Physical reservoir computing based on spin torque oscillator

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Recently, spintronics devices have been applied to artificial neural networks (ANNs). Spintronics devices are considered to have high potential due to their small size and high non-linearity. Among various types of ANNs, reservoir computing (RC) [1] is an interesting target for applying spintronics devices. RC utilizes a dynamical system, called a reservoir, driven by a time series input. The input induces transient dynamics with fading memory in the reservoir. Nonlinear tasks such as speech recognition are performed by the function of fading memory inside the reservoir. The interesting point of the RC is that various physical systems can be used as a reservoir [2]. In fact, in recent years, we have performed the physical RC using a spin torque oscillator (STO) as a reservoir, and succeeded in the speech recognition task [3].
The figure-of-merit of the RC is examined by short-term memory task which evaluate fading memory quantitatively. In addition, the ability of non-linear transformation of inputs is evaluated by parity check task. These computational abilities are quantitatively characterized by the short-term memory and parity-check capacities. These capacities have been investigated in other physical systems [2,4], as well as numerical simulation in STOs [5]. However, there is no report investigating the capacities experimentally in spintronics.
In this study, we investigated computational capability of the physical RC consisting of a vortex type STO by evaluating these capacities quantitatively. The capacities were measured by output signal from the STO with respect to modulated inputs. First, we used the voltage as the inputs [6], where the modulated voltage induced the transient dynamics through spin-transfer effect. The short-term memory capacity was evaluated to be 1.8 which means that the STO roughly memorized two bits in the reservoir. Next, we used the microwave field with phase modulation to reduce the noise of the STO [7]. Optimizing the microwave amplitude, the short-time memory capacity was maximized to be 3.6. This value is two times larger than that of voltage input. The parity-check capacity was also evaluated for the first time, which was 3.1 at maximum. The results indicated that the reduction of the noise in the STO is a key for the improvement of computing capability of physical RC.
This work was based on the results obtained from a project (Innovative AI Chips and Next-Generation Computing Technology Development/(2) Development of next-generation computing technologies/Exploration of Neuromorphic Dynamics towards Future Symbiotic Society) commissioned by NEDO.

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Artificial Neural Networks with Spintronics

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Biological neural network consisting of neurons and synapses is a model system of computation when one develops hardware executing complex cognitive tasks that the conventional von Neumann computers cannot readily complete. Here we discuss a spintronics technology to construct artificial neural networks where spintronics devices mimic the function of neurons and synapses. Spintronics devices, namely magnetic tunnel junctions, are critical building block of magnetoresistive random access memory which has been commercialized recently. In addition, recent studies have revealed unexplored functionalities of spintronics devices holding promise for the artificial neural networks [1-5].

In this presentation, we will describe our studies on artificial neural networks based on spintronics technologies. We utilize analog spin-orbit torque devices with an antiferromagnet-ferromagnet bilayer structure as an artificial synapse [6]. We will show a Hopfield-model based associative memory where the capability of supervised learning of the synaptic devices is confirmed [7]. We will also present that the spin-orbit torque switching can reproduce characteristic dynamics of biological synapses and neurons, spike-timing-dependent plasticity and leaky integrate-and-fire, respectively [8], making the systems attractive building blocks for spiking neural network. Mechanism underlying the observed neuron- and synapse-like behavior will be also discussed [9].

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Brownian computing using skyrmions and reservoir computing in magnetic dot-arrays

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Recent progress and attention regarding an artificial intelligence promotes the research on neuromorphic computing using various physical systems which is not von Neuman type computer. Spintronics is one of the candidates for such a computing technology with the low power consumption. In this study, we discuss two types of basic technology for spin computing, Brownian computing and reservoir computing.

Brownian computing utilizes the random motion of particles, such as Brownian motion, which can calculate information with low energy close to the thermodynamics limit[1)]. We use Skyrmion Brownian motion for Brownian computing. Skyrmion is the Brownian particle in solid state material and is topologically protected spin structure which can be detected and controlled at room temperature. We deposited the Skyrmion film, Ta | CoFeB | Ta | MgO | SiO_2, on Si | SiO_2 substrate. The magnetic anisotropy of CoFeB is partially modulated by changing thickness of SiO_2 capping, which forms Skyrmion circuit without strong pinning site. Figure 1 shows the magneto-optical Kerr effect (MOKE) microscope image of the Skyrmion film. The Skyrmion shown as a black dot is confined in the area surrounded by dashed lines which is the area of thin SiO_2 layer and is low potential energy for Skyrmion. Skyrmion can propagate in the Skyrmion circuit stochastically, which is the basic technology for Brownian computing.

