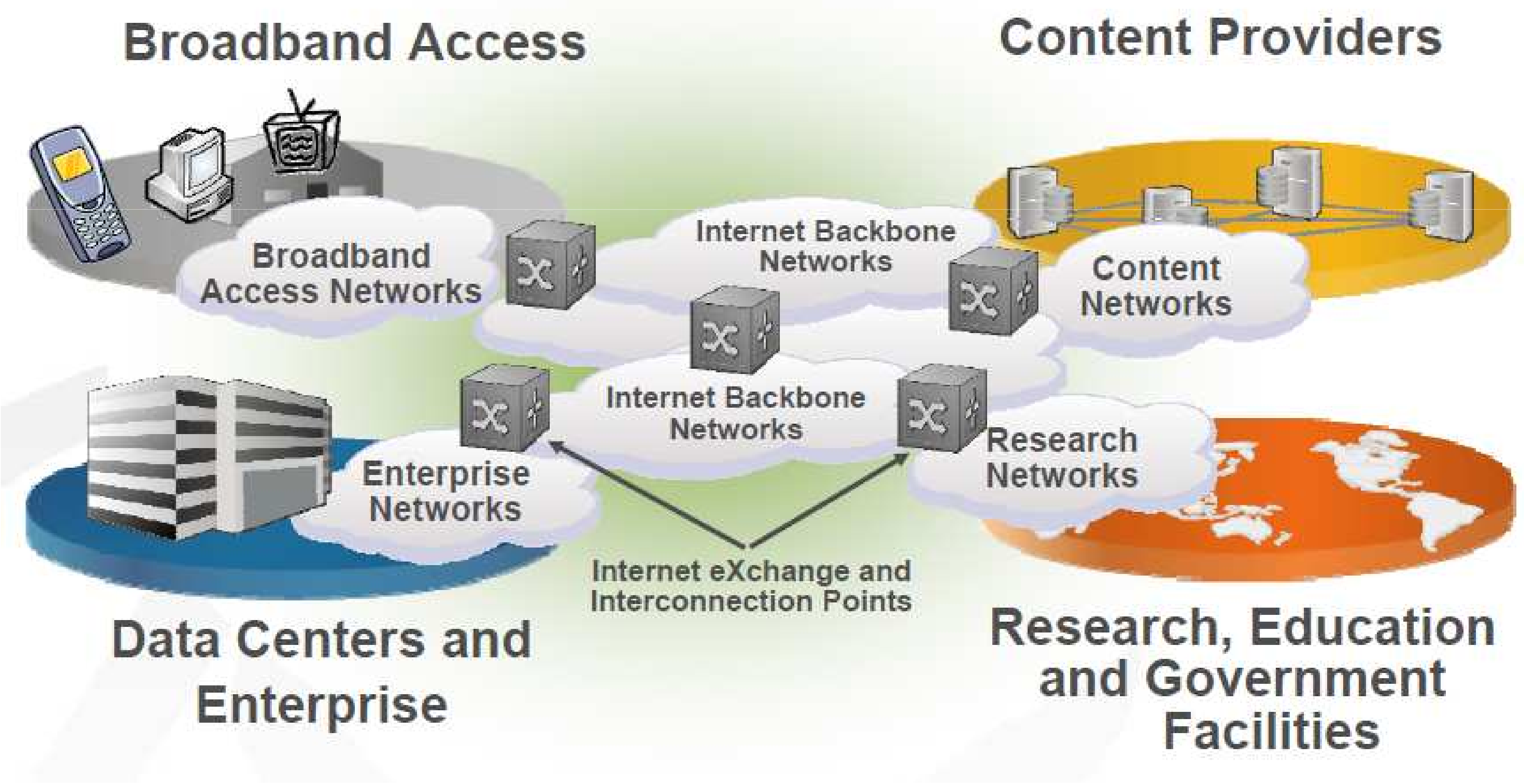
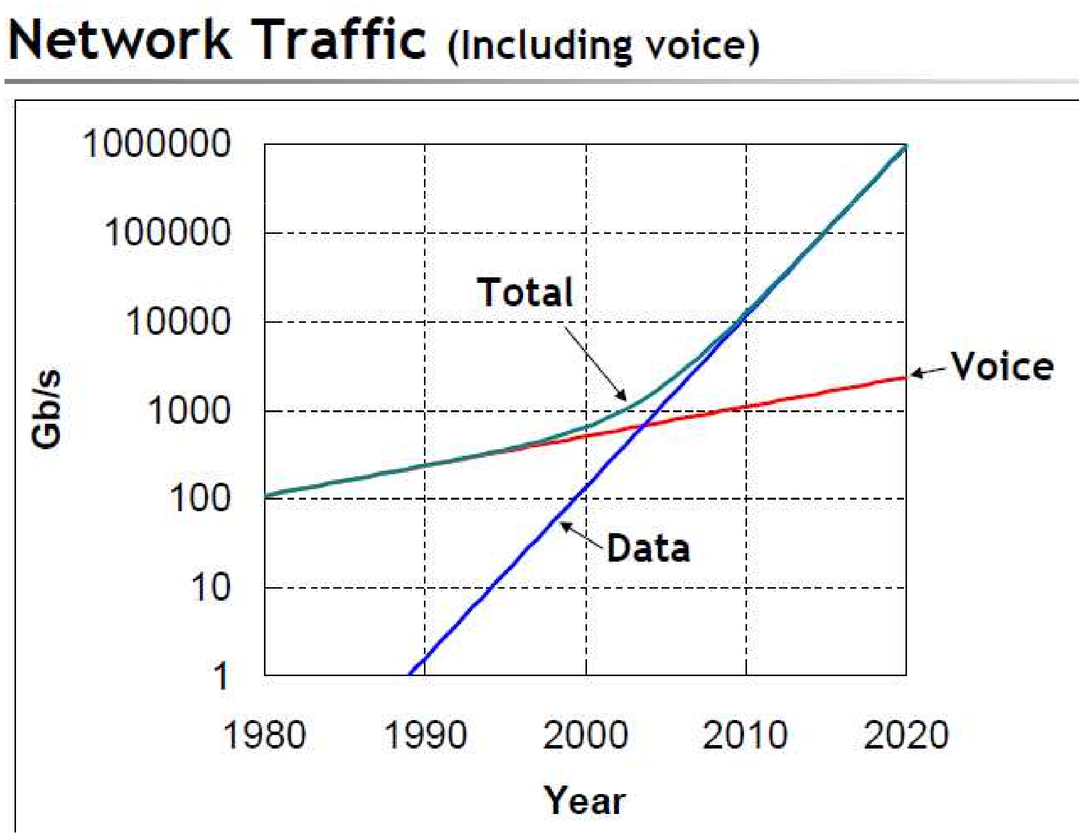
- **It's nearly all optical**



Data is King

- **Today traffic on the core network is nearly all data**



A Typical Data Center

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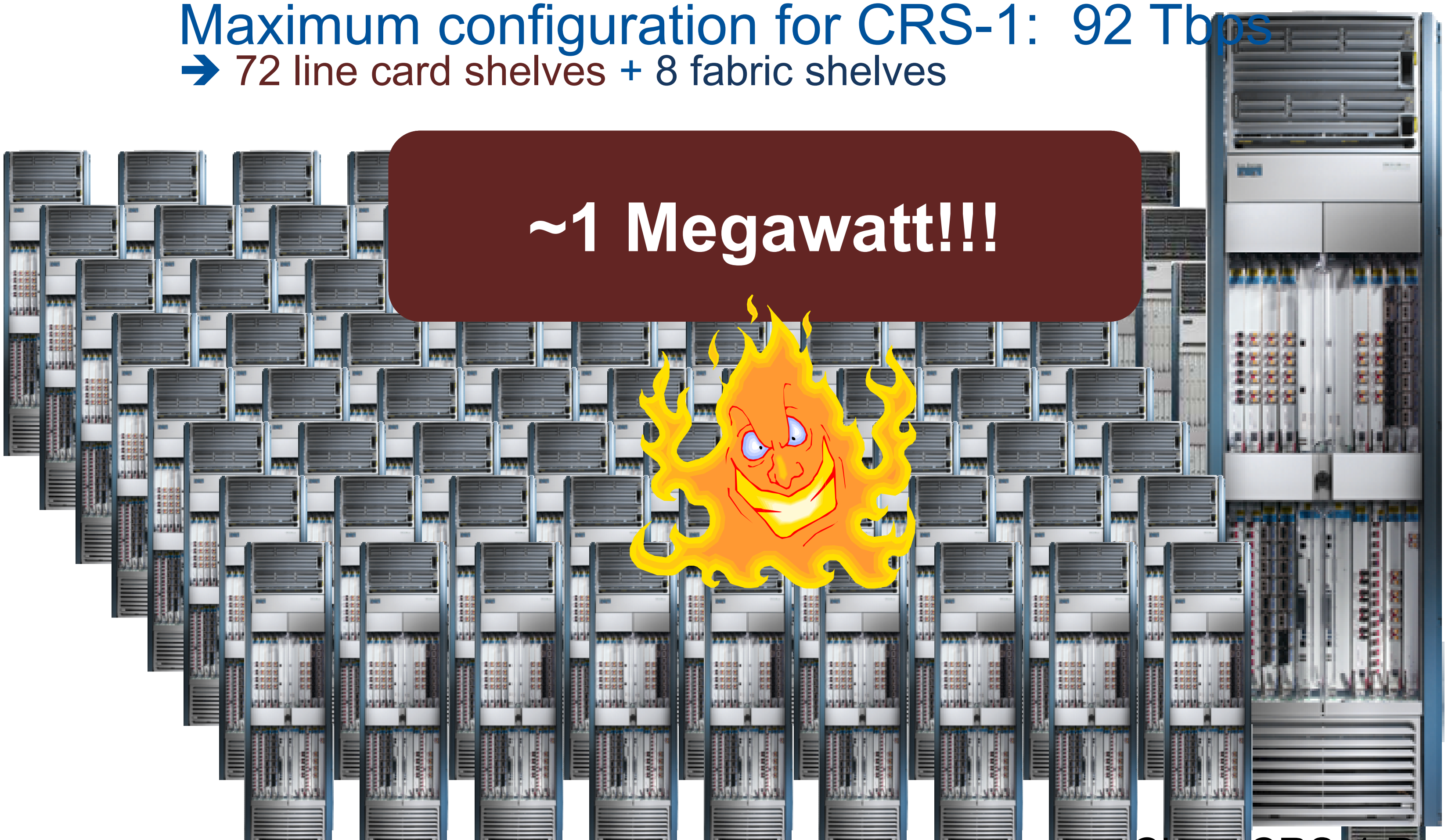
- > 30 MW power requirements
- Require many Gb/s of bandwidth—justifies 100Gb-Ethernet

Electronic Routing Burns Lots of Power

- **Problem:** Bandwidth demands scaling faster than both silicon and cooling technologies

Maximum configuration for CRS-1: 92 Tbps
➔ 72 line card shelves + 8 fabric shelves



Cisco CRS-1 Router

Optical-to-Electronic-to-Optical Switching

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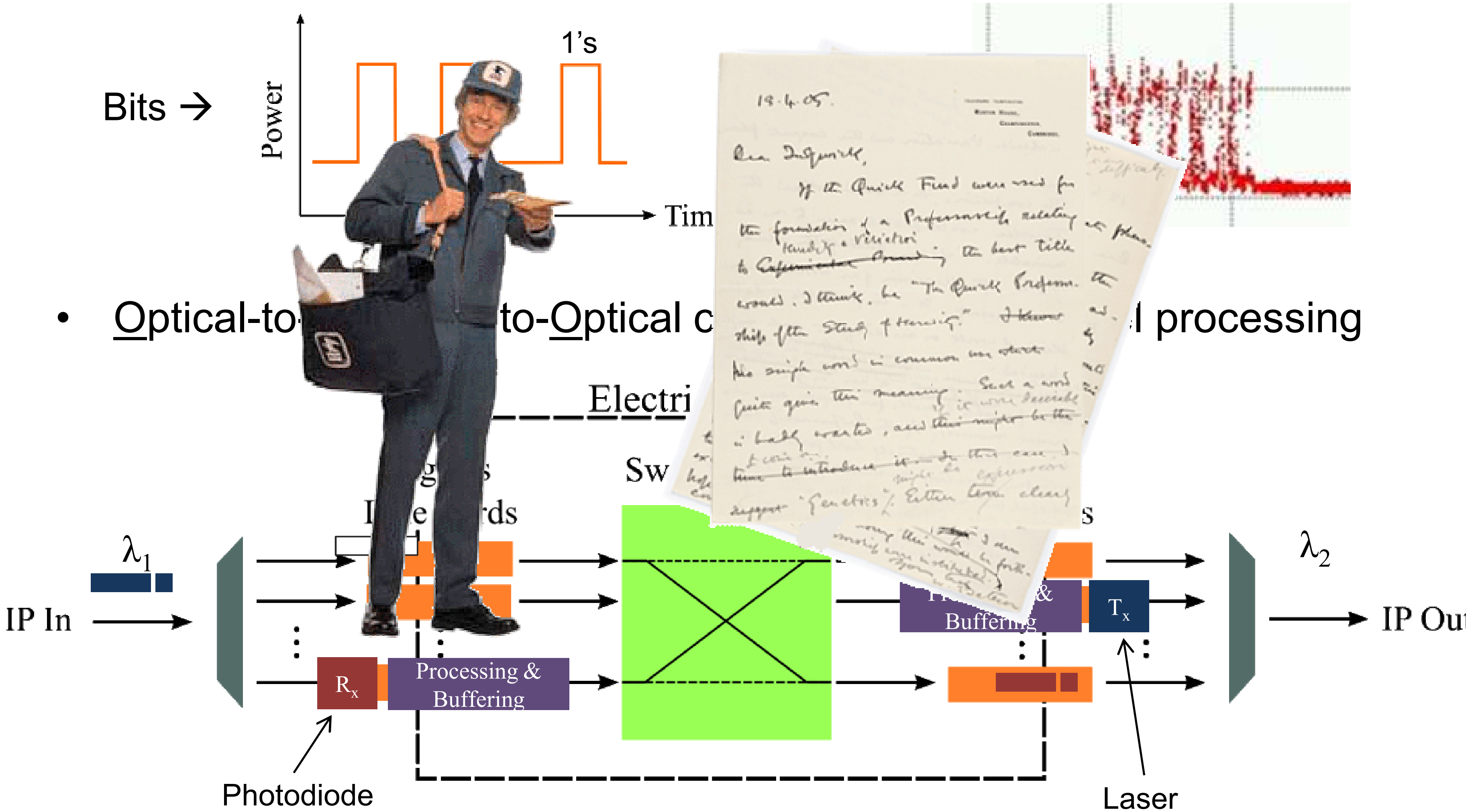
- Internet data transmitted in groups of bits = "packets"



- Optical-to- … to-Optical c … l processing

Example of a Complex PIC: A Monolithic Tunable Optical Router (MOTOR)

A UCSB Router Solution: the MOTOR Chip

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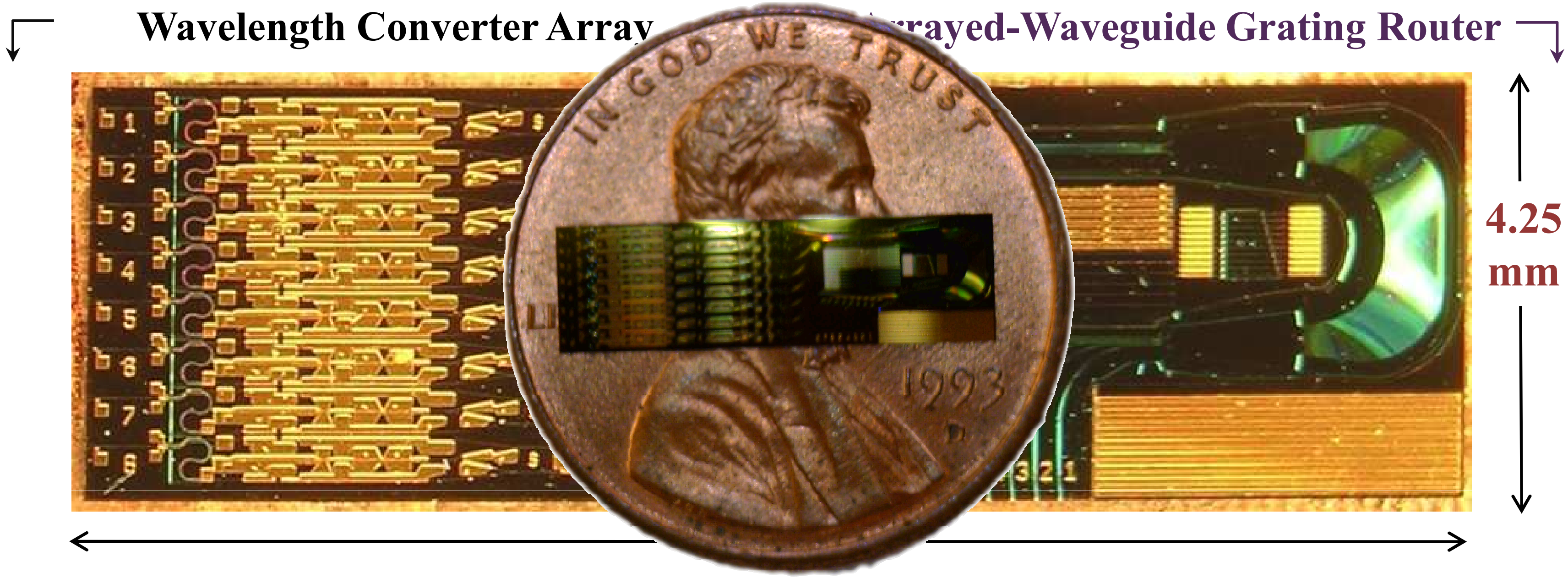

- A <u>mo</u>nolithic <u>t</u>unable <u>o</u>ptical <u>r</u>outer (MOTOR) chip to function as the switch fabric of an all-optical router
  - Line rate: 40 Gbps / channel
  - Total capacity: 640 Gbps
  - Error-free operation
- Photonic integration technologies designed for high-yield, large-scale applications
- World's largest and most complex Photonic IC

LASOR

Steven C. Nicholes, M. L. Mašanović, E. Lively, L. A. Coldren, and D. J. Blumenthal, *IPNRA '09*, Paper IMB1 (July, 2009); also *JLT*, (Jan. 2010) in press.

