Photonic Computing
Highlighting Ultimate Nature of Light
Grant-in-Aid for Transformative Research Areas(A)

KYUSHU UNIVERSITY

A Hybrid Opto-Electrical Floating-point Multiplier

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Outline

- ➢Introduction
- ➢OEFM (Opto-Electrical Floating-point Multiplier)
- ➢Evaluation
  - Arithmetic accuracy
  - Latency
  - Energy per floating-point multiplication
- ➢Conclusions

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Expected floating-point arithmetic unit

In machine learning

- Floating-point arithmetic is the most dominant process
- Latency and energy consumption are challenges
- Bfloat16 is preferred in hardware implementations of ML algorithms [1]

➢ The low latency and energy consumption floating-point arithmetic that support Bfloat16 is expected

[1] S. M. Mishra, A. Tiwari, H. S. Shekhawat, P. Guha, G. Trivedi, P. Jan, and Z. Nemec, “Comparison of floating-point representations for the efficient implementation of machine learning algorithms,” in 2022 32nd International Conference Radioelektronika (RADIOELEKTRONIKA). IEEE, 2022, pp. 1–6.

Potential of optical devices

- End of Moore’s Law
- Focus on innovative computing with novel devices
- Natures of optical devices
  - Ultra-low latency
  - Low energy consumption

➢ Floating-point arithmetic units utilizing optical devices are expected to achieve low latency and low energy consumption

Purpose

To propose a floating-point multiplier with

- Low latency
- Low energy consumption
- Sufficient arithmetic accuracy
- Supports Bfloat16

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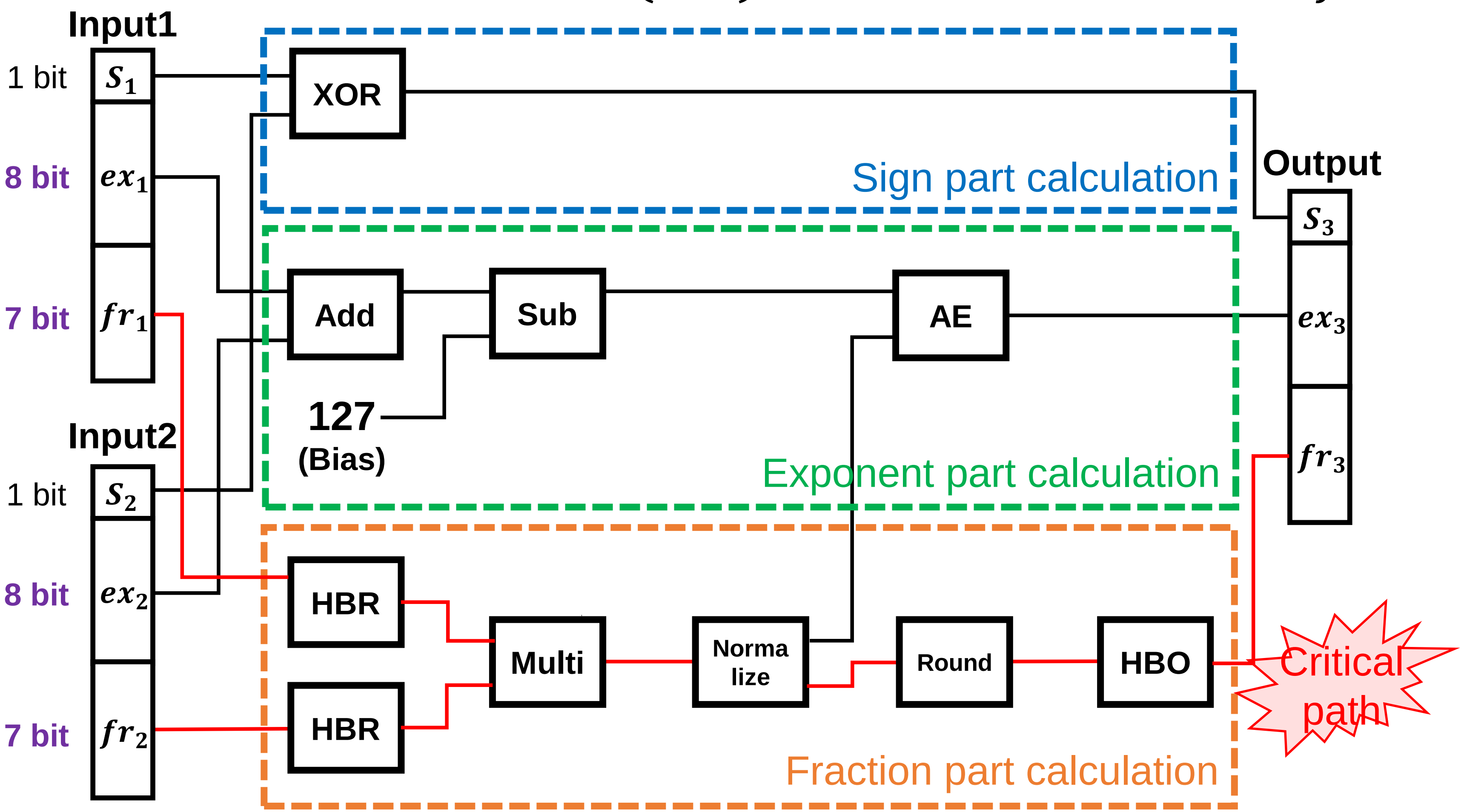
Floating-point multiplier operation flow

