Photonic-Integrated-Circuits for Coherent Communication and Sensing

Major contributions by:
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Chris Doerr—Acacia
Beck Mason—Oclaro
Fred Kish—Infinera
UCSB Collaborators

Larry A. Coldren
ECE & Materials, UC-Santa Barbara
What’s the problem?

Size, Weight, Power, Cost, Performance, Reliability

Where?

- Communication
  - Long haul
  - Metro, campus
  - Data centers, Supercomputers
- Sensing/instrumentation
- Computing
Introduction/Historical View—PICs

- 1970’s - OEICs on GaAs for high-speed computing
- 1980’s – InP photonics/fiber; integration & tunables for coherent → Reach
- 1990’s – Widely-tunables, laser-mods, EDFAs; int. for WDM and cost
- 1990’s – VCSELs for datacom and optical interconnection
- 2000’s – InP PICs & PLCs expanded and matured; increasing use of VCSELs in high-speed datacom and computing interconnects
- 2006+ – Emergence of Si-PICs with several different goals: low-cost OEICs; high-performance PICs; or stop Moore’s-Law saturation
- 2008+ - Use of advanced modulation formats/coherent receivers for improved Spectral Efficiency —need for integration at both ends of links
- 2010’s – Increased InP-PIC use; maturity of Si-photonics solutions; heterogeneous integration approaches; improved VCSEL link efficiency
- 2018 – Data-center focus; coherent LIDAR/imaging; InP & Si-PICs in ‘volume’
INTREPID

Intelligent Reduction of Energy through Photonic Integration for Datacenters

- Photonics Integrated into Switch Packages
  - Points of highest bandwidth concentration

- Analog Coherent Links Optimized for Datacenters
  - Large sensitivity gain → more energy efficient interconnects
  - Enabling technology for WDM, photonic routing and switching

- Low-Power VCSEL Links
  - Ultra-low power connections from servers to ToR or EoR switches

- New Network Architectures
  - Exploring wavelength routing and switching

- Transition to Widespread Commercial Availability
  - Technology demo in live datacenter
  - Open Compute Project (OCP), Telecom Infra Project (TIP)
Datacenter Network Architecture

- **Aggressive Integration**
  - Analog coherent WDM interfaces, with $k = 4$ to 16 wavelengths
  - Integrated directly into high-radix electronic switch ports
  - Greatly reduced cost, latency, power

- **Phase 1 Enhancements**
  - Add a layer of $k \times k$ AWGRs\(^\text{[1]}\)
  - Network scales out by a factor of $k$
  - $x2$-$4$ increase in energy efficiency, compared to conventional designs
  - Same latency and switch sizes

- **Phase 2 Enhancements**
  - Replace AWGRs by **WDM switches**\(^\text{[2]}\)
  - Enabling network configurability, including direct optical ToR-to-ToR connections, to match workload
  - Leads to further improvements in energy efficiency and latency

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Analog Coherent: Maximizing Energy Efficiency

Direct-Modulation/Direct Detection

Detected power $\propto (P_{\text{laser}} \cdot A_{\text{total}})$

- RX sensitivity sets link budget, energy efficiency
  - Poor sensitivity = higher transmitter power
- Sensitivity directly degrades with datarate
  - Problem only getting worse

Field Modulation/Coherent Detection

Detected power $\propto \sqrt{(P_{\text{laser}} \cdot A_{\text{total}}) \cdot P_{\text{LO}}}$

- ~20dB improvement in RX sensitivity possible
- Much greater tolerance to attenuation
  - Looser component specs for yield and cost
  - Ability to compensate for insertion loss of optical routing/switching devices

Optical Phase Locked Loop (OPLL) → Eliminating Power-Hungry DSP

Typical OPLLs prior to 2000

Lab-scale

Prior UCSB work

Carrier-scale, single channel

INTREPID

Chip-scale, WDM multi-channel

Photonic and Electronic Integration

- <1000X size
- <100X power

- <10X size
- <10X power

with simple mux/demux
Prior Work: Phase Locked Coherent BPSK Receiver
“Analog Coherent”