640 Gbps MOTOR

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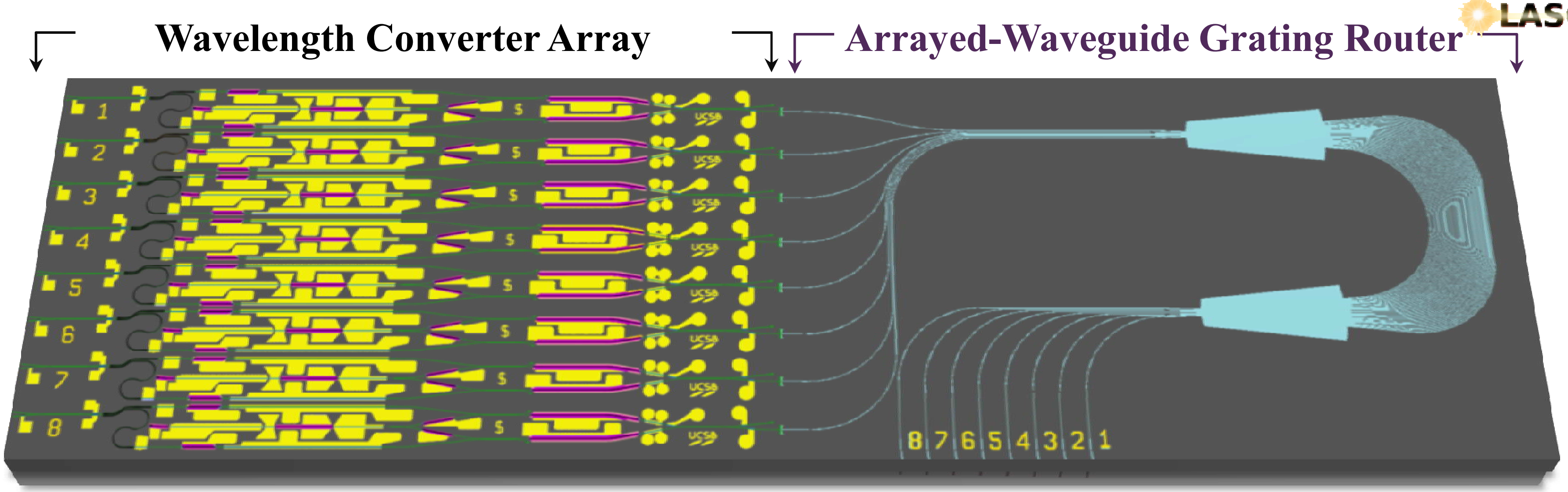
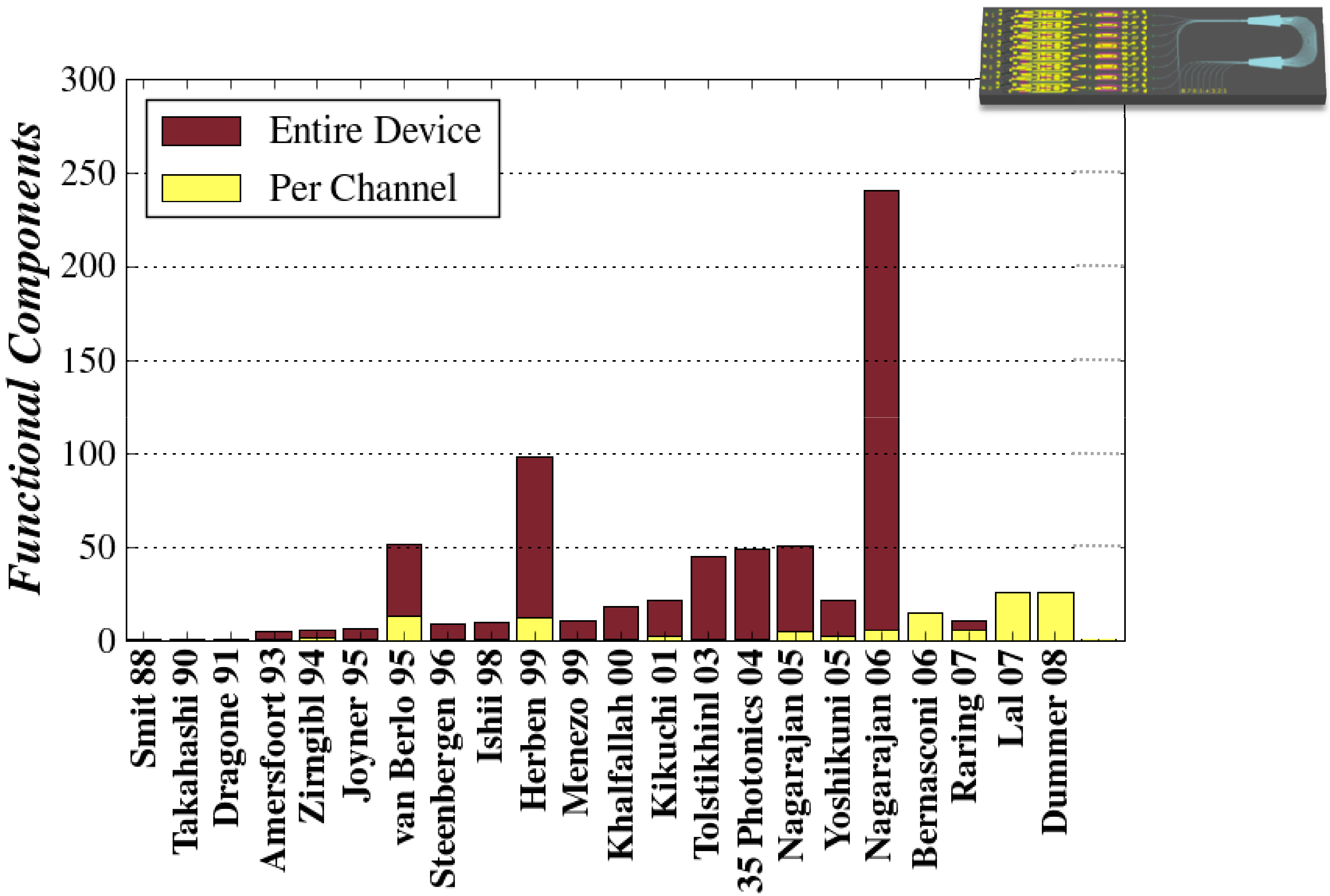
LASOR



Benefits of integrated solution:	
Size	• Smaller device footprint • Smaller rack space for increased bandwidth
Power	• No power required in passive AWGR (free switching—no transistors) • Lower power consumption with all-optical approach
Cost	• Reduced packaging and system costs • Fewer fiber alignments
Performance	• Increased reliability

Leading Edge of Monolithic Integration



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

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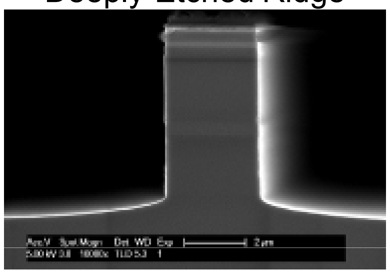
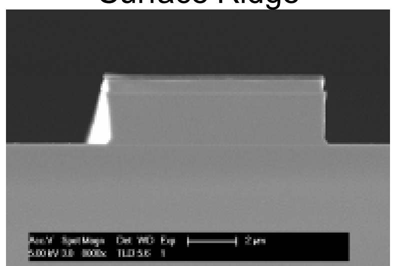
LASOR

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

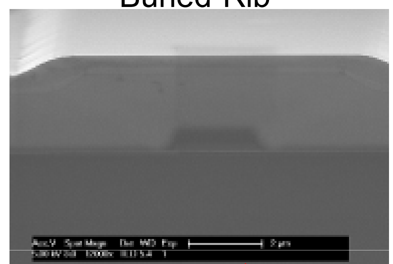
Deeply-Etched Ridge



Surface Ridge

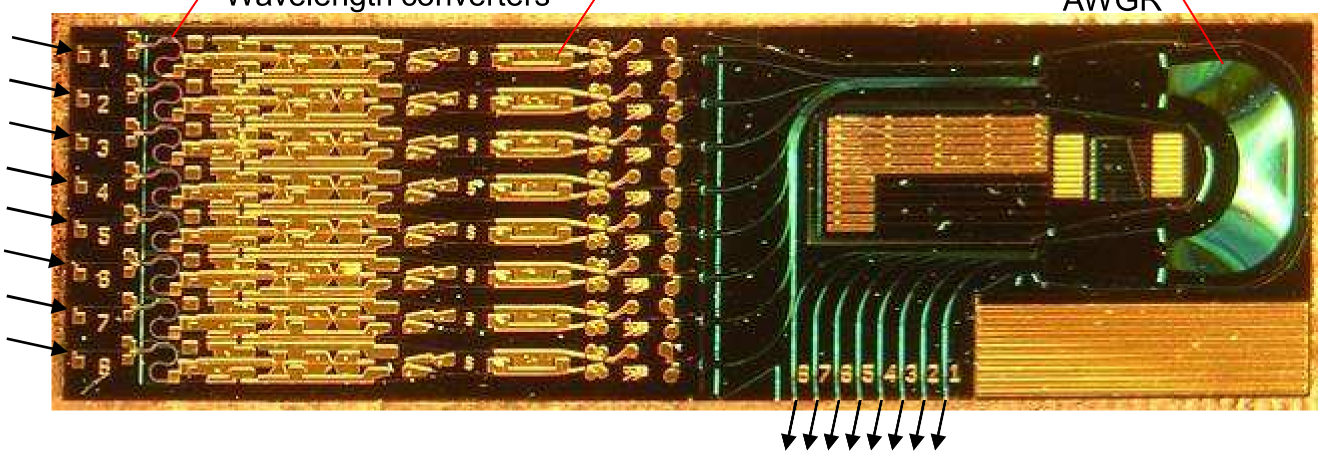


Buried-Rib

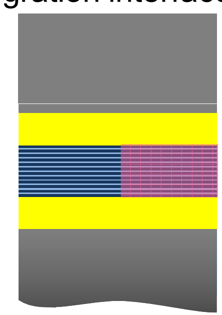


Wavelength converters

AWGR



QWI for active-passive integration interfaces



Monolithic Tunable Optical Router

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)

MOTOR Results : Constant Input Port: 40 Gbps RZ

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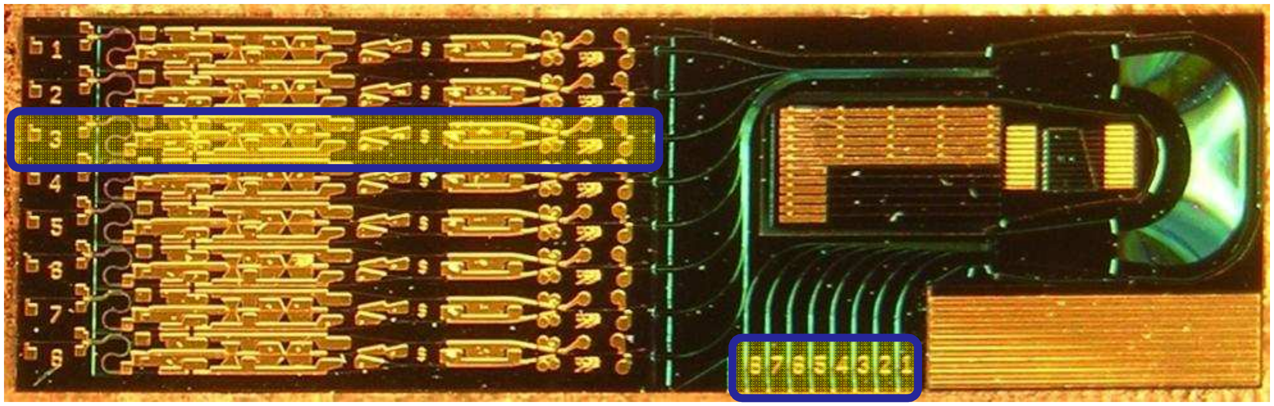
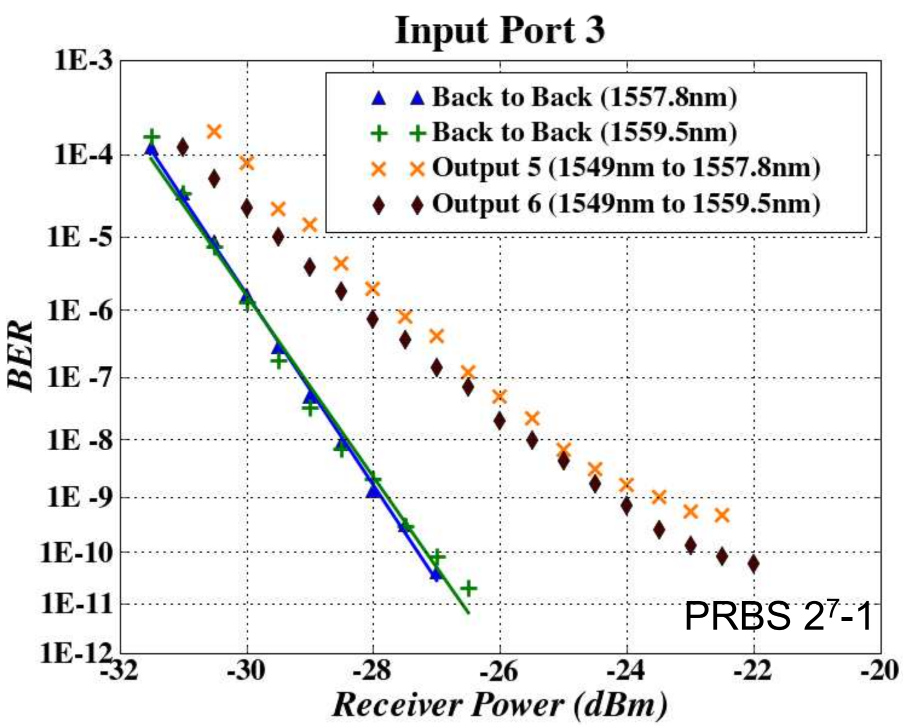
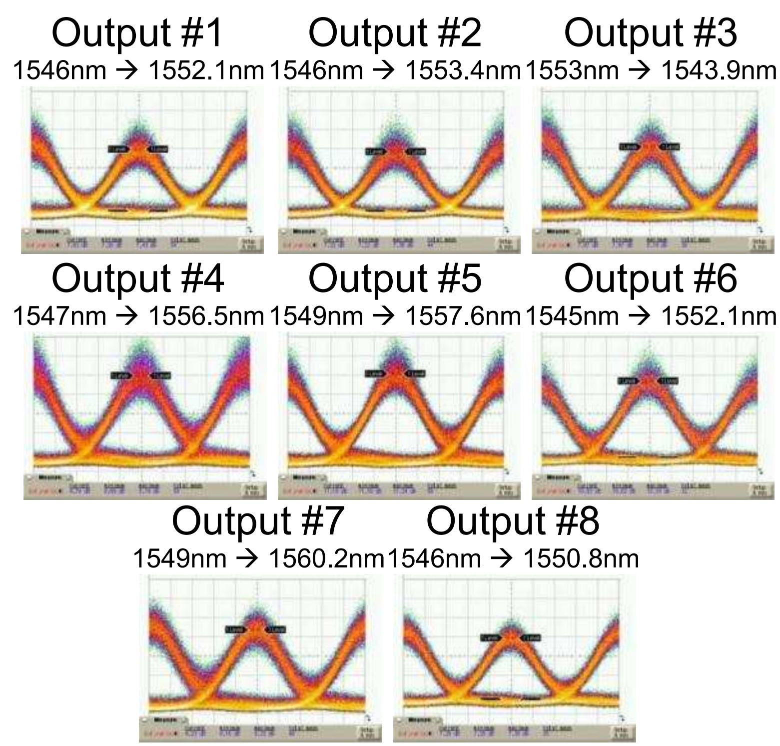
LASOR



- Power penalty at BER = 1E-9 for PRBS 2^7-1 data at 40 Gbps
  - ≥ 3.5 dB

  (no AR coating)





Indium Phosphide as the Materials Platform

Indium Phosphide

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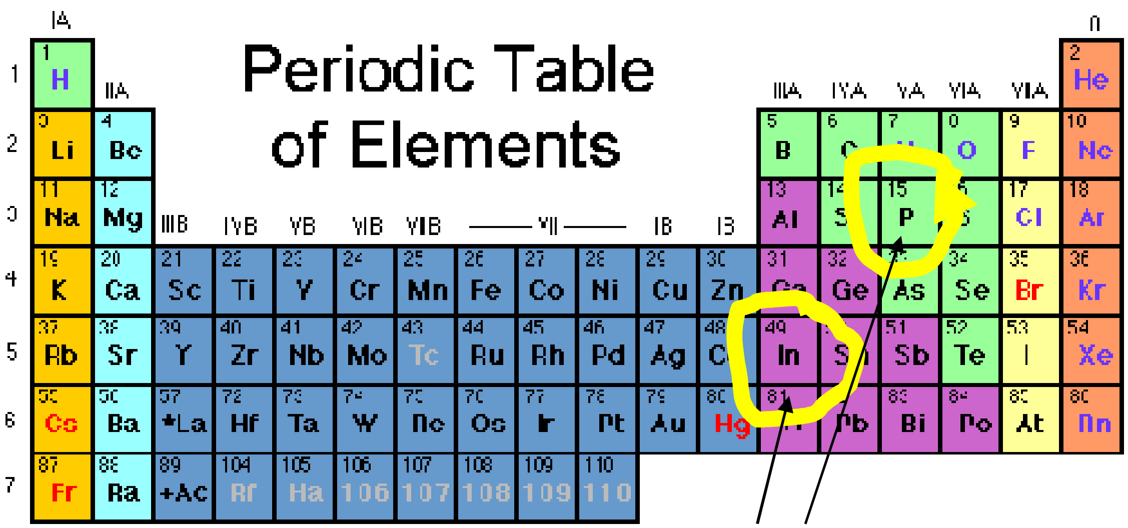
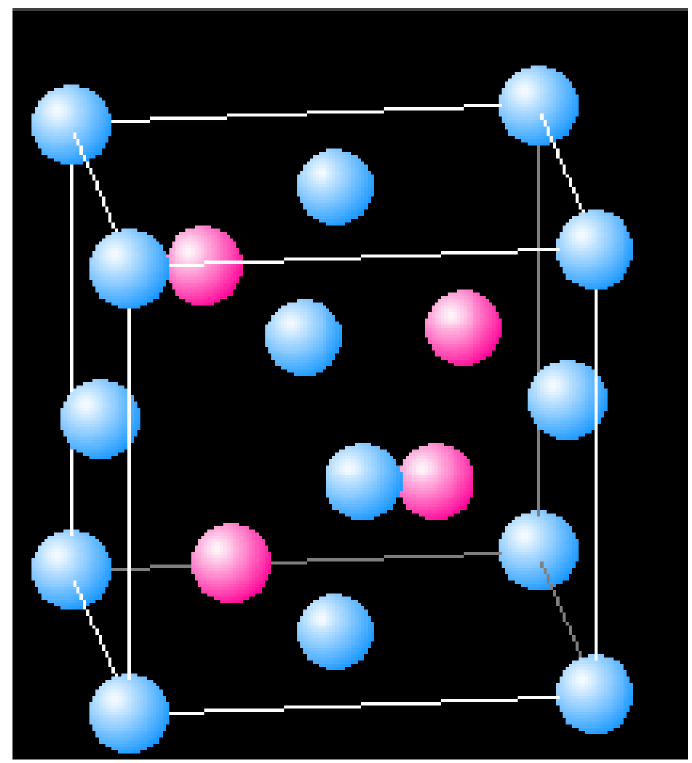


