Technology and Applications for InP-based Photonic Ics

OIDA
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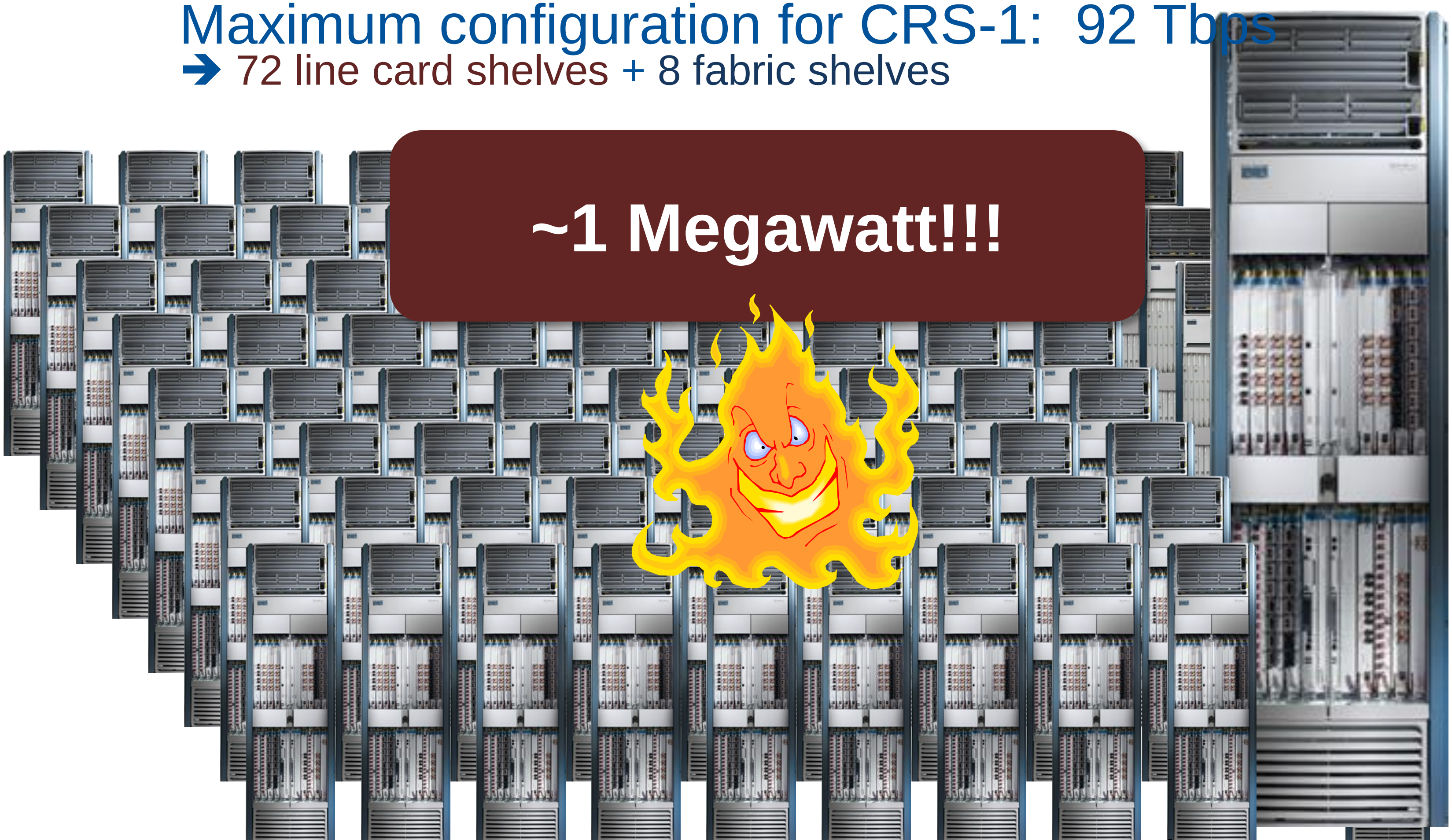
State-of-the Art Electronic Terabit IP Router

- **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



~1 Megawatt!!!

Cisco CRS-1 Router

Some of our Earliest and Latest Functional PICs

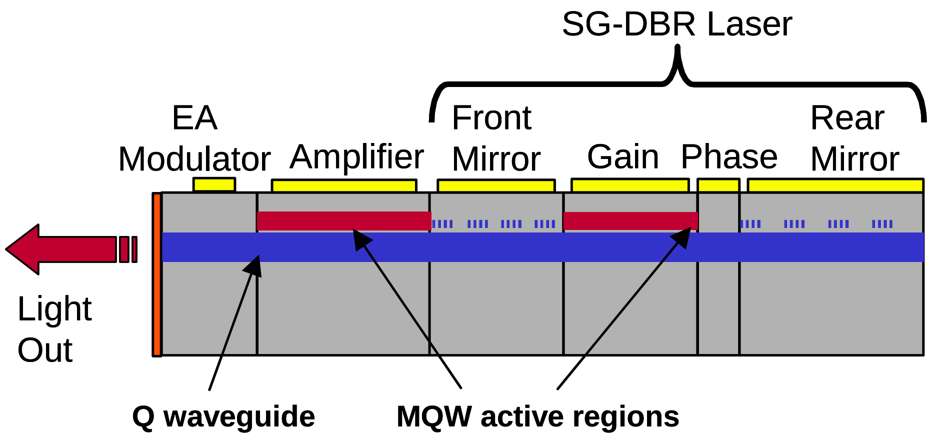
SGDBR-SOA-Modulator PIC (the earliest)

