High-Fidelity Quantum Information Processing with Machine Learning-Characterized Photonic Circuits

Andreas Fyrillas,[1,2,*] Olivier Faure,[1], Nicolas Maring [1], Jean Senellart [1] and Nadia Belabas [2]

[1] *Quandela, 7 rue Léonard de Vinci, Massy 91300, France*

[2] *Centre for Nanosciences and Nanotechnologies, CNRS, Université Paris-Saclay, UMR 9001, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France*

[*] *andreas.fyrillas@quandela.com*

Abstract: Photonic integrated circuits (PICs) are attractive platforms for manipulating quantum light. Imperfections limit the fidelity of photonically integrated quantum information protocols. We use machine learning and a clear box approach to characterize large PICs and mitigate imperfections, achieving high-fidelity for scalable implementations.

Photonic integrated circuits (PICs), compact platforms for light manipulation, have a great potential in quantum computing, communication, cryptography, sensing, and a wide range of classical applications. PIC imperfections pose challenges, leading for instance to a severe degradation in performance of optical neural networks and a marked decrease in the fidelity of quantum gates. Existing self-configuration protocols, that mitigate imperfections without requiring detailed knowledge of the device, fall short in addressing these issues. Leveraging machine learning, particularly neural networks in so-called black-box model-based approaches, has shown promise but faces scalability challenges regarding the number of data samples and computational resources required to train the model. We propose a clear-box approach, where physical intuition is embedded in an explicit model of PIC imperfections [1]. We thus significantly enhance sample efficiency and scalability of the PIC characterization. We introduce an iterative machine learning-assisted PIC characterization process to train a virtual replica of the physical device that is then harnessed by an imperfection mitigation. We achieve unparalleled optimal control on a 12-mode Clements universal interferometer (see Fig. 1b), demonstrating the effectiveness of our approach on one of the largest PICs available. Our work [1] is also the first demonstration of the retrieval of individual component parameters such as crosstalk coefficients and beamsplitter reflectivity values in complex interferometer meshes.

1. Optimal control of photonic circuit using a clear-box model-based approach

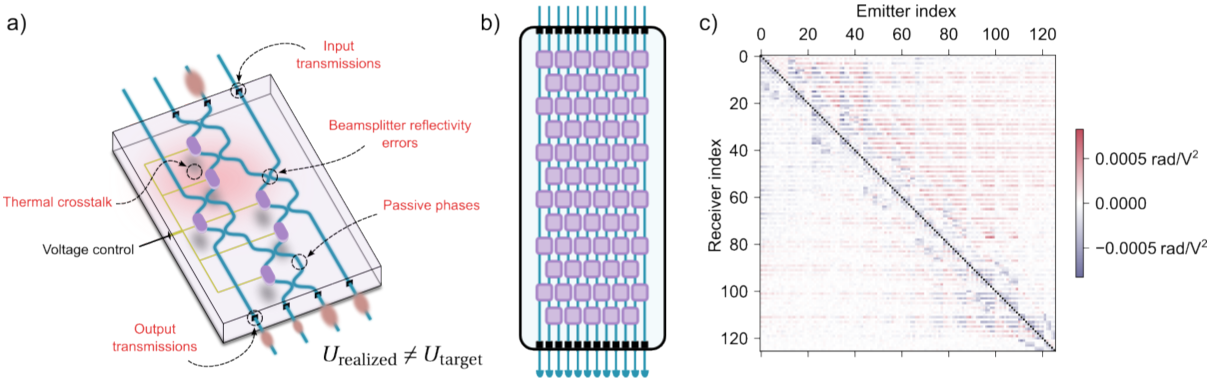

Fig. 1. **a)** Example of photonic integrated circuit (PIC) and imperfections that degrade the fidelity of photonic quantum information processing. As a result, the implemented unitary matrix U_{realized} differs from the targeted operation on light U_{target}. **b)** 12-mode Clements interferometer. Each block contains two phase shifters and two beamsplitters. Input light comes from the top and reaches the detectors on the bottom. **c)** Estimated 126×126 crosstalk matrix of a 12-mode Clements interferometer featuring 126 thermo-optic phase shifters linking the applied voltages squared to the implemented phases. An ideal circuit without crosstalk would yield a diagonal matrix.

In more details, PIC imperfections (see Fig. 1a) decrease the fidelity of the implemented matrix with respect to the target unitary matrix to apply on the input photons. We create a virtual replica of the physical device, which is built using physical models for each imperfection. For instance, thermal crosstalk is taken into account by using a crosstalk matrix to link the implemented phases to the applied voltages, where diagonal elements represent the self-heating coefficients and off-diagonal elements account for crosstalk.

Our PIC characterization method tunes the model parameters such that the virtual replica reproduces the behavior of the physical device. The model is trained using an iterative protocol which alternates between interference fringe measurements and machine learning stages. The machine learning stages, which update the estimated crosstalk matrix in particular, consist in a gradient descent algorithm that learns from acquired data samples on the physical device. This iterative process aims at enhancing the accuracy of the virtual replica at each new iteration.

Universal-scheme PICs, like Clements interferometers, can by definition implement any unitary matrix acting on the spatial input modes. Our imperfection mitigation process leverages the knowledge of the physical device acquired during the characterization stage to compute the voltages that implement the target unitary matrix, compensating for beamsplitter reflectivity errors and thermal crosstalk leading to a high-fidelity implementation of the target matrix and e.g. quantum protocols.

2. Experimental validation on a 12-mode Clements interferometer

The experimental validation of our process is conducted on a 12-mode universal-scheme PIC with a Clements mesh as shown on Fig. 1b, featuring 126 reconfigurable thermo-optic phase shifters and 132 directional couplers [3]. We characterize the phase-voltage relation, beamsplitter reflectivity errors, and input/output transmissions. We show on Fig. 1c the estimated crosstalk matrix. Experimental assessment of the characterization accuracy yields a circuit amplitude fidelity of $\mathscr{F}_a = (99.92 \pm 0.02)\,\%$ for 100 random phase configurations, demonstrating high precision of the virtual replica predictions with orders of magnitude lower sample and computational requirements compared to previous demonstrations. Compilation of 100 Haar-random unitary matrices using a deterministic method with detector relabelling achieves a unitary amplitude fidelity of $(99.77 \pm 0.04)\,\%$, resulting in the highest reported values in the literature for Clements interferometers on the most complex PIC characterized with machine learning to date (see Table 1).

Ref	Number of modes	Amplitude fidelity
[2]	6	1.3 %
[4]	20	2.6 %
[1] (this work)	**12**	**0.23%**

Table 1. State of the art in photonic circuit optimal control demonstrated on Clements meshes.

3. Discussion and outlook

Our characterization method combines machine learning with a clear-box approach, modeling both the physical PIC and its imperfections, overcoming accuracy limitations of existing methods relying solely on interference fringe measurements. Our approach requires orders of magnitude fewer training samples and computational power thanneural network-based methods, ensuring scalability, while also achieving the highest recorded fidelities. Future work includes investigating and mitigating other PIC imperfections, while developing faster compilation method. The increased reliability of photonic devices holds promise for transformative advances in quantum information processing. Photonic quantum computing reaps substantial benefits from increased PIC accuracy, by achieving for instance higher qubit fidelities. These advances open the way to efficient near-term quantum processors with demonstrations of boson sampling with reconfigurable circuits or graph problem solvers and are essential buiding blocks for fault-tolerant quantum computing harnessing integrated photonic components.

References

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