Physical reservoir computing based on spin torque oscillator

S. Tsunegi[1], T. Taniguchi[1], K. Nakajima[2], S. Miwa[3], K. Yakushiji[1], A. Fukushima[1], S. Yuasa[1], and H. Kubota[1]
1. Spintronics Research Center, AIST, Tsukuba, Ibaraki, Japan.
2. Graduate School of Information Science and Technology, The Univ. of Tokyo, Bunkyo-ku, Tokyo, Japan.
3. The Institute for Solid State Physics, The Univ. of Tokyo, Kashiwa, Chiba, Japan.

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.

Reference

1) H. Jaeger et al., Science **304**, 78 (2004).
2) K. Nakajima et al., J. R. Soc. Int. **11**, 20140437 (2014).
3) J. Tirrejon et al., Nature **547**, 428 (2017).
4) K. Fujii et al., Phys. Rev. Appl. **8**, 024030 (2018)
5) T. Furuta et al., Phys. Rev. Appl. **10**,034063 (2018).
6) S. Tsunegi et al., Jpn. J. Appl. Phys. **57**,120307 (2018).
7) S. Tsunegi et al., Appl. Phys. Lett. **114**,164101 (2019).

Artificial Neural Networks with Spintronics

S. Fukami[1-5], W. A. Borders[1], A. Kurenkov[1-3], and H. Ohno[1-5]
[1] Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku University, Sendai 980-8577 Japan
[2] Center for Science and Innovation in Spintronics, Tohoku University, Sendai, 980-8577 Japan
[3] Center for Spintronics Research Network, Tohoku University, Sendai, 980-8577 Japan
[4] Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845 Japan
[5] WPI-Advanced Institute for Materials Research, Tohoku University, Sendai, 980-8577 Japan

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].

This work is jointly carried out with S. Sato and Y. Horio of Tohoku University, P. Gambardella of ETH Zurich, F. Maccherozzi of Diamond Light Source, and their group members. A part of the work has been supported by the R&D Project for ICT Key Technology of MEXT, ImPACT Program of CSTI, JST-OPERA, JSPS KAKENHI 17H06093, 18KK0143, 19H05622, JSPS Core-to-Core Program, and Cooperative Research Projects of RIEC.

Reference

1) J. Grollier *et al.*, Proc. IEEE **104**, 2024 (2016).
2) S. Fukami and H. Ohno, J. Appl. Phys. **124**, 151904 (2018).
3) J. Torrejon *et al.*, Nature **547**, 428 (2017).
4) A. Mizrahi *et al.*, Nature Commun. **9**, 1533 (2018).
5) A. Chakravarty *et al.*, Appl. Phys. Lett. 114, 192407 (2019).
6) S. Fukami *et al.*, Nature Mater. **15**, 535 (2016).
7) W. A. Borders *et al.*, Appl. Phys. Express **10**, 013007 (2017).
8) A. Kurenkov *et al.*, Adv. Mater. **31**, 1900636 (2019).
9) A. Kurenkov *et al.*, Appl. Phys. Lett. **110**, 092410 (2017).

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

M. Goto[1,3], T. Nozaki[2], H Nomura[1,3], H. Kubota[2], and Y. Suzuki[1,2,3]
[1] Graduate School of Engineering Science, Osaka University, Osaka 560-8531, Japan
[2] National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki 305-8568, Japan
[3] Center for Spintronics Research Network (CSRN), Graduate School of Engineering Science, Osaka University, Osaka 560-8531, Japan

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 limit1). 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 computing2) 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.

Reference
1) C. H. Bennett *Int. Jour. Theo. Phys*, **21**, 905 (1982)
2) H. Jaeger and H. Haas Science, **304**, 78, (2004)

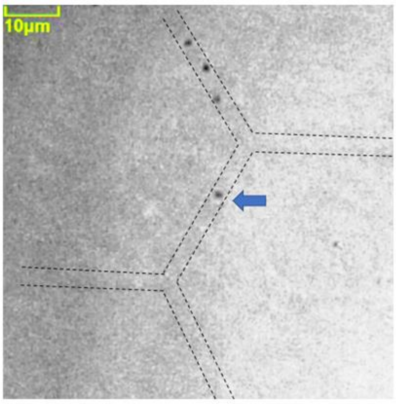


Fig. 1 MOKE microscope image of the Skyrmion film. Black dot is Skyrmion.

