Ultra-broadband and ultra-high sensitivity permeability measurements by transformer coupled permeameter (TC-permeameter)

S. Tamaru
(Spintronics Research Center, Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, 305-8568 Japan)

Magnetic materials are ubiquitously used in various high frequency electronics systems as inductors, transformers, noise filters and noise suppression sheets, which often determine the entire system performance. One such example is an inverter. Among many components used in the inverter circuit, inductors and transformers usually have the lowest high frequency performance, thus limit the entire system performance such as the switching frequency, conversion efficiency and unit size. For this reason, improvements of these magnetic components are crucial for the development of modern electronics systems. High frequency magnetic components are often made of magnetic particles by either sintering or dispersing into polymer resin. Currently the permeability of the magnetic particles can be measured only in the final component form because of the limited sensitivities of permeance measurement techniques currently available. This is a serious limitation in the development of the magnetic components, because it is impossible to study the effects of the processes done on the magnetic particles, such as crashing, micro forging, annealing and solidifying, on the permeability, and therefore one can only guess the effects by characterizing the magnetic component in the final form. In order to overcome this difficulty and accelerate the developments of high frequency magnetic components, a technique to measure the permeability with high sensitivity has been strongly sought.

For measuring the permeability of a single magnetic particle with sufficiently high sensitivity, we have developed a permeability measurement technique, which we named as "transformer coupled permeameter (TC-permeameter). Figure 1 shows the block diagram of this technique. A magnetic particle is sandwiched by two short terminated coplanar waveguides (CPWs). These two CPWs are electrically insulated by Kapton tape, thus this structure forms a loosely coupled single-turn transformer. Each CPW is connected to the port 1 (P1) and 2 (P2) of a vector network analyzer (VNA) that measures the transmission parameter (S_{21}) twice, first under the magnetic field of interest, and second under a sufficiently strong magnetic field to saturate the magnetic particle. The difference of S_{21} under these two magnetic fields reflects the permeability. Figure 2 shows the permeability of a Permalloy particle with a lateral size of approximately 100 μm and thickness of 0.5 μm, which is similar to the size of magnetic particles contained in commercial noise suppression sheets, measured by the TC-permeameter. The figure shows that the permeability can be measured over a very wide frequency range from 10 MHz up to 20 GHz with a high signal-to-noise ratio (SNR).

In the presentation, the measurement principle of the TC-permeameter technique, including the jig structure, the reason why this technique can enhance the sensitivity, how to calibrate the system to give the absolute value of the permeability, and how the measurement limits are determined, will be explained.

This work is partially supported by 'FY2018 Research support program of matching funds for AIST and Tohoku university' and 'FY2019 strategic information and communications R&D promotion programme (SCOPE) #195003002' of Ministry of internal affairs and communications (MIC) of Japan.

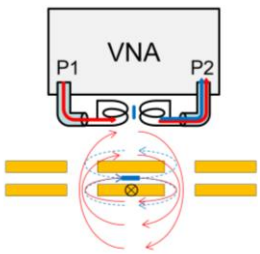

Fig. 1, Block diagram of the TC-Permeameter. The magnetic particle is sandwiched by two short terminated CPWs that form a loosely coupled transformer, and the VNA measures the S_{21} parameter.

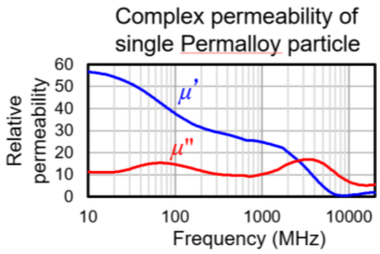

Fig. 2, Complex relative permeability of a single Permalloy particle over 10 MHz – 20 GHz.

Measurement of biomagnetic information using room temperature operation tunnel magneto-resistance sensor

K. Fujiwara[1], M. Oogane[2,3,4], S. Cakir[1], S. Kumagai[1] and Y. Ando[1,2,3,4]

[1]Spin Sensing Factory Corp., Sendai 980-0845, Japan;
[2]Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan
[3]Center for Science and Innovation in Spintronics, Tohoku University, Sendai 980-8577, Japan
[4]Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan

The tunnel magneto-resistance (TMR) sensors using magnetic tunnel junctions (MTJs) are expected as highly sensitive magnetic sensors operating at room temperature. Magnetic sensors are used for current sensing, displacement / rotation sensing, nondestructive testing, *etc*., and in recent years, biomagnetic field measurement that senses the activity of the human body with a magnetic field has been actively studied. Measurement of biomagnetic field includes magnetocardiography (MCG)[1)] resulting from electrical activity of the heart and magnetoencephalography (MEG)[2), 3)] measuring brain current. These magnetic field measurements are considered to be useful tools for medical diagnosis and basic research because they have high spatial resolution and temporal resolution compared to electrical measurements.. On the other hand, since the biomagnetic field is a very weak magnetic field of at most 100 pT, the sensors that can perform the measurement are limited.