The other is reservoir computing using magnetic dot array. Reservoir computing[2)] which extract important information from intricated signal by learning the weight of the output nodes. Figure 2 shows the time evolution of the magnetic anisotropy of the magnetic dots. Blue and yellow dots show finite and zero perpendicular magnetic anisotropy, whose states change from stage 0 to stage 6. The magnetization of dot array is numerically calculated, and the weight is optimized. We succeeded in calculating the AND, OR, and XOR operation by magnetic dots array at the temperature of 0 K. This research is the basis for experimental research of artificial spin glass.

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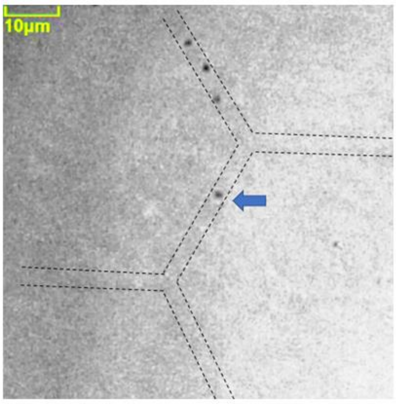

Fig. 1 MOKE microscope image of the Skyrmion film. Black dot is Skyrmion.

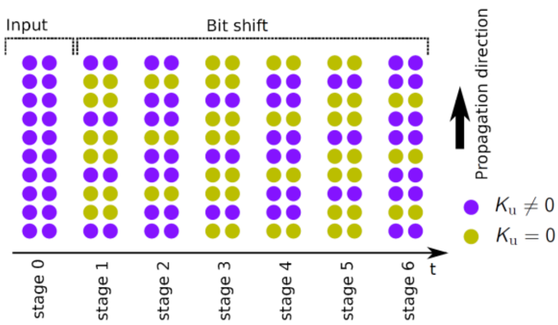

Fig. 2 Operation process of magnetic dot reservoir. Blue and yellow dots show finite and zero perpendicular magnetic anisotropy, whose states change from stage 0 to stage 6.

Coherent signal transfer along skyrmion strings

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Magnetic skyrmion, a topological soliton characterized by swirling spin texture appearing in two-dimensional system, has recently attracted attention as a stable particle-like object. In the three-dimensional system, skyrmion forms a string structure in analogy with the vortex-line in superconductors / superfluids and cosmic string in the universe, whose unique topology and symmetry may also host nontrivial response functions. In this talk, we discuss the propagation character of spin excitations on skyrmion strings. We find that this propagation is directionally non-reciprocal, and the degree of non-reciprocity, as well as the associated group velocity and decay length, are strongly dependent on the character of the excitation modes. Our theoretical calculation establishes the corresponding dispersion relationship, which well reproduces the experimentally observed features. Notably, these spin excitations can propagate over a distance exceeding 10^3 times the skyrmion diameter, demonstrating the excellent long-range nature of the excitation propagation on the skyrmion strings. The present results offer a comprehensive picture of the propagation dynamics of skyrmion string excitations, and suggest the possibility of unidirectional information transfer along such topologically-protected strings.