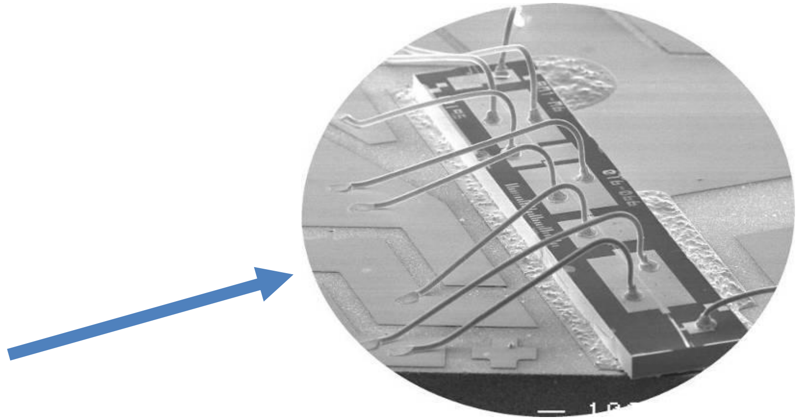
UCSB

SGDBR+X: Foundation of PIC work at UCSB

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

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

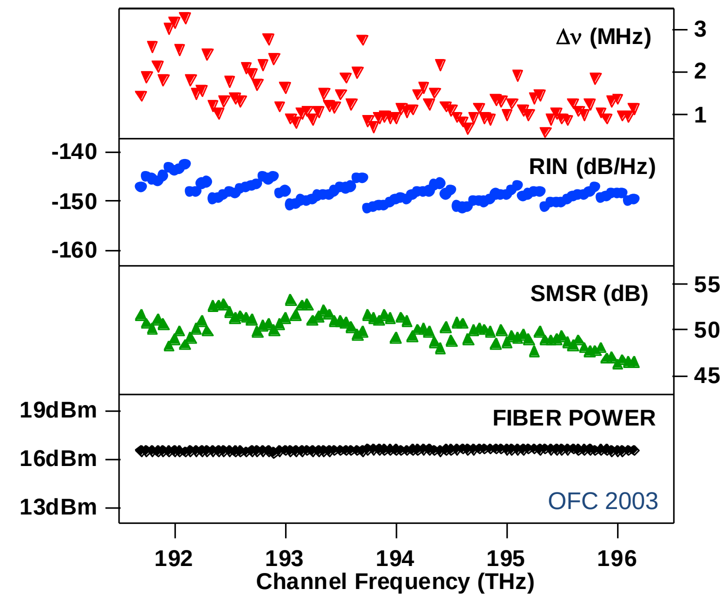




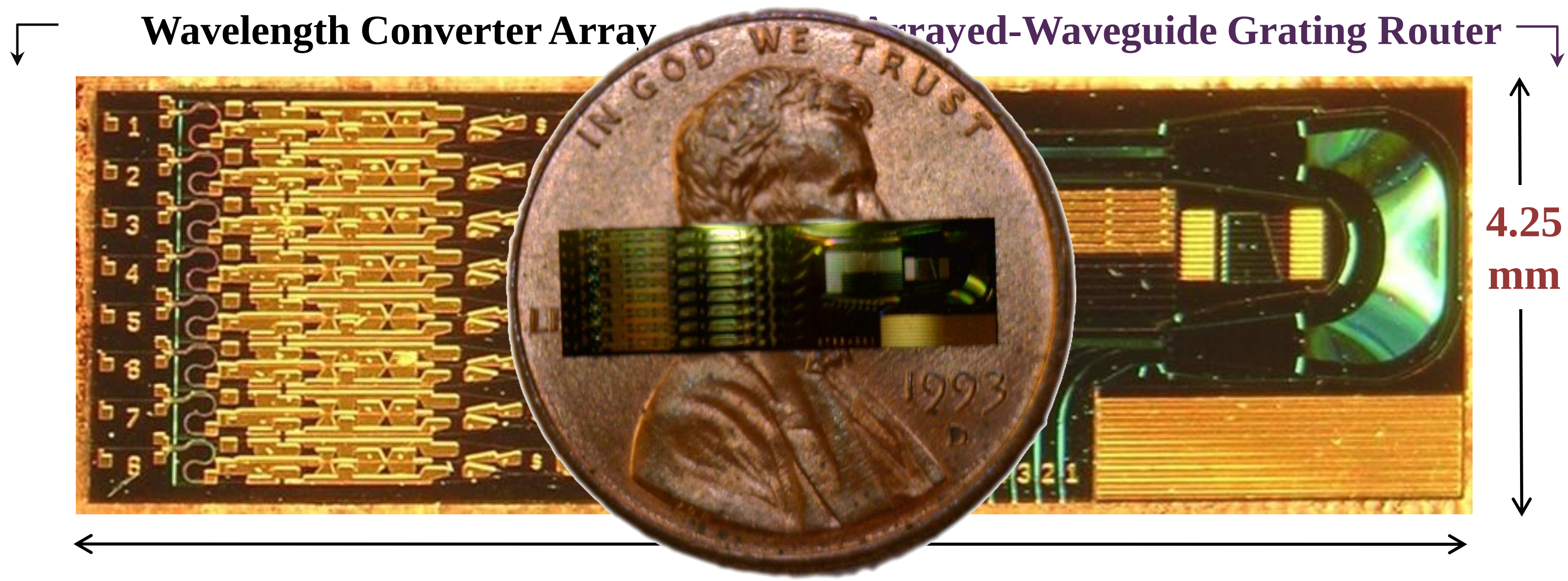
6 section InP chip

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

JDSU-ILMZ recently released as TOSA



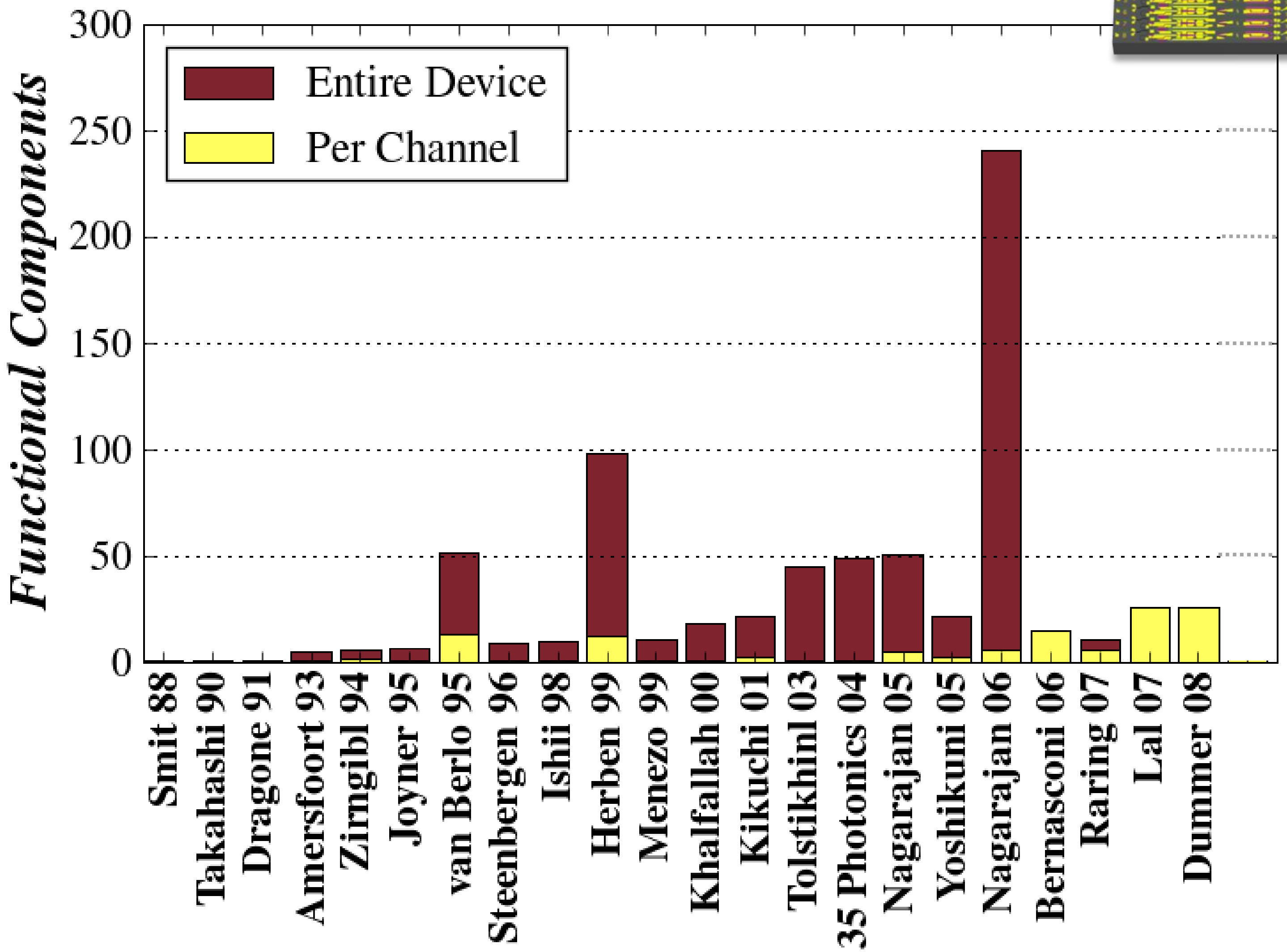
Recent PIC: MOTOR Chip (the latest)



- A monolithic tunable optical router (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

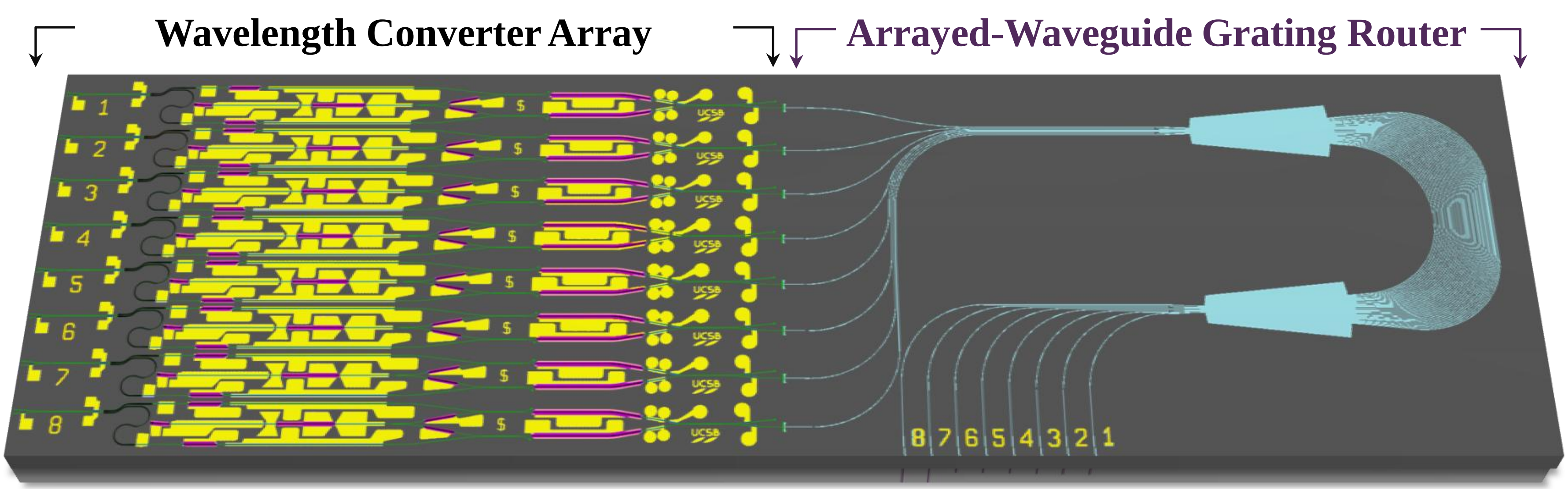
Steven C. Nicholes, M. L. Mašanović, E. Lively, L. A. Coldren, and D. J. Blumenthal, *IPNRA '09*, Paper IMB1 (July, 2009); also *JLT*, (Jan. 2010) in press.

Leading Edge of Monolithic Integration



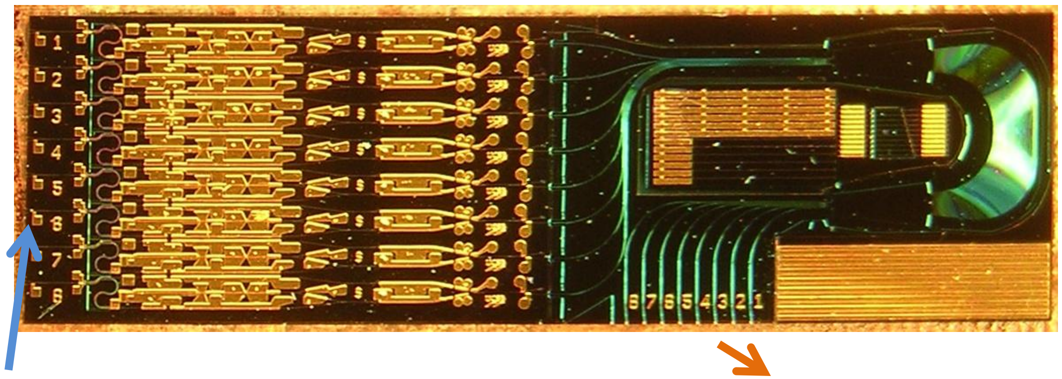
640 Gbps MOTOR

UCSB



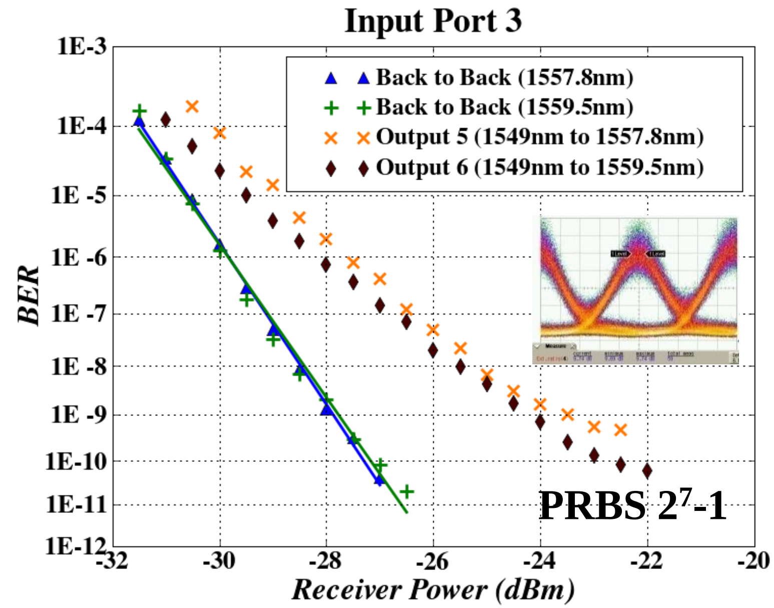
Benefits of integrated solution:	
Size	• Smaller device footprint • Smaller rack space for increased bandwidth
Power	• No power required in passive AWGR (free switching—no transistors) • Lower power consumption with all-optical approach
Cost	• Reduced packaging and system costs • Fewer fiber alignments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