We have been researching to realize the measurement of this biomagnetic field using a TMR sensor. Until now, we have succeeded in partial real-time MCG measurement using a TMR sensor and MEG measurement using averaging[4)]. The MTJ multilayer film used for the TMR sensor was deposited by ultra-high vacuum sputtering system. This multilayer film is characterized in that it has MgO barrier layer and has a synthetic structure using $Ni_{80}Fe_{20}$ in the bottom free layer. Since it was necessary to reduce the noise of the TMR sensor in order to measure a small magnetic field, we reduced $1/f$ noise by arranging a large number of MTJs in an array. The size of the fabricated MTJ array was 7.1×7.1 mm^2, and four arrays were used to construct a bridge. The output from the TMR sensor bridge was amplified and filtered and measured by a PC using an A/D converter. In MCG, the R-peak caused by the heartbeat was measured with a probability of about 1/2, and a clear QRS wave was measured by performing averaging about 16 times. Moreover, MEG succeeded in measuring the 10 Hz magnetic signal originating from the α wave by averaging 10,000 times, and confirmed that the phase of the signal is rotated 180 degrees by rotating the direction of the TMR sensor by 180 degrees. At present, we are studying to improve the multilayer film structure of the TMR sensor to further increase the sensitivity. There is a method of thinning the MgO barrier layer to reduce the noise of the TMR sensor. At this time, when the resistance value of the junction decreases, the signal is reduced due to the parasitic resistance of the lower electrode film. As a countermeasure against this parasitic resistance, a thick Cu film was deposited and a chemical mechanical polishing process was performed, and a TMR multilayer film was formed on this substrate to reduce the resistance. In addition to the improvement of the multilayer film structure, we are also examining the improvement of signal and noise by changing the spatial arrangement of the TMR sensor. In addition to the feature of room temperature operation, TMR sensor has the feature of wide magnetic dynamic range, and its output does not saturate even if it is used in geomagnetism. Therefore, it is thought that operation outside the shield room is also possible. Using this feature of wide dynamic range, we are currently studying for measuring biological information without a shield room.

Acknowledgement
This work was partly supported by the S-Innovation program, Japan Science and Technology Agency (JST).

References

1) H. Koch, J. Electrocardiol. **37**, 117 (2004).
2) N. Nakasato, *et al*., Electroencephalogr. Clin. Neurophysiol. **94**, 183 (1995).
3) D. Cohen, Science **175**, 664 (1972).
4) K. Fujiwara *et al*., Appl. Phys. Express **11**, 023001 (2018).

Development of synchrotron X-ray nano-beam dynamic force microscope

Hikaru Nomura[1], Ryouki Wakasa[2], Naoki Samura[2], Yuma Jibiki[1], Kazuki Takahashi[1], Soma Miki[1], Junya Yamaguchi[1], Ryoichi Nakatani[2], Minori Goto[1], Yoshishige Suzuki[1], Kentaro Toyoki[2], Satoshi Okamoto[3], Yoshinori Kotani[4], Tetsuya Nakamura[4]
[1]Graduate school of engineering science, Osaka University, Toyonaka, Osaka 560-8531, Japan
[2]Graduate school of engineering, Osaka University, Suita, Osaka 565-0871, Japan
[3]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai, Miyagi 980-8577, Japan
[4]JASRI, Sayo, Hyogo 679-5198, Japan

Soft X-ray magnetic circular dichroism (XMCD) measurement is one of the most powerful tools for researches on spintronics devices. In recent years, the size of magnetic materials used in spintronics devices has been reduced to several tens of nanometers. To measure the magnetization behavior in such devices, a high spatial resolution measurement technique is required. An XMCD measurements technique with Soft-X ray nano-beam has shown remarkable results for magnetization measurements. However, the spatial resolution of the soft X-ray nano-beam MCD is limited to a few tenths of nanometers. Therefore, a new method for XMCD high spatial resolution is required. A combination of XMCD and scanning probe microscopy (SPM) is one of the promising technique to enhance the spatial resolution of XMCD measurements [1-5]. Here, we developed a soft X-ray nano-beam SPM for high spatial resolution XMCD measurement.