Bfloat16 format : $(-1)^{S} \times 2^{(ex-127)} \times 1.fr$



Energy: 0.23%
Latency: 0.02 [ns]

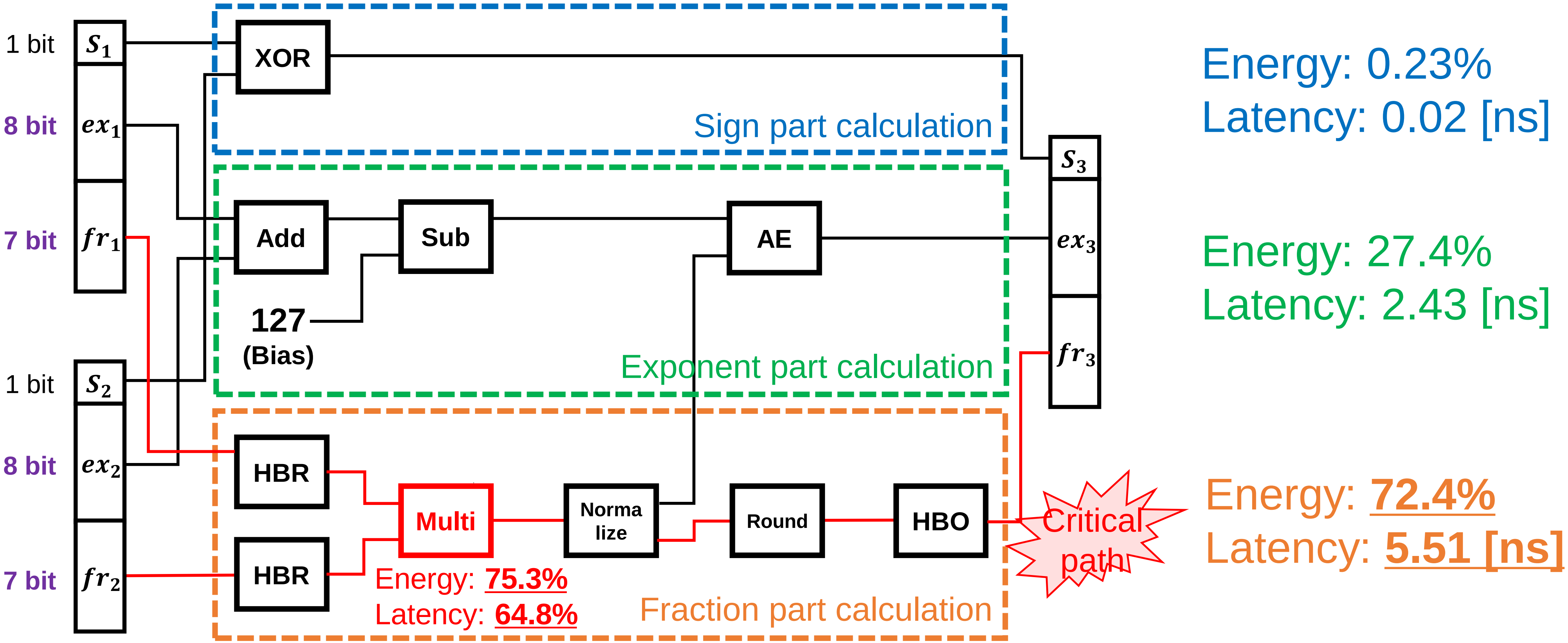
Energy: 27.4%
Latency: 2.43 [ns]