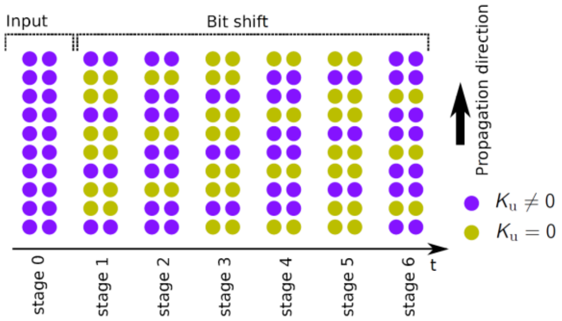


Fig. 2 Operation process of magnetic dot reservoir. Blue and yellow dots show finite and zero perpendicular magnetic anisotropy, whose states change from stage 0 to stage 6.

Coherent signal transfer along skyrmion strings

Shinichiro Seki
(Department of Applied Physics, University of Tokyo)

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.

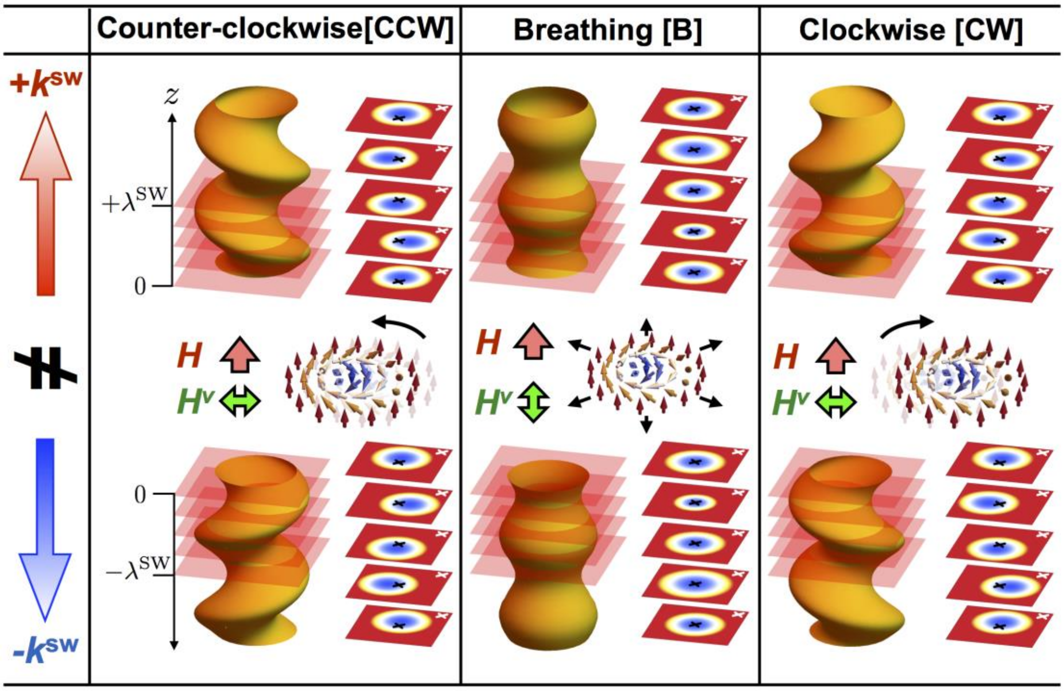


Figure 1. Schematic illustration of spin excitation propagating along skyrmion strings.

Reference

1) S. Seki, X. Z. Yu, S. Ishiwata, and Y. Tokura, Science **336**, 198 (2012).
2) S. Seki, M. Garst, J. Waizner, R. Takagi, Y. Okamura, K. Kondou, F. Kagawa, Y. Otani, Y. Tokura, arXiv:1902.10302.

Quantum magnonics in ferromagnetic insulators

Yasunobu Nakamura[1,2]
[1] Research Center for Advanced Science and Technology (RCAST), The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
[2] Center for Emergent Matter Science (CEMS), RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

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).

Reference
1) Y. Tabuchi *et al.*, Phys. Rev. Lett., **113** (2014) 083603.
2) Y. Tabuchi *et al.*, Science, **349** (2015) 405.
3) D. Lachance-Quirion *et al.*, Sci. Adv., **3** (2017) e1603150.
4) D. Lachance-Quirion *et al.*, APEX, **12** (2019) 070101.

Machine-learning computation utilizing spin waves

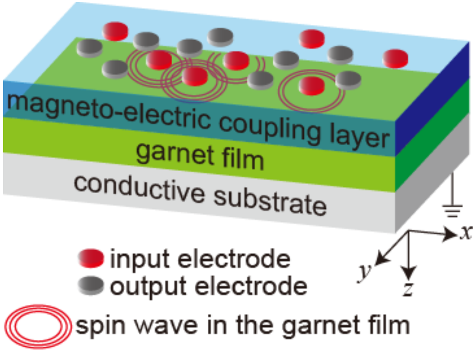
Ryosho Nakane[1,2], Gouhei Tanaka[1,2], and Akira Hirose[2,1]
[1]Institute for Innovation in International Engineering Education
[2]Department of Electrical Engineering and Information Systems,
Graduate School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

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

Acknowledgement This work was partially supported by the New Energy and Industrial Technology Development Organization (NEDO).

