MPSoC'26

NAGOYA UNIVERSITY

The Challenge to Real-time Classification for Distorted QAM Symbols using Optical Neural Networks

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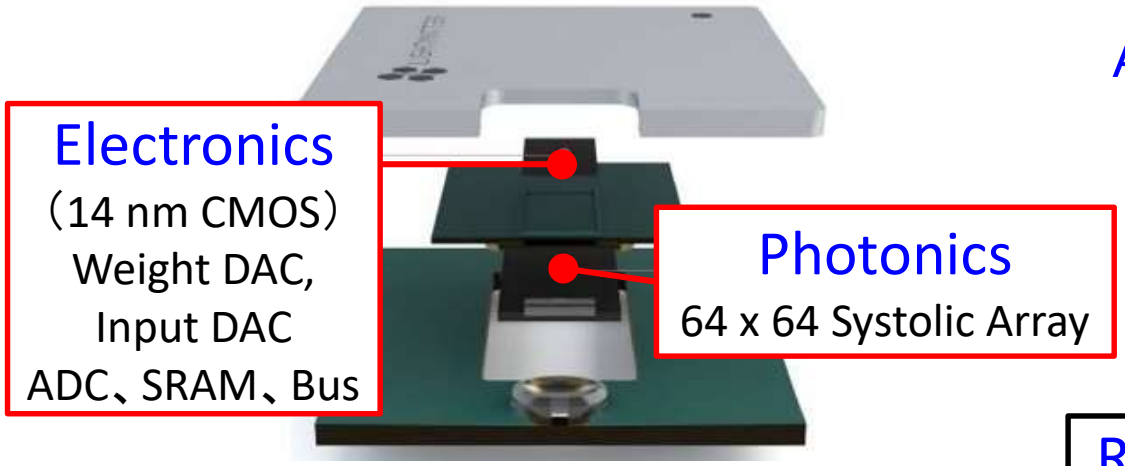
Nagoya University

