Excitation of Coherent Spin Waves at Ultrafast Thermomagnetic Writing

A. Tsukamoto, K. Nakagawa, A. Itoh, A. Kimel, A. Tsvetkov, H. Awano, N. Ohta, A. Kirilyuk, and Th. Rasing

***Abstract*—We present results of a time-resolved study of the ultrafast magnetic response of $Gd_{23.1}Fe_{71.9}Co_{5.0}$ magnetically amplified magnetooptical systems (MAMMOS) structures under conditions near actual read/write temperatures. An all-optical pump and probe method was used in which an intense (pump) light beam excited a medium due to ultrafast laser heating and a less intense (probe) beam monitored this photo-excited state through the magnetooptical Kerr effect. Our experiment clearly demonstrates that the photo-excitation effectively excites coherent spin waves in the magnetic material. Precession frequencies of several gigahertz and relaxation times in the nanosecond range were observed.**

***Index Terms*—Magnetization precession, MAMMOS, thermomagnetic writing.**

I. Introduction

THE speed limits for thermomagnetic writing are of vital importance for magnetooptical recording, which has become one of the most important technologies for removable storage media. In particular, the speed of the thermally assisted copying within magnetically amplified magnetooptical systems (MAMMOS) is of high technological interest [1]. Conventional pure magnetic recording schemes have a serious and unavoidable problem known as the ferromagnetic resonance (FMR) limit. Nevertheless, laser pulse writing was shown to lead to a potentially much faster process of magnetization reversal, of the order of a few picoseconds [2], [3]. These experiments demonstrated the intrinsic capability of ultrafast high-speed rewritable storage under the thermomagnetic scheme.

In this paper, we describe the results of a time-resolved study of the ultrafast magnetic response of $Gd_{23.1}Fe_{71.9}Co_{5.0}$ MAMMOS structures under the condition near the actual read/write temperature. For the study, we used an all-optical pump and probe method in which an intense (pump) light beam excited a medium due to ultrafast laser heating and a less intense (probe) beam monitored this photo-excited state through the magnetooptical Kerr effect in the time domain with femtosecond resolution.

The spatial resolution of this technique is limited only by the wave character of light, in principle allowing for the study of submicrometer structures. This method is also useful for the characterization of the new type of fast switching magnetic devices such as the magnetic random access memory (MRAM) [4], [5]. In contrast, the FMR method, which is widely used for the dynamic characterization of magnetic materials, is normally applied as a nonlocal technique only. Since measurements are taken in the frequency domain, information on damping can only indirectly be obtained from the broadening of the absorption lines.

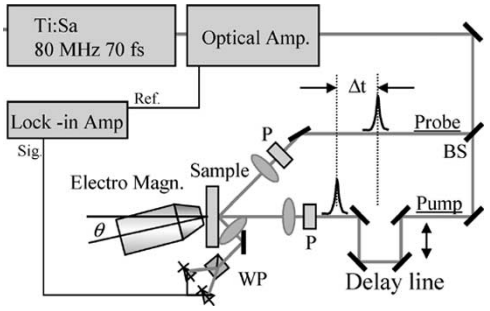

Fig. 1. Schematic diagram of measuring system.

II. Method

The experimental setup is shown schematically in Fig. 1. A commercial Ti : sapphire regenerative laser system provided 150 fs laser pulses with a center wavelength of 800 nm and a repetition rate of 1 kHz. The laser beam was split into pump and probe beams by a beam splitter. After passing a delay line, the linearly polarized pump beam was focused onto the sample surface at normal incidence. A spot diameter of approximately 100 μm led to an incident pump fluence of 50 mJ/cm^2. The sample was placed in front of a magnet pole. Using an intense laser pump-pulse, the material is almost instantaneously heated. The effect on the magnetization is measured by a much weaker, time-delayed probe-pulse using the magnetooptical Kerr effect. The probe beam was polarized with a Glan-Laser polarizer, and then focused onto the sample at an angle of incidence of 50°. The resulting spot diameter of the probe was about 25% of that of the pump beam, which guaranteed a homogeneously excited probing region. After reflection from the sample and collimation, the Kerr rotation θ was detected by using a balanced photodiode scheme.

By varying the time delay between pump and probe, the magnetization can be measured as a function of the time delay

Manuscript received October 16, 2003.

This work was supported in part by Grant-in-Aid for Scientific Research of the Ministry of Education and economy in Japan no. 15760226 and by the European Union IST project SPINOSA (Contract IST-2001-33334).

A. Tsukamoto, K. Nakagawa, and A. Itoh are with the College of Science and Technology, Nihon University, Funabashi, Chiba, Japan (e-mail: atsuka@ecs.cst.nihon-u.ac.jp).

A. Kimel, A. Tsvetkov, and T. Rasing are with the NSRIM Institute, University of Nijmegen, 6525 ED Nijmegen, the Netherlands (e-mail: theoras@sci.kun.nl).

H. Awano and N. Ohta are with the Tsukuba Research Laboratory, Hitachi Maxell Ltd., Yawara, Tsukuba-gun, Japan (e-mail: hiroyuki-awano@maxell.co.jp).