References (1) W. Maass, *et al.*, Neural Comp. **14** (2002) 2531. (2) H. Jaeger, GMD Report 148, German National Research Center for Information Technology (2001). (3) G. Tanaka, *et al.*, Neural Networks **115** (2019) 100. (4) J. Torrejon et al., Nature **547** (2017) 428. (5) T. Furuta, et al., Physical Review Applied **10** (2018) 034063. (6) Y. Katayama, *et al.*, IEEE Trans. Nanotech. **15** (2016) 762. (7) R. Nakane, G. Tanaka, and A. Hirose, IEEE ACCESS **6** (2018) 4462.

Magnon transistor for next generation computing

Koji Sekiguchi
Faculty of Engineering, Yokohama National University,
Tokiwadai 79-5, Hodogaya, Yokohama 240-8501, Japan

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.

References

1) A. V. Chumak, A. A. Serga, and B. Hillebrands: ”Magnon transistor for all-magnon data processing”, Nature Communications 5, 4700 (2014).
2) T. Schneider:”Realization of spin-wave logic gates”, Appl. Phys. Lett. 92, 022505 (2008).
3) N. Sato, S.J. Lee, S. W. Lee, K. J. Lee, and K. Sekiguchi: ”Phase stability of magnonic logic operation in microfabricated metallic wires”, Appl. Phys. Exp. 9, 083001(2016).; N. Sato, K. Sekiguchi, et.al: ”Electrical Demonstration of Spin wave logic operation”, Appl. Phys. Exp. 6, 063001(2013).
4) K. Sekiguchi, K. Yamada, S. M. Seo, K. J. Lee, D. Chiba, K. Kobayashi, and T. Ono: ”Time-domain measurement of current-induced spin wave dynamics”, Phys. Rev. Lett. 108, 017203(2012).
5) N. Kanazawa, T. Goto, K. Sekiguchi, A. B. Granovsky, C. A. Ross, H. Takagi, Y. Nakamura, H. Uchida, and M. Inoue: ”The role of Snell’s law for a magnonic majority gate”, Scientific Reports 7, 7898(2017).
6) N. Kanazawa, T. Goto, K. Sekiguchi, A. B. Granovsky, C. A. Ross, H. Takagi, Y. Nakamura, H. Uchida, and M. Inoue: ”Demonstration of a robust magnonic spin wave interferometer”, Scientific Reports 6, 30268(2016).
7) R. Nakane, G. Tanaka, A. Hirose: ”Reservoir Computing With Spin Waves Excited in a Garnet Film”, : IEEE Access 6, 4462(2018).
8) K. Sekiguchi, S. W. Lee, H. Sukegawa, N. Sato, S. H. Oh, R. D. McMichael, and K. J. Lee: ”Spin wave propagation in cubic anisotropic materials”, NPG Asia Materials 9, e392(2017)

Logic gates using spin waves

Taichi Goto[1,2]
[1] Toyohashi Univ. of Tech., Toyohashi 441-8580, Japan
[2] MIT, Cambridge 02139, USA

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)

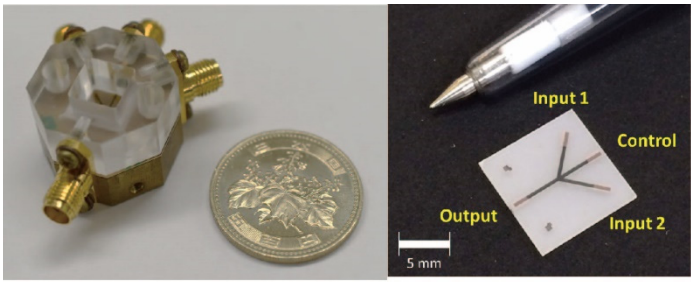


Fig. 1 Fabricated four ports spin wave logic gate using ~10 μm thick single crystalline YIG film.

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.

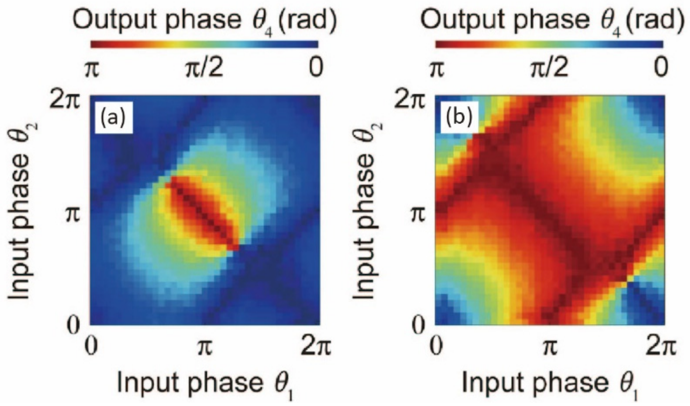


Fig. 2 AND (left) and OR (right) operation configuration obtained by experiment.

