Multi-function Integrated InP-Based Photonic Circuits

ECOC'08 Tutorial

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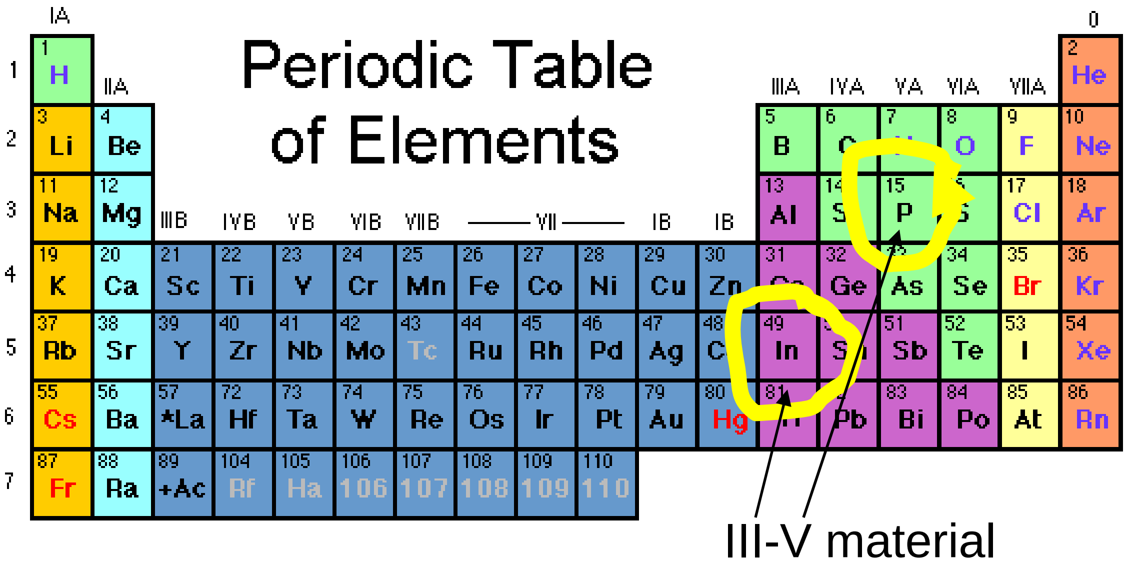
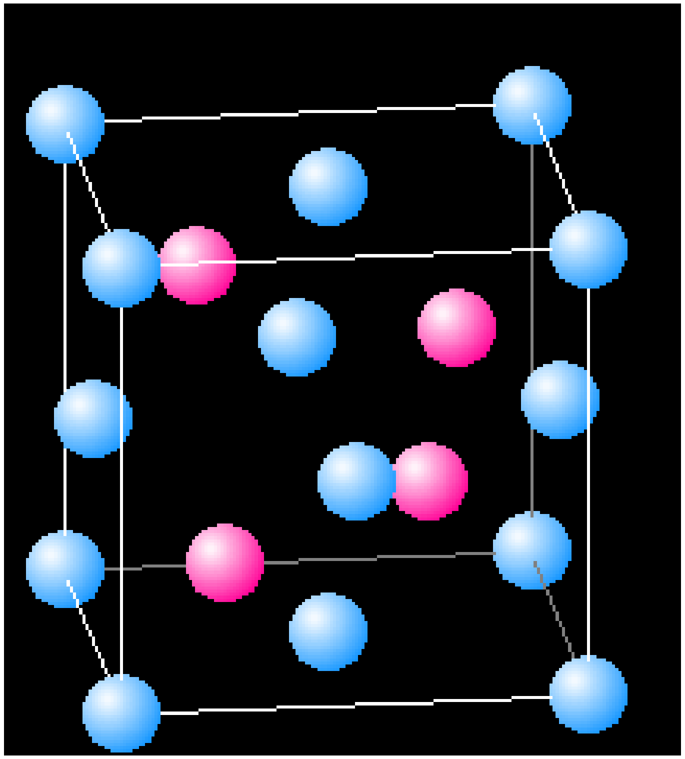
Acknowledgements: Chris Doerr, Alcatel-Lucent; Chuck Joyner, Infinera; UCSB colleagues

Outline/Contents

- Integration Platforms/Technology
- Transmitters
- Receivers
- Transceivers/Wavelength Converters
- Conclusions

Indium phosphide



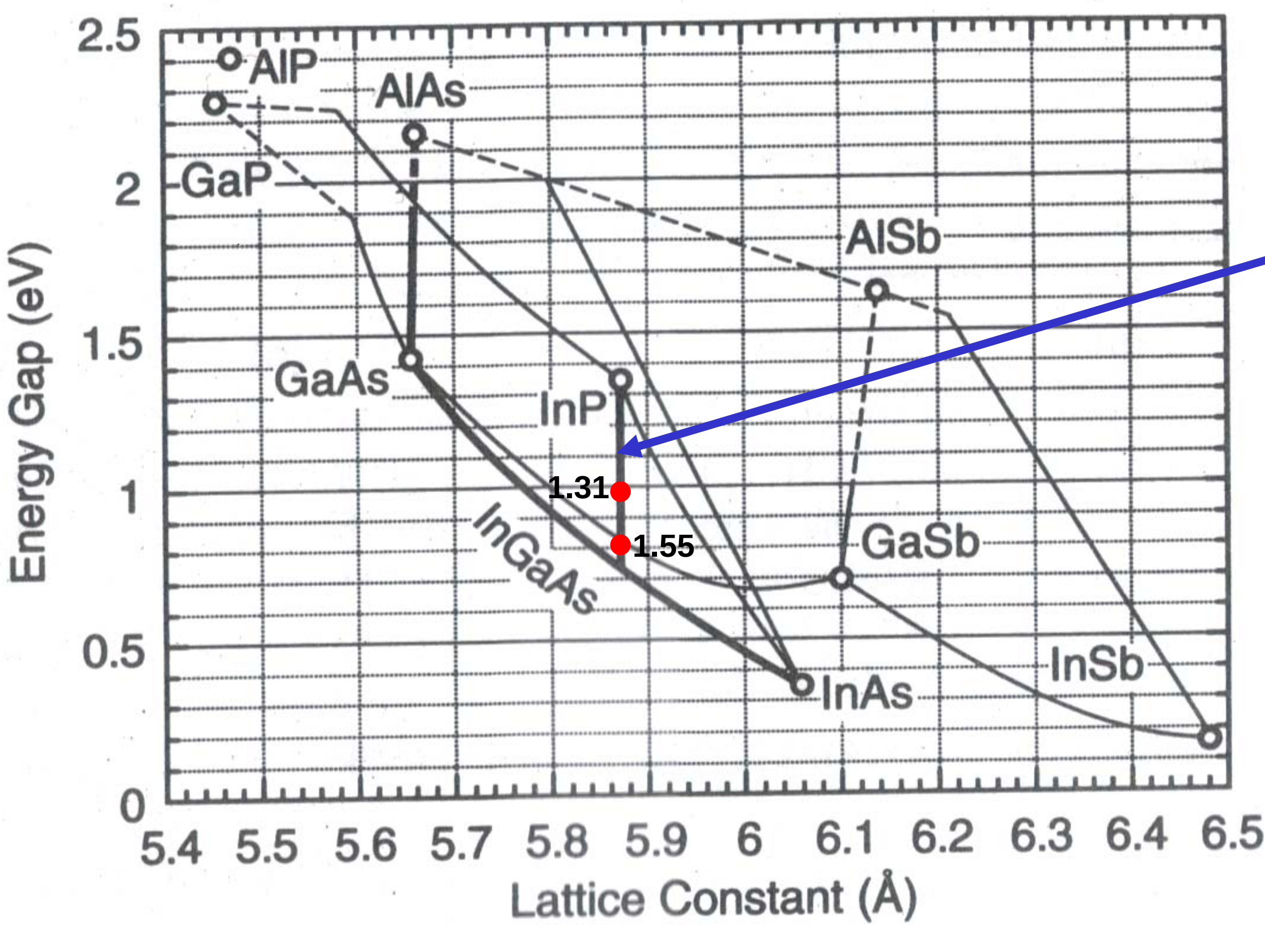


Zincblende structure

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

Lattice constant = 5.87 A at 300K

InGaAsP/InP lattice-matched alloys

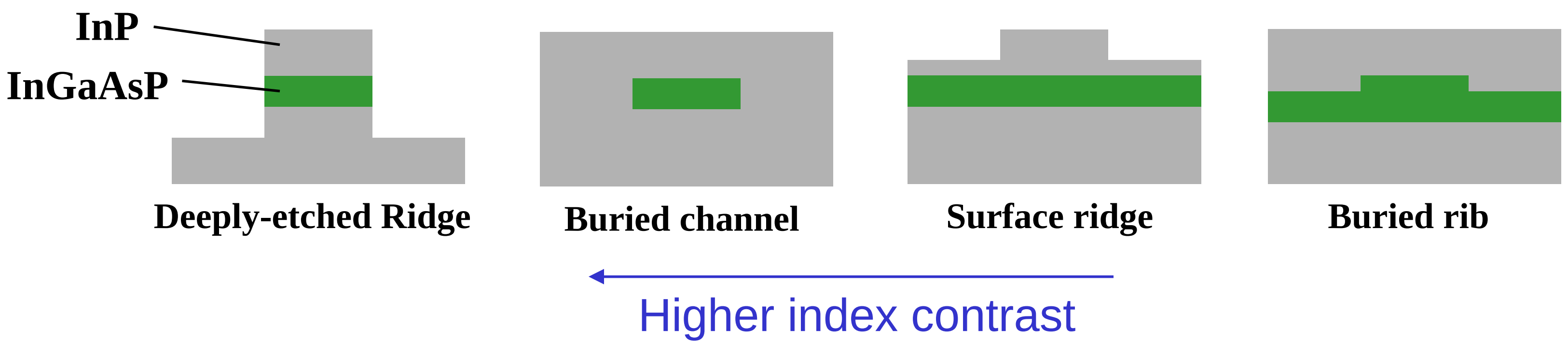


InGaAsP lattice-matched to InP

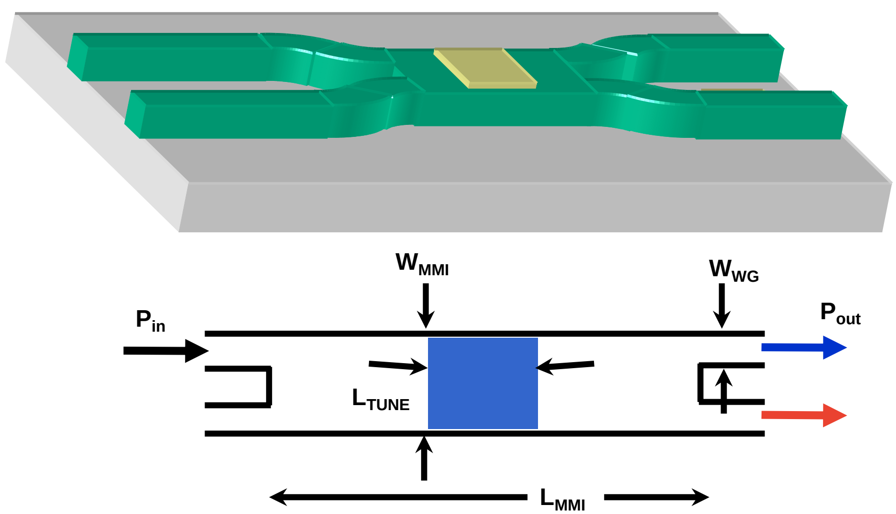
$\lambda_g(\mu m) = 1.24/ E_g(eV)$

Lateral waveguides/couplers

Waveguide cross sections

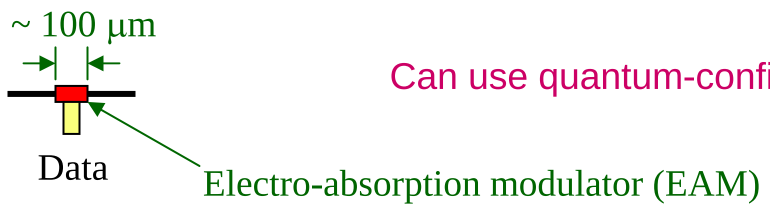


MMI coupler



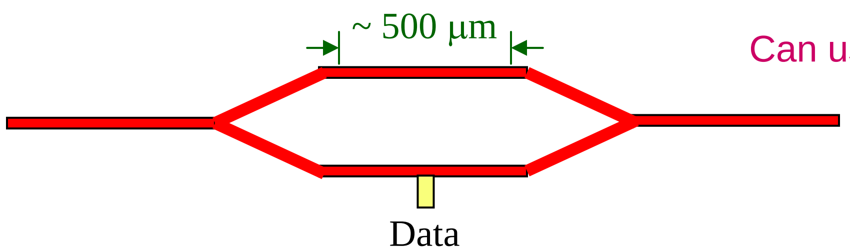
Modulators

Electro-absorption modulator (EAM)



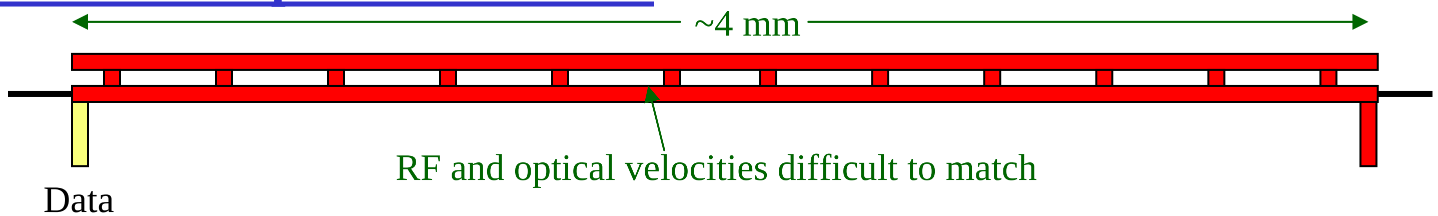
Can use quantum-confined Stark effect for large $\Delta\alpha$

Mach-Zehnder modulator (MZM) lumped



Can use quantum-confined Stark effect with larger $\Delta\lambda$

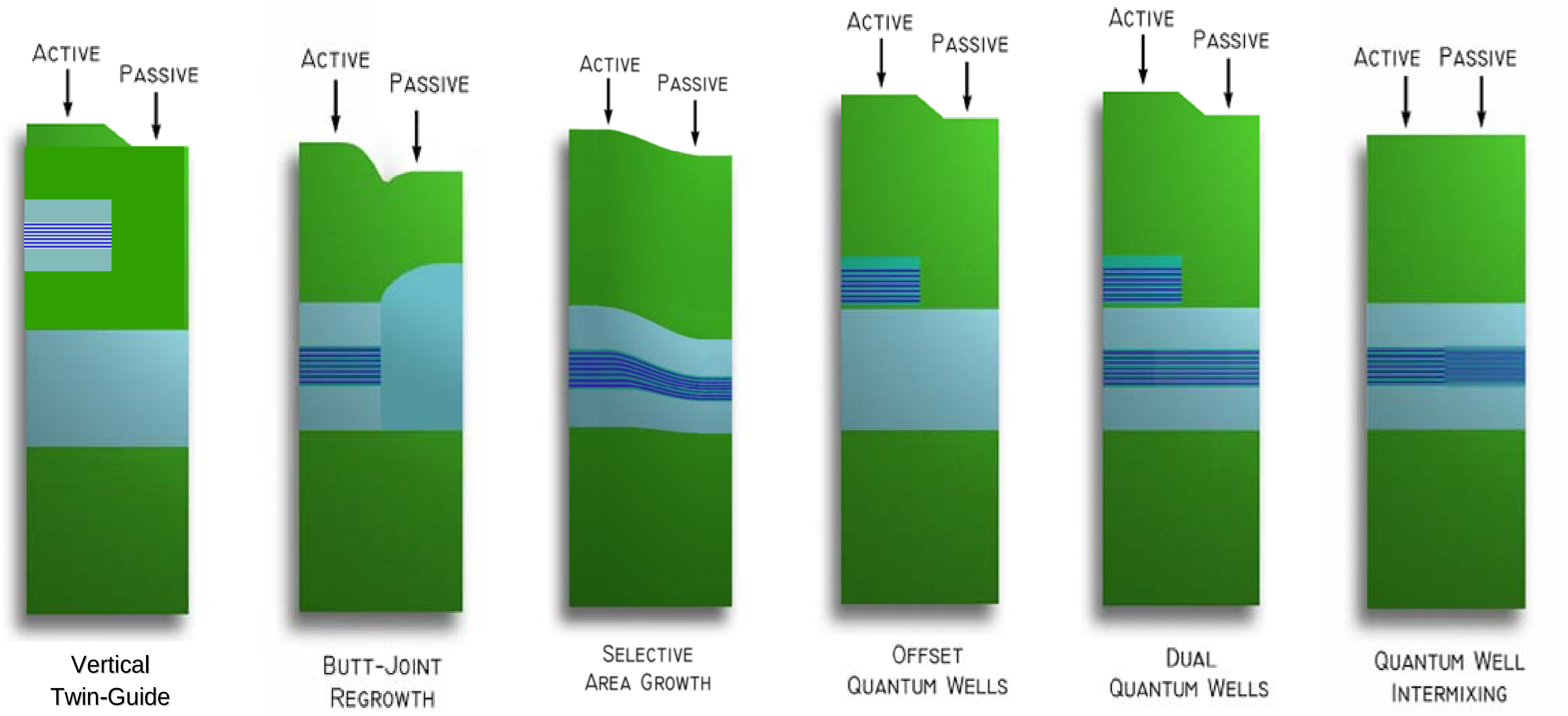
Traveling-wave linear phase modulator



(Can get away with lumped phase modulator up to ~10 GHz)
(Also, current injection for < 1 GHz)

Active-Passive (axial) Integration

Desire lossless, reflectionless transitions between sections



Partially transmissive mirrors

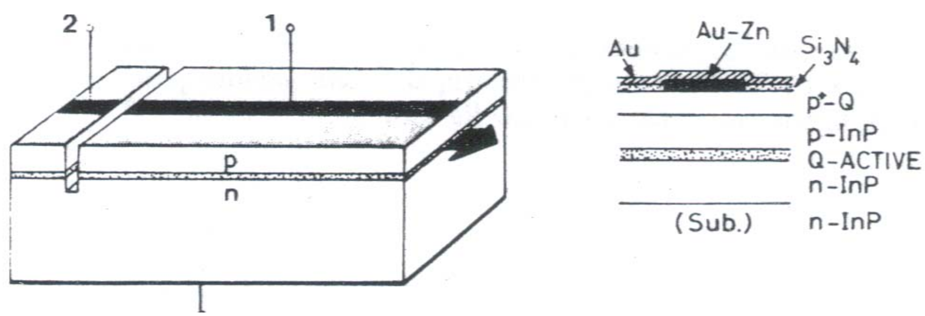
- **Coupling mirrors between integrated active and passive sections**

First integrated InP (laser – X) devices

→ Etched grooves

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

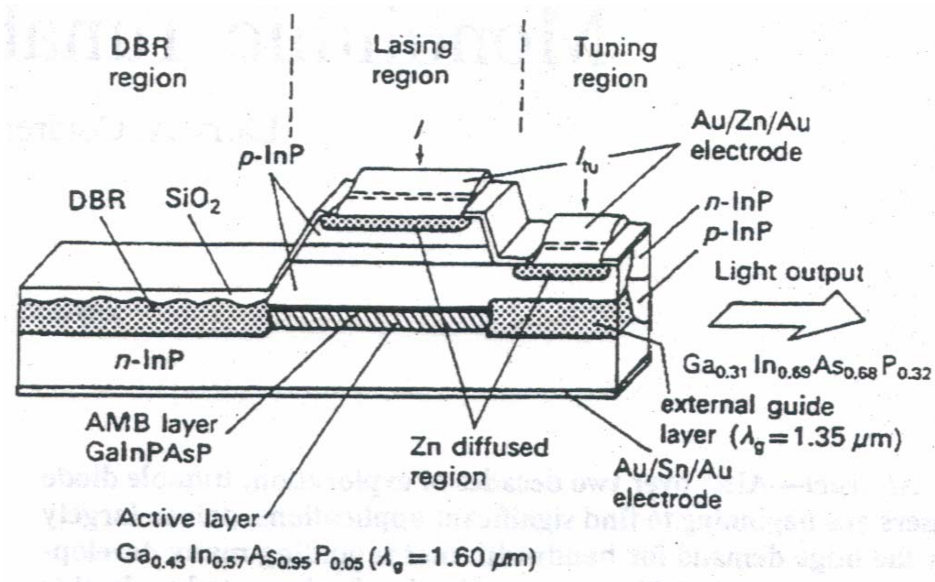
L.A. Coldren, B.I. Miller, K. Iga, and J.A. Rentschler, "Monolithic two-section GaInAsP/InP active-optical-resonator devices formed by RIE," *Appl. Phys. Letts*., **38** (5) 315-7 (March, 1981).



