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

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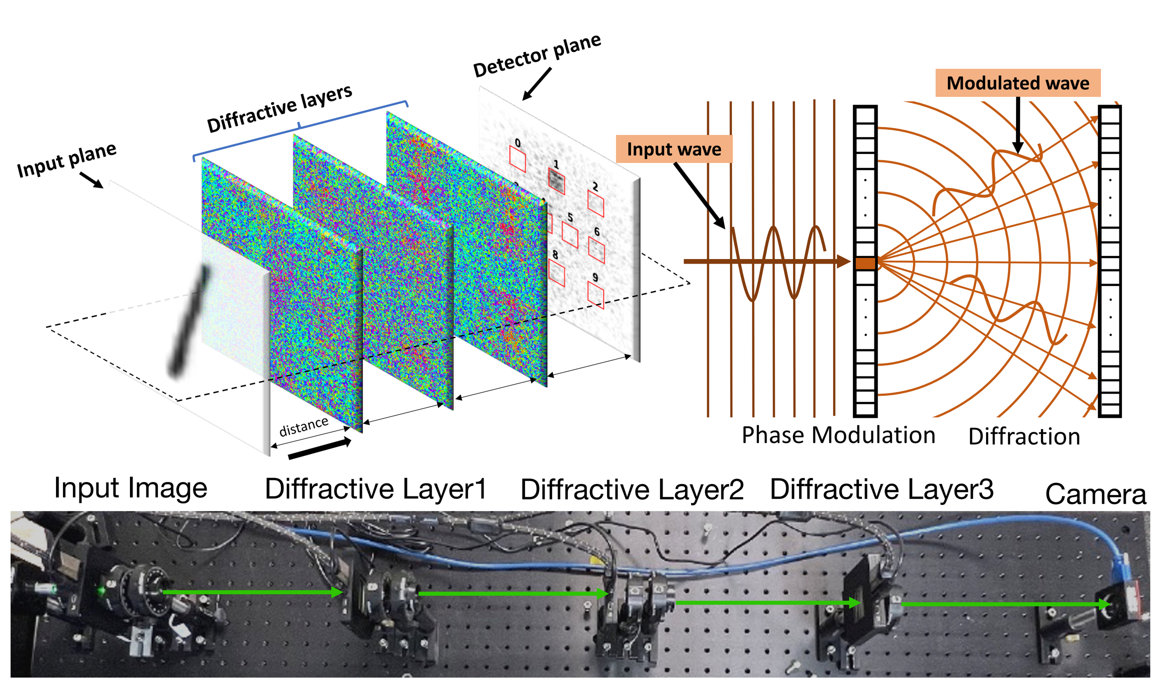
Introduction

- **Diffractive Optical Neural Networks (DONNs):** mimicking the propagation and connectivity properties of FCN.
  - Light-speed computation
  - Easily scaled and paralleled
  - High energy efficiency
  - Complex-valued description
- **Challenges** for implementation :
  - Domain knowledge required
  - Lack of accelerated physics computation kernels
  - Algorithm-hardware miscorrelation gap

	Optics kernels	CPU	GPU	Batch Ops	LoC (val)	LoC (train)
LightRidge	✓	✓	✓	✓	1	1
LightPipe[1]	✓	✓	✗	✗	1.2×	n/a
Customized Pytorch/TF	✗	✓	✓	✓	20×	50×