Energy: <u>**72.4%**</u>
Latency: <u>**5.51 [ns]**</u>

Fraction part calculation is the bottleneck

Floating-point multiplier operation flow

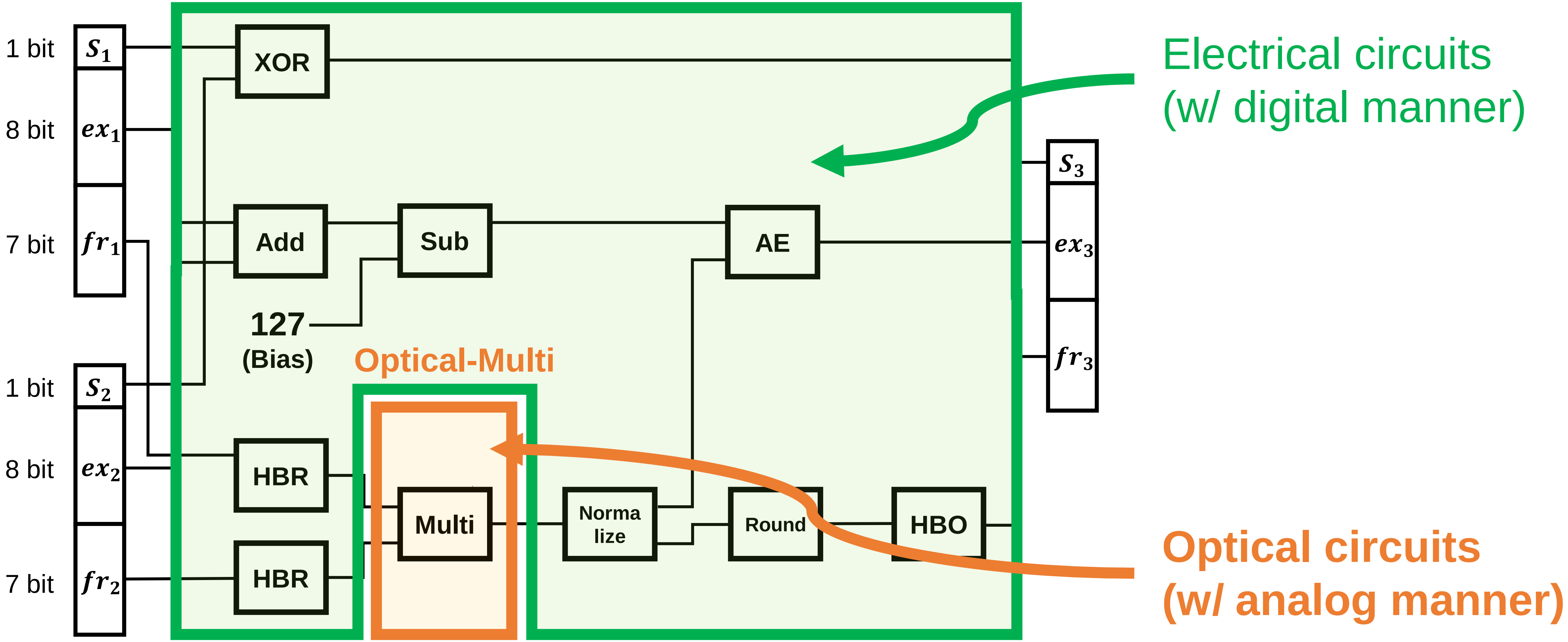
Bfloat16 format : $(-1)^S \times 2^{(ex-127)} \times 1.fr$



Fraction part (Multi) calculation is the bottleneck

Proposed approach

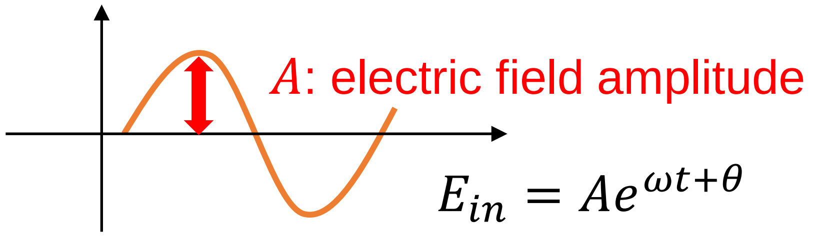
Hybrid Opto-Electrical Floating-point Multiplier

