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Performance evaluation of reservoir computing with two-dimensionally connected Josephson junctions for image recognition

Next-generation machine learning technology reservoir computing demonstrated in an image recognition task that is close to real-world applications

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Summary

- **An image recognition task similar to that in real-world applications was performed in the simulation of reservoir computing circuits using Josephson junctions, which are superconducting devices.**

- **Numerical images were successfully classified with 92% accuracy; power consumption of 12.8 μW, which is equal to or lower than that of other leading physical reservoir candidates.**

- **Applications range from superconducting machine learning hardware to quantum computers.**

Currently, research on "reservoir computing," which can perform calculations suitable for high-speed machine learning, is accelerating. This is owing to its simple processing structure, easier device implementation, and its power-saving and high-speed capabilities. A research group including Kohki Watanabe at the Graduate School of Engineering, Tohoku University, simulated a reservoir computing circuit using Josephson junctions, which are superconducting devices. Their simulation achieved a classification of numeric images with 92% accuracy and a power consumption of 12.8 μW, which is similar to or lower than other leading candidate materials for physical reservoirs. Based on the cryogenic operating characteristics of this study, potential applications include superconducting machine-learning hardware and even quantum computers.

Detail

High speed, low power consumption, easy for device implementation

Large-scale data analysis using machine learning has become indispensable in modern society. As the amount of electricity used for machine learning grows each year in response to social demand, the research and development of low-power machine learning devices is being sought. In this context, reservoir computing has attracted considerable attention. The advantages of this technology, such as high-speed learning, low power consumption, and a simple processing structure that easily facilitates device creation, are currently accelerating research and development in various fields.

Reservoir computing has a processing structure consisting of input, reservoir (intermediate layer), and output layers (Figure 1). The reservoir layer uses a "recurrent neural network" (*1), which is indispensable for machine learning. In a typical recurrent neural network, learning adjusts the coupling between neurons, updating the weights of the entire network. Therefore, physical implementation involves high implementation hurdles in hardware, such as the requirement to use elements that store changing weights, and inevitably consumes more power. However, reservoir computing has a processing structure that does not change the weights within the reservoir layer. In other words, the weights are adjusted only between the reservoir and output layers. Owing to this processing structure, reservoir computing is characterized by easy physical implementation and low power consumption.

A research group including Kohki Watanabe at the Graduate School of Engineering, Tohoku University has been studying a superconducting device, the Josephson transmission line (JTL), as a "physical reservoir" that replaces the reservoir layer with a physical device. A physical reservoir must be nonlinear, which can be realized in memristors, spin devices, neurons, and optical resonators. Previous studies on reservoir computing using a JTL, which is a superconducting device, have been investigated; moreover, their feasibility has been reported. This study reports the success of an image recognition task, which is close to real-world applications, by reservoir computing using JTL through simulations. This study goes beyond previous research and realizes realistic computing.

Reservoir computing is close to real-world applications

The JTL is being used in superconducting digital computers (SFQ circuits *2). It is a circuit composed of a chain of Josephson junctions (JJs). When a current pulse is applied as an input into this circuit, a quantized magnetic flux or flux quantum is trapped within the circuit. In addition, in response to changes in the input signal, JJ switches from a superconducting state to a resistive state, and the magnetic flux quantum propagates in the circuit. In this case, JJ acts as a threshold element, and thus, JTL exhibits a nonlinear response to the input signal.

“A JTL is a one-dimensional superconducting transmission line. A unique feature of this study is the construction of a JTL reservoir by arranging these lines in two dimensions. We constructed a more complex network by making the network two-dimensional. The accompanying optimization of the circuit parameters enabled us to perform an image-recognition task (Figure 2). As a result, we were able to correctly classify numeric images with 92% accuracy. There has not yet been any prior study on image recognition in reservoir computing using JTL. Previous studies only consisted of simulations of basic tasks. The novelty of our study is that we simulated a task similar to that in real-world applications using reservoir computing. In the future, we hope to implement this in hardware,” said Watanabe.

The power consumption of the JTL reservoir was 12.8 μW when the input voltage to the circuit and the bias voltage of each junction were calculated. Although the power consumption varies based on the task to be performed and cannot be compared in general, it is 10 mW for photonics and 1-100 μW for spin materials. These are the leading candidates for physical reservoirs, indicating that the JTL in this study has a low power consumption equivalent to or lower than that of the leading candidates.

Application to quantum computers

"Reservoir computing uses a recurrent neural network in the reservoir layer, which indicates that when a signal is input, it is stored for a certain period. Therefore, it is suitable for analyzing time-series data. The JTL reservoir used in this study could also be applied to time series data classification," says Watanabe about future prospects.

Professor Shigeo Sato of Graduate School of Engineering, Tohoku University, and Research Institute of Electrical Communication, Tohoku University, who is involved in this study, also considers that "the seemingly disadvantageous features of JTL reservoirs, which operate at low temperatures, could open applications in quantum computers."

The JTL reservoirs are superconducting devices that operate at extremely low temperatures. Therefore, it is unsuitable for edge computing (*3). However, most quantum computers operate at low temperatures. Research on the use of machine learning to adjust the state measurement of qubits is already underway, and there is a possibility that reservoir computing with JTL reservoirs can be used in this machine learning process.

"Their advantage is that they can only operate at low temperatures when working with a quantum computer. Currently, the integration of digital computing and machine learning and that of quantum computing and machine learning are being explored. The recurrent neural networks used in reservoir computing can be applied to other machine learning; therefore, they are a good match. Additionally, because quantum computers are currently being developed at the national level, the development of reservoir computing could also be an important theme," said Shigeo Sato.

