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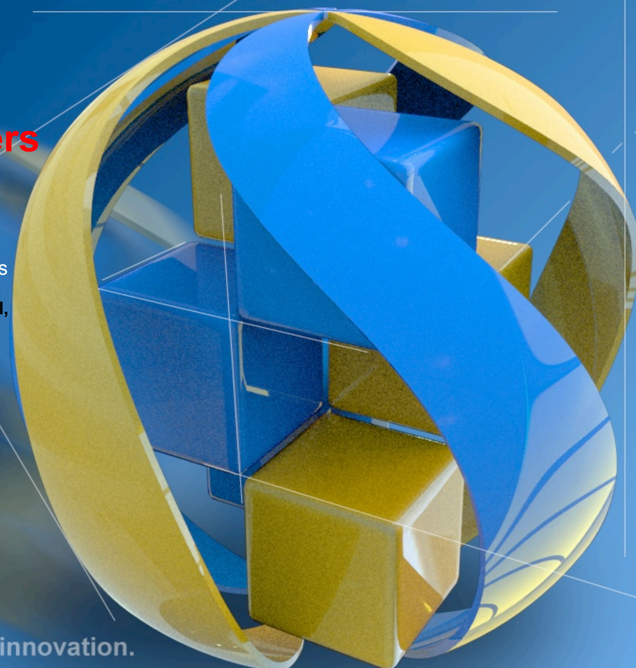
engineering

ECOC
September 18, 2012

Single-Chip Integrated Transmitters and Receivers



Larry A. Coldren
Fred Kavli Professor of Optoelectronics and Sensors

L. Johansson, M. Lu, A. Sivananthan, and M. Rodwell,
ECE and Materials Departments
College of Engineering
UCSB

Acknowledgements
Funding from: DARPA, Rockwell-Collins, JDSU
Content contributions from : T. Koch, P. Winzer, F. Kish

The convergence of research and innovation.

Introduction and Overview

- Why integration?
- Photonic IC technology—focus on InP
- Early development of PICs—serial and parallel approaches
- Coherent and WDM drove needs--tunable transmitters and receivers, or transmitter and receiver arrays resulted
- After focus on WDM due to EDFA, coherent has returned for more spectral efficiency
- Heterodyne vs. Intradyne—optical phase locked loops (OPLLs) for energy efficiency in sensors and communication
- What about Active Si-Photonics

Why Integration

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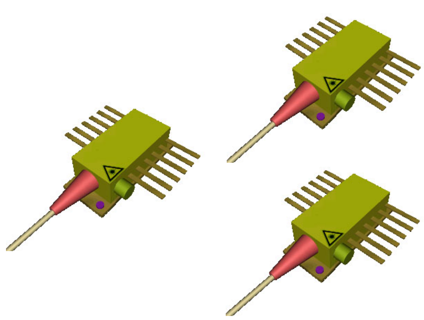
Motivation for Photonic Integration

- Reduced size, weight, power
- Improved performance (coupling losses, stability, etc.)
- Improved reliability (fewer pigtails, TECs…)
- Cost

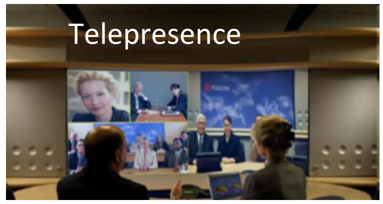


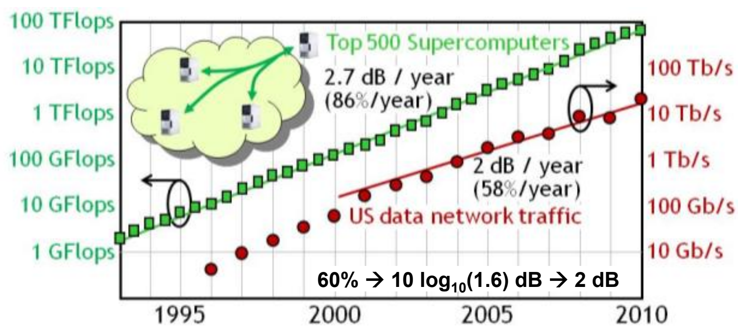
Horizontal and vertical integration possible
- multiple functionality and arrays of chips in one

Network traffic, Data Center and Supercomputer connections are growing exponentially

You Tube

facebook





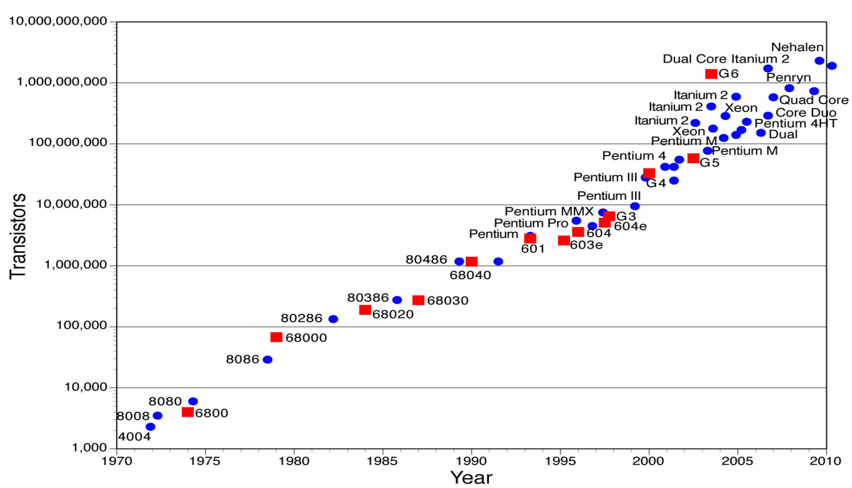
Exponential network traffic growth is driven by high-bandwidth digital applications

Video-on-demand, telepresence, wireless backhaul, cloud computing & services

Courtesy P. Winzer

Similar to Moore's Law for Electronics

- *A full-featured cell phone with discrete electronics would be unreliable, the size of a large building, and unimaginably expensive to assemble, test, and power.*
- *We are now beginning to make similar statements about photonic ICs and the systems they enable*



courtesy of T. Koch

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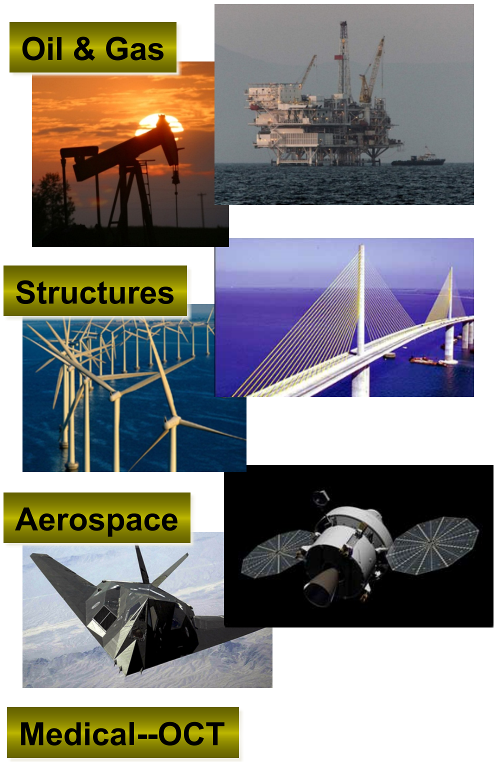
New Applications include structural & industrial sensors



Bragg gratings:

- Temperature
- Pressure
- Displacement / Strain
- Damage/Delamination

Coherent Fiber Sensing

- Distributed Acoustics
- Vibration
- Flow
- Intrusion
- Perimeter Monitoring

New lasers, such as all-semiconductor very high-speed swept lasers (>kHz rates), are enabling new methodologies

(photo courtesy of Insight Photonic Solutions)

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Integration Platforms

Indium Phosphide
- Excellent active components
- Mature technology
- Complexity/propagation losses for passive elements

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

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

Hybrid Solutions

Silicon Photonics
- Interconnects
- Integration with electronics
- Constantly improving performance
- No laser

Focus on InP for Actives

- Most mature and widely used
- Driven by communication and sensor applications
- Examples
  - Widely tunable laser (SGDBR)
  - Externally modulated laser (EML)
    - EAM based
    - MZI based
  - Preamplified receiver
  - Transmitter/Receiver Arrays
  - Coherent (vector) transmitters and receivers
  - Wavelength converters

PIC Technology

Focus on InP for Actives

- Most mature and widely used
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  - Widely tunable laser (SGDBR)
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Early Active PICs

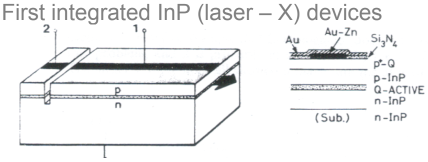
Partially transmissive mirrors and active-passive integration needed

→ 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).

First integrated InP (laser – X) devices



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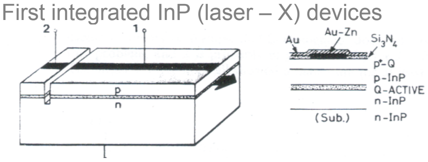
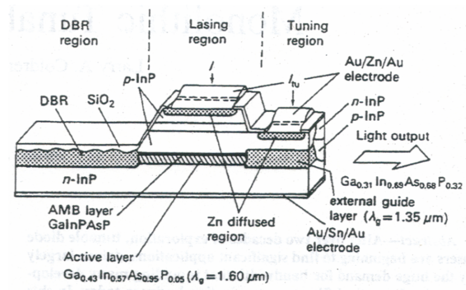


→ DBR gratings and vertical couplers

- 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).



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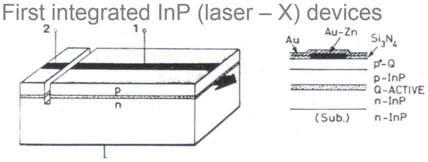

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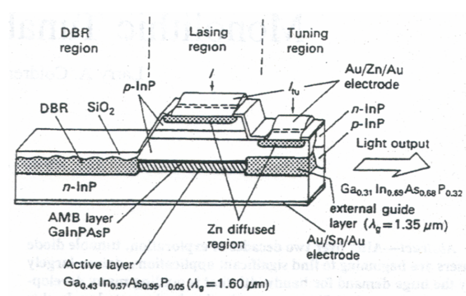
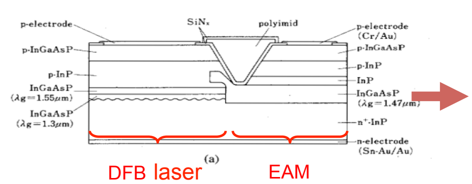


→**EML =** electroabsorption-modulated laser

- Still in production today

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



Coherent Communication Motivated Photonic Integration

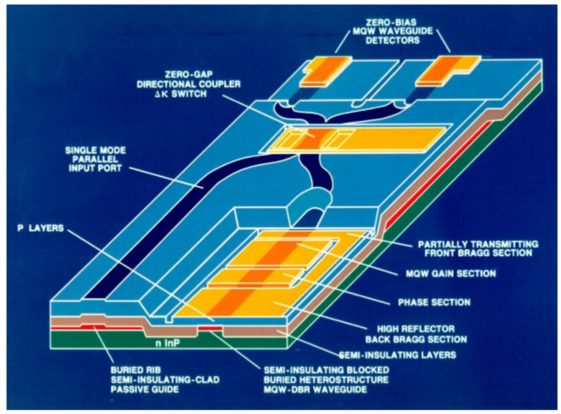
- In the 1980's coherent communication was widely investigated to increase receiver sensitivity and repeater spacing. It was also seen as a means of expanding WDM approaches because optical filters would not be so critical.