OPLL + Costas Loop $\rightarrow$ 1 cm$^2$ footprint

**Photonic IC:** SGDBR laser, optical hybrid, and un-balanced PDs

**Electronic IC:** limiting amplifiers and phase & frequency detector (PFD)

**Hybrid loop filter:** Feed-forward technique, op-amplifier and 0603 SMDs

InP Widely-tunable Coherent Receiver PIC-2
(Heterodyne or Intradyne—also for Optical Synthesis)

- SG-DBR laser (LO)
  - 30 mW output power
  - (~100 mW after SOA)
  - 40 nm tuning range
  - 25 mA threshold current

- 90 deg hybrid
  - 1x2 MMI couplers
  - Directional couplers
  - Phase shifters

- UTC photodetectors
  - 29 GHz 3-dB bandwidth with -2V bias
  - 18 mA saturation current at -5V bias.

No phase error
4% power imbalance

- I and Q outputs normally connected to ADC and DSP for Receiver
- Much lower SWaP-C Optical Phase Locked Loop (OPLL) used

Feasibility Established: Analog Coherent OPLLs

- **1.1GHz** closed loop bandwidth
- **120ps** loop propagation delay
- **100kHz** SGDBR-linewidth (as ref. laser)
- **-100dBc/Hz** at **above 50kHz** phase noise
- **600ns** frequency pull-in time
- **<10ns** phase lock time

High-Speed Operation:
- 40 Gb/s back-to-back
- 10 Gb/s 25km SMF

Error-free up to 35Gb/s:

- S. Ristic et al., JLT (2010)
- M. Lu et al., Optics Express, (2012)
- P. R. A. Binetti et al., JQE (2012)
- M. Lu et al., JLT (2013)
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**Operation at 1550nm**

**High-Speed Operation:**
- 40 Gb/s back-to-back
- 10 Gb/s 25km SMF

**Error-free up to 35Gb/s:**

**INTREPID Focus**
- O-band operation at maximum energy efficiency
- Co-optimization and tighter integration of photonics and electronics
- Flip-chip packaging supporting multi-channel WDM scaling

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*References:*
- S. Ristic et. al., JLT (2010)
- M. Lu et. al., Optics Express, (2012)
- P. R. A. Binetti et. al., JQE (2012)
- M. Lu et. al., JLT (2013)
For coherent use Vector modulation:

- OOK
- BPSK
- PAM4
- QPSK
- 16 QAM
- DP-QPSK

**Modulation formats**

- $b/\text{baud} = 1$
- $b/\text{baud} = 2$
- $b/\text{baud} = 4$
Waveguides: InP vs SiP  
(Lumentum Slides—M. Larson)

- Ridge width ~2um
- Core thickness 200-300nm
- Moderate index step (3.4 <-> 3.17) 
  $\Delta n \sim 0.2$

- Ridge width ~1.2-1.8um
- Core thickness 200-300nm
- Moderate vertical index step
- Large lateral index step (3.3 <-> 1.45) 
  $\Delta n \sim 2$

- 450 x 220nm typical
- Large index step vertical & lateral (3.5 <-> 1.45) 
  $\Delta n \sim 2$

Waveguides in both systems are polarization sensitive
# Passive PIC Elements

<table>
<thead>
<tr>
<th>Passive Element</th>
<th>InP</th>
<th>SiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Splitter/Combiner</td>
<td>Multimode Interference Couplers (MMIs)</td>
<td>MMIs&lt;br&gt;Directional Couplers&lt;br&gt;Adiabatic Couplers&lt;br&gt;Y Junctions</td>
</tr>
<tr>
<td>90 degree hybrid co-mixer</td>
<td>2x4 MMI cascaded 2x2 couplers</td>
<td>2x4 MMI cascaded 2x2 couplers</td>
</tr>
<tr>
<td>Off-chip coupling</td>
<td>Cleaved Facet&lt;br&gt;Spot size converter (vertical/lateral taper)</td>
<td>Spot size converter to SiNx&lt;br&gt;Grating coupler</td>
</tr>
<tr>
<td>Polarization diversity</td>
<td>hybrid</td>
<td>Polarization Beam Splitter/Rotator (PBSR)</td>
</tr>
<tr>
<td>Isolator</td>
<td>hybrid</td>
<td>hybrid</td>
</tr>
</tbody>
</table>
Laser Building Blocks