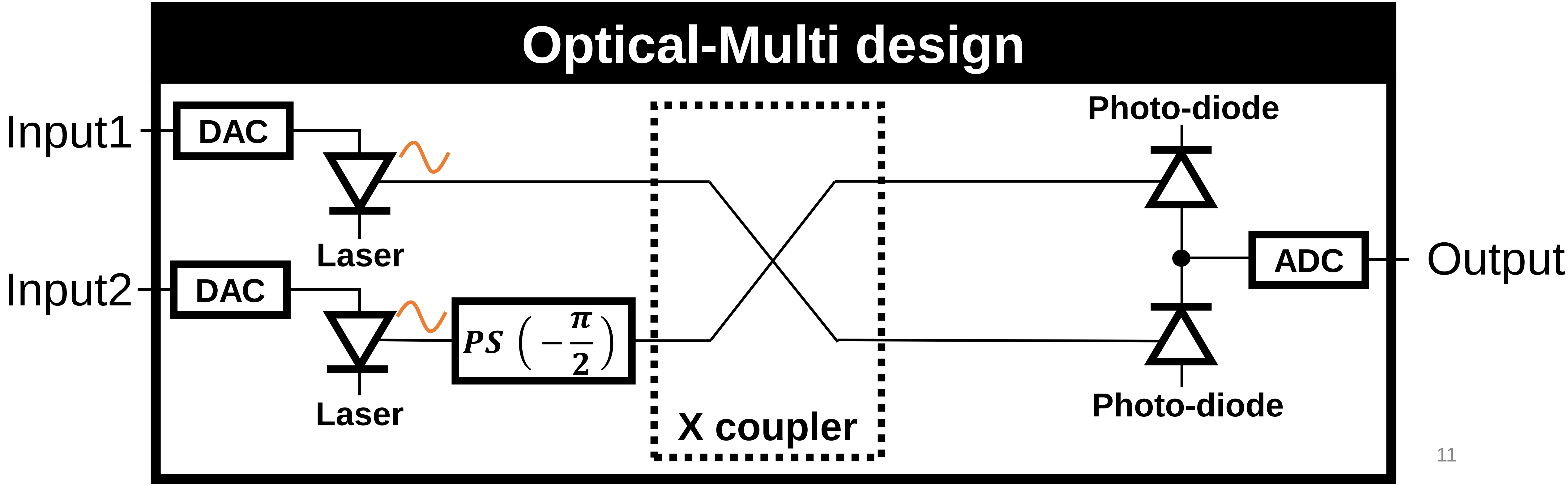


Implement Multi with optical devices

A novel optical analog integer multiplier
~ Optical-Multi ~

The electric field amplitude of light is the information carrier



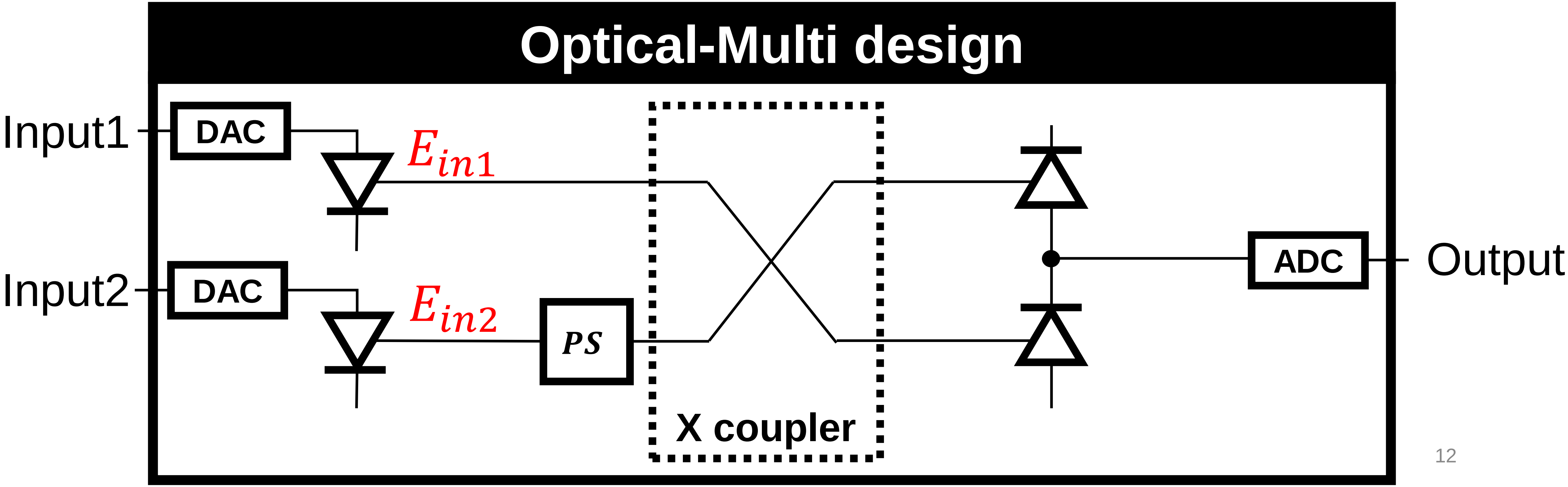


A novel optical analog integer multiplier

Input

$$E_{in1} = A_1 e^{\omega_1 t + \theta_1}$$
$$E_{in2} = A_2 e^{\omega_2 t + \theta_2}$$

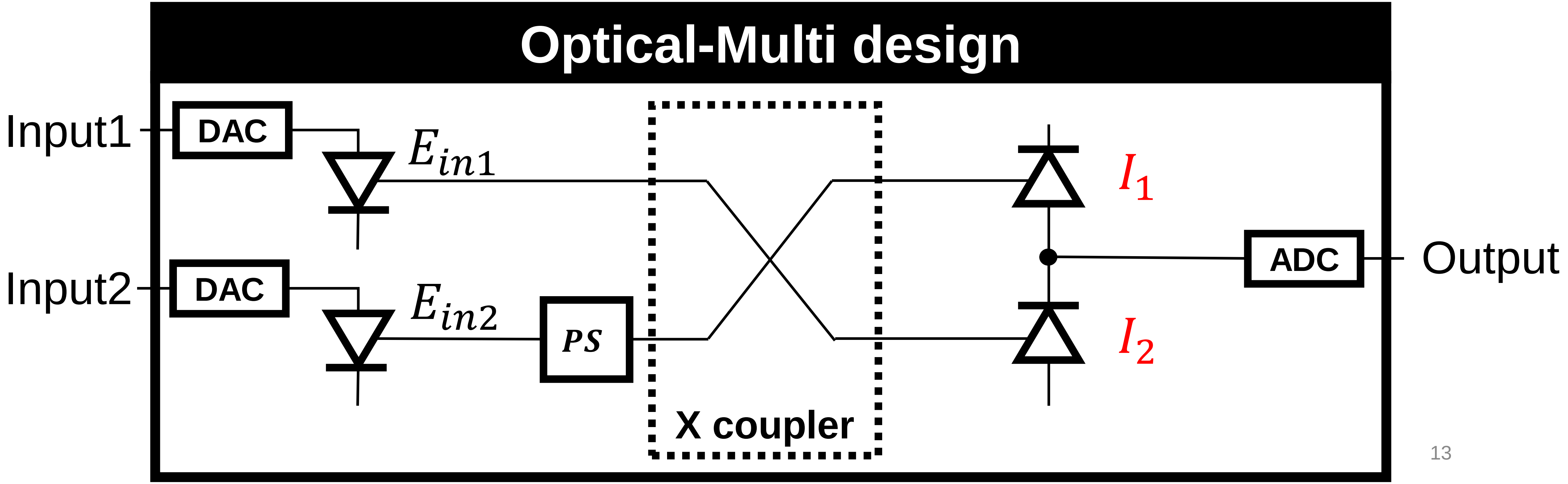
A : electric field amplitude
ω : the angular frequency
t : the time
θ : the initial phase



