Recent Advancements in Integrated Photonics

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Introduction
Fiber-optic link distances

**Ultra-long haul**
- 3,000 – 20,000 km

**Long haul**
- 600 – 3,000 km

**Metro**
- 10 – 600 km

**Campus**
- 2 – 10 km

**Short reach**
- 0 – 2 km
Modulation formats

IMDD
(intensity modulation, direct detection)

OOK

PAM4

QPSK

16 QAM

BPSK

DP-QPSK

Coherent

b/baud = 1

b/baud = 2

b/baud = 4
Transmitter

IMDD

Coherent

Laser

Modulator

or

Tunable laser

Laser

Modulator
Receiver

IMDD

Signal → PD

Coherent

Signal → PBS → X-pol → PD → IX

Signal → PBS → Y-pol → PD → QX

LO → 90° hybrid → PD → IY

LO → 90° hybrid → PD → QY
Reach vs. module rate

- Red = coherent 50 Gbaud
- Orange = coherent 100 Gbaud
- Blue = IMDD 50 Gbaud
- Green = IMDD 100 Gbaud

- 400G LR4 (800-GHz sp)
- 400G FR4 (20-nm sp)
- 400G DR4
- 800G LR8 (800-GHz sp)
- 800G FR8 (200-GHz sp)
- 800G DR8
- 1.6T 2FR4
- 1.6T DR8
- 1.6T ZR2
- 1.6T ZR4
- 3.2T 4FR4
- 3.2T DR16
- 3.2T ZR2
- 3.2T ZR4

Red text: 400G 800G 1600G 3200G
Blue text: 0.5 km
Orange text: 2 km
Green text: 80 km

Calculated BER curves, 125 Gbaud

-25 -20 -15 -10 -5 0
OMA (dBm)

-10 -9 -8 -7 -6 -5 -4 -3
Log (bit error ratio)

~12 dB gain with coherent, dependent on Tx linearity

Assuming 20 pA/sqrt(Hz) TIA noise

200G PAM4, ideal
800G 16QAM, ideal
200G PAM4, 45G BW
800G 16QAM, 45G BW
200G PAM4, 45G BW, NL Tx
800G 16QAM, 45G BW, NL Tx
Silicon photonics

12" (300 mm) wafer

Boule

Silicon on insulator (SOI) wafer
Material transparency

Transmit through Si and receive in Ge

Typical integration scheme

SiN waveguide

Heater

Si waveguide

Ge photodetector

SiN

Ti

Al

Ge
Electro-refraction/absorption in Si

Refraction
\[ \Delta n_r = -8.8 \times 10^{-22} N_e - 8.5 \times 10^{-18} N_h^{0.8} \]

Absorption
\[ \Delta n_i = 1.0 \times 10^{-22} N_e + 7.4 \times 10^{-23} N_h \]

\( N_e \) = free electron density
\( N_h \) = free hole density

## Modulators

<table>
<thead>
<tr>
<th>Type</th>
<th>$V_{\pi L}$</th>
<th>$\alpha V_{\pi L}$</th>
<th>Opt. BW</th>
<th>Elec. BW</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>20 V-cm</td>
<td>2 V-dB</td>
<td>800 nm</td>
<td>200+ GHz</td>
<td>Pure Pockels effect</td>
</tr>
<tr>
<td>Si depletion</td>
<td>2 V-cm</td>
<td>20 V-dB</td>
<td>400 nm</td>
<td>90 GHz</td>
<td>Temperature and wavelength independent</td>
</tr>
<tr>
<td>InP QCSE</td>
<td>1 V-cm</td>
<td>0.2 V-dB</td>
<td>40 nm</td>
<td>150 GHz</td>
<td>Temperature and wavelength dependent</td>
</tr>
</tbody>
</table>

Diagram: 
- LiNbO$_3$ modulator with $p+$ and $n+$ layers.
- Si depletion modulator with $p+$, $p$, and $n+$ layers.
- InP QCSE modulator with $p+$, $n+$, and $n$ layers.
60-Gbaud case

With de-emphasis EQ

Modulator EO frequency response
Fits well to 2-pole filter

No spectral shaping.

