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

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

Exponential network traffic growth is driven by high-bandwidth digital applications
Video-on-demand, telepresence, wireless backhaul, cloud computing & services

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
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)

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

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

Hybrid Solutions
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
Early Active PICs

Partially transmissive mirrors, and active-passive integration needed

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


- **DBR gratings** and vertical couplers
  - Tunable single frequency
  - Combined integration technologies

Early Active PICs

- Etched grooves
  - Tunable single frequency
  - Laser-modulator
  - Laser-detector


- DBR gratings and vertical couplers
  - Tunable single frequency
  - Combined integration technologies


- EML = electroabsorption-modulated laser
  - Still in production today


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.


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


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

Offset Quantum Well Process

Active–Passive Region Definition
Grating Formation
InP/InGaAs Regrowth

Metalization/Anneal
Passivation/Implant
InP Ridge Etch

• 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


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

- InP
- InGaAsP
- Deeply-etched Ridge
- Buried channel
- Surface ridge
- Buried rib

Higher index contrast

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
Solutions for Tunable Lasers

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

- **External Cavity Lasers (≥ 32 nm)**
  - Littman-Metcalfe/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)


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

Supermode (multiband) tuning

- 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

JDSU Roadmap Enabled by InP Monolithic Integration

- 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)

SGDBR laser

OSA

MZM

ILMZ TOSA (~18mm)

SGDBR SOA-modulator transmitters @ 40 Gb/s

Research initiatives:

1. QWI/EAM:
   
   Wideband-Thermal
   SG-DBR Laser
   QW EAM

   40 Gb/s TRANSMITTER EYES:
   
   1533 nm, ER=10 dB
   1543 nm, ER=12 dB
   1559 nm, ER=14 dB


2. Dual QW/TW-EAM:
   
   40 Gb/s NRZ
   
   1533 nm
   1543 nm
   1559 nm

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


3. Series Push-Pull MZI:
   
   Integrated load R and bypass C
   
   30 GHz Bandwidth
   40 Gb/s error free operation
   Low/negative chirp

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

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

• 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 bias applied to chip—photocurrent directly drives EAM → 1W/40Gb/s → 25 pJ/bit
• 40 nm wavelength tuning range


Eye Diagrams

Research initiatives: 8 x 8 MOTOR Chip

More functionality: 8 x 8 MOTOR Chip

• 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

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°
Early Wavelength-selectable Laser PIC and EAM

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


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, $\Delta \lambda \sim 16$ nm ($\Delta T = 25K$) x 6 devices
- Multi $\lambda$-locker integrated Wide-band WSL module (OFC'02)
  $\Delta \lambda \sim 40$ nm ($\Delta T = 45K$)
WSLs for S-, C-, L- bands applications

- $\Delta \lambda \sim 16 \text{ nm (}\Delta T 25K) @ 15 - 40 \ ^\circ \text{C}$
- 6 devices $\rightarrow$ 135 channels @100-GHz ITU-T grid
- SMSR $> 42 \text{ dB}$
- $P_f > \sim 10 \text{ mW @ } I_{\text{DFB}} = 100 \text{ mA, } I_{\text{SOA}} = 200 \text{ mA}$

Early PIC multi-wavelength receiver

Wavelength Demultiplexer + Detectors

1/64 WDM Channel Selector


ASPICs made in the first EuroPIC MPW runs

courtesy of M. Smit
Wide Deployed Commercial “WDM” PICs

EML’s:
- DFB Laser Section
- EA Modulator Section
- n-InP Substrate
- InGaAsP Grating
- Fe:InP Blocking
- p-InGaAs/InP Cap
- Selective-Area MOCVD Grown
- MQW - SCH - HR - AR

Tunables & Selectable Arrays:
- 1 x 12 DFB MMI SOA S-Bent -50 -40 -30 -20 -10 0 10 20 1520 1530 1540 1550 1560 1570 Wavelength [nm]
- Intensity [dBm]
- courtesy of T. Koch