→ DBR gratings and vertical couplers

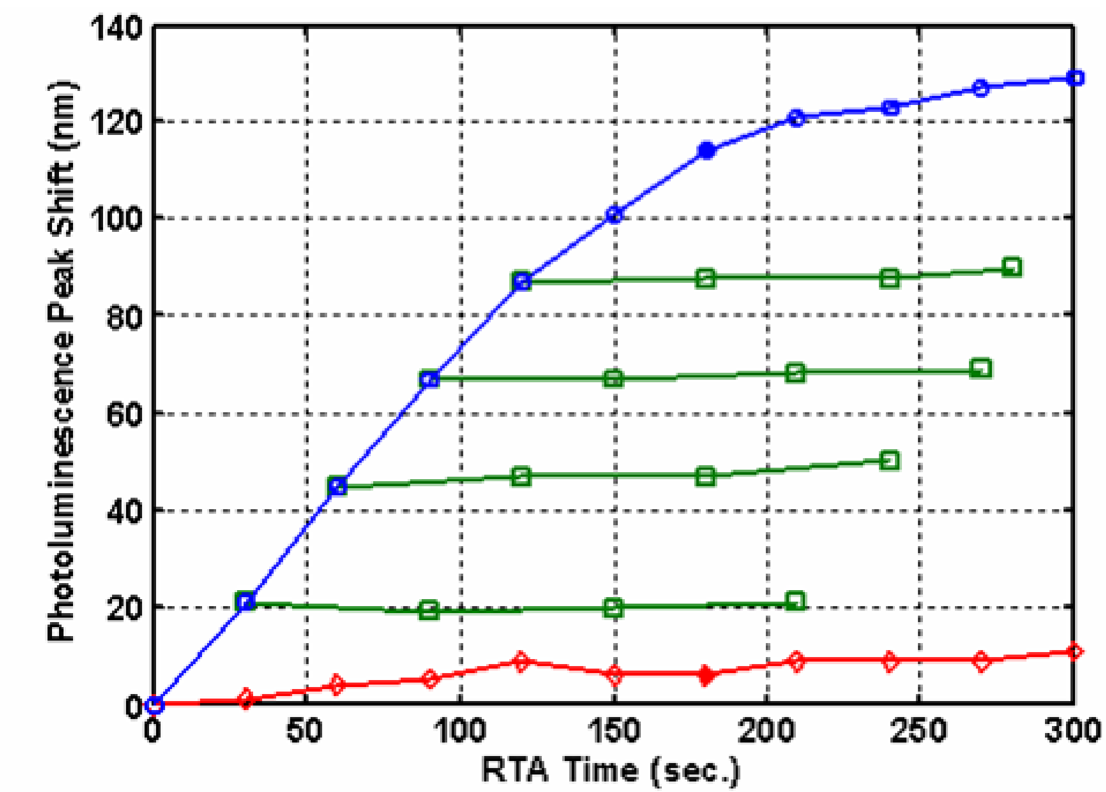
- **Tunable single frequency**
- **Combined integration technologies**

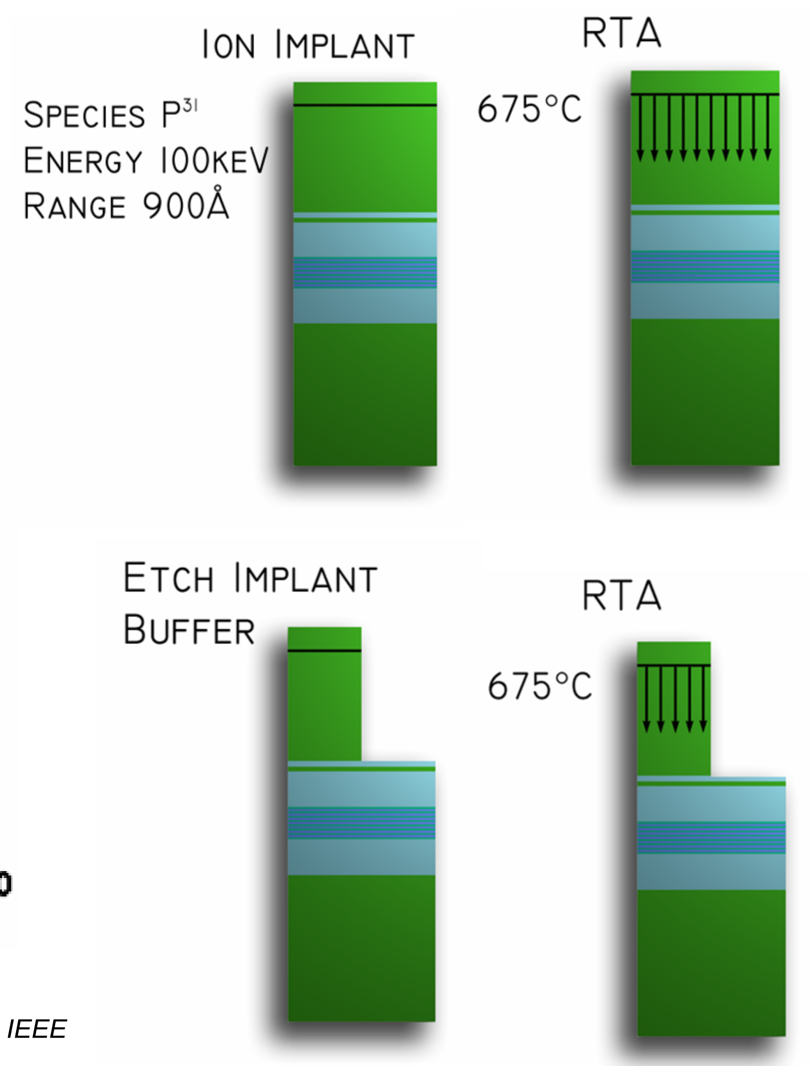
Y. Tohmori, Y. Suematsu, Y. Tushima, and S. Arai, "Wavelength tuning of GaInAsP/InP integrated laser with butt-jointed built-in DBR," *Electron. Lett*., **19** (17) 656-7 (1983).



QWI For Multiple-Band Edges/Single Growth

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



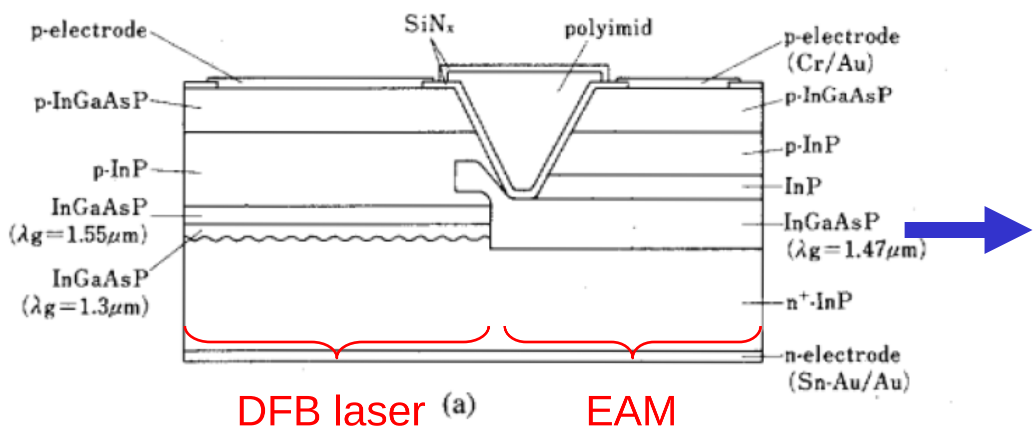


E. Skogen et al, "Post-Growth Control of the Quantum-Well Band Edge for the Monolithic Integration of Widely-Tunable Lasers and Electroabsorption Modulators," *IEEE J. Sel. Topics Quantum Electron.*

PIC Transmitters

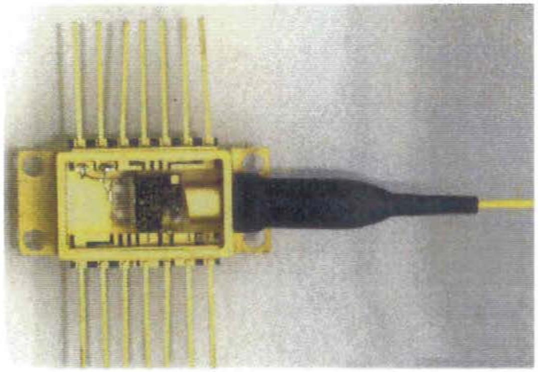
Early PIC transmitter: EML

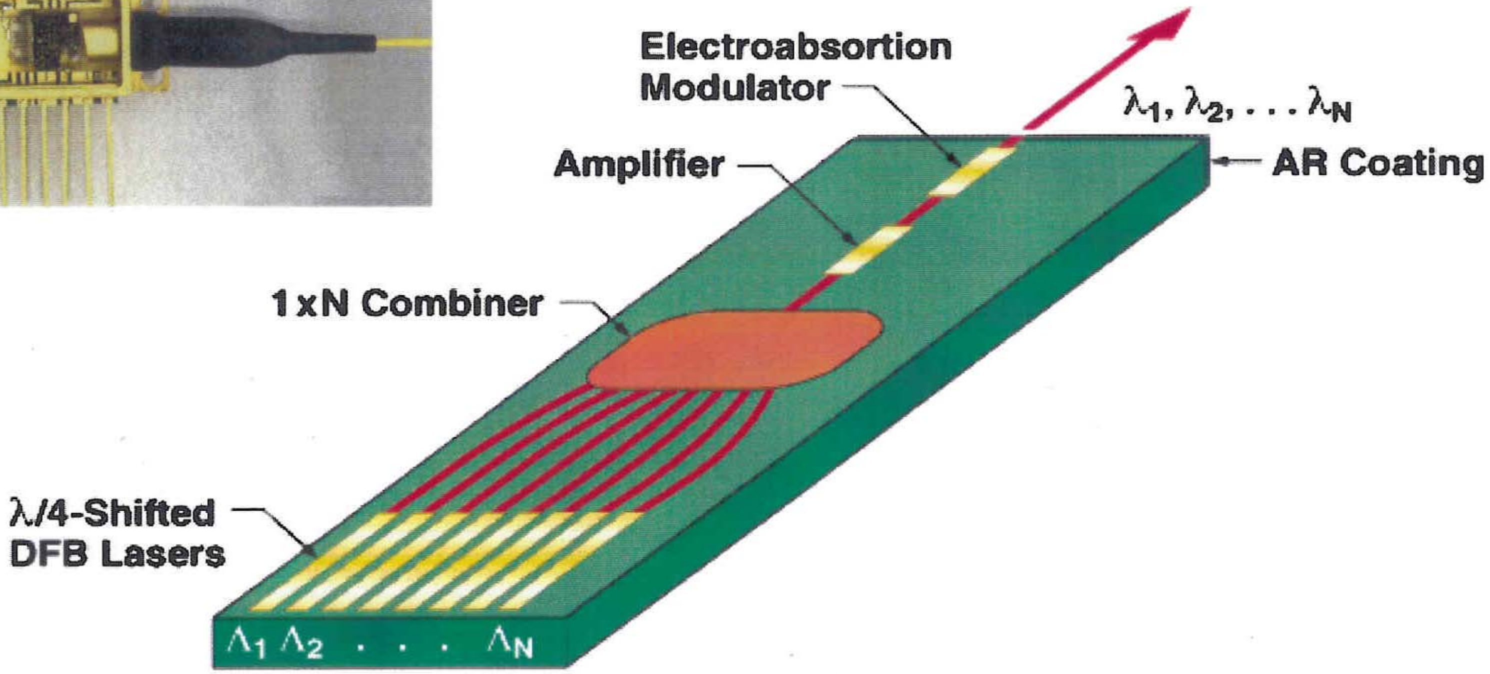
EML = electroabsorption-modulated laser



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

Early PIC with wavelength-selectable laser and EAM



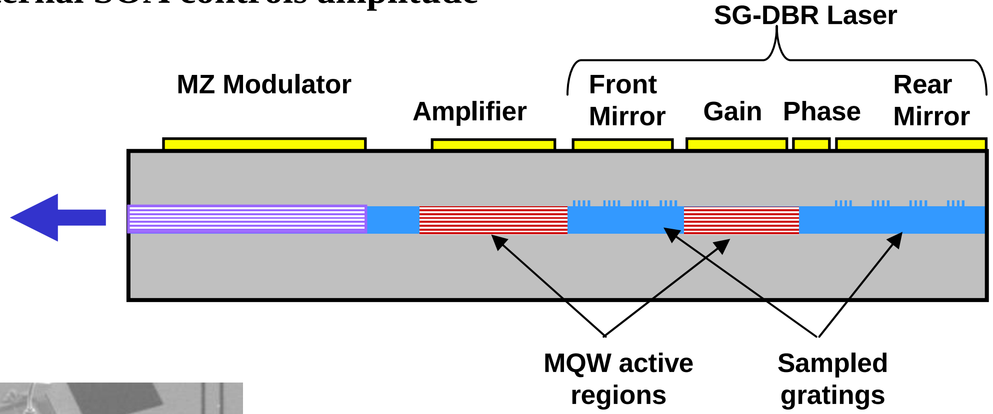


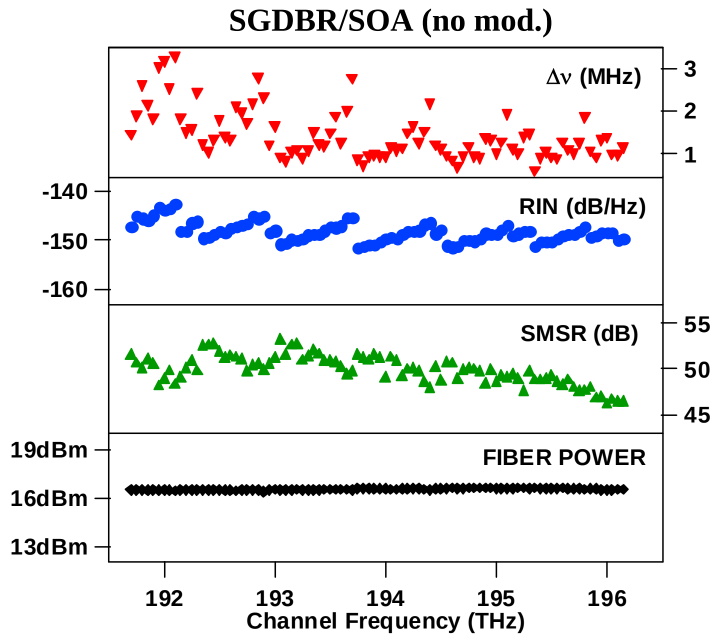
M. G. Young, et al., *Electron. Lett.*, **31**, pp. 1835-1836, 1995.

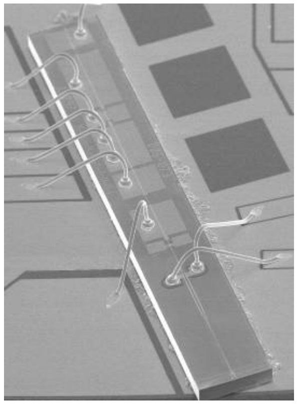
Early PIC with widely-tunable laser and EA or MZ-modulator

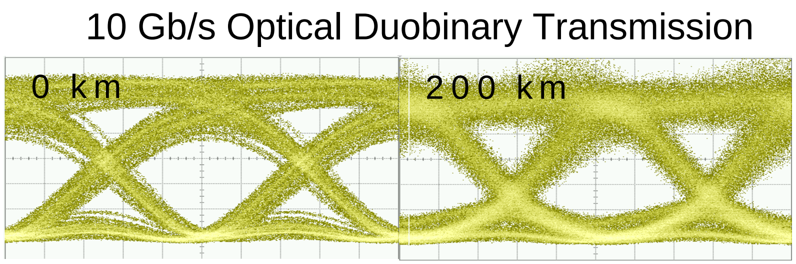
SGDBR+X: (UCSB'91-'08 → Agility'99-'05 → JDSU'05→)

- Vernier sampled DBRs and phase set wavelength
- External SOA controls amplitude









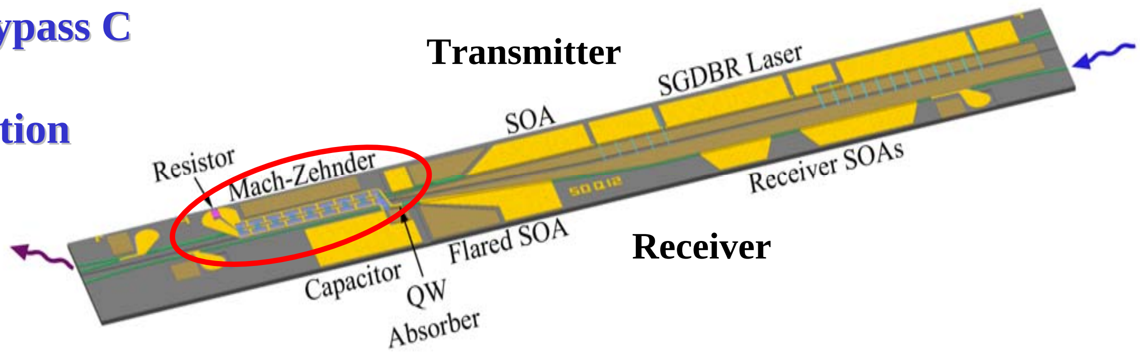
Courtesy of JDSU + UCSB

L.A. Johansson, L.A. Coldren, P.C. Koh, Y.A. Akulova, and G.A. Fish, "Transmission of 10 Gbps Duobinary Signals Using an Integrated Laser-Mach Zehnder Modulator" *Optical Fiber Communication* (*OFC*), paper no. OThC4, San Diego, CA, MARCH, 2008

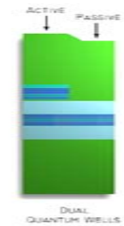
SGDBR- Mach-Zehnder transmitter stage of transceiver (wavelength converter)

Series-push-pull SGDBR-MZ transmitter

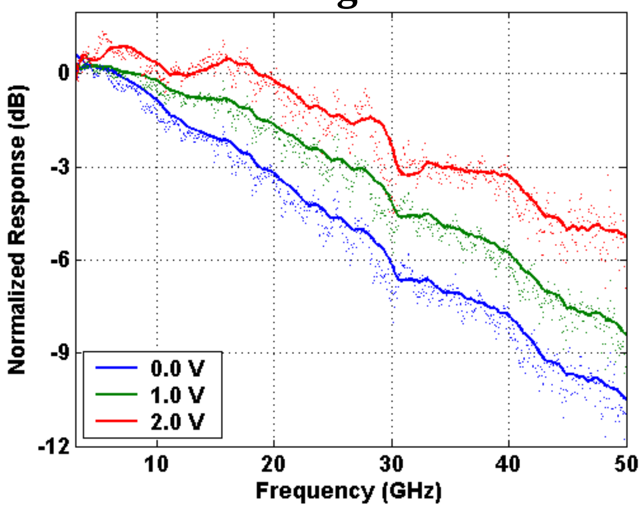
- Integrated load R and bypass C
- 30 GHz Bandwidth
- 40 Gb/s error free operation
- Low/negative chirp



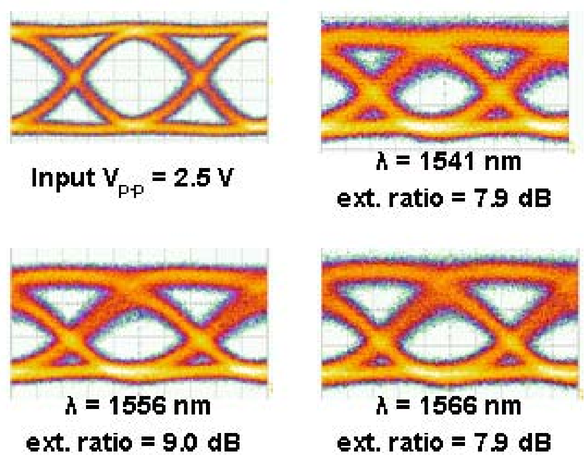
DQW



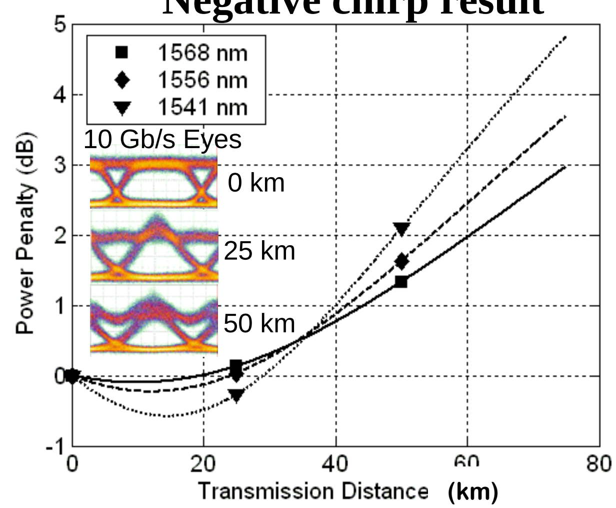
MZ small-signal bandwidth



40 Gb/s eyes

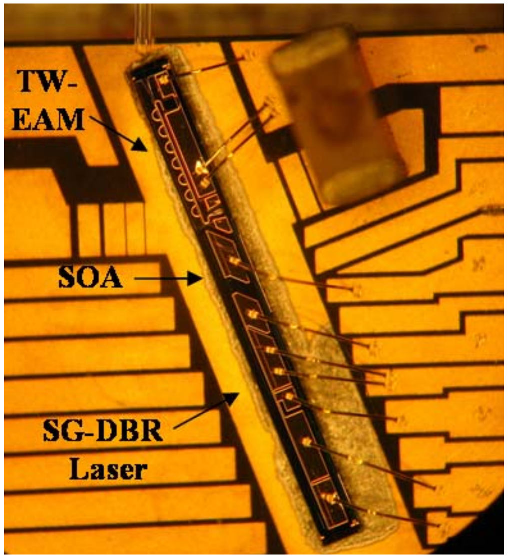


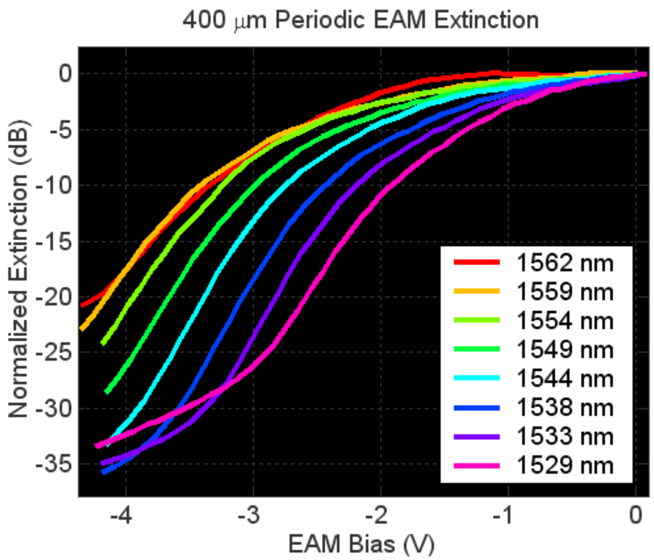
Negative chirp result

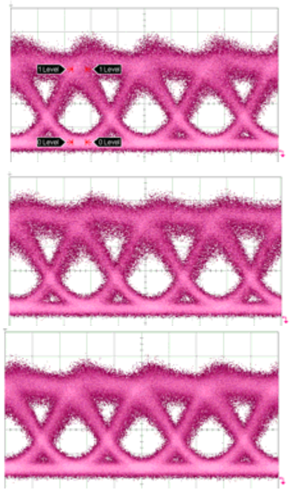


A. Tauke-Pedretti, M.N. Sysak, J.S. Barton, L.A. Johansson, J.W.Raring, and L.A. Coldren, "40 Gbps series-push-pull Mach-Zehnder Transmitter on a dual-QW integration platform," *Photon. Tech. Lett.*, **18** (18) 1922-4 (2006).