III-V material



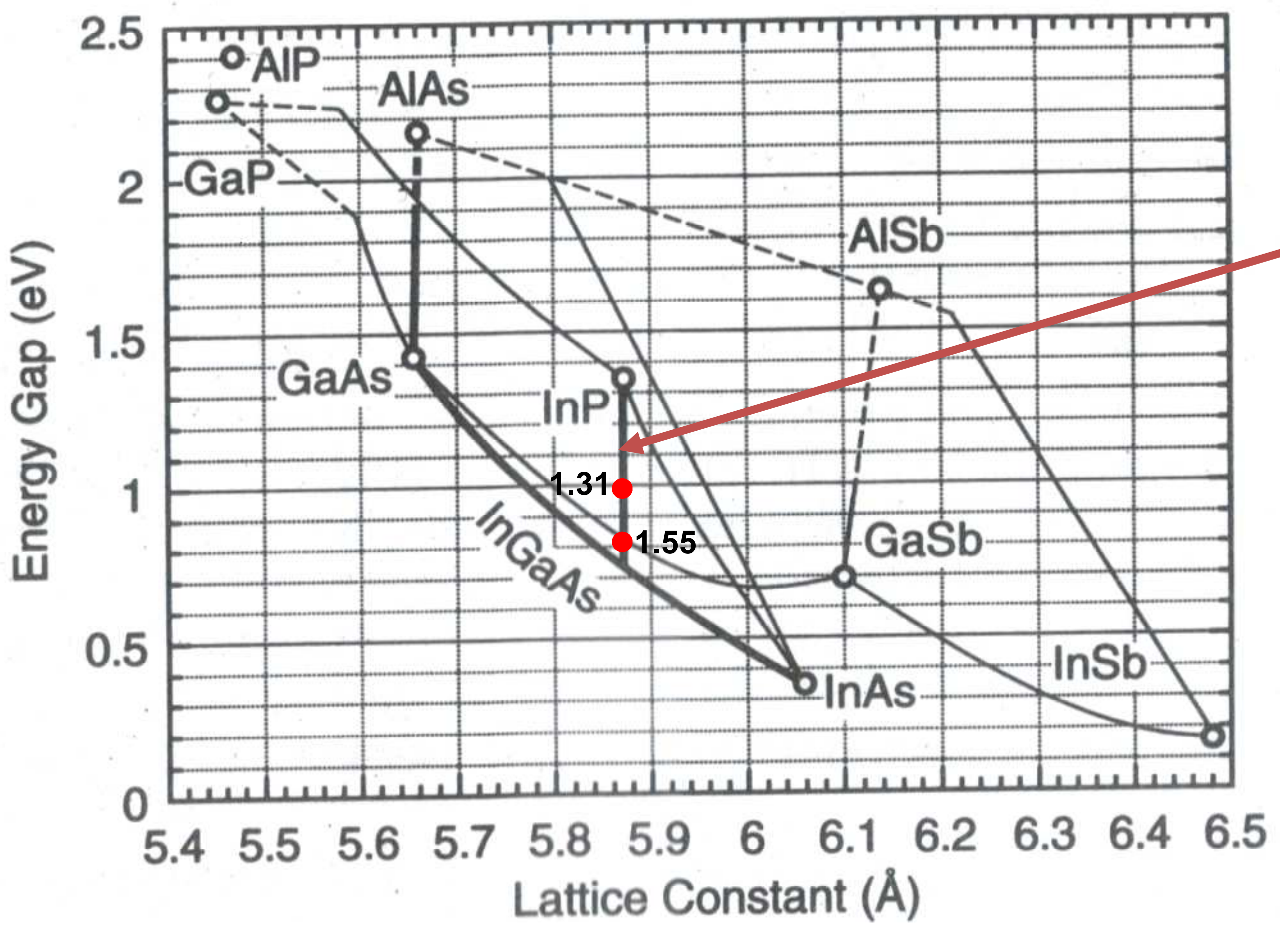
Zincblende structure

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

Lattice constant = 5.87 A at 300K

courtesy of C. Doerr

InGaAsP/InP lattice-matched alloys

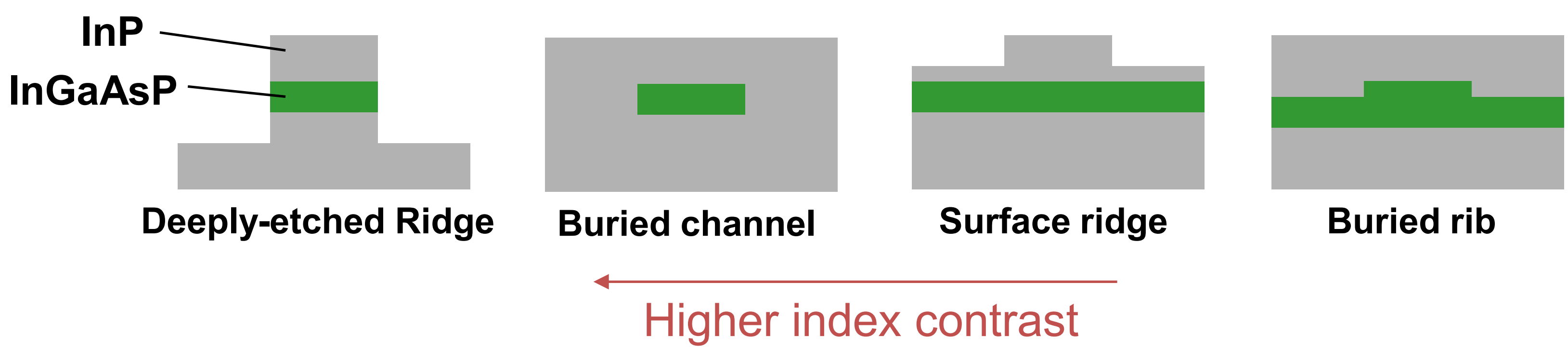


InGaAsP lattice-matched to InP

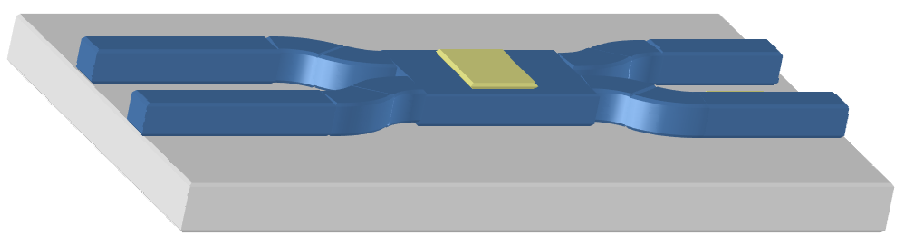
$\lambda_g(\mu m) = 1.24/\ E_g(eV)$

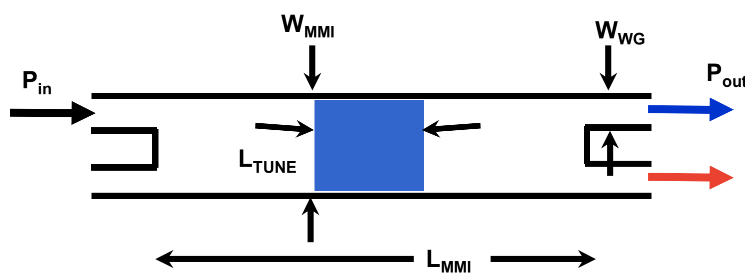
Lateral waveguides/couplers

Waveguide cross sections



MMI coupler





Active-Passive (axial) Integration

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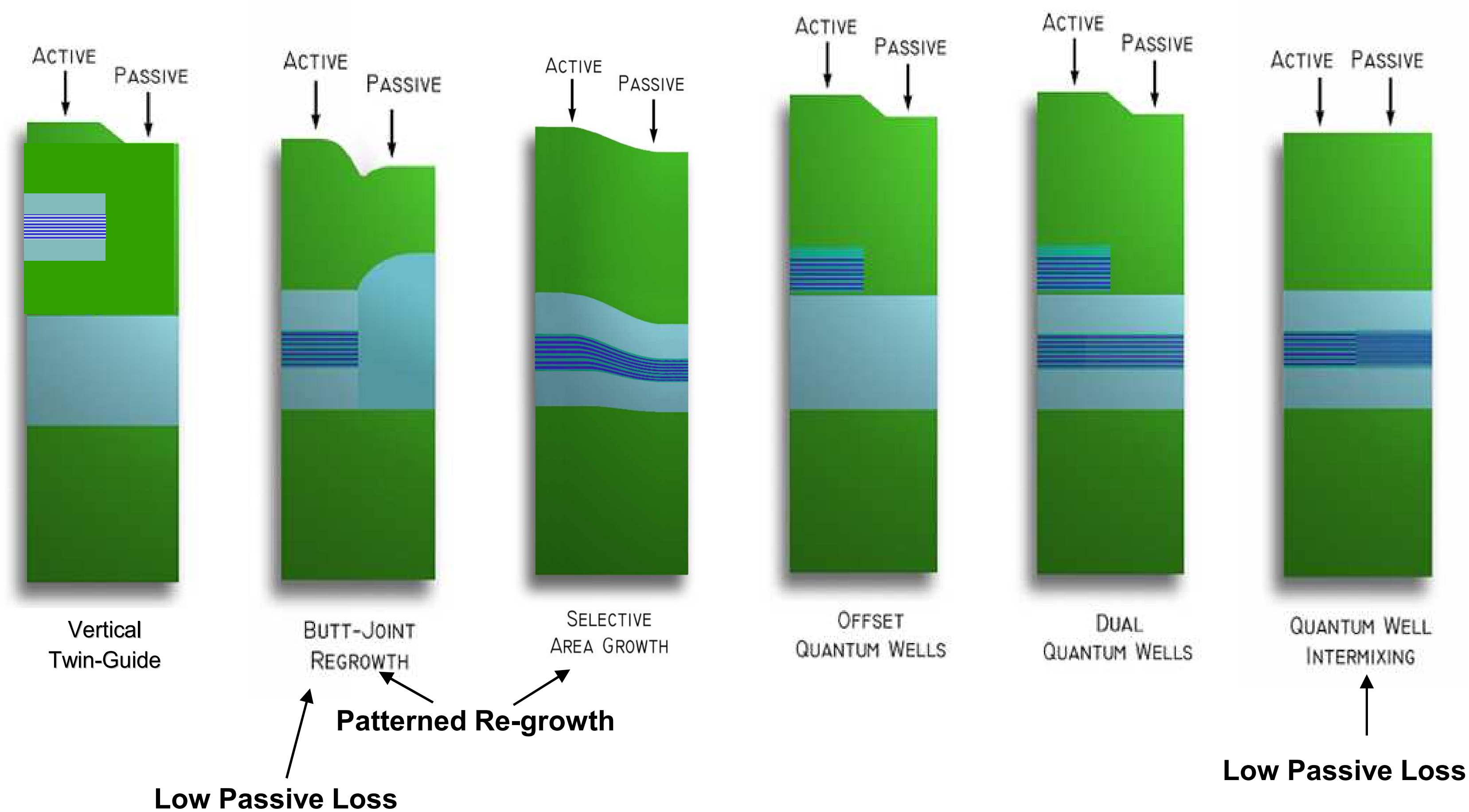
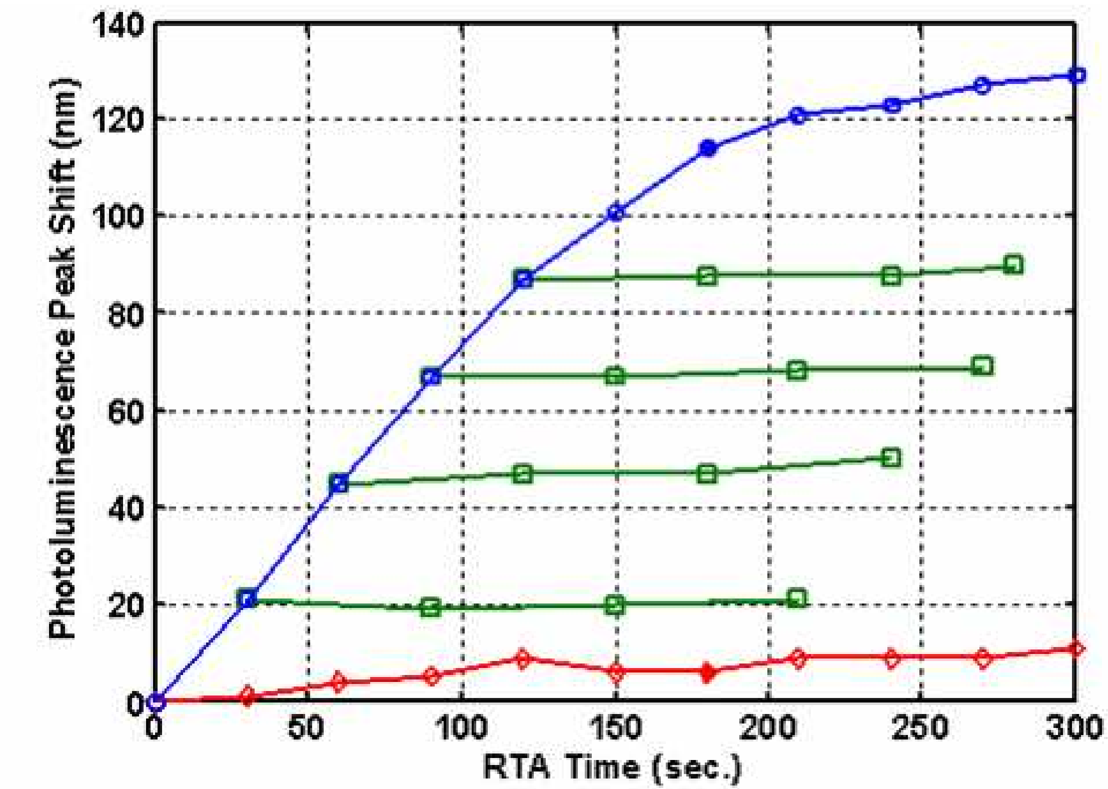
Desire lossless, reflectionless transitions between sections

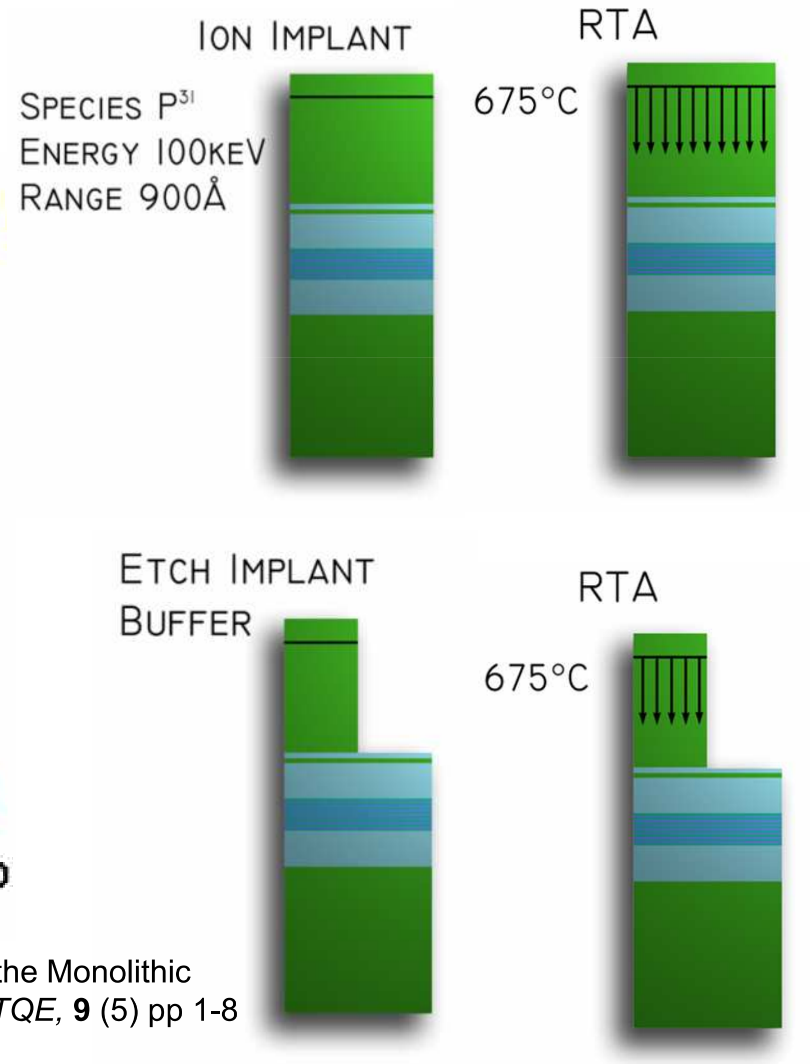


3 Bandgaps usually desired

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).

Integration Strategy: MOTOR Chip

Integration Platform for MOTOR Chip

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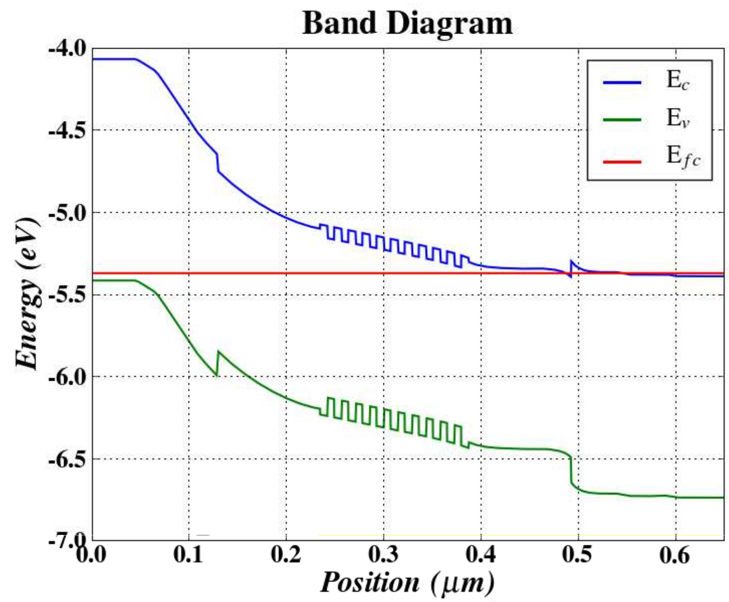
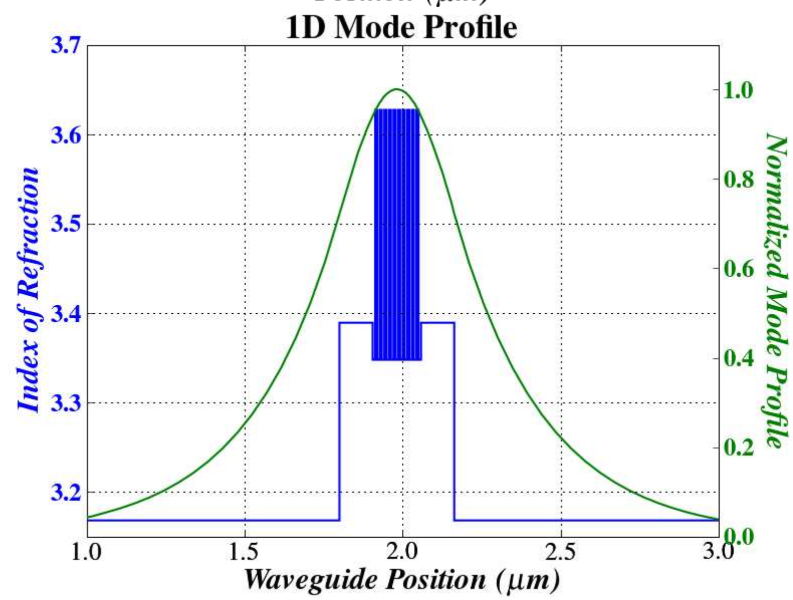
- Strategy:
  1. Centered MQW base structure
  2. Quantum-well intermixing for active/passive definition
  3. Single blanket cladding regrowth

- Trade-offs:
  1. Limited total number of regrowths → need multiple waveguide architectures
  2. Efficient active diodes → higher passive losses due to Zn in cladding
  3. Efficient high-gain, low-saturation power elements → nonlinear preamplifiers
  4. Polarization sensitivity





Multiple Waveguide Architectures

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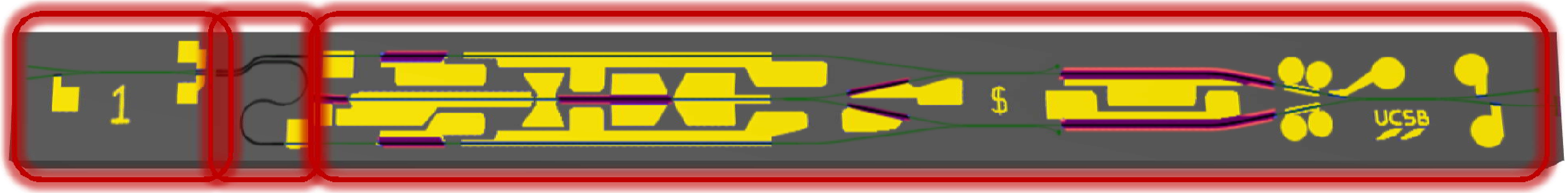
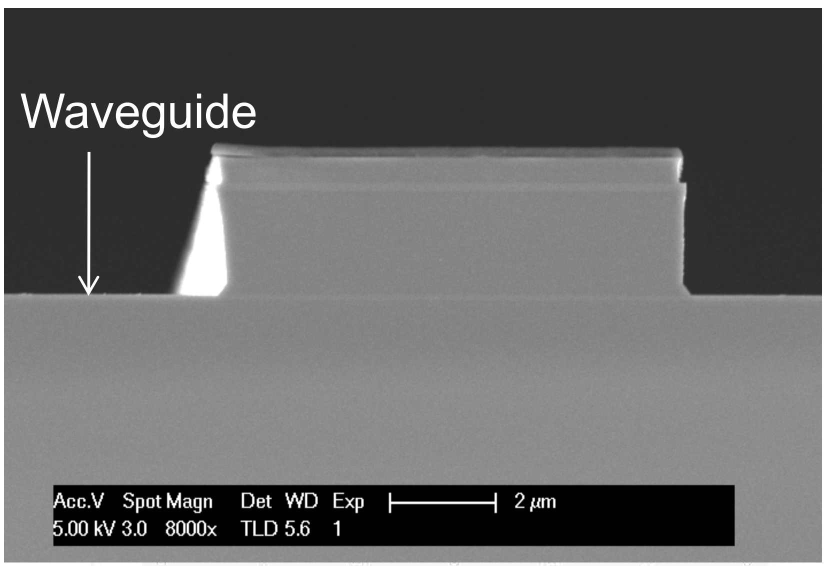
- Need multiple waveguide designs to integrate diverse range of components