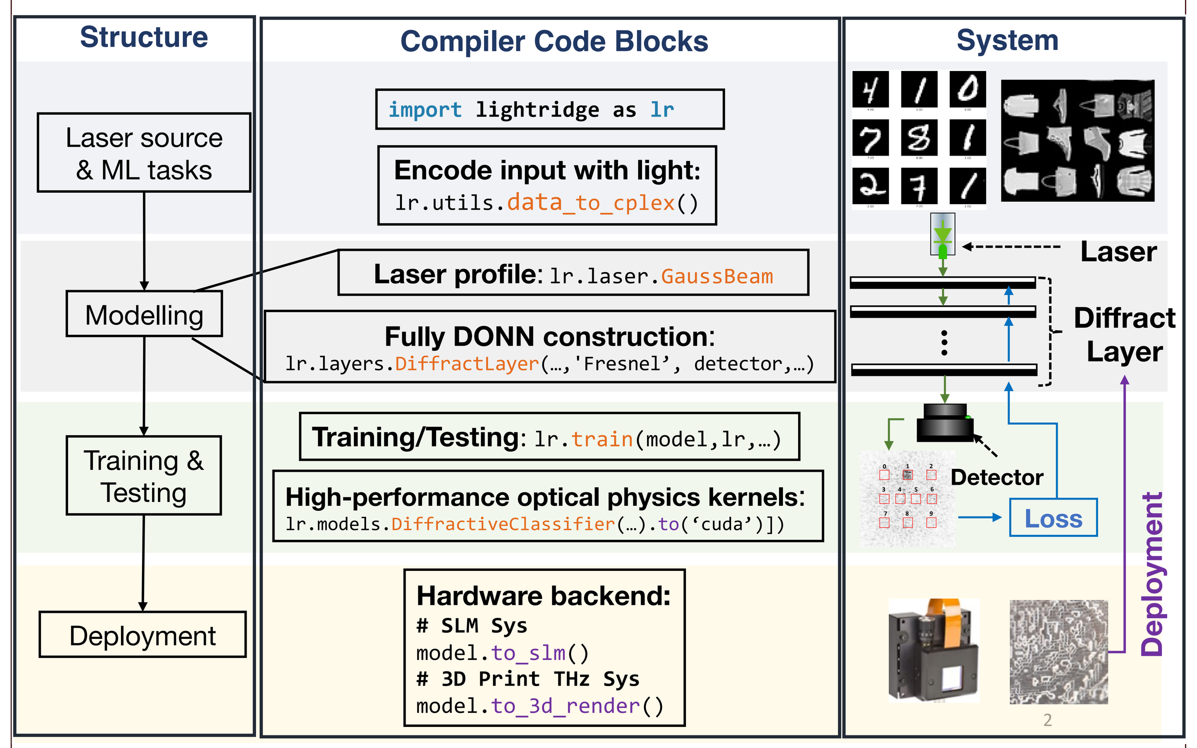
- **LightRidge**: an end-to-end open-source compiler framework for the design, training , design exploration, and hardware deployment for DONNs systems.
  - Precise physical emulation algorithm w regularization
  - GPU-accelerated complex-valued computation kernel
  - User-friendly and versatile DSL

Diffractive Optical Neural Networks (DONNs)



Low-level Modeling	Description	Model-level APIs
Lase source & Profiles	Encode & transfer information in complex value	lr.laser
Light Diffraction	• Connect neurons • Non-trainable • Mathematical approximations • FFT involved	lr.layers
Phase Modulation	• Modify light waves • Targeted trainable • Matrix multiplication • Inverse FFT involved	lr.layers
Measurement	Capture light intensity for predication	lr.layers.detector
Training	Train, optimize, accelerate the system	lr.train.utils
Hardware Deployment	• Coherent laser source • Spatial Light Modulator • CMOS camera	lr.weight_dump lr.to_system