40 Gb/s SGDBR/TW-EAM



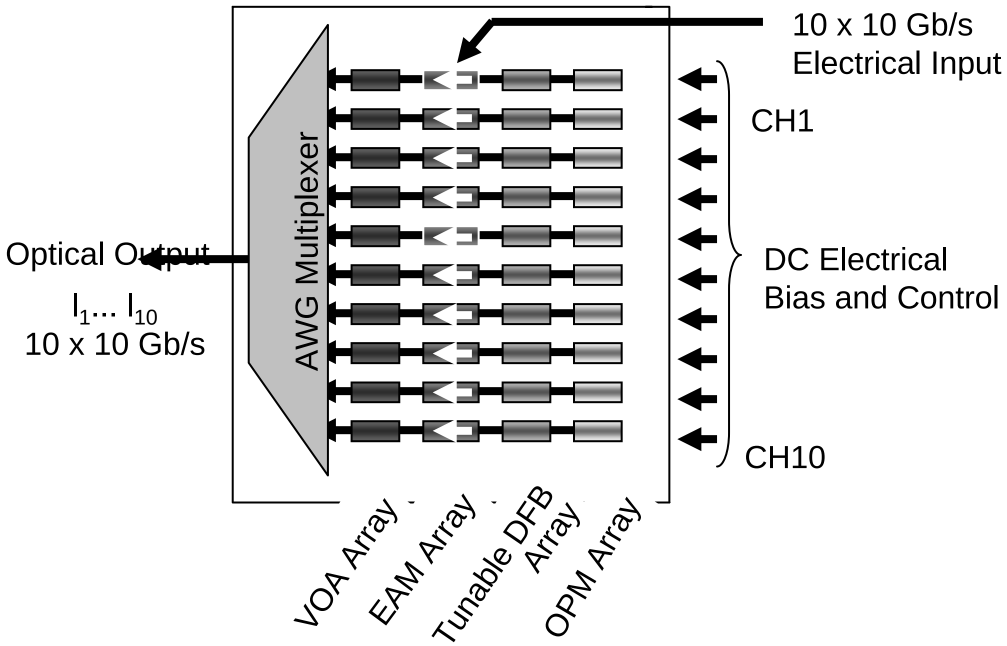


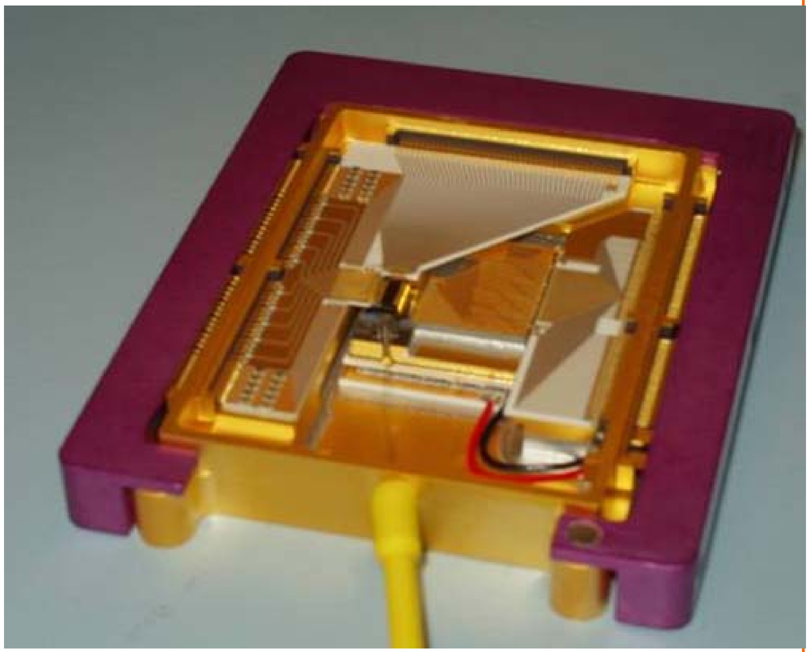


- **Integration of traveling-wave EAM designs with SG-DBR laser**
- **Modulation efficiency 15 – 20 dB/V over the tuning range**
- **Open eyes at 40 Gb/s for all wavelengths**
  - **6 – 10 dB extinction with 2.1V**

M. M. Dummer, J.Klamkin, E. J. Norberg, J. W. Raring, A. Tauke-Pedretti, and L A. Coldren, " Periodic Loading and Selective Undercut Etching for High-Impedance Traveling-Wave Electroabsorption Modulators", *OFC'08*, March, 2008.

Recent multi-channel transmitter PIC



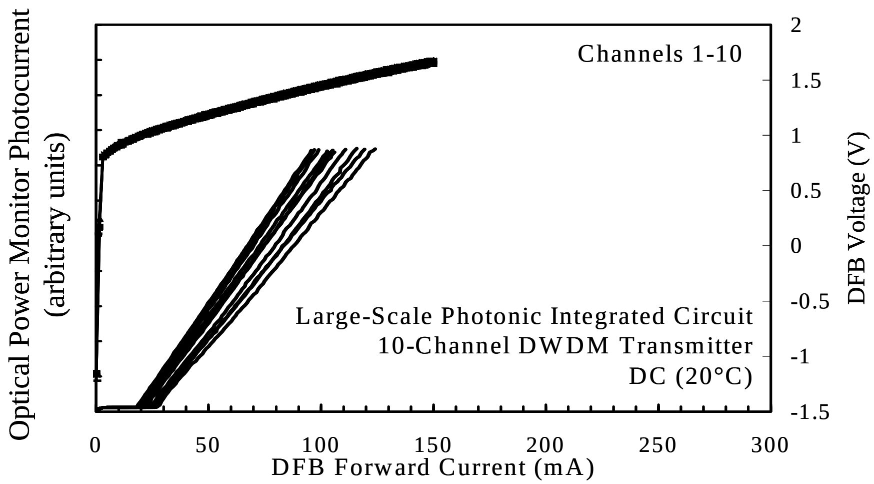


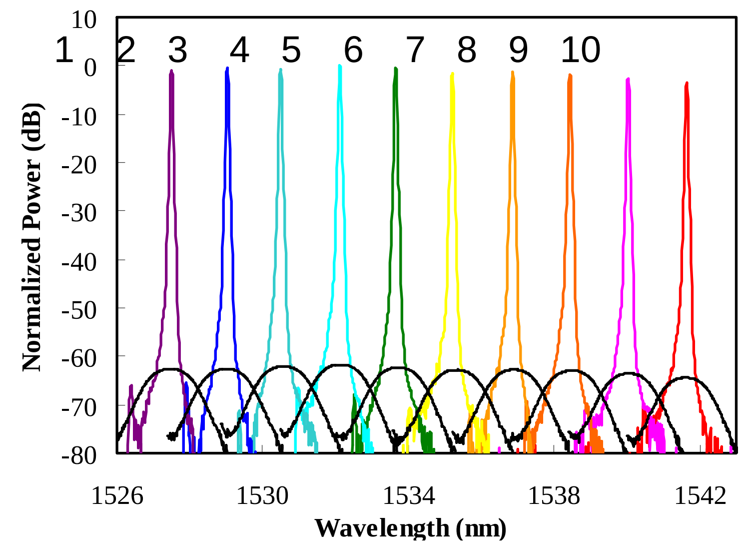
R. Nagarajan, et al., *Sel. Top. Quant. Electron.*, **11**, pp. 50-65, 2005.

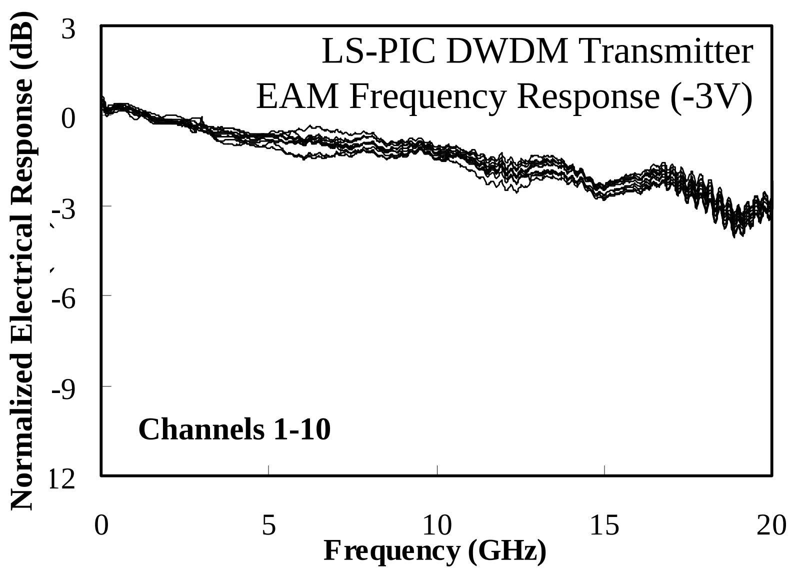
Slide courtesy of C. Joyner

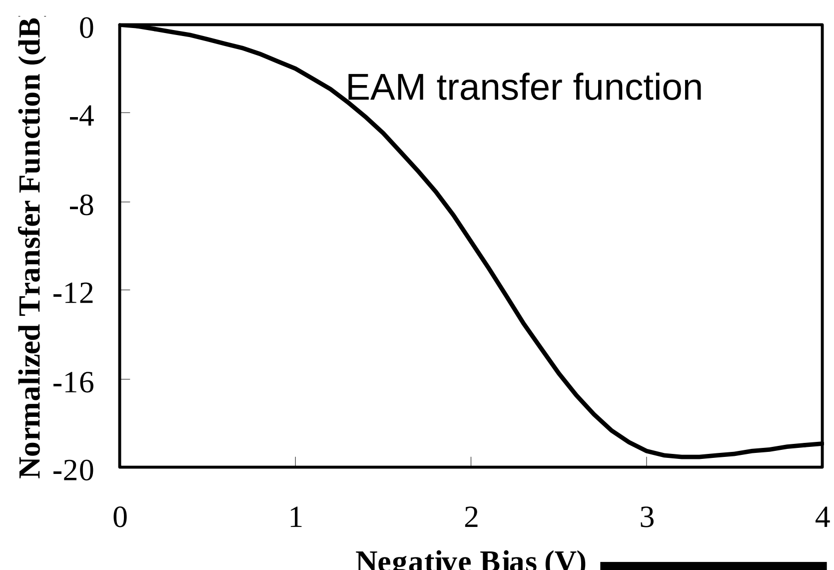
infinera

Multi-channel transmitter results



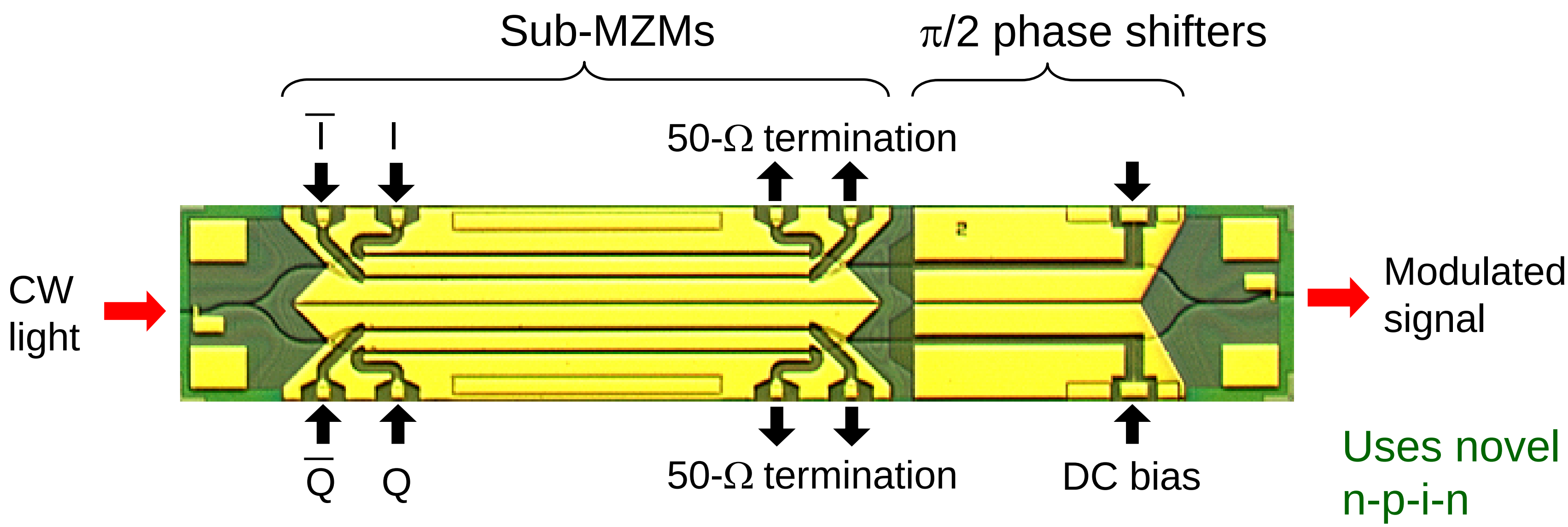






Slide courtesy of C. Joyner

Traveling-wave MZM DQPSK PIC



Uses novel n-p-i-n structure

Wavelength range: L-band (λ_{PL} = 1.47 μm)

RF input: Differential

EO interaction length: 3 mm (Sub-MZMs),

1.5 mm (π/2-phase shifter)

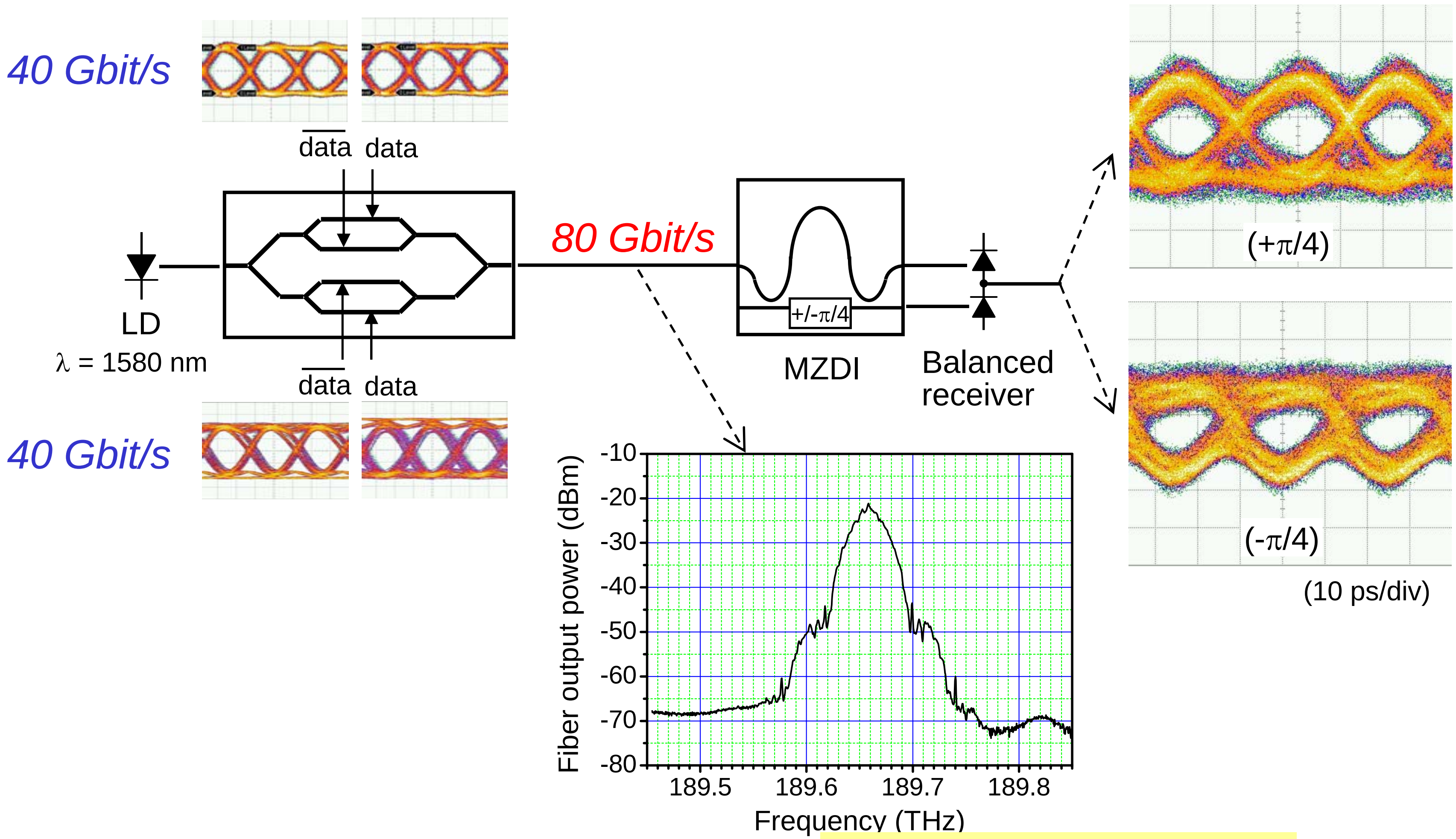
Chip size: **7.5 mm x 1.3 mm**

Courtesy of N. Kikuchi

N. Kikuchi, *ECOC*, 10.3.1, 2007.

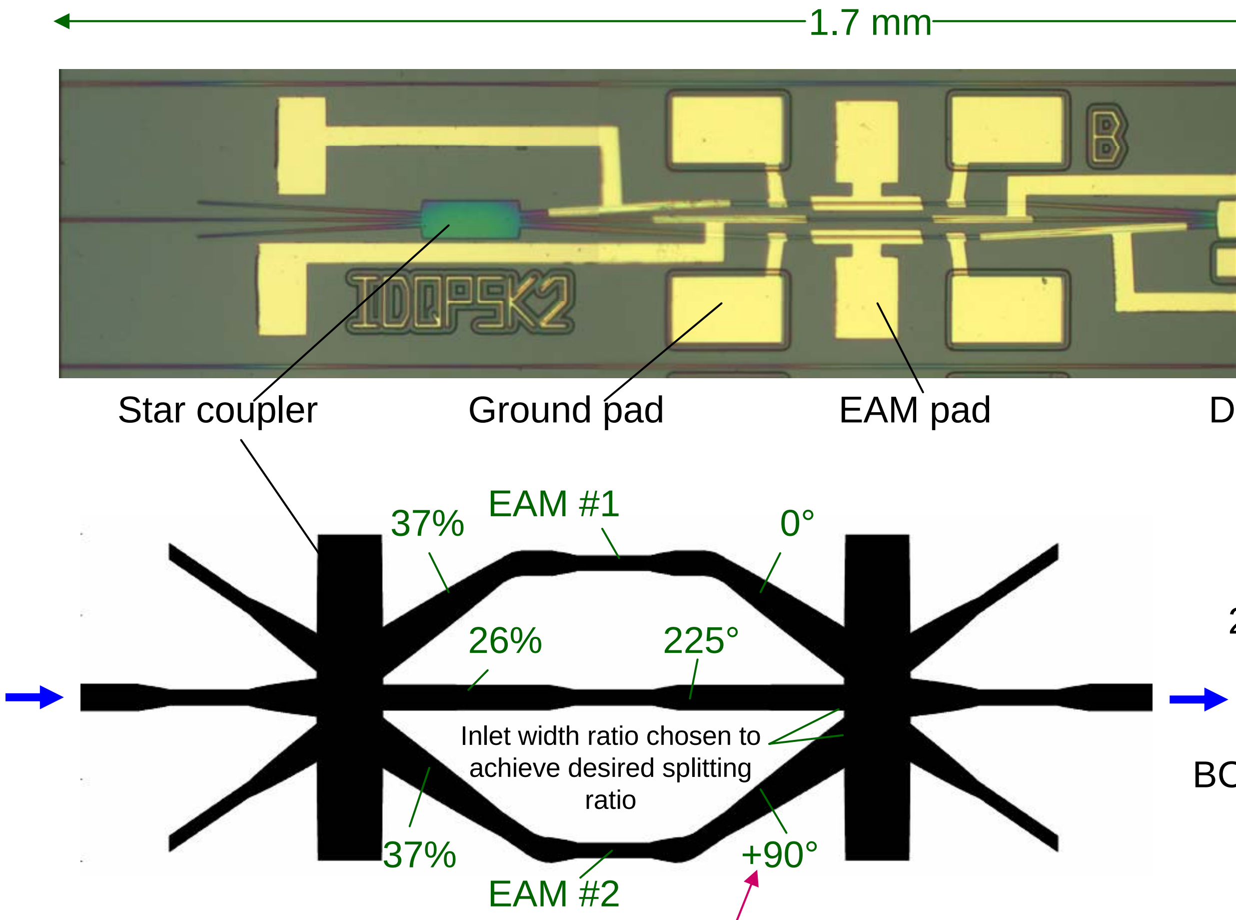
TW-MZM DQPSK Results

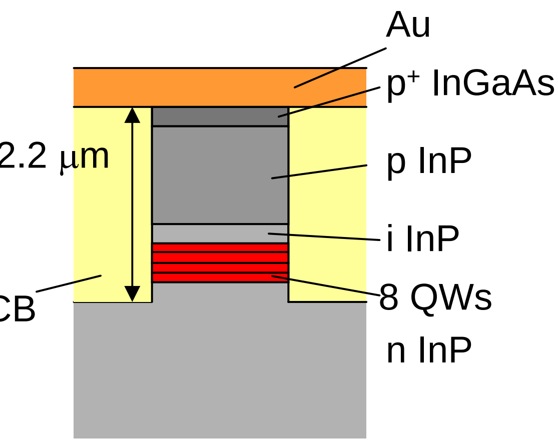
Driving voltage: 3 V_{pp} (V_π) for each