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

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

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

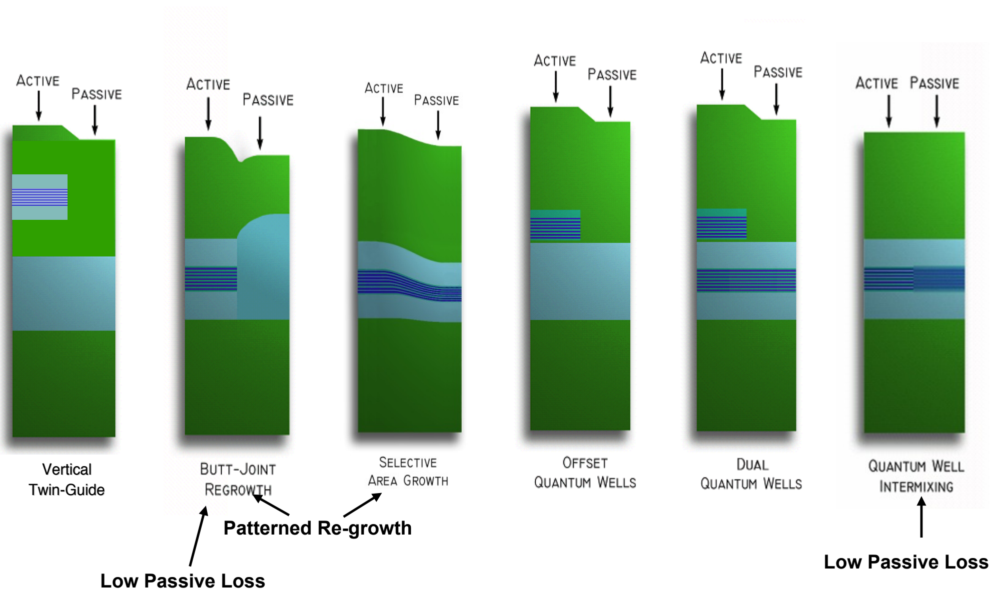
Integrated Coherent Receiver
(Koch, et al)



- The EDFA enabled simple WDM repeaters (just amplifiers) and coherent was put on the shelf

PIC Enablers: Active-Passive Integration

Desire lossless, reflectionless transitions between sections



3 Bandgaps usually desired
Need simple, high-yield process

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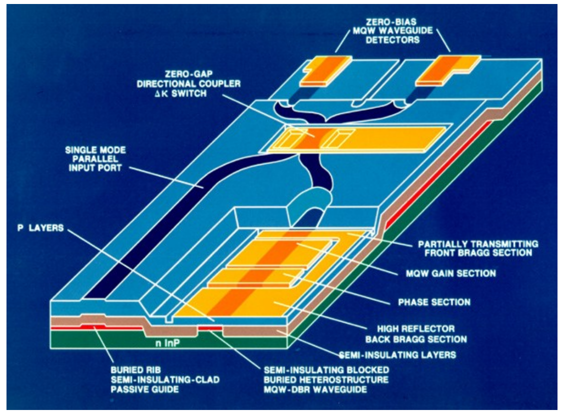

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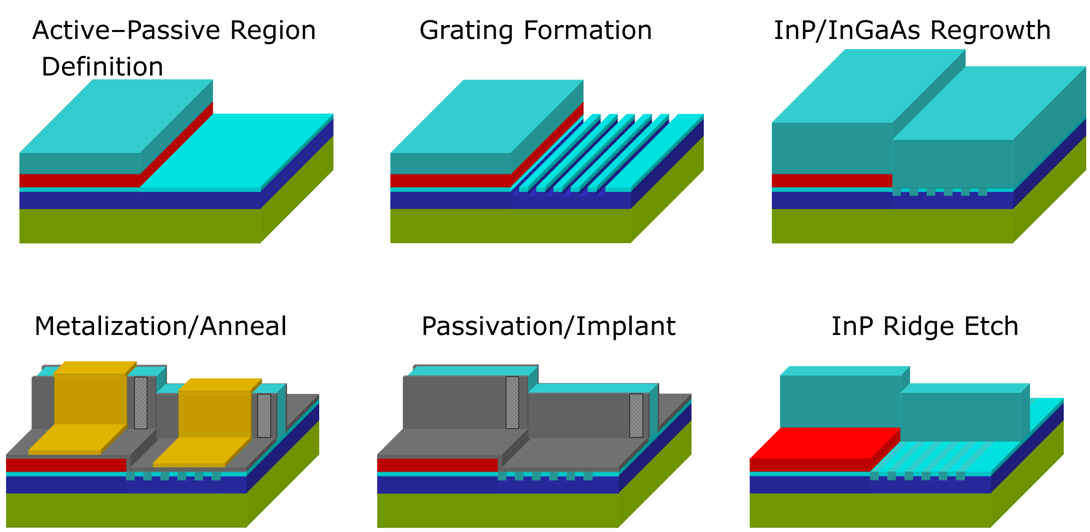
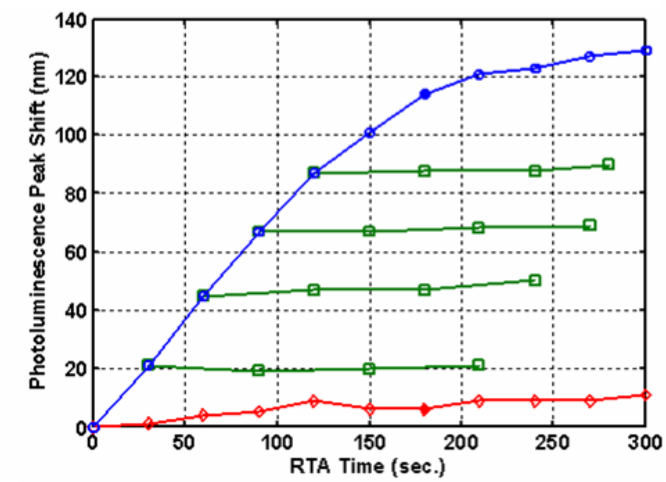
Offset Quantum Well Process

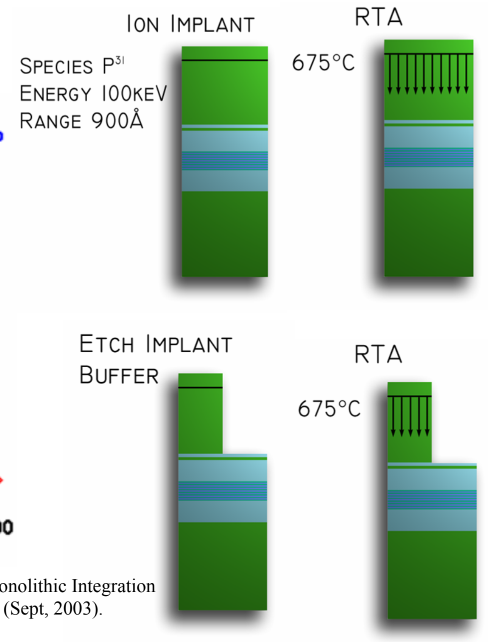


•Most Mature SGDBR Fabrication Technology
•Requires Single 'Planar' MOCVD Regrowth

QWI For Multiple-Band Edges

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

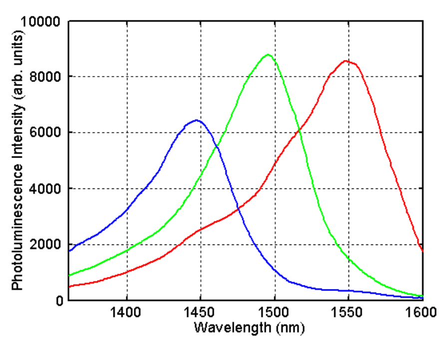


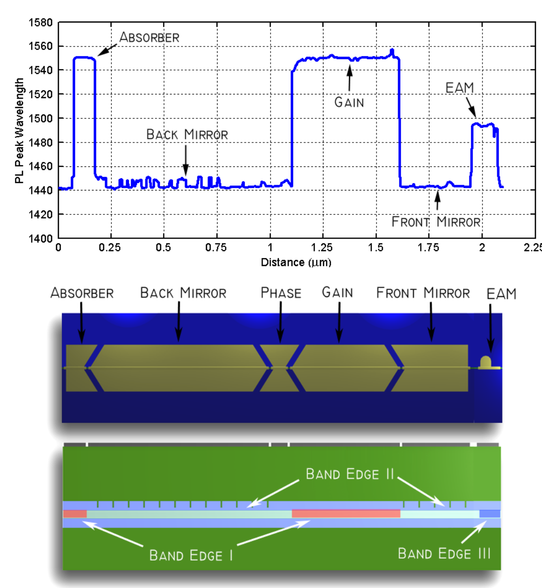


E. Skogen et al, "Post-Growth Control of the Quantum-Well Band Edge for the Monolithic Integration of Widely-Tunable Lasers and Electroabsorption Modulators," *JSTQE,* **9** (5) pp 1-8 (Sept, 2003).

QWI-Tunable-Laser with Integrated EA-Modulator

- Optimized band edges for various devices
- Three band edges across wafer
- Widely-tunable SGDBR laser/EAM

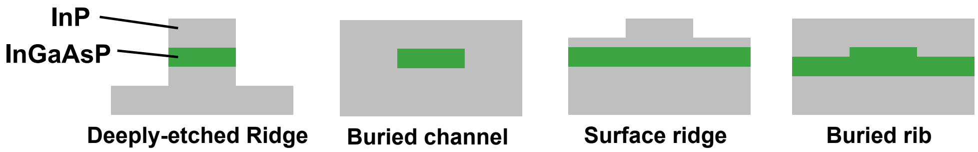




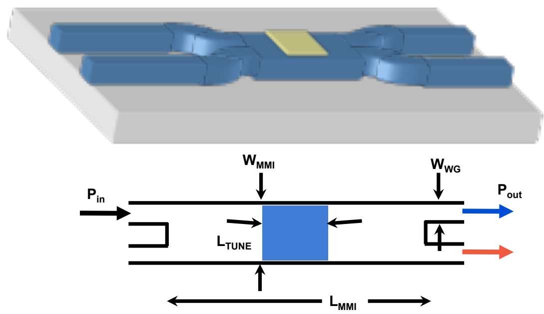
Raring, Skogen, Coldren, et al

Lateral waveguides/couplers

Waveguide cross sections

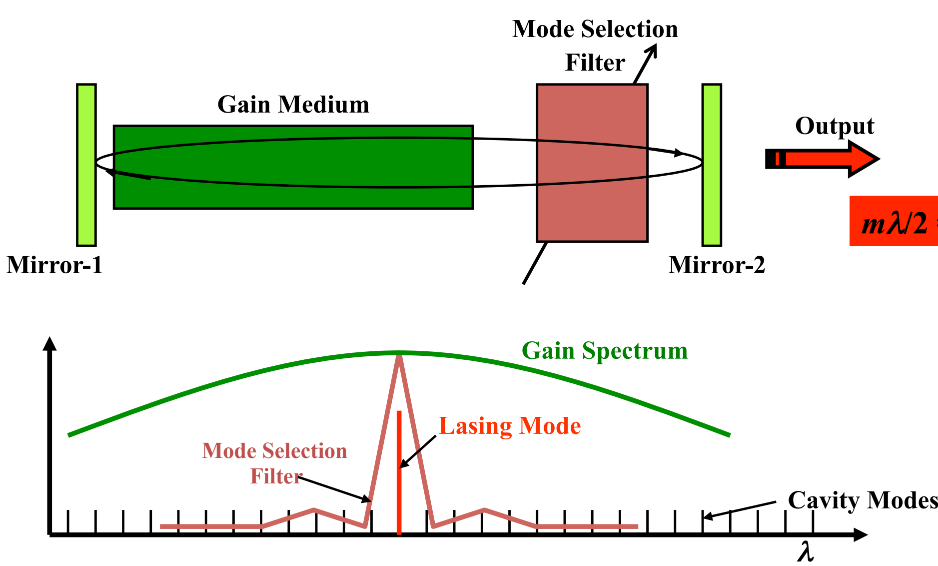


MMI coupler



Desire for Practical Tunable Lasers Motivates Integration

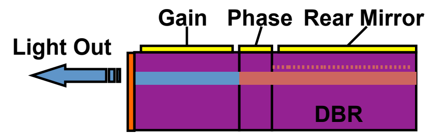
- Both WDM and coherent communication systems desired tunable lasers
- Sensor systems also needed tunable sources
- Mechanically-tuned 'External-cavity' tunable lasers exist, but they tend to be costly, bulky, tune slowly, and are subject to vibration