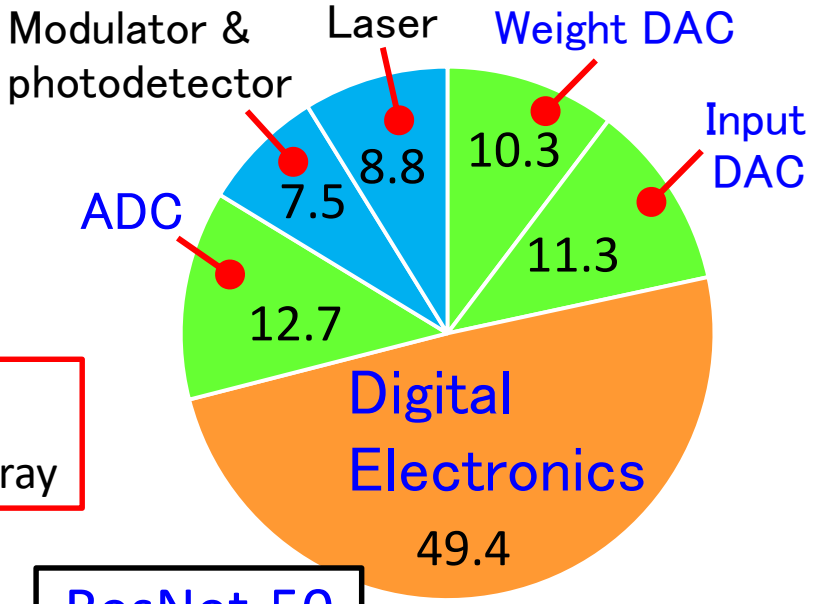
Challenges in Optical Neural Network

Lightmatter Mars

World-first 3D stacked ONN

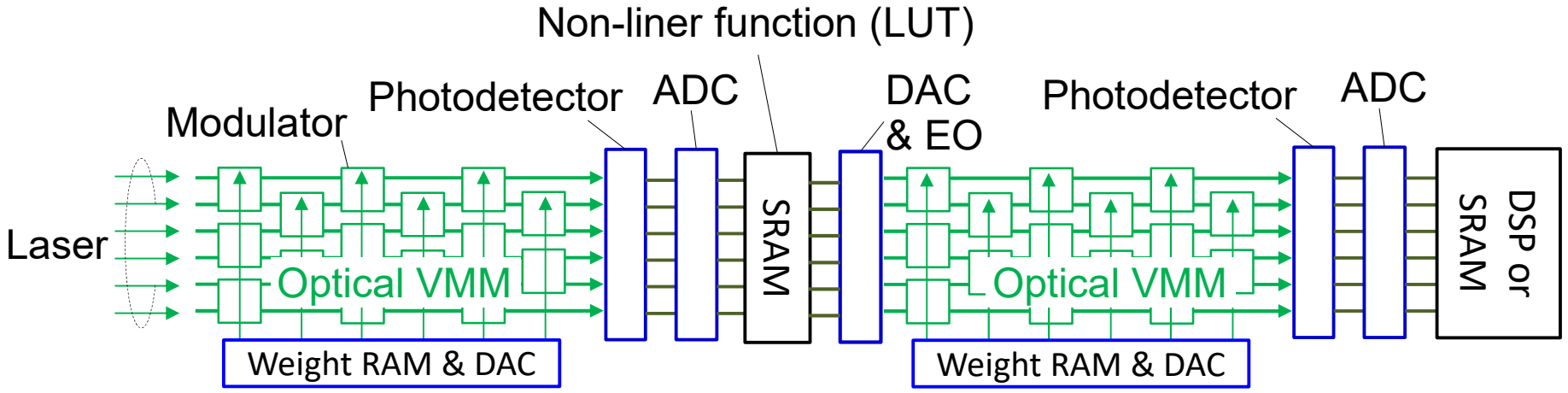


Source：HOT Chips 2020



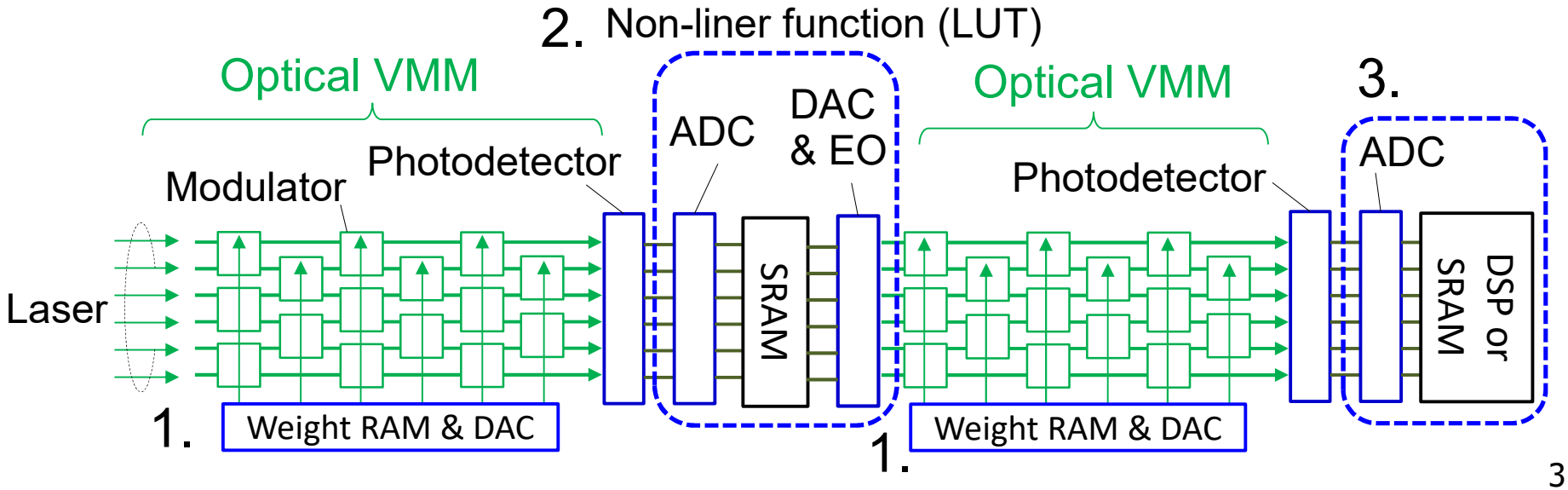
ResNet-50

Power breakdown of Mars (%)



Our Strategy

1. Targeting QAM symbol identification tasks.
   - ✓ Help eliminating access to weight memory.
2. Exploiting energy efficient O-E-O conversion for non-linear function.
3. Incorporating AD-conversion functionality into neural network.
   - ✓ Help replacing multi-bit ADC with 1-bit ADC.



Targeting QAM Classification Tasks

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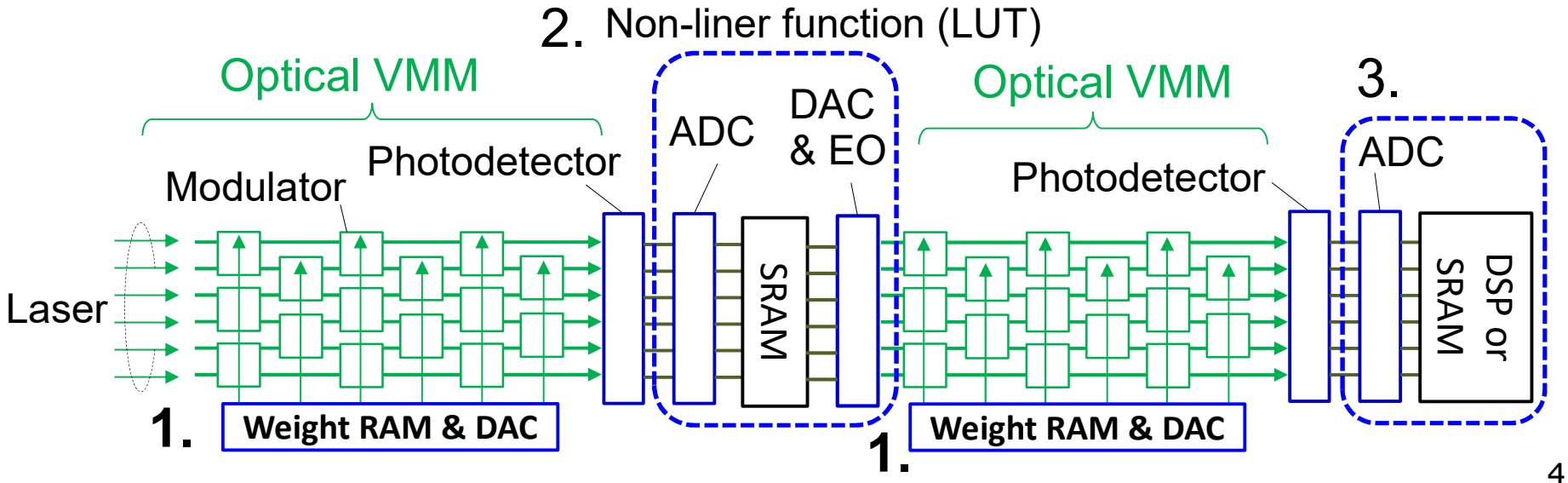
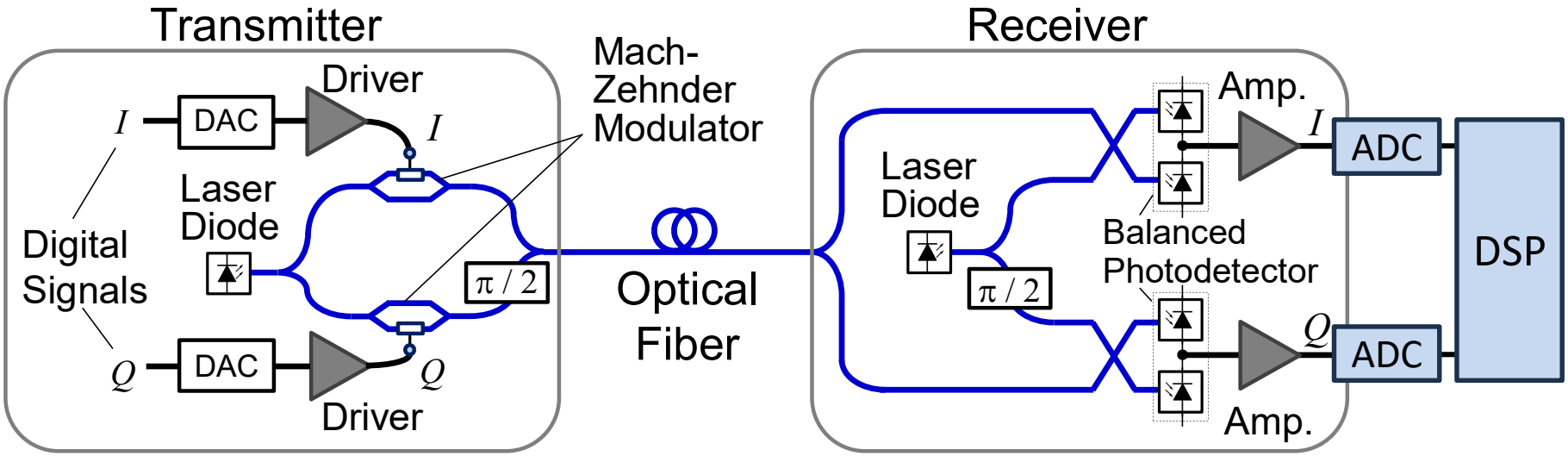
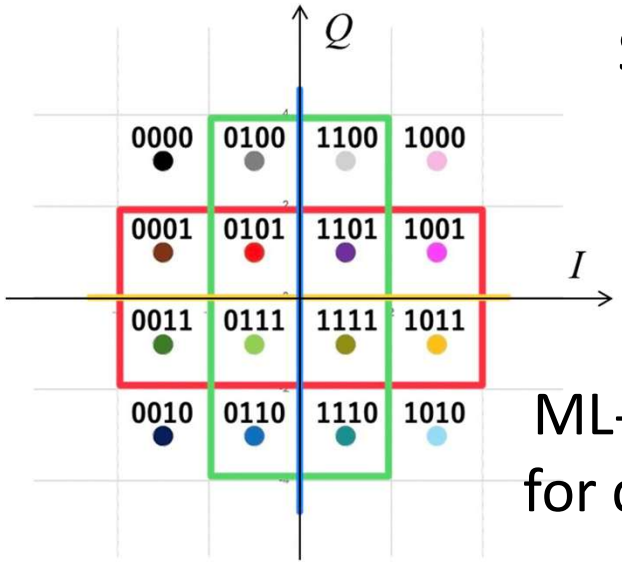
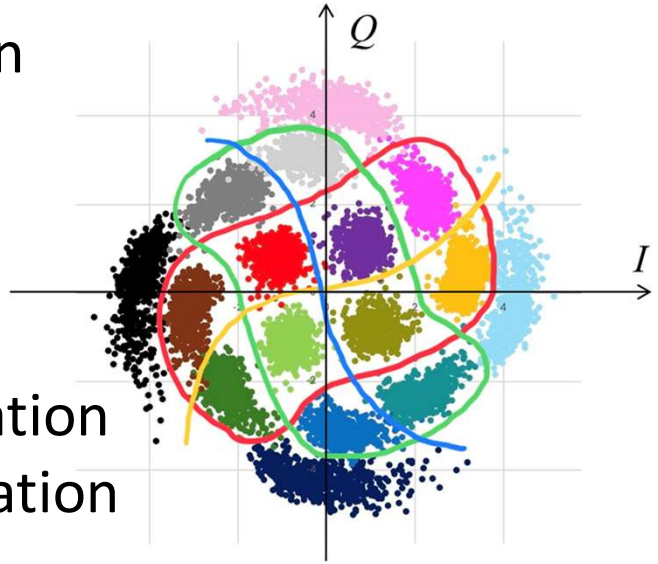