Slide courtesy of N. Kikuchi

Recent InP DQPSK modulator PIC

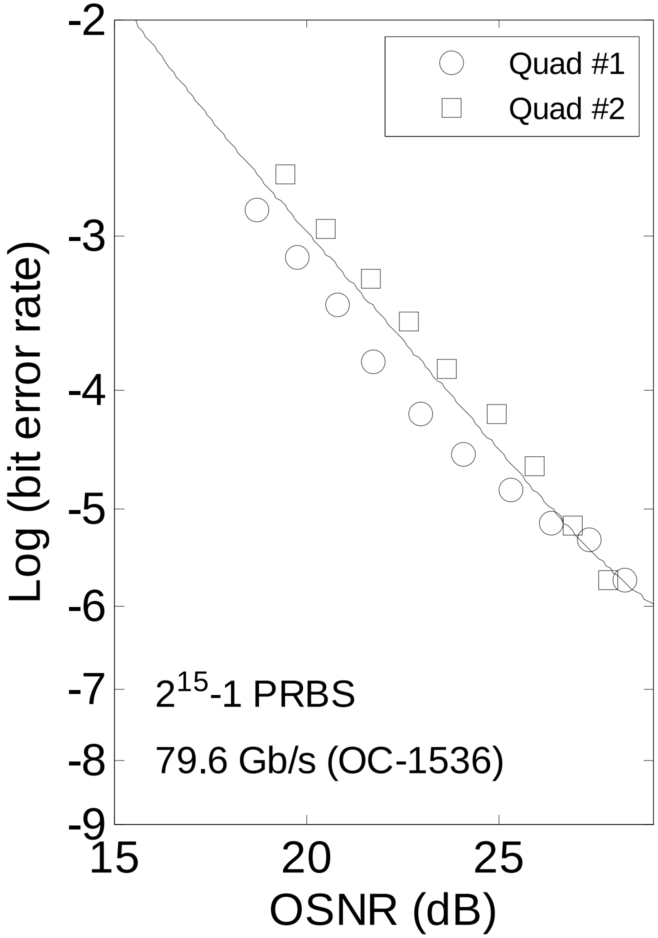


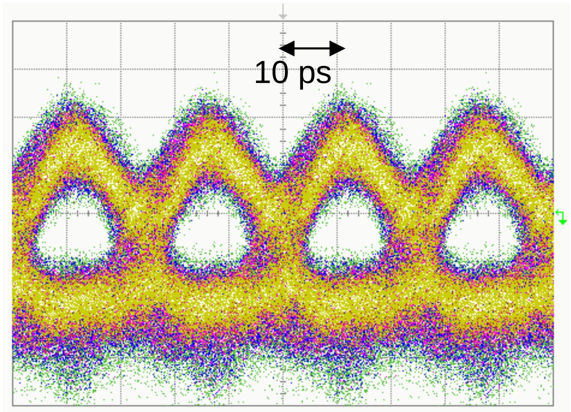


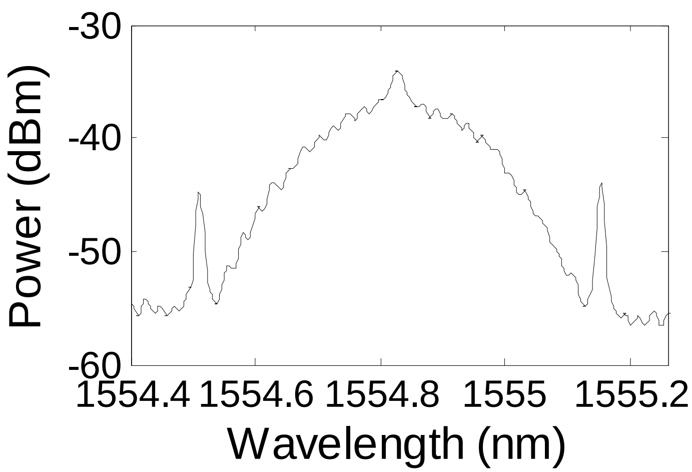
Set to 90° bias by design (using extra path length in one arm)

C. R. Doerr, et al., *OFC*, PDP33, 2007.

DQPSK modulator results



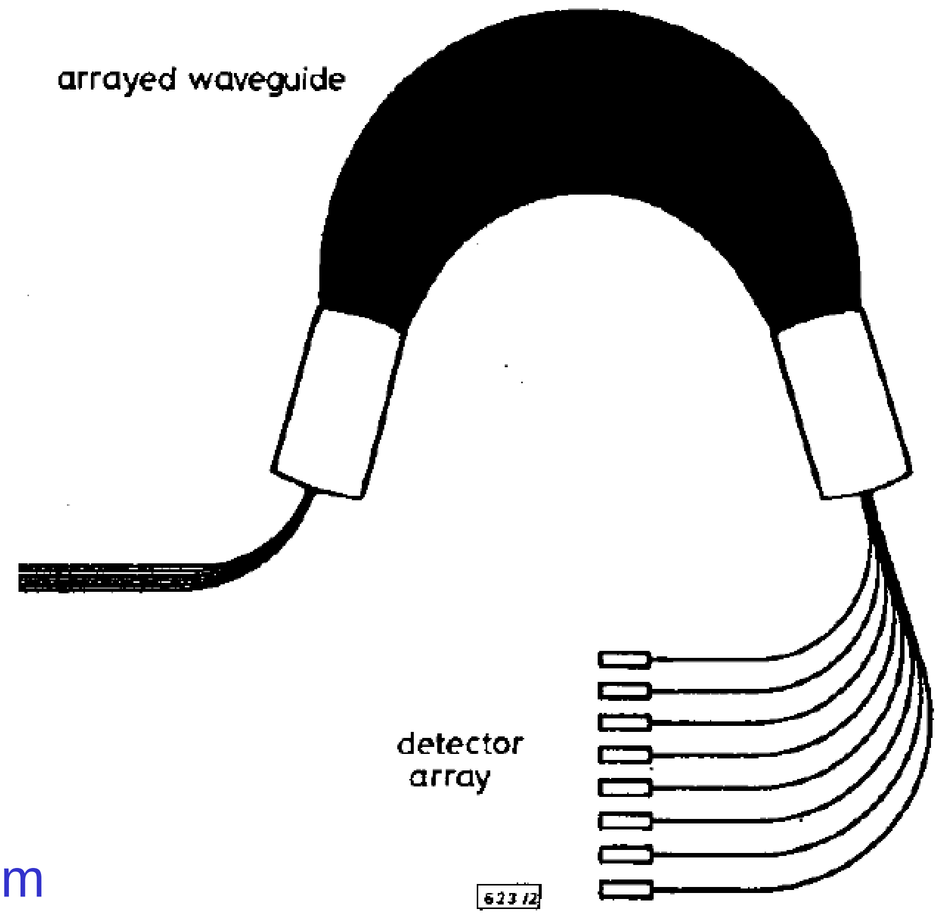




C. R. Doerr, et al., *OFC*, PDP33, 2007.

Receivers

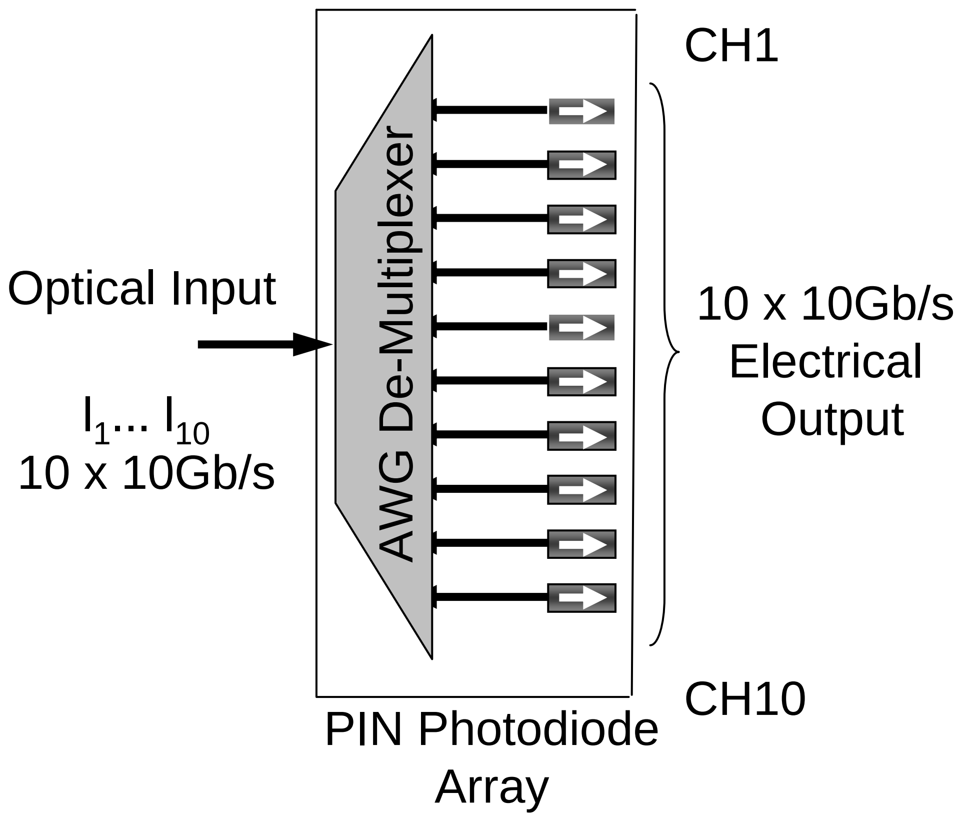
Early PIC multi-wavelength receiver

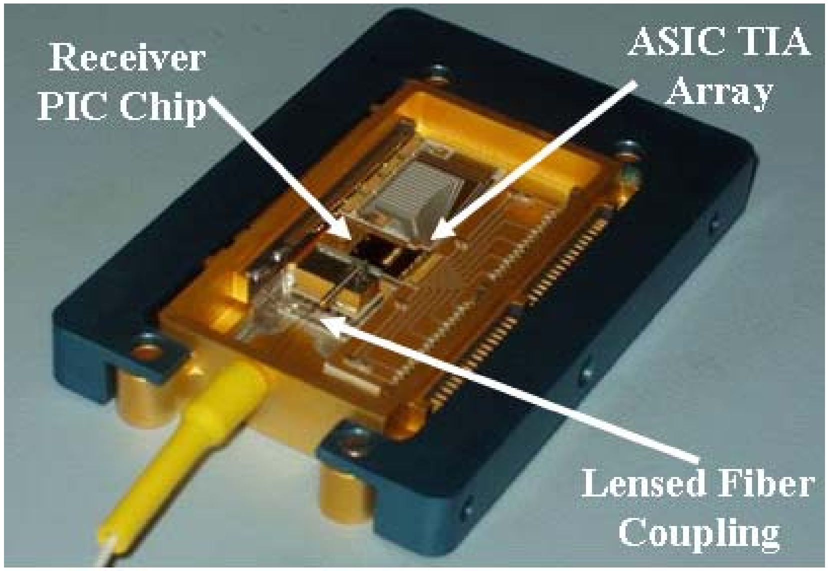


8 × 2 nm

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

Recent multi-channel receiver PIC

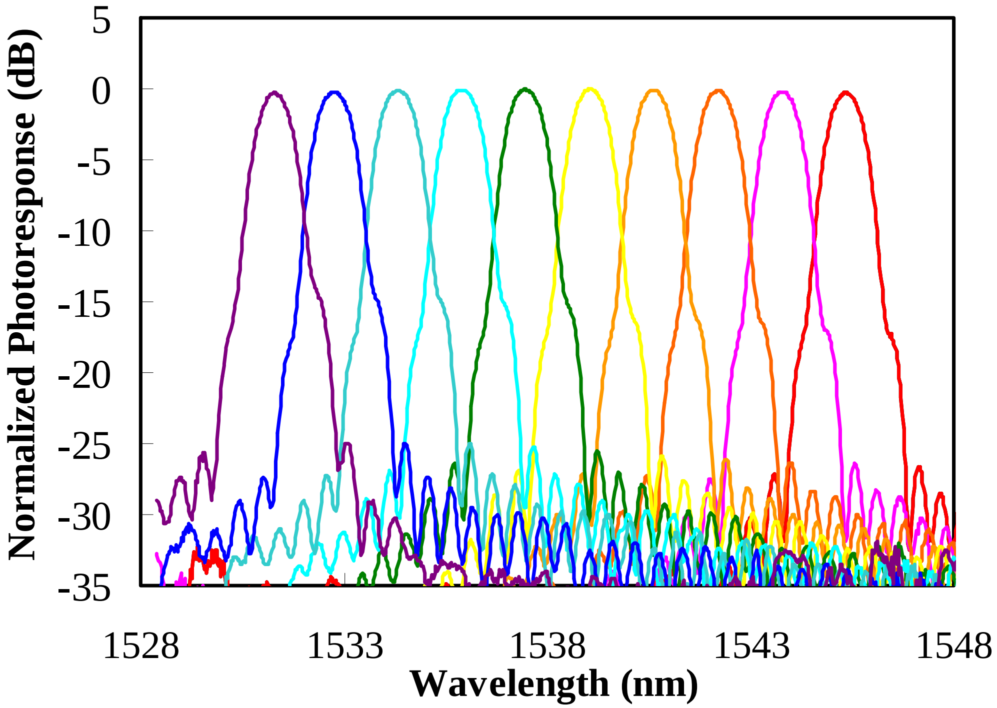


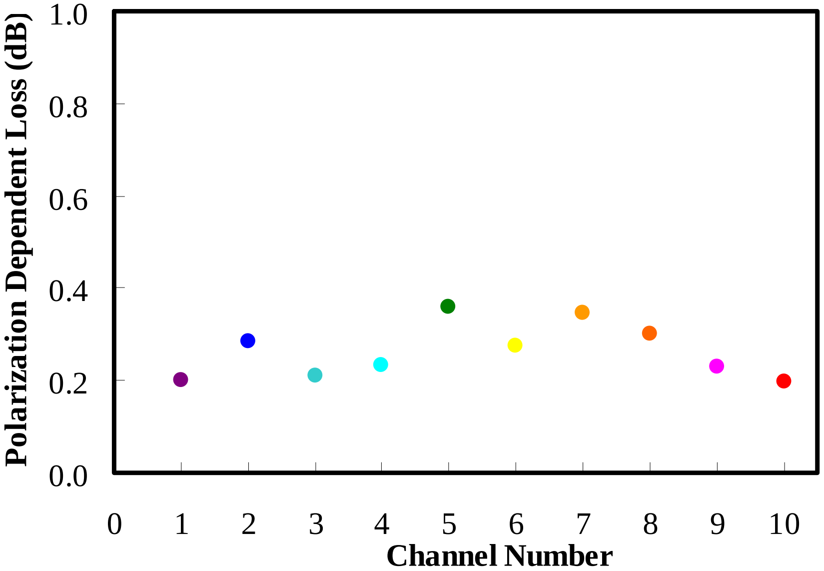


Slide courtesy of C. Joyner

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

Multi-channel receiver results

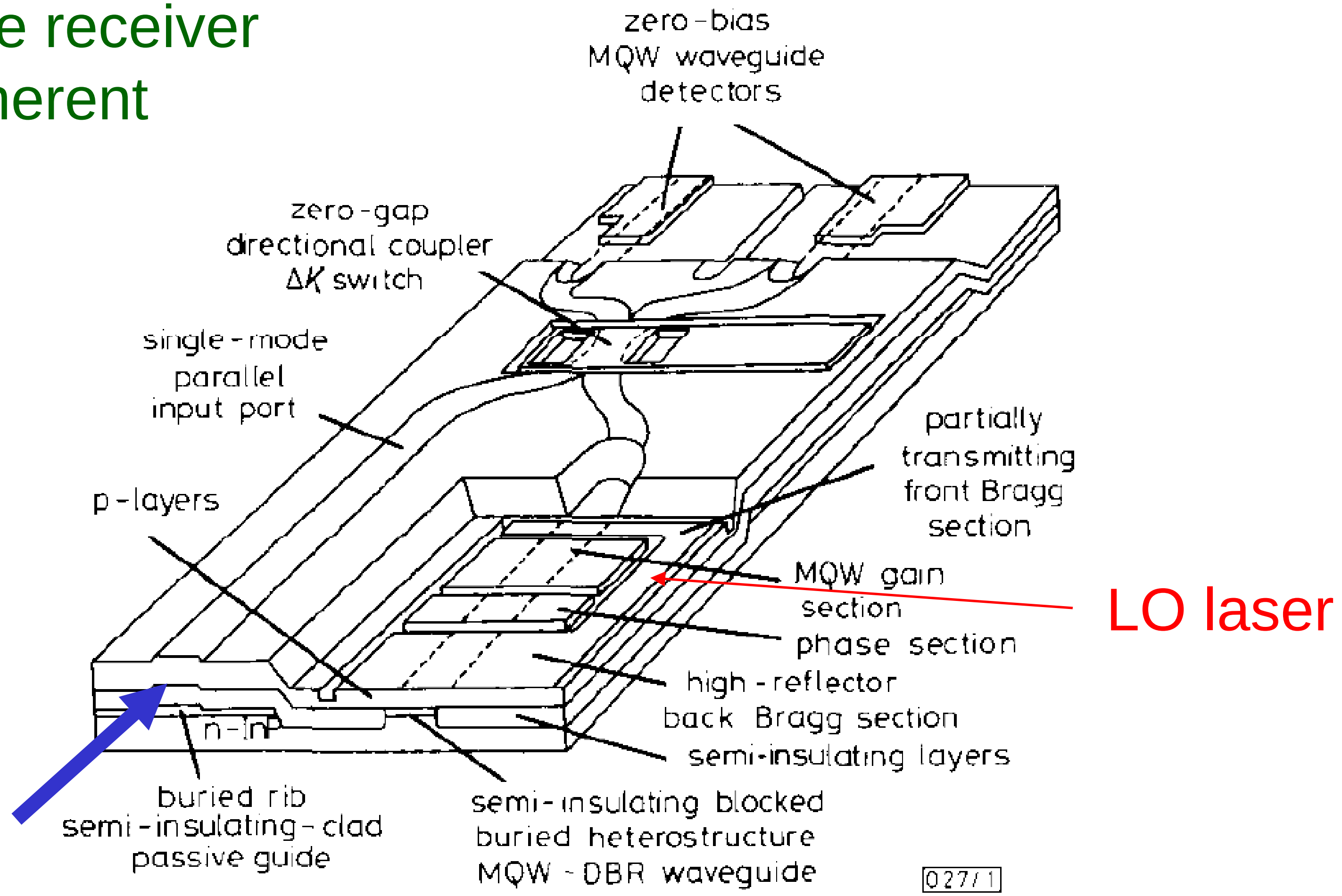




Slide courtesy of C. Joyner

Early heterodyne receiver PIC

Heterodyne receiver for coherent

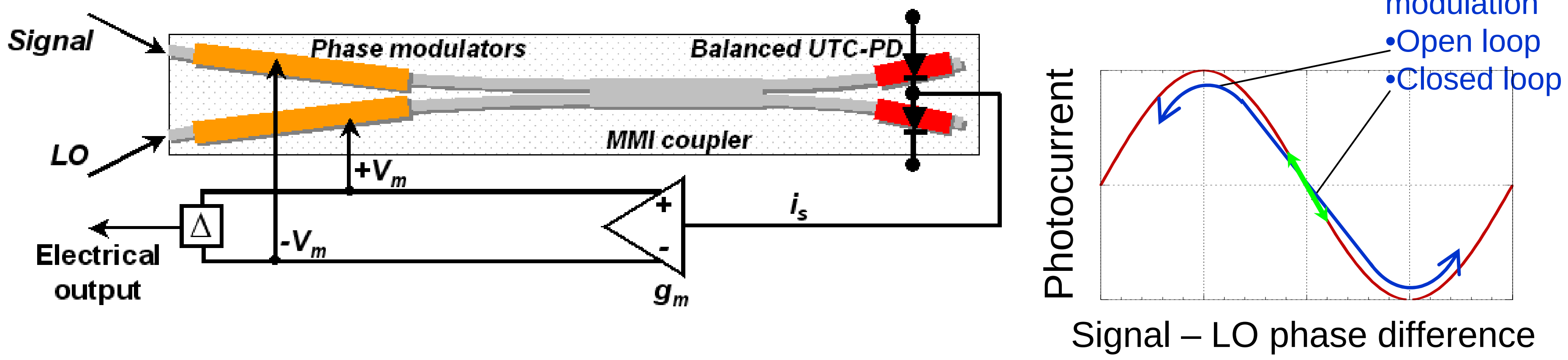


T. L. Koch, et al., *Electron. Lett.*, **25**, pp. 1621-1622, 1989.

Also, H. Takeuchi, et al., *IEEE Photon. Tech. Lett.*, **1**, pp. 398-400, 1989.