For soft X-ray nano-beam SPM, we developed an original dynamic force microscope (DFM) with UNISOKU Co., Ltd. The soft X-ray nano-beam SPM was installed in Spring-8 BL25SU (Fig. 1). Fig. 2 shows a schematic diagram of our soft X-ray nano-beam SPM. The DFM is fully controlled by the original controller developed with LabVIEW FPGA. The controller can be remotely controlled by python programs. With this system, we can enhance the spatial resolution of the XMCD measurements.

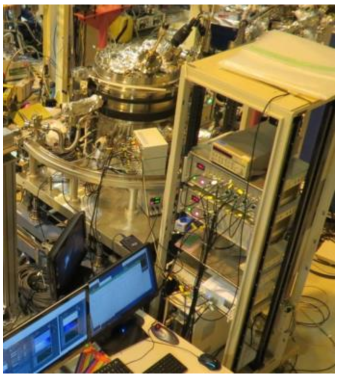

Fig. 1. Photograph of soft X-ray nano-beam SPM.

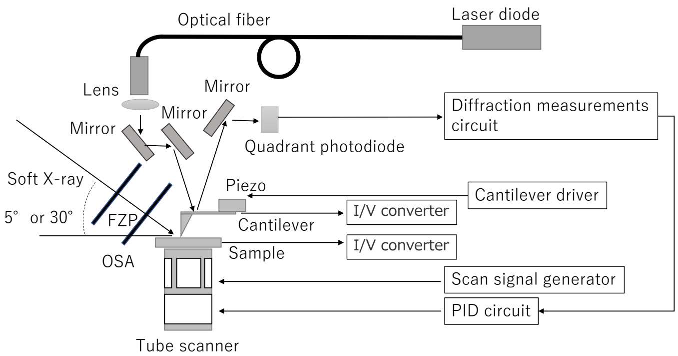

Fig. 2. Schematic diagram of soft X-ray nano-beam dynamic force microscope.

This work was supported by MEXT/JSPS KAKENHI Grant Number JP15H02244 and JASRI SOLUTUS. Part of this work was supported by Center for Spintronics Research Network (CSRN) Osaka University, Ministry of Internal Affairs and Communications and MEXT/JSPS KAKENHI Grant Number JP19140198.

Reference

1) I. Schmid, et al.: Ultramicroscopy, 110 (2010) 1267.
2) A. Saito, et al.: Jpn. J. Appl. Phys., 45 (2006) 1913.
3) A. Saito, et al.: J. Synchrotron Rad., 13 (2006) 216.
4) N. Shirato, et al.: Nano Letters, 14 (2014) 6499.
5) S. Suzuki, et al.: Chem.Lett., 33 (2004) 636.

高次高調波発生を用いたMCD計測用光源の開発

高橋栄治
(理研 光量子工学研究センター)

Femtosecond soft x-ray sources via high-order harmonics for ultrafast MCD measurements

Eiji J. Takahashi
(RIKEN Center for Advanced Photonics, RIKEN)

1　はじめに

大型放射光は磁性材料等の物質の状態を計測する上で非常に有用な光源であり，多くの研究者が使用している．一方でレーザーからの波長変換プロセスである高次高調波発生を利用したアト秒光源開発は，超短パルスレーザー技術の進展と共にそのパルス幅を 50 アト秒以下にまで短縮している．また発生光子エネルギーも長波長・超短パルスレーザーの高度化により，カーボンや酸素の K 吸収端 [1] にまで拡張されるようになっており，X 線吸収微細構造 (XAFS) 計測 [2] に高調波ビームが利用されるまでになっている．さらに 2015 年に実現された円偏光高次高調波光源 [3] の登場により，軟 X 線磁気円二色性分光 (MCD) への高調波光源応用も始まろうとしている．高次高調波光源は比較的小型なレーザーシステムを用いて発生させることが可能であり，高精度に時間同期されたポンプ・プローブ計測を行う事ができることから，例えば放射光では不可能なフェムト秒 XFAS やフェムト秒 MCD といった新しい測定法への展開が期待されている．一方で広域なアプリケーション開発において必要不可欠となる高次高調波パルス自身の出力エネルギーは未だに低く，光源応用の範囲は吸収分光等に限定されている．