The group plans to conduct further research and development for the physical implementation of JTL reservoirs and identify specific issues.

Annotation

*1. **RNN / recurrent neural network:** A neural network that behaves dynamically over time by regressing the output of a node back on its input. It can be applied to tasks, such as sentence generation and speech recognition, and is used in many modern machine learning applications.
*2. **SFQ / single flux quantum circuit:** A logic circuit in which the presence or absence of a magnetic flux quantum in a superconducting circuit corresponds to a binary signal "1" or "0." It was proposed by Nakajima et al. at Tohoku University and systematized by Likharev et al. at Moscow State University. They are used in various applications ranging from digital arithmetic circuits to readout circuits for superconducting qubits.
*3. **Edge computing:** Computational processing is performed at the edge (periphery) of a computer network. In a narrower sense, this refers to the computational processing within devices, such as those used in IoT.

Figures

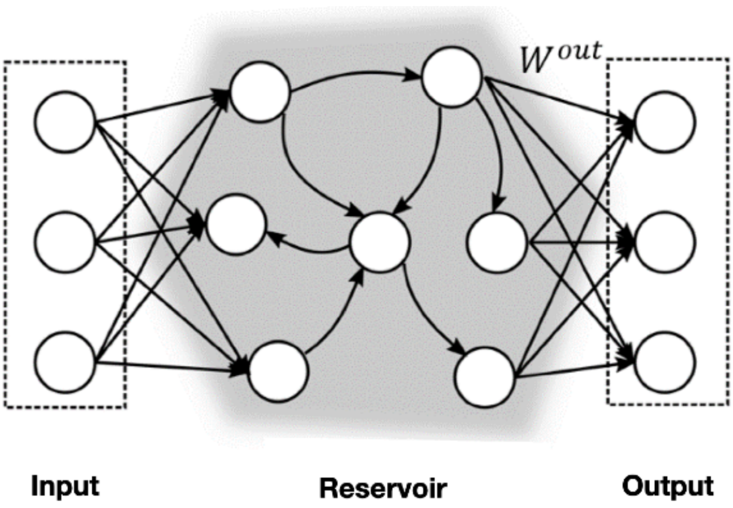

Figure 1: Network structure in reservoir computing.

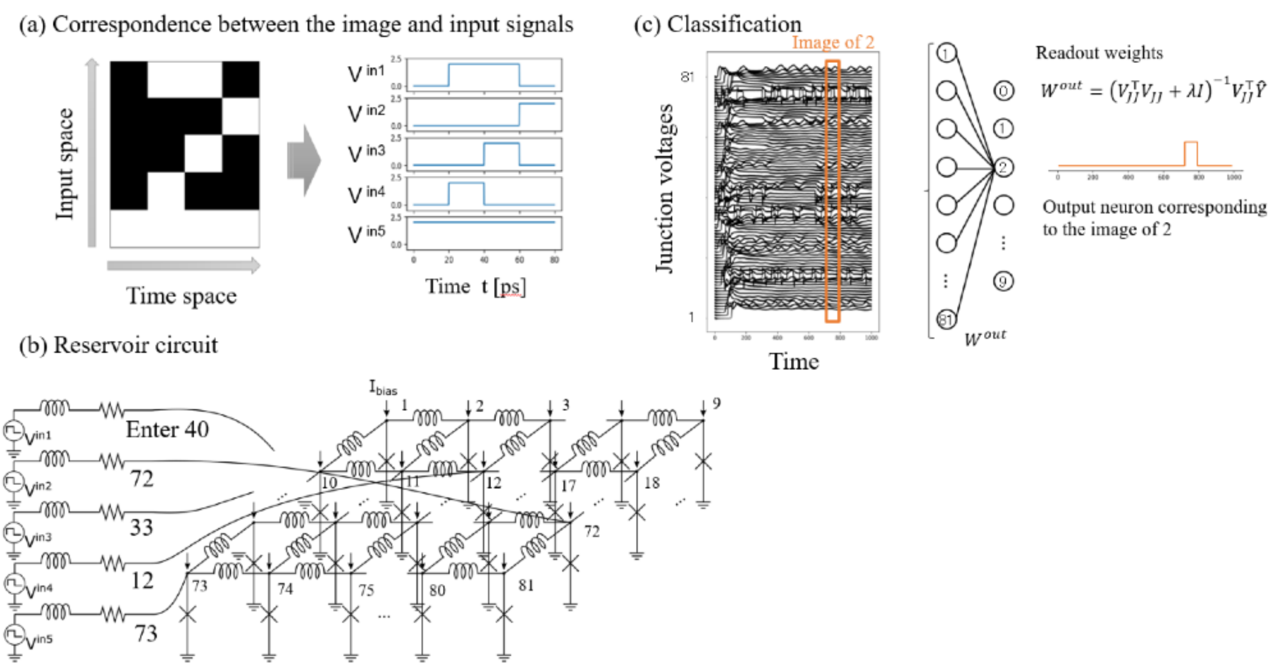

Figure 2 Image recognition in this study is the task of classifying images of handwritten numbers. The 5 × 4 image in Figure (a) is divided into five rows and fed as input voltage for four time frames to a random node of the reservoir circuit in Figure (b). The readout weights are computed by ridge regression, as shown in Figure (c). As a result, the JTL reservoir was able to classify the numeric images with 92% accuracy.