Waveguides



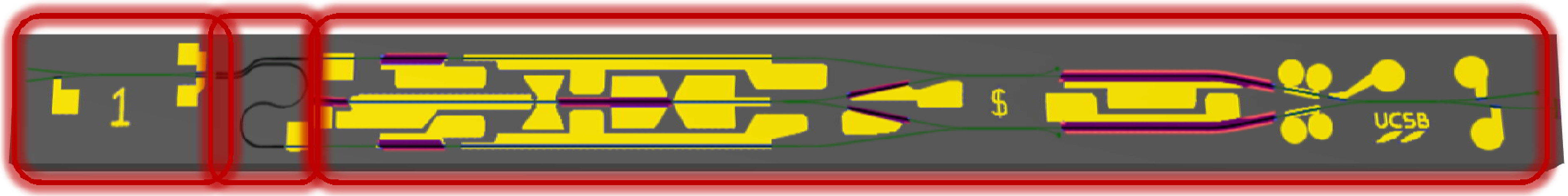
Horizontal Waveguide Position (µm)

<u>Surface Ridge</u>

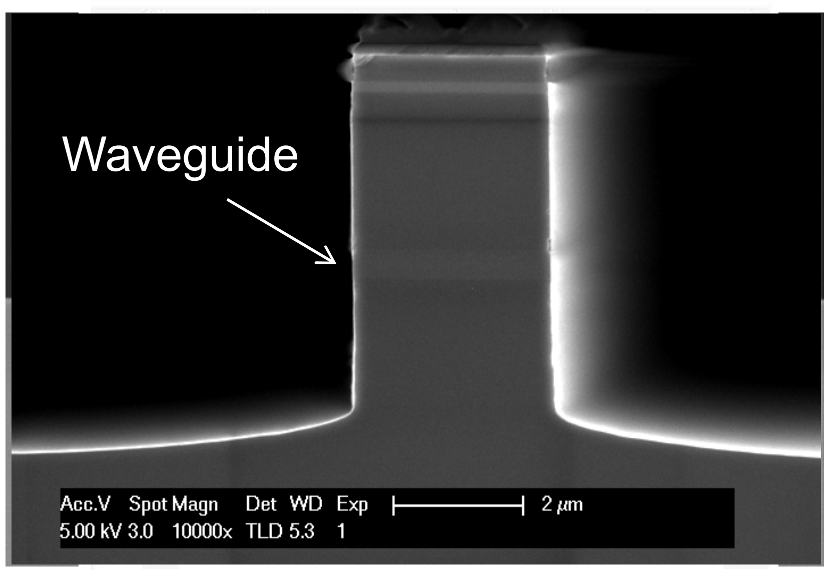
- Ridge defined through p-type cladding and stops at waveguide layer
  - Dry etch + selective "cleanup" wet etch
  - Wet etch is crystallographic → <u>no bends over ~15°</u>

Multiple Waveguide Architectures

- Need multiple waveguide designs to integrate diverse range of components



Waveguides



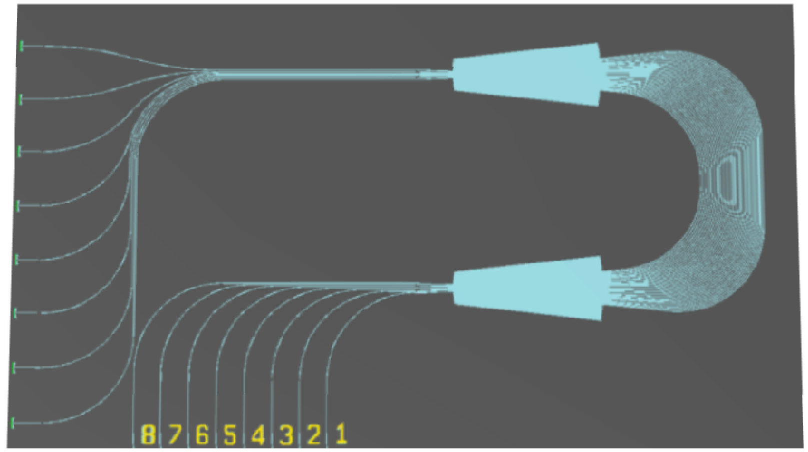
Horizontal Waveguide Position (µm)

Deeply Etched Ridge

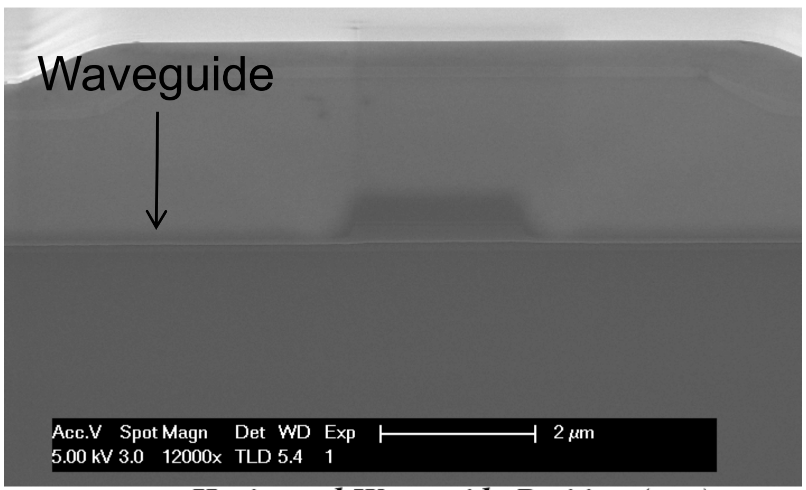
- Ridge defined through waveguide layer
  - Dry etch only
  - Strong lateral confinement → sharp bends possible

Multiple Waveguide Architectures

UCSB



Need short mode transition elements to maximize coupling between waveguide regions



Horizontal Waveguide Position (µm)

- Partial etch into upper waveguide prior to cladding regrowth, which buries it
  - Low index contrast
    - → Larger footprint
  - Dry etch due to high-angle bends

QWI Implant Buffer for Low-Loss Waveguides

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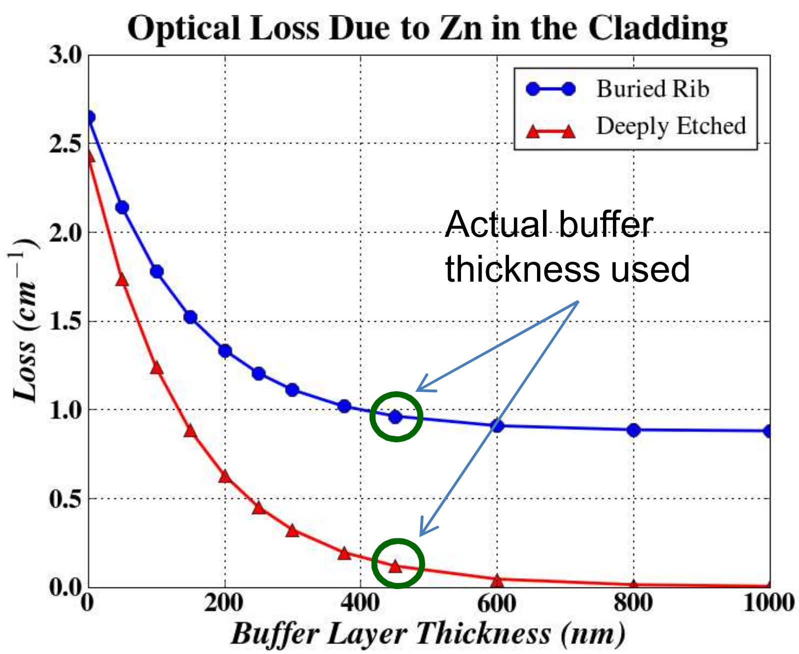
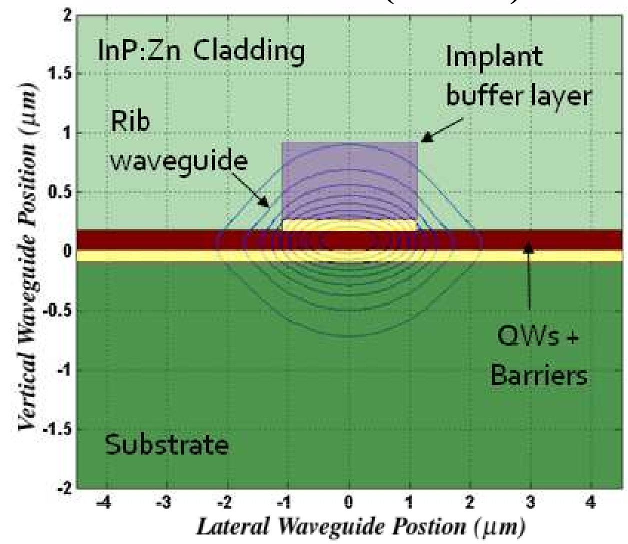
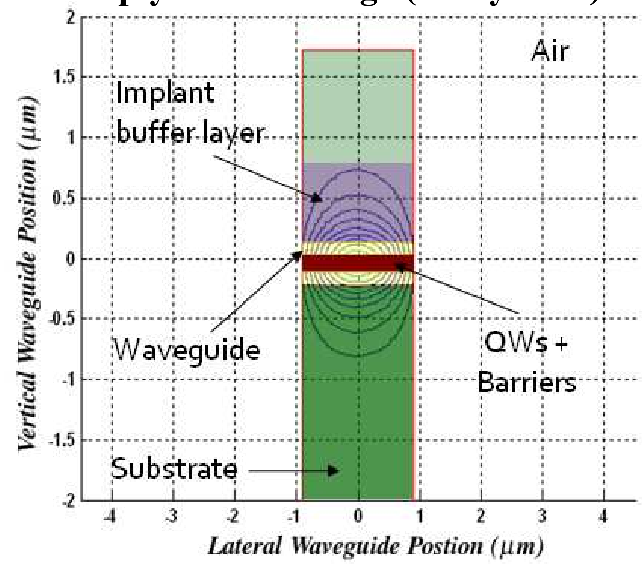
- Use QWI implant buffer to provide undoped setback layer between optical mode and Zn atoms
- Simulated *reduction* in optical loss:
  - Deeply-etched > Buried rib
  - No lateral mode interaction with Zn doped cladding



Buried Rib (AWGR):



Deeply-Etched Ridge (Delay Line):



Transitions Between Waveguide Designs

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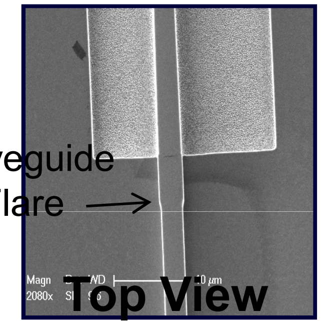
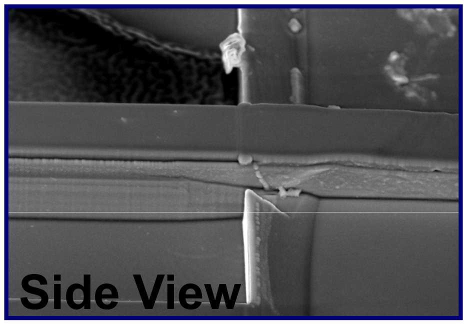
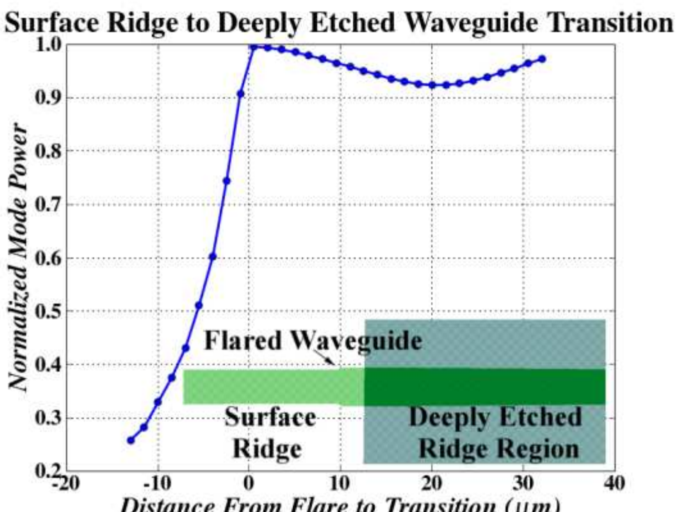
Surface-to-Deep Ridge Transition

- "Mode matching" transition [1]
  - Surface ridge flares and tapers before deep ridge section
  - No lateral misalignment issues

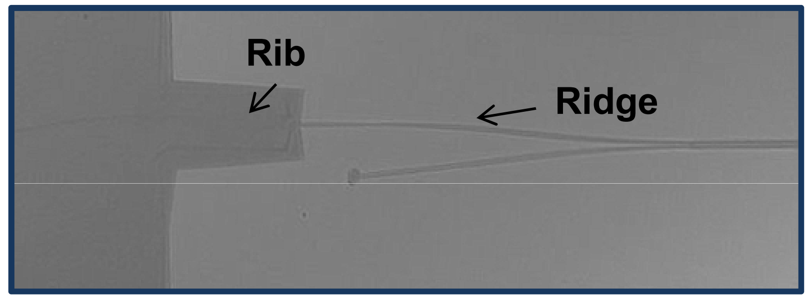


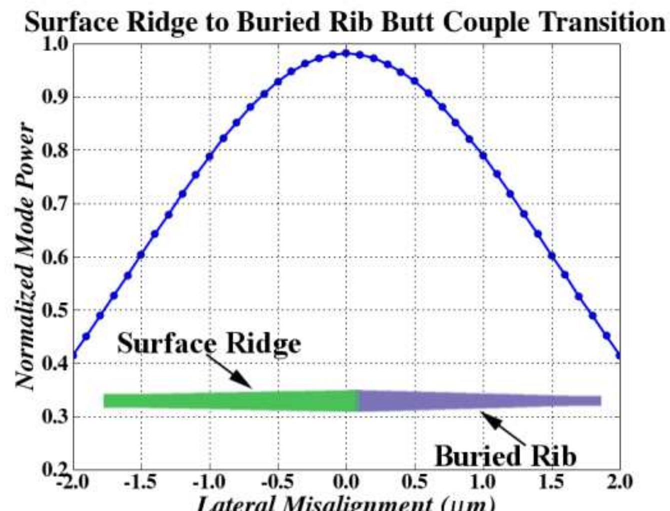




Surface-to-Buried Rib Transition

- Flared/tapered butt-couple transition
  - Surface ridges flares and butt couples to tapering rib waveguide
  - Fairly tolerant to lateral and longitudinal misalignment





[1] *J. H. den Besten et al., Photon. Tech. Lett., vol. 14, Jan. 2002*

Widely-Tunable-X PICs
(Mostly serial integration)

Early PICs

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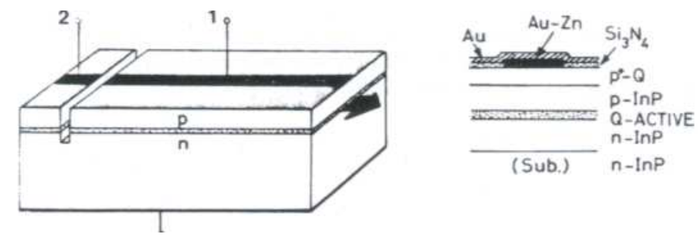
→ Etched grooves

- Tunable single frequency
- Laser-modulator
- Laser-detector

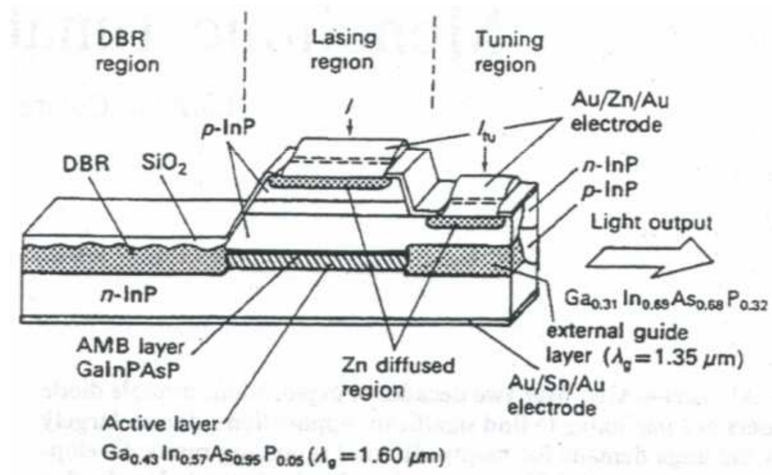
L.A. Coldren, B.I. Miller, K. Iga, and J.A. Rentschler, "Monolithic two-section GaInAsP/InP active-optical-resonator devices formed by RIE," *Appl. Phys. Letts*., 38 (5) 315-7 (March, 1981).



→ DBR gratings and vertical couplers

- Tunable single frequency
- Combined integration technologies

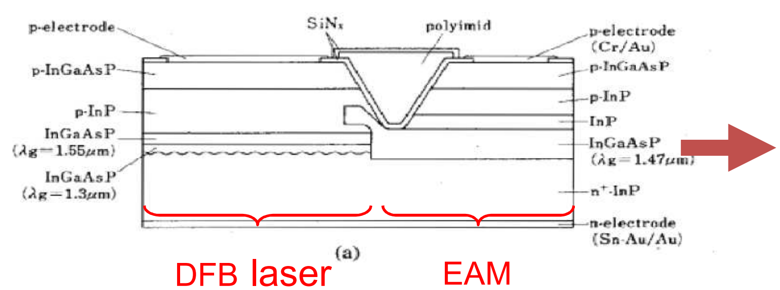
Y. Tohmori, Y. Suematsu, Y. Tushima, and S. Arai, "Wavelength tuning of GaInAsP/InP integrated laser with butt-jointed built-in DBR," *Electron. Lett*., 19 (17) 656-7 (1983).



