Training a Neural Network via All-Optical Coupling Control in Polariton Condensate Lattices

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Exciton-polariton condensates have recently been explored theoretically and experimentally as ultrafast nonlinear optical elements for both digital and analog computing [1]. This growing interest comes from their all-optical tunability and measuring their response *in situ*, as well as the possibility of building distinct lattice configurations using structured excitation light (e.g. spatial light modulators) [2]. In this scenario, we explore the possibility of employing a lattice of polariton condensates as a neural network (NN), see Fig. 1(a). Distinct from previous works that mostly focus on reservoir computing [3] and binarized networks [4], here we propose a deep-learning device whose interactions between polariton condensates from distinct lattice sites are trainable by all-optical means [5]. We start our preliminary analysis by describing the condensate NN using the discretized driven-dissipative Gross-Pitaevskii equation (dGPE) [5]. Considering the limit of fast active reservoir relaxation and equal condensation density in all lattice sites, the dGPE particularly corresponds to the paradigmatic Kuramoto model of phase-coupled oscillators [Fig. 1(b)], which allows obtaining a variational energy function that depends on both the condensate phase and interaction between nearest neighbor condensates. Due to this variational feature, we propose applying equilibrium propagation [6] for training the NN of polariton condensates. We expect that through proper training of the synaptic weights, i.e., the interaction between nearest neighbor condensates, the number of required neurons (condensates) will dramatically decrease, making a practical device design much more feasible. We further expect that our optical-based training strategies will enhance the overall energy efficiency of the proposed polariton NN architecture while maintaining high accuracy.

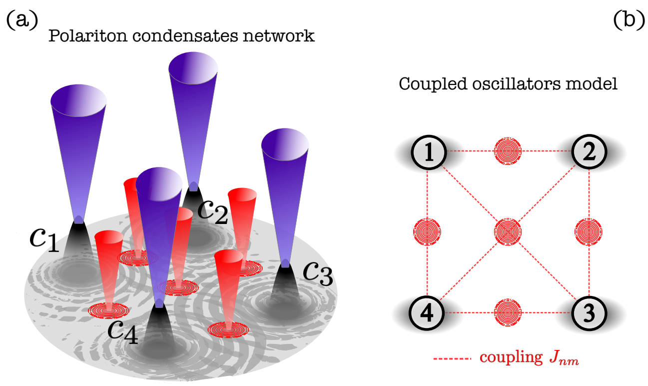

Figure 1: (a) Sketch of a representative NN of polariton condensates in a square lattice, with c_n describing each condensate ($n = 1, \ldots, 4$). Non-resonant pump beams with power above the condensation threshold excite each condensate (purple-colored), while pumps below the condensation threshold (red-colored) modulate the interaction between condensates from distinct sites. (b) Mapped NN from panel (a) into a four-coupled oscillator model.

[1] A. Opala and M. Matuszewski, *Opt. Mater. Express* **13**, 2674-2689 (2023).
[2] J. D. Töpfer, I. Chatzopoulos, H. Sigurðsson, et al., *Optica* **8**, 106–113 (2021).
[3] D. Ballarini, A. Gianfrate, R., A. Opala, et al., *Nano Letters* **20** (5), 3506-3512 (2020).
[4] R. Mirek, A. Opala, P. Comaron, et al., *Nano Letters* **21** (9), 3715-3720 (2021).
[5] S. Alyatkin, J.D. Töpfer, A. Askitopoulos, et al., *Phys. Rev. Lett.* **124**, 207402 (2020).
[6] B. Scellier Y. and Bengio, *Front. Comput. Neurosci.* **11**, 24 (2017).