Wavelength Conversion and Routing Performance



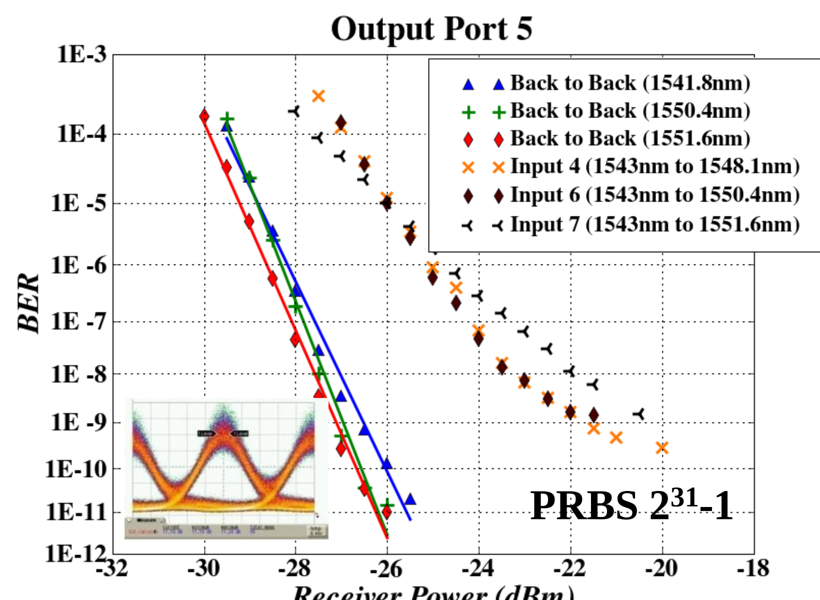
PRBS Data at λ_1 **IN**

Data at λ_2 **OUT** to BERT



Key Results: WC

- BER < 1E-9 achieved for conversion and routing
- Power penalty (BER 1E-9):
  - 10 Gbps NRZ > **1.3 dB**
  - 40 Gbps RZ:
    - PRBS 2^7-1 > **3.5 dB**
    - PRBS 2^{31}-1 > **4.5 dB**
    - Extinction ~ **11.2 dB**



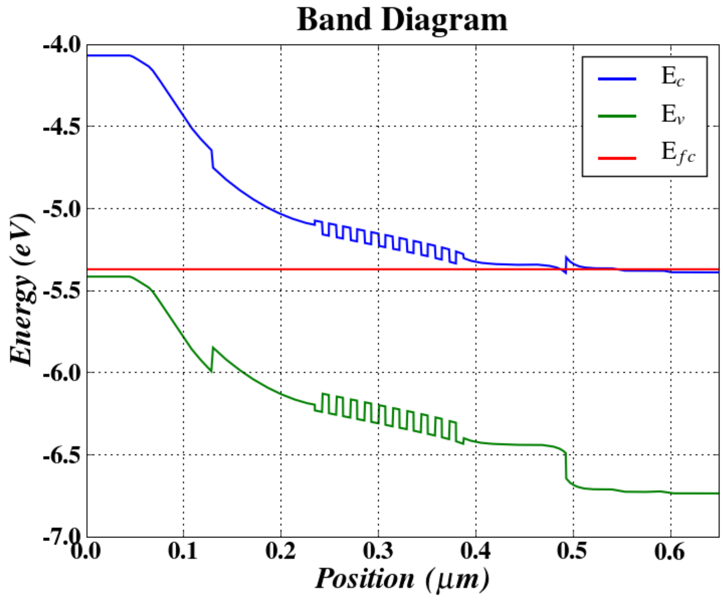
No AR coatings; low P_{sat} Preamp SOAs

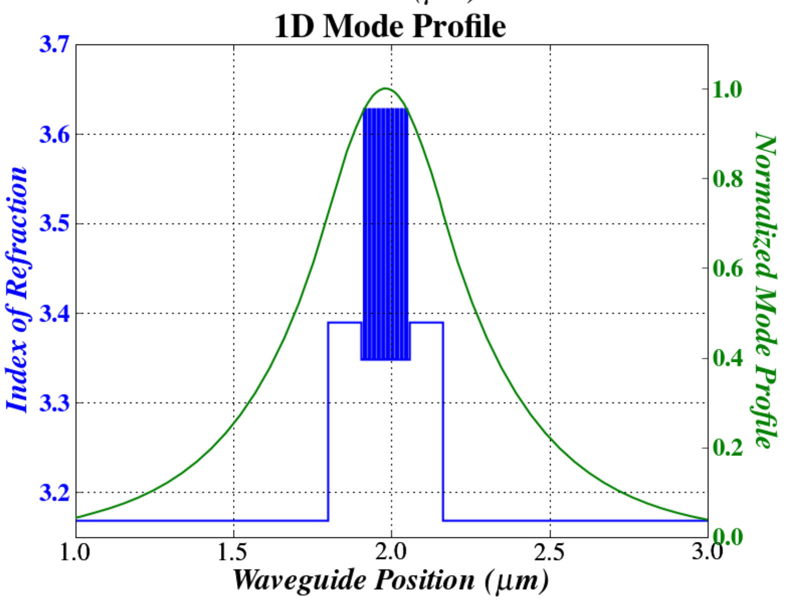
Integration Strategy

Integration Platform

- 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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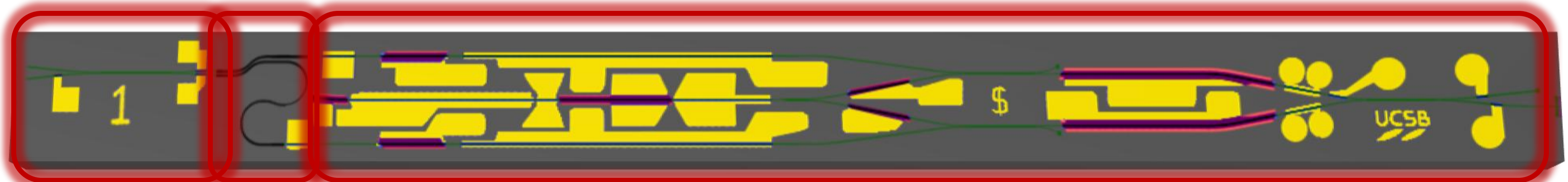
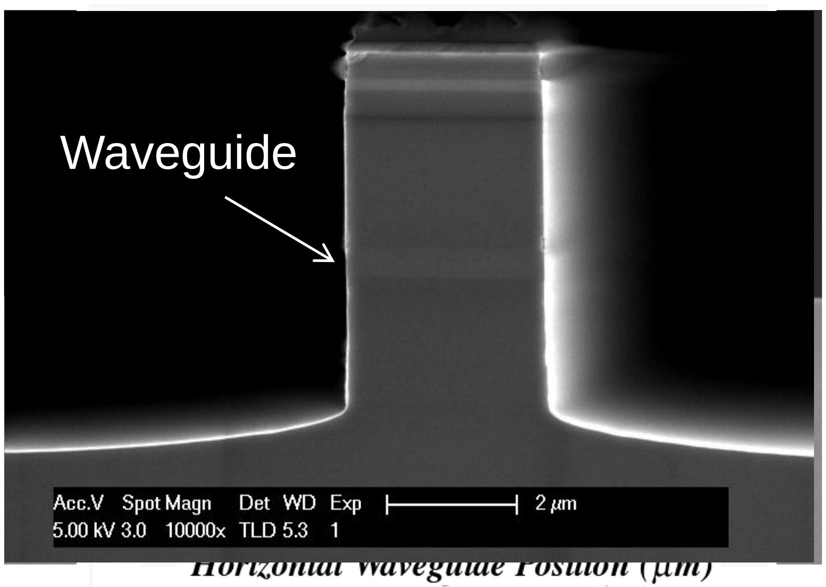
- Need multiple waveguide designs to integrate diverse range of components



Waveguides



Surface Ridge

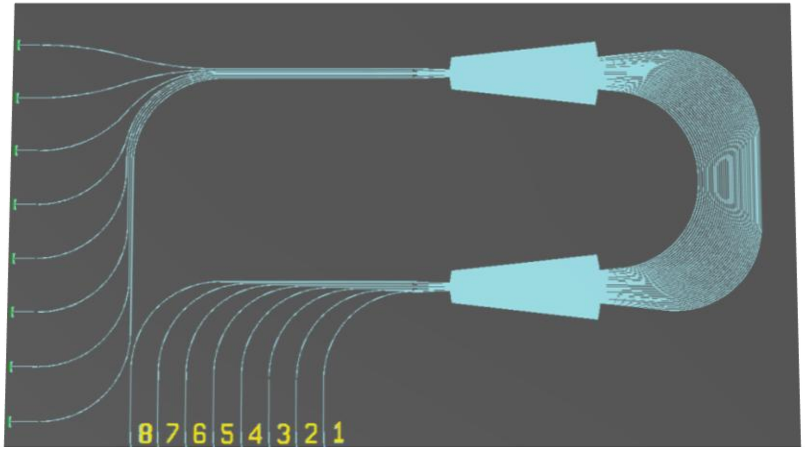
- Ridge defined through p-type cladding and stops at waveguide layer
  - Dry etch only
  - Dry etch + selective "cleanup" wet etch
  - Wet etch is crystallographic → no bends over ~15°

