Integrated DWDM Photonics 2.0 for Green Exascale Supercomputing in HPE

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ARPA-E ENLITENED Annual Review Meeting
Oct. 30 – Nov. 1, 2019, Coronado, CA, USA
Exascale computing

**Exascale computing** | a billion billion calculations per second | \(1,000\times\) the first petascale computer in 2009

- Manufacturing
- Weather
- Energy
- Retail
- Financial Services
- Life Sciences

1989 **apollo**

2016 **sgi**

2019 **PathForward ($80M)**
Photonic Interconnected Exascale

100’s racks can behave as a single server

Reduces energy to move data

Reduces cost to move data

Optimizes bandwidth per pin

High-radix topologies become possible
HPE DWDM Photonics 1.0

Chen, OI (2015); Wu, APC (2016)
Li, JSSC 50, 3145 (2015)
HPE DWDM Photonics 2.0
ARPA-E OPEN 2018 Program

– Title: **ULTRA-ENERGY-EFFICIENT INTEGRATED DWDM OPTICAL INTERCONNECT (ULTRALIT)**

– Goal: A fully-integrated, silicon-based, DWDM optical transceiver solution with over 1 Tb/s data rate and <1.5 pJ/bit energy efficiency at 50 °C
Heterogeneous InAs/GaAs QD comb lasers

- Low-threshold and robust operation up to 100 °C
- 14 comb lines (100 GHz) for error-free external modulation
- Noise comparable to the best commercial lasers

Kurczveil, OE 24, 16167 (2016); PTL 30, 71 (2018); ISLC (2018)
High-speed MOS capacitor modulation

Athermal tuning and faster photon lifetime modulation

- Leakage current: 20-50 fA @ +/-4 V swing $\Rightarrow$ ~1.6 nm/pW vs. thermal/carrier injection tuning
  ~sub or a few nm/mW:
  >1,000,000,000X improvement!

- Lock the laser and modulator wavelength to the grid within 10 °C

- Zero-chirp operation

- Faster photon lifetime laser direct modulation

Dai, NJP 11, 125016 (2009)
Huang, IPC (2017)
Liang, OFC (2018)
Enhanced heterogeneous passive components

- Coupled ring add/drop or interleaver with athermal power-free controllability
- Grating coupler with enhanced coupling efficiency and spectral bandwidth
Low-voltage SiGe avalanche photodetectors

- Operation voltage: <-10 V
- Quantum efficiency: 83%

Breakdown voltage: -6 V

Huang, Optica 3, 793 (2016); Zeng, Optica 6, 772 (2019)
Unique strategies in ULTRALIT

<table>
<thead>
<tr>
<th>Power</th>
<th>Bandwidth</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon-based DWDM light source</td>
<td>↓</td>
<td>↑</td>
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<tr>
<td>Smart interleaver/splitter</td>
<td>↓</td>
<td>↑</td>
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<tr>
<td>MOSCAP modulation</td>
<td>↓</td>
<td>↑</td>
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<tr>
<td>MOSCAP athermal tuning</td>
<td>↓</td>
<td>↓</td>
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<tr>
<td>Sensitive APD Rx</td>
<td>↓</td>
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<tr>
<td>Enhanced passive PICs</td>
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</tbody>
</table>

- on-chip laser (WPE=5%)
- off-chip laser (WPE=5%)
- MRR thermal total (ref. only)
- MRR modulator
- SiGe APD
- Total w/ on-chip laser
- Total with off-chip laser

Energy efficiency (pJ/bit) vs. Rx sensitivity (dBm)

- 25 Gb/s/Ch.
- ~9X improvement
- ~10 dBm improvement
### Pros and Cons to use quantum-dot lasing medium

<table>
<thead>
<tr>
<th>Feature</th>
<th>Comb laser with external modulation for &gt;Tb/s traffic (up to 2 km)</th>
<th>Directly modulated ring laser array for x00 Gb/s traffic (up to 500 m)</th>
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</thead>
<tbody>
<tr>
<td>Gain stability at high temperature</td>
<td>😊</td>
<td>😊</td>
</tr>
<tr>
<td>Wide gain bandwidth</td>
<td>😊</td>
<td>😞</td>
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<tr>
<td>Low amplitude noise (RIN)</td>
<td>😊</td>
<td>😊</td>
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<tr>
<td>Low sensitivity to reflection</td>
<td>😊</td>
<td>😊</td>
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<tr>
<td>Better immunity to defects</td>
<td>😊</td>
<td>😊</td>
</tr>
<tr>
<td>Quick gain saturation</td>
<td>😐</td>
<td>😞</td>
</tr>
</tbody>
</table>

Arakawa, APL 40, 939 (2011)
Huang, JOSA-B 35, 2780 (2018)
Heterogeneous QD microring lasers

- 20 °C threshold current: 1.5-3 mA ($J_{th} \approx 200-400$ A/cm$^2$)
  [Hero device: $I_{th} = 0.7$ mA ($\approx 90$ A/cm$^2$)]
- Max. output power: $\sim 1$ mW
- cw lasing up to 70 °C stage temperature
- Single-mode possible, multi-mode typical
- Direct modulation bandwidth up to 8 GHz, 2-5 GHz typical

Zhang, Optica 6, 1145 (2019); Fan, OFC (2019)
Optical injection locking (OIL)

- Enhance modulation bandwidth
- Reduce the relative intensity noise (RIN)
- Reduce the frequency noise
- Lock slave’s phase and frequency

M#  SMSR
M1: 48 dB
M2: 49 dB
M3: 51 dB
M4: 55 dB
M5: 55 dB
M6: 56 dB
M7: 56 dB
M8: 54 dB
M9: 54 dB
M10: 49 dB
M11: 44 dB

10 dB
Proposed heterogeneous DWDM OIL System-on-chip

- 1 master to lock multiple slave
- Enable single-mode slave operation
- Extend slave modulation bandwidth
- Guide slaves to uniform DWDM grid
- Provide selective optical gain to master comb
- Enable comb line power equalization

Liang, ACP (2019)
Optical injection locking setup

PPG: Pseudorandom pattern generator (PRBS: $2^{15}$)
LCA: lightwave component analyzer
DCA: digital communication analyzer
PD: photodetector
TIA: transimpedance amplifier.
OIL-enabled single-mode operation

- Tunable single-\(\lambda\) Santec laser (up to 13 dBm)
- \(\Delta\lambda_{\text{comb}}=50\ \text{GHz} \ (\sim 0.3\ \text{nm})\), FSR\(_{\text{ring}}=3\ \text{nm}\)
- Tunable optical filter to select 1 or 5 comb line(s) to inject
Dynamic performance enhancement

Free-running slave

- 4 Gb/s, SNR=2.4 dB

Comb master (1λ) (5λ)

- 15 Gb/s, SNR=4.7 dB
- 15 Gb/s, SNR=4.3 dB

Free-running slave (5λ) adjacent mode

- 15 Gb/s

Comb master (1λ)

- 20 Gb/s, SNR=4.7 dB
- 20 Gb/s, SNR=NA

Graph showing S21 response (dB) vs. Frequency (GHz):

- Free running 21 mA
- Free running 18.5 mA
- QIL, comb (1λ), slave 21 mA
- QIL, comb (1λ), slave 18.5 mA
- QIL, Santec, slave 21 mA
Acknowledgement
– LSIP group members and alumni
– Collaborators: John Bowers (UCSB), Zhixin Liu (UCL)
– Funding agencies