

Reservoir computing architecture with integrated photonic circuit for time-series forecasting

Rosario Di Bartolo¹, Simone Piacentini², Francesco Ceccarelli², Giacomo Corrielli², Roberto Osellame²,
Valeria Cimini¹, Fabio Sciarrino¹

¹Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy

²Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy

Quantum reservoir systems offer a promising route to mitigate some of the optimization challenges affecting variational quantum machine-learning models, including trainability issues. In reservoir computing, the quantum dynamics are kept fixed, while only a classical readout is trained, making the approach particularly suitable for near-term photonic implementations [1, 2]. The quantum device is therefore used as a physical feature map that transforms the input into a high-dimensional set of observables. For temporal data, however, access to a large feature space is not sufficient. A useful reservoir must simultaneously provide nonlinear expressivity, so that a linear output layer can reconstruct complex input-output relations, and fading memory, so that its present state retains information about a finite history of previous inputs. In a physical reservoir they must instead emerge from the dynamics and measurement architecture of the hardware. Quantum systems can potentially enrich the accessible feature space through coherence, entanglement and many-particle interference, but only a few photonic experimental platforms have so far demonstrated the feedback loops required to provide memory and enable the processing of time-series data [3].

In this work, we present a photonic quantum reservoir protocol for time-series forecasting implemented on a reconfigurable integrated photonic chip operating in the multiphoton regime [4]. The platform enables programmable feedback and allows us to study how feedback dynamics and quantum correlations affect computational performance. As illustrated in Fig. 1(a), the input sequence is sequentially injected into a fixed reservoir, whose output features are processed by a trained linear layer to forecast future values. The physical realization, shown in Fig. 1(b), consists of a four-mode femtosecond-laser-written programmable interferometer. We show that the presence and depth of feedback loops determine the reservoir memory capacity, allowing the system to retain information about past inputs and capture temporal correlations. At the same time, indistinguishable multiphoton states introduce quantum interference effects that enrich the reservoir dynamics and enhance nonlinear expressivity.

The input sequence is encoded into a programmable optical phase of the integrated device and the output probability vector, reconstructed from repeated photon-counting measurements, is used in the next step of the sequence to set feedback phase values. Once the sequence of outcome probability vectors has been collected for the entire input sequence, the only trained component is a classical linear regression layer that maps the measured probabilities to the target. The platform enables a controlled comparison between three input configurations: a single photon, two distinguishable photons and two indistinguishable photons. The performance comparison for the different input configurations is done under the same circuit transformation, measurement statistics and readout protocol to isolate the contribution of multiphoton interference. In particular, indistinguishable photons generate coherent interference between multiphoton probability amplitudes, producing nonclassical correlations and a qualitatively richer dependence of the measured probabilities on the encoded input and feedback phases.

For a fixed circuit transformation, both the presence and the depth of feedback loops directly determine the reservoir's memory capacity, with deeper feedback enabling the system to capture more effectively temporal correlations in the input sequence. On the other hand, the most significant enhancement, in terms of computational capabilities, arises when the input is a quantum-correlated state. Injecting indistinguishable multiphoton states introduces quantum interference effects that enrich the reservoir's dynamics, substantially increasing its expressivity. This allows the system to model higher-order nonlinearities and achieve superior performance with respect to scenarios involving distinguishable photon inputs, especially in tasks with strong nonlinear structure. This advantage becomes even more pronounced when increasing the number of indistinguishable photons, up to a saturation point determined by the system's dimensionality and the complexity of the transformation, resulting in improved accuracy on classical time-series prediction benchmarks.

The computational properties of the platform are assessed through both task-independent characterization and standard time-series benchmarks. Its memory is quantified by training the readout to reconstruct inputs applied at increasing temporal delays, whereas its nonlinear expressivity is evaluated through the approximation of monomials and polynomial functions of progressively increasing order. The indistinguishable-photon configuration consistently provides lower reconstruction errors for the more complex nonlinear targets, demonstrating that quantum interference enlarges the set of functions that can be accessed by a linear output layer. This improvement then translates into superior performance on temporal XOR and NARMA tasks, where the correct output depends on nonlinear combinations of present and past inputs.

The same behavior is observed in the forecasting of the Mackey–Glass chaotic time series. Although all configurations can reproduce part of the dominant temporal structure of the signal, the richer spectrum of nonlinear features generated by multiphoton interference enables the indistinguishable-photon reservoir to achieve enhanced performance in regimes where both memory and nonlinearity are required.

Overall, these results demonstrate that photonic quantum reservoirs can be tuned to balance memory and expressivity, providing a scalable architecture for time-series forecasting carried out with integrated quantum photonic platforms. The next key step is to scale the reservoir to larger photonic circuits and higher photon numbers, where a substantially richer set of multiphoton interference pathways can be accessed. This increase in dimensionality should enable the platform to move beyond classical time-series forecasting and address the learning of genuinely quantum temporal processes.