Reference

1) N. Kanazawa, T. Goto, *et al.*, Sci. Rep. **6**, 30268 (2016).
2) N. Kanazawa, T. Goto, *et al.*, Sci. Rep. **7**, 7898 (2017).

磁気光学効果による炭素鋼の局所的磁気物性評価

室井慎平，高瀬つぎ子，山口克彦，内一哲哉※，高木敏行※
（福島大，※東北大）

Local magnetic property evaluation of carbon steel by magneto-optical effect

S. Muroi, T. Takase, K. Yamaguchi, T. Uchimoto※, T. Takagi※
(Fukushima Univ. ※Tohoku Univ)

はじめに

現在，構造材料の非破壊検査には電磁超音波探触子(EMAT)などの手法が用いられており，実際に EMAT による鋳鉄の非破壊評価も行われている $^{1)}$．しかし，新品の炭素鋼管を用いた測定にて，Fig.1 に示すようにパイプ周方向におけるエコー振幅に差異が生じた．このことより，試料周方向にて超音波信号の発生要因である磁歪効果やローレンツ力，伝搬，反射等について炭素鋼管の物性の差異が影響していると考えられる．

本研究では，磁区観察及び局所的磁気特性とエコー振幅の関連性に着目し，比較，検討を行うため，Fig.1 のようなエコー振幅の差異に注目してサンプルを切り出し，マイクロ磁気光学カー効果顕微鏡(μ-MOKE 顕微鏡)を用いて磁区観察及び局所的磁気特性の測定を行った．その結果をもとに，EMAT と局所領域における磁気物性の対応関係を確認した．

実験手法・結果

本実験では，EMAT によるエコー振幅(信号強度)の大きい箇所を sample S，小さい箇所を sample W とし，各々の箇所から 7.0×7.0×2.0[mm]サイズの炭素鋼試料を切り出した．その後，鏡面研磨を行い，μ-MOKE 顕微鏡にて試料の同視野における磁区観察と局所的(スポット径φ2~3[μm])磁気特性の測定を行った．Fig.2, Fig.3 に sample S と sample W 双方の磁区観察像と局所的磁気特性の測定結果を示す．

Fig.2 より，sample S は sample W よりサイズが大きい磁区の割合が多いことが確認された．また，Fig.3 より sample S は sample W より磁気光学カー効果による旋光角の値が大きいことが確認できた．このことから，磁性領域の形成や局所的な磁性の違いが EMAT におけるエコー振幅の差異に影響を与えていると考えられる．

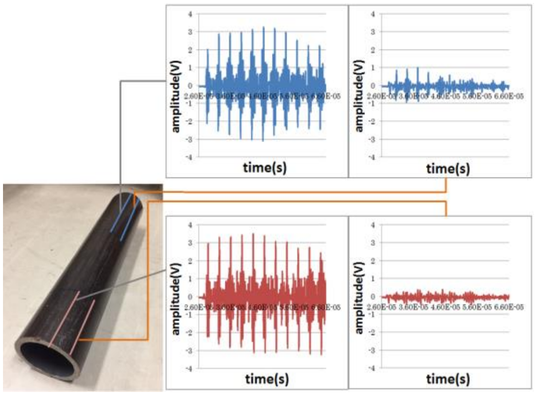


Fig.1 Difference of echo amplitude
(in the circumferential direction)

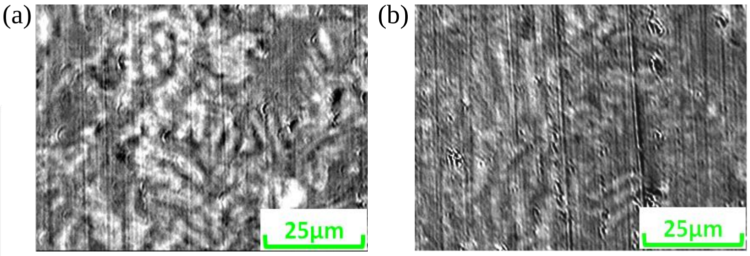


Fig.2 Magnetic domain image (magnetic fields :1100Oe)
(a) sample S, and (b) sample W

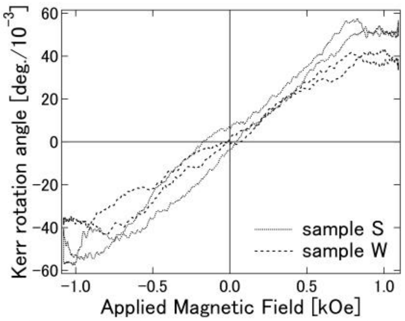


Fig.3 Local magnetic properties of sample S and W

参考文献

1) 大瀧　啓太郎，内一　哲哉，高木　敏行：“電磁超音波-渦電流複合プローブを用いた鋳鉄の非破壊材質評価”，日本機械学会論文集(A 編)76 巻 767 号，pp.186-193(2010).