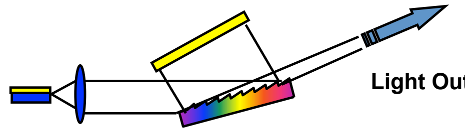
$$m\lambda/2 = \bar{n}L$$

Solutions for Tunable Lasers

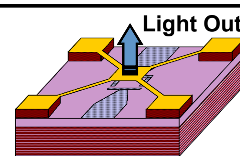
- DBR Lasers
  - Conventional DBR (<8 nm)
  - Extended Tuning DBR's (≥ 32 nm)



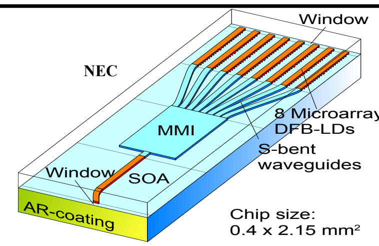
- External Cavity Lasers (≥ 32 nm)
  - Littman-Metcalf/MEMs
  - Thermally tuned etalon



- MEMS Tunable VCSEL (< 32 nm)
  - Optically or electrically pumped



- DFB Array (3-4 nm X #DFBs)
  - On-chip combiner + SOA
  - Or, off-chip MEMs combiner
  - Thermally tuned



Widely-Tunable-X PICs
(Mostly serial integration)

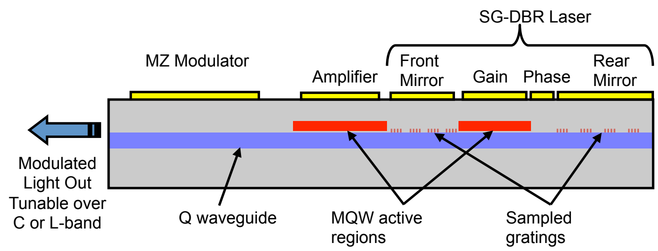
Sampled-Grating DBR: Monolithic and Integrable

SGDBR+X widely-tunable transmitter:

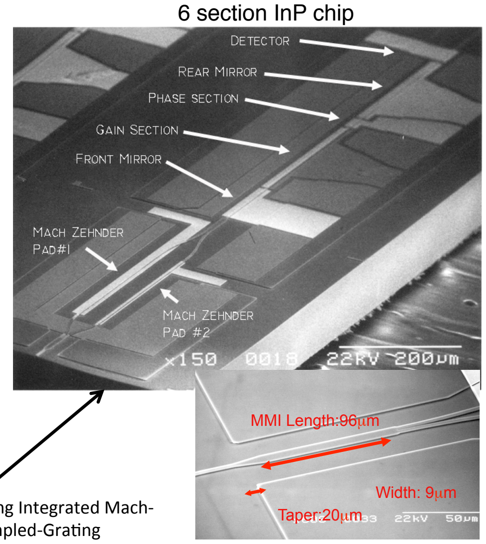
- Foundation of PIC work at UCSB

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

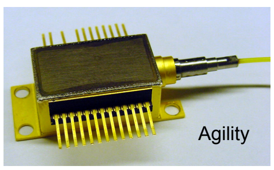
"Multi-Section Tunable Laser with Differing Multi-Element Mirrors," US Patent # 4,896,325 (January 1990)



6 section InP chip



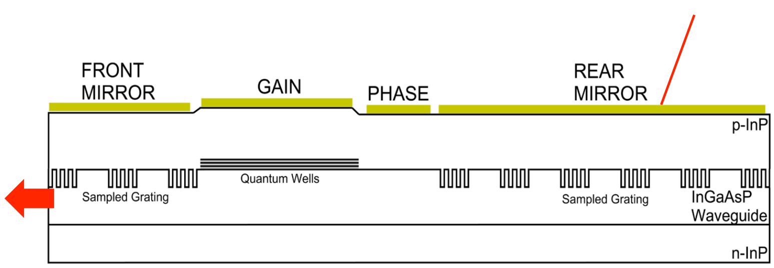
- Vernier tuning over 40+nm near 1550nm
- SOA external to cavity provides power control
- Currently used in many new DWDM systems (variations)
- Integration technology for much more complex PICs



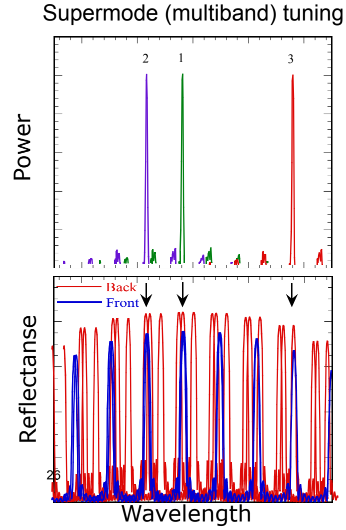
J. S. Barton, et al, "Tailorable Chirp using Integrated Mach-Zehnder Modulators with Tunable Sampled-Grating Distributed Bragg Reflector Lasers," *ISLC,* TuB3, Garmish, (Sept, 2002)

Sampled-Grating DBR Laser

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



Supermode (multiband) tuning



JDSU Roadmap Enabled by InP Monolithic Integration

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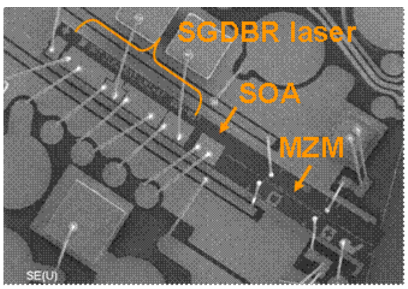
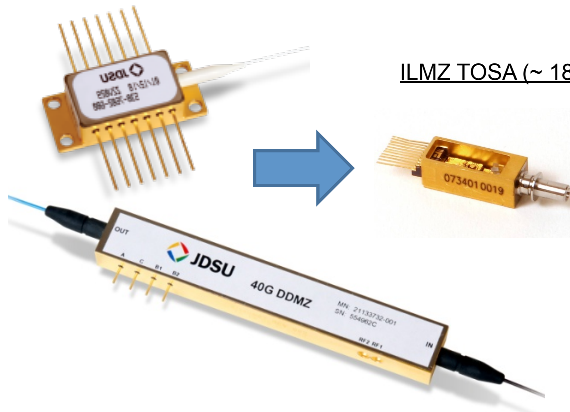
- Volume deployment typically needs form factors optimized for port count, size, power dissipation and cost
  - Transceiver module form factors are MSA driven and ecosystem is more mature
  - Photonic integration is essential to achieve cost, power and size roadmap
  - ILMZ is a good example of photonic integration

ILMZ chip (~ 4mm)



ILMZ TOSA (~ 18mm)



SGDBR-SOA-modulator transmitters @ 40 Gb/s

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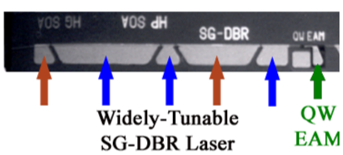
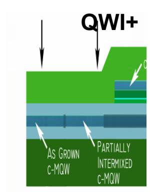
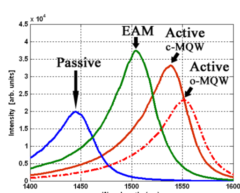
Research initiatives:

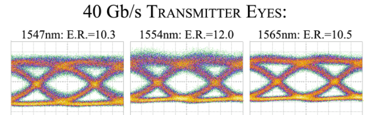
1. QWI/EAM :







40 Gb/s Transmitter Eyes:

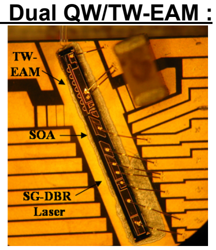


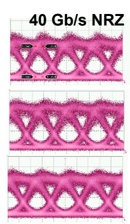
f_{3dB}=32 GHz/175μm—20dB/V (1536-1560nm)

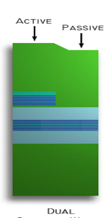
V_{pp} = 2.5V

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

2. Dual QW/TW-EAM :







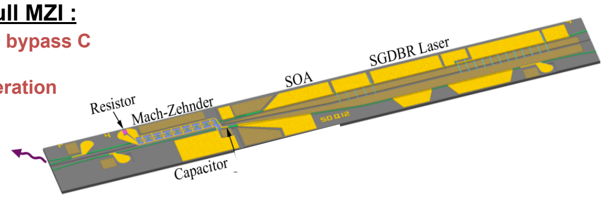
LASOR

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

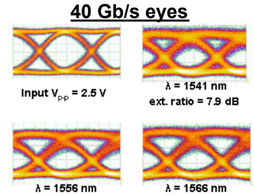
M. M. Dummer, et al, *OFC'08*, San Diego, Mar, 2008.

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).

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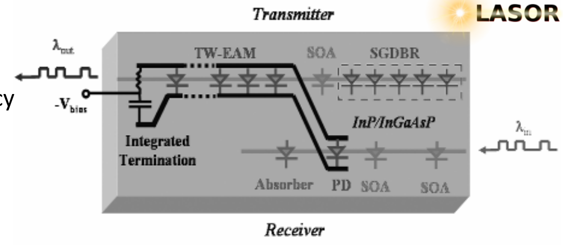
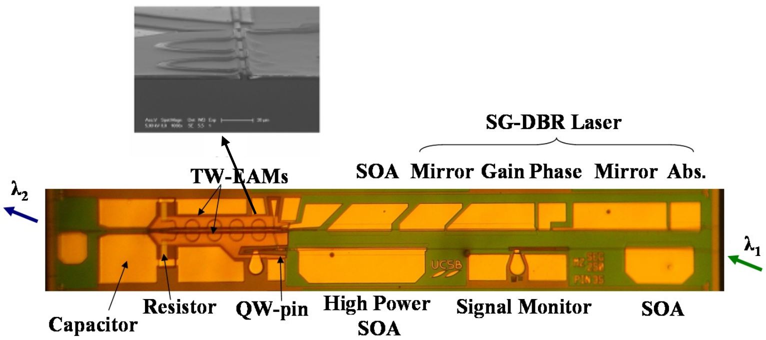
Evolution of InP Integration technology enables more functionality —Tranceivers/wavelength converters

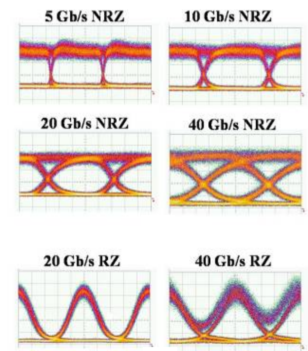
Research initiatives: High-efficiency SOA-PIN Receiver & SGDBR-TW/EAM Transmitter

LASOR

- Data format and rate transparent 5-40Gb/s
- No filters required (same λ in and out possible)
- Two-stage SOA pre-amp for high sensitivity & efficiency
- 2R regeneration possible
- Traveling-wave EAM with on chip loads; ~ 0 dB out/in optical insertion loss
- Only DC biases applied to chip—photocurrent directly drives EAM → 1W/40 Gb/s → 25 pJ/bit
- 40 nm wavelength tuning range







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

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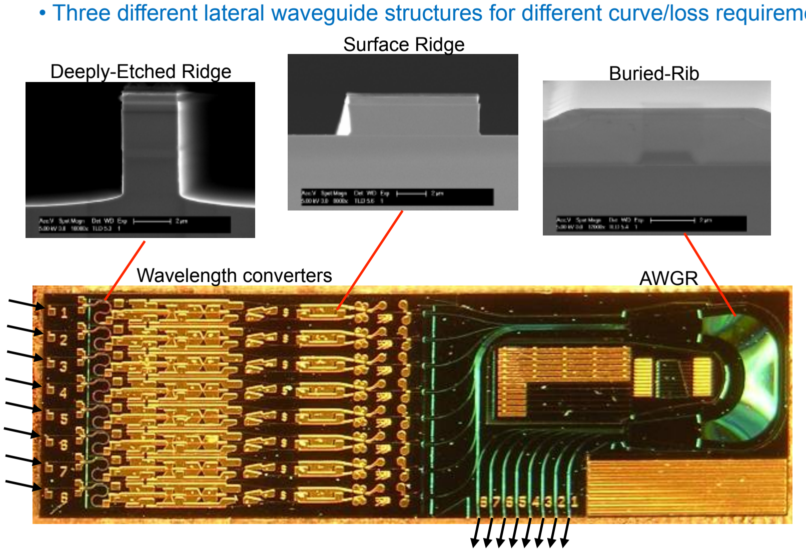
More functionality: 8 x 8 MOTOR Chip