2　MCD 計測を目指した次世代アト秒高次高調波光源の開発

我々の研究チームでは高次高調波の高出力化及び高光子エネルギー化を目指し，独自の高エネルギー化法やその為の励起レーザーシステムの開発に取り組んでいる．開発目標としている高次高調波光源の光子エネルギー域は sub-keV から数 keV であり (図 1 参照)，具体的な光源アプリケーションとして XAFS, MCD，コヒーレントイメージング法との組み合わせによるナノ構造イメージングを検討している．特に MCD 計測においては強磁性体材料の L 吸収端をカバーできる次世代のアト秒高次高調波光源を開発し，ポンプ・プローブ法と組み合わせる事でフェムト秒スピントロニクス研究という新しいサイエンスを切り開くことを目指している．その為の高調波励起レーザーシステムとして研究チームでは，二重チャープ光パラメトリック増幅 (DC-OPA) を用いた TW 級超短パルス中赤外レーザー [4]，及び 3 色の超短パルスレーザーを用いた光シンセサイザーの開発に現在取り組んでいる．講演では最新のレーザー開発状況を紹介すると共に，磁性体研究に資する次世代アト秒高調波光源の開発状況とその展開について講演する予定である．

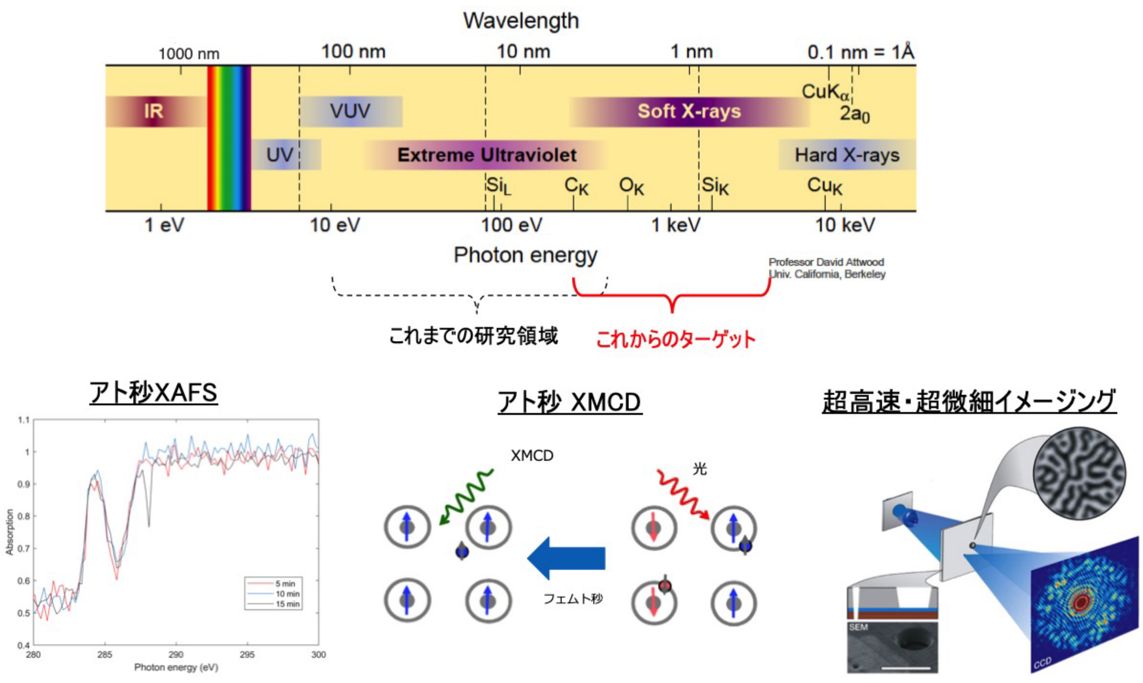

Fig. 1　高強度アト秒パルス光源の波長域の拡張と応用研究例

References

1) E. J. Takahashi, T. Kanai, K. L. Ishikawa, Y. Nabekawa, and K. Midorikawa, "Coherent Water Window X Ray by Phase-Matched High-Order Harmonic Generation in Neutral Media," Physical Review Letters, vol. 101, no. 25, p. 253901, (2008).
2) D. Popmintchev et al., "Near- and Extended-Edge X-Ray-Absorption Fine-Structure Spectroscopy Using Ultrafast Coherent High-Order Harmonic Supercontinua," Physical Review Letters, vol. 120, no. 9, p. 093002, (2018).
3) D. D. Hickstein et al., "Non-collinear generation of angularly isolated circularly polarized high harmonics," Nature Photonics, vol. 9, no. 11, pp. 743-750, (2015).
4) Y. Fu, K. Midorikawa, and E. J. Takahashi, "Towards a petawatt-class few-cycle infrared laser system via dual-chirped optical parametric amplification," Scientific Reports, vol. 8, no. 1, p. 7692, (2018).