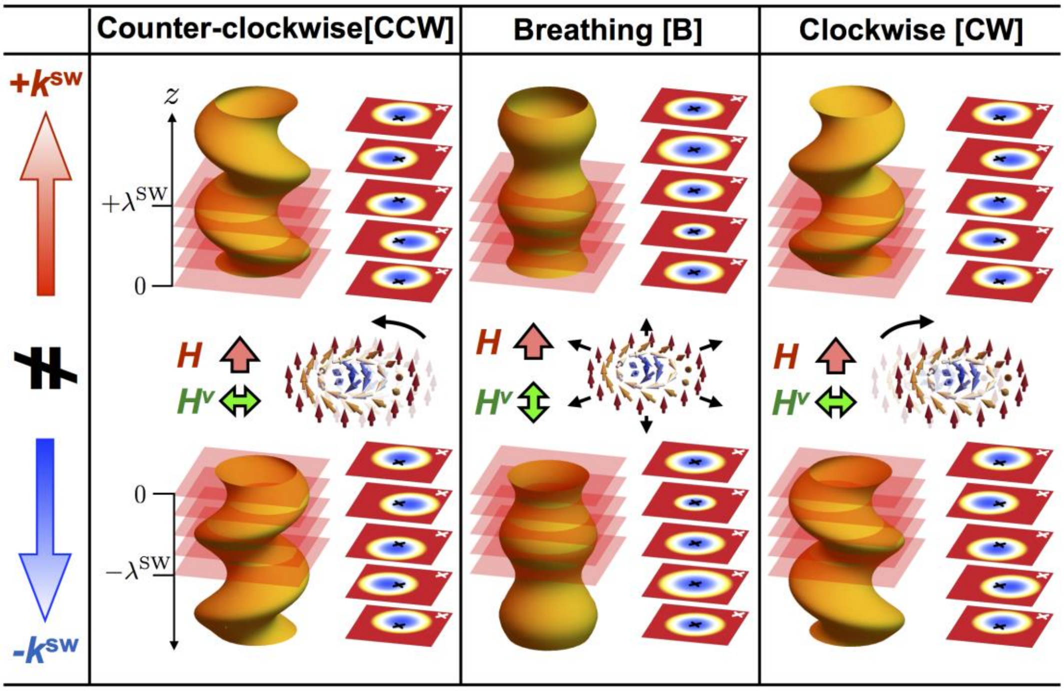

Figure 1. Schematic illustration of spin excitation propagating along skyrmion strings.

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Quantum magnonics in ferromagnetic insulators

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Ferromagnetic resonances (FMR) have been studied for decades. They generate high-quality oscillations of magnetization at microwave frequencies and are applied to various devices such as frequency-stabilized oscillators, narrow-band filters, etc. However, it was very recent that the quest for quantum control and measurement of the collective spin excitations in ferromagnetic materials started.

For FMR at $\omega_m/2\pi$= 10 GHz, a quantum of the magnetostatic oscillation mode, a magnon, has the energy $\hbar\omega_m$ corresponding to the thermal energy of $k_B\times$ 0.5 K. Thus, at 10 mK in a dilution refrigerator, the number of thermally excited magnons in the mode could be negligibly small, i.e., the mode could be in a magnon vacuum.

We use the Kittel mode of a single crystalline yttrium iron garnet sphere and couple the spatially uniform collective spin precession with microwave photons in a cavity, demonstrating strong coupling between the two harmonic oscillator modes.[1)] We next accommodate in the same cavity a superconducting qubit which consists of a Josephson junction and two antenna pads.[2)] The nonlinearity provided by Josephson effect results in an effective two level system, i.e., a quantum bit, with which we control the quantum state of the magnetostatic mode at a single magnon level. We observe an energy level splitting of the qubit excitation due to the interaction with the magnon vacuum via the virtual photon excitation in the cavity. When the magnon and qubit frequencies are detuned, the dispersive interaction between them enables us to count the number of magnons excited in the millimeter-sized sphere one by one.[3)]

We also use this strong dispersive interaction to demonstrate novel protocols for quantum-enhanced sensing of magnons. First, we demonstrate a magnon detection sensitivity of about 10^{-3} magnons/$\sqrt{\text{Hz}}$ by using a simple quantum sensing protocol that relies on dephasing of the qubit from the excitations of magnons in the ferromagnetic crystal. In a second experiment, we entangle the Kittel mode with the qubit through a conditional excitation of the qubit, which we use to demonstrate the single shot detection of a single magnon with a detection efficiency close to 70%, therefore bringing the equivalent of the single photon detector to the field of magnonics.

For a recent review of the progress in the field, see Ref. 4).