Research initiatives:

(40 Gb/s per channel)

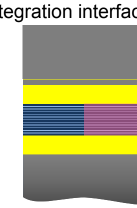
LASOR

- 8 x 8 'all-optical' crossbar switch
- 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



Monolithic Tunable Optical Router

QWI for active-passive integration interfaces

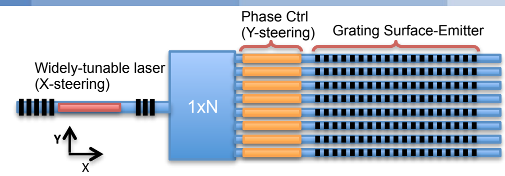


See S. Nicholes, et al, "Novel application of quantum-well intermixing implant buffer layer to enable high-density photonic integrated circuits in InP," *IPRM '09*, paper WB1.2, Newport Beach (May, 2009)

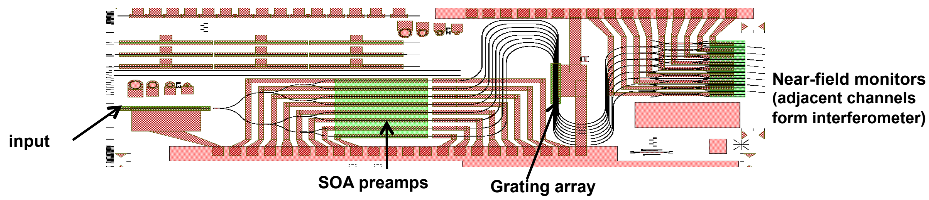
Free-space 2-D Beam Sweeper

Research initiatives:

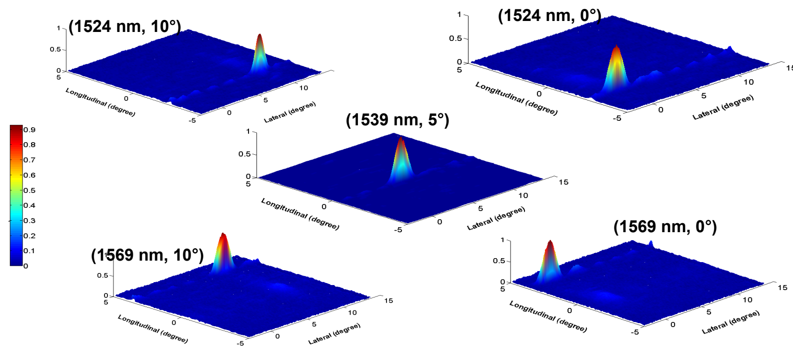
Concept: Wavelength sweeps beam in x-direction; 1-D phased array sweeps beam in y-direction



PIC layout:



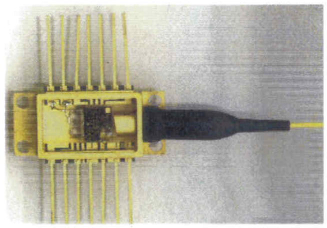
2-D beam sweeping results:
10° x 10°

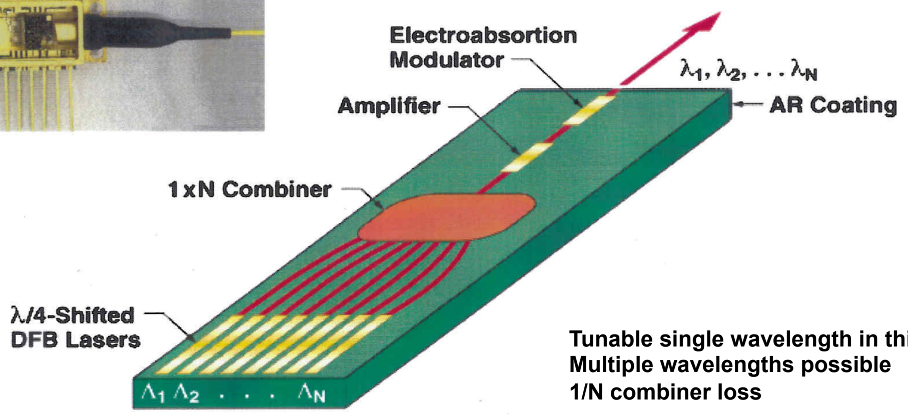


Integrated Multi-Channel PICs

(Mostly parallel integration)

Early Wavelength-selectable Laser PIC and EAM





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.

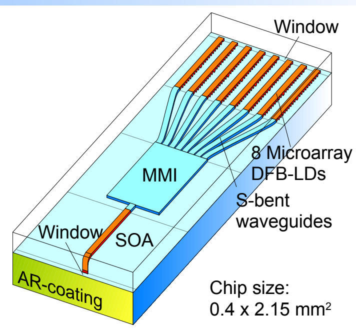
Wavelength-selectable light sources (WSLs)

Feature

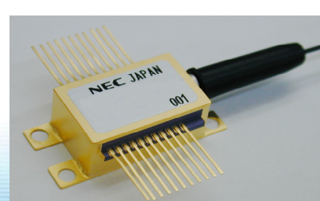
- *DFB-LD-array-based structure*
- *Wide-band tunability*
- *Compact & stable*
  Multi-λ locker module

Performance

- *WSLs for S-, C-, L- bands (OFC'02)*
  8 array, Δλ ~ 16 nm (ΔT = 25K) x 6 devices
- *Multi λ-locker integrated*
  Wide-band WSL module (OFC'02)
  Δλ ~ 40 nm (ΔT = 45K)



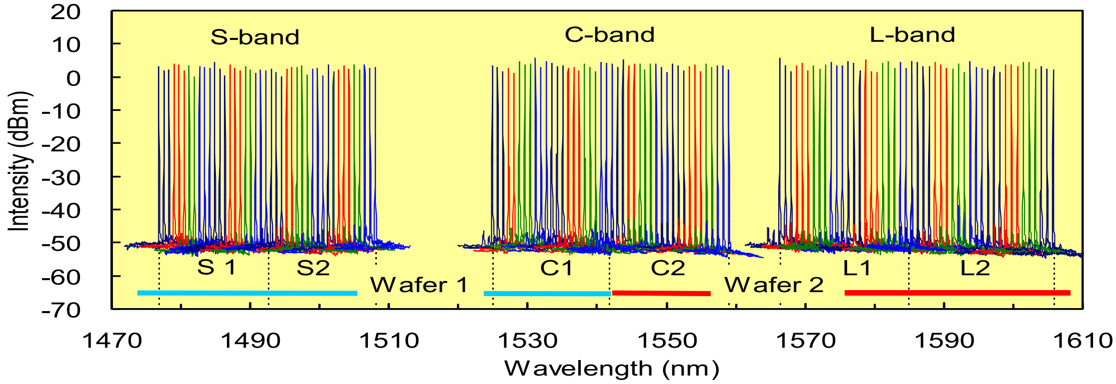
Schematic of wide-band WSL



Multi λ-locker integrated Wide-band WSL module

Empowered by Innovation NEC

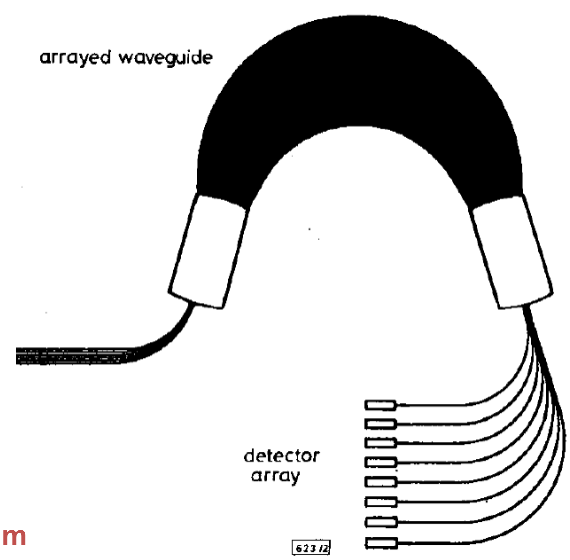
WSLs for S-, C-, L- bands applications



- $\Delta\lambda$ ~ 16 nm (ΔT 25K) @15 - 40 ℃
- 6 devices → 135 channels @100-GHz ITU-T grid
- SMSR > 42 dB
- P_f > ~ 10 mW @ I_{DFB}= 100 mA, I_{SOA}= 200 mA

Early PIC multi-wavelength receiver

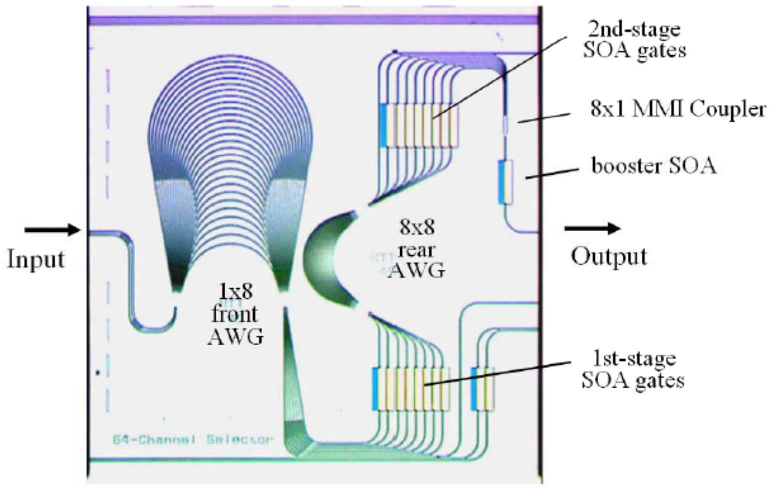
Wavelength Demultiplexer + Detectors



8 × 2 nm

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

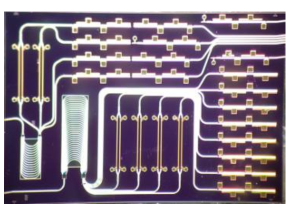
1/64 WDM Channel Selector



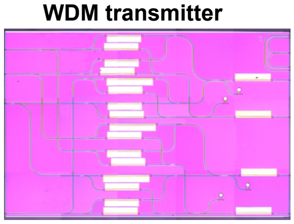
(chip size : 7.0 x 7.0 mm²)

Kikuchi (NTT), EL, Volume 39, Issue 3, p.312–314 , 2003

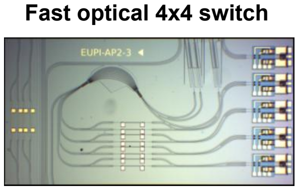
ASPICs made in the first EuroPIC MPW runs



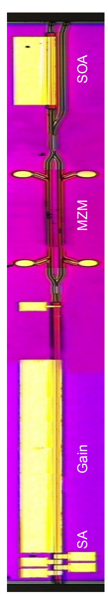
WDM transmitter



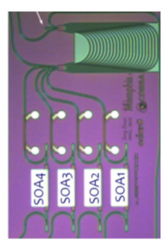
Fast optical 4x4 switch



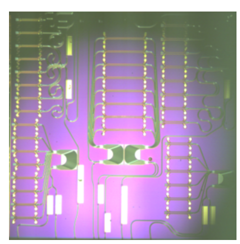
FBG readout chip



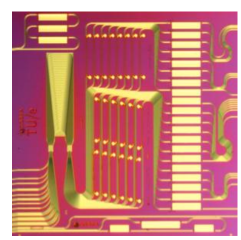
Pulse laser with variable rep rate



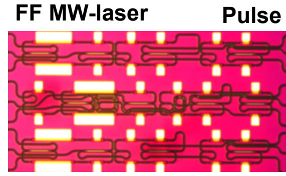
FF MW-laser



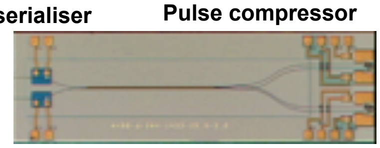
Pulse serialiser



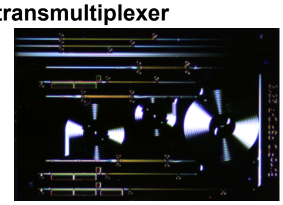
Pulse compressor



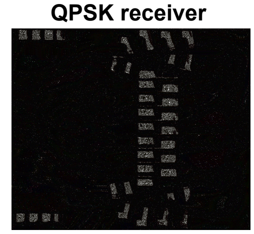
WDM-TDM transmultiplexer



QPSK receiver



60 GHz RoF transmitter



WDM crossconnect

courtesy of M. Smit

Widely Deployed Commercial “WDM” PICs

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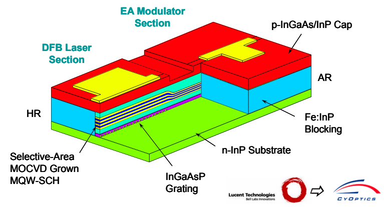
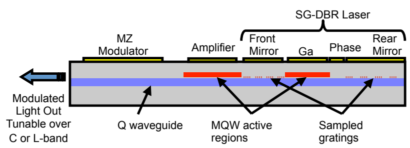
EML’s:

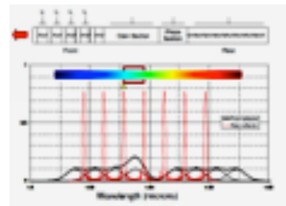


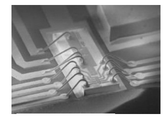
into XFP transceivers, etc.