→EML = electroabsorption-modulated laser

- Still in production today

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



SGDBR-SOA-Modulator PIC

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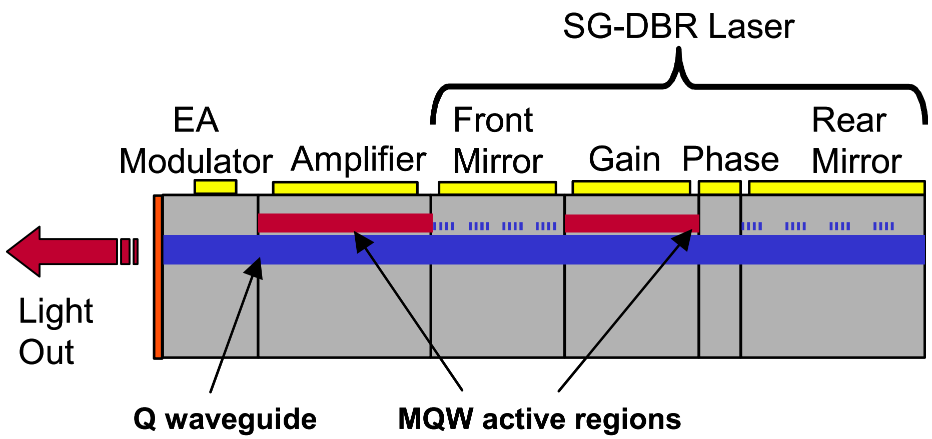
SGDBR+X: Foundation of PIC work at UCSB Heart of Wavelength Converter

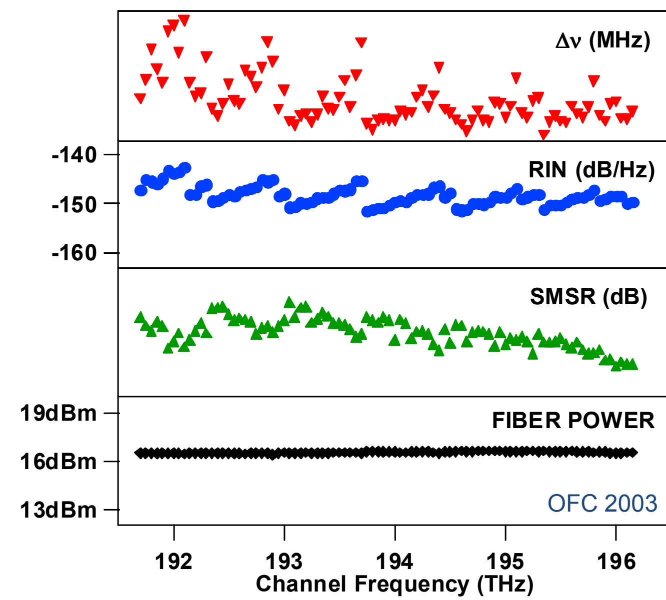
"Multi-Section Tunable Laser with Differing Multi-Element Mirrors," US Patent # 4,896,325 (January 1990)

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



6 section InP chip

- SOA external to cavity provides power control
- Both EAM and MZ modulators integrated



- Over a million in the field today carrying live traffic
- JDSU-ILMZ recently released as TOSA

SGDBR-SOA-modulator transmitters @ 40 Gb/s

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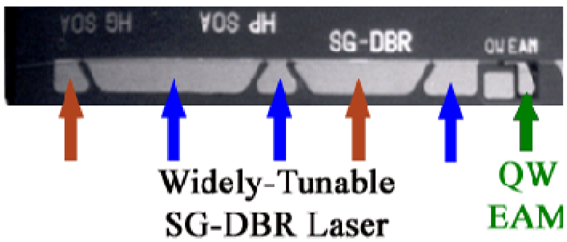
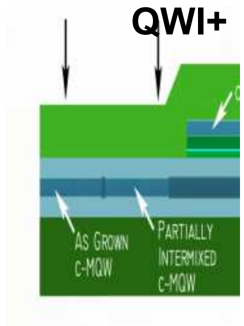
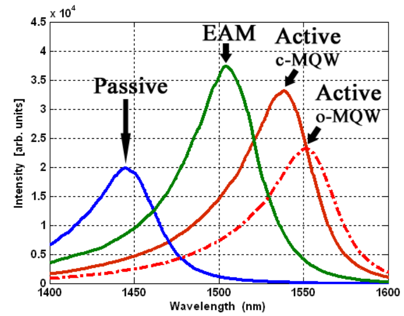
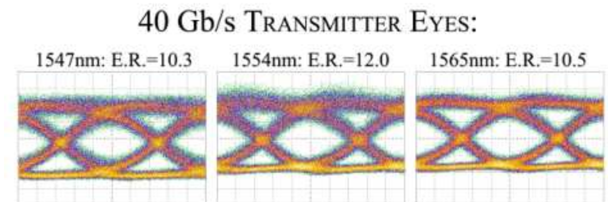
1. QWI/EAM :







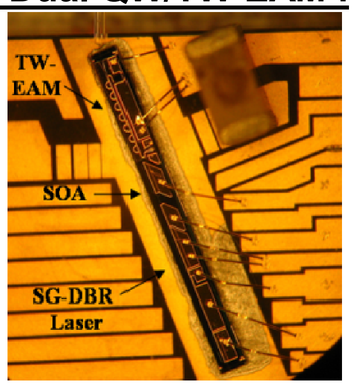


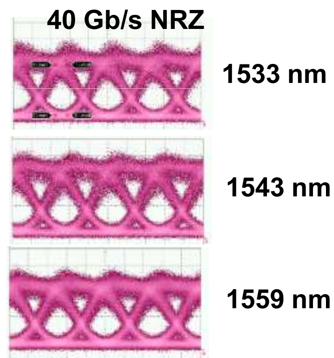
f_{3dB}=32 GHz/175μm—20dB/V (1536-1560nm)

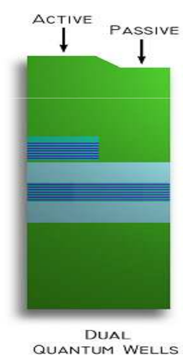
V_{pp} = 2.5V

J.W. Raring and L.A. Coldren, *JSTQE* **13**, (1), pp. 3-14, (Jan. 2007)

2. Dual QW/TW-EAM :







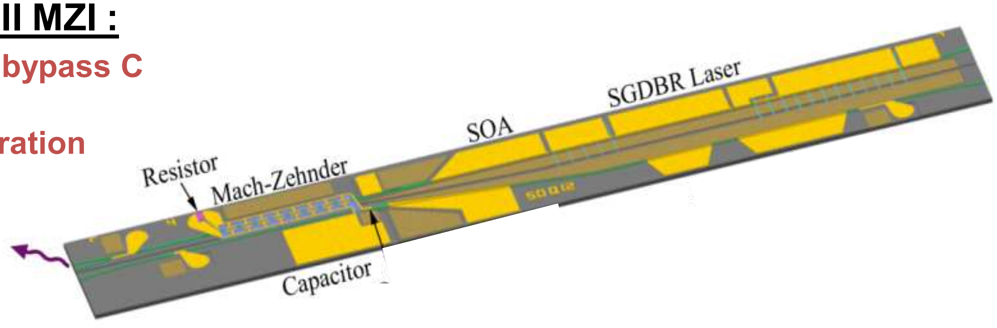
LASOR

- 15 – 20 dB/V for 600 μm over range
- Open eyes for all wavelengths
  - 6 – 10 dB extinction with 2.1V

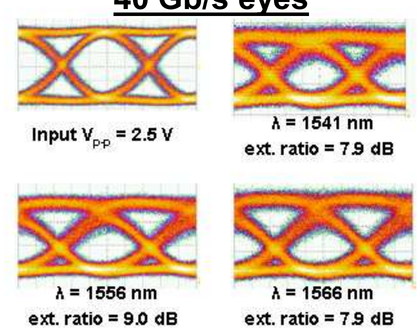
M. M. Dummer, et al, *OFC'08*, San Diego, Mar, 2008.

3. Series Push-Pull MZI :

Integrated load R and bypass C
30 GHz Bandwidth
40 Gb/s error free operation
Low/negative chirp



40 Gb/s eyes



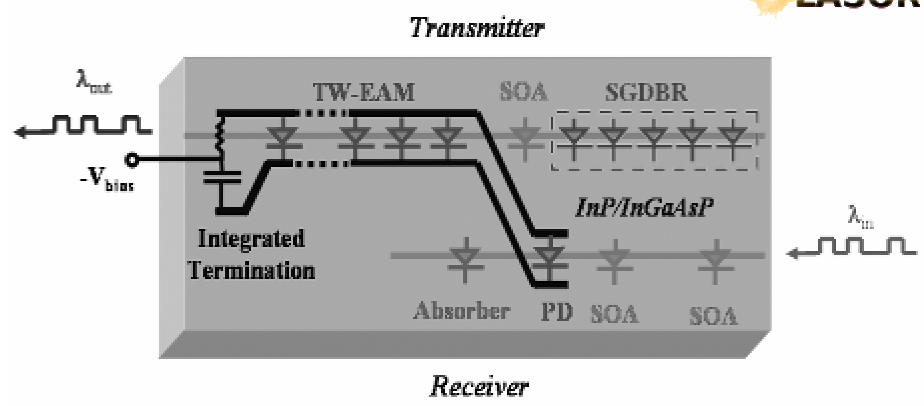
A. Tauke-Pedretti, etal, *Photon. Tech. Lett.*, **18** (18) 1922-4 (2006).

Transceiver/wavelength-converter: 2-stage-SOA-PIN & SGDBR-TW/EAM

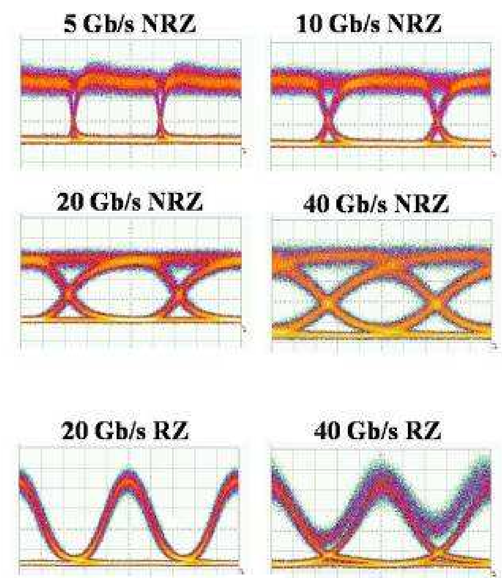
UCSB

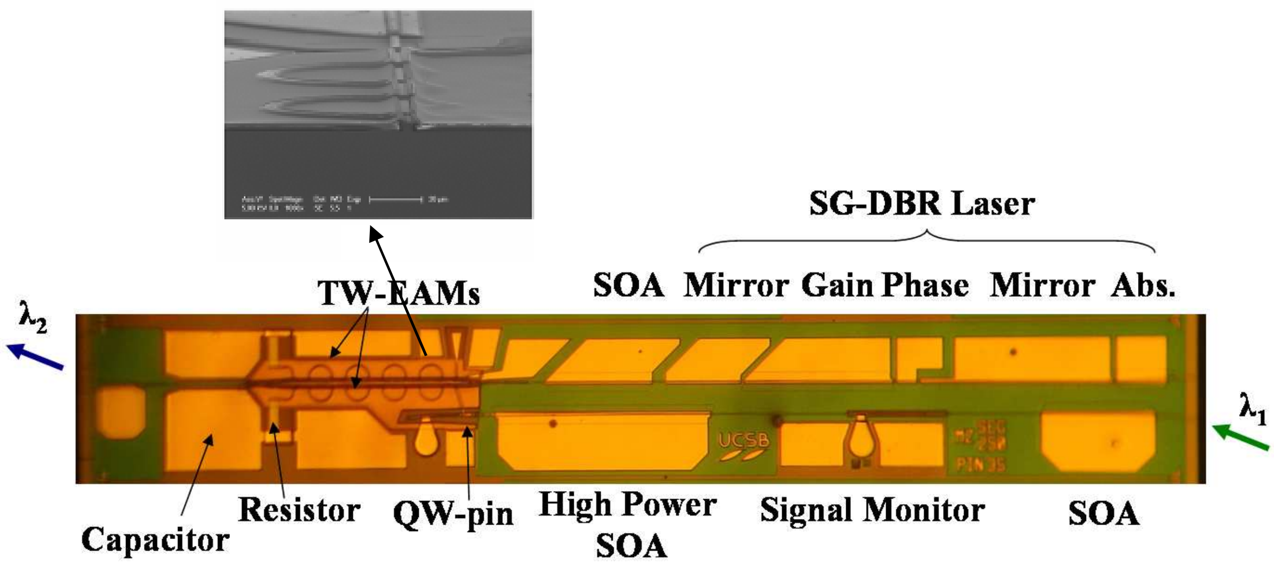
LASOR

- Data format and rate transparent 5-40Gb/s
- No filters required (same λ in and out possible)
- On-chip signal monitor
- Two-stage SOA pre-amp for high sensitivity, efficiency and linearity
- Traveling-wave EAM with on chip loads
- Only DC biases applied to chip—photocurrent
- directly drives EAM
- 40 nm wavelength tuning range



Eye Diagrams





M. Dummer et al. Invited Paper Th.2.C.1, *ECOC 2008.*

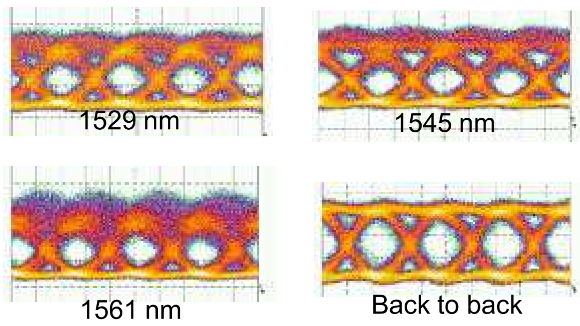
Wavelength converter/SOA-PIN receiver & SGDBR-Mach Zehnder transmitter

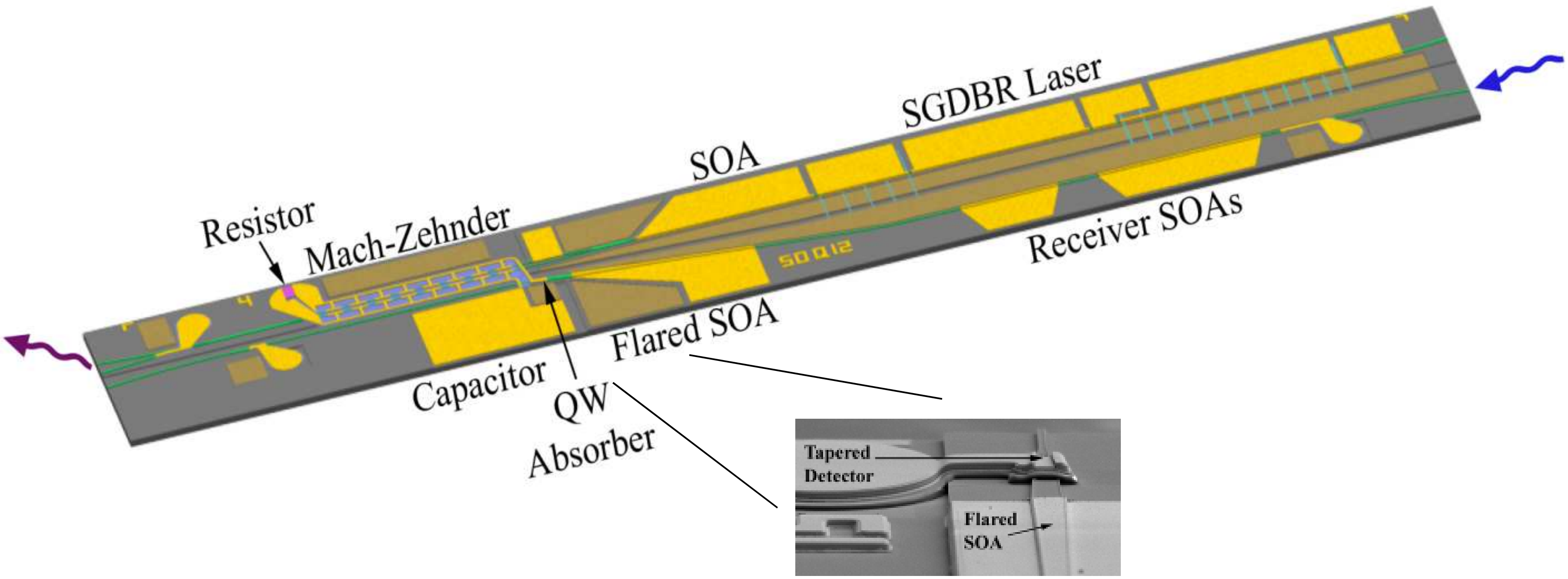
UCSB

LASOR

- Photocurrent driven
- 35 µm QW absorption region in receiver
  - Tapered for reduced capacitance
- 300 µm traveling-wave Mach-Zehnder modulation region
  - Series-push-pull design to maximize bandwidth
  - Chirp management
- Data format and rate transparent
- No optical filter required
- Integrated termination resistor and bypass Capacitor
  - No external bias tees used

40 Gb/s Eyes



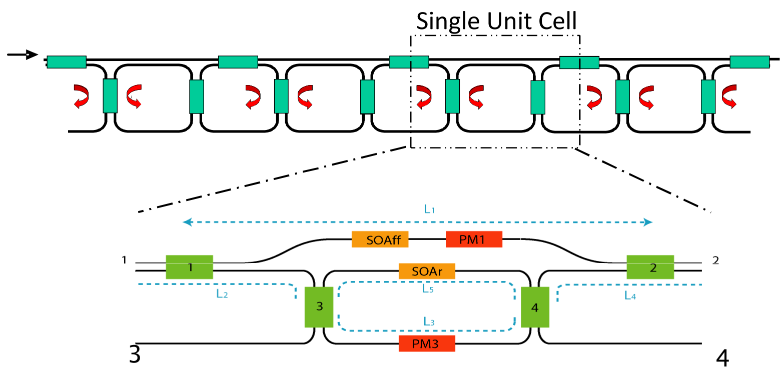


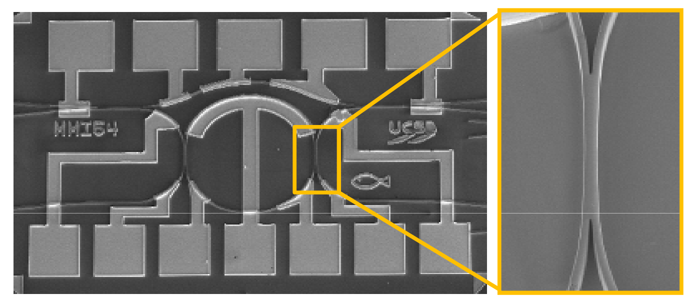
A. Tauke-Pedretti, et al, *J. Lightwave Tech.* **26** (1) pp91-98 (Jan. 2008)

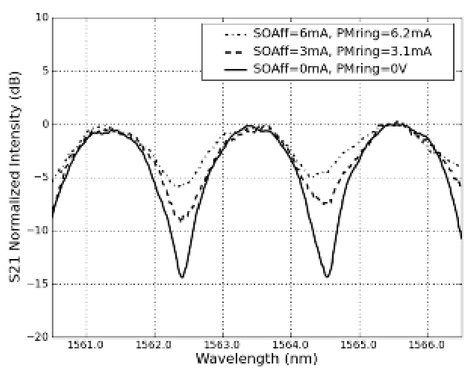
Programmable Photonic Lattice Filters

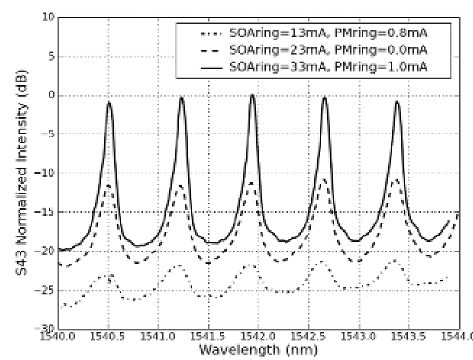
UCSB

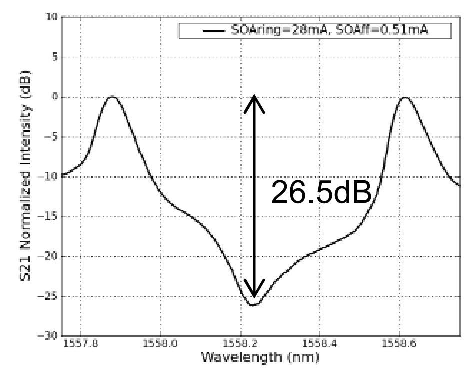
- Prefilter information, avoiding the latency and bandwidth restrictions of purely digital signal processing approaches
- Demonstrate programmable poles and zeros from a single unit cell that can be cascaded to form complex lattice filters
- Incorporate <u>SOAs</u> and <u>Phase Modulators</u> to control filter parameters











See E.J. Norberg, R.S. Guzzon, S. Nicholes, J.S. Parker, and L. A. Coldren, "Programmable photonic filters fabricated with deeply etched waveguides," *IPRM '09*, paper TuB2.1, Newport Beach (May, 2009)

Revolutionary Research . . . Relevant Results

Bistable Ring Resonators for Digital Logic

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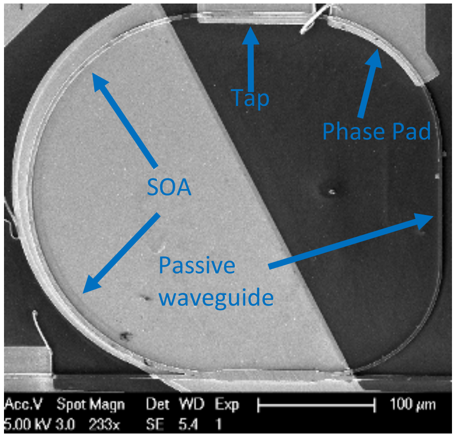
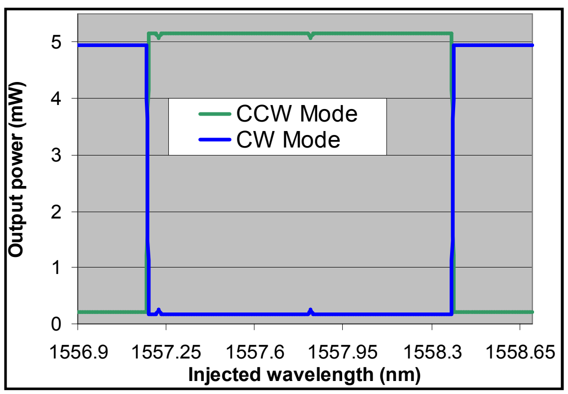
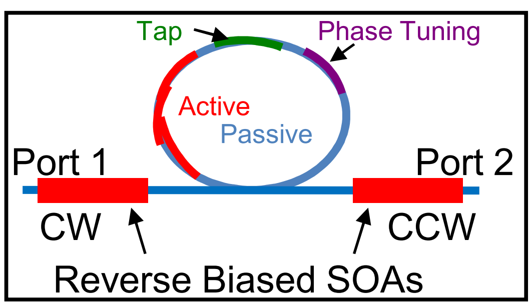


SEM image of single ring resonator

Separate gain, phase-shift, and monitoring (tap) sections added to passive waveguide in ring



Injection triggered switching in a ring resonator

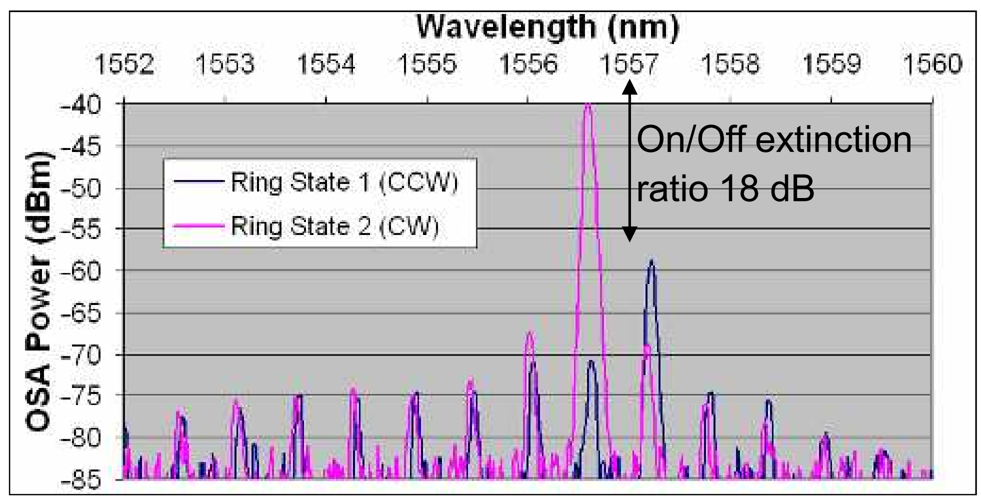


Schematic of ring resonator

Single-port injection:

- Injected tunable laser switches ring between CW / CCW lasing.
- CW mode > 98% power into Port 1.
- CCW mode > 98% power into Port 2.
- Single-port switching reduces design complexity and round trip delay.
- SMSR >25 dB.
- Injected laser -35 dB below ring lasing power.