A. Kirilyuk is with the NSRIM Institute, University of Nijmegen, 6525 ED Nijmegen, the Netherlands, and also with the Tsukuba Research Laboratory, Hitachi Maxell Ltd., Yawara, Tsukuba-gun, Japan.

Digital Object Identifier 10.1109/TMAG.2004.834201

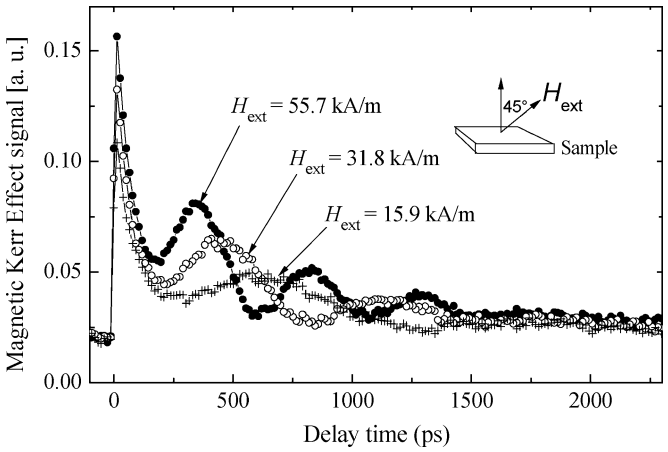

Fig. 2. Typical measurement on a 20 nm GdFeCo film displaying the perpendicular component of the magnetization for various external fields (15.9, 31.8, 55.7 kA/m). The magnetization is measured by the polarization state of the reflected probe pulse.

after excitation. An external magnetic field was applied with an electromagnet under various angles with respect to the sample normal. The bias temperature $T_{\rm bias}$ of the sample was controlled by a ceramic heater. Throughout this study, $T_{\rm bias}$ was constant (150 °C).

The sample was a MAMMOS read-out layer, consisting of a multilayer structure. A 100 nm thick layer of AlTi on top of the glass substrate served as a heat sink and enhanced the reflectivity of the sample. The sample used was a SiN(60 nm)/$Gd_{23}Fe_{72}Co_5$(20 nm)/SiN(5 nm)/AlTi(100 nm)/glass grown by magnetron sputtering.

III. Results and Discussions

Typical measurements on a 20 nm thick GdFeCo film displaying a perpendicular component of the magnetization $\boldsymbol{M}_{\rm z}$ for various external fields (15.9, 31.8, 55.7 kA/m) are shown in Fig. 2. When the pump-pulse heats the material at delay time $\Delta t = 0$, a sharp decrease in M_Z is observed (the vertical scales in Figs. 2 and 4 are reversed). This effect is caused by a sudden change in magnitude of the temperature dependent magnetization. The subsequent recovery of M_Z on a time scale of about 100 ps is due to rapid heat diffusion into the substrate. In addition, a clear damped oscillation is observed, with a frequency that increases with external applied field.

A. Excitation Process

Fig. 3 shows a schematic diagram of the excitation process. By applying an appropriate external field $H_{\rm ext}$, the magnetization is canted. The canting angle $\theta_{\rm e}$ is determined by a balance between the external field and the anisotropy field of the film, including the shape anisotropy. Upon sudden heating by the pump-pulse (i) the magnetization decreases leading to a change of the shape anisotropy, and (ii) the magnetocrystalline anisotropy changes as well [4]. Altogether, this results in a change of the equilibrium orientation from $\theta_{\rm e}$ to $\theta'_{\rm e}$, triggering an initial precession of the magnetization around its new equilibrium orientation. Heat diffusion into the film quickly removes the excess heat, and, after some hundreds of

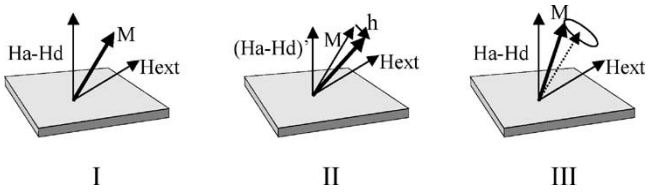

Fig. 3. Schematic diagram of the excitation process. I: equilibrium direction; II: anisotropy and M change due to heating; III: precession starts.

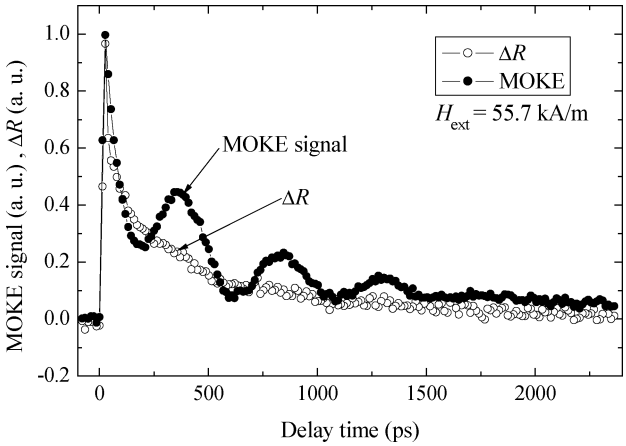

Fig. 4. Magnetization of the GdFeCo (solid circle) and simultaneously measured changes of linear reflectivity (ΔR) monitoring the transient electron temperatures (open circle) a function of pump probe delay.

picoseconds for metallic films, the original equilibrium angle is restored. However, at this point the magnetization is still not in equilibrium due to its initial displacement, and will continue to precess for a few nanoseconds.