正方配列 Au 粒子/Bi:YIG 複合構造体におけるファラデー効果および極カー効果の FDTD シミュレーション

板橋悠人[1]，Ilham Surya Priasmoro[1]，髙田一紀[1]，水戸慎一郎[2]，Andrey Fedyanin[3]，
後藤太一[1]，中村雄一[1]，P. B. Lim[1]，内田裕久[1]，井上光輝[1]
（[1]豊橋技科大，[2]東京高専，[3]Lomonosov Moscow State University）

FDTD simulations of Faraday and polar Kerr effects for composite structures with squarely arranged Au particles and Bi:YIG films

Y. Itabashi[1], S. P. Ilham[1], K. Takada[1], S. Mito[2], A. Fedyanin[3], T. Goto[1], Y. Nakamura[1], P. B. Lim[1],
H. Uchida[1], M. Inoue[1]
([1]Toyohashi Univ. of Tech., [2]NIT, Tokyo College, [3] Lomonosov Moscow State University)

はじめに

透明な磁性ガーネットは磁気光学効果を利用した磁気イメージングセンサなどに用いることが可能である．例えば，磁性材料の傷を探査する場合，測定対象物に磁気光学膜を近づけて反射光の回転角を測定する極カー効果測定が適し，その回転角が大きいことが望ましい．また，周期配列させた Au 粒子と磁性ガーネット(Bi:YIG)薄膜との複合構造体では，局在型表面プラズモン共鳴によってファラデー回転角を増大させることができるが[1,2]，カー効果についてはまだ十分に研究が行われていない．したがって将来の応用を考えて，本研究では，正方配列 Au 粒子/Bi:YIG 複合構造体のファラデー効果と極カー効果について FDTD シミュレーションを用いて回転角を大きくする方法について考察する．

磁気光学応答の FDTD シミュレーション

Au 粒子は電子線描画装置を用いて作製するが，Fig. 1(a)は周期 200nm の正方配列 Au 構造であり，この上に Bi:YIG を成膜した複合構造体について FDTD シミュレーションを行った．モデルは Au 粒子の長軸直径 109 nm，短軸直径 92.2 nm の扁平楕円体であるとし，Bi:YIG の厚さを 110 nm とした．Fig. 1(b)に計算で得られた透過率とファラデー回転角を，Fig.1(c)に反射率と極カー回転角を示す。透過率とファラデー回転角はプラズモン共鳴波長で回転角が増大した．この結果は，実験結果とよく一致する．また極カー効果も変化したが，このモデルでは角度変化が小さかった．

次に，扁平楕円体 Au の長軸直径を 130 nm，短軸直径を 110 nm と大きくし，Bi:YIG の厚さも 120 nm にしたときの透過率とファラデー回転角，反射率とカー回転角の計算結果を Fig. 2(a)と(b)にそれぞれ示す．Au 粒子のサイズを大きくすることで，波長 660 nm 付近のファラデー回転角が正の大きな値に変化し，またカー回転も同じ波長で大きくなった．また極カー効果は，光の往復によるファラデー回転の単純な 2 倍の値になる訳ではないことも分かった．このように本研究により，ファラデー回転角だけでなく，極カー回転角の大きさも構造によって制御できる可能性があることが明らかになった．

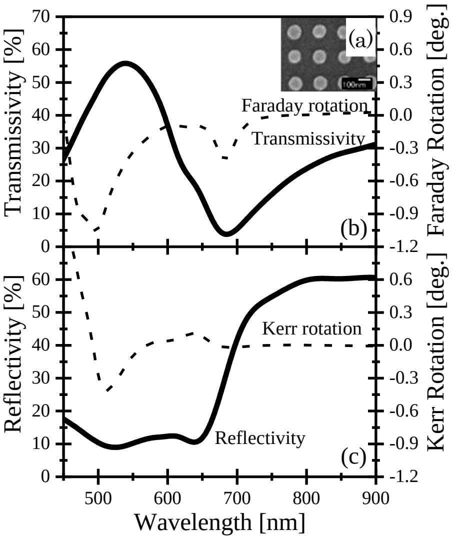


Fig. 1 (a) A top view of fabricated Au particles, (b) calculated transmissivity and Faraday rotation, and (c) reflectivity and polar Kerr rotation.