My talk in MPSoC 2025





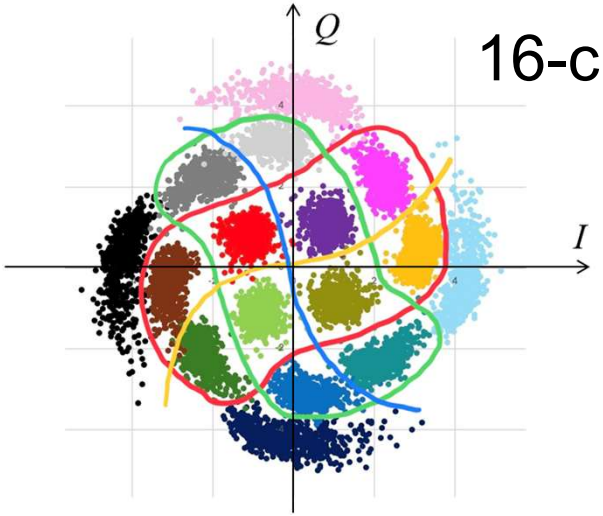
Signal distortion in
16-QAM format



ML-assisted classification
for distorted constellation

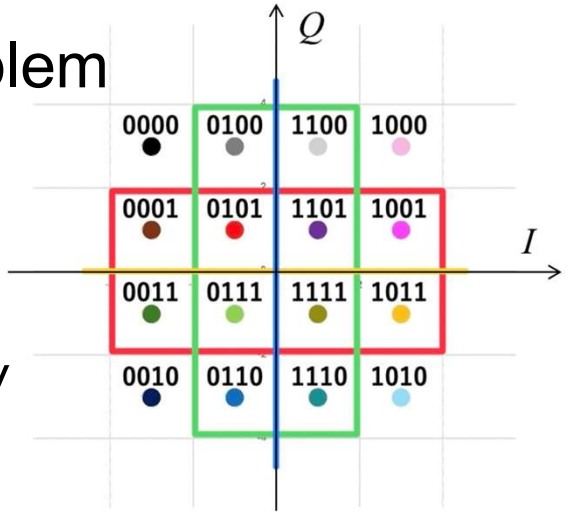
Targeting QAM Classification Task

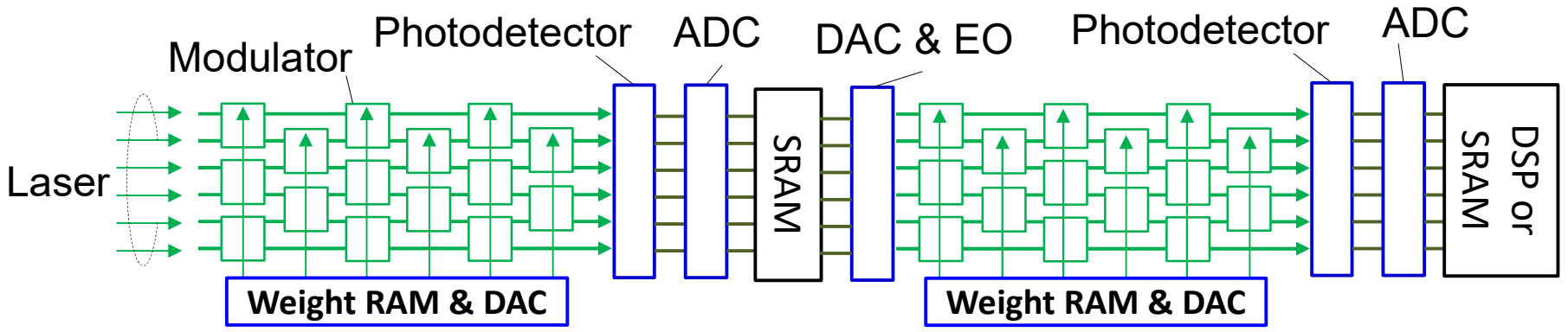
- Simple but non-trivial classification task.
  - ✓ Model size is much smaller than LLM.
  - ✓ Need several tens of GHz operation.