A novel optical analog integer multiplier

$$I_1 = \frac{1}{2}(A_1^2 + A_2^2 + 2A_1A_2\cos((\omega_1 - \omega_2)t + \theta_1 - \theta_2))$$

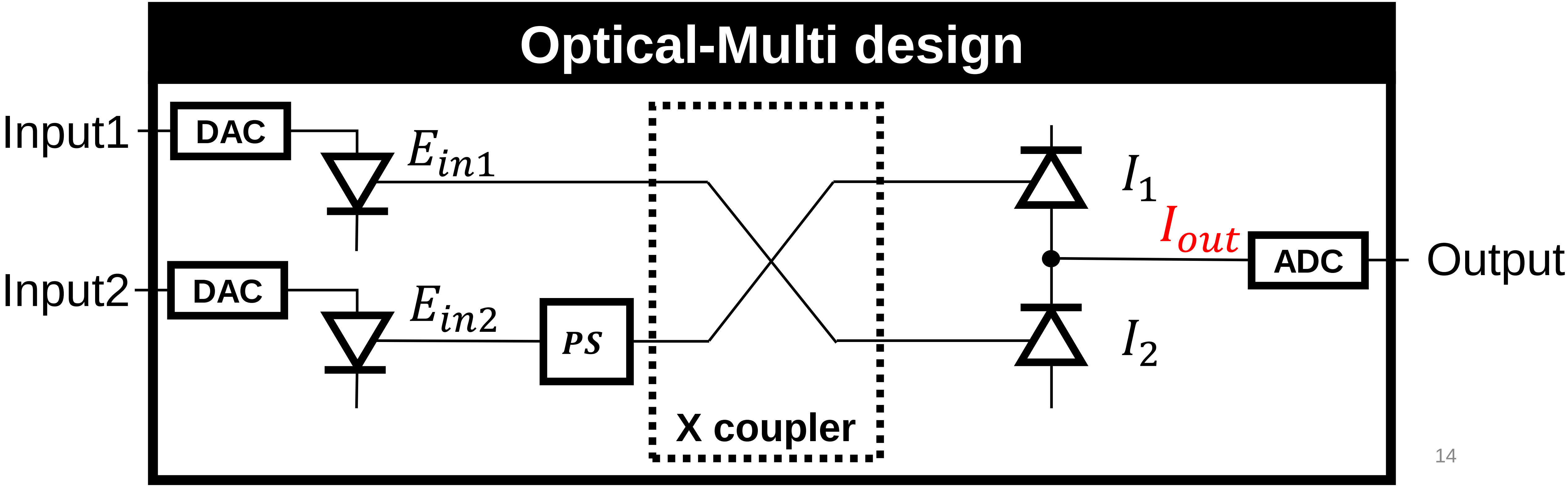
$$I_2 = \frac{1}{2}(A_1^2 + A_2^2 - 2A_1A_2\cos((\omega_1 - \omega_2)t + \theta_1 - \theta_2))$$



A novel optical analog integer multiplier

Output

$$I_{out} = I_1 - I_2$$
$$= 2A_1A_2\cos((\omega_1 - \omega_2)t + \theta_1 - \theta_2)$$



A novel optical analog integer multiplier

Output

$$I_{out} = I_1 - I_2$$
$$= 2A_1A_2\cos((\omega_1 - \omega_2)t + \theta_1 - \theta_2)$$

When $\omega_1 = \omega_2$ and $\theta_1 = \theta_2$, I_{out} is $2A_1A_2$

➡ **Optical-Multi can function as a multiplier**

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Experimental summary

Purposes

1. Clarify the arithmetic accuracy of OEFM (mixed-signal circuit)
2. Show the performance potential of OEFM

Experimental methods

1. Accuracy analysis:
   - ✓ Simulate on OptiSystem 19.0.0 w/ in-house simulator (Python)
2. Performance [latency / energy]:
   - ✓ Estimate latency and energy consumption based on models

1. Accuracy analysis

- Environment
  - Add noise source on 2 input ports of OEFM
  - Variance of noise : 10^{-15}, 10^{-14}, 10^{-13}, 10^{-12}, 10^{-11}, 10^{-10}, 10^{-09}, 10^{-08}, 10^{-07}, 10^{-06}
  - Input data: random bit sequences (for Bfloat16 format)