LightRidge Compiler



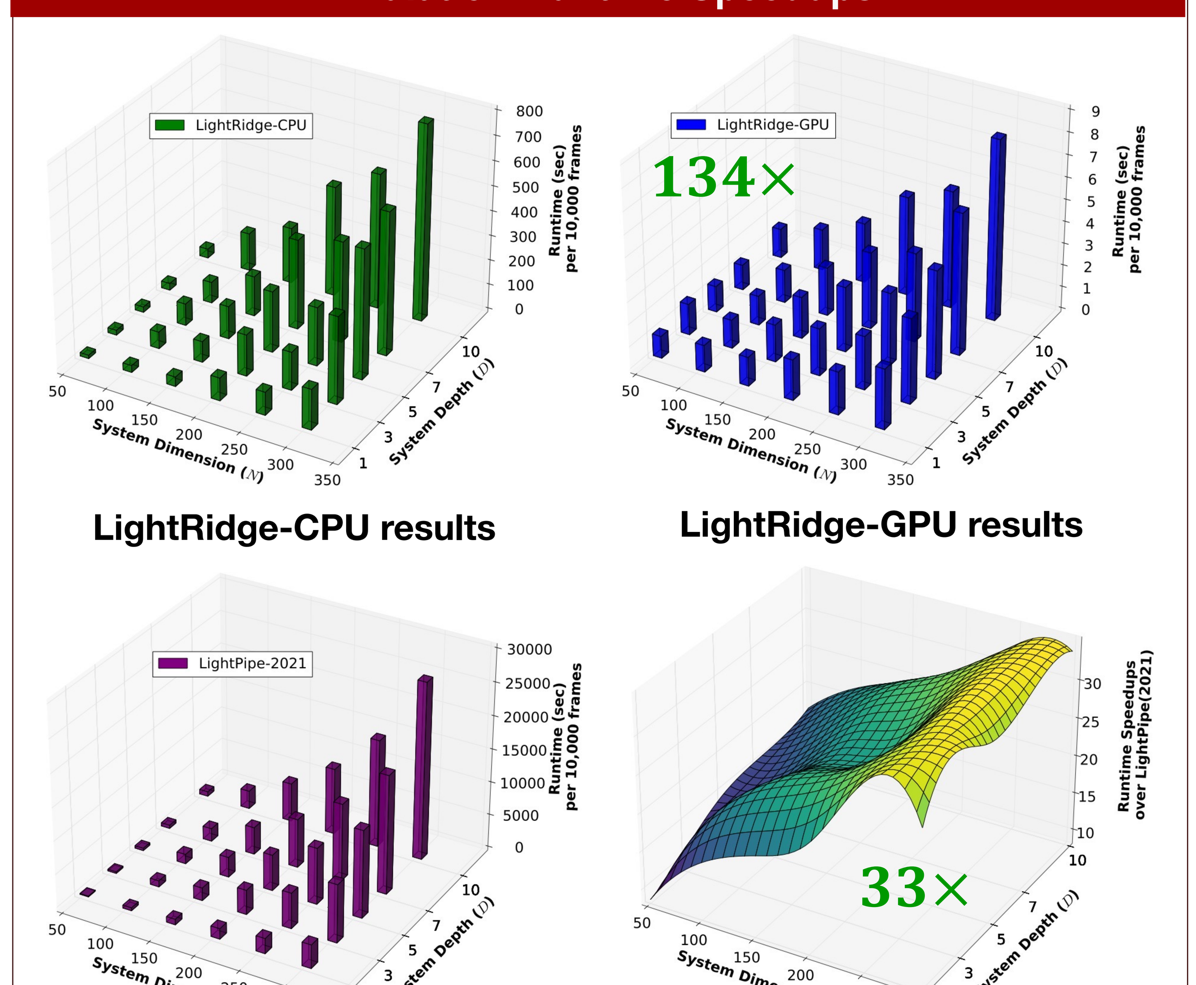
- Novel training algorithms with complex-valued regularization
  - Light intensity captured at detector as **loss function**
  - Seamless integration with SOTA ***auto-differential*** engines
  - Enable training with **iterative SGD** optimizations

LightRidge Code Example

```python
class Model(torch.nn.Module):
    # initial arguments definition for the model
  def __init__(...)
        ...
    self.diffractive_layers_1=l1
    self.diffractive_layers_2=l2
        ...
    self.last_diffraction=layers.DiffractiveLayer(...,
     phase_mode = False)
    self.detector = lr.layers.Detector(...)
  def forward(self, x):
    x = self.diffractive_layers_1(x)
    x = self.diffractive_layers_2(x)
    ...
    x = self.last_diffraction(x)
    output = self.detector(x)
    return output

# emulation and training will be executed on Nvidia GPU.
model = Model(...).to("cuda")
```