Commercialization of WDM PICs: 2nd Gen. PICs

Large-Scale DWDM Photonic Integrated Circuits

100Gb/s Receive
- 10 x 10Gb/s Optical Input
- 10 x 10Gb/s Electrical Input
- 10 x 10Gb/s Electrical Output
- CH1

100Gb/s Transmit
- 10 x 10Gb/s Electrical Input
- DC Control & Bias
- Optical Output
- CH1

courtesy of C. Joyner
2004: First Commercial Large-Scale InP PICs

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

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

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

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

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

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

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

Coherent returns to extend spectral efficiency++

N. Kikuchi, ECOC, 10.3.1, 2007.
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

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 (5 x 114 Gb/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

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)

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)

3dB BW > 26GHz

courtesy of F. Kish

© Infinera Corporation.
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]

High D/A and A/D resolution
- 60 GHz

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

- 960 Gb/s (10 subcarriers) 32-QAM
  - 7 bits/Hz
  - 2000 km transm. [Liu et al., ECOC'11]

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

Optical Phase Locked Loops
To save Power and Cost?

- More parallel channels
- More 'linear' electronics needed
- More dispersion/impairments
- Costly/non-existent electronics

Or, use superchannels??

- 300 GHz

- Courtesy P. Winzer
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 power and are expensive 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

Ristic, et al. JLT v.28 no.4, pp526-8, Feb., 2010
### Applications/Challenges

#### Coherent receiver

- **PM input**
- 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_

---

### OPLL Receiver Layout

#### InP Coherent Receiver PIC

- Ceramic carrier
- Loop filter
- 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

---

**Sampled-grating DBR laser:**
- 40nm tunability
- Low linewidth
- Higher power

---
Complete OPLL Circuit

• OPLL loop bandwidth test setup

- Sweeping the modulation frequency $f_{\text{mod}}$, measuring the sidebands strength on ESA.
Heterodyne Phase Noise (Swept Source)

- Phase noise is comparable to commercial RF synthesizer
  - $<-100 \text{ dBC/Hz}$ phase noise above 5 kHz
  - $0.03 \text{ rad}^2$ phase error variance (Integration from 100Hz)

Homodyne BPSK OPLL Receiver (Phase Noise)

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*

BPSK Data Reception—BERs

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

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

See Postdeadline Th3A.2 Room A
What about Si-Photonics for Active PICs?

Why Silicon Photonics?

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

- 2 Billion transistors onto a chip at low cost?
  - Huge $$ annual investments to achieve extreme quality of materials, precision of fab tools, process yields
  - 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?**

**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**

**DFB Cross section**

Bowers, et al, 2009

**Integrated AlGaAs-silicon evanescent racetrack laser and photodetector**

Alexandre W. Fang\(^1\), Richard Jones\(^1\), Hyunsoo Paul\(^1\), Olvid Colburn\(^1\), Doree Hauer\(^1\), Maria J. Provencio\(^2\), A. John E. Amos\(^1\)

5 March 2007 / Vol. 15, No. 5 / OPTICS EXPRESS 2316
Record 340 GHz Gain-Bandwidth Product Ge/Si APD’s

- Outperforming InP!!

Invited Paper at GFP 2009:

- Normal-incident meso-type Ge/Si APDs
- Waveguide type Ge/Si APDs

Receiver results @ 10 Gb/s with TIA:
- -28dBm (normal incident type)
- -30.4 dBm (waveguide type)

Summary

- Active InP-based Photonic ICs can be created with size, weight, power and stability 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 sensor applications may be enabled in addition to higher-spectral-efficiency communications.

- Close integration 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.

- New high-volume (client) applications may emerge as low-cost, high-performance PIC/EIC transmitter/receiver engines are developed—interconnect, computing, sensing, communication, etc.

- Active integrated Si-photonics is rapidly emerging, 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