- Laser source required for transmitter and local oscillator
- Narrow linewidth, high power, full C-band tunable
- Vernier tuning architecture with 2 or more filters to overcome refractive index tuning limitations
- Laser must be temperature stabilized or suffer environmentally-induced frequency drift

<table>
<thead>
<tr>
<th>Cavity Modes</th>
<th>Filter</th>
<th>Gain Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>1540</td>
<td>1580</td>
</tr>
</tbody>
</table>

### Optical Gain Medium

<table>
<thead>
<tr>
<th>InP</th>
<th>SiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAsP or InGaAlAs quantum wells</td>
<td>hybrid or heterogeneous</td>
</tr>
</tbody>
</table>

### Filters / Mirrors

<table>
<thead>
<tr>
<th>InP</th>
<th>SiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically-etched gratings in InGaAsP waveguide</td>
<td>Micro-ring resonators; Laterally-patterned gratings</td>
</tr>
<tr>
<td>Microring resonators</td>
<td></td>
</tr>
</tbody>
</table>

### Tuning mechanism

<table>
<thead>
<tr>
<th>InP</th>
<th>SiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier injection or thermal (microheater)</td>
<td>Thermal (microheater)</td>
</tr>
</tbody>
</table>
Single or Multiple PICs?  
**InP Practical View (Lumentum)**

- Separate Tx and Rx PIC for thermal considerations
  - Laser + Modulator must be temperature controlled; Receiver is uncooled

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**Diagram:**
- **Driver IC**
- **TIA IC**
- **Electrical I/O**
- **Optical I/O**

**Components:**
- Tunable Laser
- SOAs
- I/Q Modulator
- MZs
- PBSR
- MPDs
- PDs
- Balanced detector array
- Coherent mixer
- Dual polarization, vector modulation
- 2-90° hybrids plus PDs
Narrow linewidth thermally tuned Sampled Grating DBR laser in InP (Lumentum)

- Vernier-tuned SGDBR Laser, comb spacing ~700GHz
- +16dBm output power, 100kHz linewidth
- <1.4W Pdiss at 75C (laser TEC at 52C)

![Diagram of laser design with InGaAsP MQW active regions, Q1.3 tuning waveguide, sampled gratings, thermal isolation, and optical output.]

**LineWidth**

- Plot showing linewidth (MHz) vs. Optical Frequency (GHz) with peaks and valleys indicating tuning and stability.

**Fiber Coupled Power**

- Scatter plot showing fiber coupled power (dBm) vs. Optical Frequency (GHz) with data points clustering around a specific range.

**Total Power dissipation at 75C (Laser+TEC)**

- Graph showing power dissipation (W) vs. Optical Frequency (GHz) with a decline trend as frequency increases.

See Larson et al., OFC 2015, M2D.1
InP Coherent Tx PIC

- Integrated Narrow Linewidth Tunable Laser with Dual Polarization IQ modulator and LO Output

![Diagram of InP Coherent Tx PIC]

- SGDBR laser
- Tx SOA
- Ty SOA
- LO SOA
- X
- LO
- Y

- Carry RF data traffic
- Maintain I and Q at quadrature
- Provide null-bias for each child Mach-Zehnder

**Phase vs Bias**

**Amplitude^2 vs Bias**

**“Box” Sweeps**

**Differential sweep**

Bias = -4V

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Normalized optical output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1550 nm</td>
<td>0.9</td>
</tr>
<tr>
<td>1560 nm</td>
<td>0.85</td>
</tr>
</tbody>
</table>

3.2 x 8 mm^2
Single or Multiple PICs?
SiP Preferred View (Acacia, NTT)

- Separate Tunable Laser PIC from Modulator+Receiver PIC for thermal considerations