Emulation Runtime Speedups



LightRidge-CPU results

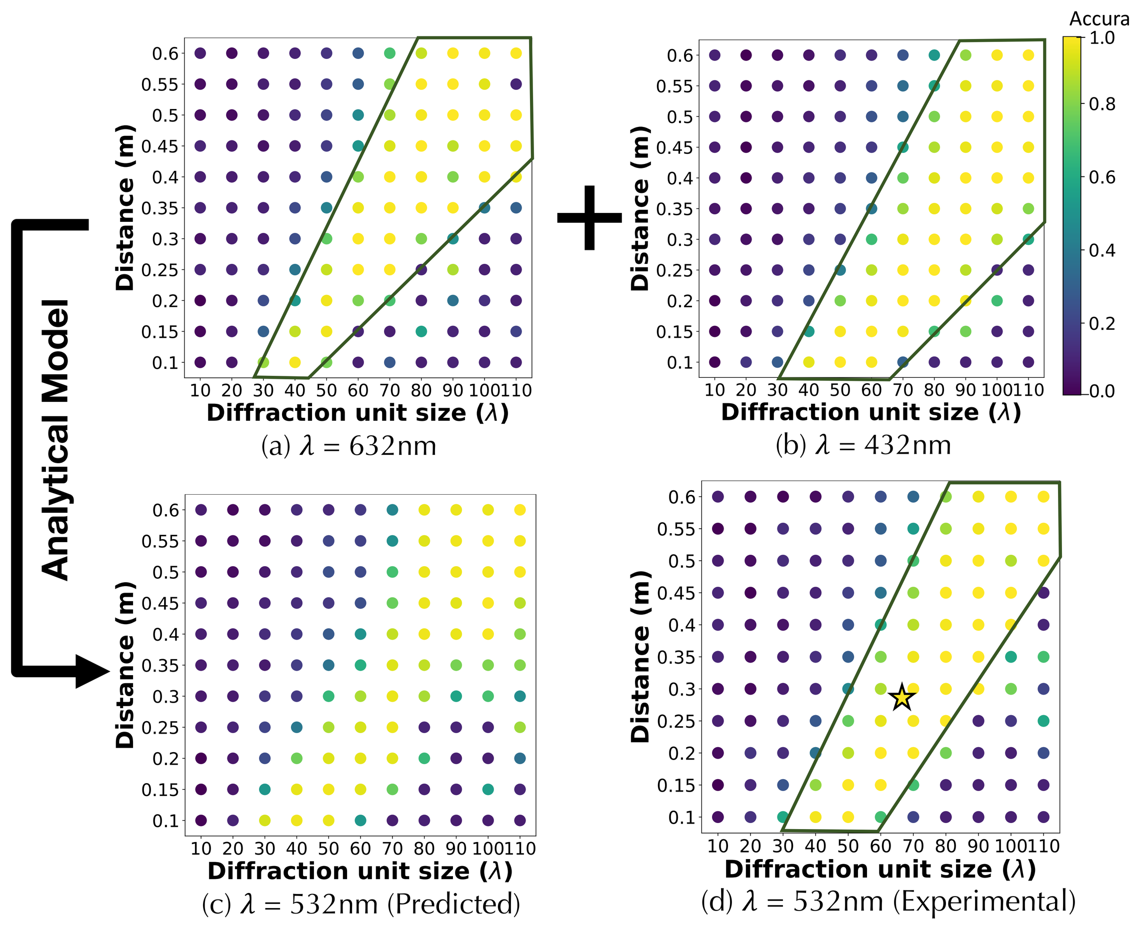
LightRidge-GPU results

LightPipe-CPU [1] results

CPU speedups

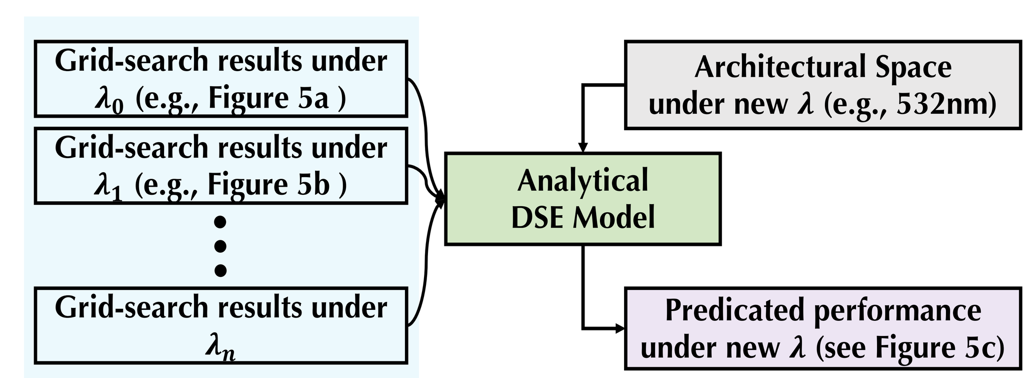
Design Space Exploration of DONNs Architecture