Balanced receiver for phase modulated signals with feedback—NEED for OEICs!!

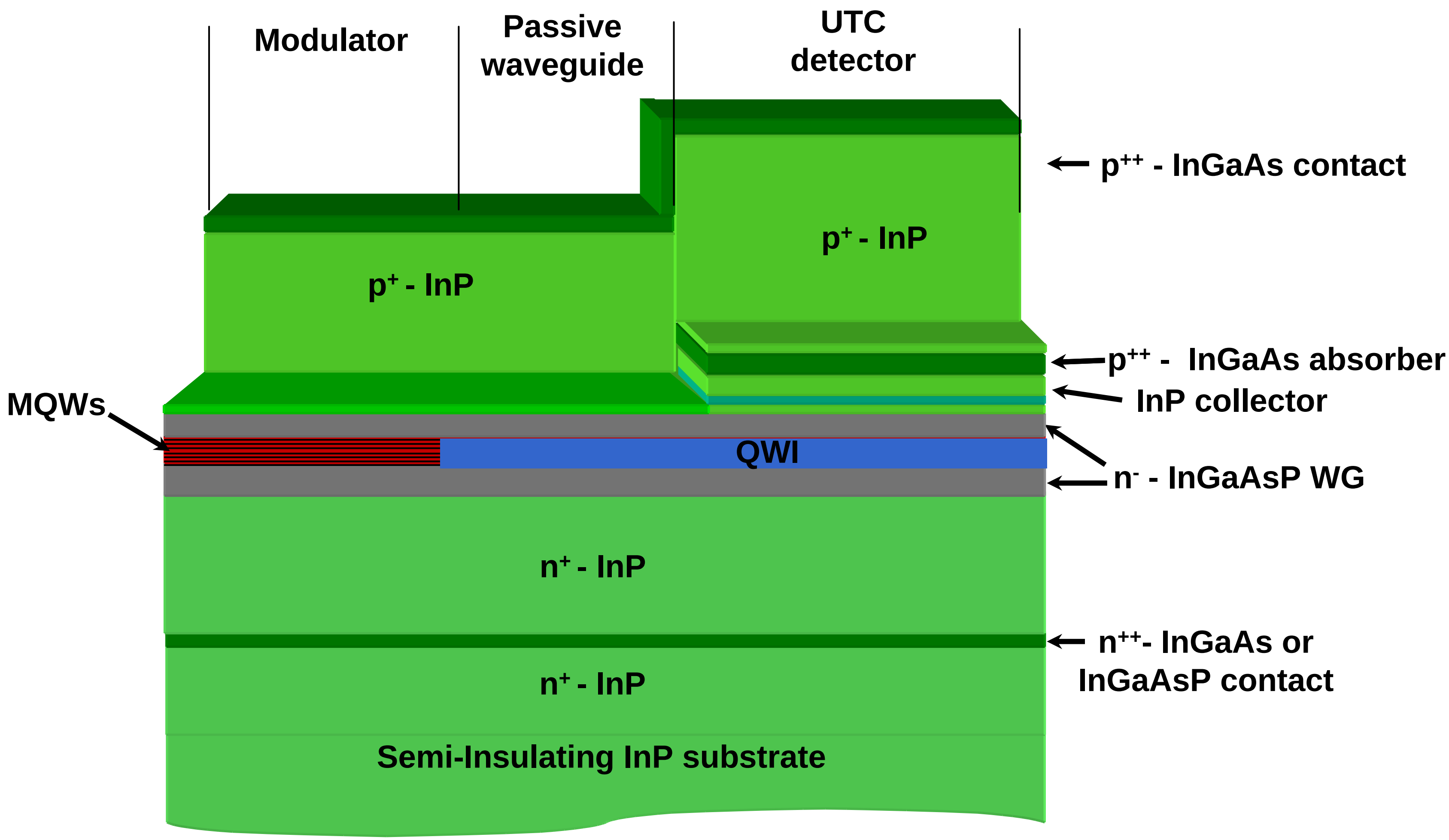
$$i_s \sim \sin(\varphi_{signal} - \varphi_{LO})$$



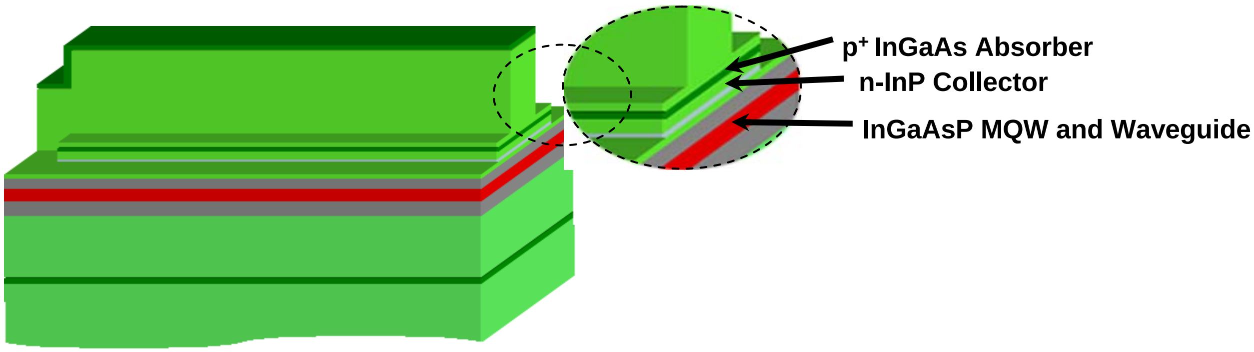
- **Signal mixed with local oscillator to demodulate optical phase**
  - **Detected differential photocurrent represents signal-LO phase difference**
  - **Response of interferometer based demodulator is sinusoidal**
- **With feedback the differential photocurrent is reduced by the loop gain:** ***1/(1+T)***
  - **Hybrid integrated EIC* provides transconductance amplification**
  - **Closely track received optical phase to operate within linear regime**
  - **NEED VERY SHORT FEEDBACK PATH**

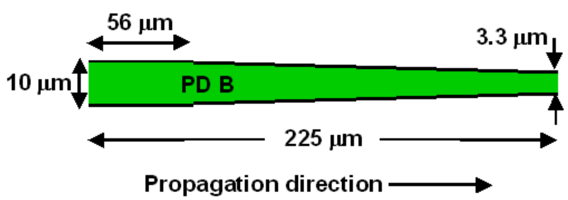
L.A. Johansson, H.F. Chou, A. Ramaswamy, L. A. Coldren, and J.E. Bowers, "Coherent optical receiver for linear optical phase demodulation," *Proc. MTT-S Microwave Sym.*, Tu3D-01 (June, 2007).

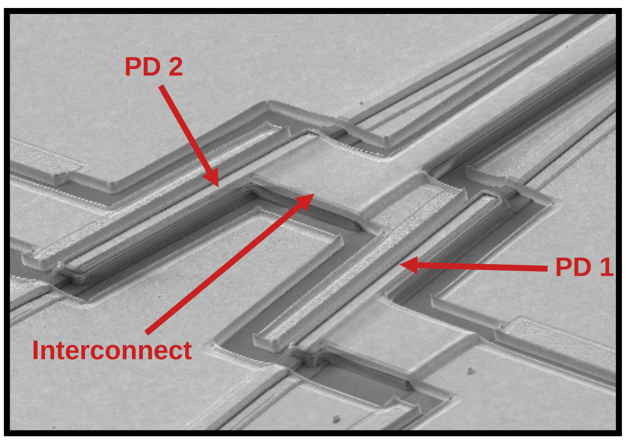
QWI/offset absorber PIC PM receiver

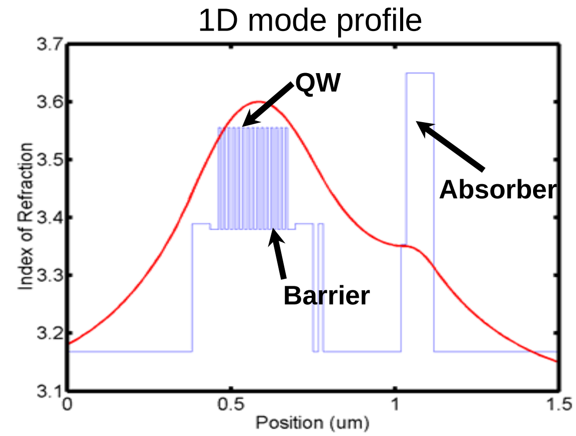


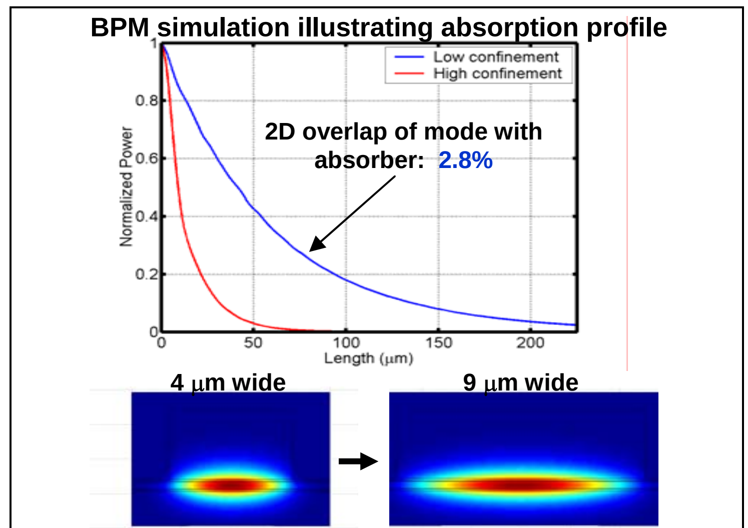
Balanced UTC-PD design







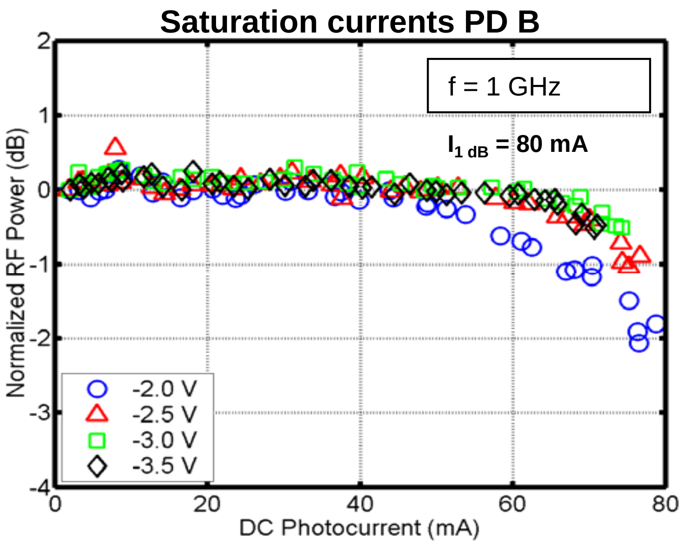


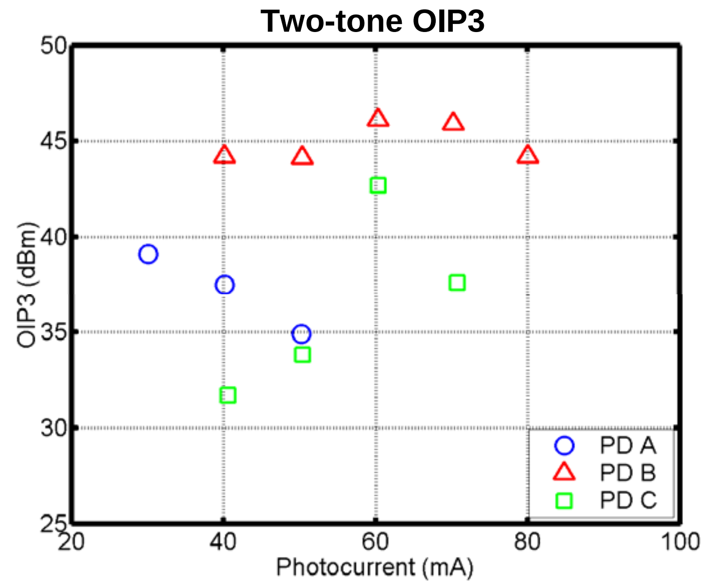


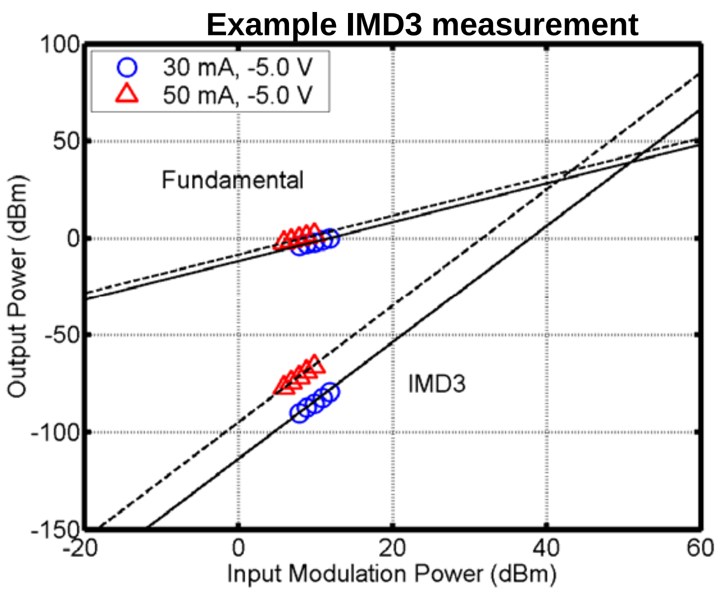
Long absorption profile and wide input reduce front end saturation

J. Klamkin, A. Ramaswamy, L. A. Johansson, H-F Chou, M.N. Sysak, J. W. Raring, N. Parthasarathy, S.P. DenBaars, J.E. Bowers, and L. A. Coldren, "High-output-saturation and high-linearity uni-traveling-carrier waveguide photodiodes," *Photonics Tech. Letts.* **19** (3) 149-151 (Feb. 2007).

Linearity Results





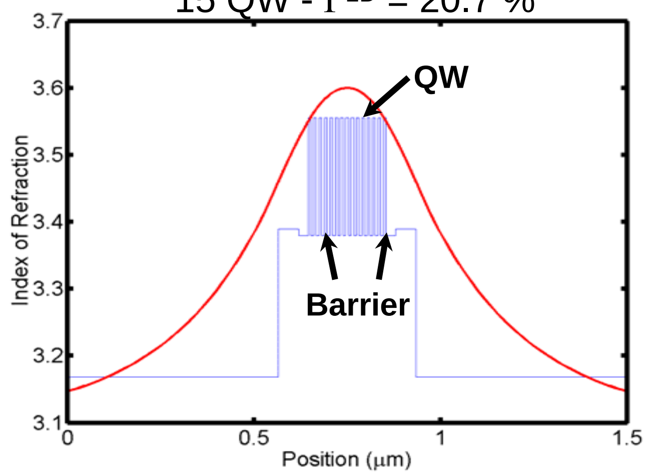


PD B: OIP3 = 46.1 dBm at 60 mA
44.2 dBm at 80 mA

*Record OIP3 for a WG PD

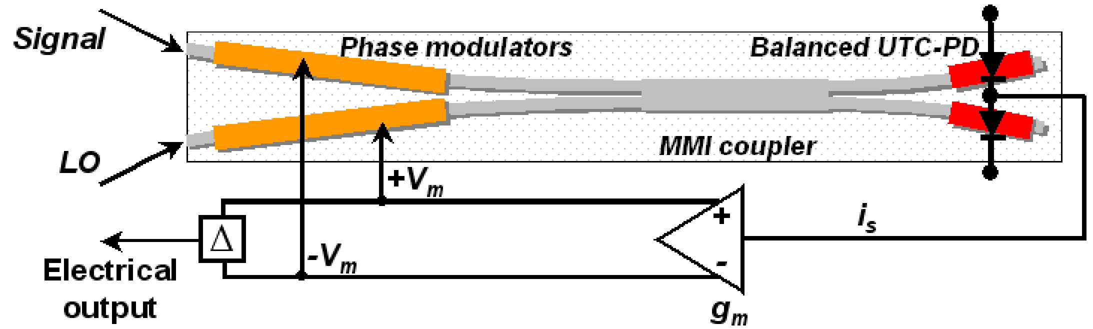
Phase modulator design

15 QW - Γ^{2D} = 20.7 %

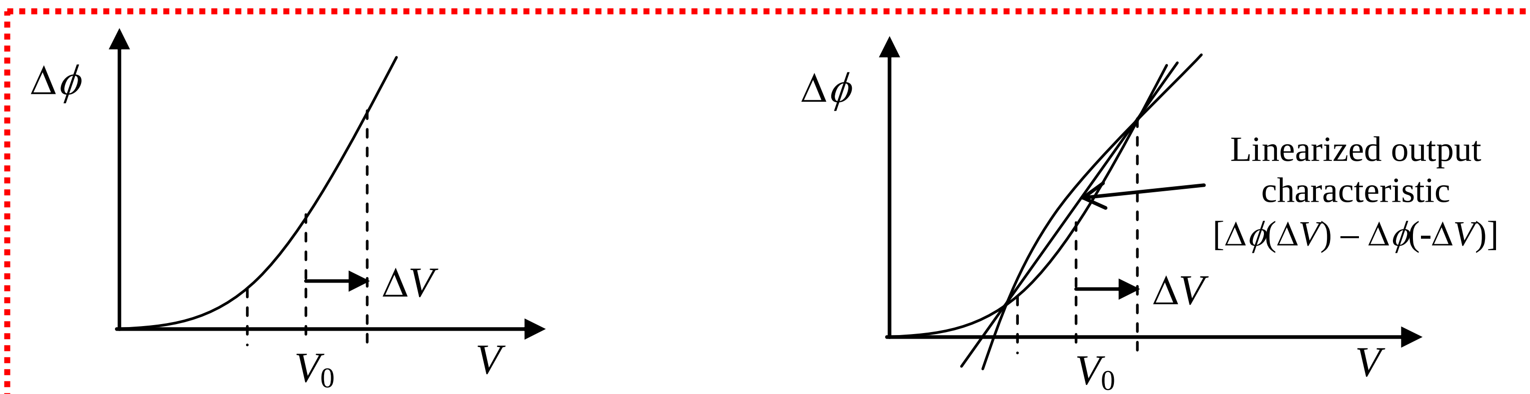


V_π^{DC} = 2.1 V•mm

Push-pull modulation

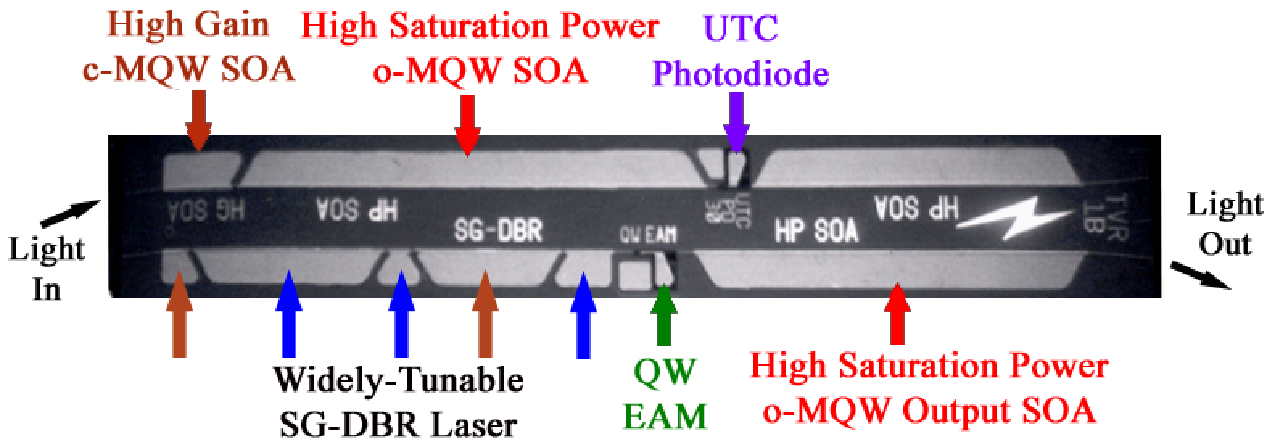


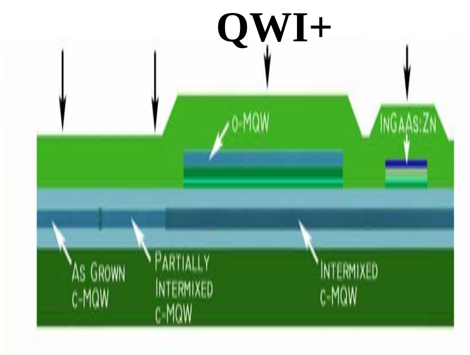
- **Linear term doubled, even order terms cancelled**
- **Third order distortion suppressed with bias optimization**

