Reservoir computing using dynamics of magnetic skyrmions

Tomoyuki Yokouchi
RIKEN Center for Emergent Matter Science (CEMS), Wako 351-0198, Japan.
Department of Basic Science, The University of Tokyo, Komaba, Tokyo 153-8902, Japan

Artificial neural networks, mimicking human brains, exhibit great abilities in several tasks such as image recognition. Nowadays, most artificial neural networks rely on silicon-based general-purpose electronic circuits such as a central processing unit (CPU) and a graphics processing unit (GPU). However, in these circuits, a large amount of energy is consumed. Moreover, the absence of memory functionality in CPU and GPU is a disadvantage especially for recurrent-type artificial neural networks, in which past data is stored in the network as actual human brains. Therefore, developing devices specialized for brain-inspired computing, namely neuromorphic devices, are highly required. So far various neuromorphic computing models using spintronic devices have been proposed and demonstrated[1]. Among them, one of the promising models is a physical reservoir computing model. In the physical reservoir computing model, the input data are nonlinearly converted into multi-dimensional outputs by using nonlinear dynamics of spintronic devices. Incidentally, this nonlinear mapping of input data into the high-dimensional space is a key to neuromorphic computing; the mapping enables linearly inseparable data to be linearly separable, like the kernel method.

In this presentation, we demonstrate physical reservoir computing by using a magnetic-field induced nonlinear dynamics of skyrmions. A skyrmion is a particle-like topological spin structure and can be manipulated with low power consumption. Thus, skyrmions are expected to be applied to energy-saving devices. Moreover, skyrmions are theoretically predicted to show high performance in reservoir computing[2]. We use Pt/Co/Ir film deposited on $LiNbO_3$ substrate in which the formation of disordered skyrmion has been observed[3]. Our skyrmion-based physical device consists of parallelly connected Hall-bar shaped devices in which various constant magnetic field are applied (Fig. 1). In each Hall-bar device, we input a time-dependent out-of-plane magnetic field [$H_{AC}(t)$] whose waveform is the same as what we want to compute. The output is anomalous Hall voltage [$V^i(t)$] (Here, i denotes the output from i-th Hall bar); $V^i(t)$ changes in response to $H_{AC}(t)$ because of $H_{AC}(t)$-induced change in magnetic structures and is nonlinear with respect to $H_{AC}(t)$. In this way, the input signal is nonlinearly converted into multi-dimensional data set $\boldsymbol{V}(t) = [V^1(t), \cdots, V^N(t)]$. Then, the final output is calculated by a linear combination of $\boldsymbol{V}(t)$ (i.e. $\sum W_i V^i$), in which the coefficients (W_i) of the linear combination are optimized by using a training data set so that the final output is desirable.

We succeeded in a waveform recognition task, which is a conventional benchmark. Notably, the recognition rate of the skyrmion-based neuromorphic computing device is better than a neuromorphic computing device in which ferromagnetic-domain structures were used instead of skyrmions. This is attributed to a more complex nonlinear mapping and the larger number of the output dimension, both of which originate from the large degree of freedoms of the disordered skyrmion system such as the position and the size of skyrmions. Our results provide a guideline for developing energy-saving and high-performance neuromorphic computing devices with the use of skyrmions.

Reference

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2) D. Prychynenko, et al., Phys. Rev. Appl. **9,** 014034 (2018).
3) T. Yokouchi, et al., Nat. Nanotech. **15,** 361 (2020).

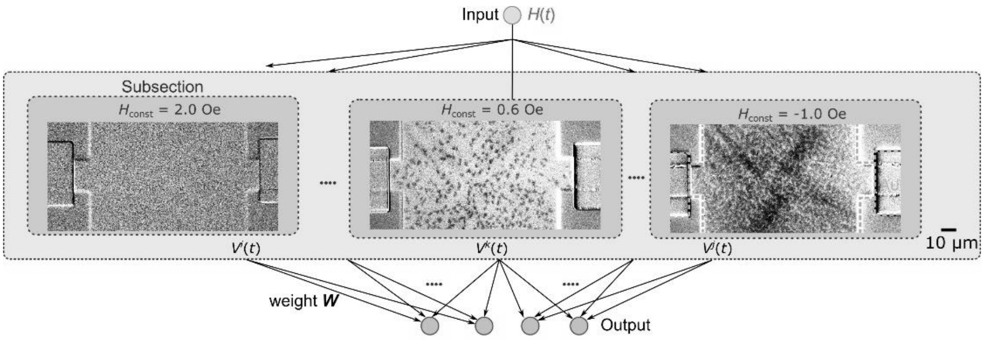

Fig. 1 Schematic illustration of a skyrmion-based neuromorphic computer. Polar Kerr images of Hall bar device with various constant magnetic field (H_{const}) are also presented.