Deeply Etched Ridge

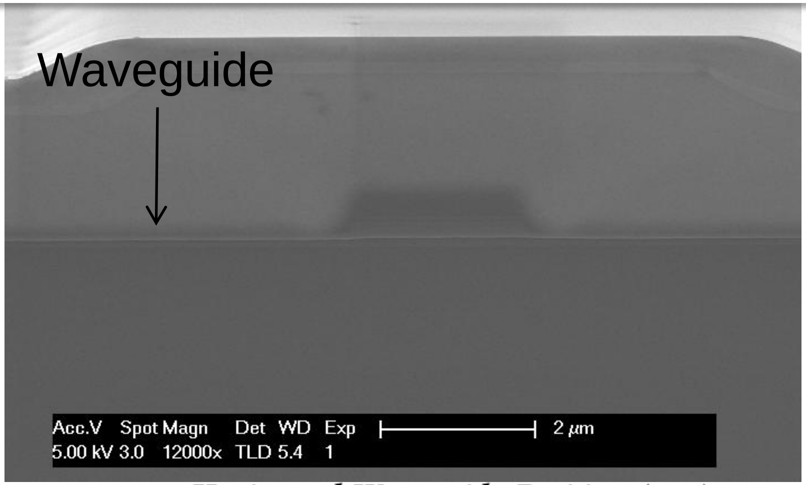
- Ridge defined through waveguide layer
  - Strong lateral confinement → sharp bends possible

Multiple Waveguide Architectures

UCSB



Need short mode transition elements to maximize coupling between waveguide regions



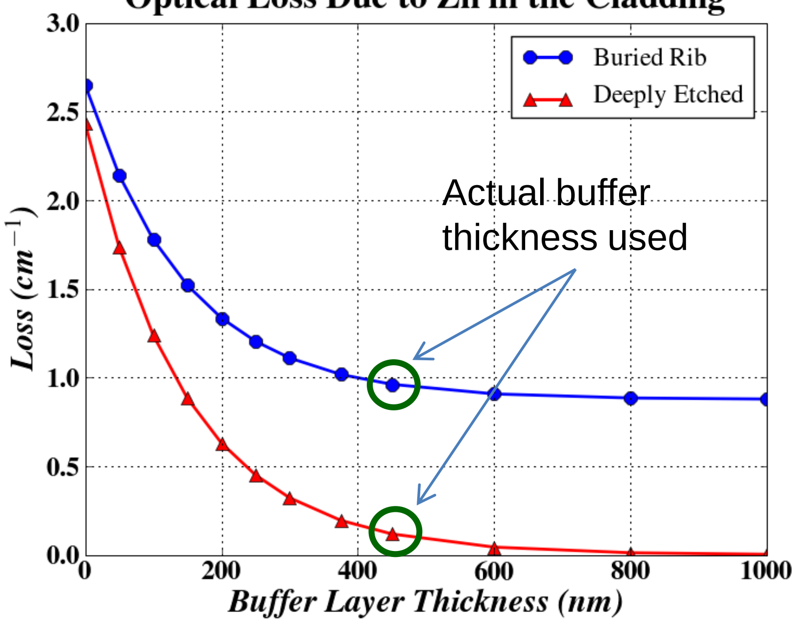
Horizontal Waveguide Position (µm)

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

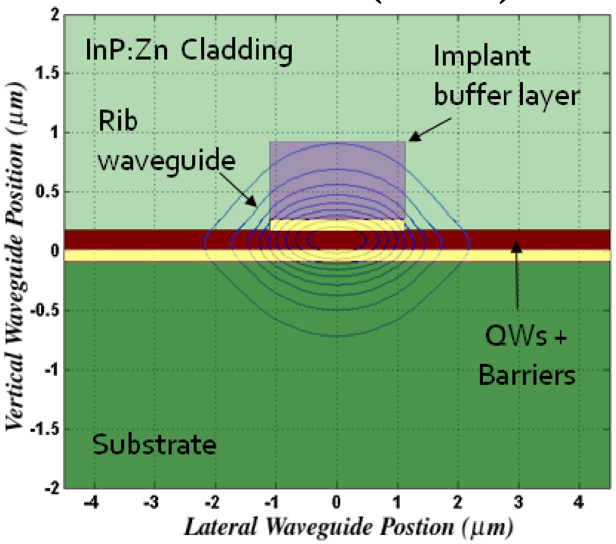
QWI Implant Buffer for Low-Loss Waveguides

UCSB

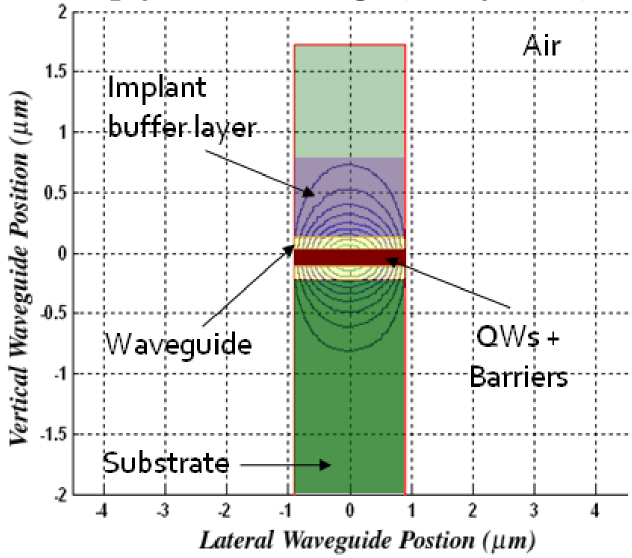
- Use QWI implant buffer to provide undoped setback layer between optical mode and Zn atoms
- Simulated *reduction* in optical loss:
  - Deeply-etched > Buried rib
  - No lateral mode interaction with Zn doped cladding



Buried Rib (AWGR):



Deeply-Etched Ridge (Delay Line):



Transitions Between Waveguide Designs

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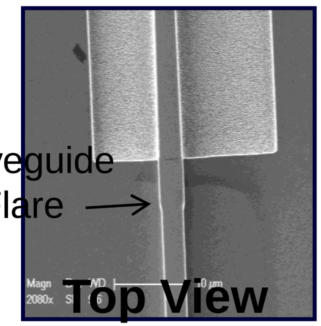
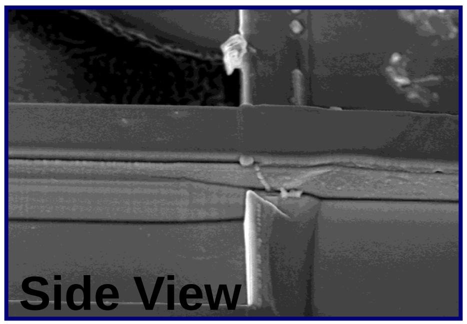
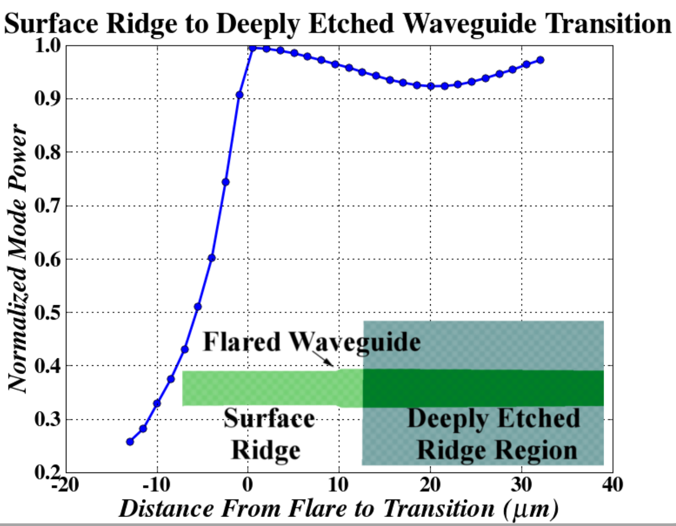
Surface-to-Deep Ridge Transition