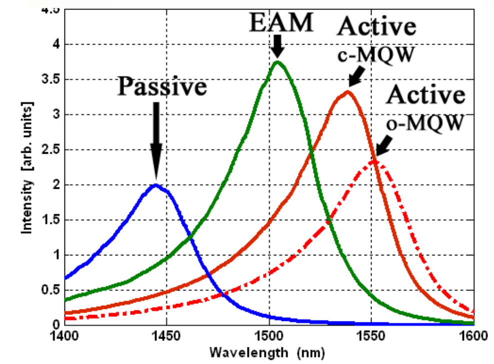


Tranceivers/wavelength converters

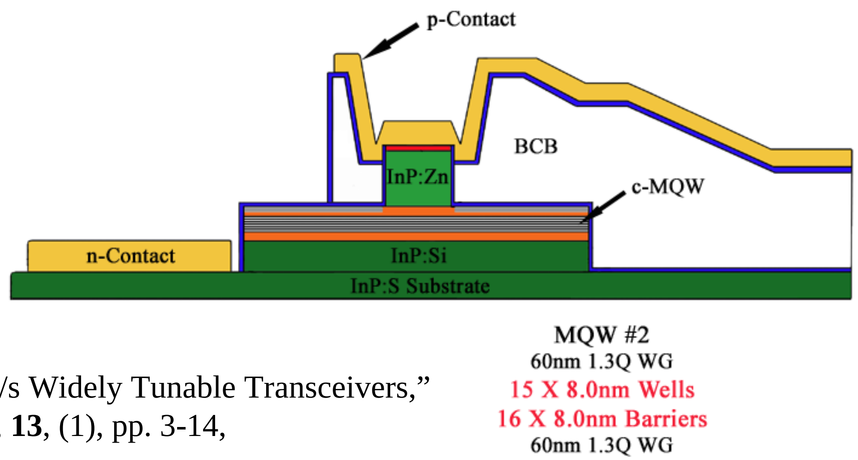
1. QWI+ widely-tunable transceiver/ SOA-PIN & SGDBR-EAM







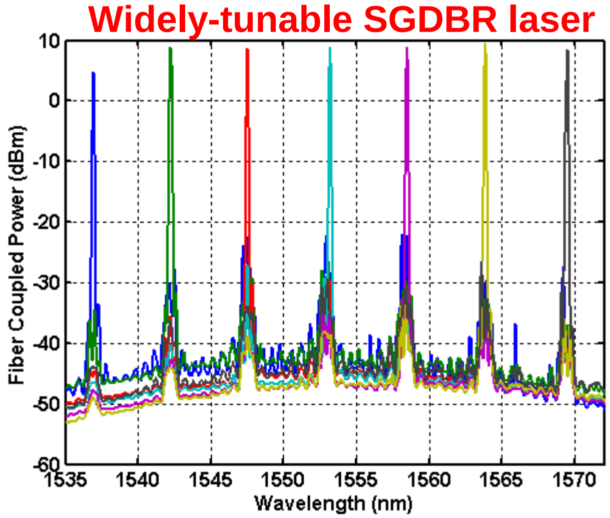
- Current from UTC directly modulates EAM
- Only dc biases & no filters required for wavelength conv.
- Any wavelength in to any out over C-band
- Signal monitoring available

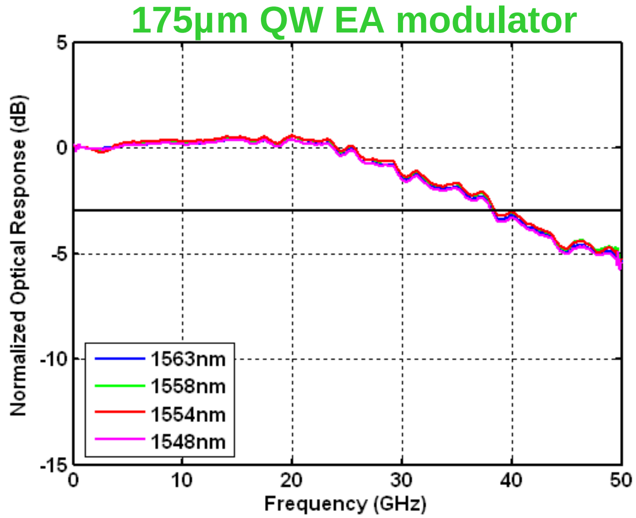


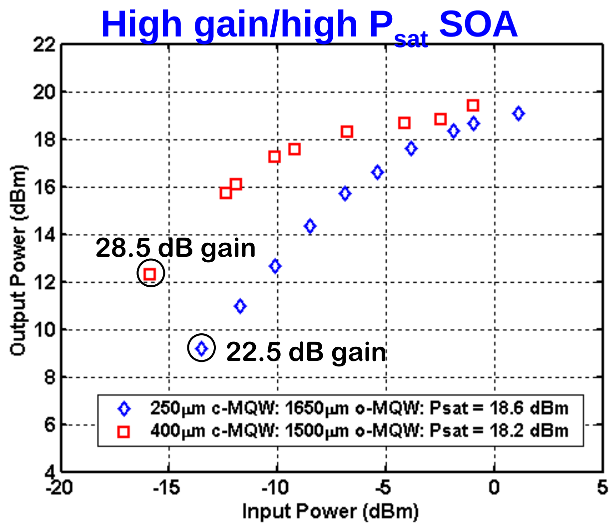
J.W. Raring, and L.A. Coldren, "40-Gb/s Widely Tunable Transceivers," *IEEE J. Sel. Topics Quantum Electron.*, **13**, (1), pp. 3-14, (January/February 2007)

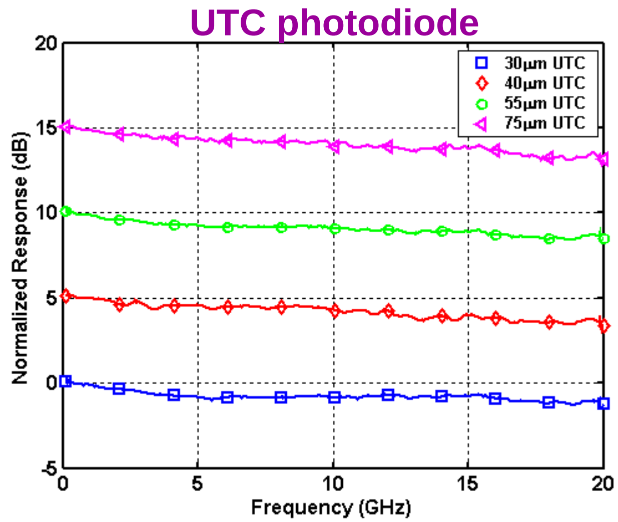
QWI-Transceiver chip elements

- High-gain/high P_{sat} 2-stage SOA pre-amps + UTC photodiode receiver
- SG-DBR laser + QW EAM transmitter



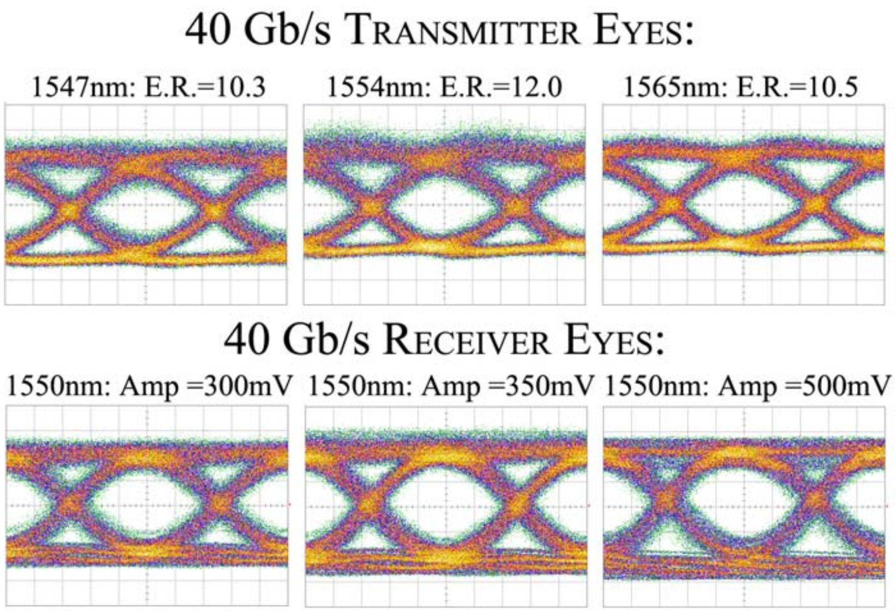


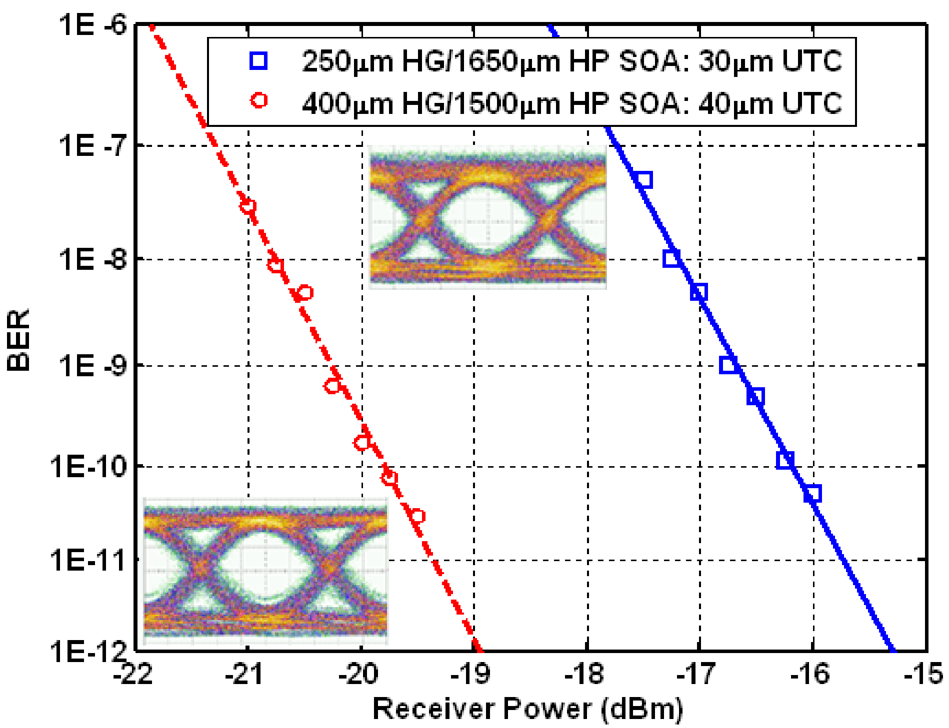




QWI+ transceiver 40 Gb/s transmit and receive functionality

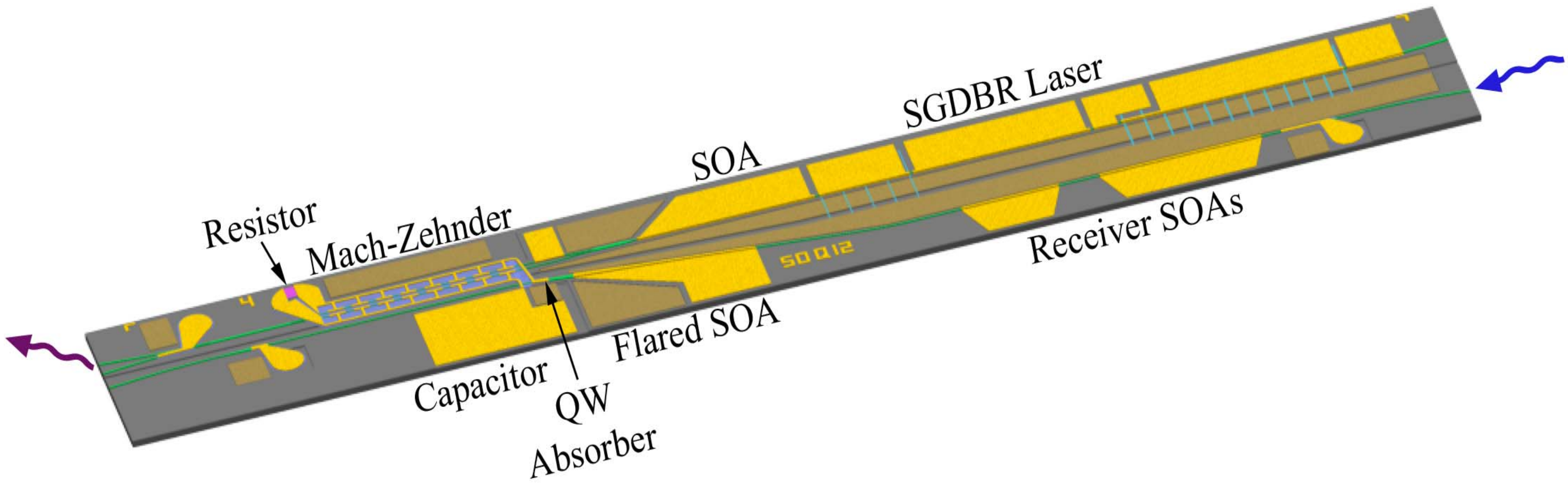
- Transmitter: 175µm EAM
- DC = 2.5-4.5V: $V_{PtoP} = 2.5$
- Receiver: 400 µm high-gain SOA with 40µm UTC





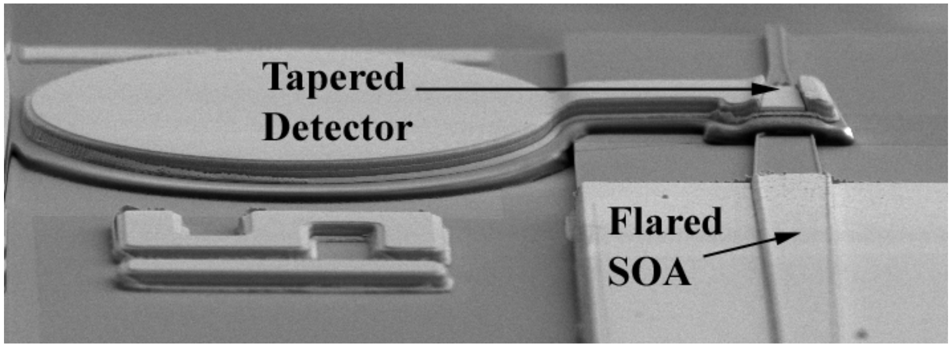
2. Wavelength converter/SOA-PIN receiver & SGDBR-Mach Zehnder transmitter

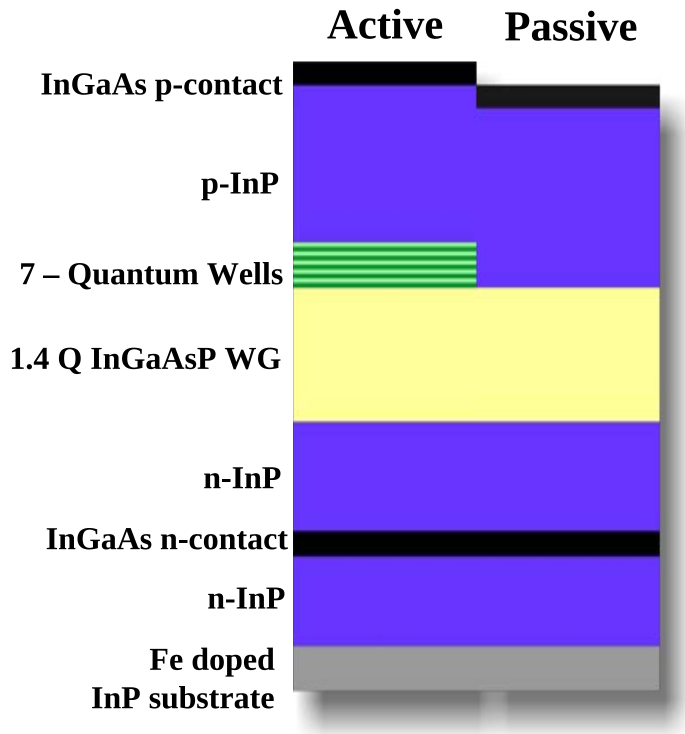
- Photocurrent driven
- 35 µm QW absorption region in receiver
  - Tapered for reduced capacitance
- 300 µm traveling-wave Mach-Zehnder modulation region
  - Series-push-pull design to maximize bandwidth
- Data format and rate transparent
- No optical filter required
- Integrated termination resistor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



Simple offset QW integration platform

Use simplest integration platform to do the job





- **Receiver SOA**
  - **Offset quantum wells provide gain (23 dB achieved)**
  - **Linearly flared waveguide (16 dBm P_{sat})**
  - **13 dBm (20mW) → 1 V rms (2.8 V_{pp}) over 50 Ω**
- **Quantum-well PIN detector**
  - **Reverse biased laser QW provide high absorption coefficient**
  - **Wide front end prevents saturation**
  - **Tapering reduces capacitance**

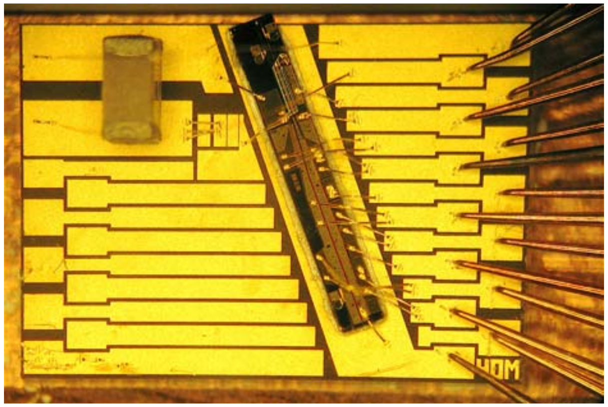
A. Tauke-Pedretti, M.M. Dummer, M.N. Sysak, J.S. Barton, J.W. Raring, J. Klamkin, and L.A. Coldren, "Monolithic 40 Gbps Separate Absorption and Modulation Mach-Zehnder Wavelength Converter," *Proc. OFC*, paper no. PDP36, Anaheim, CA (March 25-29, 2007)

Mach-Zehnder Wavelength Converter

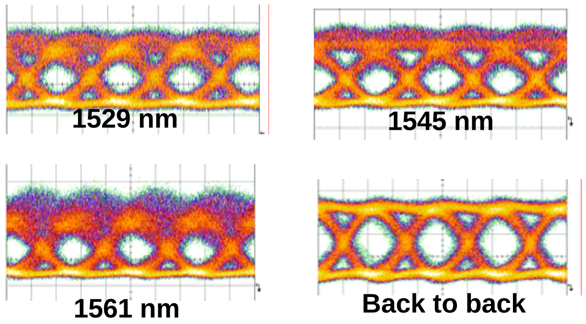
Current from absorber drives SPP-MZM

WC Performance

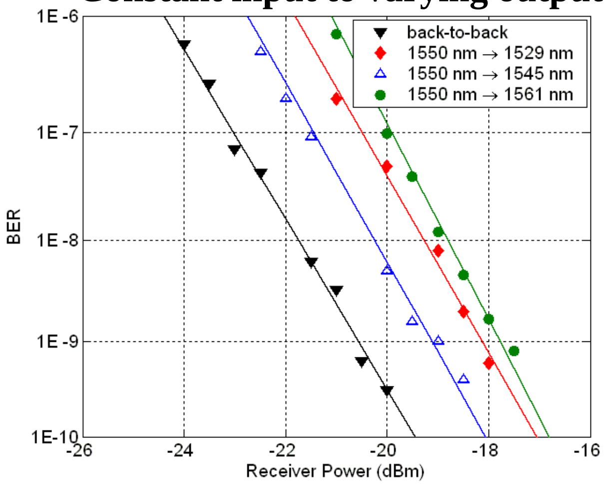
- **40 Gb/s NRZ operation**
- **<2.5 power penalty for varying input and output wavelengths**