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Machine-learning computation utilizing spin waves

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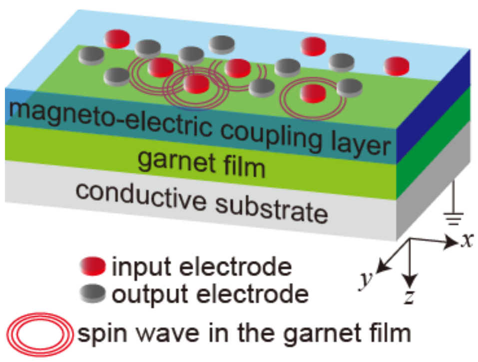
In next-generation internet of things (IoT) era, information processing near/at terminal devices, so-called “edge computing”, is necessary to receive the merits of big data by constructing a load distribution network. Since such information processing contains information extraction, compression, and disposal from time-sequential data detected by sensors, it requires machine-learning devices. The most effective edge computing system can be realized if each terminal has an on-chip machine-learning device with high performance and extremely low power consumption.

Reservoir computing is a computational framework which is originally based on recurrent neural networks [1, 2]. A reservoir computing system is composed of a reservoir part and a readout part. In the reservoir part, input time-sequential data are nonlinearly transformed to high-dimensional spatiotemporal signals. In the readout part, the high-dimensional signals generated by the reservoir in response to input sequential data are used for pattern analysis of dynamical features of the input sequential data with a learning process. Notably, recent studies have demonstrated that reservoir computing is technically advantageous for on-chip machine-learning device [3]: Reservoir computing can be realized with nonlinear physical phenomena for the reservoir part and feasible numbers of weights for the readout part. For successful reservoir computing in pattern recognition tasks, it was found that a physical reservoir should satisfy several requirements, such as input history-dependent response, nonlinearity, and fading memory.

Spins in a magnetic material are intrinsically nonvolatile and history-dependent characteristics can be obtained in their distribution and dynamic motions. Thus, the spin system in a ferromagnetic material (or a ferrimagnetic material) has a potential capability for reservoir computing devices. There have been some successful reports on reservoir computing utilizing on-chip spin devices with one input node and one output node, in which time-sequential discrete values in the output were *virtually* used as multiple nodes for computing [4, 5]. However, feasible on-chip reservoir computing devices, which have many *real* inputs/outputs for advanced information processing, have not been proposed or demonstrated since there are some difficulties to overcome, particularly, the wiring explosion problem. To create such devices, on-chip wave-based computing devices are very promising since it requires a small number of wirings [6].

Motivated by these backgrounds, we proposed an on-chip spin-wave-based reservoir computing device with multiple inputs and outputs, as shown in Figure [7], where spin waves are locally excited by the input electrodes, then they transmit through the continuous magnetic garnet film, and finally the resultant spin waves are locally detected by the output electrodes. A notable feature is that nonlinear interference and history-dependent characteristics of spin waves are used as computation, which can be realized by moderately-unstable precession of spins with a vertical magnetic field below 500 Oe that is available in the matured magnetic bubble technology. Utilizing this device as the reservoir part, reservoir computing can be performed by the weighted sum of multiple outputs in the output part. From successful computation using a micromagnetics simulator based on Landau-Lifshits-Gilbert (LLG) equation, we demonstrated that this device works well as a reservoir showing good generalization characteristics applicable to machine-learning information processing.



Spin-wave-based reservoir computing device

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Magnon transistor for next generation computing

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Advanced electronics uses the charge of conduction electron as an information carrier, and the nanotechnology allows a robust control of charge flow. Electronics developed highly integrated systems such as LSI which leads to a laptop computer and a smart phone. We are facing the drastic change of CPS/IoT society. The developments of semiconductor technology suggest a new class of devices such as the wearable and CPS/IoT devices, and generate enormous amount of information up to YB (10^{24}B). While, the CPS/IoT society requires a clean energy source and more energy efficient devices for the signal processing. The electronics is now facing the dilemma: realization of the fast processing and low energy loss operation.

A research field which seeks for a ultralow power consumption device by manipulating spin waves in micro fabricated devices is now called "magnonics or magnon spintronics", in which a spin-wave is treated quantum mechanically and described by a quasi-particle of "magnon".[1] The crucial difference of magnonics from electronics is that a flow of magnon is a flow of angular momentum and generate no Joule heating.[2–4] Furthermore, magnons have a potential to transmit information with GHz-THz carrier frequencies. Magnon can be created by electric microwave in general, however magnon is also possible to be generated by thermal and optical methods. Magnonics now becomes a multi-disciplinary research field including electronics, magnetics, thermal engineering, and optics, and shows a potential to create multi-functional device principles.[5,6] For example, there is the possibility to create a non-Boolean magnon transistor and a neuron-like signal processing with multi-input/output architecture [7].