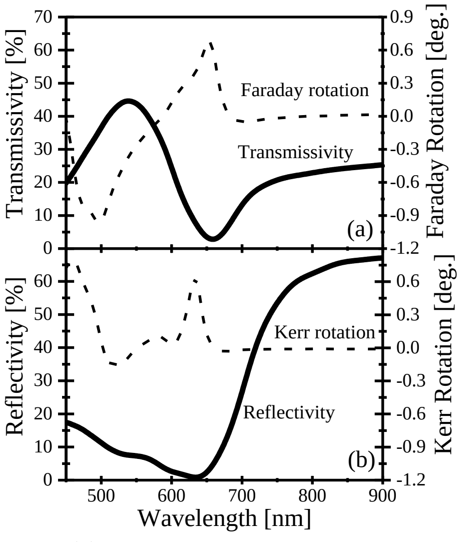


Fig. 2 (a) Calculated transmissivity and Faraday rotation, (b) reflectivity and polar Kerr rotation.

参考文献

1) H. Uchida et al., J. Phys. D: Appl. Phys., 44, 064014 (2011).
2) 板橋悠人他，第 42 回日本磁気学会学術講演会概要集 11pPS-11 (2018).

X線磁気円偏光発光を利用した放射光磁気顕微鏡

稲見俊哉、菅原健人、中田崇寛*、阪口友唯*、高橋真*
(量研放射光、*JFE テクノリサーチ)

Scanning magnetic microscope based on x-ray magnetic circularly polarized emission

T. Inami, K. Sugawara, T. Nakada*, Y. Sakaguchi*, and S. Takahashi*
(QST, *JFE-TEC)

1　はじめに

X線磁気円二色性は、磁化した試料に円偏光X線を入射した際にその吸収量が円偏光の左右に依存するという現象であり、元素選択的な磁化測定が出来ること、微小試料の観察や微小モーメントの検出に適していること、磁気光学総和則が使える場合があることなどから、磁気測定において標準的な手法の一つとなっている。しかしながら、物質透過能の高い硬X線領域においては、3d遷移金属に対して感度が低い(反転比で0.5%以下)という問題が存在していた。薄膜試料等、透過法の使える試料についてはこの問題は改善されてきたものの、バルク測定が必要な対象については、硬X線領域で3d遷移金属に対し大きな反転比を持つ新しい測定手法の開発、測定原理の発見が求められている。

この問題に対し、最近我々はX線磁気円偏光発光という新しいX線磁気分光法の発見に成功した[1)]。これは、磁化した試料の発する蛍光X線(特性X線)が円偏光を含むという現象であり、蛍光X線の円偏光度から発光領域の磁化(の出射方向成分)を見積もることができる。硬X線領域にある3d遷移金属の$K\alpha$発光において20%近い大きな反転比を示すという優れた特徴を持ち、応用研究への発展が期待される。現在、本手法を利用した放射光励起の走査型磁気顕微鏡の開発を進めており、この発表では開発の現状について報告する。

2　結果および考察

開発は大型放射光施設SPring-8の量研ビームラインBL11XUで行っている。本手法による磁気顕微鏡の構成図をFig.1に示す。入射X線は、まず集光光学系により試料上に集光される。空間分解能はここで決まり、当面は樹脂製屈折レンズを用いた10 μm集光で開発を進めている。試料からは蛍光X線が発せられ、これを集めて平行化し、後ろの円偏光解析装置に供給する部分が平行化光学系である。Montel型多層膜ミラーで実現され、高効率測定に必須の光学素子である。円偏光解析装置はダイヤモンド移相子とGe(400)エネルギー兼直線偏光分析器からなる。移相子により円偏光と直線偏光の相互変換を行い、続いてエネルギー兼直線偏光分析器でエネルギー分解すると同時に直線偏光度を評価し、ここから円偏光度を得る。得られた円偏光度から発光領域の磁化が求まり、試料を走査することにより、磁化の2次元マップを得る。

試料は、磁区が比較的大きく、また、3d遷移金属元素が主たる磁性を担っているという観点から、方向性電磁鋼板を選んだ。入射X線のエネルギーは17.3 keV、出射角は45度とした。この場合、表面から10 μm程度の領域の情報を得ていると見積もっている。横65 μmステップ、縦30 μmステップで、約3 mm×3 mmの領域を走査し、ストライプ状の磁区と複数のlancet磁区を観察することができた。今後は、入射X線のエネルギーを上げたより深部の測定等を検討している。

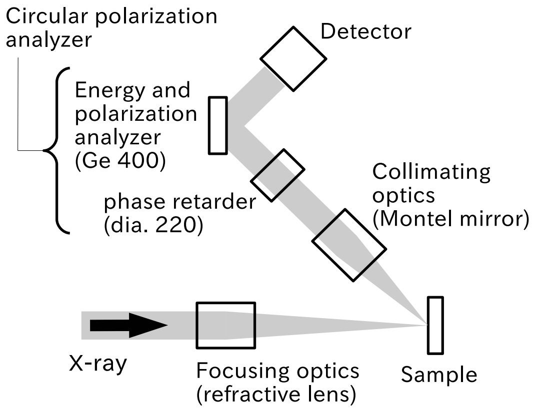


Fig. 1　Top view of experimental layout.