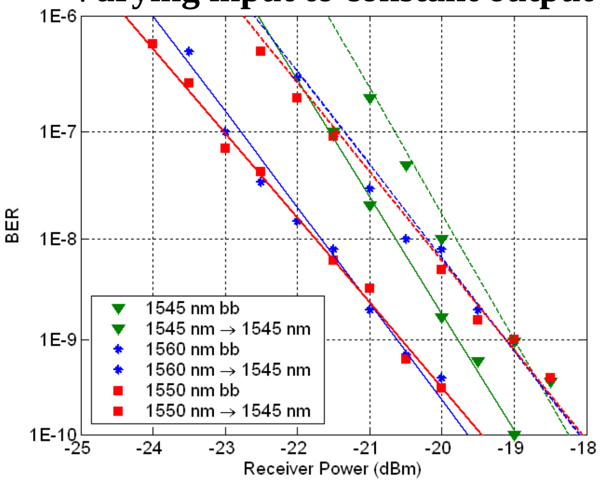
DQW



Constant input to varying output



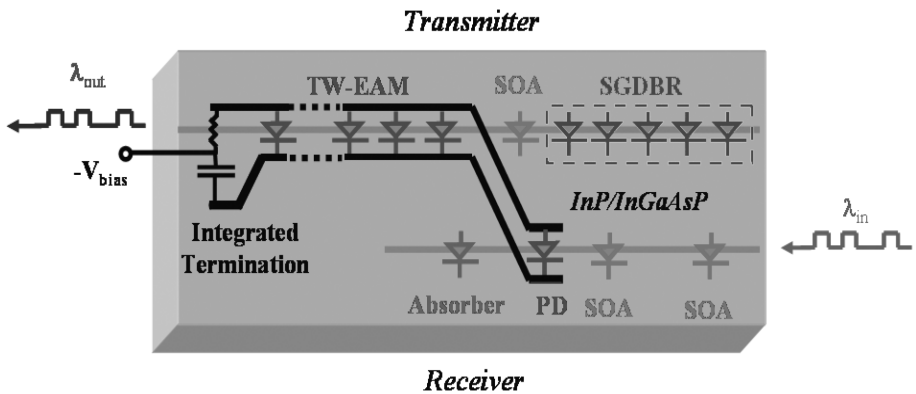
Varying input to constant output

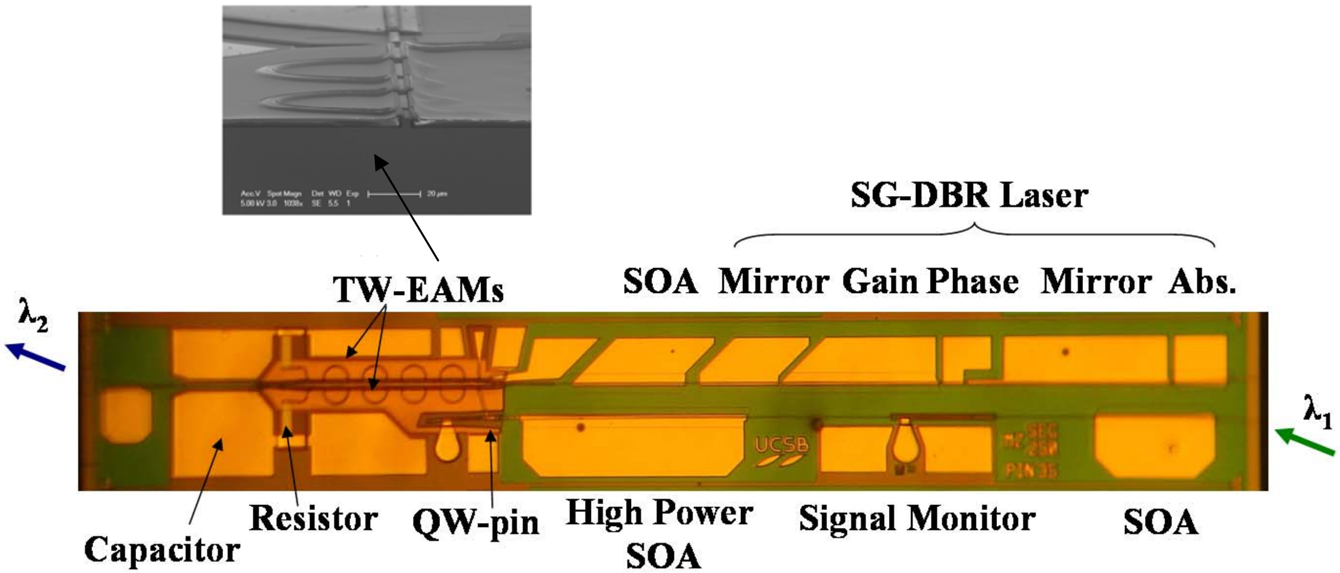


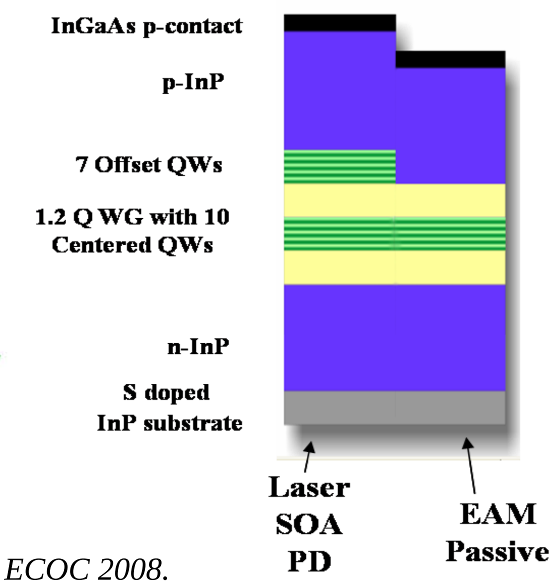
A. Tauke-Pedretti, M.M. Dummer, M.N. Sysak, J.S. Barton, J. Klamkin, J.W. Raring and L.A. Coldren, "Separate Absorption and Modulation Mach-Zender Wavelength Converter," *J. Lightwave Tech.*, **26**, (1), 91-98 (Jan. 2008)

4. SOA-PIN & SGDBR-TW/EAM wavelength converter

- 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
- 40 nm wavelength tuning range





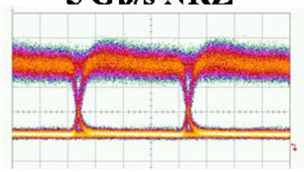


M. Dummer et al. *OFC 2008* OThC6 (2008), and Invited paper, *ECOC 2008.*

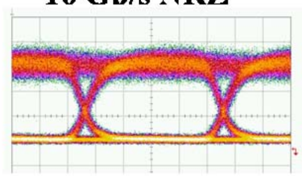
SGDBR/TW-EAM WC RF/DATA Characteristics

Eye Diagrams

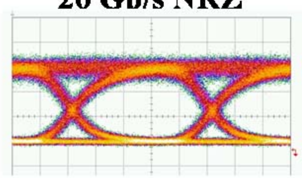
5 Gb/s NRZ



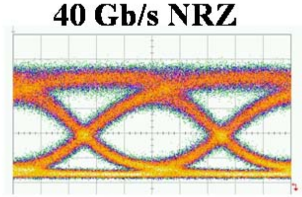
10 Gb/s NRZ



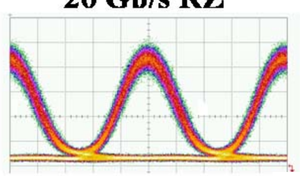
20 Gb/s NRZ



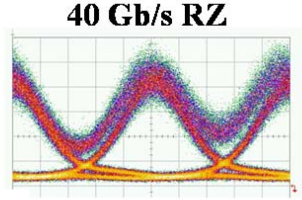
40 Gb/s NRZ

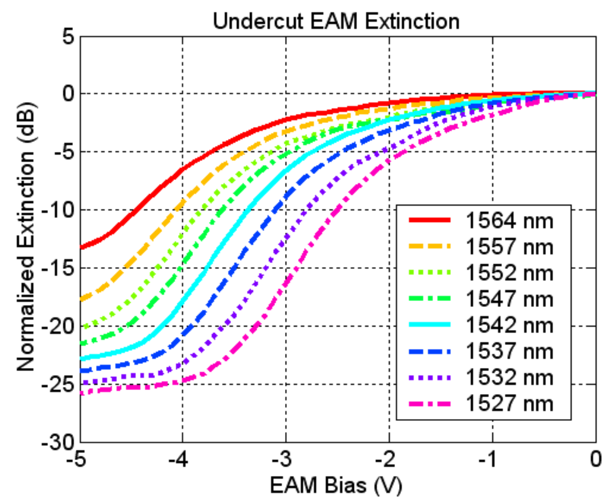


20 Gb/s RZ

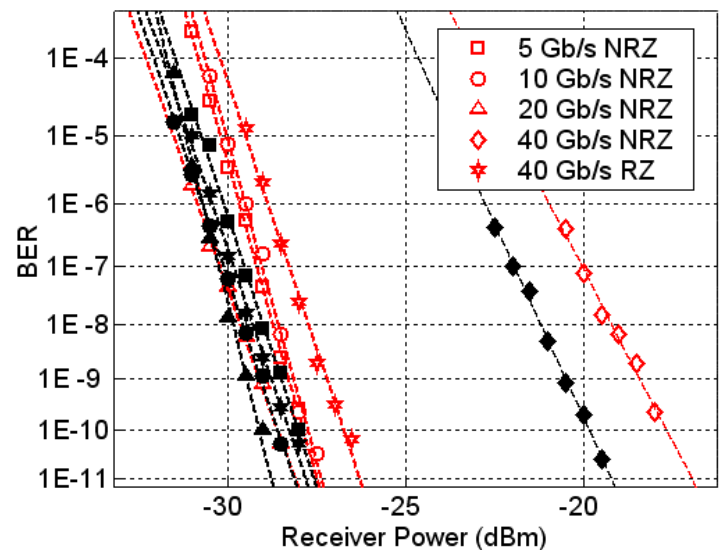


40 Gb/s RZ





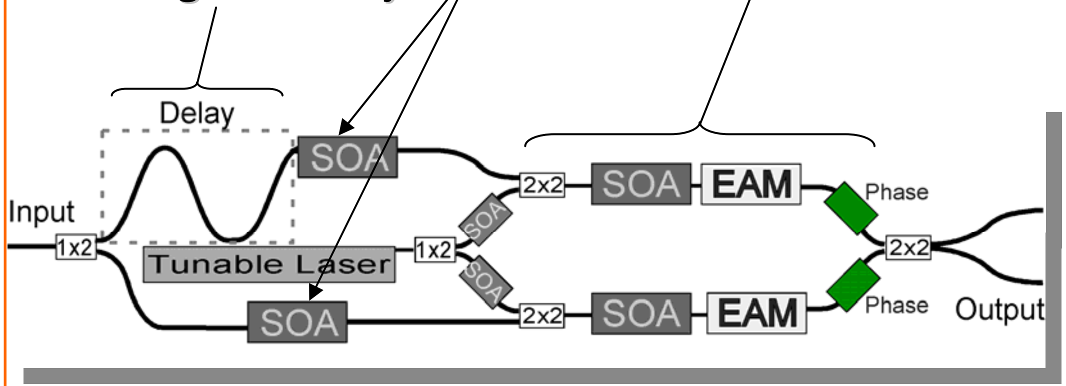
Bit-Error-Rate

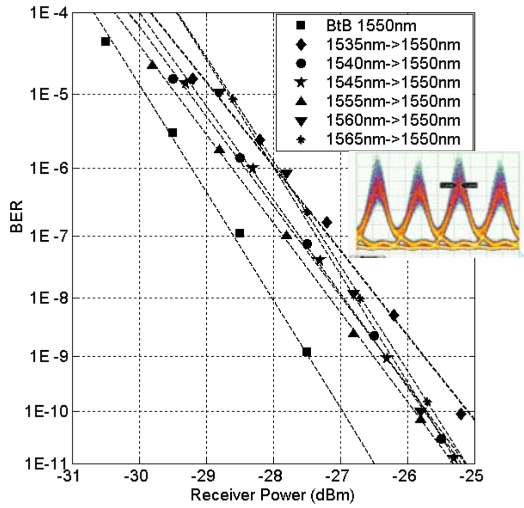


Wavelength converted (1560 to 1548 nm) bit error ratio (open symbols) compared with back-to-back transmission (solid symbols) (1548 nm) for PRBS 2^{31}-1 data at various bit rates

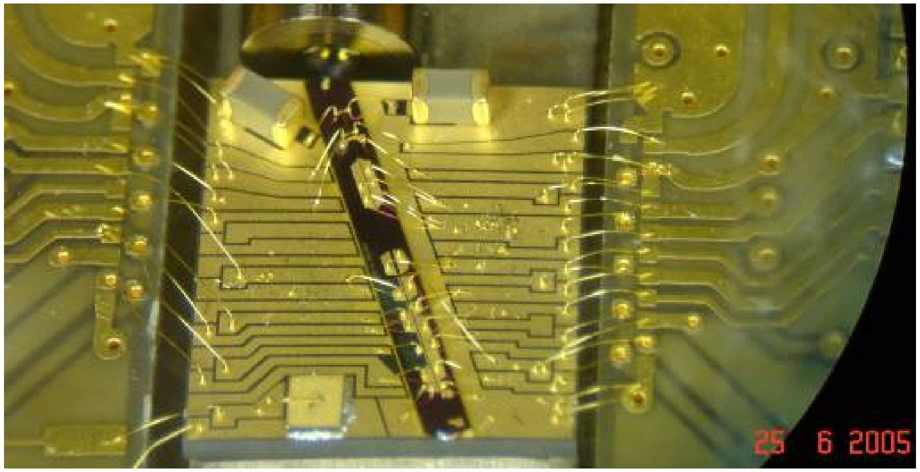
5. SOA-MZI Wavelength Converter PICs: 40 Gb/s Packet Forwarding Chip

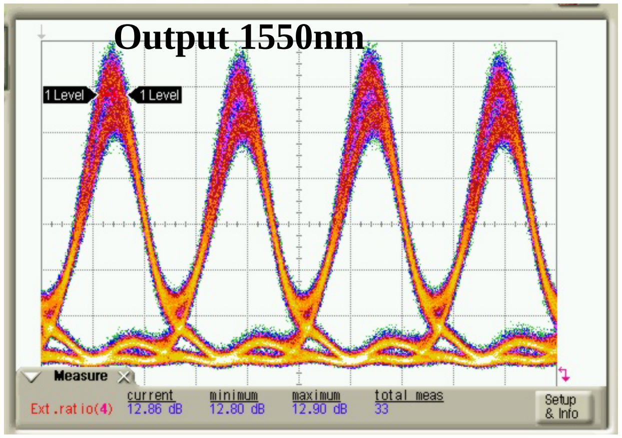
- Fast Tunable SGDBR Laser
- Differential Mach-Zehnder Interferometer SOA Wavelength Converter ('all-optical')
- Preamplifier SOAs
- Integrated delay





OQW & Butt-joint regrowth



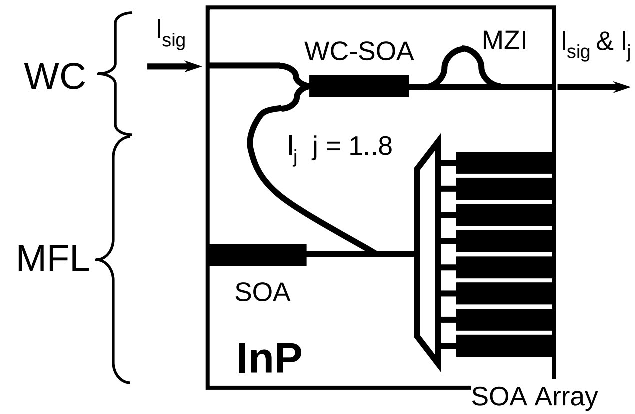


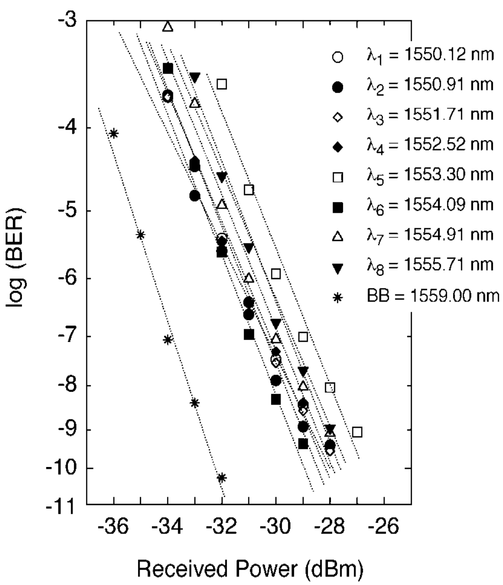
Coldren ECOC Tutorial 092308

V. Lal, M. L. Masanovic, J. A. Summers, G. Fish, and D. J. Blumenthal, "Monolithic Wavelength Converters for High-Speed Packet-Switched Optical Networks," *JSTQE*, **13,** pp. 49-57, 2007.

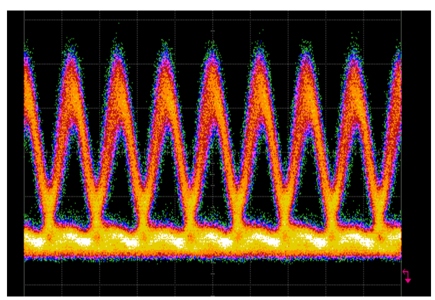
6. Tunable wavelength converter using AWG-laser + SOA + filter

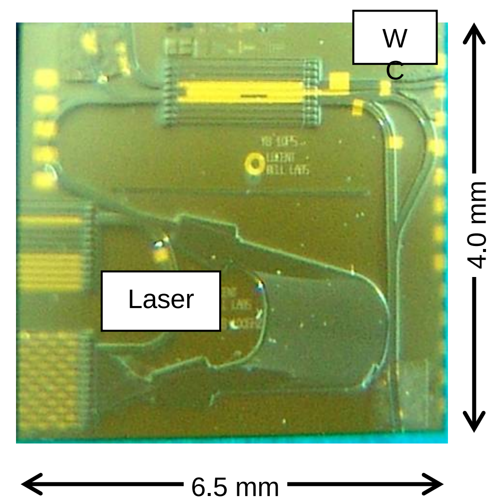
- **Fast-tunable 40G wavelength converter**
  - **8-channel multi-frequency laser (MFL)**
  - **λ-conversion via <u>nonlinear SOA</u> and delay filter**





Converted optical eye diagram at 40 Gb/s





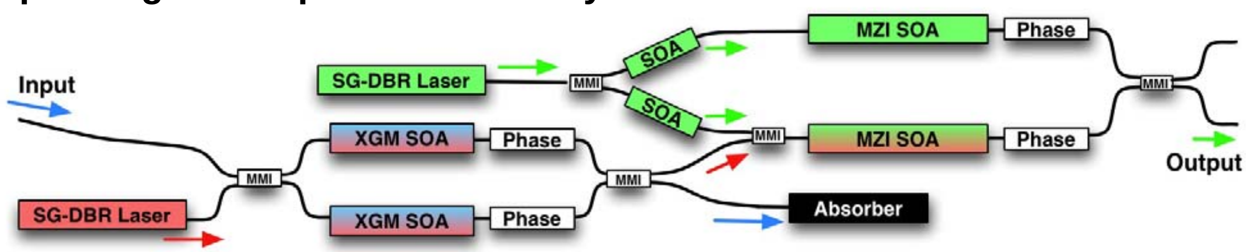
P. Bernasconi, et al., PDP16, *OFC* 2005.