Tunables & Selectable Arrays:

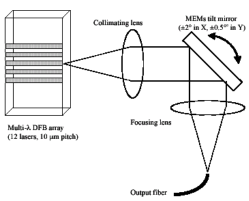


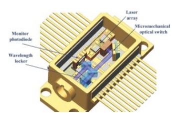
UCSB ⇨ AGILITY ⇨ JDSU



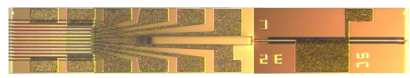


Bookham ⇨ oclaro

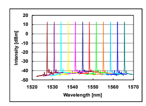




Santur



1 x 12 DFB S-Bent MMI SOA



FURUKAWA ELECTRIC

courtesy of T. Koch

Commercialization of WDM PICs: 2nd Gen. PICs

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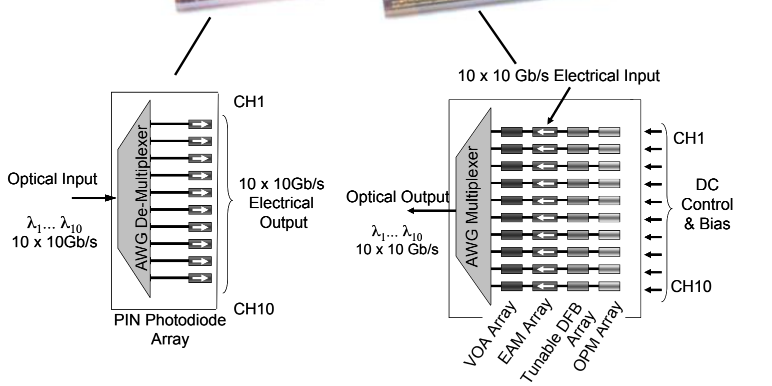
The convergence of research and innovation.

Large-Scale DWDM Photonic Integrated Circuits



infinera

courtesy of C. Joyner

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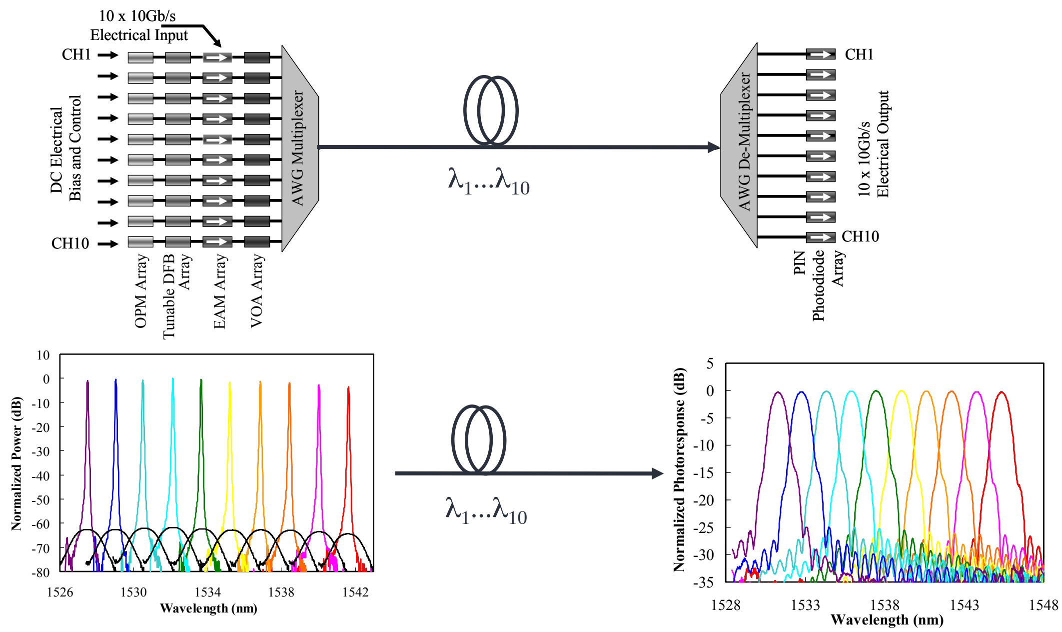
The convergence of research and innovation.

2004: First Commercial Large-Scale InP PICs

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



infinera

courtesy of F. Kish

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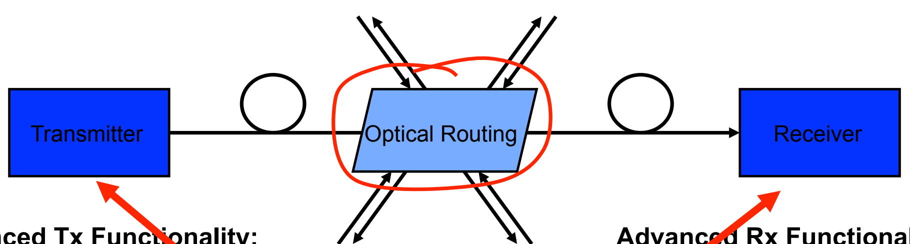
The convergence of research and innovation.

What is the 3rd Generation of InP PICs??

– what are the critical "stable configurations"



Advanced Tx Functionality:

1ST Generation:

- *Modulation*
- *Tunability*
- *Multi-λ WDM*

Advanced Rx Functionality:

1st Generation:

- *Multi-λ WDM*

COHERENT …

Optical Network Routing Functionality:

1st Generation

- *Reconfigurable Optical Add/Drop Multiplexers*

Research (3rd Generation?)

- *Optical Packet Routing*
- *Wavelength Conversion*
- *Optical Clock Recovery*
- *…*

Still exploratory …

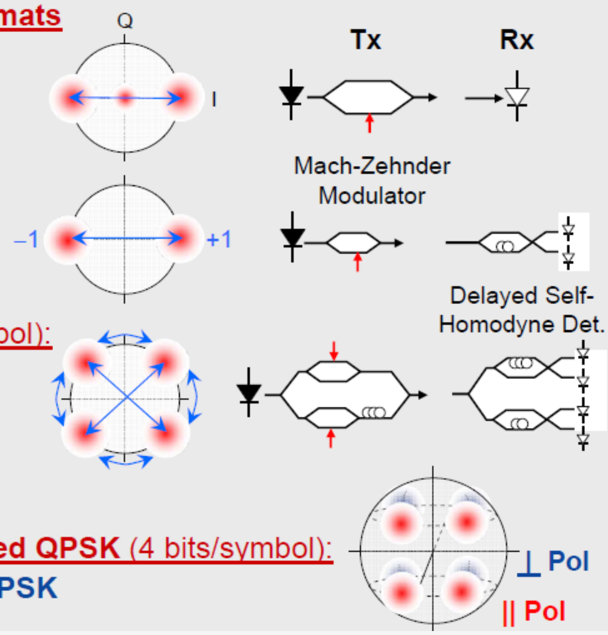
… i.e., not proven "stable applications"

courtesy of T. Koch

Coherent returns to extend spectral efficiency++

- **Vector modulation/coherent detection utilizes full complex field to enhance spectral efficiency**
- **Increase bit-rate without increasing baud rate**

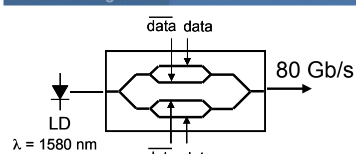
- ❑ **Binary modulation formats** (1 bit/symbol):
  - **Optical duobinary / PSBT**
  - **NRZ- / RZ-DPSK ("bipolar" ASK)**
- ❑ **Quaternary** (2 bits/symbol):
  - **NRZ- / RZ-DQPSK**
- ❑ **Polarization-multiplexed QPSK** (4 bits/symbol):
  - **Dual-Polarization QPSK**

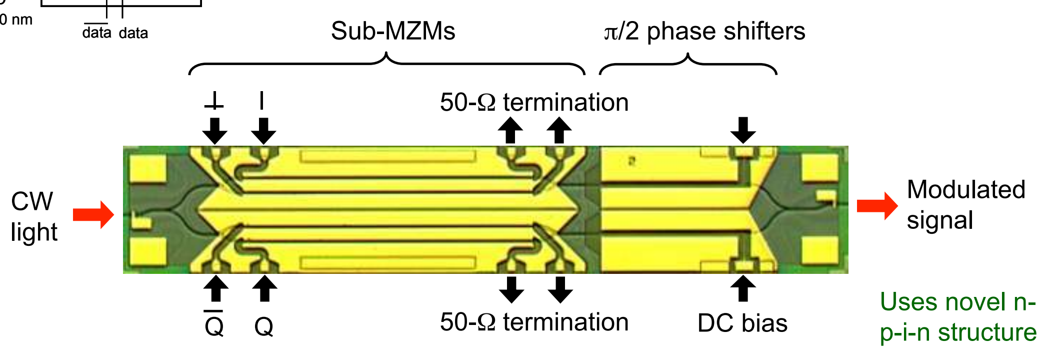


Other approaches for S.E. improvement include QAM (both amplitude and phase) and OFDM (Orthogonal Frequency Division Multiplexing →no guardbands)

Courtesy B. Mason

Traveling-wave InP MZM DQPSK PIC





Uses novel n-p-i-n structure

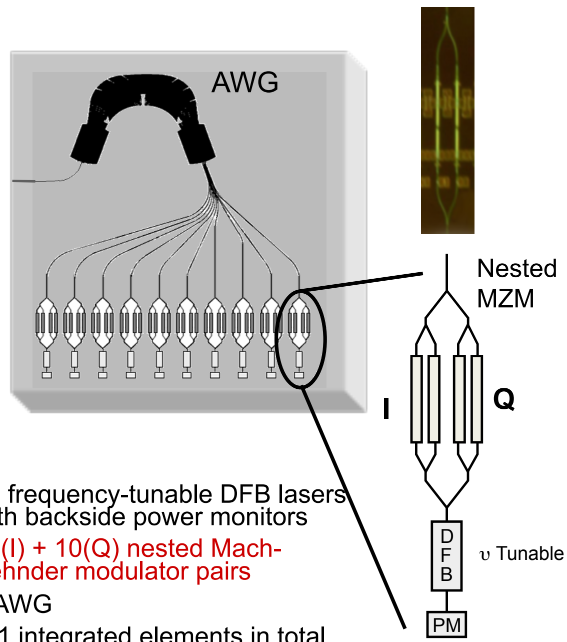
Wavelength range: L-band (λ_{PL} = 1.47 μm)
RF input: Differential
EO interaction length: 3 mm (Sub-MZMs),
1.5 mm (π/2-phase shifter)
Chip size: **7.5 mm x 1.3 mm**

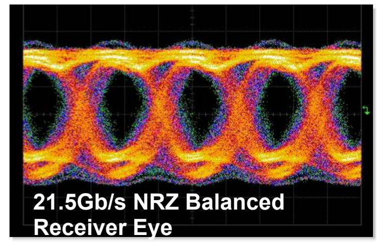
N. Kikuchi, ECOC, 10.3.1, 2007.