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

Waveguide Flare

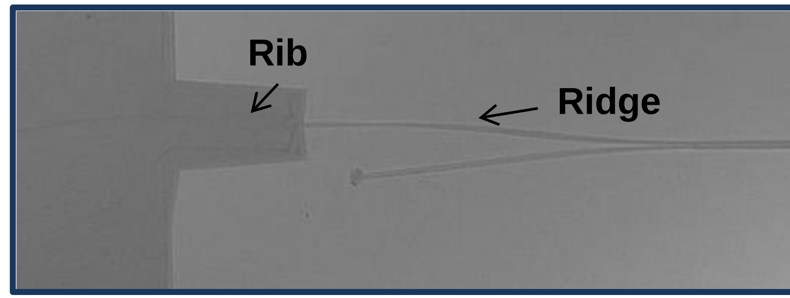


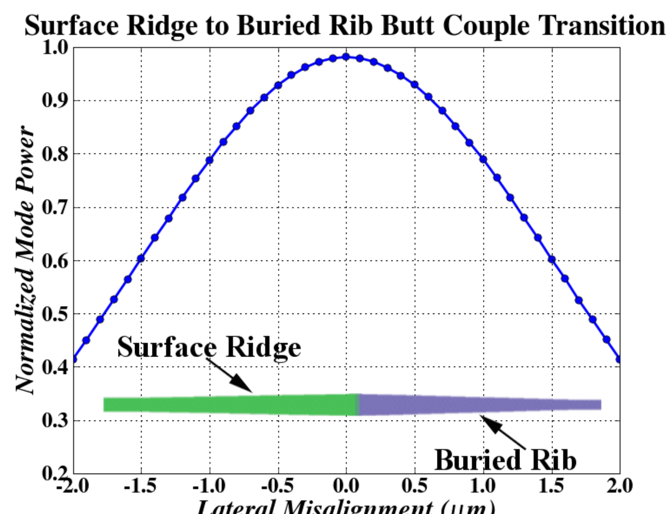




Surface-to-Buried Rib Transition

- 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*

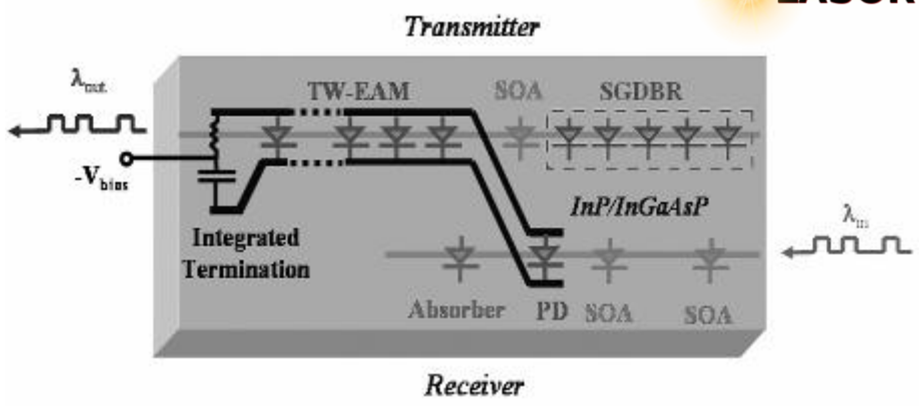
Other PICs

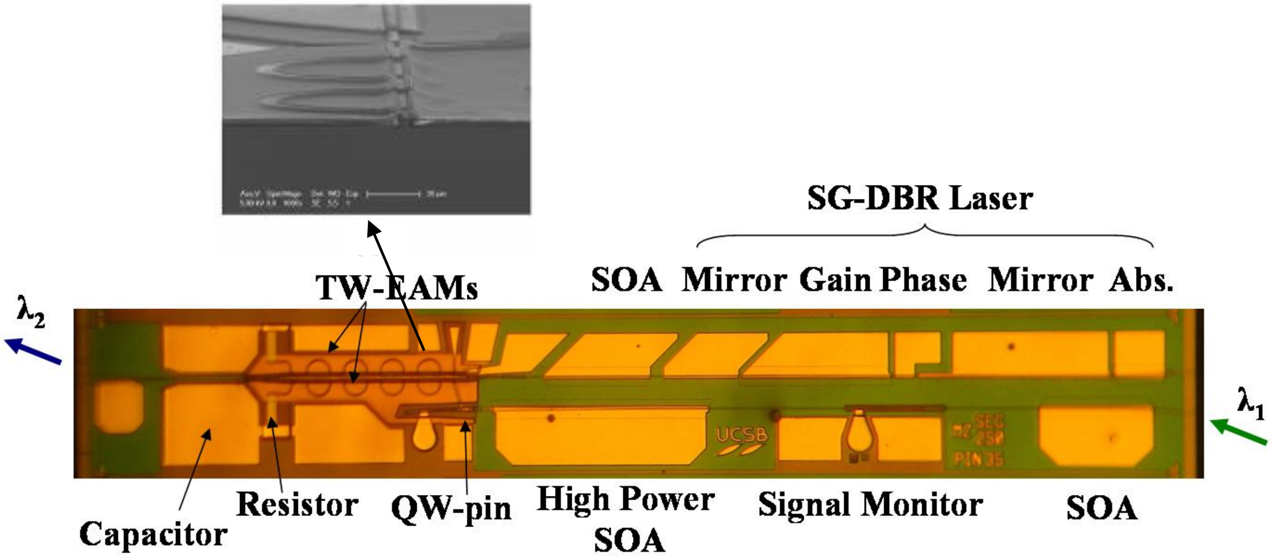
Transceiver/wavelength-converter: 2-stage-SOA-PIN & SGDBR-TW/EAM

UCSB

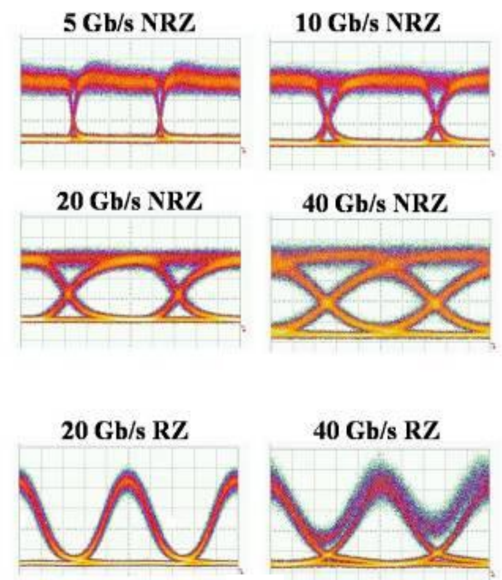
LASOR

• 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



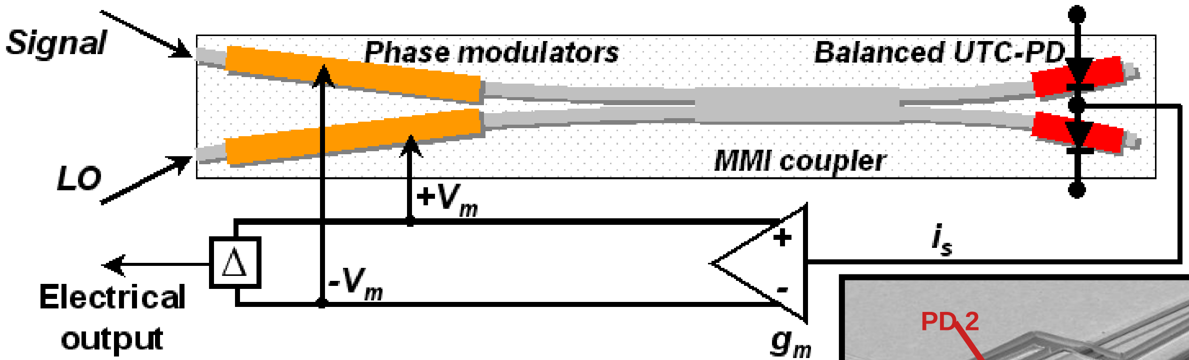
M. Dummer et al. Invited Paper Th.2.C.1, *ECOC 2008.*

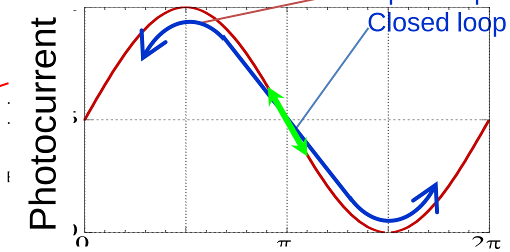
Coherent Receiver for Phase Modulated Signals

OPLL—NEED for PICs & close integration/EICs

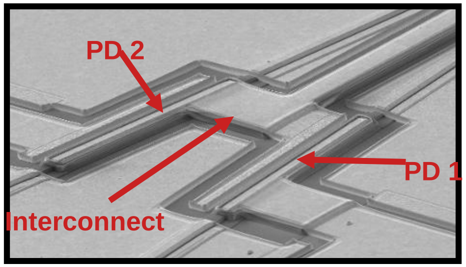
Homodyne:

$i_s \sim \sin(\varphi_{signal} - \varphi_{LO})$

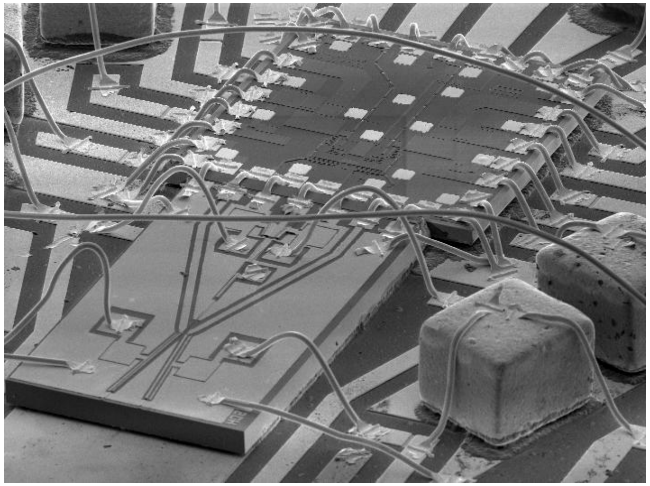




Signal – LO phase difference



Surface ridge



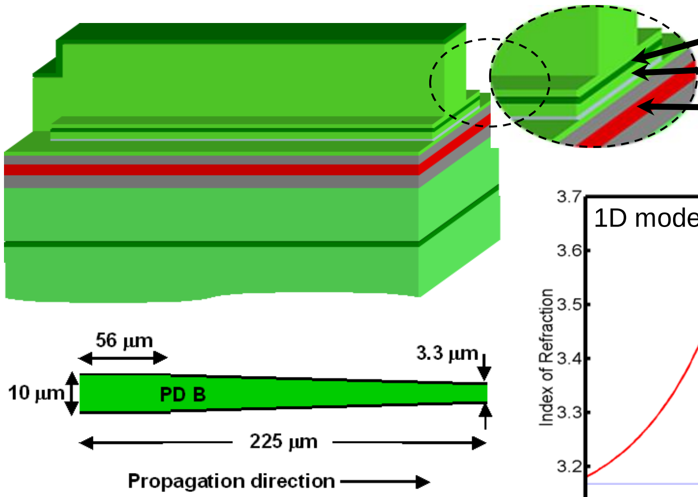
Close collaboration with NGST

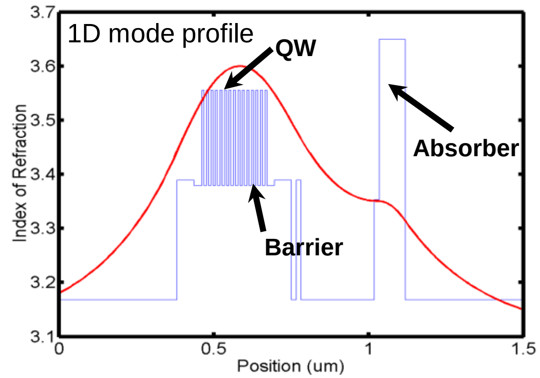
- Signal mixed with LO to demodulate optical phase
  - Detected photocurrent ~ signal-LO phase difference
  - Response is sinusoidal
- With feedback, output reduced by the loop gain: *1/(1+T)*
  - Hybrid integrated EIC* provides amplification
  - Operation within linear regime
  - NEED VERY SHORT FEEDBACK PATH

L.A. Johansson, H.F. Chou, A. Ramaswamy, L. A. Coldren, and J.E. Bowers, “Coherent optical receiver for linear optical phase demodulation,” *Proc. MTT-S Microwave Sym.*, Tu3D-01 (June, 2007).