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C. Doerr et al., OFC 2016
K. Kikuchi et al., Compound Semiconductor Integrated Circuit Symposium (CSICS), 2017
Early SiPh coherent receivers


Single-chip coherent transceiver

Power consumption = 4.3 W

C. Doerr, et al., OFC, Th5C.4, 2016
ASIC-PIC co-packaging

Improved heat dissipation

• Heat flows directly from die backside to lid

Very high bandwidth connections
Modulator Material Physics

- **InP: Quantum Confined Stark Effect**
  - Applied reverse bias causes a redshift of the multiple quantum well excitonic absorption edge
  - \( \Delta n \propto V, V^2 \)

- **SiP: plasma dispersion effect**
  - \( \Delta n \propto \) carrier concentration \( \Delta N, \Delta P \).
  - Carrier concentration is a non-linear function of applied \( V \)

\[
\Delta n(\lambda) = -3.64 \times 10^{-10} \lambda^2 \Delta N - 3.51 \times 10^{-6} \lambda^2 \Delta P^{0.8}
\]

'Soref' equation. Fitting parameters are empirical.


Phase Shifter Transfer Functions

- Phase & attenuation vs applied voltage for 3 modulator materials
  - InP: nonlinear phase and attenuation (electro-absorption) with increasing reverse bias
  - SiP: complicated phase and attenuation; notice: vertical scale range is ½, horizontal scale (V) is 2.5X

Lumentum/McGill NSERC Project, SiP MZM design work, Fall 2016 (M Jacques, A Samani, J Sonkoly)
Power Dissipation Budget Comparison: 64 Gbaud DP-16QAM IC-TROSA component level estimate

- Conservative estimates for budgetary purpose
- InP PIC + TEC is 3.3W vs. 2.3W for SiP + External Laser: 1W SiP advantage
- SiP solution is disadvantaged by high Vpp => high driver power dissipation

<table>
<thead>
<tr>
<th>Power dissipation Item (max)</th>
<th>InP IC-TROSA Tx PIC + Rx PIC</th>
<th>SiP IC-TROSA TxRx PIC + Laser PIC</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx PIC active load (W)</td>
<td>0.9</td>
<td>0.1</td>
<td>InP case includes laser</td>
</tr>
<tr>
<td>Tx TEC (W)</td>
<td>2.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>External Laser + TEC (W)</td>
<td>0</td>
<td>2.2</td>
<td>SiP case only</td>
</tr>
<tr>
<td>Driver (W)</td>
<td>1.9</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>TIA (W)</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Total (W)</td>
<td>6.3</td>
<td>6.9</td>
<td>maximum</td>
</tr>
</tbody>
</table>
Summary

- As long as laser is temperature sensitive and requires TEC, single PIC solution is unlikely the lowest power dissipation
  - At 1310 may be able to use uncooled laser

- High Vpi of SiP modulator is a challenge for driver power dissipation and scaling to higher baud rates
  - SiP modulators may not be good choices within data centers
InP Modulator Integration Evolution

2008
20 Gbaud
QPSK MZ

2013
32 Gbaud
MZ-SOA

2014
Multi-MZ
PIC

2015
64 Gbaud
MZ-SOA

2016
43 Gbaud
fold MZ-SOA

2017
64 Gbaud
fold MZ-SOA

2018
100/200G Coherent Transmission

2019
100/200G ULH and 600G Metro/Edge

2020
200G Low power compact

100Gbaud fold MZ-SOA

400G CDM

400G Low Power

1T single λ

Accelerating InP modulator PIC development

- Increasing integration and functionality
- Higher modulation rates
- Low cost optics architecture
- Efficiency improvements
Accelerating InP modulator PIC development

- Increasing integration and functionality
- Higher modulation rates
- Low cost optics architecture