16-class classification problem

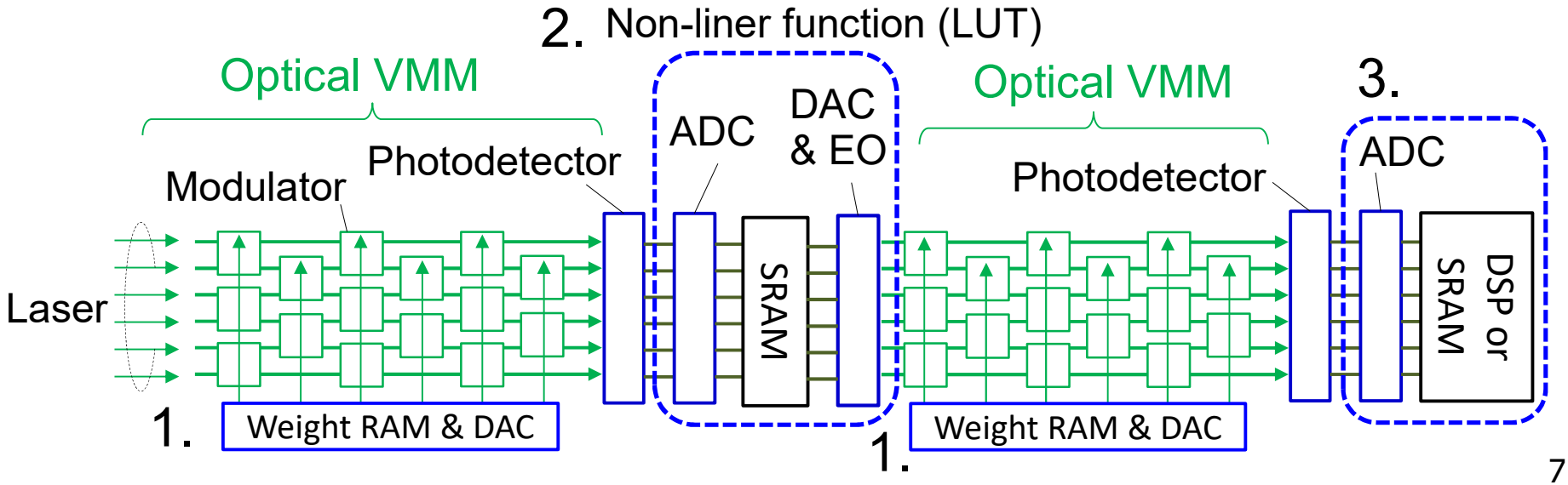
- Typical DSP task
- Causes a large energy consumption





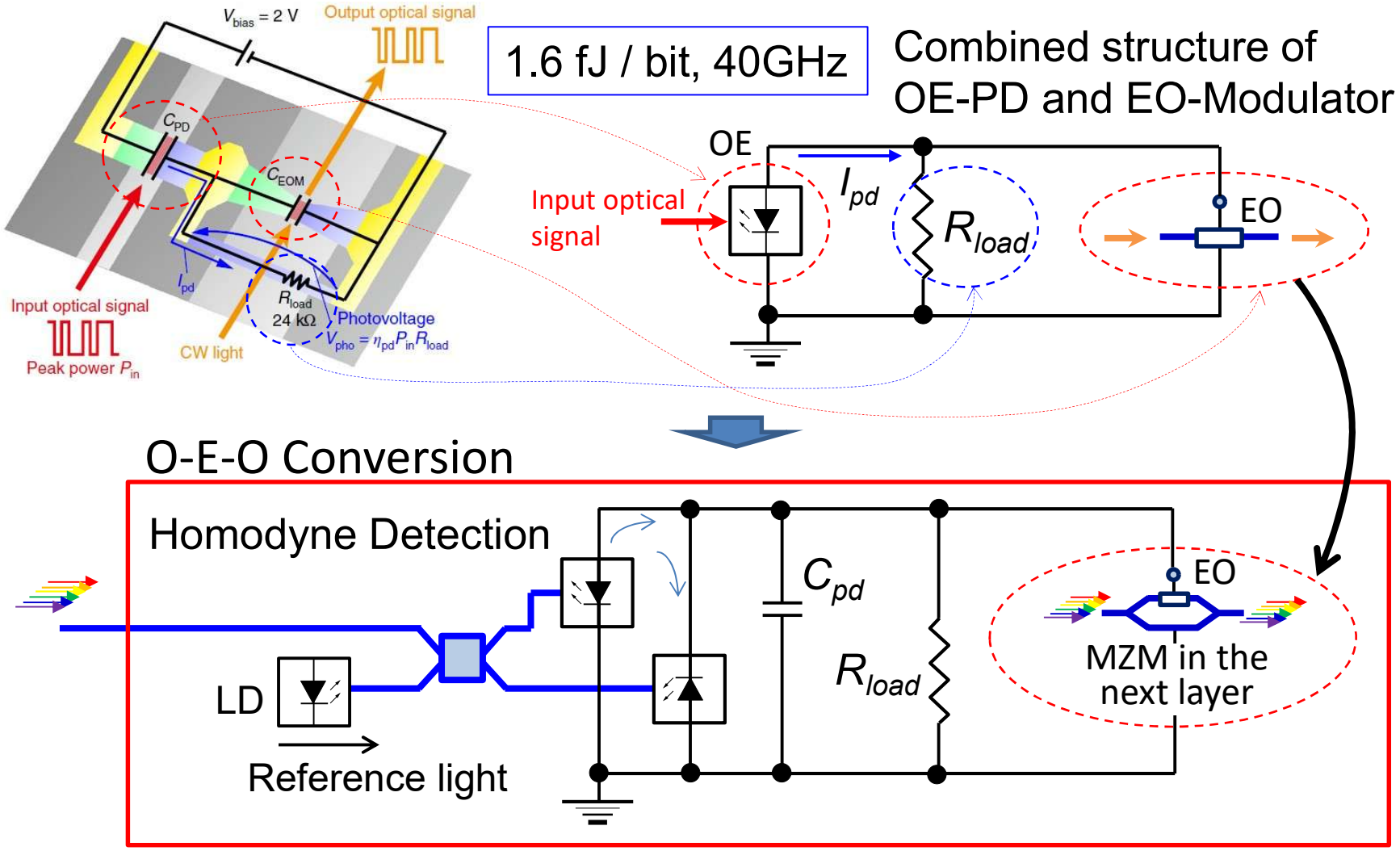
Exploiting Energy Efficient O-E-O

1. Targeting QAM symbol identification tasks.
   - ✓ Help eliminating access to weight memory.
2. Exploiting energy efficient O-E-O conversion for non-linear function.
3. Incorporating AD-conversion functionality into neural network.
   - ✓ Help replacing multi-bit ADC with 1-bit ADC.

