Ising machine, Optical computing, Combinatorial optimization, Statistical learning

Low-rank computing models of spatial photonic Ising machines

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Abstract

The spatial photonic Ising machine (SPIM) is an optical Ising machine utilizing spatial light modulation for fast, efficient computation of combinatorial optimization (Fig. 1). Owing to the parallel nature of light, SPIM can handle large-scale combinatorial optimization problems with over 10,000 variables. However, the class of problems it can handle has been significantly limited, which has posed challenges for practical applications. In this study, we proposed a computing model that significantly expands the class of combinatorial optimization problems SPIM can accommodate. This model enables SPIM to handle fully connected Ising problems efficiently and shows a unique advantage in efficiency, particularly for problems with low-rank structures. We are currently conducting a collaborative research project on improving low-rank computing models and multiplexed implementations of the SPIM (Fig. 2).

Background & Results

Ising machines are dedicated hardware designed for efficiently solving combinatorial optimization problems known as Ising problems. Since many important combinatorial optimization problems can be formulated as Ising problems, various Ising machines have been proposed based on different principles, including quantum annealing.

The SPIM, proposed in 2019, uses spatial light modulation to solve Ising problems, achieving superior scalability, as each iteration is processed in constant time, regardless of the number of variables (Fig. 1). This makes SPIM capable of efficiently solving large-scale Ising problems with over 10,000 variables. Additionally, its optical nature eliminates the need for physical wiring, enabling straightforward handling of fully connected problems. However, SPIM's practical applicability has been significantly limited due to constraints on the types of Ising problems it can handle.

In this study, we proposed a new computing model that enables SPIM to handle arbitrary Ising problems without changing its hardware implementation. This model allows SPIM to efficiently solve large-scale, fully connected Ising problems while showing particularly high efficiency for low-rank Ising problems. We demonstrated the model's capabilities by formulating the integer-weighted knapsack problem as a low-rank Ising problem, making it solvable with SPIM. Furthermore, we derived a concrete statistical learning rule for the model, successfully applying low-rank learning to handwritten digit image data.

Significance of the research and Future perspective

This computing model paves the way for new optical computing technologies capable of solving large-scale combinatorial optimization problems. Expanding SPIM's practical applicability could lead to faster computations and reduced power consumption for large-scale combinatorial problems. Potential applications of this technology include complex societal problems, where it could contribute to super-smart societal systems, including improvements in energy efficiency and achieving carbon neutrality by reducing CO_2 emissions.

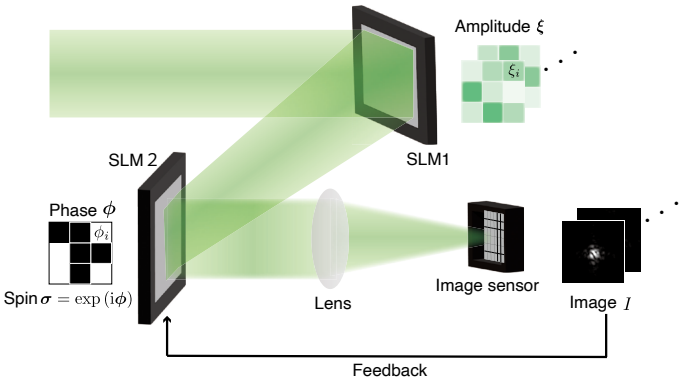

Fig. 1. Spatial photonic Ising machine

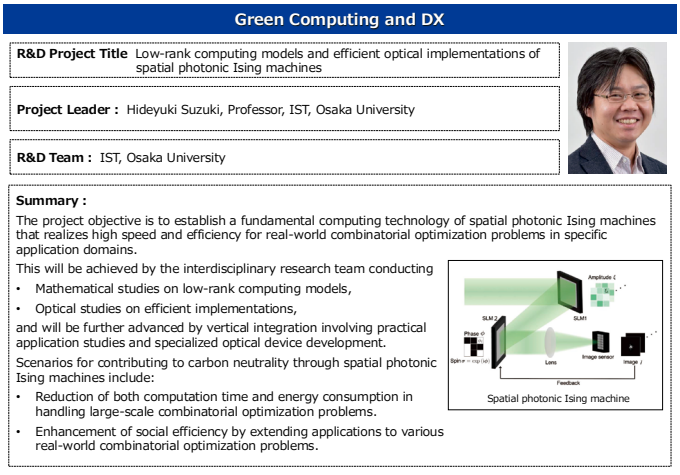

Fig. 2. Overview of JST ALCA-Next project

Patent	
Treatise	Yamashita, Hiroshi et al. Low-rank combinatorial optimization and statistical learning by spatial photonic Ising machine. Physical Review Letters. 2023, 131(6), 063801. doi: 10.1103/PhysRevLett.131.063801 Sakabe, Takumi et al. Spatial-photonic Ising machine by space-division multiplexing with physically tunable coefficients of a multi-component model. Optics Express. 2023, 31(26), 44127-44138. doi: 10.1364/OE.508069 Ogura, Yusuke. Spatial photonic Ising machine with time/space division multiplexing. In: Suzuki, Hideyuki et al. (eds) Photonic Neural Networks with Spatiotemporal Dynamics. 2023, Springer, Singapore, 153-174. doi: 10.1007/978-981-99-5072-0_8 Suzuki, Hideyuki; Tanida, Jun; Hashimoto, Masanori. Photonic Neural Networks with Spatiotemporal Dynamics. 2023, Springer, Singapore. doi: 10.1007/978-981-99-5072-0
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