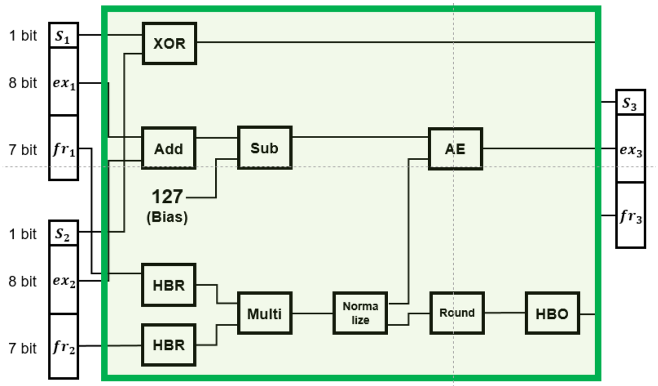
- Evaluation metrics
  1. Arithmetic error rate: How often do arithmetic errors occur?
     - $\frac{the\ number\ of\ arithmetic\ errors}{the\ number\ of\ arithmtic\ calculation} \times 100$
  2. OEFM error: How much scale does the arithmetic error have?
     - mean: $\frac{1}{\mathrm{N}}\sum_{i=1}^{N}(OETM\ output\ - true\ value)$
     - standard deviation: $\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{N}(OETM\ output\ - true\ value) - \text{mean}}$

2. Performance analysis

- Environment
  - Estimate latency and energy consumption based on models
  - Comparison Target: Electrical-FM, OEFM

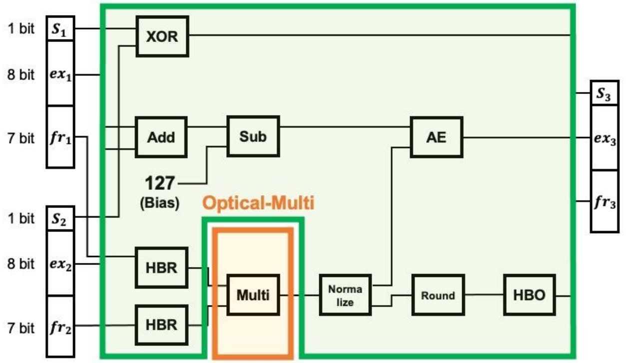
- Evaluation metrics
  1. Latency
  2. Energy consumption

Electrical-FM



V.S

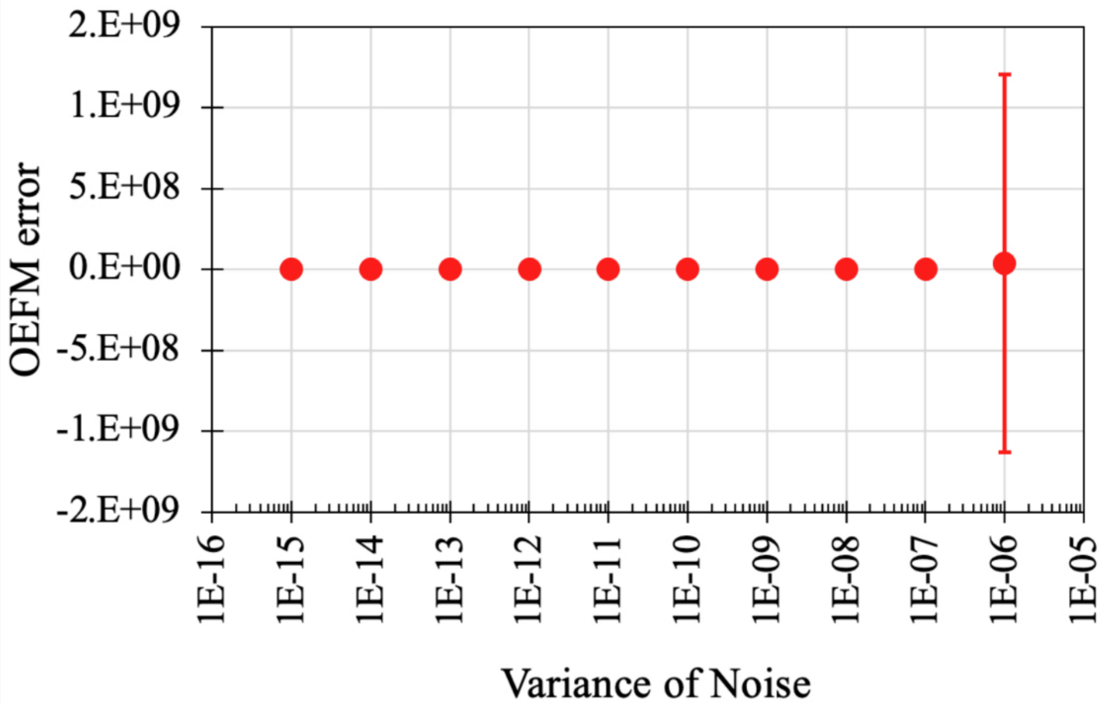
OEFM



Arithmetic accuracy

Arithmetic error rate

Variance of Noise	10^{-15}	10^{-14}	10^{-13}	10^{-12}	10^{-11}	10^{-10}	10^{-09}	10^{-08}	10^{-07}	10^{-06}
OEFM [%]	0	0	0	0	0	0	0	0.12	0	0.81