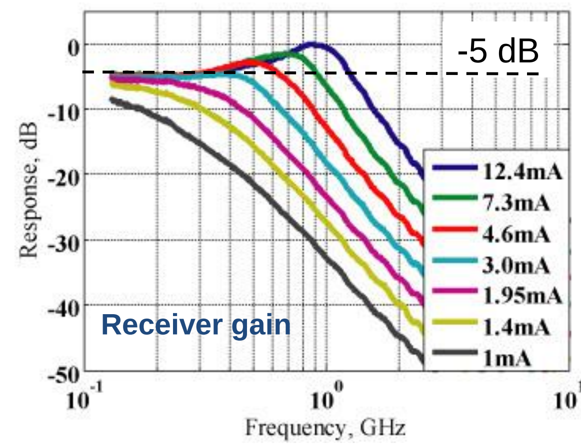
Integrated Coherent Receiver Results

UCSB



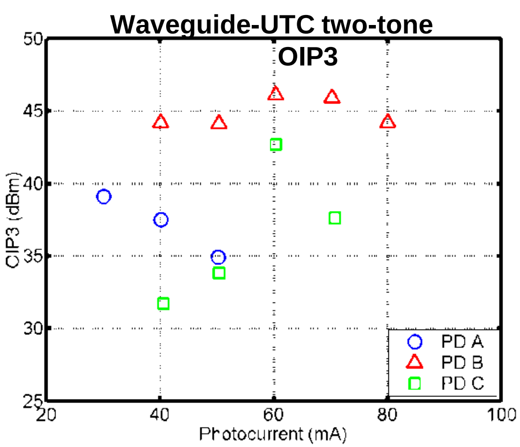


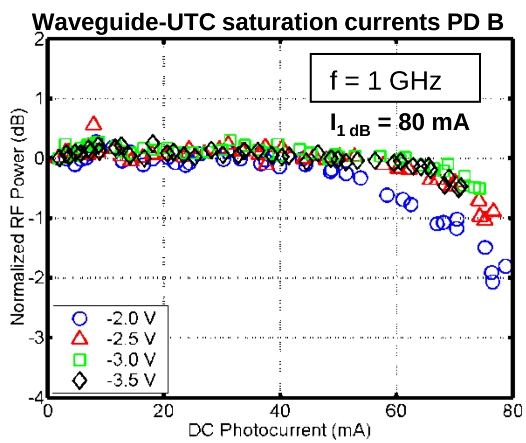
1.4 GHz OPLL BW—Loop delay limited
SFDR = 131 dB-Hz$^{2/3}$ @ 300 MHz



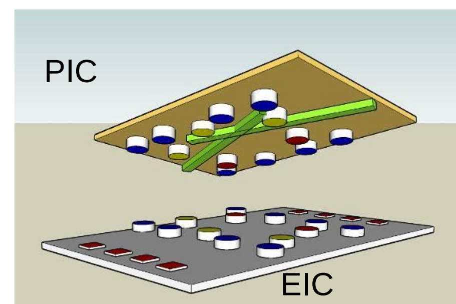
A. Ramaswamy, et al, *JLT*, **26** (1) pp209-216 (Jan., 2008).

→ Record OIP3 for waveguide PD
= 46.1 dBm at 60 mA (PD B)

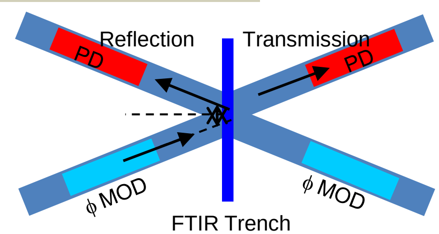




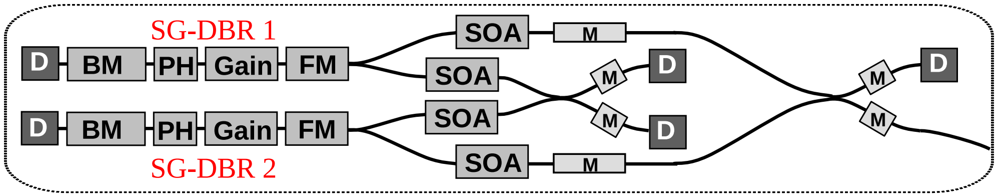
J. Klamkin, et al, *JSTQE,* **44** (4) pp354-359 (Apr., 2008).

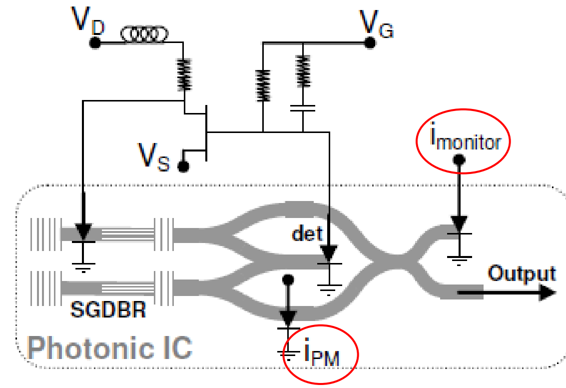


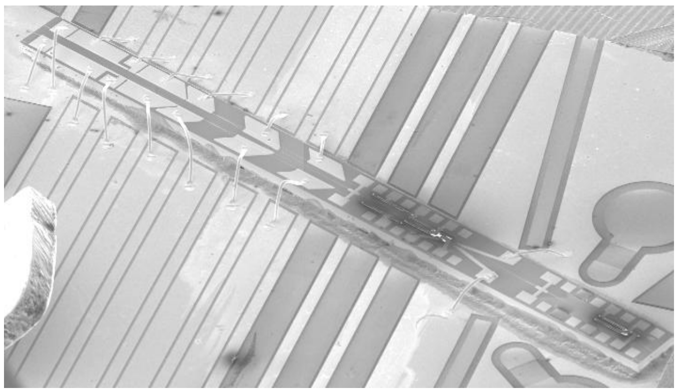
Phase II

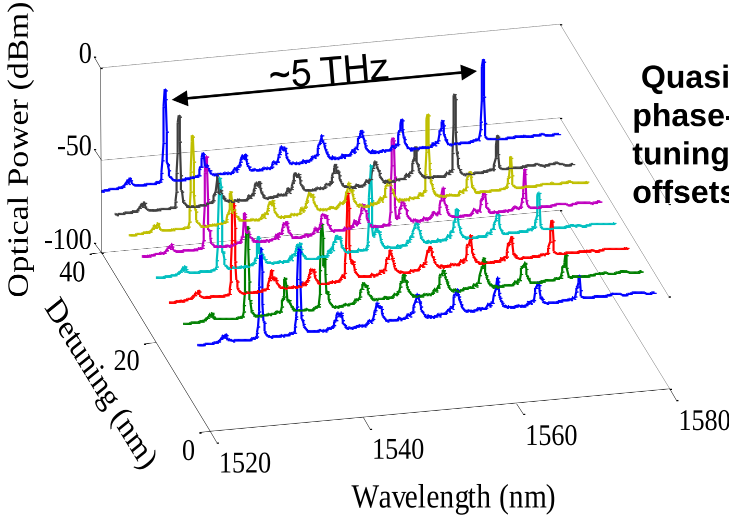


Phase-Locked SGDBRs/OPLL



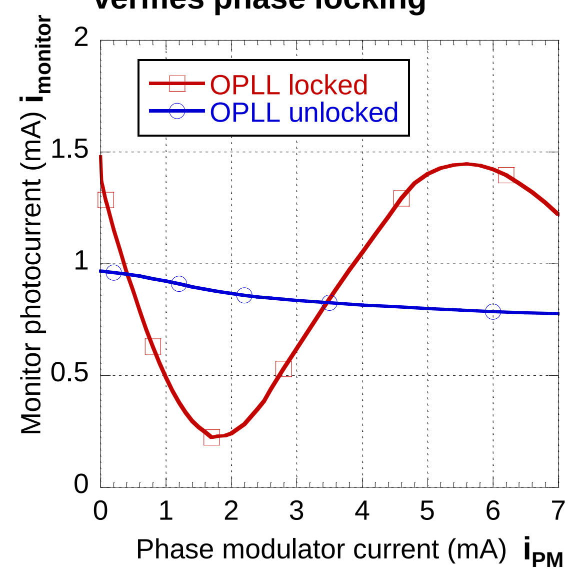






Quasi-continuous phase-locked digital tuning up to 5 THz offsets possible

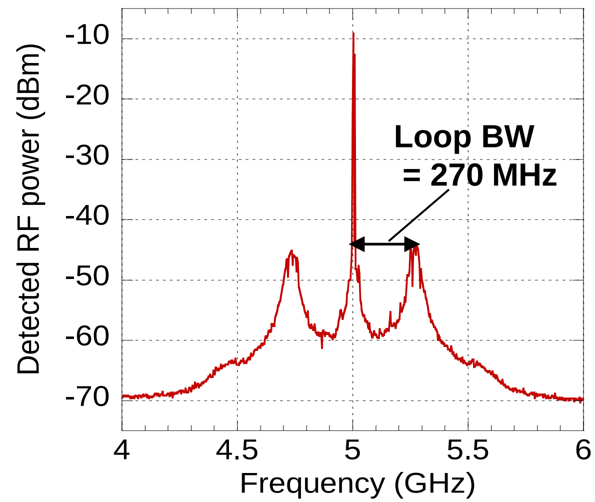
Coherent interference at monitor verifies phase locking