Average loss ~ 0.028 = -15.5 dB
Includes I/Q 3-dB loss
SiPh modulator optical loss

- DC loss ~1 dB/mm
- $V_{\pi}L$ at DC ~ 2 V-cm
- Modulation loss
  - Coherent
    - $\sin^2(\phi_{pp}/4)/2$
    - 16-QAM: $P_{\text{avg}} = 5/9 \sin^2(\phi_{pp}/4)/2$
    - Even more loss if have spectral shaping
  - PAM4
    - $\text{OMA}_{\text{outer}} = \sin^2(\pi/4+\phi_{pp}/4) - \sin^2(\pi/4-\phi_{pp}/4)$
      - If ER is 5 dB, OMA = $P_{\text{avg}} = 0.5$

### Coherent 16-QAM

<table>
<thead>
<tr>
<th>Item</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>4</td>
</tr>
<tr>
<td>Modulation loss</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>19</strong></td>
</tr>
</tbody>
</table>

Assumptions:
4mm, 4V, 5-dB roll-off @ Nyquist (thus $\phi_{pp} = 1.4\text{rad} @ Nyquist$)

### PAM 4

<table>
<thead>
<tr>
<th>Item</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>3</td>
</tr>
<tr>
<td>Modulation loss</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>

Assumptions:
3mm, 4V, 5-dB roll-off @ Nyquist (thus $\phi_{pp} = 1.1\text{rad} @ Nyquist$)
Required total laser power for 1.6T module, 2km

Because of the higher modulation loss and requirement of LO, coherent’s sensitivity advantage is nearly erased for unamplified links!

Coherent has a shallower slope—benefits more from FEC

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X. Zhou, et al., JLT, p. 475-484, 2020
Modulators
Modulator linearity


SiPh modulator performance similar to LiNbO$_3$
Equalization

- DAC
- Driver
- Modulator

= equalization (attenuate low frequencies)

= limited BW (attenuates high frequencies)
Silicon photonics depletion modulator speed limit

Depletion region (~0.1-0.3 µm wide)

E field > $10^4$ V/cm

Hole velocity: > $3 \times 10^6$ cm/s

For movement of 0.15 µm, takes 5 ps

~$0.44 / 5\text{ps} = 90 \text{GHz (180 Gbaud)}$

120-Gbaud case, same modulator

With de-emphasis EQ

Average loss ~ 0.009 = -20.5 dB

Thus ~ 5.0 dB extra loss when doubling baud rate if use same modulator, provided modulator has 2-pole roll-off. May be worse due to DAC, driver, and package roll-off.
Digital equalization (and short modulator) example
InP modulator

Fig. 4. EO responses of latest IQ modulator PIC (1.5-V $V_T$ design)

Y. Ogiso, OFC 2018.


120 GBd
128 GBd
112 GBd

160-GBd PAM4

Y. Ogiso, OFC 2018.
Si and InP modulator comparison

Si

InP

Driver

SiPh modulator

Termination

Driver

InP modulator

Termination

Shorter due to smaller $V_{\pi L}$ (InP: 1 V-cm, Si: 2 V-cm)
Lower RF losses since n-doped InP has low optical loss

The series resistance causes voltage to drop along the line at high frequencies

- p- and n-doped Si has high optical loss
- p-doped InP has high optical loss but n-doped InP does not
Modulation mechanism comparison

\[ \Delta n_r = -8.8 \times 10^{-22} N_e - 8.5 \times 10^{-18} N_h^{0.8} \]

\[ \Delta n_i = 2.5 \times 10^{-26} N_e^{1.2} + 2.2 \times 10^{-24} N_h^{1.08} \]

*\( N_e \) = free electron density

*\( N_h \) = free hole density
Temperature control

The QCSE effect in InP requires temperature control to keep the band edge from moving too much.
Ring modulators

- Very compact
- Wavelength and temperature sensitive
  - Need integrated laser so laser and modulator track together
- Self-heating of ring causes pattern-dependence
- Can reach 50 Gbaud, but very difficult to reach 100 Gbaud
  - Benefit of ring comes from high Q


53 Gbaud
2.5 Vpp drive
Photodiodes
Photodetectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Dark current</th>
<th>Resp.</th>
<th>Opt BW</th>
<th>Elec BW</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge p-i-n</td>
<td>2 nA @ -1V</td>
<td>1.2 A/W</td>
<td>1000 nm</td>
<td>90 GHz</td>
<td>4% Ge – Si lattice mismatch</td>
</tr>
<tr>
<td>InP p-i-n</td>
<td>1 nA @ -2V</td>
<td>1.0 A/W</td>
<td>600 nm</td>
<td>150 GHz</td>
<td>Higher mobility</td>
</tr>
</tbody>
</table>
Low optical losses