Miniaturisation

Integration

100/200G Coherent Receiver

100-600G Coherent Receiver

100-400G Compact

Integrating VOA

100Gbaud wafer process

1T single λ

100 Gbaud Rx

20Gbaud QPSK Rx

32Gbaud Rx
64 Gbaud Tx & Rx dual channel 400G today

Folded MZ-SOA Tx

Integrated Compact Rx/VOA
Data Capacity Scaling in The Network

Scaling of InP-Based Transmitter Chips Utilized in Telecommunications Networks

- LED
- DML
- EML
- Tunable EML

Infinera System-on-Chip Commercial DWDM PICs

- 4.9 Tbps
- 1.2 Tbps (16-QAM)
- 500 Gbps (QPSK)
- 100 Gbps (OOK)

State-of-the-Art Research Result
Fig. 21. Scaling of four generations of multi-channel DWDM SOC photonic IC modules. From their first commercial deployment in 2004 to 2016 (12 years), the data capacity of these modules has scaled 24x in roughly the same footprint (images shown to scale).

F. Kish, et al, *JSTQE*, **24** (1) 2018
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
2016: 1.2Tbps Extended C-Band tunable coherent 32GBaud/16-QAM coherent Transceiver

- 1.2 Tbps, 6-Channel transmitter and receiver PICs in single Module
- Independent extended C-Band tunable channels
- 200Gbps per channel (33GBaud/16QAM) capable to 1500km Reach.
- 44GBaud data rate demonstrated

Typical laser output spectrum

B2B Constellations
Back-to-back transmitter constellations on PIC with potential capacity of 4.9 Tb/s

Fig. 19. Back-to-back 44 Gbaud constellations for PM 16-QAM modulation for all 14 channels on a SOC DWDM coherent transmitter PIC (measured using a companion widely tunable multi-channel receiver PIC). The figure shows only the outermost sub-carrier on each polarization for a dual-pol 16-QAM signal. The total capacity of this photonic IC is $>4.9$ Tb/s.
2D-Beam Sweeping

• Our approach: 1D array + grating
• Scaling as $N + 1$, not $N^2$

32 x N: Surface-emitting grating phased-array
Optical Beam SWEEPER—InP-PIC

- Waveguide spacing varied to suppress lateral side lobes.
- Grating duty-factor weighted to extend effective length
- Nearly Gaussian shape

Integrated SGDBR tuning

Powers into 32 SOAs

Power entering the SOA array (mW)

Channel number

Surface ridge
Deep ridge
Surface ridge
Deep ridge

3.5 mm
9.6 mm

Surface ridge
Deep ridge
Surface ridge
Deep ridge

Surface ridge
Deep ridge
Surface ridge
Deep ridge

Surface ridge
Deep ridge
Surface ridge
Deep ridge

Tunable laser
Splitter
Phase shifter
SOA
Grating
Monitor

Tunable Laser
PMs
SOAs
EA
PDs
Shuttering pre-amplifier

M1 T G M2 P-A
2D Beam Sweeping results (32 x N)

Flip-chipped PIC-on-carrier

110 good contacts

- 2D beam steering demonstrated

(1524nm, 5)

(1545nm, 0)

(1524nm, -5)

(1567nm, -5)

(1567nm, 5)

Far-field beam profiles (x & y)

1.2 x 0.3°

N ~ 120

~20 dB sidelobes

MOABB LIDAR Project (2016→)

Similar sweeping concept, but wider angles & larger arrays + LIDAR

Phase 1 Cell
Demonstrates all key building blocks
Demonstrates full operation of 1x10 mm emission aperture cell

Phase 2 Tile
Demonstrates ability to generate arrays of cells
Operating as coherent apertures
Demonstrates 16 independent sensing channels
Demonstrates Phase 1 cell operation as lidar

Phase 3 Multi-Tile
Demonstrates large aperture scalability
Stacks PIC layers 2-4 vertically
Integrates PICs, ASICS in 3D
Demonstrates Phase 2 tile as lidar
MOABB Mock-up Showing InP and SiP PICs

Phase 1:

- Laser Locker Board
- InP Tx-Rx PIC
- Receiver Front End Board
- SiP Emission PIC (OPA)
- Phase Shifter DACs

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Schematic of InP Transceiver PIC