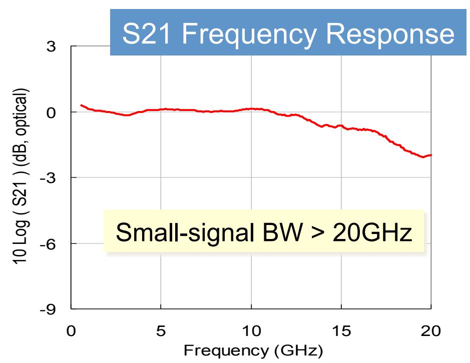
NTT

First Multi-Channel QPSK Transmitter PIC

10 channels x 40 Gb/s net







- 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

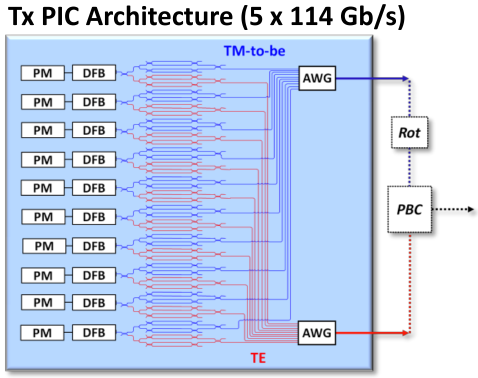
S.W. Corzine, et al, *OFC'08*, PDP18, 2008

courtesy of C. Joyner

infinera

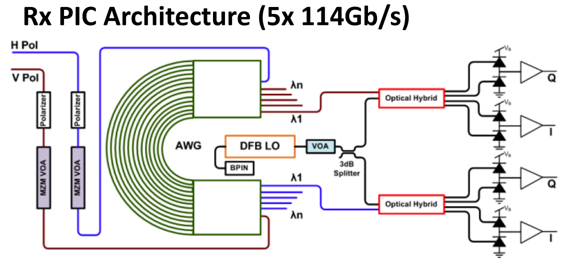
2011: 500 Gb/s PM-QPSK Coherent PICs

Tx PIC Architecture (5 x 114 Gb/s)



- > 450 Integrated Functions
- 8 Different Integrated Functions

Rx PIC Architecture (5x 114Gb/s)



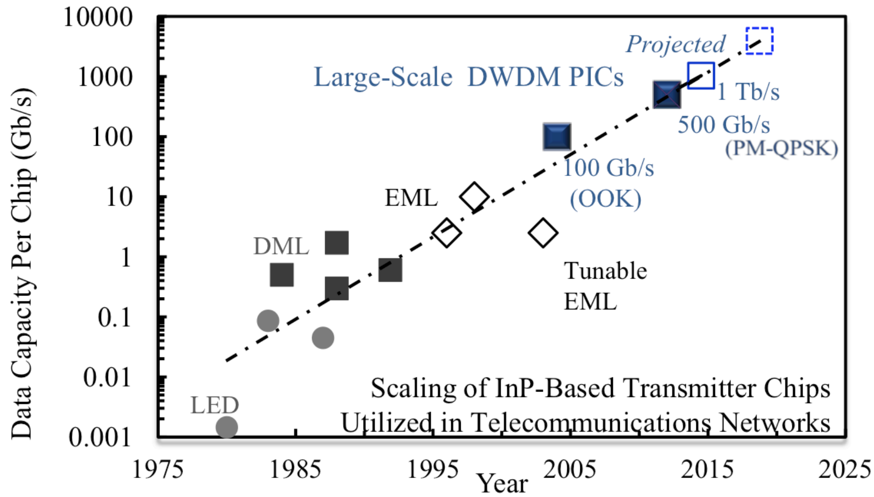
- > 150 Integrated Functions
- 7 Different Integrated Functions

10 tunable DFBs,
20 nested MZ modulators (40 total MZMs)
All of PIC sense and control functions

infinera

courtesy of F. Kish

Data Capacity Scaling in The Network



Large-Scale DWDM PICs	Concurrent serial and parallel integration
Large-Scale DWDM PICs (PM-QPSK)	Next generation serial and parallel integration (device diversity / scale)

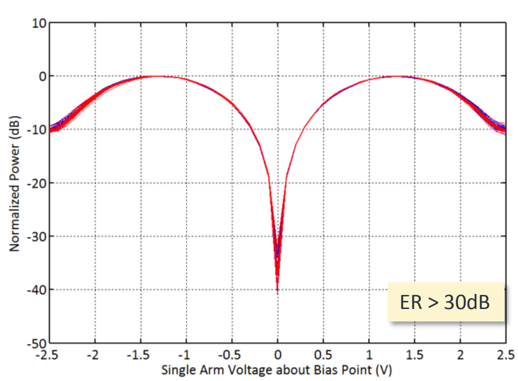
infinera

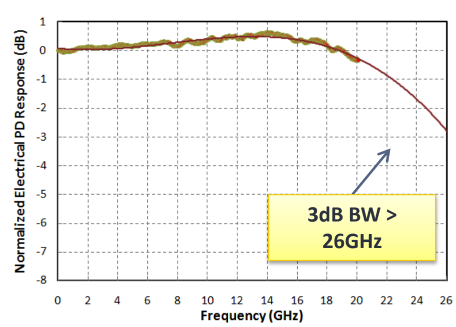
courtesy of F. Kish

Integration Enables the Terabit Age:

1.12 Tb/s PM-QPSK Transmitter and Receiver PICs

1.12 Tb/s (10 x 112 Gb/s) Tx + Rx PICs (28.4 Gbaud)



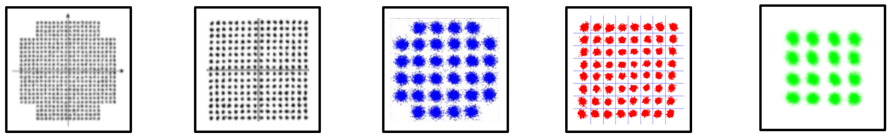


1.12 Tb/s Tx → Rx PICs Transmission (Back-to-Back)

infinera

courtesy of F. Kish

Increase modulation complexity or Baud rate?



PDM 512-QAM
3 GBaud (**54 Gb/s**)
[Okamoto et al., ECOC'10]

PDM 256-QAM
4 GBaud (**64 Gb/s**)
[Nakazawa et al., OFC'10]

PDM 32-QAM
9 GBaud (**90 Gb/s**)
[Zhou et al., OFC'11]

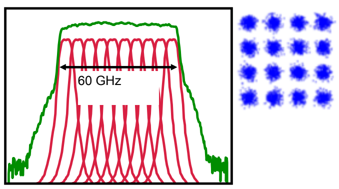
PDM 64-QAM
21 GBaud (**256 Gb/s**)
[Gnauck et al., OFC'11]

PDM 16-QAM
56 GBaud (**448 Gb/s**)
[Winzer et al., ECOC'10]

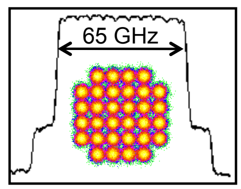
- More parallel channels
- More 'linear' electronics needed

- More dispersion/impairments
- Costly/non-existent electronics

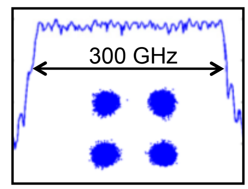
Or, use superchannels??



448 Gb/s (10 subcarriers) 16-QAM
5 bit/s/Hz
2000 km transm.
[Liu et al., OFC'10]



606 Gb/s (10 subcarriers) 32-QAM
7 bit/s/Hz
2000 km transm.
[Liu et al., ECOC'10]



1.2 Tb/s (24 subcarriers) QPSK
3 bit/s/Hz
7200 km transm.
[Chandrasekhar et al., ECOC'09]

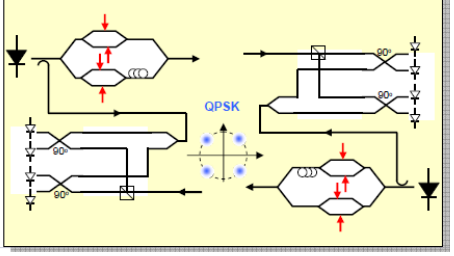
Courtesy P. Winzer

Optical Phase Locked Loops
To save Power and Cost?

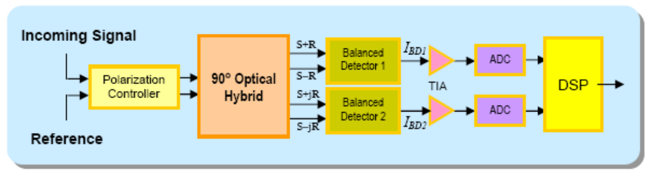
Intradyne or Heterodyne for generic sensor and short-reach communication applications?

Intradyne Coherent Detection

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



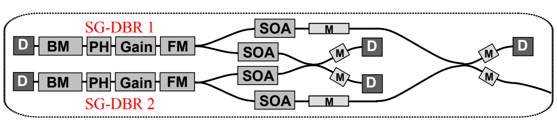
Typical Intradyne receiver architecture

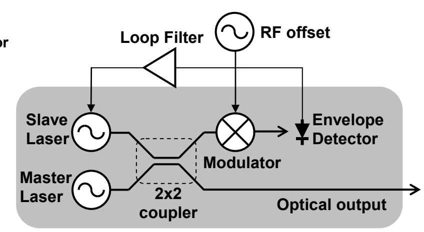


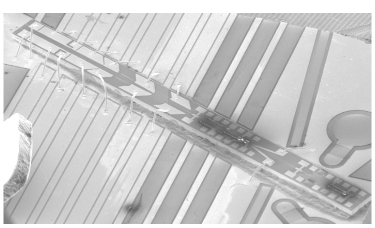
❖ Use 'Intradyne' without phase-locked LOs, or do we need true Heterodyne detection?
- Desire data-rate independent generic chips—when are phase-locked narrow-linewidth LOs desired?
- High-speed A/Ds & DSPs require lots of <u>power</u> and are <u>expensive</u> to design, especially as data rate increases
- Some impairments can be removed with much slower, lower-power, lower-cost signal-processing circuits

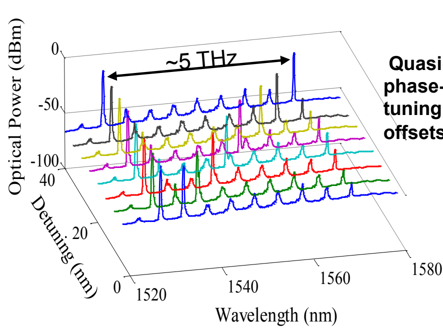
Integrated Optical Phase Locked Loops (OPLLs): provide a new stable control element

- Offset locking of two SGDBRs→ viable using close integration of PICs with electronics in a OPLL
- Hz-level relative frequency control, potentially over 5 THz

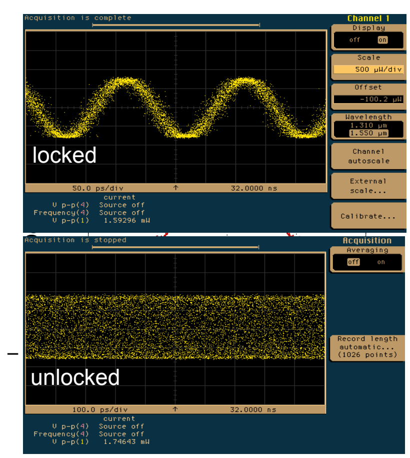








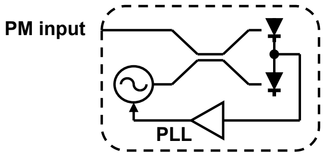
Quasi-continuous phase-locked digital tuning up to 5 THz offsets possible



Ristic, *et al: JLT* v.28 no.4, pp526-8, Feb., 2010

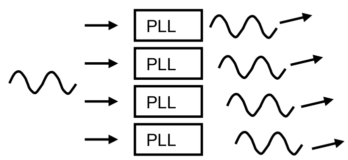
Applications/Challenges

Coherent receiver



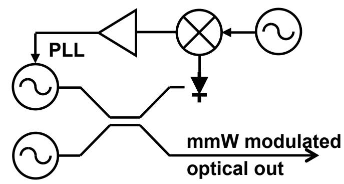
- Costa's Loop for BPSK, QPSK demodulation
- Complex DSP circuits not required, but simpler ones can be added for CD and PMD
- Challenge: Develop receivers for high speed (>100Gbaud) or high constellations (n-QAM)
- Matched with development of coherent sources

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 high-speed, high-power 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

