Programmable Nanophotonics for Quantum Information Processing and Artificial Intelligence

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Funding
Outline

1. Programmable nanophotonic processor
2. Photonic quantum information processing
3. Optical neural network
Programmable nanophotonic processor

88 MZIs, 26 input modes, 26 output modes, 176 phase shifters

Image courtesy of AFRL Rome
The array in action

Strong laser input
Unit cell performance

\[ U = \begin{bmatrix} e^{i\phi} \cos \theta & e^{i\phi} \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \]

\[ \Omega \in \{\theta, \phi\} \]

\[ \Omega (\text{rads}) \]

\[ T (W) \]

> 70 dB visibility
Quantum simulator architecture

Unit cell performance as a qubit

(a) Dual rail encoding

\[ |\psi\rangle = \cos \theta |0\rangle + e^{i\phi} \sin \theta |1\rangle \]

(b) Waveguide

(c) Number of States

\[ 1 - F(\rho, \sigma) = 1 - \text{Tr}[\sqrt{\sqrt{\rho} \sigma \sqrt{\rho}}] \]
Randomized benchmarking
Photosynthesis and quantum transport

Noisy scattering simulations
Fully-integrated photonic quantum computer
Heralded single-photon sources

Nicholas C. Harris, Davide Grassani, Angelica Simbula, Mihir Pant, Matteo Galli, Tom Baehr-Jones, Michael Hochberg, Dirk Englund, Daniele Bajoni, Christophe Galland
On-chip single-photon detectors


In collaboration with Prof. Karl Berggren at MIT
Deep learning
Artificial neural network

\[ Z^{(1)} = W_0X \quad h^{(i)} = f(Z^{(i)}) \quad Y = W_n h^{(n)} \]
Can it be done with light?

Singular value decomposition

$M = U \Sigma V$
Optical neural network
Vowel recognition task

- 90 people speak 4 vowels
- Power in log-spaced freq. bands
- Fourier transform
- 360 samples: 180 training + 180 test

a) ONN

<table>
<thead>
<tr>
<th>Vowel spoken</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>39</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>5</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>0</td>
<td>16</td>
<td>25</td>
</tr>
</tbody>
</table>

b) 64-bit computer

<table>
<thead>
<tr>
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<th>B</th>
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<th>D</th>
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<tr>
<td>A</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>35</td>
</tr>
</tbody>
</table>

c) Correctness (%)

Correctness: 90

360 samples: 180 training + 180 test
The case for optical neural network

- Fast, low-energy matrix computation
- Low thermal noise: good for analog encoding
- NN’s more resilient to errors than general-purpose computer

Equivalent compute performance of ONN:

$$R = m \times N^2 \times BW \text{FLOPS}; \ m=\text{layers}, \ N \times N \text{matrix multiplication}, \ BW=\text{bandwidth (}>10 \ \text{GHz})$$

<table>
<thead>
<tr>
<th></th>
<th>Energy/FLOP</th>
<th>Error propagation?</th>
<th>Classification error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Electronic (GPU)</td>
<td>~100 pJ/FLOP*, including memory retrieval</td>
<td>zero</td>
<td>Low</td>
</tr>
<tr>
<td>Optical NN</td>
<td>~ 10/N fJ (signal re-gen)</td>
<td>Better than 10-bit precision for N=4096 with 16-bit phase settings</td>
<td>Low (at least for low N&lt;4096)</td>
</tr>
</tbody>
</table>

*M. Horowitz, Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2014 IEEE International, 10–14. IEEE.*
Summary

1. Quantum simulation

2. Optical neural network: potential for nearly energy-free matrix multiplication
Outlook

- CMOS and photonic integration
- Novel quantum photonic devices
  - Single-photon sources
  - Single-photon detectors: Ge APDs
  - MEMS integration

Mikkel Heuck, Mihir Pant, Dirk Englund arXiv:1708.08875
Tae Joon Seok, Niels Quack, Sangyoon Han, Richard Muller, Ming Wu Optica 3 (1) 64-70 (2016)