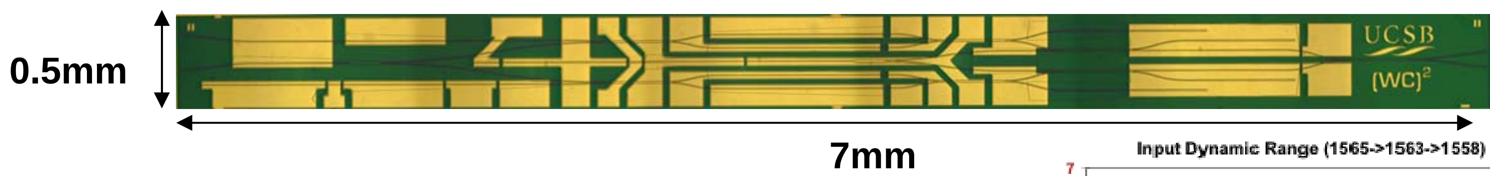
Slide courtesy of P. Bernasconi Alcatel-Lucent—IRIS Project

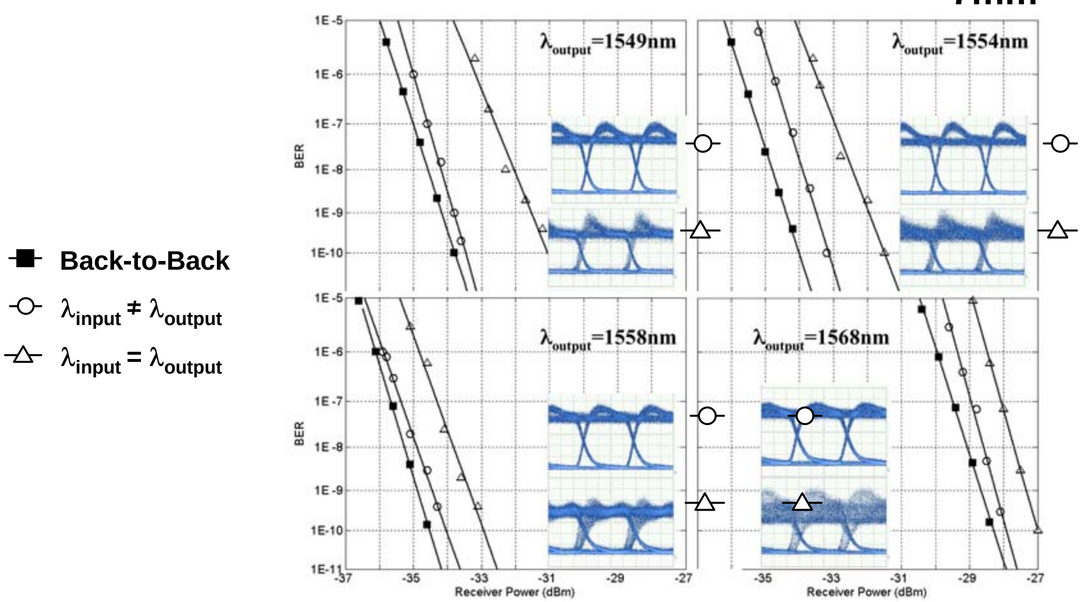
Packet Switching Technology

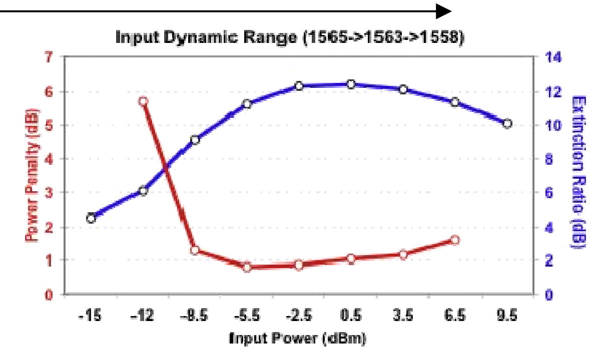
2-Stage Tunable Wavelength Converters

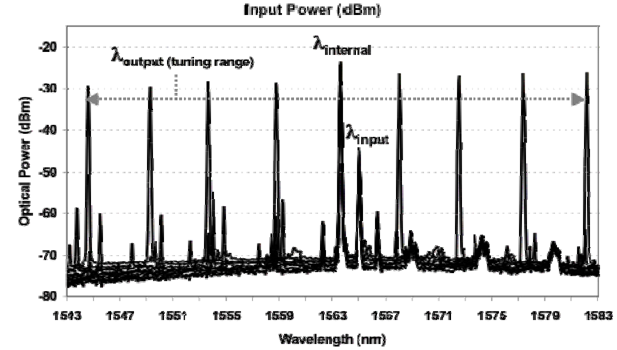
• **First stage generates known out of band wavelength to avoid need for filters and provide known input wavelength to output stage for improved efficiency**





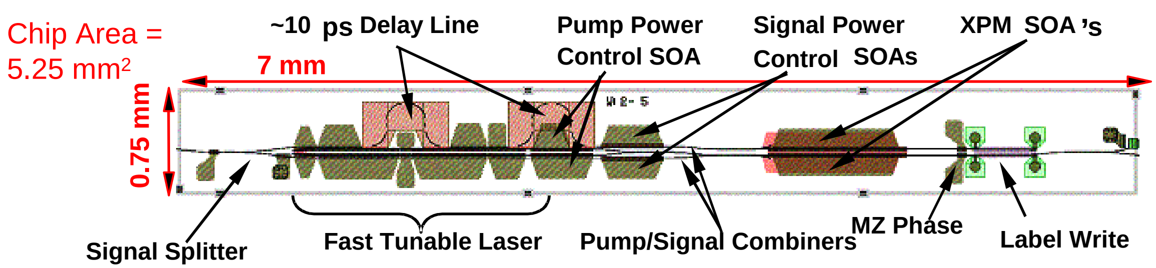


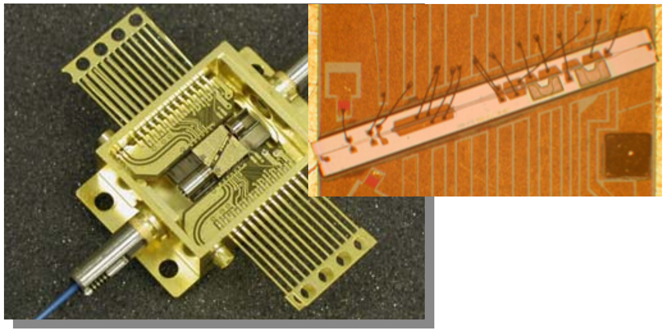




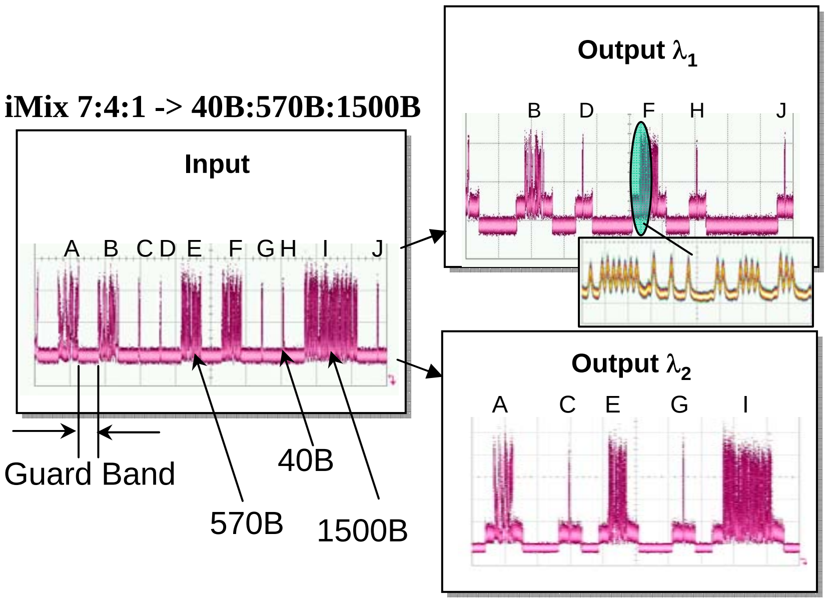
OFC 2007: OThT2: Monolithically Integrated Multi-Stage All-Optical 10Gbps Push-Pull Wavelength Converter, *Joseph A. Summers, Milan L. Masanovic, Vikrant Lal, Daniel J. Blumenthal*

Packet Forwarding Chip (PFC) - Packet λ-Conversion and Optical Label Re-Write

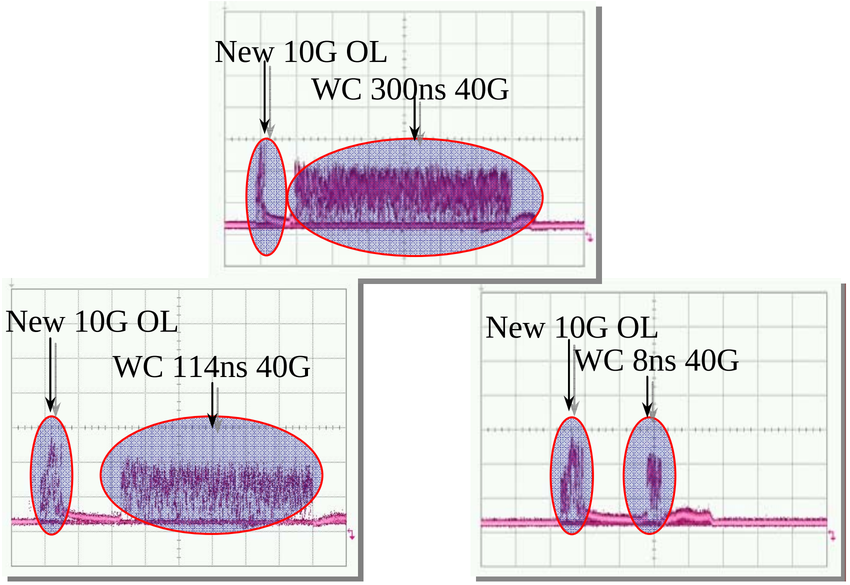




Variable Length Packets and Dynamic Forwarding



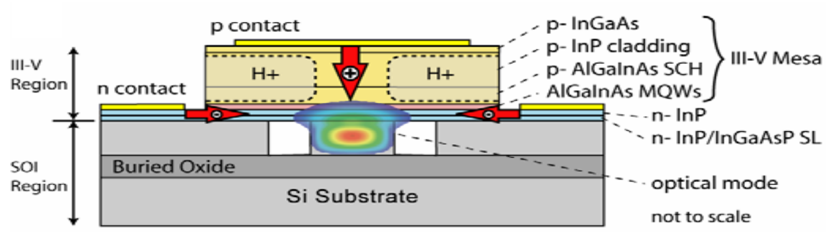
10G Optical Header Re-Write

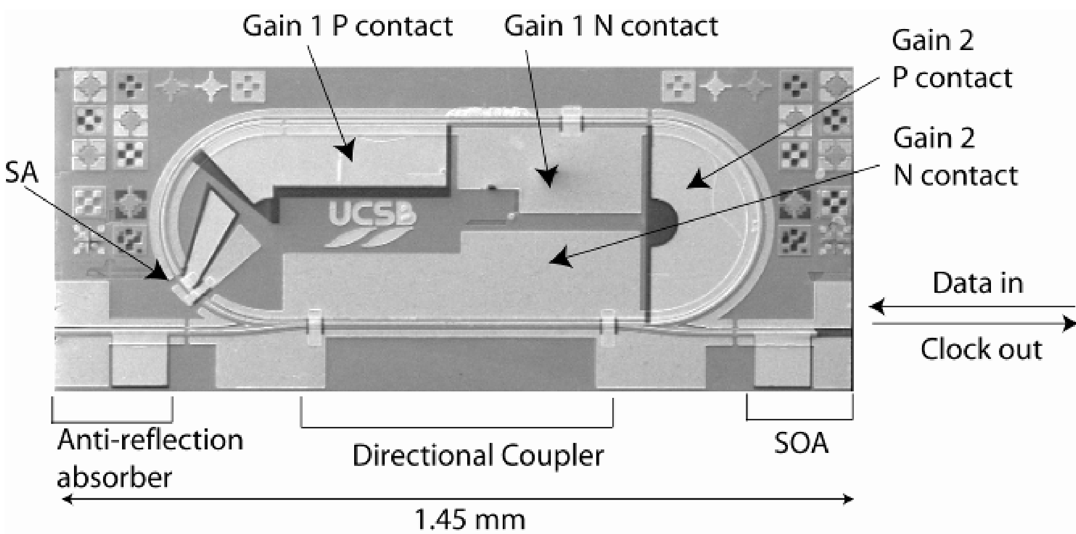


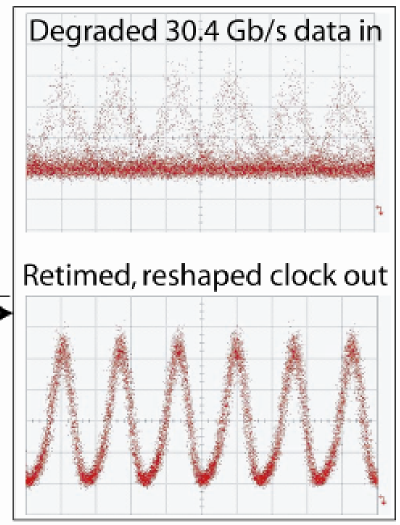
"Monolithic Widely Tunable Optical Packet Forwarding Chip in InP for All-Optical Label Switching with 40 Gbps Payloads and 10 Gbps Labels," V. Lal, M. Mašanović, D. Wolfson, G. Fish, C. Coldren, and D. J. Blumenthal, Postdeadline Paper, ECOC 2005 Glasgow, Scotland.

InP/Silicon Ring MLL and All-Optical Clock Recovery

- Mode locked laser with III-V quantum wells wafer bonded to silicon waveguides
- All-optical clock recovery with significant retiming and reshaping
  - 30 Gb/s 2^{31}-1 PRBS data input, 30 GHz clock output
  - Input wavelength insensitive
  - 14 ps input jitter, 1.7 ps output jitter
  - 4 dB input ER, >10 dB output ER







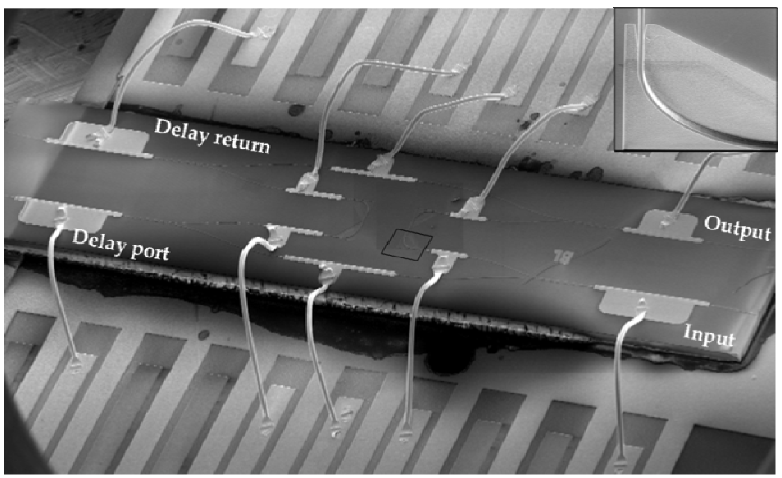
"A Racetrack Mode-Locked Silicon Evanescent Laser," A. Feng, et. al., Optics Express, http://www.opticsexpress.org/abstract.cfm?id=149007

"All-Optical Clock Recovery with Retiming and Reshaping Using a Silicon Evanescent Mode Locked Ring Laser," OFC 2008, Brian R. Koch1, Alexander W. Fang1, Henrik N. Poulsen1, Hyundai Park1, Daniel J. Blumenthal1, John E. Bowers1, Richard Jones2, Mario J. Paniccia2, Oded Cohen3; 1Univ. of California at Santa Barbara, USA, 2Intel Corp., USA, 3Intel Corp., Israel.

Hybrid InP/Si Switch & Photonic Chip Buffer

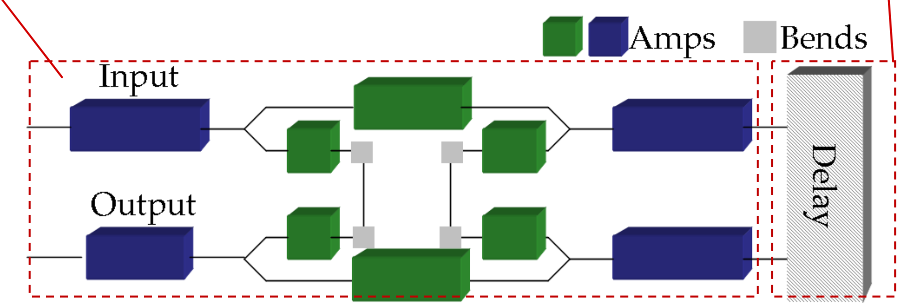
- InP Chip Insertion loss
  - Fiber-to-fiber gain : 2 dB
- Extinction ratio > 38 dB
- Switching time (longest SOA)
  - Rise time < 750 ps
  - Fall time < 1ns

- Silica on silicon chip
  - 0.04 dB/cm loss
  - Butt-coupled to switch
  - 450 cm (23ns)
  - PDL : 1 dB
  - CD : 130ps/nm-km



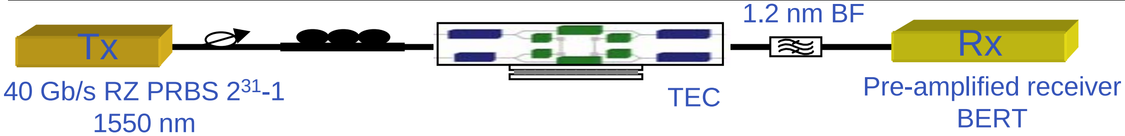
Switch: InP

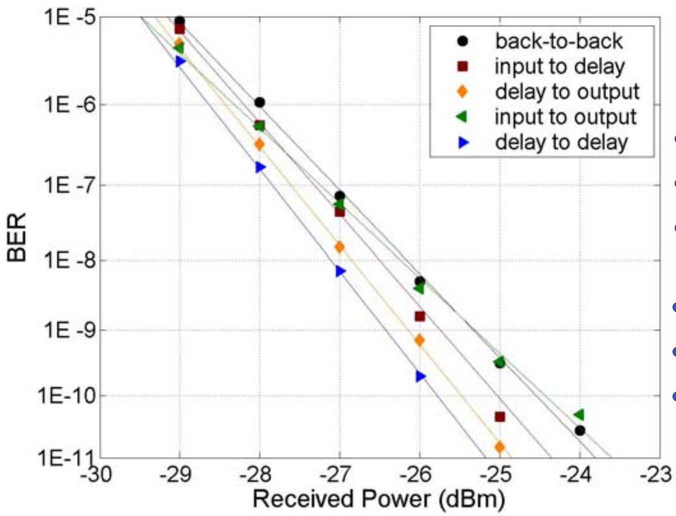
Delay loop: SiO_2



Burmeister, Bowers, PTL 18(1).

40 Gb/s Switch & Buffer Performance

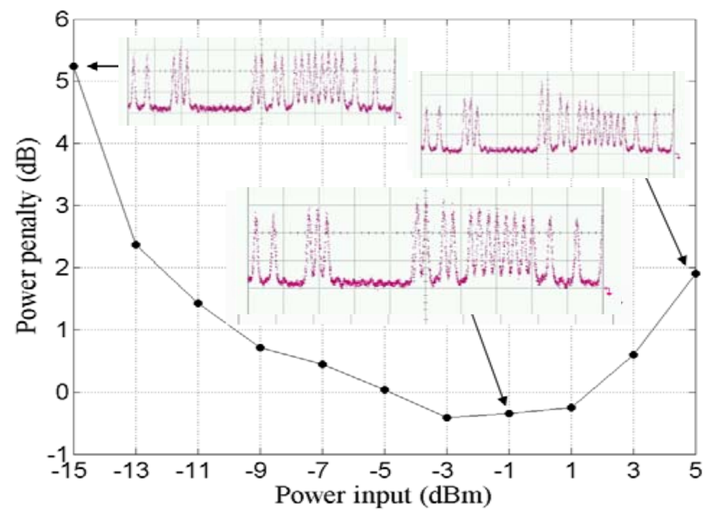


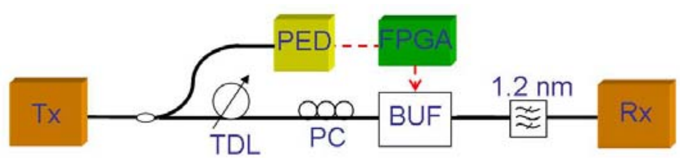


SWITCH

- Negative power penalty
- Gain from the amplifiers
- ASE reduced by filter

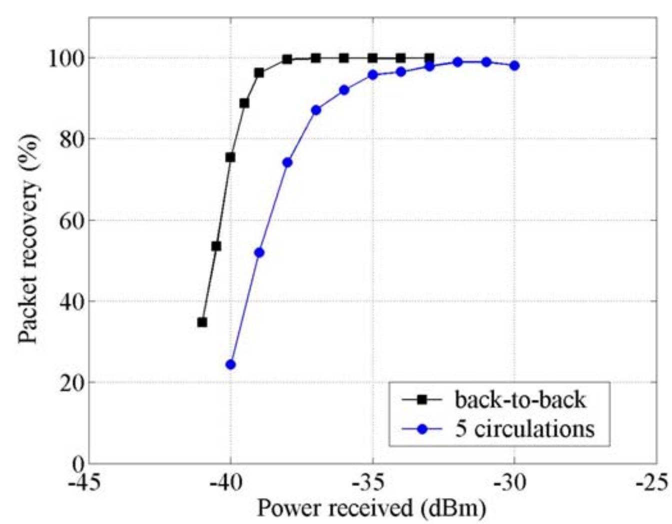
- Power penalty at 1e-9 BER
- Dynamic range : 15dB
- With <2 dB power penalty





- Packets contain 64 bit identifier strings
- 5 circulations, or 64 ns of delay with 98% packet recovery
- More circulations possible with less loop loss, lower noise figure

BUFFER



Burmeister et al. Optics Express (2008).

Conclusions

- **Multi-functionality InP-based Photonic ICs can now be made with state-of-the-art performance and reductions in power dissipation, size, and <u>perhaps</u> cost in sufficient numbers.**

- **Multi-channel WDM transmitters, receivers, and wavelength converters demonstrated**

- **Many future PICs now on the 'drawing board'**