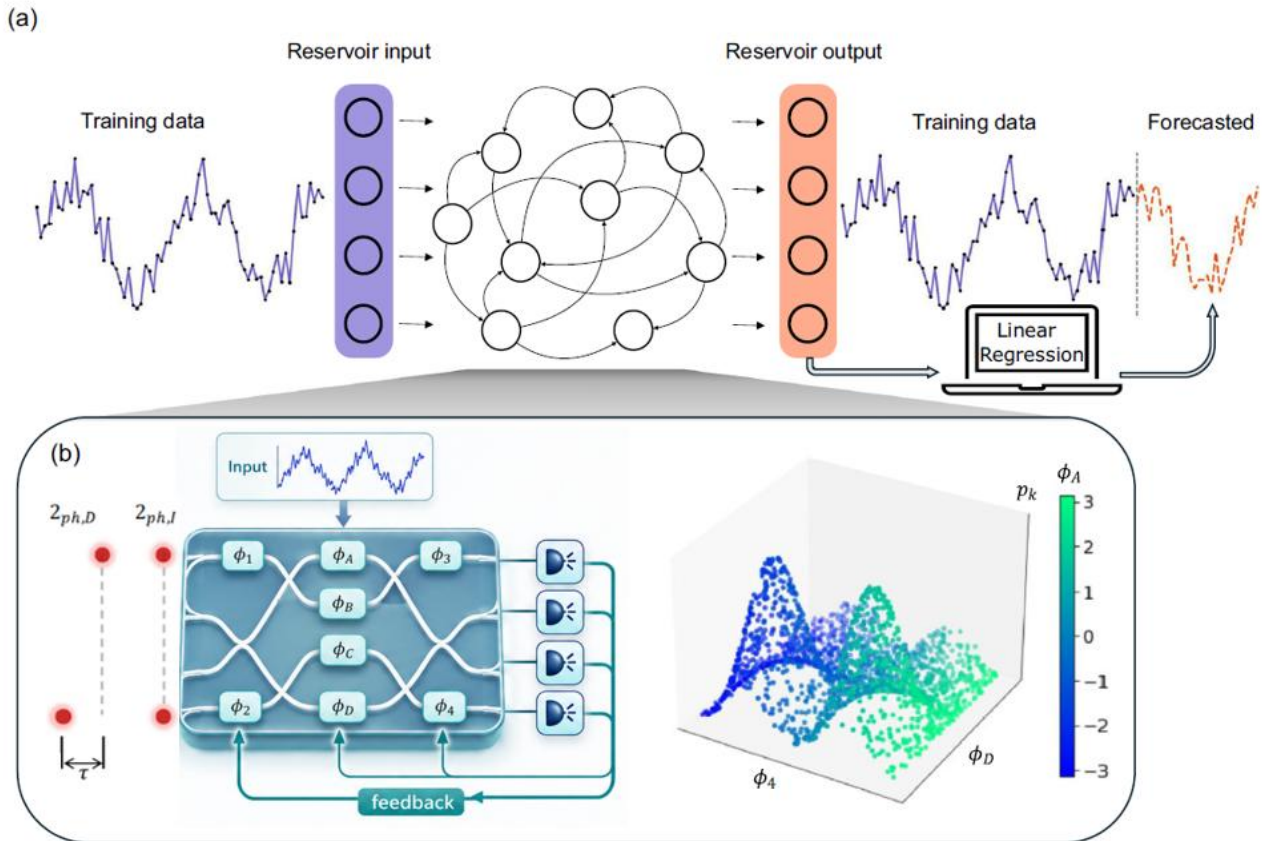


Figure 1 (a) Scheme of the realized photonic quantum reservoir computing for time series forecasting. (b) Multi-arm integrated photonic architecture with different multiphoton input states. Reconstructed outcome probability distribution as the internal phases of the circuit are varied.

References

- [1] Valeria Cimini, Mandar M. Sohoni, Federico Presutti, Benjamin K. Malia, Shi-Yuan Ma, Ryotatsu Yanagimoto, Tianyu Wang, Tatsuhiro Onodera, Logan G. Wright, and Peter L. McMahon, Large-scale quantum reservoir computing using a Gaussian Boson Sampler. *Npj Quantum Inf.* 12, 104 (2026).
- [2] Danilo Zia, Luca Innocenti, Giorgio Minati, Salvatore Lorenzo, Alessia Suprano, Rosario Di Bartolo, Nicolò Spagnolo, Taira Giordani, Valeria Cimini, G. Massimo Palma, Alessandro Ferraro, Fabio Sciarrino, Mauro Paternostro, Quantum reservoir computing for photonic entanglement witnessing. *Sci. Adv.* 11, eady7987 (2025).
- [3] Iris Paparell, Johan Henaff, Jorge García-Beni, Émilie Gillet, Daniel Montesinos, Gian Luca Giorgi, Roberta Zambrini, and Valentina Parigi, Experimental memory control in continuous-variable optical quantum reservoir computing. *Nature Photonics* 20, 413-420 (2026).
- [4] Rosario Di Bartolo, Simone Piacentini, Francesco Ceccarelli, Giacomo Corrielli, Roberto Osellame, Valeria Cimini, Fabio Sciarrino, Time-series forecasting with multiphoton quantum states and integrated photonics. *Npj Quantum Inf.* 12, 91 (2026)