- **Grid-search based DONN DSE**



DSE of DONNs w.r.t diffractive unit size, and diffraction distance

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



Analytical based DSE flow

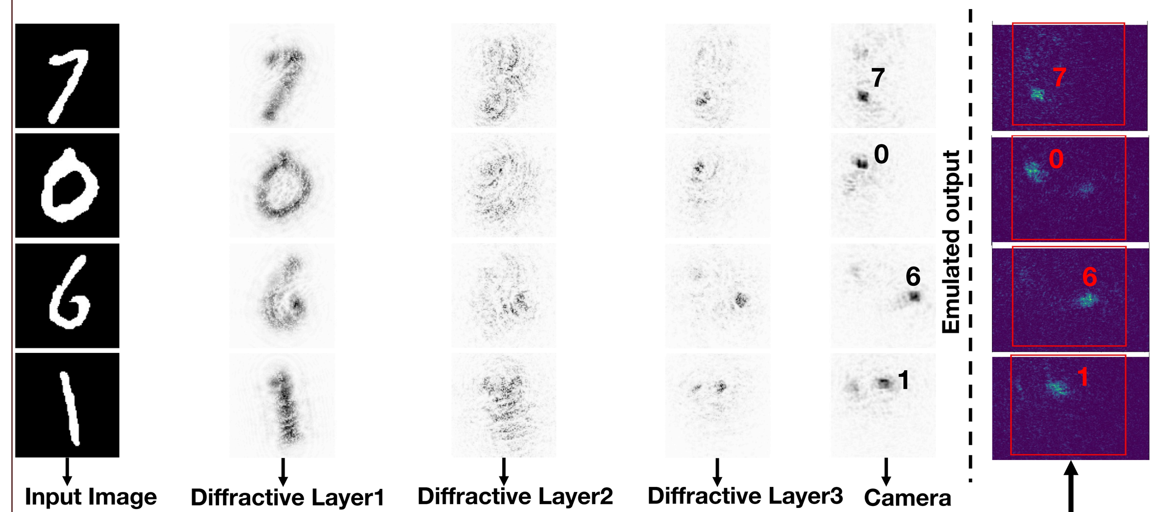
Experimental Results

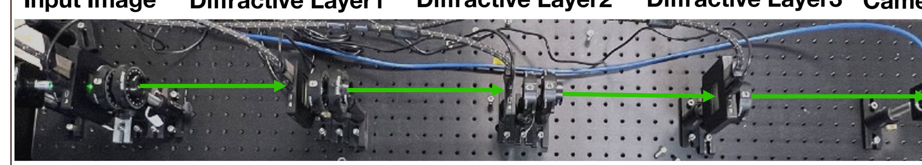
- **Emulation Accuracy Evaluation**
  - Similar high accuracy regardless of system complexity
- **DONNs Confidence Evaluation**
  - Random uniform noise at detector with 1%, 3%, 5%
  - Less accuracy degradation for more complex models

Confidence evaluation of DONNs trained with laser wavelength of 532nm

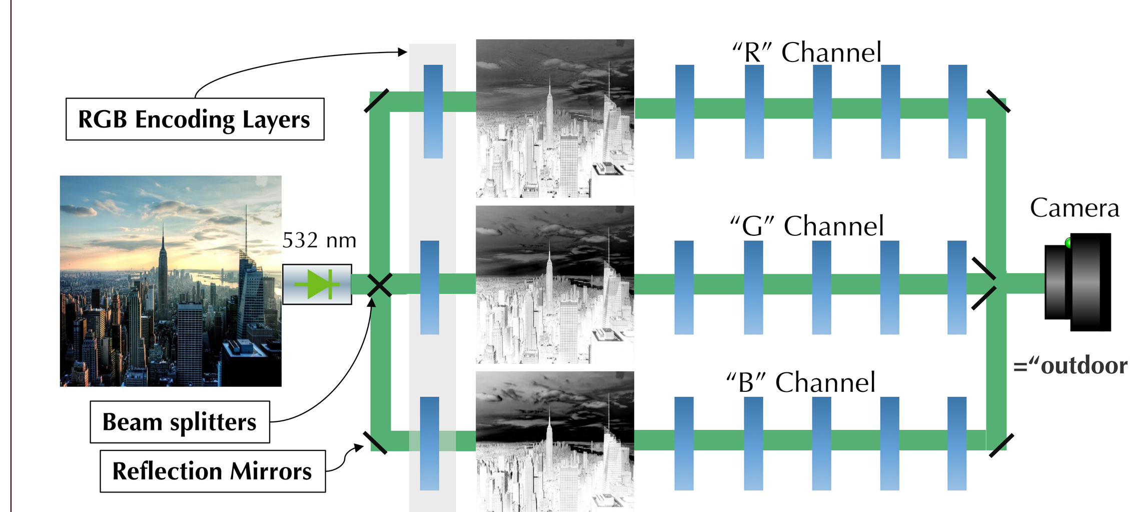
Dataset	Depth	Lin et.al	0%	1%	3%	5%
MNIST	D=1	0.670	0.960	0.398	0	0
	D=3	0.910	0.978	0.961	0.876	0.661
	D=5	0.950	0.979	0.979	0.979	0.977
FMNIST	D=1	0.540	0.874	0.340	0.001	0
	D=3	0.830	0.889	0.791	0.518	0.278
	D=5	0.870	0.890	0.889	0.886	0.883