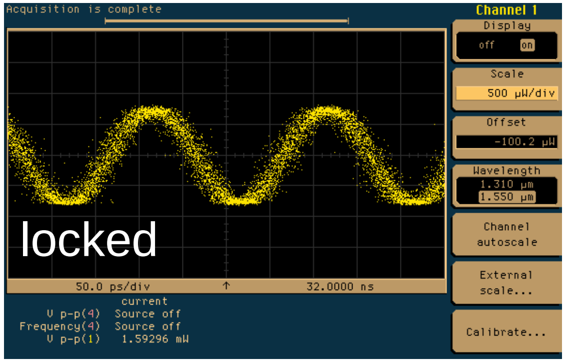


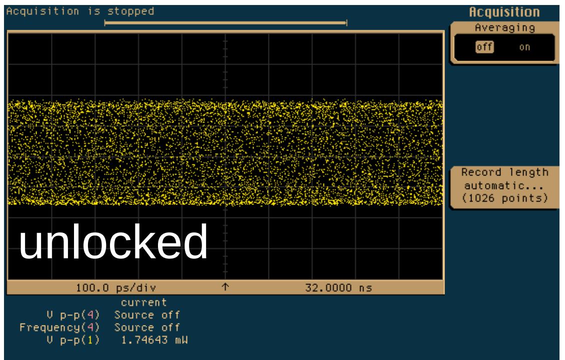
S. Ristic, et al, *OFC '09*, PDPB3, San Diego, (Mar., 2009)

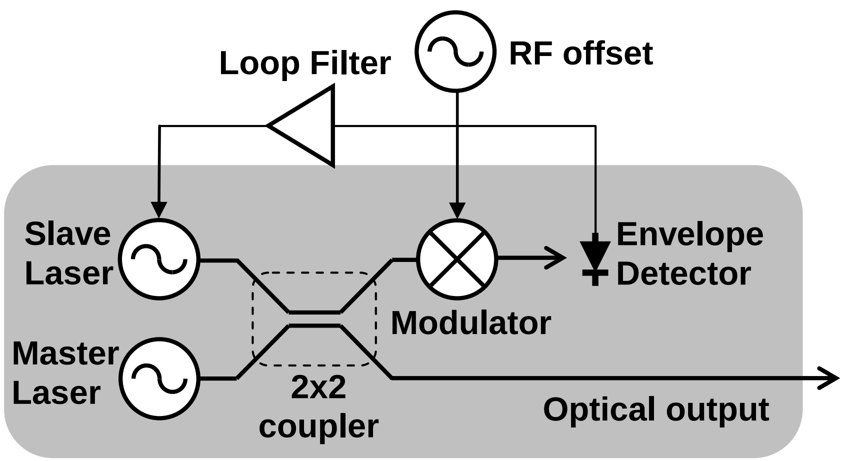
OPLL'd SGDBRs—Heterodyne

- **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**





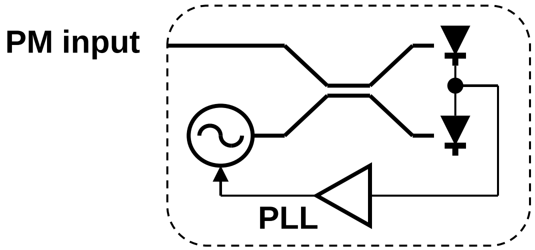




Ristic et al: JLT v.28 no.4, 2010, in press, also at MWP2009, paper Th 1.5

Additional OPLL Applications/Challenges

Coherent receiver



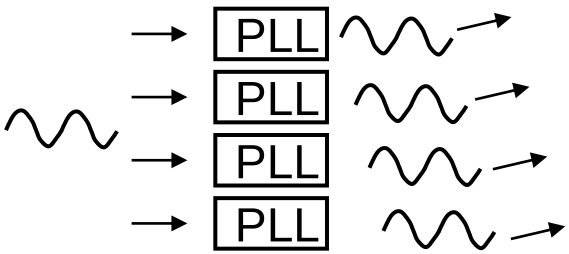
Costa's Loop for BPSK, QPSK demodulation

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

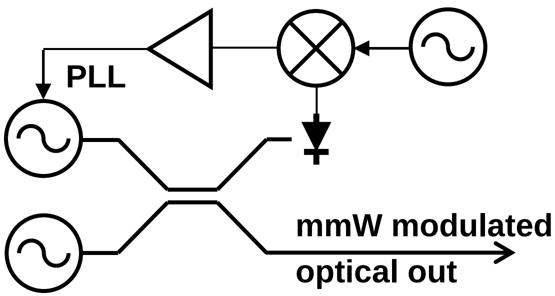
Arrays of locked OPLLs

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

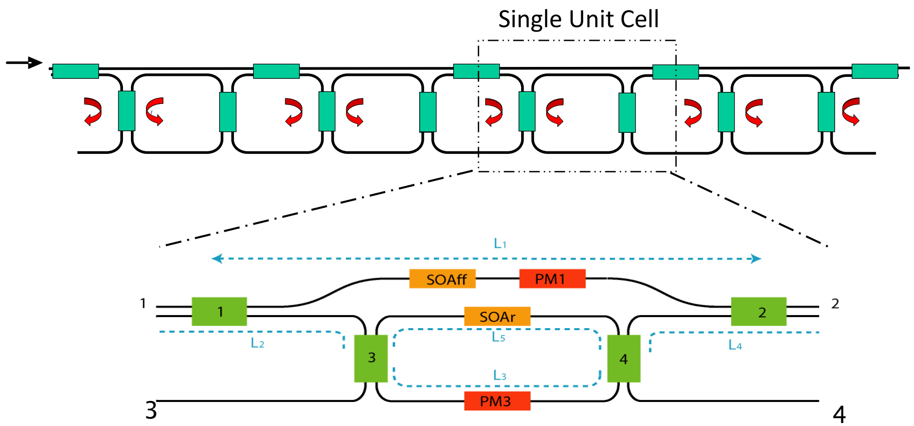
Speed determined by UTC photodiode and feedback electronics: Can be very high

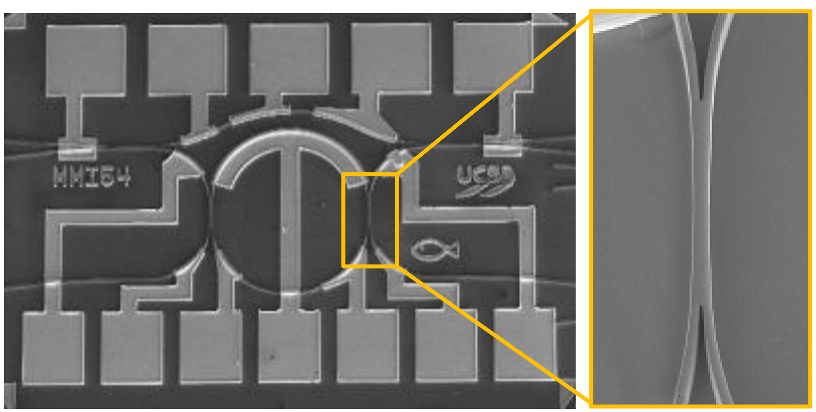
Combined with antenna designs for complete TRX links with free-space path

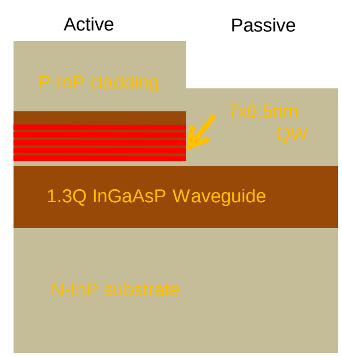
All require close integration of electronics with photonics

Programmable Photonic Lattice Filters

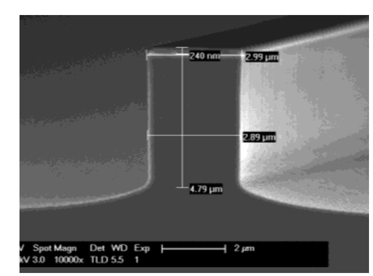
- Demonstrate programmable poles and zeros from a single unit cell that can be cascaded to form complex lattice filters
- Incorporate <u>SOAs</u> and <u>Phase Modulators</u> to control filter parameters







Offset Quantum Well Platform



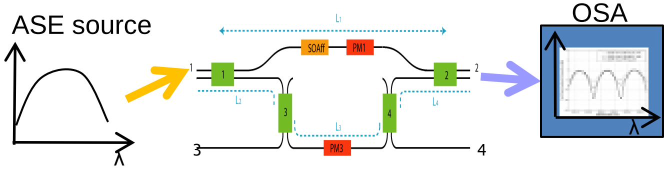
Deeply Etched Waveguide

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)