FMCW LIDAR Transceiver

Locker Electronics

Frequency Discriminator

2x1

Tunable Laser

2x2

Gain

Front Mirror

1x2

2x2

SOAs

SiP

OPA

Receiver Electronics

Filter

2x2

PD

PD

LO

return

output

PD
Prior work showing linewidth reduction with optical frequency locked loop

- Laser – SGDBR (40 nm tunability)
- Frequency Error Sensor – Asymmetric MZI
- Filter FSR = 10 GHz
- Open loop tuning-to-lock in 30 ns

- Open loop $\rightarrow$ > 5MHz linewidth
- Closed loop $\rightarrow$ 150 kHz linewidth

A. Sivananthan, et al, OFC, 2013
InP Transceiver Mask Layout

Design features

✓ Fully integrated frontend transceiver
  • Maximizes coupling between sections, avoids optical isolators

✓ Sampled Grating DBR laser (SGDBR)
  • Proven widely tunable laser technology

✓ Dual use laser for transmitter and LO
  • Balanced detection for common mode rejection

✓ Asymmetric Mach-Zehnder interferometer (AMZI) locker
  • Stabilizes wavelength and provides stable chirp for laser

✓ Integrated semiconductor optical amplifiers (SOAs)
  • In-situ monitoring, power amplifier, blanking during wavelength tuning, diode-based temperature sensor

Sampled Grating DBR laser

Critical Fabrication steps

Grating etch
Ridge formation
Device isolation
Vias
SGDBR Laser Performance

PIC on carrier under test

Light-current-voltage characteristics

Overlaid lasing spectra

Wavelength tuning map

Side-mode suppression ratio

• Custom automated testbeds built for all measurements
• Typical laser performance:
  • Threshold current \(\sim 45-70 \text{ mA}\)
  • Output power \(\sim 15 \text{ mW} \) at 100 mA
  • Tuning range \(\sim 40 \text{ nm}\)
  • SMSR \(\sim 40-50 \text{ dB}\)
• Maps can provide lookup table for laser tuning
InP transceiver PIC mounted on AlN PIC subcarrier, then mounted on supercarrier with locker and receiver circuits/boards
**Test 1:** Laser and PIC DC characteristics
- SOA-1 used to measure laser LI characteristics
- PD-1 and PD-2 used to measure AMZI response

**Test 2:** Locking functionality (Tune laser)
- DC bias the laser
- Sweep phase section and measure AMZI response

**Test 3:** Chirp control (Tune filter)
- Sweep chirp control current
- Measure chirp response with PD-1 and PD-2

**Test 4:** Receiver functionality
- DC bias the laser and sweep phase
- Measure receiver response with PD-3, PD-4

**AMZI response**
- Laser frequency (Mode spacing = 45 GHz)
- Tune Laser 30 GHz

**Chirp control**
- Tune AMZI filter
- AMZI FSR: 60 GHz
- Chirp response: 4.4 GHz/mA

**Receiver response**
- Laser frequency
- PD-3
- PD-4
Output coupling to SiP emitter PIC
SiP—STAR Coupler

Design

Power Distribution

Wavelength Uniformity

Far-Field Power Distribution
SiP-OPA full-run PIC

1. Deep etch: Directional couplers, ring resonators and loop mirrors test structures
2. Modulator test structures (MZI, loss spiral)
3. 32-channel devices (can be probed)
4. Reduced pitch 240-channel full device (to be bonded to interposer)
5. Standard pitch 240-channel full device (to be bonded to interposer)
6. Shallow etch: Directional couplers, ring resonators and loop mirrors test structures + loss spirals (both etch depths)

6 dies per 4 inch (100 mm) wafer
Take-Aways

• PICs are desirable for modest to high volume communication and sensing applications, where size, weight, power and cost (SWAP-C) reductions are desired.

• PICs are important because of the inherently stable phase relationships and possibly seamless interfaces between elements.

• PICs generally bring better reliability once properly designed; yield and some aspects of performance may be compromised, although other aspects can be improved.

• Although InP-PICs are currently being produced in higher volume, the use of SiP-PICs is growing more rapidly.