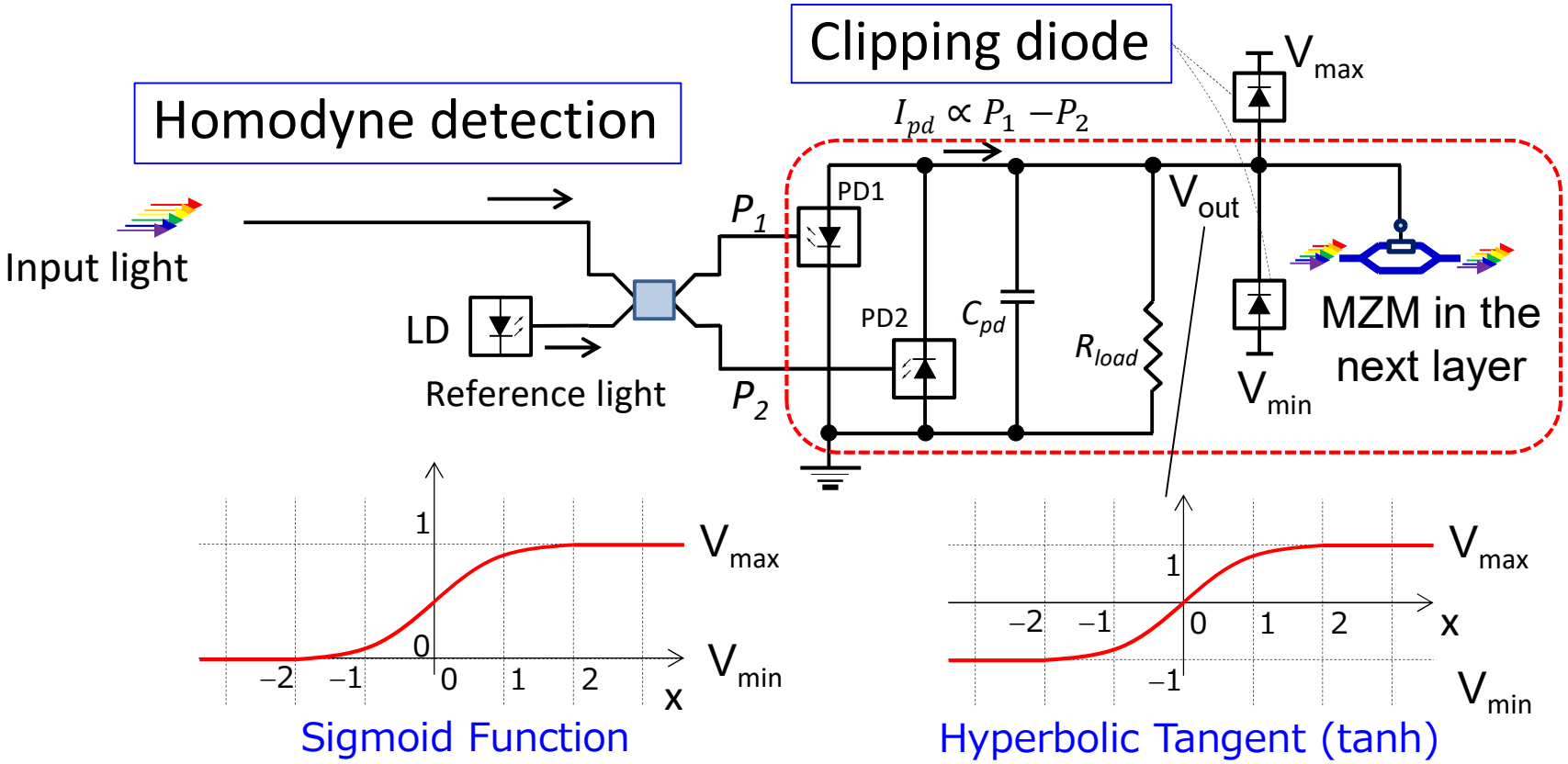


Energy Efficient O-E-O Conversion

K. Nozaki, *et al.* "Femtofarad optoelectronic integration demonstrating energy-saving signal conversion and nonlinear functions," *Nature Photonics* **13**, 454–459 (2019).



Non-Linear Function with O-E-O



1. N. Hattori, Y. Masuda, T. Ishihara, J. Shiomi, A. Shinya, and M. Notomi, “Optical-Electronic Implementation of Artificial Neural Network for Ultrafast and Accurate Inference Processing,” Proc. SPIE OPTO, Mar. 2021.
2. N. Hattori, Y. Masuda, T. Ishihara, A. Shinya, and M. Notomi, “Power-Aware Pruning for Ultrafast, Energy-Efficient, and Accurate Optical Neural Network Design,” Proc. Design Automation Conference (DAC), pp. 1285 – 1290, July 2022.