Excitation and Propagation Dynamics of Spin Waves Observed by Spin-wave Tomography

Yusuke Hashimoto
Advanced Institute for Materials Research, Tohoku University

In magnetic media, waves of precessional motion of magnetization serve as an elementary excitation, called spin wave. To know its properties, one should measure how its frequency with its wavenumber vector. This relation is called dispersion relation. Spin waves, mediated by dipole-diploe interaction, are called pure-magnetostatic waves. The dispersion relation of pure-magnetostatic spin waves is characterized by complicated and anisotropic dispersion relations; their slope may even become negative for the so-called backward volume magnetostatic waves. The magnetostatic waves have been employed in spintronic and magnonic devices, while the observation of dispersion relations of pure-magnetostatic waves was one of the challenges.

Recently, we developed a new method for the direct observation of the dispersion relation of pure-magnetostatic waves by developing a table-top all-optical spectroscopy; we named spin-wave tomography (SWaT) [1]. Spin waves are excited by the illumination of an ultrashort light pulse focused on a very small surface area of a magnet medium. When the pulse duration and the excitation area of the light pulse are infinitesimally small, the pulse includes all temporal and spatial wave components according to the Fourier theorem. Then, spin waves of all frequency and wavenumber vector are created simultaneously and propagate from the excitation point. The created spin waves are observed by using a time-resolved magneto-optical imaging technique [2]. The Fourier transformation of the observed waveform along the time and spatial coordinates gives the power spectra of spin waves as a function of the frequency and the wavenumber vector. The spectra represent the dispersion relation of spin waves. This is the basic concept of SWaT [1].

In this talk, I will introduce our recent studies about the excitation and the propagation dynamics of spin waves using time-resolved SWaT [1,3] and phase-resolved SWaT [4,5], of which typical data are shown in Figs. 1(a) and 1(b), respectively.

References

1) Y. Hashimoto, *et al.*, Nature Communications **8**, 15859 (2017).
2) Y. Hashimoto, et. al., Review of Scientific Instruments **85**, 063702 (2014).
3) Y. Hashimoto, et. al., Physical Review B **97**, 140404 (2018).
4) Y. Hashimoto, *et al.*, Applied Physics Letters **112**, 072410 (2018).
5) Y. Hashimoto, *et al.*, Applied Physics Letters **112**, 232403 (2018).

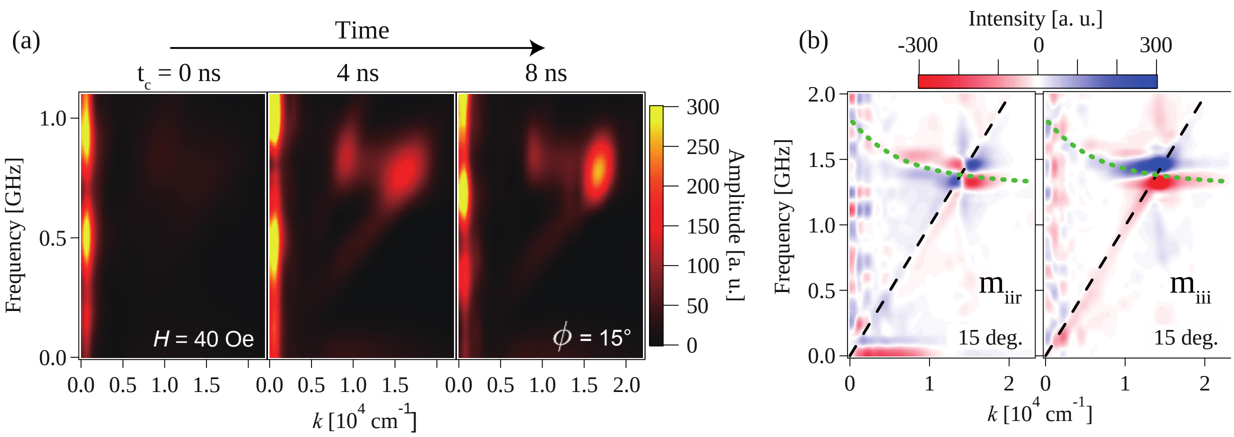

Fig. 1 Typical data of (a) time-resolved SWaT [1,3] and (b) phase-resolved SWaT [4,5].