Physical Validation



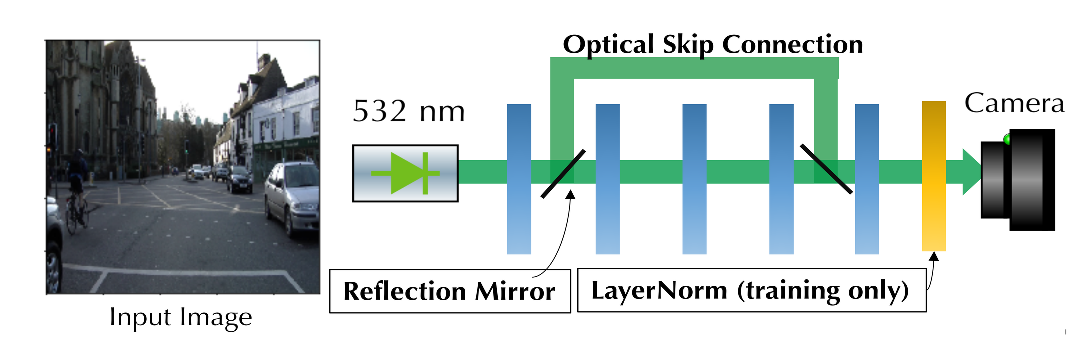


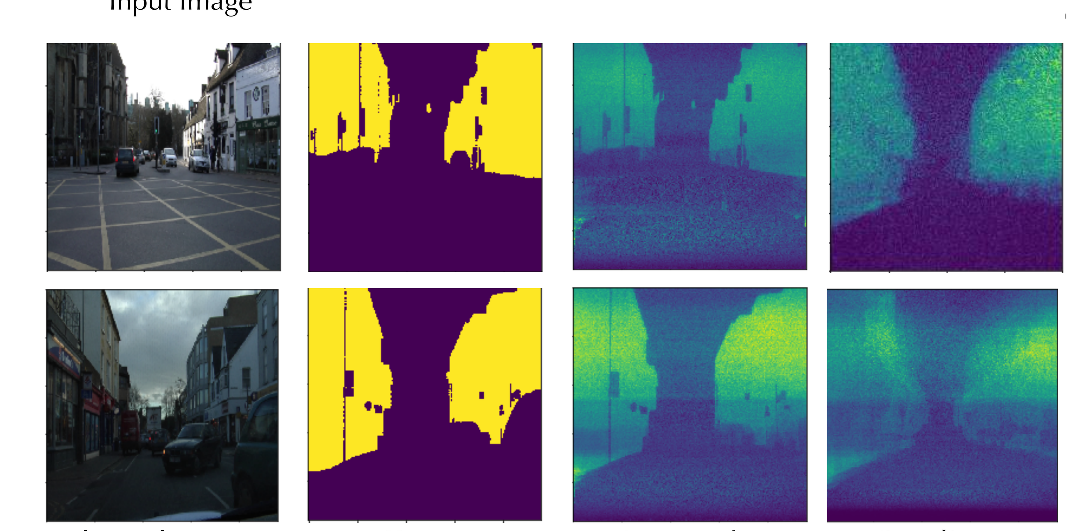
All-optical RGB Image Classification



Place 365	Top-1	Top-3	Top-5
LightRidge	0.52	0.73	0.84
Lin et.al.	0.23	0.48	0.67

All-optical Image Segmentation





Reference

[1] Lightpipes (CPU-only): Software for education in coherent optics," https://github.com/opticspy/lightpipes .

[2] Lin, Xing, et al. "All-optical machine learning using diffractive deep neural networks." Science 361.6406 (2018): 1004-1008.

[3] Li, Yingjie, et al. "Real-time multi-task diffractive deep neural networks via hardware-software co-design." Nature *Scientific reports*11.1 (2021): 1-9.

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