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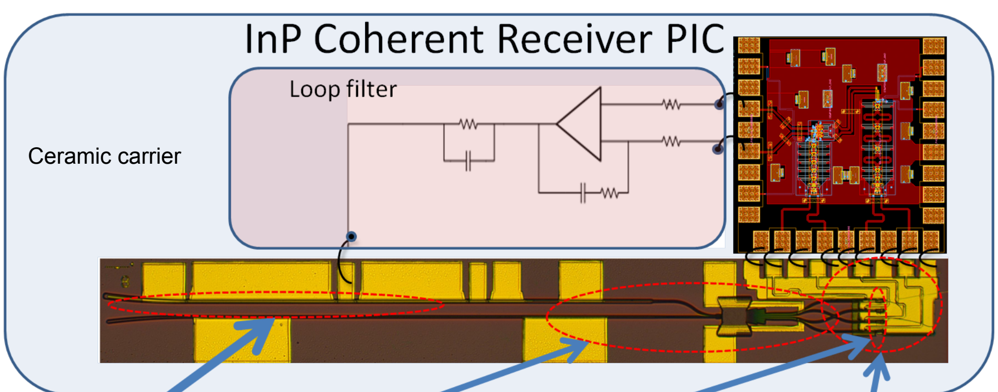
OPLL Receiver Layout



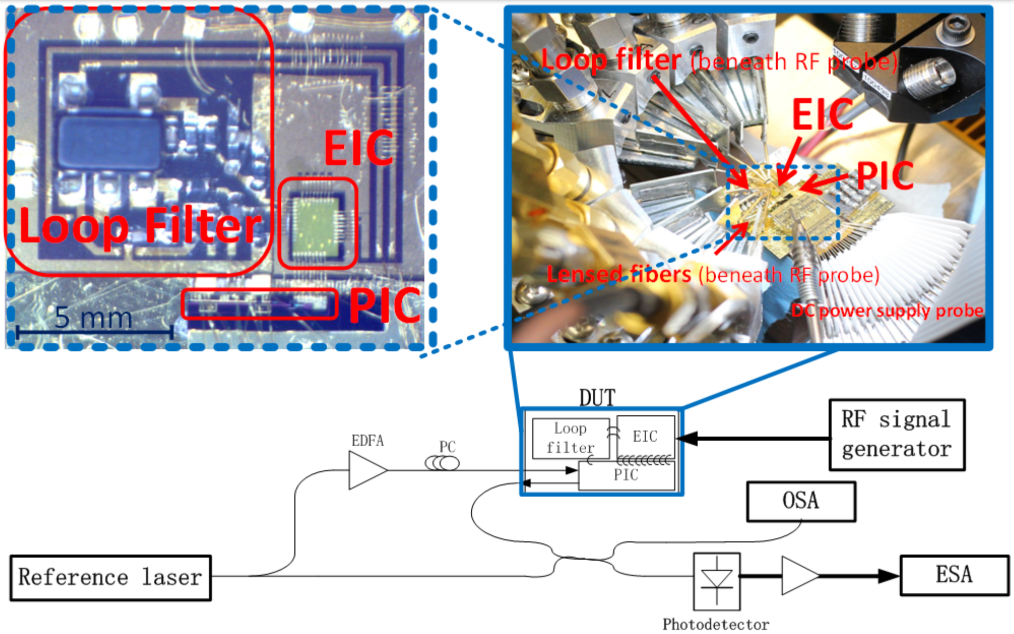
Sampled-grating DBR laser:
- 40nm tuna-bility
-Low linewidth
- Higher power

Two designs of 90 degree hybrid (only the first one is shown in the figure):
-MMI coupler based
-Star coupler based

Two designs of Photodetectors:
-QW detectors
-Uni-traveling detectors

On-PIC RF circuit:
-Microstrip transmission lines
- on-chip capacitors

Complete OPLL Circuit



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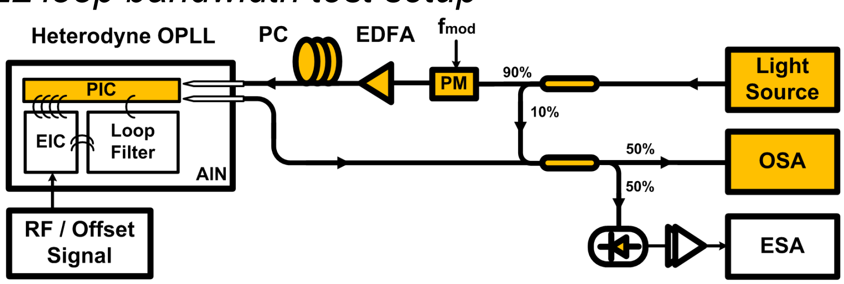
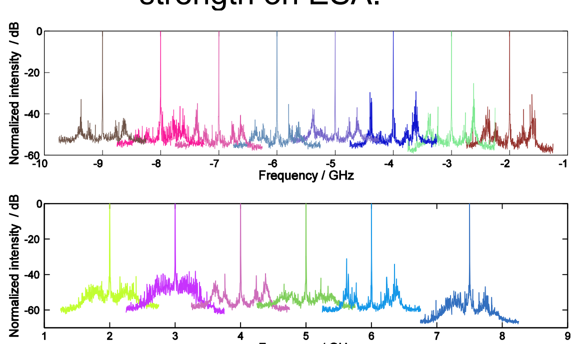
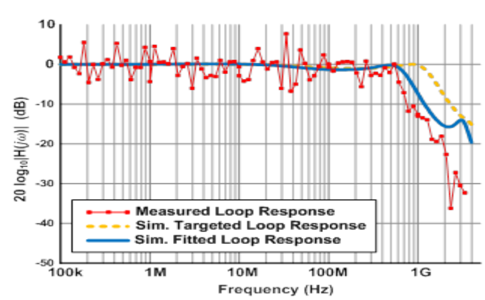
Swept OPLL Source While Phase Locked

- *OPLL loop bandwidth test setup*



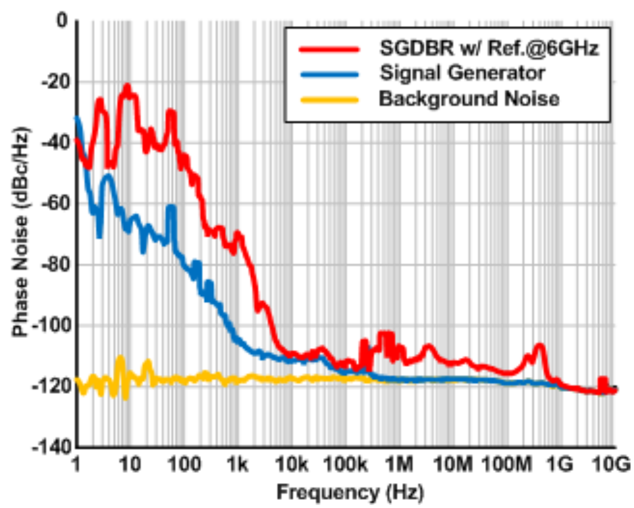
  – Sweeping the modulation frequency f_{mod}, measuring the sidebands strength on ESA.





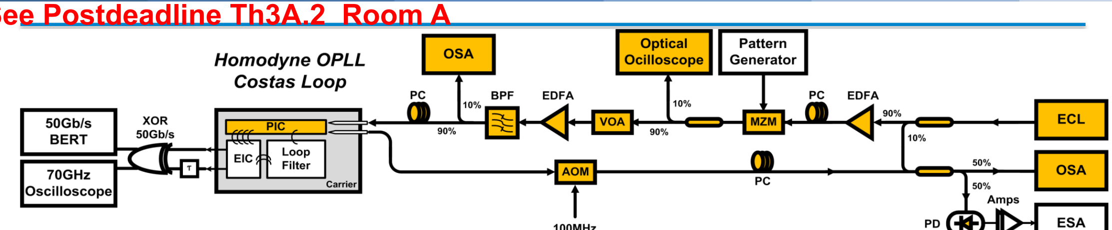
Heterodyne Phase Noise (Swept Source)

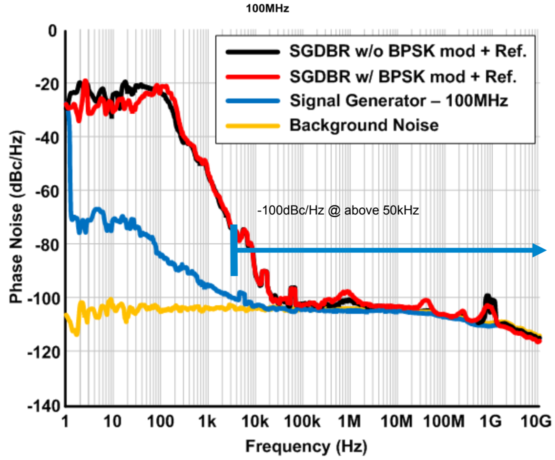
- *Phase noise is comparable to commercial RF synthesizer*
  - *< -100 dBc/Hz phase noise above 5 kHz*
  - *0.03 rad^2 phase error variance (Integration from 100Hz)*



Homodyne BPSK OPLL Receiver (Phase Noise)

See Postdeadline Th3A.2 Room A





Cross correlation between SG-DBR and reference lasers

-100dBc/Hz @ above 50kHz

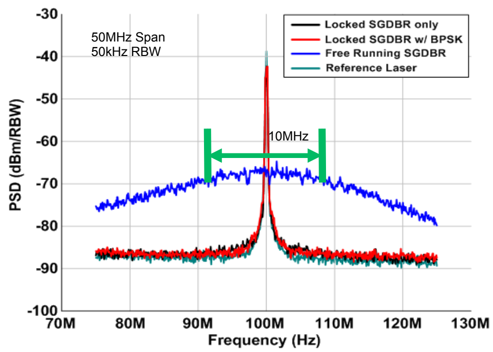
SG-DBR Laser Linewidth

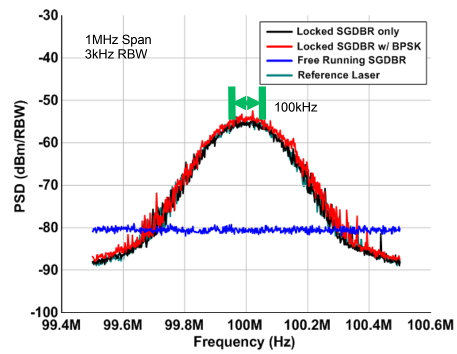
Self-heterodyne using 25km optical fiber