References

1) T. Inami: *Phys. Rev. Lett*, **119**, 137203 (2017).

マイクロレンズアレイを用いた磁気光学3次元ディスプレイの高視野角化と像拡大化

○Altankhuyag Khishig-Ochir、木村陽太、伊藤誉敏、堀米秀嘉*、後藤太一、中村雄一、
Lim Pang Boey、内田裕久、井上光輝
（豊橋技科大，*ホーリーマイン）

Increasing viewing angle and magnifying image for magneto-optical 3D display using microlens array

A. Khishig-Ochir, Y. Kimura, Y. Ito, T. Goto, Y. Nakamura, P. B. Lim, H. Uchida, M. Inoue
(Toyohashi Univ. of Tech., *Holymine)

はじめに

眼精疲労が生じにくく、広い視野角を持つ、ホログラフィック３次元(3D)ディスプレイを実現するために磁気光学効果が応用されている1)。大きな視野角を得るためには微小なピクセルが必要であり、1 μmサイズで大規模領域にピクセルを形成すること、および書き換え時間を短くすることが、3D ディスプレイの実用化への課題である。先行研究ではホログラムをページデータとして記録することで記録時間の短縮を図ってきたが，走査距離が媒体の書き込むホログラムの全域と広く、高分解能で広範囲に書き込むことが困難であった。そこで我々はマイクロレンズアレイ（MLA）と呼ばれる微小レンズが配列された素子を用いて、多数のピクセルを同時に書き込み、かつ走査距離を短縮する方法を用いた2)。本研究では、この MLA を用いた光学系によるホログラムの記録と 3 次元像の再生において、視野角を広げることと像を拡大する方法について検討する。

光学系

ホログラムの形成では、レーザ光をデジタルミラーデバイス（DMD）で強度変調をした後、MLA によって集光し、縮小したピクセルを磁気光学媒体に書き込んだ。MLA のレンズピッチは DMD のピクセルピッチと同一で 13.68 μm である。このとき DMD のピクセル間隔に相当する 13.68×13.68 μm^2 の面積を走査することで DMD のサイズである 1 cm^2 の画面サイズの磁気書込みが可能となり、ピエゾステージの使用が可能になり、動作速度を向上させることができる。また焦点距離と移動距離を調整することで、ピクセルサイズを変えることができる。再生は、ホログラム記録媒体からの 0 次透過光が小さくなるように、偏光子とλ/4 波長板を透過した楕円偏光を入射させ、検光子で反射光の変調成分を取り出す。像の拡大は、レンズを二つ用いて幾何光学による 2 倍の結像光学系で再生像を拡大する方法を用いた。

計算機ホログラムによって、立方体フレームのホログラムを計算した。記録・再生に用いる磁性薄膜にはイオンビームスパッタ法によって成膜した SiN(30 nm)/ *a*-TbFe(50 nm)/ SiN(20 nm)/ガラス基板を用いた。

3D 像の再生

熱磁気記録を用いてホログラムを磁性体に記録し、波長 532 nm のレーザ光によって再生した立方体フレームのホログラフィを Fig. 1 に示す。計算で求めた通りに 2.5 mm 角の立方体の 3 次元像が再生された。ピクセルピッチは1 μmであり、このとき視野角 29 deg.が得られた。次に 2 倍の結像光学系を用いて磁気ホログラフィの再生像の拡大を行った。その結果、横倍率が 2 倍になることを確認することができた。

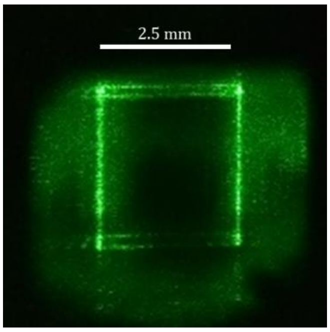


Fig. 1. A 3D cubic frame image reconstructed using magneto-optical holography.

参考文献

1) K. Nakamura, et al., *Appl. Phys. Lett.* 108, 022404 (2016).
2) 木村陽太他，第 42 回日本磁気学会学術講演会概要集 12aPS-60 (2018).

