Hardware-aware lightweight photonic spiking neural network for pattern classification

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Today, artificial intelligence is advancing at a breathtaking pace. Intelligent applications represented by large language models and computer vision have fully integrated into industry and daily life—from facial recognition on smartphones, intelligent voice interaction, and industrial quality inspection to autonomous driving—all rely on massive, high speed computing support. However, electronic chips based on the von Neumann architecture frequently suffer from the “memory wall” and “power wall” bottlenecks when processing large scale data, making them unable to meet the ongoing demand for higher computing power, lower power consumption, and shorter latency in the intelligent era.

With its ultra high speed, low power consumption, and large scale parallel processing capabilities, photonic neural networks have emerged as a next generation disruptive computing paradigm. Over the past decade, the global academic and industrial communities have continuously advanced photonic neural network technologies. From early linear optical computing units based on microring resonators and Mach Zehnder interferometers to laser neuron chips capable of nonlinear activation, the integration, programmability, and practicality of photonic neural networks have steadily improved. Among these, photonic spiking neural networks—which incorporate the efficient, sparse processing mechanisms of the biological brain—are regarded as an ideal hardware solution for edge computing and real time intelligent processing.

Nevertheless, a long standing core challenge has hindered the transition of photonic spiking neural networks from laboratory research to real world deployment: the scale mismatch between physical photonic neuromorphic chips and the requirements of neural network algorithms. Simply put, chips are too small while networks are too large. Software algorithms cannot be efficiently adapted to hardware constraints, leaving many high performance photonic neural network designs unable to be truly deployed on chips for end to end practical tasks. This scale mismatch has severely blocked the industrial translation of photonic spiking neural networks.

To tackle this pain point, the Xidian University team innovatively proposed a lightweight design philosophy of hardware–algorithm co design, breaking through technical bottlenecks across the full chain of architecture, chip, and training.

The research group of Prof. Xiang from Xidian University proposed a frequency-domain lightweight spiking neural network architecture based on the Discrete Cosine Transform (DCT). After applying the two-dimensional DCT to 28×28 images, the core low-frequency features are extracted, reducing the input dimension from 784 to only 45. This design perfectly matches the input/output port count of available photonic chips, fundamentally lowering network computational complexity and hardware deployment difficulty.

At the hardware level, the team independently designed and fabricated two core chips: Silicon-based simplified MZI mesh photonic synapse chip: A 16×16 lightweight structure using only 152 phase shifters to realize low-loss, low-power linear matrix-vector multiplication in the optical domain, with an energy efficiency of 1.39 TOPS/W and a computing density of 0.13 TOPS/mm^2. InP-based 16-channel DFB-SA laser array photonic neuron chip: Implements brain-like LIF neuron nonlinear spike activation, with a maximum self-pulsation frequency of 5.23 GHz, an ultra-high energy efficiency of 987.65 GOPS/W, and an end-to-end latency of only 320 ps for a single layer.

To accommodate the non-ideal characteristics of photonic hardware, the team also proposed a three-stage collaborative training framework: software pre-training, photonic hardware in-situ training, and hardware-aware software fine-tuning. Using surrogate gradient backpropagation and temporal pruning, the SNN inference latency is compressed to a single time step (T=1), effectively compensating for accuracy loss caused by chip fabrication imperfections and system noise.

Experimental validation shows that the lightweight photonic spiking neural network achieves 90% classification accuracy on the MNIST dataset and 80.5% accuracy on the Fashion-MNIST dataset in software-hardware collaborative inference. Among photonic neural network chips supporting optical-domain nonlinear computing, its performance in energy efficiency, latency, and trainable parameters reaches the international leading level. System performance can be further improved through heterogeneous integration and all-optical DCT preprocessing in the future.

This achievement represents the first hardware-constrained lightweight deployment of photonic spiking neural networks, breaking the scale barrier between algorithms and chips. It paves the way for the hardware implementation of photonic spiking neural networks in lightweight visual perception, edge computing, embodied intelligence and other scenarios, marking that photonic neuromorphic computing has entered a new stage of practical application.

Keywords: photonic neuromorphic, photonic spiking neural network, pattern classification

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Prof. Xiang has long been engaged in research on photonic neuromorphic computing and photonic spiking neural networks. As the first author or corresponding author, she has published more than 150 SCI-indexed papers in high-impact journals including Optica, Laser & Photonics Reviews, PhotoniX, Opto-Electronic Advances, IEEE Transactions on Neural Networks and Learning Systems, Photonics Research, among which over 90 papers are in CAS Journal Ranking Q1 and Q2. She has been invited to contribute 10 review articles in the field of photonic neuromorphic computing and has been listed among the World's Top 2% Scientists for three consecutive years. In 2025, she was awarded the First Prize of Natural Science by the Chinese Optical Engineering Society (ranked first). She was selected for the National Postdoctoral Innovation Talent Support Program in 2016 (supervised by Prof. Yue Hao). She leads 1 National Key R&D Program Project, 5 NSFC projects, and 2 Frontier Exploration Projects of JKW, among other major research programs.
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Yahui Zhang is an Associate Professor from Xidian University, she is also the deputy Director of Xi'an Key Laboratory of Optoelectronic Computing and Brain-inspired Intelligence. She has long been engaged in the research of photonic spiking neural networks and photonic brain-inspired computing. As the first author or co-corresponding author, she has published 18 SCI-indexed papers in prestigious journals including Laser & Photonics Reviews and Photonics Research, among which 14 papers are included in CAS Journal Ranking Q1 and Q2. She has been invited to write 1 review article on photonic spiking neural networks.
Dr. Zhang was listed in the World's Top 2% Scientists 2024 and received the First Prize of Natural Science from the Chinese Optical Engineering Society in 2025 (ranking 2nd out of 5).

She presides over the Youth Project of the National Natural Science Foundation of China and a JKW Frontier Exploration Project, and participates in the National Key R&D Program of China and the Joint Fund of the National Natural Science Foundation of China, among other key research projects.
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