In this background, a new type of magnon transistor was proposed using a magnon nonreciprocity discovered in an anisotropic ferromagnetic Fe waveguide 8). Since the cubic anisotropy of Fe allows four different magnetization directions for a fabricated waveguide, a magnon generated by the source antenna shows an asymmetric wavefront, according to the magnetization directions; the magnon densities of top and bottom sides of the waveguide, at the detection antenna, exhibit a strong nonreciprocity (edge-mode magnon nonreciprocity). By combining the two units of Fe waveguide, the XOR and XNOR gates can be constructed. With a similar way, the combination of three units provides AND, NAND, OR, and NOR gates. Logic gates using the edge-mode magnon nonreciprocity allow a no-field operation and a simple architecture. To construct next generation magnonic computing, these logic architectures suggest the important progress of magnon transistor: reconfigurable and nonvolatile operations.

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Logic gates using spin waves

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Magnonics is an important research field that aims to realize post-CMOS devices by taking advantage of spin waves (SWs). The wave properties of SWs enable multiple input/output logic operation modes depending on the orientation of the wavevector/wavelength and the magnetization direction. A yttrium iron garnet (YIG) is suitable as a SW propagation medium because of its low damping constant. And a forward volume SW mode is preferable for construction of SW logic circuits because it enables the use of waveguides with curved and bent section. However, the logic gate using forward volume SWs propagating in YIG films were not demonstrated. Hence, we show our recent works on the development of the devices and discuss future work related to new computation using SWs.

First, we fabricated the three port SW ExNOR gate using ~20 μm thick YIG film.[1)] This gate worked as a SW phase interferometer. The device size was 1 mm × 16 mm. Edge reflection of SWs was totally canceled by abruption boundaries using gold films.

Second, four port SW AND and OR gates were demonstrated (Figure 1).[2)]

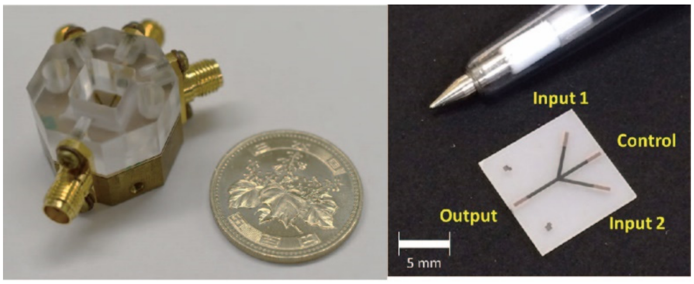

Fig. 1 Fabricated four ports spin wave logic gate using ~10 μm thick single crystalline YIG film.

This device also worked as a majority gate. The interferometer consisted of 10 μm thick monocrystalline YIG film grown a gadolinium gallium garnet substrate. The Ψ shaped waveguide was composed of three input ports. Input 1 and input 2 entered the junction area with 45° angle of incidence. The ridge waveguide was fabricated using photolithography and a micro-sandblasting technique. The film was magnetized perpendicular to the plane so that forward volume SWs were excited. Figure 2 showed the obtained results. Multilevel AND and OR gates were demonstrated. In the conference, miniaturized SW logic gates would be also shown.

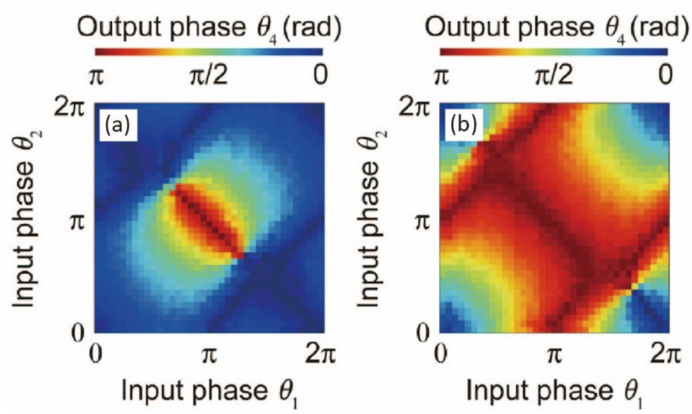

Fig. 2 AND (left) and OR (right) operation configuration obtained by experiment.

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