Incorporating ADC into NN

1. Targeting QAM symbol identification tasks.
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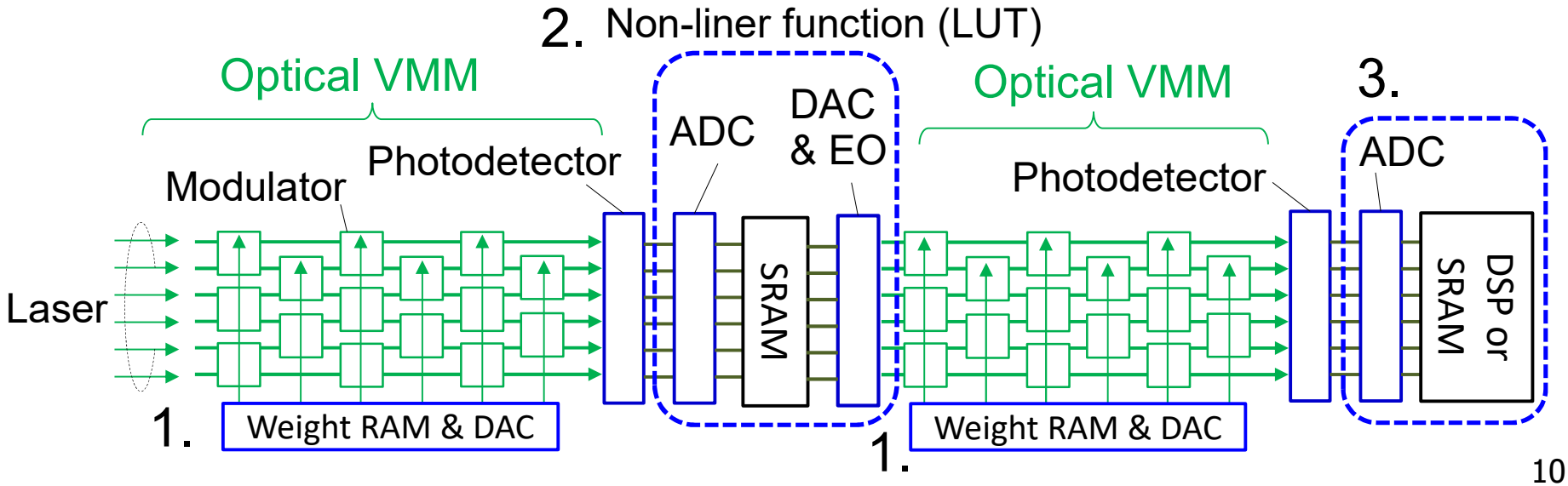
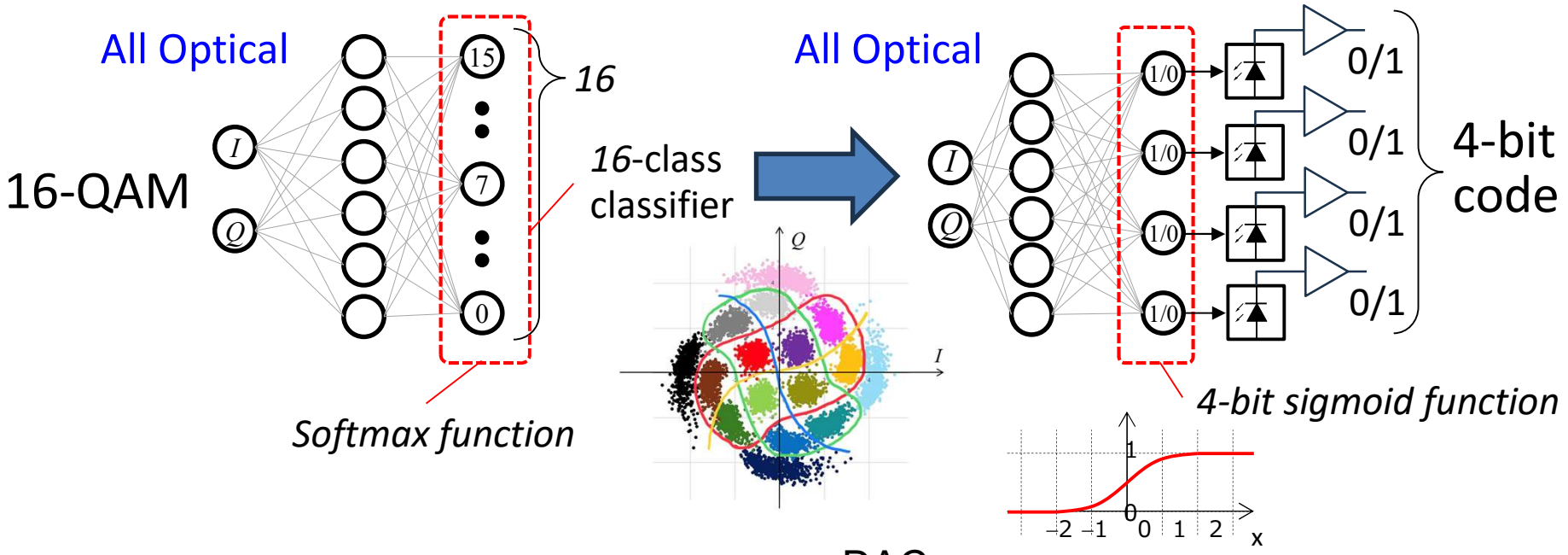
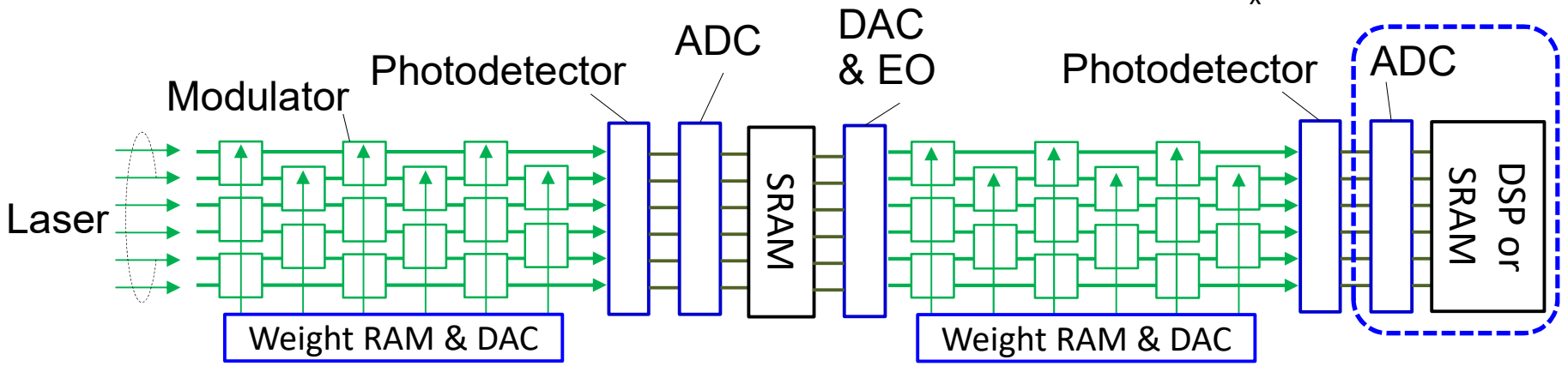


