LightRidge: An Open-source Compiler Framework for Diffractive Optical ML Architectures

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Introduction

- Diffractive Optical Neural Networks (DONNs): mimicking the propagation and connectivity properties of FCN.
  - Light-speed computation
  - Easily scaled and parallelized
  - High energy efficiency
  - Complex-valued description

- Challenges for implementation:
  - Domain knowledge required
  - Lack of accelerated physics computation kernels
  - Algorithm-hardware miscorrelation gap

- LightRidge: an end-to-end open-source compiler framework for the design, training, and hardware deployment, and performance evaluation of DONNs systems.
  - Precise physical simulation algorithm w/ regularization
  - GPU-accelerated complex-valued computation kernel
  - User-friendly and versatile DSL

Diffractive Optical Neural Networks (DONNs)

Low-level Modeling

<table>
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<tr>
<th>Description</th>
<th>Model-level APIs</th>
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<tr>
<td>Lase source &amp; Profiles</td>
<td>lr.laser</td>
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<tr>
<td>Light Diffraction</td>
<td>lr.layers</td>
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<td>Phase Modulation</td>
<td>lr.layers</td>
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<td>Measurement</td>
<td>lr.layers</td>
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<td>Training</td>
<td>lr.train.utils</td>
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<td>Hardware Deployment</td>
<td>lr.weight_dump, lr.to_system</td>
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Optics details

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<tr>
<th>LightRidge</th>
<th>CPU</th>
<th>GPU</th>
<th>Batch Opt</th>
<th>LoC (MB)</th>
<th>LoC (train)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LightPipe</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>1.2x</td>
<td>n/a</td>
</tr>
<tr>
<td>Customized (PyTorch)</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>20×</td>
<td>50×</td>
</tr>
</tbody>
</table>

Emulation Runtime Speedups

- LightRidge-CPU results
- LightRidge-GPU results
- LightPipe-CPU (1x results)
- CPU speedups

Design Space Exploration of DONNs Architecture

- Grid-search based DONN DSE
  - Novel training algorithms with complex-valued regularization
    - Light intensity captured at detector as loss function
    - Seamless integration with SOTA auto-differential engines
    - Enable training with iterative SGD optimizations

- Analytical model based DONN DSE
  - Polynomial analytical estimator to bypass and transfer physics-aware domain knowledge between systems
  - Gradient boosting regression & MLE optimization

LightRidge Code Example

```python
class Model(torch.nn.Module):
    def __init__(self,...)
    self.diffraction_layers_1 = ...
    self.diffraction_layers_2 = ...
    self.last_diffraction = 
    def forward(self, x:)
        a = self.diffractive_layers(x)
        a = self.last_diffraction(a)
        return output
```

Experimental Results

- Emulation Accuracy Evaluation
  - Random uniform noise at detector with 1%, 3%, 5%
  - Less accuracy degradation for more complex models

Confidence evaluation of DONNs trained with laser wavelength of 532nm

Dataset | Depth | Lin et al. | 0% | 1% | 3% | 5% |
--------|-------|------------|----|----|----|----|
MNIST   | D=1   | 0.670      | 0.960 | 0.398 | 3 | 0 | 0 |
D=3     | 0.910 | 0.978      | 0.961 | 0.876 | 0.661 |
D=5     | 0.950 | 0.979      | 0.979 | 0.979 | 0.977 |
MNIST   | D=1   | 0.540      | 0.874 | 0.340 | 0.001 | 0 | 0 |
D=3     | 0.830 | 0.889      | 0.791 | 0.518 | 0.278 |
D=5     | 0.870 | 0.890      | 0.889 | 0.886 | 0.883 |

Reference