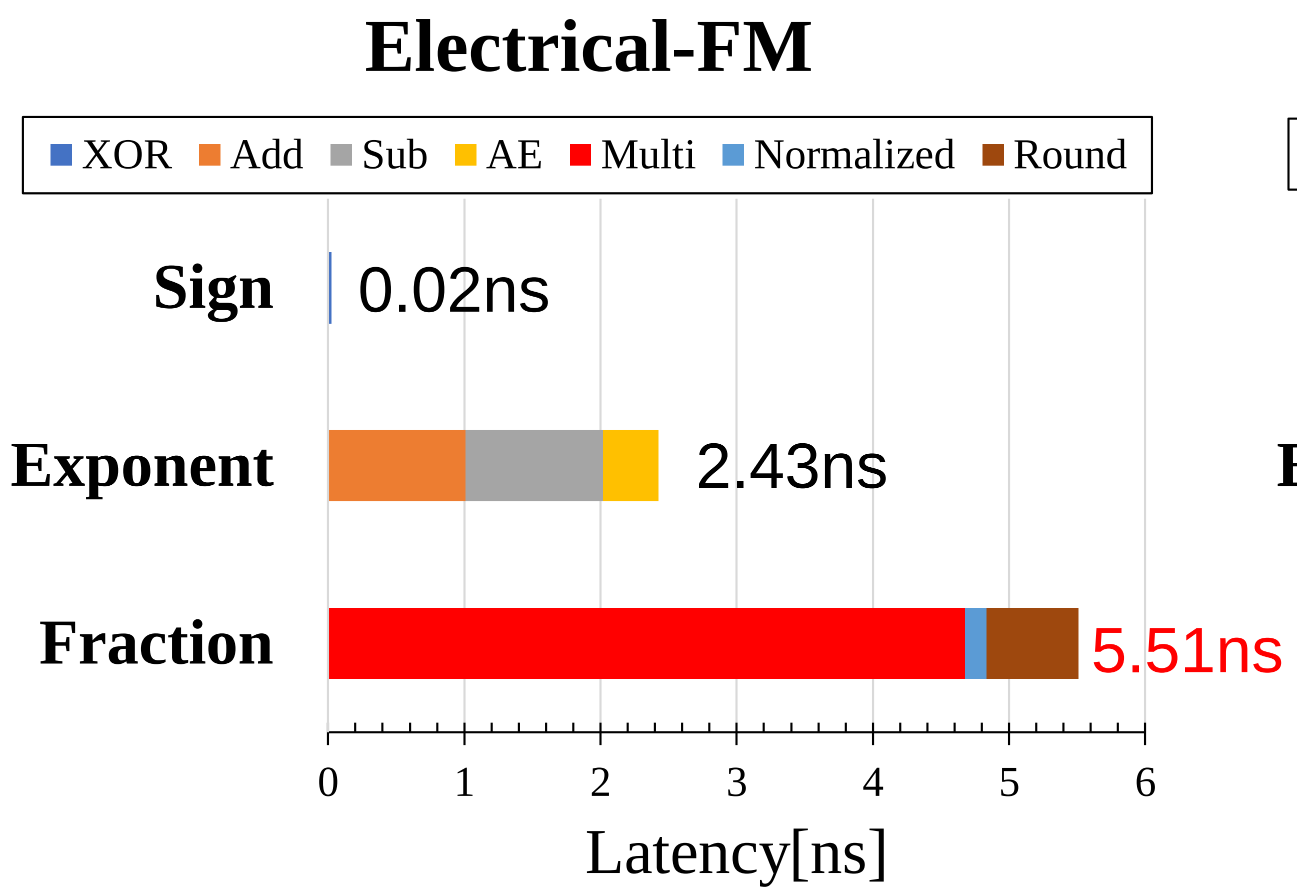


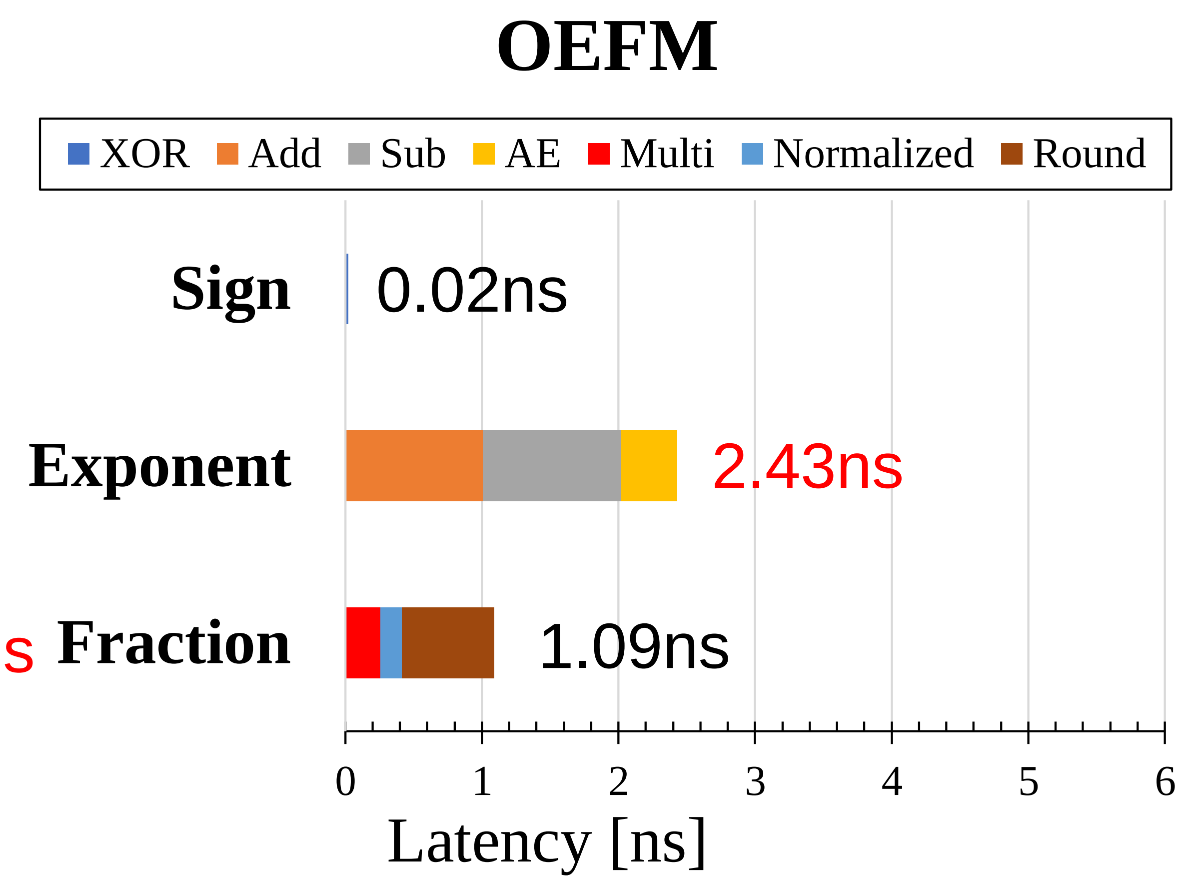
When the Exponent part is large, the OEFM error is large

If the arithmetic error rate ≠ 0, the OEFM error can be large

When the noise variance is less than 10^{-09}, the OEFM output is reliable

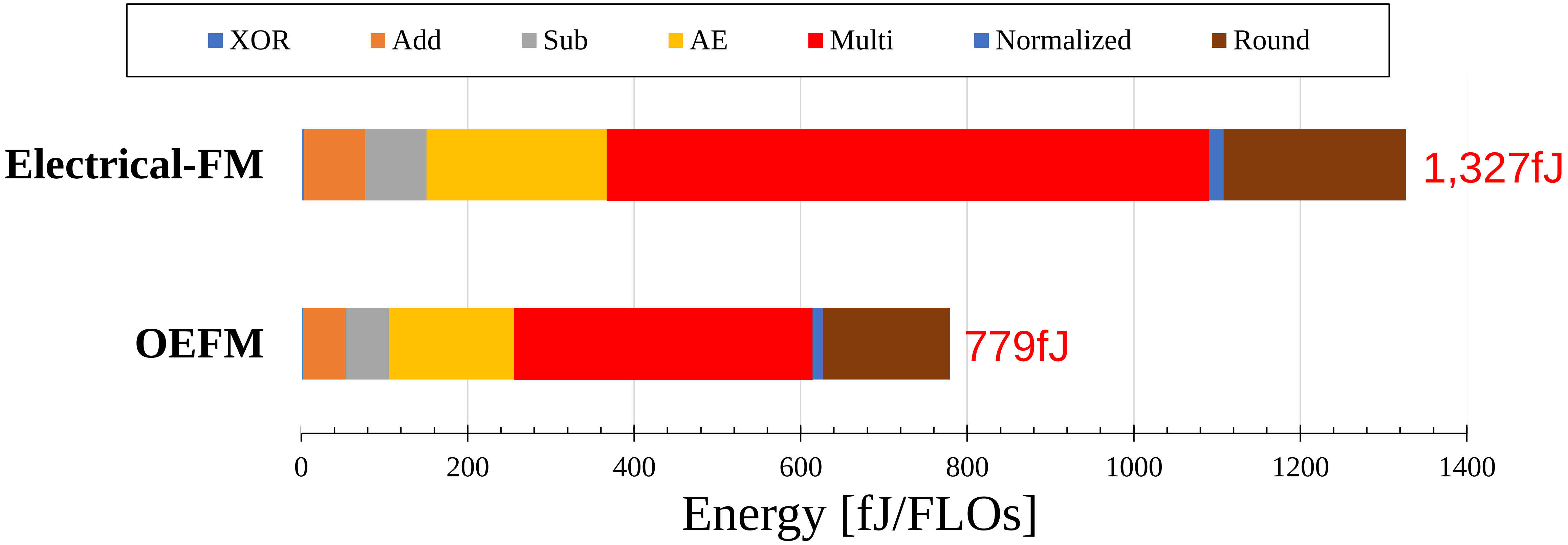
Latency





56% latency improvement

Energy per floating-point multiplication



41% energy reduction

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Conclusions and future work

Conclusions

- We propose OEFM with a novel optical analog integer multiplier
- OEFM is reliable with the variance of noise < 1.00×10^{-9}
- OEFM achieves
  - 56% latency improvement
  - 41% energy reduction

Future work

- Find the optimal hybrid opto-electrical architecture

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number JP22H05194, JP22H05000.

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