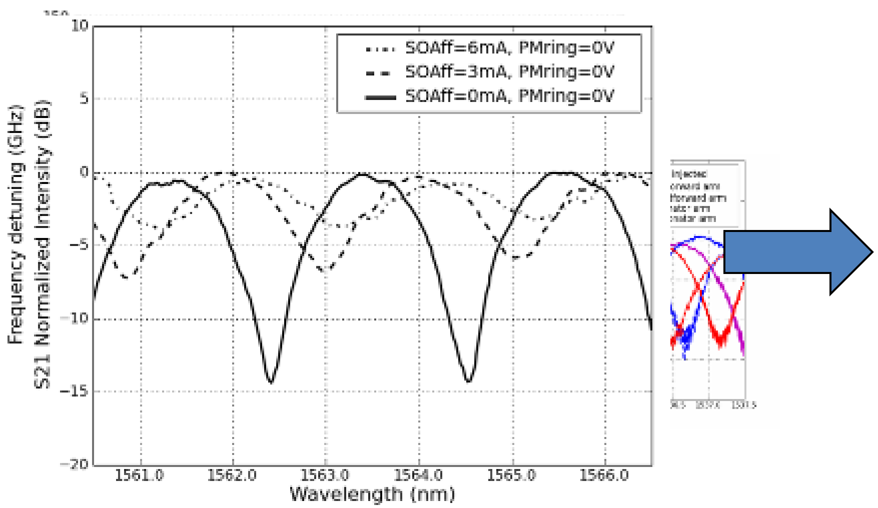
Single Unit Cell – Isolated Zero

- FIR filter response synthesized with MZI
  - Ring SOA reversed bias – no optical feedback from resonator
- SOA on feed forward arm used to tune zero amplitude
  - ~14dB maximum extinction ratio (ER)
  - Parasitic frequency shift due to current injection in SOA
    - Use phase modulators (PM) to align filter response
- Phase modulators used to tune filter in frequency
  - 270GHz (110% of FSR) total tunability of MZI response

SEM of Single Unit Cell Filter

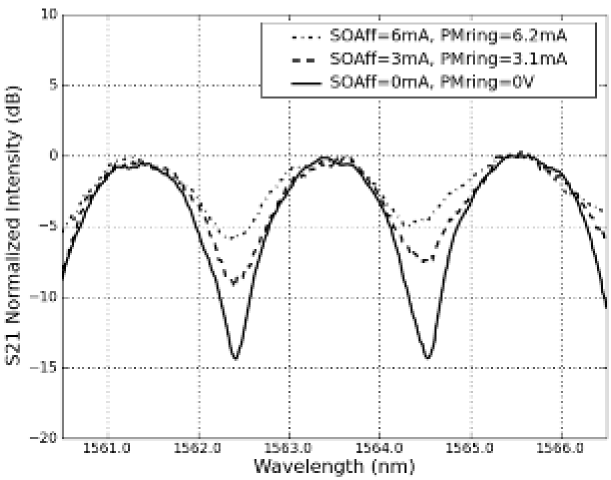


Schematic of measurement



S21 MZI response tuned in frequency (wavelength)

S21 MZI response – without PM

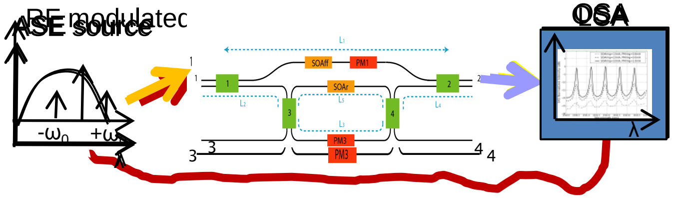


S21 MZI response – with PM

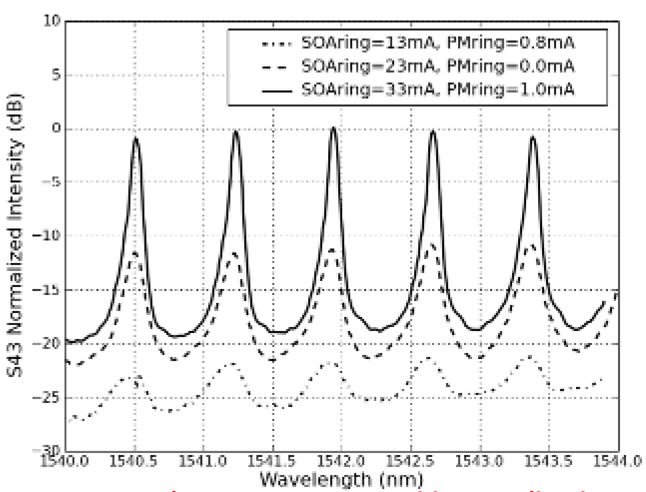
Single Unit Cell – Isolated Pole
Single Unit Cell – Pole and Zero

- IIR filter response synthesized with ring resonator
  – S43 or S21 with feed forward SOA reversed biased
- SOA in ring resonator used to tune pole amplitude
  – ~18dB of ER, FWHM=0.067nm (7.9GHz), Q=23,000, 50 GHz frequency tunability
- RF filter response measured with Lightwave Component Analyzer
  – Characteristic π phase shift
- Enhancing ER by utilizing both zeros and poles
  – >25dB extinction by placing zero in between poles

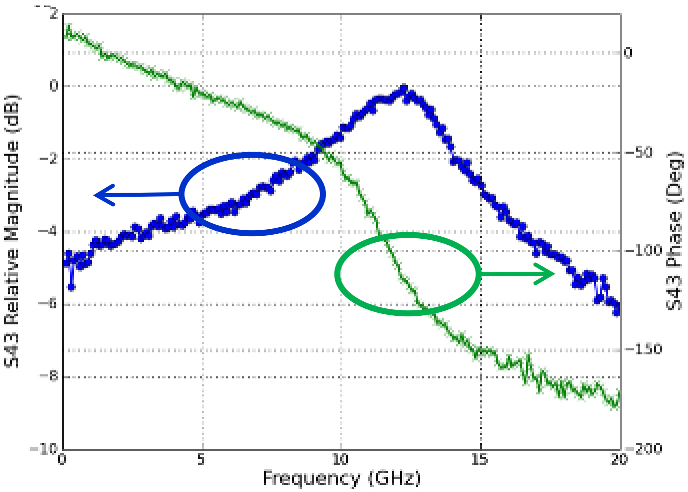
SEM of Single Unit Cell Filter



Schematic of measurement



S43 Pole response tuned in amplitude

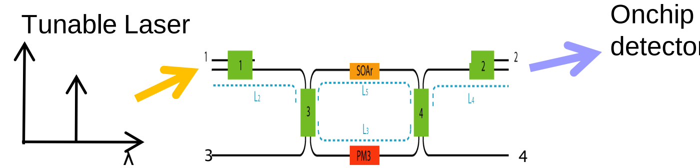


S21 RF Pole response

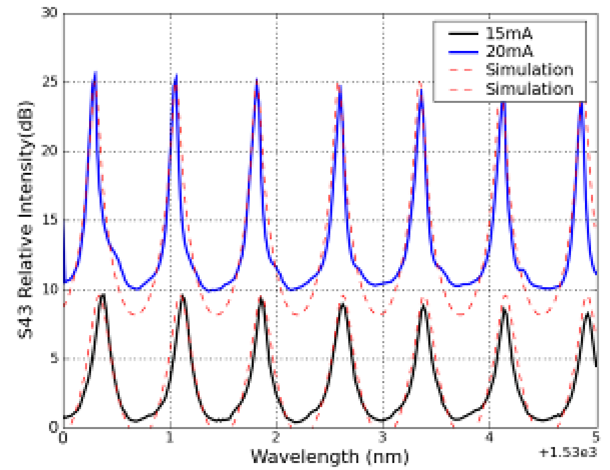
S43 Pole Zero response

Flattened Ring Unit Cell

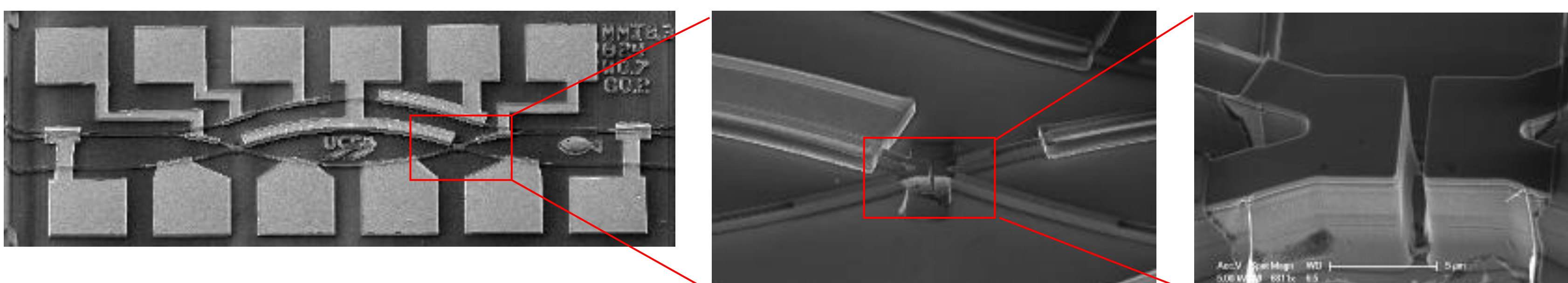
- Resonator in/out coupling with Etched Beam Splitters (EBS)
  - <u>EBS coupled ring resonator in InGaAsP demonstrated for the first time</u>
- Pole response
  - E.g. Biased 20mA (I_{th}=23mA)
  - FWHM of 7GHz, Q=27500
- EBS power splitting ratio
  - *R*=55~60%, *T*=2.9~3.2%
  - Back calculated from resonator response and measured relative splitting ratio



Schematic of measurement



Measured and Simulated Resonator Pole Response – Varied Ring SOA Current (curves shifted for clarity)



Summary

UCSB

- Illustrated medium-scale highly-functional PIC integration technology requiring only one blanket regrowth.
  - Indicated usefulness of quantum-well intermixing for integrating high-confinement active regions with low-loss passive regions.
  - Demonstrated efficient, robust techniques to integrate very different lateral waveguides together.
- This technology provided largest and most complex PIC ever (at least for UCSB).
  - Performance adequate for many digital photonic switching functions
  - Prior work has shown that the addition of one more blanket regrowth can greatly enhance the performance of such PICs
- Illustrated other functional InP-based PICs
  - All-photonic transceivers using photocurrent-driven modulators
  - Coherent receiver using an optical phase-locked loop for phase-modulated rf-photonics
  - Locking of SGDBRs for mmW - THz generation using an OPLL + other possibilities
  - Programmable photonic lattice filters