27pB－8

機械学習と非線形フィルタによる高速磁区観察像のノイズ低減

小田切 雄介、阿部 正英*、洞口 勇太*、柳沢 栄二、目黒 栄、川又 政征*、斉藤 伸*
（ネオアーク株式会社、*東北大学）

Noise reduction for high speed domain observation images using machine learning and non-linear filters

Y. Odagiri, M. Abe*, Y. Horaguchi*, E. Yanagisawa, S. Meguro, M. Kawamata*, S. Saito*
(Neoark Corporation, *Tohoku University)

はじめに　電磁鋼板や軟磁性薄帯は変圧器やモーターのコア材として幅広く活用されており、その性能改善はエネルギー利用効率上昇に直結するため、地球温暖化対策の一環として極めて重要である。これら軟磁性材料の磁気特性把握の手法としては実働状態における磁区観察が有用である。我々はこれまで磁気光学Kerr効果を利用したcmオーダ領域の広視野磁区観察装置の開発を行ってきており1)、商用周波数励磁下で繰り返し再現性の低い磁区観察を行うために、10,000 fps以上のフレームレートでのワンショット撮像に取り組んできた。受光画素の大きい高速度カメラの採用、光学系の伝送効率の改善といった工夫により50 Hzの磁場掃引においてFeSi系アモルファス薄帯の磁化過程のワンショット観察を達成できている。しかしながら高速度撮像の性質上、時間・空間領域の平均化が制限されるため、ショットノイズ等のノイズ低減が課題であった。そこで本研究では、高速磁区観察時のノイズを低減するために、画像処理によるノイズフィルタを検討した。

フィルタの検討　時間変化に伴う磁区構造の変化が緩慢になることを避けるためには、まず，フレーム単位で空間領域のフィルタによるノイズ低減が必要である。これを実現する手法として機械学習を用いた画像処理を発案した。今回の機械学習ではConvolutional Neural Networkによるオートエンコーダを用い、教師あり学習を行った。学習素材については、教師データとして256回の平均化を行った画像を、入力データとしてワンショットで取得した画像を用いた。次に、時間変化によるちらつきを低減するためには非線形フィルタを時間領域に適用することが有効である。今回は突発的な輝度値の時間変化を取り除く効果が期待できるメディアンフィルタを用いた。

観察結果　Fig. 1はアモルファス薄帯を高速度カメラで観察した動画から1フレームを切り出したものであり、(a) は飽和像差分画像、(b) は (a) に対しノイズ低減フィルタを適用した画像である。どちらの画像も8ビットの色深度で処理を行っている。左上部に注目すると、ショットノイズが大幅に低減された結果、複雑な磁区パターンが顕在化したことがわかる。(c) は (a)、(b) の像中の直線部に対応する輝度のラインプロファイルを示しており、ノイズが大幅に低減されていることがわかる。(a)、(b) の像中の四角で囲んだ領域の輝度ヒストグラムの分散半値幅を評価すると、フィルタ適用前は75だったのに対して、フィルタ適用後は5.1へと改善しており、フィルタ効果を定量的に確認できる。

講演では、機械学習フィルタと非線形フィルタの構成の詳細および、時間方向のフィルタリングの効果を動画も用いて報告する。

参考文献　1) S. Meguro et al.: 28th *Ann. Conf. Magn. Soc. Jpn.*, 24aF-9 (2004).

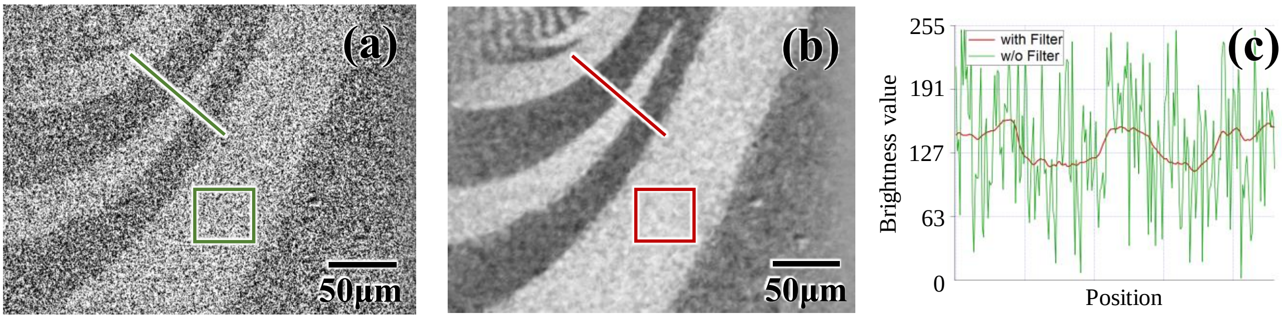


Fig. 1　Magnetic domain images (a) without and (b) with machine learning and non-linear filters. (c) Brightness line profiles.