‘Photon Brain’ Unlocks Complex Laser Networks - Parallel Prediction of High-Dimensional Chaotic Dynamics

Accurately forecasting the high-dimensional chaotic dynamics of semiconductor laser (SL) networks is essential in photonics research

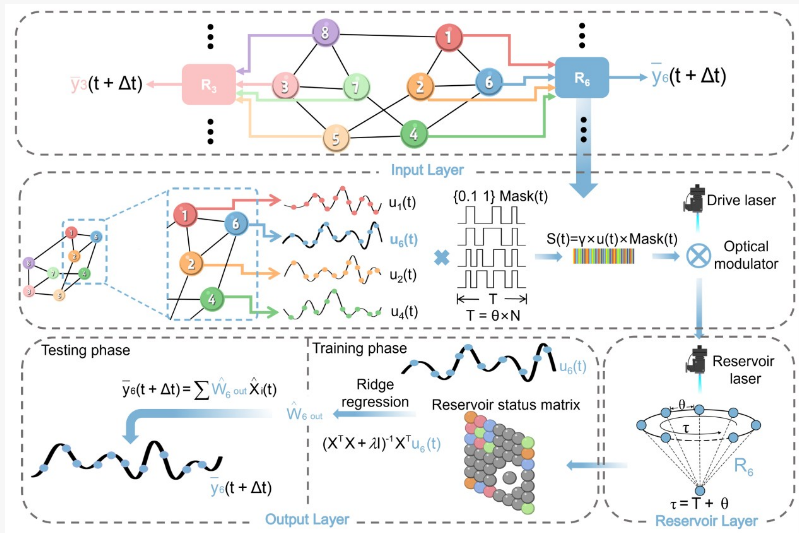

Figure 1 | Schematic of the STM-PRC architecture. Each node in the network is assigned an independent reservoir. The reservoir corresponding to SL6 (denoted as R6) is shown here as an example.

CHINA, December 3, 2025 /EINPresswire.com/ -- The chaotic dynamics generated by semiconductor lasers have attracted considerable attention due to their potential applications in various cutting-edge technologies. Such nonlinear phenomena have demonstrated great promise in fields including chaotic secure communication, high-speed physical random number generation, and photonic neuromorphic computing. Intuitively, chaotic dynamics can be regarded as a complex yet structured evolution of optical signals seemingly unpredictable, but with underlying order, much like weather systems or neural activity in the brain. Over the past few decades, researchers have pursued two primary approaches to describe and predict such behaviors: one involves constructing simplified nonlinear mathematical models based on physical principles, and the other focuses on reconstructing the underlying dynamics from experimental observations. However, traditional approaches often rely on idealized assumptions and fail to capture key nonlinearities and high-dimensional interactions, leading to significant prediction errors. These limitations become particularly severe in semiconductor laser networks, where multiple coupled lasers interact, resulting in highly nonlinear and high-dimensional dynamics that amplify modeling inaccuracies.

To overcome these challenges, machine learning has emerged in recent years as a powerful tool for predicting the behavior of complex systems. Unlike conventional model-driven approaches, machine learning learns directly from observed data and can effectively capture the nonlinear features of a system, thereby enhancing prediction accuracy. Among various machine learning paradigms, reservoir computing (RC) has gained widespread popularity for its simplicity and efficiency. RC is a specialized form of recurrent neural network comprising an input layer, a reservoir layer, and an output layer. In this framework, the internal connections and input weights of the reservoir are fixed, and only the output weights are trained, which greatly reduces computational cost and simplifies implementation. This design makes RC particularly suitable for modeling and predicting chaotic time series.