Verifies sensitive cw-to-ccw sample-and-hold



Output optical spectrum of ring resonator in CW and CCW states

J. Parker, et al, IPNRA '09, IWA2, Honolulu

Integrated Multi-Channel PICs
(Mostly parallel integration)

Early PIC with wavelength-selectable laser and EAM

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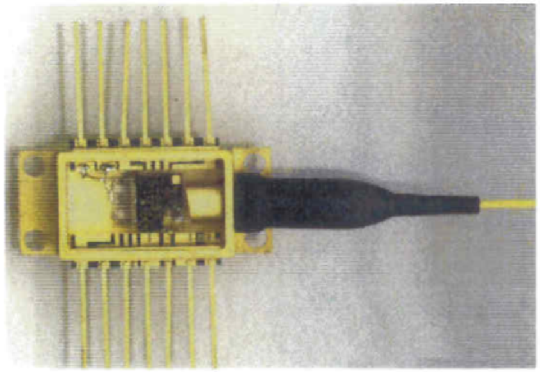

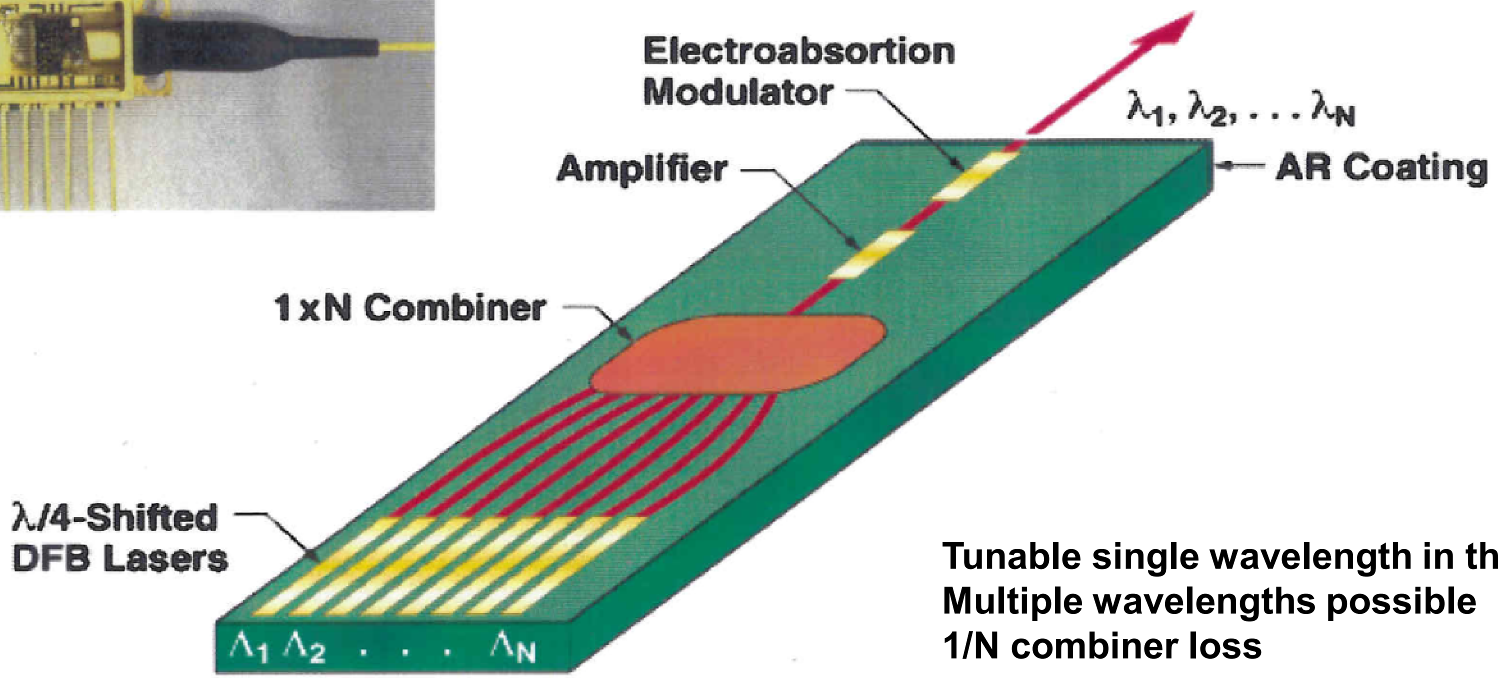

Tunable single wavelength in this case
Multiple wavelengths possible
1/N combiner loss

M. G. Young, et al., *Electron. Lett.,* **31**, pp. 1835-1836, 1995.

Early PIC multi-wavelength receiver

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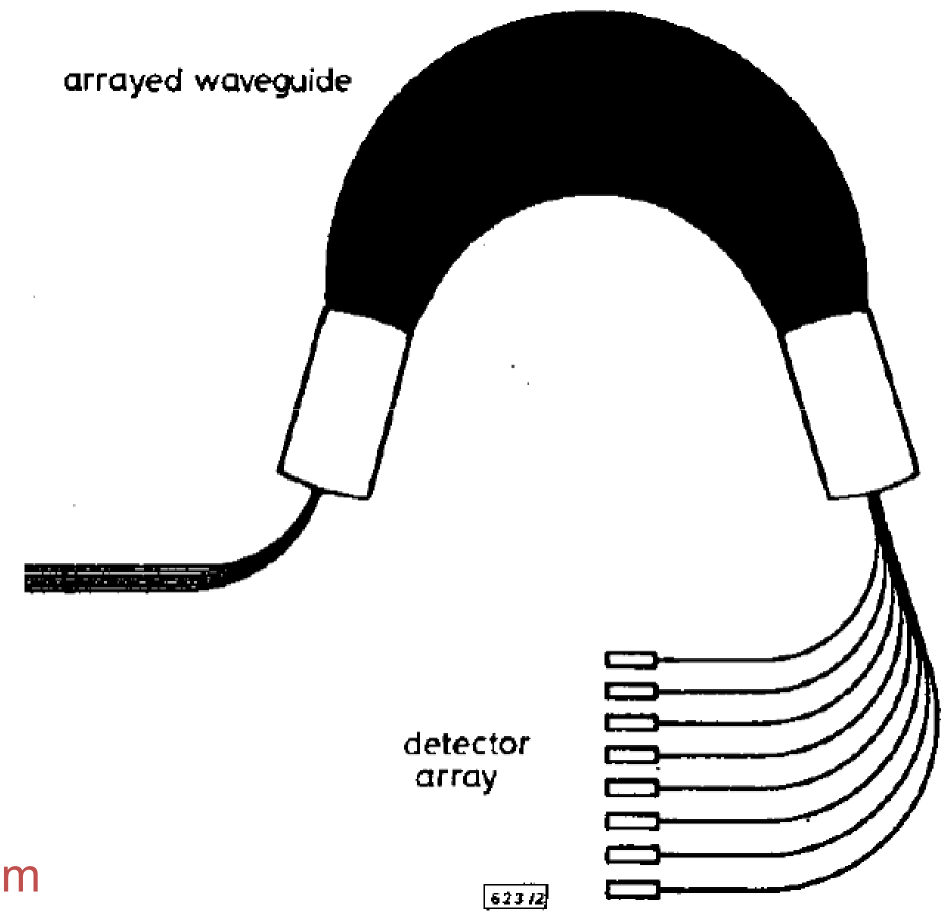
Wavelength Demultiplexer + Detectors



8 × 2 nm

J. B. D. Soole, et. al., *Electron. Lett.,* pp. 1289-1290, 1995.

Infinera multi-channel commercial transmitter & receiver PICs: 10 x 10 Gb/s

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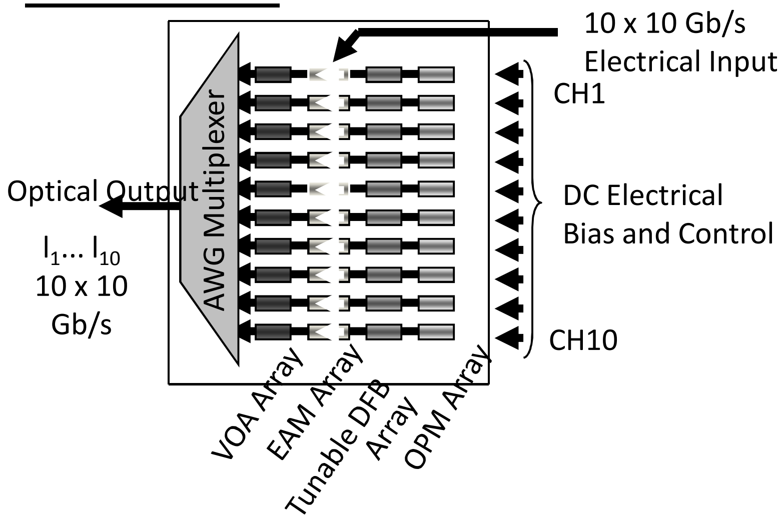
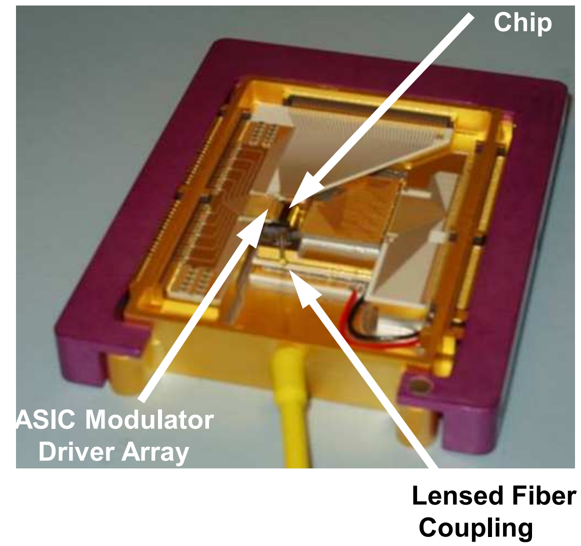
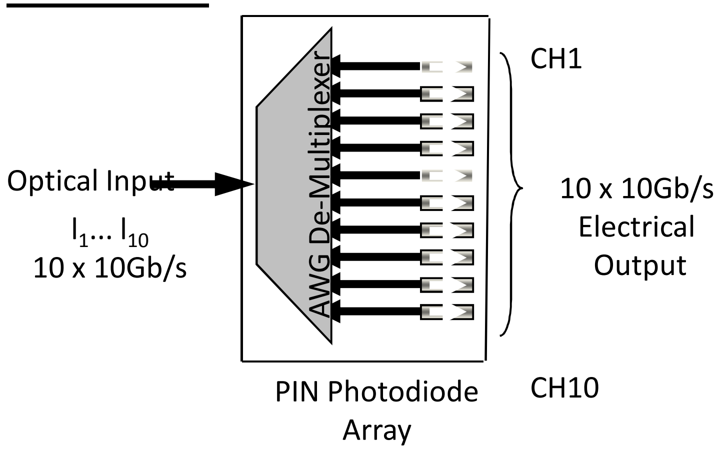
Transmitter:



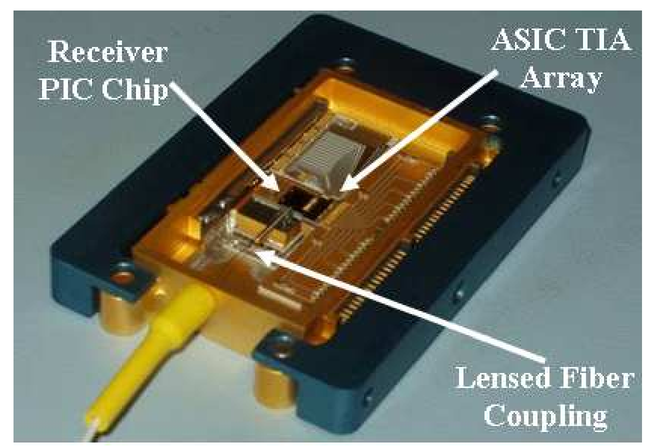


Receiver:



Low polarization dependant loss

Receiver < 0.38 dB



R. Nagarajan, et al., *Sel. Top. Quant. Electron.*, **11**, pp. 50-65, 2005.

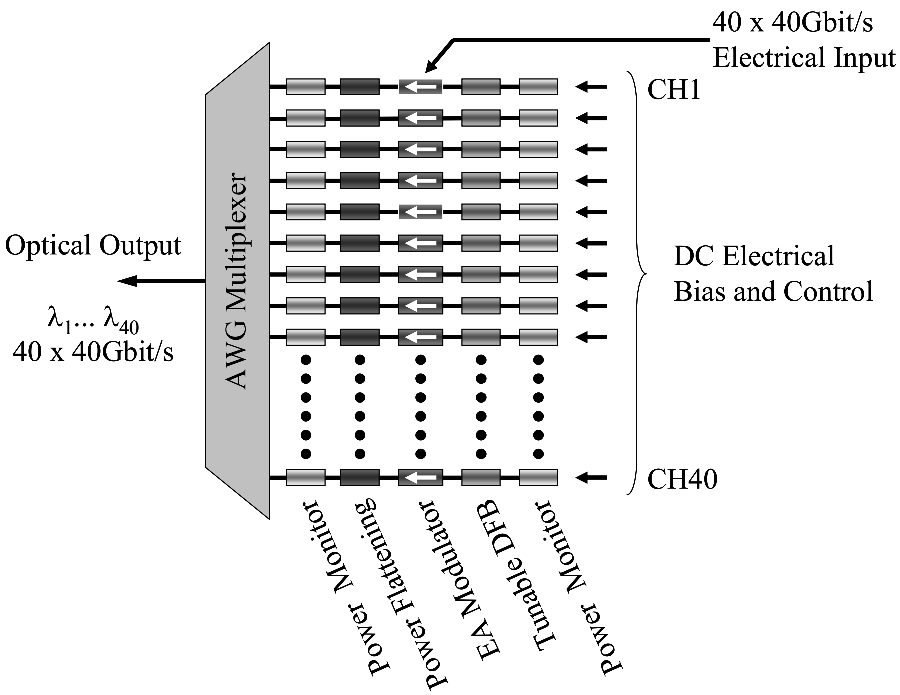
courtesy of C. Joyner

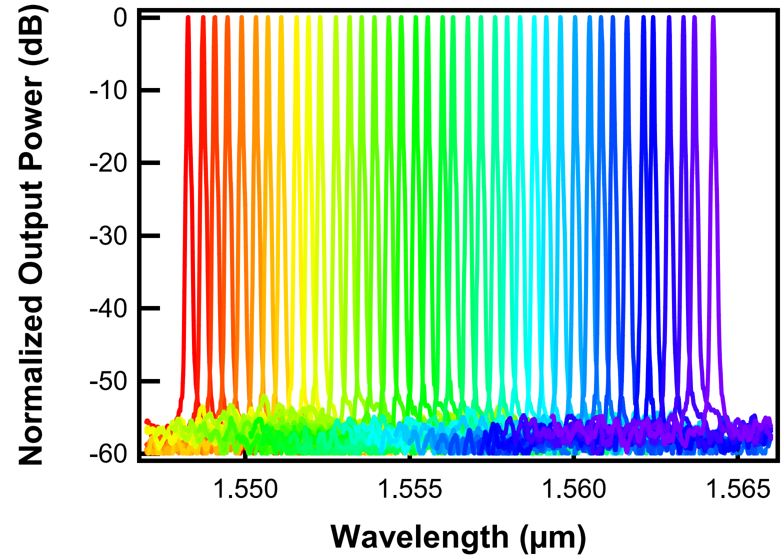
infinera

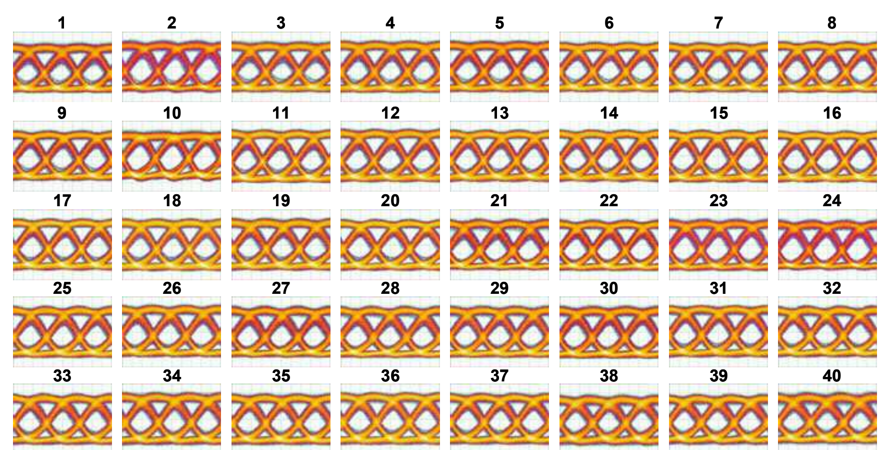
40 x 40 Gb/s results

UCSB

1.6Tbit/s DWDM Large-Scale PIC Transmitter







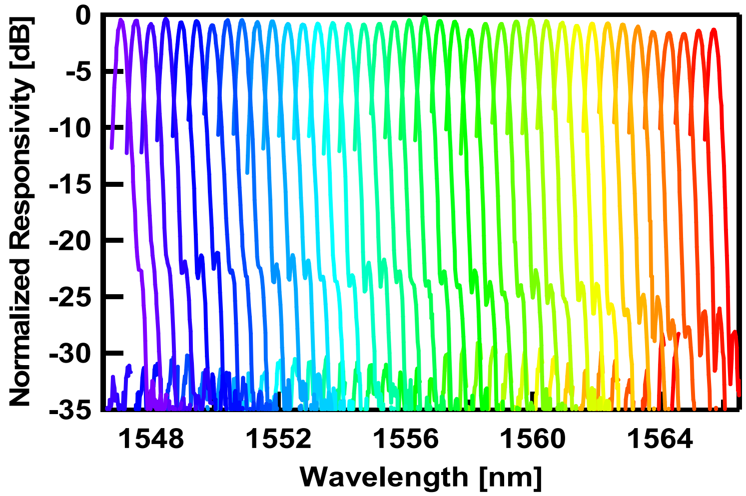
1.6 Tb/s single chip
40 channels
40 Gb/s modulation / channel

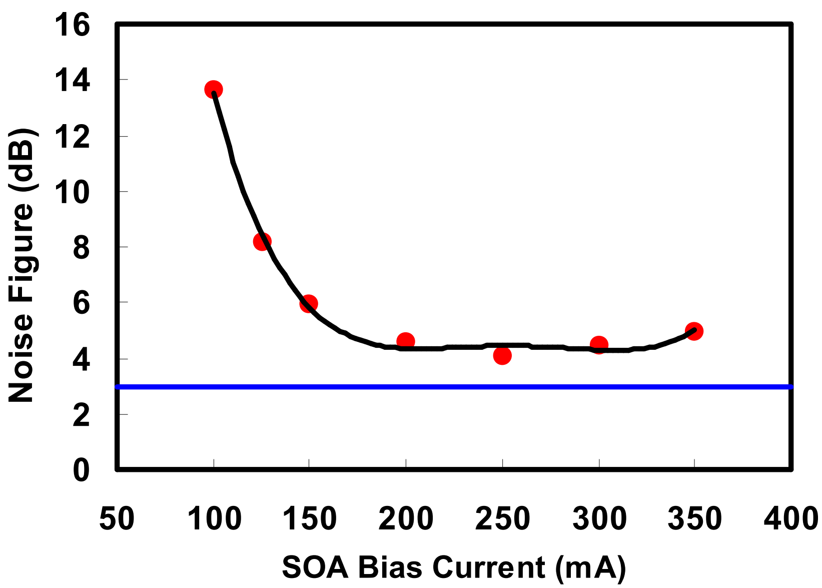
R. Nagarajan, et.al., *IEE Electronic Letters*, Vol. 42, no. 13, pp771-773 (2006).

