Technology and Applications for InP-based Photonic Ics

OIDA
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Larry A. Coldren

ECE and Materials Departments
University of California, Santa Barbara, CA 93106
coldren@ece.ucsb.edu
Problem: Bandwidth demands scaling faster than both silicon and cooling technologies

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

~1 Megawatt!!!
Some of our Earliest and Latest Functional PICs
SGDBR-SOA-Modulator PIC (the earliest)

SGDBR+X: 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)

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

JDSU-ILMZ recently released as TOSA
Recent PIC: MOTOR Chip (the latest)

Wavelength Converter Array

Arrayed-Waveguide Grating Router

- A monolithic tunable optical router (MOTOR) chip to function as the switch fabric of an all-optical router
  - Line rate: 40 Gbps / channel
  - Total capacity: 640 Gbps
  - Error-free operation
- Photonic integration technologies designed for high-yield, large-scale applications

Benefits of integrated solution:

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

Key Results: WC

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

No AR coatings; low $P_{sat}$ Preamp SOAs
Integration Strategy
Integration Platform

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

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

- Need multiple waveguide designs to integrate diverse range of components

Waveguides

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

**Deeply Etched Ridge Waveguide**
- Ridge defined through waveguide layer
- Dry etch only
- Strong lateral confinement → sharp bends possible
Multiple Waveguide Architectures

Need short mode transition elements to maximize coupling between waveguide regions

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

Waveguide

Horizontal Waveguide Position (μm)

- Buried Rib
  - Partial etch into upper waveguide prior to cladding regrowth, which buries it

- Low index contrast → Larger footprint

- Dry etch due to high-angle bends
Use QWI implant buffer to provide undoped setback layer between optical mode and Zn atoms

Simulated *reduction* in optical loss:
- Deeply-etched > Buried rib
- No lateral mode interaction with Zn doped cladding
Transitions Between Waveguide Designs

Surface-to-Deep Ridge Transition

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

Surface-to-Buried Rib Transition

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

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

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

Coherent Receiver for Phase Modulated Signals

OPLL—NEED for PICs & close integration/EICs

Homodyne:

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


Close collaboration with NGST
Integrated Coherent Receiver Results

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

Waveguide-UTC two-tone

Waveguide-UTC saturation currents PD B

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


Phase-Locked SGDBRs/OPLL

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

Coherent interference at monitor verifies phase locking

EA modulator used to generate 5 GHz offset frequency

- Slave laser locked to modulation sideband
- Coherent beat observed — 0.03 rad² phase error variance in +/-2GHz BW estimated from captured spectrum

- Up to 20 GHz offset locking demonstrated

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

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

LIDAR

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

mmW / THz generation

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

All require close integration of electronics with photonics
Programmable Photonic Lattice Filters

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

Single Unit Cell – Isolated Zero

- FIR filter response synthesized with MZI
  - Ring SOA reversed bias – no optical feedback from resonator
- SOA on feed forward arm used to tune zero amplitude
  - ~14dB maximum extinction ratio (ER)
  - Parasitic frequency shift due to current injection in SOA
    - Use phase modulators (PM) to align filter response
- Phase modulators used to tune filter in frequency
  - 270GHz (110% of FSR) total tunability of MZI response
- IIR filter response synthesized with ring resonator
  - S43 or S21 with feed forward SOA reversed biased
- SOA in ring resonator used to tune pole amplitude
  - ~18dB of ER, FWHM=0.067nm (7.9GHz), Q=23,000, 50 GHz frequency tunability
- RF filter response measured with Lightwave Component Analyzer
  - Characteristic π phase shift
- Enhancing ER by utilizing both zeros and poles
  - >25dB extinction by placing zero in between poles
- Resonator in/out coupling with Etched Beam Splitters (EBS)
  - EBS coupled ring resonator in InGaAsP demonstrated for the first time

- Pole response
  - E.g. Biased 20mA ($I_{th}=23mA$)
  - FWHM of 7GHz, $Q=27500$

- EBS power splitting ratio
  - $R=55\sim 60\%$, $T=2.9\sim 3.2\%$
  - Back calculated from resonator response and measured relative splitting ratio
Summary

- Illustrated medium-scale highly-functional PIC integration technology requiring only one blanket regrowth.
  - Indicated usefulness of quantum-well intermixing for integrating high-confinement active regions with low-loss passive regions.
  - Demonstrated efficient, robust techniques to integrate very different lateral waveguides together.

- This technology provided largest and most complex PIC ever (at least for UCSB).
  - Performance adequate for many digital photonic switching functions
  - Prior work has shown that the addition of one more blanket regrowth can greatly enhance the performance of such PICs

- Illustrated other functional InP-based PICs
  - All-photonic transceivers using photocurrent-driven modulators
  - Coherent receiver using an optical phase-locked loop for phase-modulated rf-photonics
  - Locking of SGDBRs for mmW - THz generation using an OPLL + other possibilities
  - Programmable photonic lattice filters