Adaptive Boson Sampling for quantum machine learning applications

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Abstract: We present Adaptive Boson Sampling for quantum machine learning via linear optics and adaptive operations. Experimentally validated using programmable integrated circuits and multi-photon states, this method demonstrates clear utility for diverse near-term quantum hardware applications.

The realization of a universal photonic quantum computer remains a significant challenge due to the difficulty of implementing efficient nonlinear gates, leading research toward non-universal models like Boson Sampling that offer limited applications beyond specific sampling tasks. In this work, we investigate an intermediate regime by exploring the computational potential of adding moderate adaptivity to linear optical circuits. Specifically, we introduce and experimentally validate a paradigm known as Adaptive Boson Sampling (ABS) tailored for quantum machine learning applications [1,2]. The ABS framework utilizes a subset of optical modes within a Boson Sampling interferometer to act as a feature map for encoding classical data into quantum states. This is enabled by performing intermediate measurements on a subset of modes: the detected photon configurations trigger specific unitary transformations on the remaining modes, establishing a direct correspondence between classical input and quantum state preparation (Fig 1a). We report the experimental implementation of this paradigm emulated in post-selection using fully reprogrammable and universal integrated optical circuits fabricated via femtosecond-laser-writing [3] with up to 8-mode and a semiconductor quantum dot source (Fig. 1b). The system allowed for the execution of three-photon experiments and the estimation of quantum kernels with varying dimensionalities (Fig. 1c-d). We demonstrated the utility of the ABS kernels for enhancing the performance of support-vector machines in the classification of datasets [2]. Our results highlight a viable path for enhancing the functionality of near-term photonic hardware, providing a flexible tool for quantum machine learning. Future perspectives regard achieving real-time adaptivity to ensure the protocol scalability and its feasibility for implementation of more complex scheme, such as quantum neural networks.

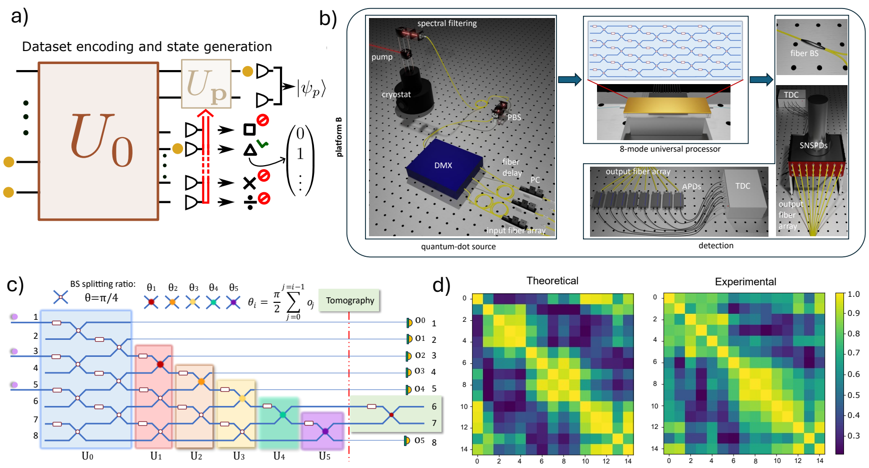

Fig. 1 Adaptive Boson Sampling architecture. a) Feature map encoding via adaptive measurements that trigger different operations U_p on the unmeasured photons. b) Overview of the experimental platform. c) Internal structure of the chip to emulate adaptive measurements via post-selection. d) The experimental quantum kernel utilized for dataset classification. Figures from [2] under

References

[1] U. Chabaud, D. Markham, and A. Sohbi, "Quantum machine learning with adaptive linear optics," Quantum, vol. 5, p. 496, 2021.
[2] F. Hoch, E. Caruccio, G. Rodari, T. Francalanci, A. Suprano, T. Giordani, G. Carvacho, N. Spagnolo, S. Koudia, M. Proietti, C. Liorni, F. Cerocchi, R. Albiero, N. Di Giano, M. Gardina, F. Ceccarelli, G. Corrielli, U. Chabaud, R. Osellame, M. Dispenza, and F. Sciarrino, "Quantum machine learning with Adaptive Boson Sampling via post-selection," Nature Communications, vol. 16, 2025.
[3] F. Ceccarelli, S. Atzeni, C. Pentangelo, F. Pellegatta, A. Crespi, and R. Osellame, "Low Power Reconfigurability and Reduced Crosstalk in Integrated Photonic Circuits Fabricated by Femtosecond Laser Micromachining," Laser & Photonics Reviews, vol. 14, 2020.