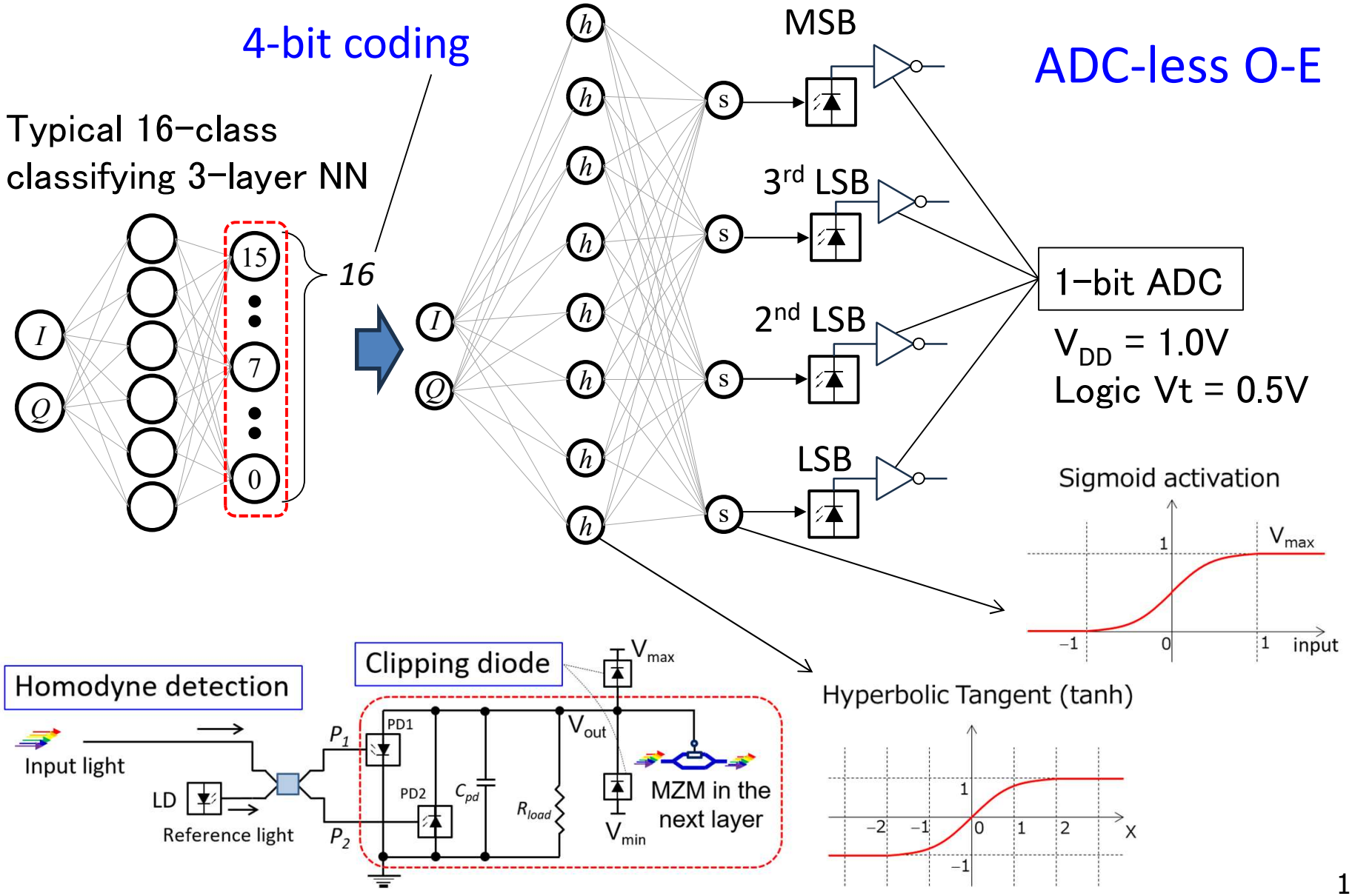
Incorporating ADC into NN

Bandyopadhyay, S., Sludds, A., Krastanov, S. *et al.* Single-chip photonic deep neural network with forward-only training. *Nat. Photon.* **18**, 1335–1343 (2024).





ADC-less Optical Neural Network

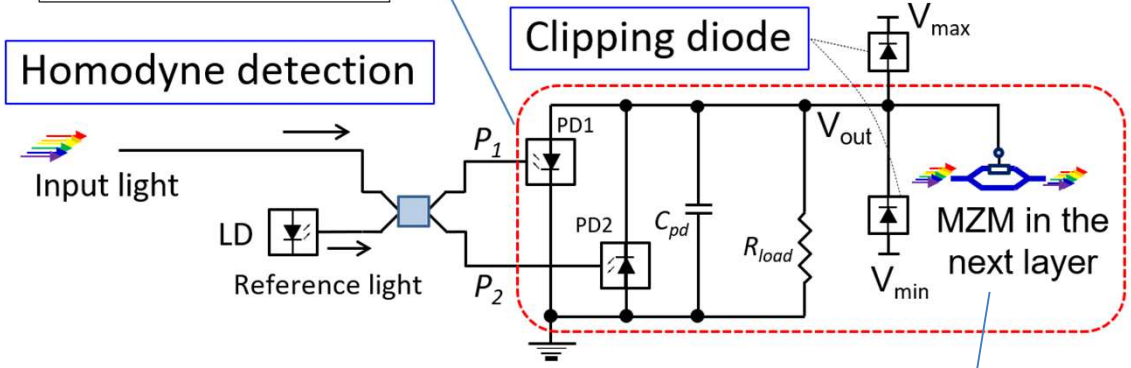


Verilog-SPICE Co-Simulation

- Cadence Xcelium framework
  - ✓ Verilog-AMS, Spectre-SPICE, PSpice

Photodiode SPICE netlist

```
.SUBCKT PHOTODIODE anode cathode
* Define the photodiode as a diode with
* a current source for light
D1 anode cathode MyPhotodiode
* Define the photodiode model parameters
.MODEL MyPhotodiode D (
+ IS=1e-12 N=1 BV=60 IBV=1e-6
+ RS=10 VJ=0.7 CJO=1e-12 M=0.5 FC=0.5
+ + TNOM=25 )
* Add a current source to model light
I_light anode cathode LAPSE=0.001
*  Example: 1mA light current at time = 1ms
.ENDS PHOTODIODE
```



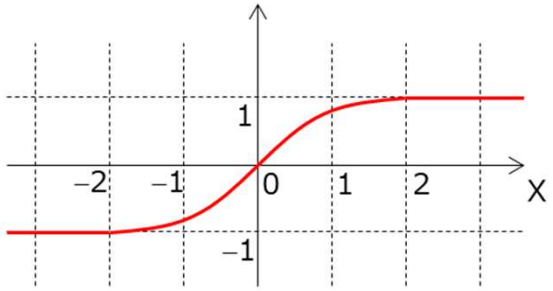
CMOS Logic SPICE netlist

```
Subcircuit Dlatch(clock, xin, yout)
    Instantiate m1 (p-type)
    Instantiate m2 (n-type)
    Instantiate m3 (p-type)
    Instantiate m4 (n-type)
    Instantiate c0
End Subcircuit

Set vdd_S1 = 1.2, vss_S1 = 0.0
Instantiate vdd_I1, vss_I1
```

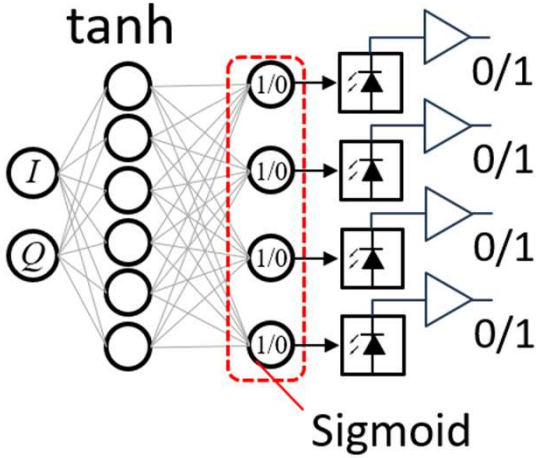
Modulator Verilog-AMS

```
module modulator (out, fbk, wt);
output out;
input fbk, wt;
wreal wt, fbk, out;
real product;
parameter pai = 3.1416 ;

always @(fbk or wt)
  product = $sin( fbk * ( pai / 8 ) ) * ( 1 / 0.383 ) * wt ;
assign out = product;

endmodule
```

Hyperbolic Tangent (tanh)