10MHz linewidth for free-running SG-DBR

Reference laser (Koshin) linewidth 100kHz

100kHz linewidth for locked SG-DBR laser





OPLL Locking Speed

400MHz/512bits ON-OFF laser

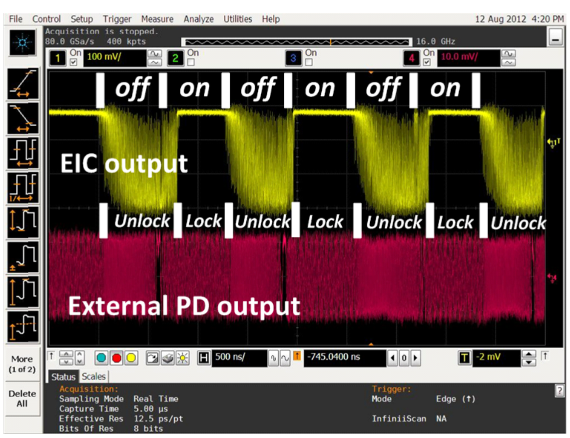
Locking conditions: EIC output – DC,

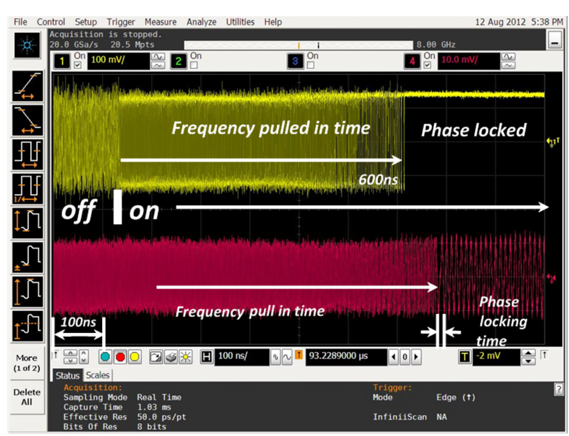
External PD output – 100MHz

Frequency pull-in time ~600ns

Phase lock time <10ns

** Worst conditions*

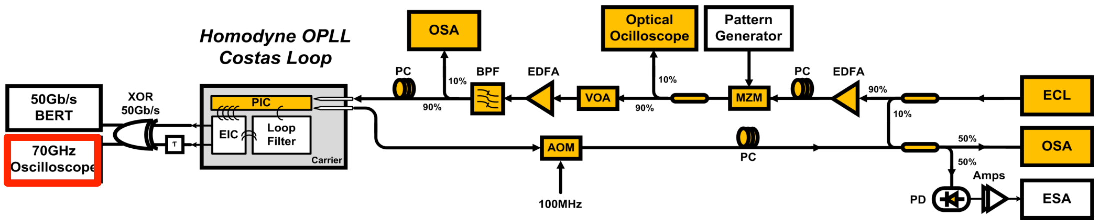


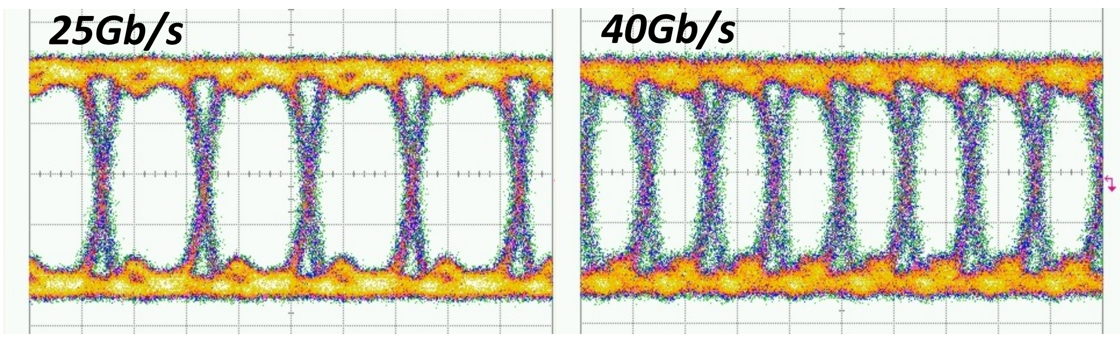


BPSK Data Reception—Eyes

PRBS 2^{31}-1 signals – up to 40Gb/s BPSK data

Open eye diagrams for 25Gb/s and 40Gb/s





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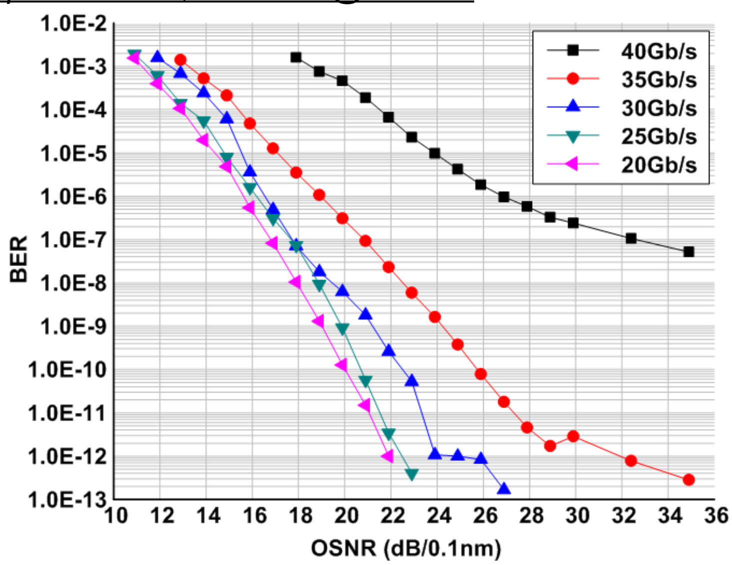
BPSK Data Reception—BERs

See Postdeadline Th3A.2 Room A

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

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



What about Si-Photonics for Active PICs?

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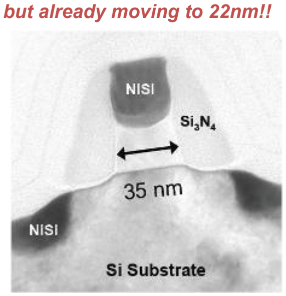
Why Silicon Photonics?

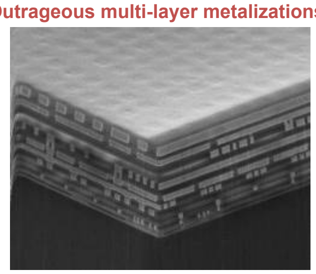
- *Harness unprecedented process control platform that gives ever-increasing functionality per unit area at low cost*

65 nm Generation Transistors …
but already moving to 22nm!!

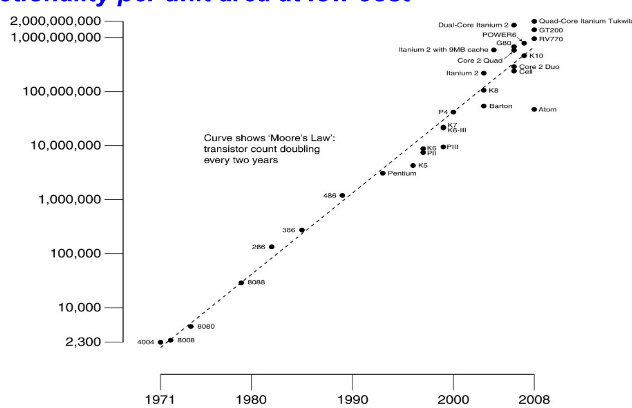


From Intel Corp.

Outrageous multi-layer metalizations …



From ICE Corp.



- 2 Billion transistors onto a chip at low cost?
  - → Huge $$ annual investments to achieve extreme quality of materials, precision of fab tools, process yields
- IC product development team project done when tape-out complete!
  - → Extreme predictability, mature CAD tools

CMOS IC Development – a world of difference from most of today's photonic chip design

courtesy of T. Koch

Why Silicon Photonics?

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In brief:

1) Cost
2) Performance
3) "Saving Moore's Law"

—very different drivers

- But can one get access to these state-of-the-art Si fabs? Likely not—however, probably can gain access to last generation fabs generating legacy EIC products

Performance reasons:

- Ultra-high index contrast
  - Low bending losses, compact devices
  - Benefits of TM polarization for some apps
- High performance actives? Lower power devices?
  - *High confinement, small active volumes …??*
- Potential for on-board integrated electronics
  - Reduced parasitics, eliminate impedance matching issues …→ no 50 Ω loads !!!
  - Low-cost, highly sophisticated CMOS drive, preamp, digital processing, …
  - Proliferation of new applications?
- Critical to continued scaling of traditional electronic functionality?

courtesy of T. Koch

Hybrid-Si Laser via Wafer Bonding

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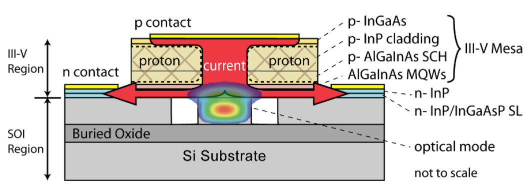
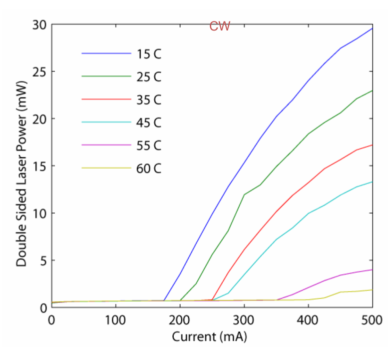
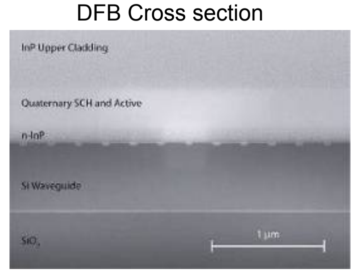
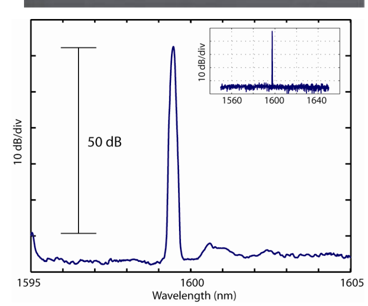




DFB Cross section





Integrated AlGaInAs-silicon evanescent racetrack laser and photodetector

Alexander W. Fang[1], Richard Jones[2], Hyundai Park[1], Oded Cohen[3], Omri Raday[3], Mario J. Paniccia[2], & John E. Bowers[1]

5 March 2007 / Vol. 15, No. 5 / OPTICS EXPRESS 2316

intel UCSB

Bowers, et al, 2009

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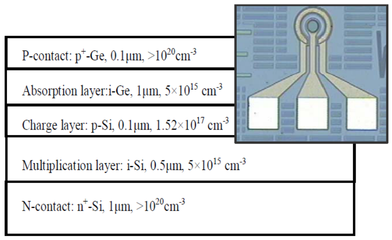
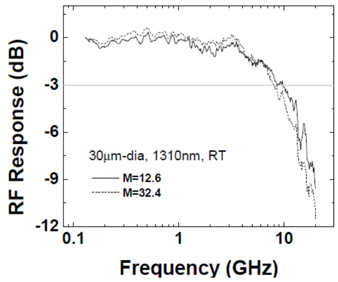
Record 340 GHz Gain-Bandwidth Product Ge/Si APD's

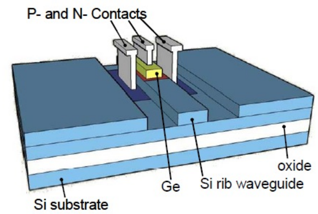
– *Outperforming InP!!*

Normal-incident mesa-type Ge/Si APDs

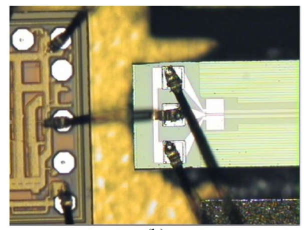




Waveguide type Ge/Si APDs



(a)



(b)

Receiver results @ 10 Gb/s with TIA:

- **-28dBm (normal incident type)**
- **-30.4 dBm (waveguide type)**

Invited Paper at GFP 2009:

WB6 11:45 AM - 12:15 PM (Invited)

Monolithic Ge/Si Avalanche Photodiodes, Y. Kang, M. Morse, M. Paniccia, *Intel Corporation, Santa Clara, CA, USA*, M. Zadka, Y. Saad, G. Sarid, *Numonyx Israel Ltd, Kiryat Gat, Israel*, A. Pauchard, *Chemin de Crey-Derrey 152, Chatel-St-Denis, Switzerland*, W. S. Zaoui, H.-W. Chen, D. Dai, J. E. Bowers, *University of California - Santa Barbara, Santa Barbara, CA, USA*, H.-D. Liu, D. C. McIntosh, X. Zheng and J. C. Campbell, *University of Virginia, Charlottesville, VA, USA*

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Summary

- **Active InP-based Photonic ICs can be created with size, weight, <u>power</u> and <u>stability</u> as well as system performance metrics superior to discrete solutions in many situations. If produced in some volume, the cost can be much lower.**
- **Coherent approaches will be greatly improved by the use of Photonic Integration, and numerous <u>sensor</u> applications may be enabled in addition to <u>higher-spectral-efficiency communications.</u>**
- **<u>Close integration</u> of control/feedback electronics will be desirable in many future PIC applications—it is required for low-cost Optical Phase Locked Loop (OPLL) systems with conventional semiconductor lasers, but efficiency can be high.**
- **<u>New high-volume (client) applications</u> may emerge as low-cost ,high-performance PIC/EIC transmitter/receiver engines are developed—interconnect, computing, sensing, communication, etc.**
- **Active integrated <u>Si-photonics is rapidly emerging</u>, and many applications are being explored. Integrated PIC/EIC devices would appear to be compelling, but not on the horizon yet.**

- Available now
- Worked examples throughout
- New homework problems
- New material:
  - VCSELs
  - GaN lasers
  - DFB, MMI, AWGR, & other component design
  - FTP site with software and color figs