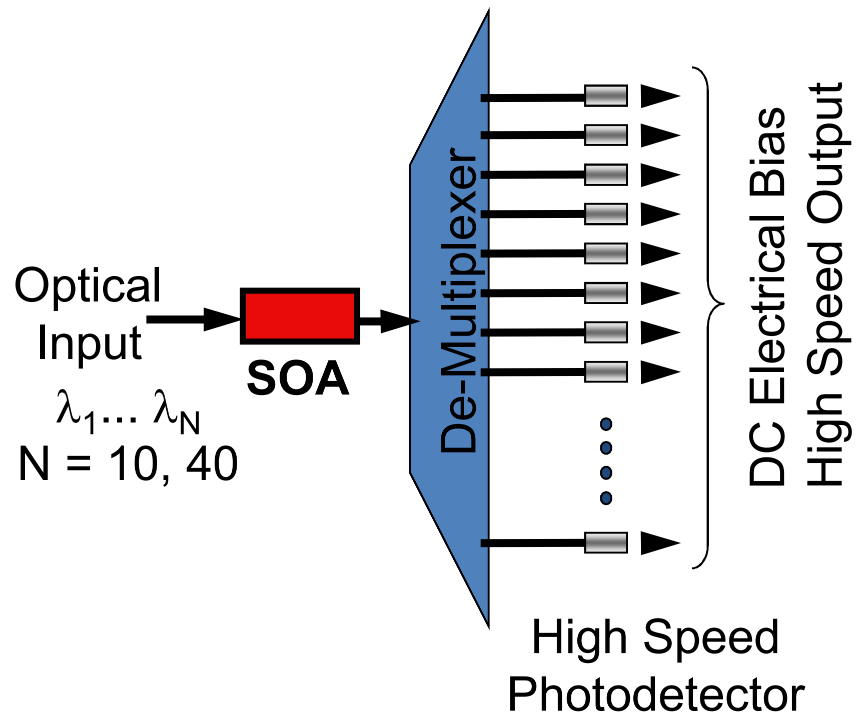
courtesy of C. Joyner

infinera

Amplified 40 channel receiver spectrum







Nagarajan, PDP32 *OFC* 2007

courtesy of C. Joyner

Meeting the Future Demand

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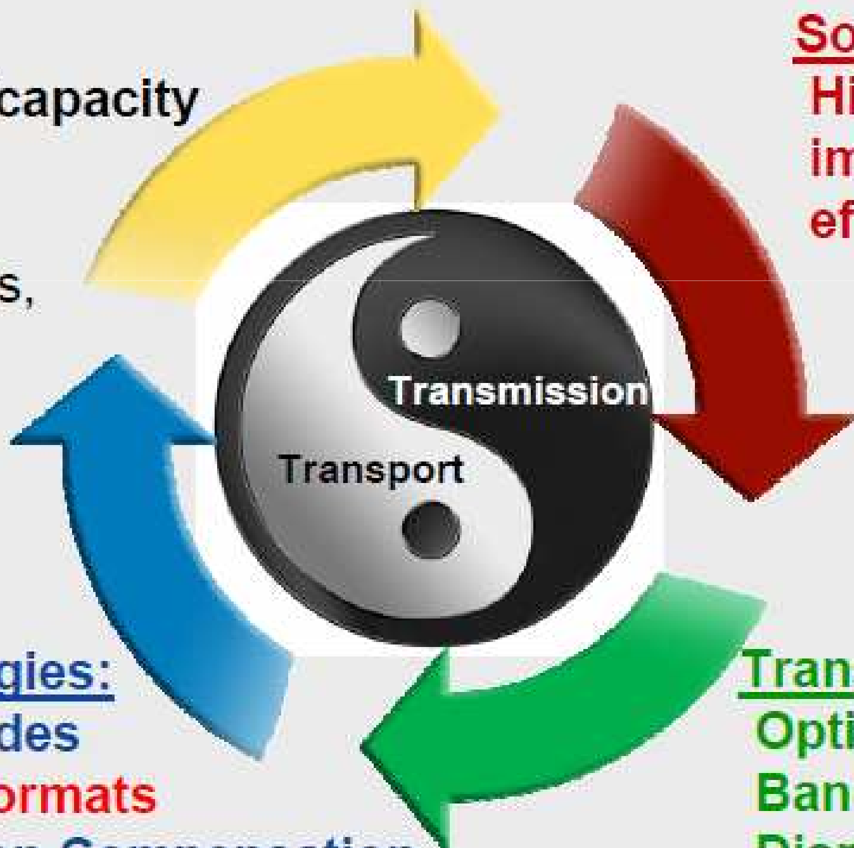
Upgrading Systems to 40 Gb/s or even 100 Gb/s Faces Serious Transport and Transmission Issues

Goal:
More bandwidth/capacity over installed infrastructure
(with existing fibers, EDFAs, DCMs, and OADMs)

Solution:
Higher data rates and improved spectral efficiency



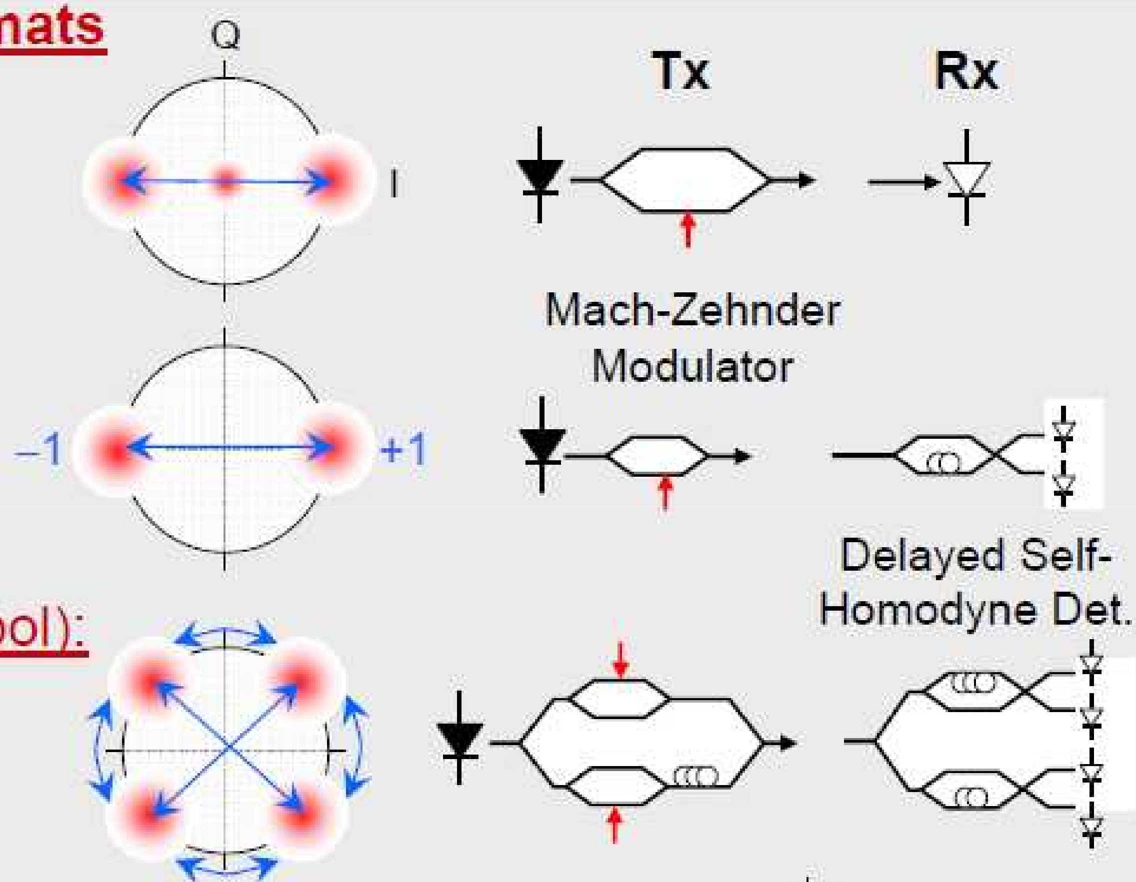
Enabling Technologies:
- Advanced FEC Codes
- New Modulation Formats
- Adaptive Dispersion Compensation
- Coherent Detection / Electronic DSP

Transport Impediments:
- Optical Noise (OSNR)
- Bandwidth Narrowing
- Dispersion (CD, PMD)
- Nonlinearities (SPM, XPM)

Advanced Modulation Formats

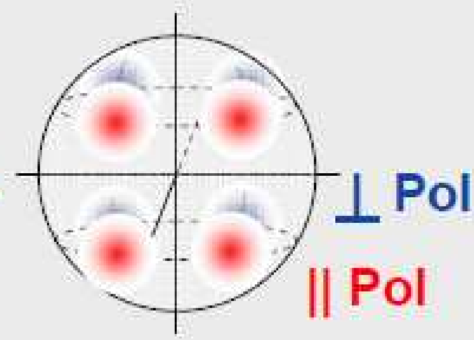
UCSB

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



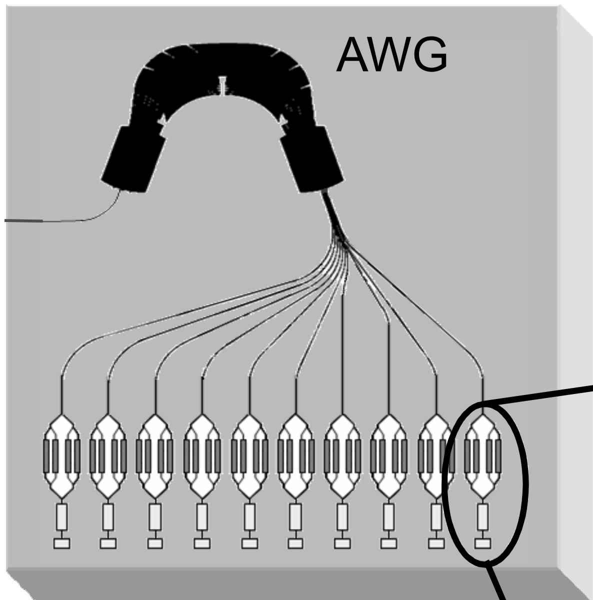
- **Quaternary** (2 bits/symbol):
  - **NRZ- / RZ-DQPSK**

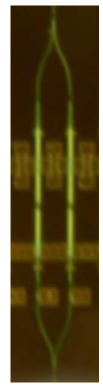
- **Polarization-multiplexed QPSK** (4 bits/symbol):
  - **Dual-Polarization QPSK**

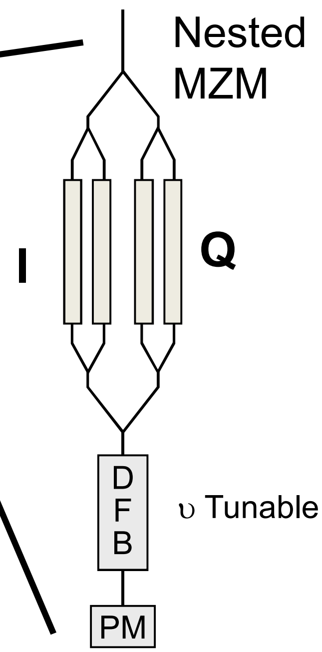


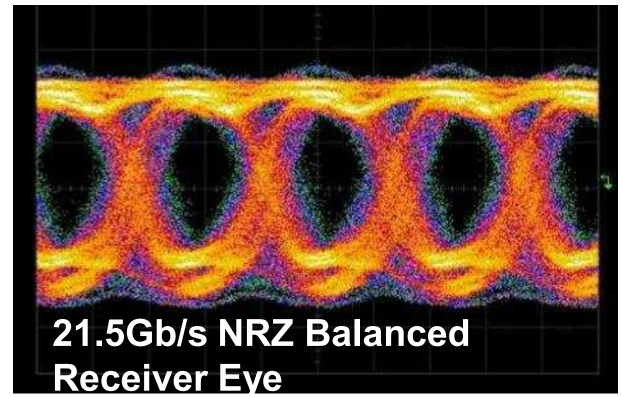
Large-scale DWDM DQPSK transmitter PIC 10 channels x 40 Gb/s

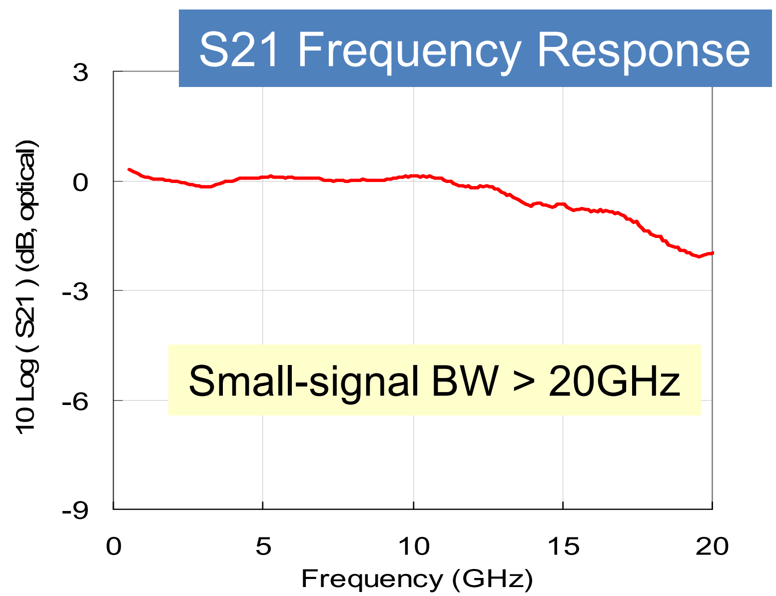
UCSB











- 10 frequency-tunable DFB lasers with backside power monitors
- 10(I) + 10(Q) nested Mach-Zehnder modulator pairs
- 1 AWG
- 111 integrated elements in total on chip

S.W. Corzine, et al, *OFC'08*, PDP18, 2008

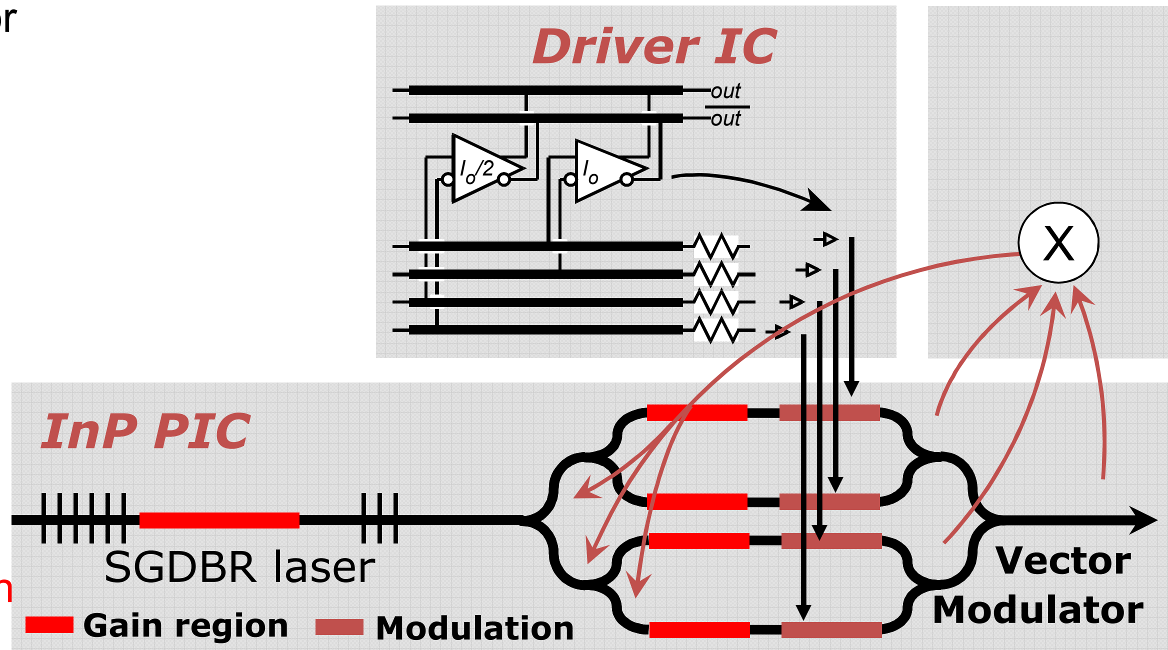
courtesy of C. Joyner

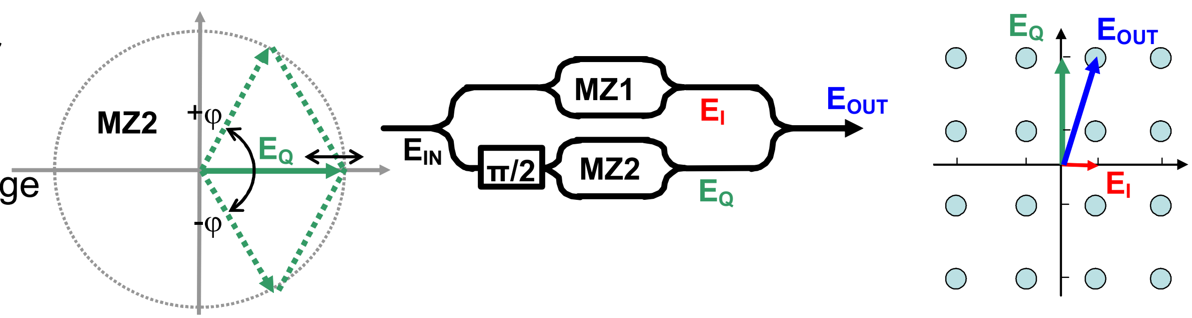
Infinera

SGDBR + Multilevel Optical Modulation
(unpublished)

UCSB

- High order modulation required for high spectral density / channel rate
- Lower symbol rate – improved dispersion tolerance
- Semiconductor modulator
  - –Nonlinear response
  - –AM coupled with PM
  - –Compact, integrated with high-performance sources
- Challenge: Produce QAM modulation with required precision
  - –Improved response required, modulator nonlinearities results in ill-defined data levels.
  - –Use electronics to compensate for non-linear response → <u>close integration electronics-photonics</u>
  - –Capture potential of 1V drive voltage
- Integrated QAM transmitters
  - –Up to 64-QAM