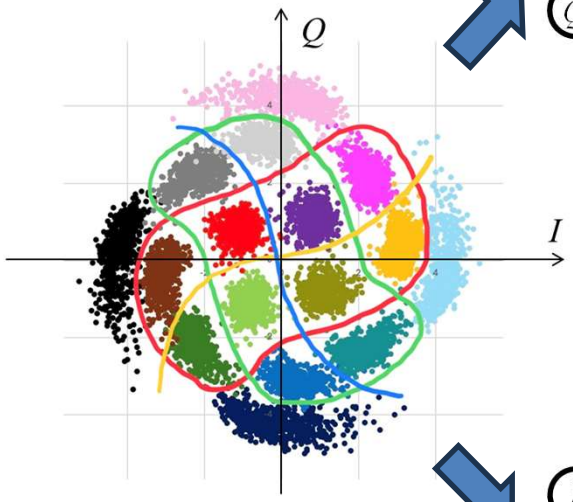


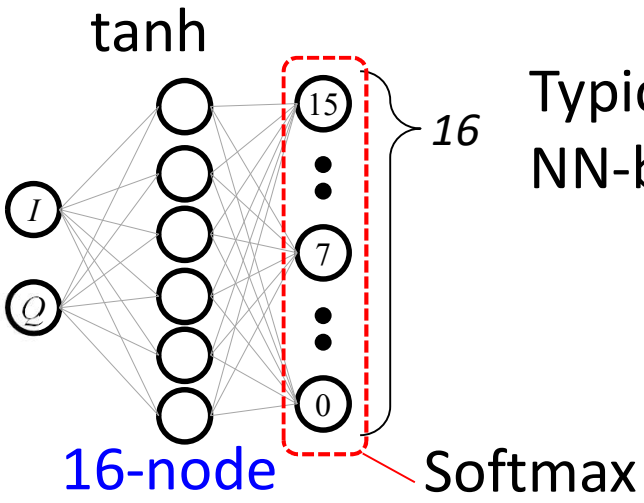
CMOS amp.



3-Layer Neural Network Classification

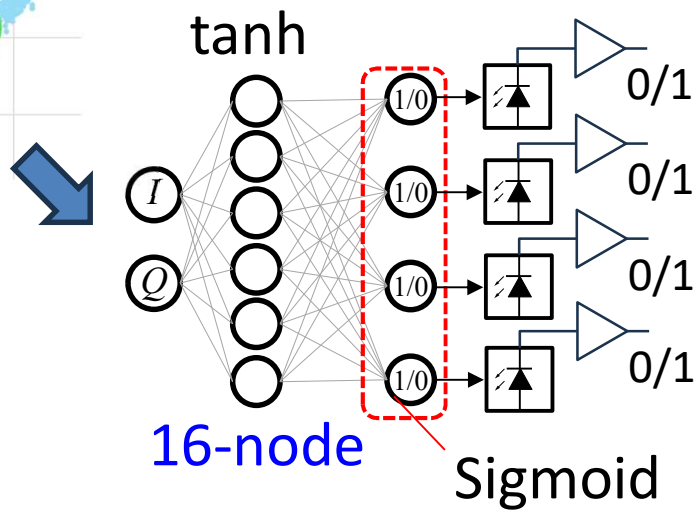
Train: 100K symbols
Test: 10K symbols





Typical *16*-class NN-based classifier

Classification accuracy: 99.07%



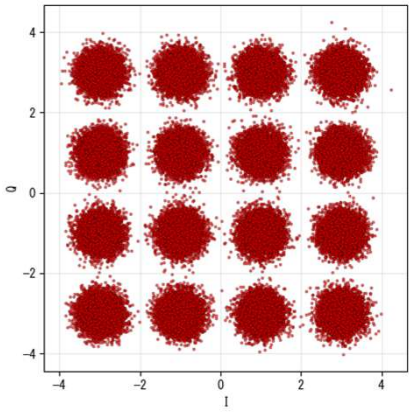
4-output *ADC-less* NN-based classifiers

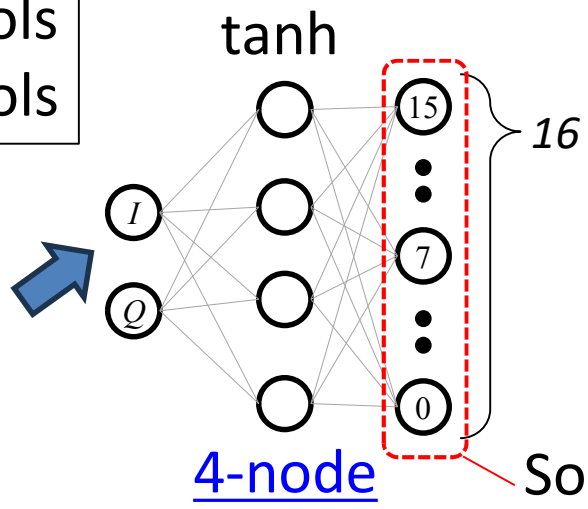
Classification accuracy: 99.04%

Non-Distorted Symbol Classification

Train: 100K symbols
Test: 10K symbols

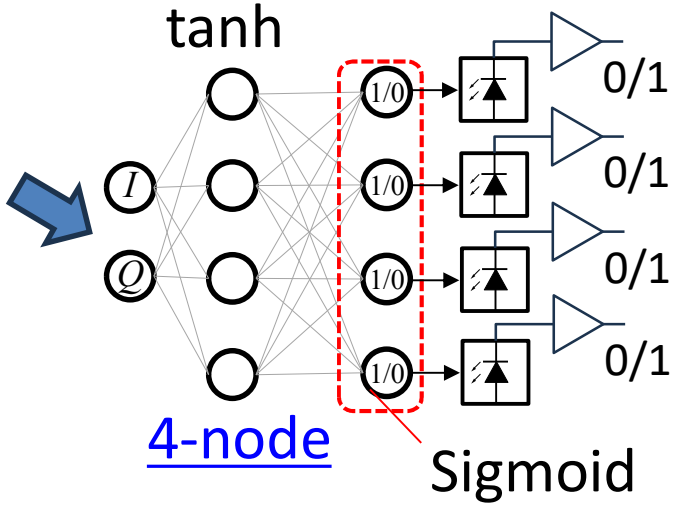
Standard deviation: 0.25





Typical *16*-class NN-based classifier

Classification accuracy: 100%



4-output *ADC-less* NN-based classifiers

Classification accuracy: 100%

Conclusions

- QAM symbol classification task has shown to be a very good application for optical neural networks.
  - ✓ NN model size can be small that helps eliminating access to weight memory.
- Neural network architecture exploiting energy efficient O-E-O conversion for non-linear function is shown.
  - ✓ Help implementing energy-efficient non-linear functions.
- Neural network architecture incorporating AD-conversion functionality into neural networks is shown.
  - ✓ Help replacing multi-bit ADC with 1-bit ADC.
  - ✓ Lead to a reduction of energy consumption of ADC.

Acknowledgement

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- **MEXT/JSPS KAKENHI** Grant Number 24H00072
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Thank you very much!