Equivalent resp: 0.7 A/W
Excess loss: 2.5 dB

1 A/W
1.0 dB

Theoretical limit: lossless, 100% quantum efficiency
(1.25 A/W)

(intrinsic loss: 12 dB)

fiber to PD responsivity, A/W in dB

50 mA/W
Ge-on-Si photodetectors

p-i-n structure is most used today

Ge absorption spectrum

Avalanche in Si is dominated by one carrier, unlike InP, so APD has lower noise.
Faster photodetectors + TIA

Speed limited by transit time

Saturated velocity in Ge $\sim 5 \times 10^6$ cm/s

For 0.25 $\mu$m wide junction, $\sim 90$ GHz BW (130 Gbaud).
Integration and packaging
Single-chip coherent transceiver

370-nm bandwidth demonstration

240 Gb/s 16-QAM

Bit Error Rate

Received Power (dBm)

-30 -25 -20 -15 -10

1260 nm
1310 nm
1350 nm
1500 nm
1530 nm
1550 nm
1580 nm
1620 nm
1630 nm

1310 nm

1550 nm

1610 nm

11.5-13.0 dBm
Pluggable coherent module evolution

All using only SiPh (> 150,000 shipped)
Packaging

2.5D


3D


Monolithic

Acacia, unpublished.

MCM


B. Milivojevic, et al., OFC, paper Oth1D.1, 2013.
MCM packaging

Driver
PIC
Fiber v-groove block
TIAs
Passives

LTCC ceramic

Solder balls

64 Gbaud 16 QAM

400G pluggables using 3D + MCM
Trends in Coherent Transceivers

- 30-40% year over year reduction in size, power and cost
SiPh transceiver history

Coherent detection

IMDD

1 km 10 km 100 km 1000 km 10000 km


Reach

Time

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PIC commercial deployment

- 1-2 elements/PIC
- 10-100 elements/PIC
- 1,000+ elements/PIC if deep learning or beam steering becomes successful commercially

Quantity shipped worldwide:
- 10M
- 1M
- 100k
- 10k

Year:
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

Technologies:
- SiPh VOA
- EML
- PLC AWG
- SiPh PAM4 40G
- InP 10-ch OOK TXR
- SiPh coh TXR
- SiPh PAM4 400G

- 10M
- 1M
- 100k
- 10k
- 2030
Lasers
Integrated lasers in silicon photonics

Monolithic

Er-doped oxide

Er-doped Al₂O₃

Wafer-to-wafer

Die-to-wafer

Die-to-die


Jung et al., APL (2017)

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Tunable laser using SiPh external cavity

- Compact yet long cavity
- Easy to control (many monitors)
- Low tuning power consumption
- Low-noise (i.e., thermal) phase shifters
Dual laser used as multi-channel WDM source

Potential EDFA solution for pluggables

Achieve optical gain with mostly software and electronics changes and relatively minor PIC changes
No additional III-V chip
No extra footprint except 3-m EDF coil

EDF vs. SOA
1. Better NF
2. Uncooled
3. No nonlinearity
4. Pol. indep.
5. Lower power cons.

Foundries
Foundries

• 6 SiPh foundries today
  – 3 @ 200 mm wafers, 3 @ 300 mm wafers
  – 2 @ 248-nm litho, 4 @ 193-nm litho
  – 4 offer PDKs
IC commercial deployment

- EICs
  - 3 orders of magnitude difference!
  - Large foundries won’t heavily invest in PICs
  - PIC costs will be high compared to EICs
  - PICs will use old EIC generations

Unless…

Consumer application for PICs comes along
Outlook
SiPh in coherent and IMDD

Coherent

IMDD

69-Gbaud 64 QAM

600 Gb/s

53-Gbaud PAM4 x 4

400 Gb/s

Courtesy of Acacia Communications
What is coming in 1-5 years?

• 106 – 140 Gbaud transceivers
  – Enables 800G LR1 (coherent), 1.6T DR8 (IM-DD)
• Coherent lite
  – 10 km reach
• Multi-carrier coherent PICs
What is coming in 5-10 years?

- On-board optics for integration with switch, AI, and similar ASICs
- < 2 pJ/bit short-reach optics
Conclusion
Conclusion

• Modulator speeds heading toward 130-140 Gbaud
  – SiPh can get there with heavy equalization
  – InP is already there, but is wavelength- and temperature-sensitive
• 50-Gbaud SiGe APDs reported
• Multi-channel tunable lasers reported
• Compact optical gain reported

Thank you