16 QAM

From Direct to Coherent Detection

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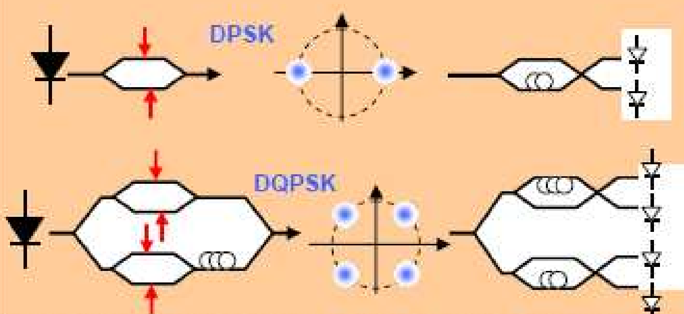
Direct Detection

- On-Off keying only
- Simple Tx and Rx

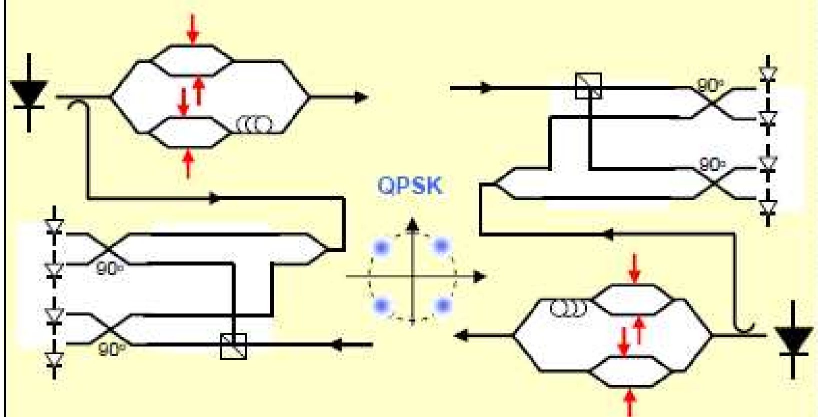
Self-Homodyne Detection

- Differential PSK encoding
- Decoding via 1-bit self-delay Mach-Zehnder interferometer
- Balanced Rx



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

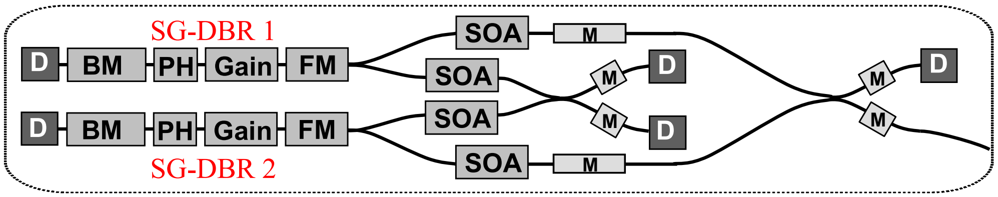


- **Use 'Intradyne' without phase-locked LOs, or do we need true Heterodyne detection?**
  - **High-speed A/Ds & DSPs require lots of power and are expensive to design if optical phase must be tracked, especially as data rate increases**
  - **Impairments can be removed with much slower, lower-power, lower-cost signal-processing circuits**

Optical Phase Locked Loops: Locking Two SGDBRs

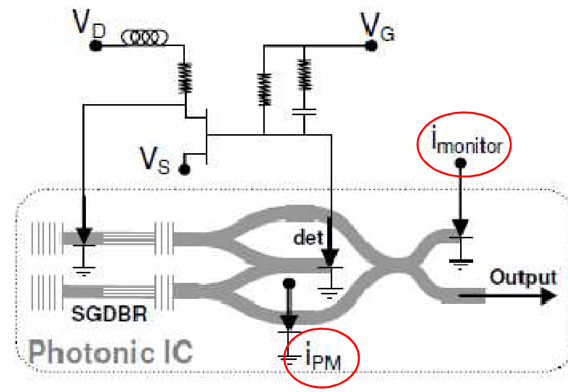
UCSB

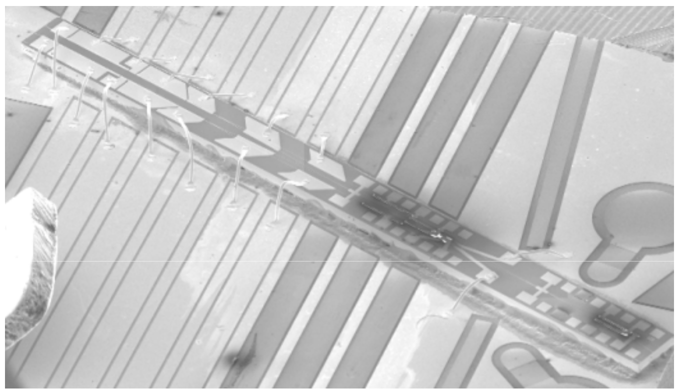
Optical phase-locked loops (OPLLs) are viable using close integration of PICs with electronics

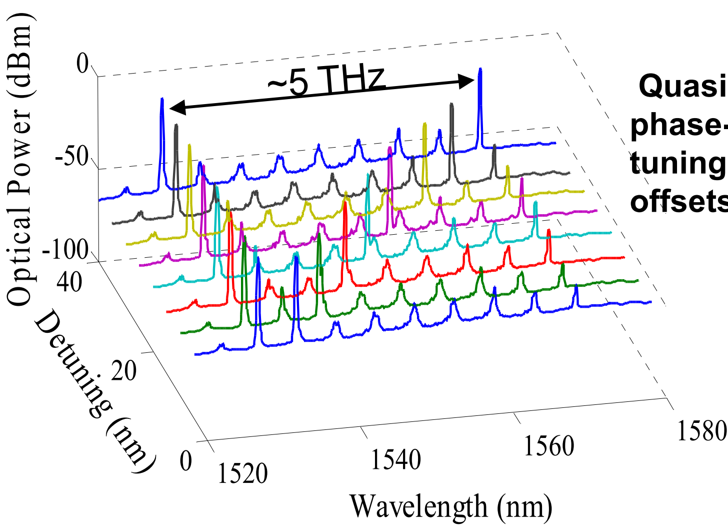


D Photodetector

M Modulator

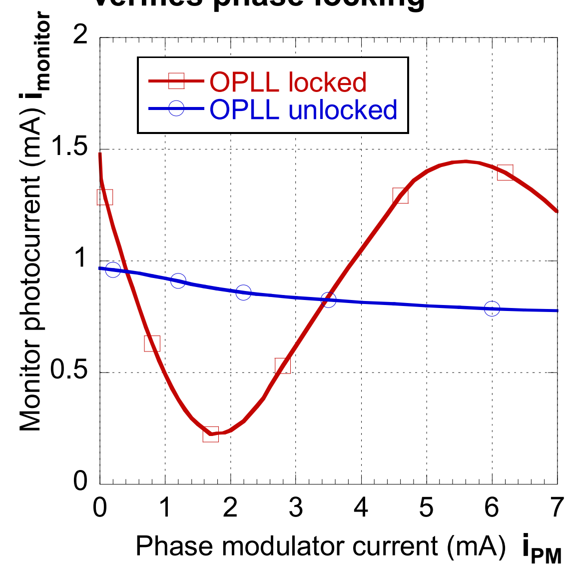






Quasi-continuous phase-locked digital tuning up to 5 THz offsets possible

Coherent interference at monitor verifies phase locking

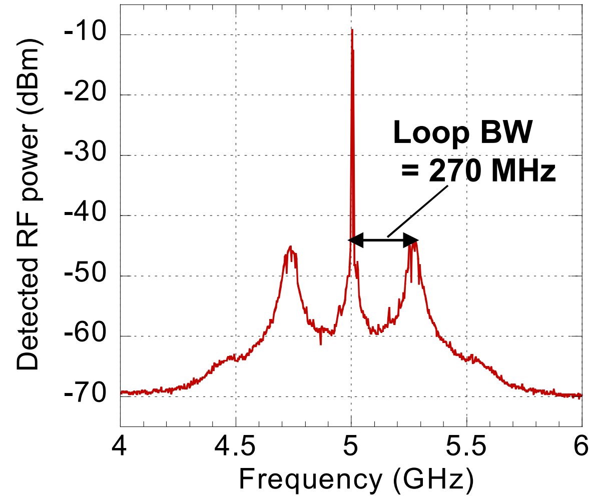


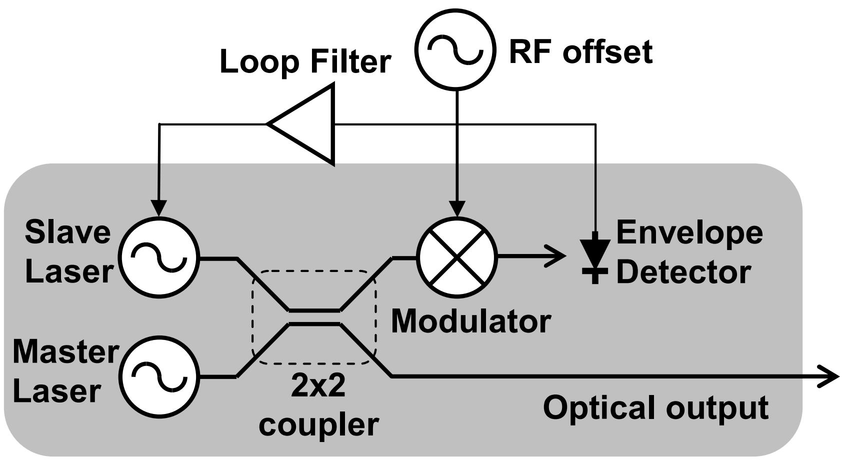
S. Ristic, et al, *OFC '09*, PDPB3, San Diego, (Mar., 2009)

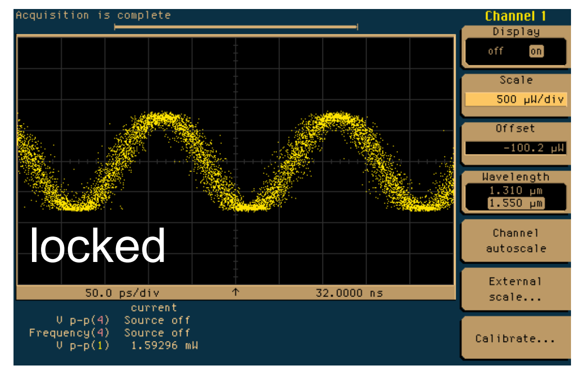
OPLL'd SGDBRs—Heterodyne

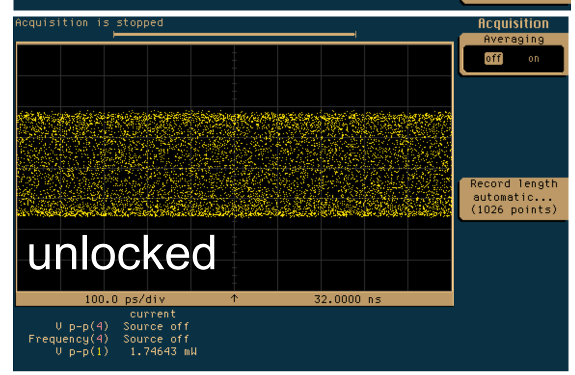
UCSB

- **EA modulator used to generate 5 GHz offset frequency**
- **Slave laser locked to modulation sideband**
- **Coherent beat observed**
  - 0.03 rad^2 phase error variance in +/-2GHz BW estimated from captured spectrum
- **Up to 20 GHz offset locking demonstrated**









Ristic et al: JLT v.28 no.4, 2010, in press, also at MWP2009, paper Th 1.5

Additional OPLL Applications/Challenges

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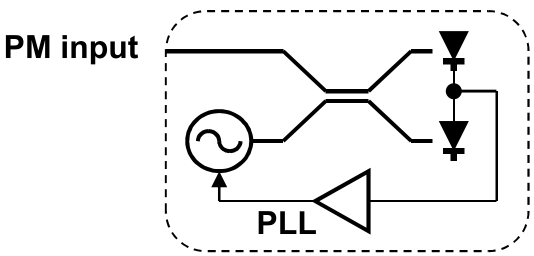
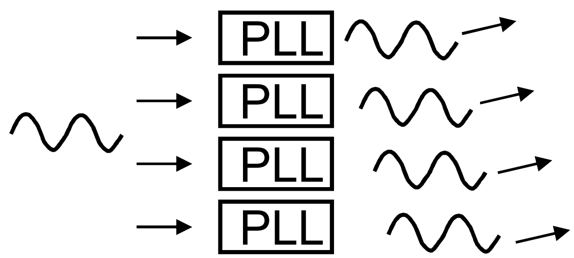
Coherent receiver



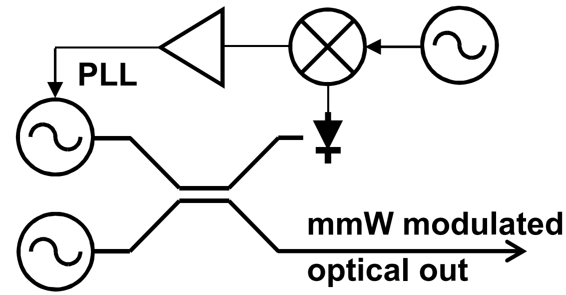
- Costa's Loop for BPSK, QPSK demodulation
- No requirement for complex DSP circuits
- Challenge: Develop receivers for high speed (>100Gbaud) or high constellations (n-QAM)
- Matched with development of coherent sources

LIDAR



- Very rich/challenging area
- Locking tunable lasers
- Arrays of locked OPLLs
- Swept microwave reference
- Time / Phase encoding of directed output
- Need for rapid scanning and locking rates

mmW / THz generation



- Locking of two tunable lasers
- Requires Integration of high-speed UTC photodiode
- Speed determined by UTC photodiode and feedback electronics: Can be very high
- Combined with antenna designs for complete TRX links with free-space path

All require close integration of electronics with photonics

Can Spectral Efficiency Increase Enough?

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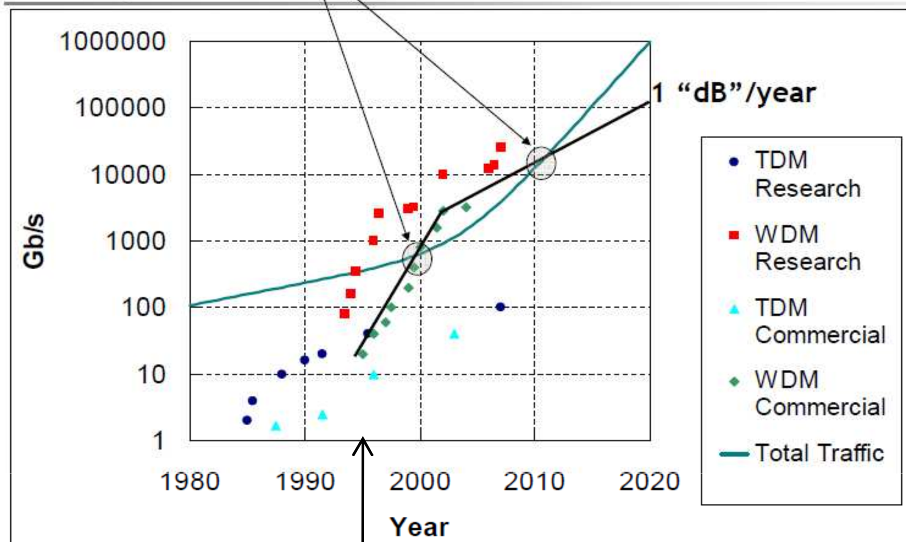
Two Special Years 2000 and 2011



Introduction of EDFA and WDM
→ OEO repeaters vastly reduced

- **Excess fiber capacity disappears after 2015**

- **Must improve Spectral Efficiency (SE) → Bits/Hz of bandwidth**

- **But vast improvements are required!**

System Evolution

1990s	2000	2010	2020
2.5-10 Gb/s channel rate	10 Gb/s channel rate	100 Gb/s channel rate	1 Tb/s ! channel rate
8,16, 40 Channels	100 Channels	100 channels	100 Channels
20-160 Gb/s Capacity	1 Tb/s Capacity	10 Tb/s Capacity	100 Tb/s Capacity
SE = .025-.05	SE = 0.2	SE = 2.0	SE = 20 !
History	*History*	*Planned*	*Needed*

SE = Spectral Efficiency = Channel Rate / Channel Spacing

Even with this aggressive 2020 target, traffic growth will exceed capacity growth by a factor of 10

13 | R. W. Tkach | OIDA Annual Forum 2009 | 2 December 2009 Alcatel-Lucent

Fiber Capacity Estimate

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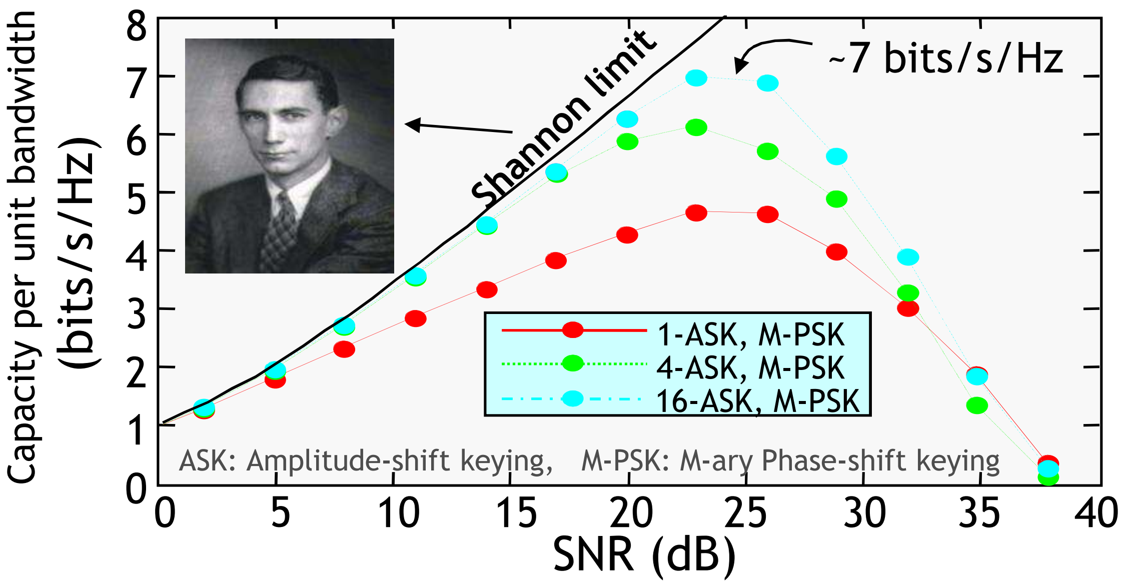
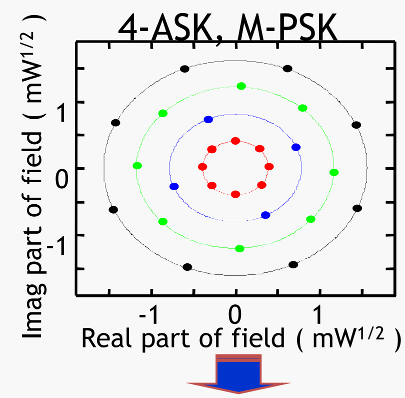
Capacity per unit bandwidth (spectral efficiency) for 2000-km transmission



Constellation Example



Complex optical transmitter and receivers

- For 2000 km, a spectral efficiency of ~7 bits/s/Hz per polarization can be achieved which corresponds to an increase of about one order of magnitude in spectral efficiency over commercial systems
- Deployed systems can transmit ~5 Tb/s over ~2000 km. For such a distance, the capacity limit of fiber is expected to be ~500 Tb/s or ~100 times the capacity of commercial systems

Courtesy: Rene Essiambre, Rod Alferness
Alcatel-Lucent

New Ideas are needed!

UCSB

"Don't bother me with new ideas; I've got a battle to fight!"

Summary

- Active InP-based photonic ICs can be created with size, weight, power and system performance metrics superior to discrete solutions in many situations. However, cost can only be less if the market size is sufficient.
- Close integration of control/feedback electronics will be desirable in many future PIC applications
- Coherent approaches will be greatly enabled by the use of photonic Integration, and numerous sensor applications may be enabled in addition to higher-spectral-efficiency communications.