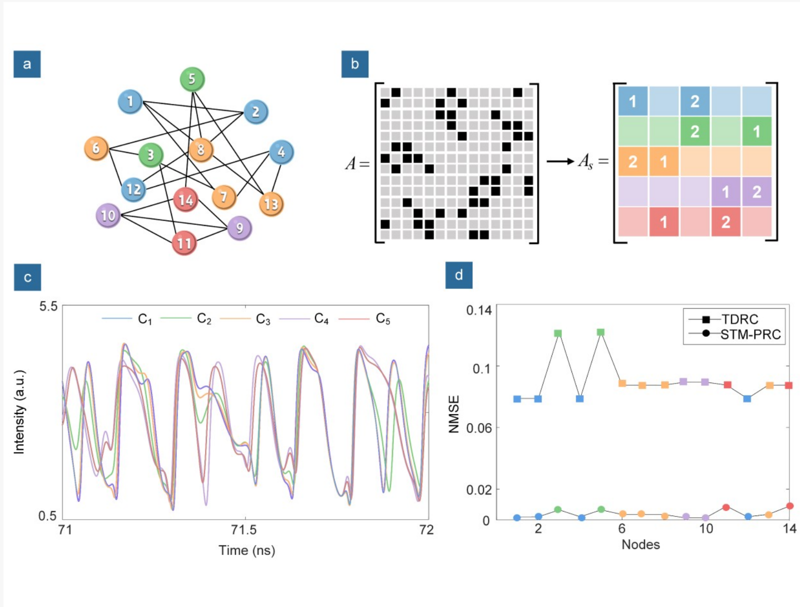

Figure 2 | (a)–(b) Schematic diagrams of the complex semiconductor laser network topology, where nodes of the same color belong to the same synchronization cluster. (c) Output dynamics of the SL nodes corresponding to the network shown in (a).

Photonic reservoir computing (PRC) extends this concept by leveraging the nonlinear properties and high-dimensional state space of photonic systems to perform efficient computation. Among its implementations, time-delay reservoir computing (TDRC) is one of the most representative schemes. It maps spatial interactions into temporal sequences through a single nonlinear node, thereby simplifying hardware requirements. Previous studies have shown that TDRC performs remarkably well in predicting the chaotic pulse amplitudes and continuous intensity time series of semiconductor lasers.

Despite its success in low-dimensional time-series prediction, the performance of TDRC deteriorates significantly when dealing with large-scale, high-dimensional dynamics in complex semiconductor laser networks. This degradation stems from the need to employ a large number of virtual nodes to capture intricate network interactions, resulting in high computational cost and slow processing speed. Moreover, most existing research has focused on predicting the chaotic dynamics of isolated semiconductor lasers, while systematic exploration of high-dimensional chaotic signals in semiconductor laser networks remains limited. In such networks, the overall evolution depends not only on the intrinsic dynamics of individual lasers but also on the complex coupling among interconnected nodes. Therefore, achieving lightweight, fast, and accurate prediction of large-scale complex semiconductor laser networks within the photonic reservoir computing framework remains an important and challenging research direction.

To address the aforementioned challenges, Professor Lianshan Yan's research team at Southwest Jiaotong University proposed and experimentally demonstrated a spatiotemporal multiplexed parallel photonic reservoir computing (STM-PRC) architecture for accurate prediction of high-dimensional chaotic dynamics in complex semiconductor laser networks. By leveraging the intrinsic topological characteristics of the network, the team decomposed the high-dimensional prediction task into multiple simplified reservoir modules operating in parallel, thereby improving both prediction accuracy and computational efficiency across different network scales. As illustrated in Fig. 1.

Furthermore, to facilitate hardware implementation, the team introduced a dimensionality reduction strategy tailored for high-dimensional chaotic datasets. This strategy exploits the intrinsic symmetry of the network topology to simplify complex coupling relationships, effectively reducing the dimensionality of the prediction task and improving computational efficiency. As illustrated in Fig. 2, the synchronization-based dimensionality reduction method enables accurate prediction of semiconductor laser network dynamics using fewer parallel reservoirs. This approach maintains high prediction accuracy while significantly enhancing computational efficiency and resource utilization, thereby making hardware implementation more feasible and practical.

Finally, the team experimentally validated the feasibility and effectiveness of the proposed framework through the prediction of high-dimensional chaotic dynamics generated by semiconductor laser networks. The results confirmed the strong predictive performance and practical applicability of the spatiotemporal multiplexed photonic reservoir computing approach. This work, entitled “Spatiotemporal Multiplexed Photonic Reservoir Computing: Parallel Prediction for the High-Dimensional Dynamics of Complex Semiconductor Laser Network,” was published in Opto-Electronic Advances, Volume 11, 2025.

The Information Photonics and Communication Research Team focuses on addressing national strategic needs and advancing the frontiers of photonics and communication science. The team conducts innovative research in several key areas, including high-speed optical fiber communication, optoelectronic information processing, optoelectronic integrated systems, and high-speed railway network security. Over the past five years, the team has led four national key R&D projects and more than ten major projects supported by the National Natural Science Foundation of China (NSFC), achieving significant breakthroughs in fundamental and applied research. They have published over 300 high-quality papers in top international journals, including Nature sub-journals, demonstrating strong academic influence and international visibility. In education, the team has developed one national-level first-class undergraduate course, received one second prize for national teaching achievements, and earned two provincial-level teaching awards. They have also trained 35 Ph.D. candidates and over 150 master’s students, many of whom have received prestigious honors such as the IEEE Photonics Society Graduate Student Award and the SPIE Optics and Photonics Education Scholarship. In terms of talent development, the team has recruited and nurtured three national-level young talents and more than ten provincial or ministerial-level talents, forming a vibrant research ecosystem with strong innovation capacity and a high-standard talent cultivation system.

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