In order to measure the changes of the magnetooptical response, which were exclusively caused by transient electron and lattice temperature, we applied a permanent saturation field of 55.7 kA/m. Corresponding results are shown in Fig. 4. The magnetization dynamics is compared with the simultaneously measured changes of reflectivity that monitor the time evolution of the electron temperature. After the excitation the electron temperature reached its maximum value within a few picoseconds and then decreased with a time constant of $t_{\rm tc} = 145$ ps. In this period, the changes of both the magnetic anisotropy and the magnetization took place. This is equivalent to a short effective magnetic field applied to the sample [6].

Additionally, it follows that the exact excitation mechanism is not of importance for the result; i.e., the short time excitation determines the amplitude and phase of the final precession, but not its precession frequency and damping.

B. Precession Dynamics

The spin dynamics of the ferrimagnetic GdFeCo system can be correctly described in terms of the Landau–Lifshitz equation including sublattices and the Gilbert damping term

$$\frac{{\rm d}\boldsymbol{M}}{{\rm d}t} = \gamma(\boldsymbol{M}\times\boldsymbol{H}) - \alpha\left(\boldsymbol{M}\times\frac{{\rm d}\boldsymbol{M}}{{\rm d}t}\right). \qquad (1)$$

The value of γ is given by $-g\mu_{\rm B}/{\rm h}$, where $\mu_{\rm B}$ and γ are the Bohr magneton and the spectroscopic splitting factor, respectively. The Gilbert damping of the system is represented by α. In

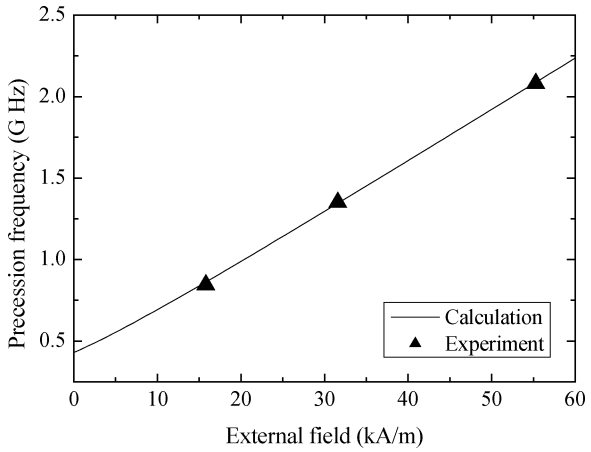

Fig. 5. External field dependence of the precession frequency. The solid line shows the fit with (3).

our fits to the measured precessions, we took $g_{\mathrm{RE}} = g_{\mathrm{TM}} = 2$, $\gamma = \gamma_{\mathrm{RE}} = \gamma_{\mathrm{TM}} = 17.6 \times 10^6\ (\mathrm{G \cdot s})^{-1}$. In (1), $\boldsymbol{H}$ denotes the total field within the system

$$\boldsymbol{H} = \boldsymbol{H}_{\mathrm{ext}} + \boldsymbol{H}_{\mathrm{a}} + \boldsymbol{H}_{\mathrm{s}} \tag{2}$$

where $\boldsymbol{H}_{\mathrm{ext}}$ is the external applied field; $\boldsymbol{H}_{\mathrm{a}}$ and $\boldsymbol{H}_{\mathrm{s}}$ represent the effective perpendicular and shape anisotropy fields of the film, respectively.

In general, the precession frequency ω is given by the determinant of the coupled system of differential equations. The exact calculation of ω is rather complicated since the time-dependent effective field has to be included. For large external applied fields, however, its value is given in good approximation by assuming that $\boldsymbol{M}$ is constant and equal to the saturation magnetization $\boldsymbol{M}_{\mathrm{s}}$ after excitation.

It is then straightforward to obtain

$$\omega = \frac{\gamma}{(1+\alpha^2)} \sqrt{(H_{\mathrm{ext}} \cos\theta + H_a + H_s)^2 - (H_{\mathrm{ext}} \sin\theta)^2} \tag{3}$$

where θ represents the angle between external field and the normal to the film plane. A change of this effective field in the thin film will influence the precession frequency.

Fig. 5 shows the external field dependence of the precession frequency. The precession frequencies were determined by nonlinear fitting of the measured results in Fig. 2 with a damped harmonic function. Equation (3) was then used to fit the determined values as shown in Fig. 5 (solid line). As shown, the external field is added to the effective internal field and the vector sum will increase the precession frequency. This procedure yields $\alpha = 0.32$. This value is rather large compared to the typical values obtained from FMR experiments and could be related to a rather high sample temperature large value of the precession amplitude. In fact, the α parameter could also be derived by directly fitting the time dependencies of Fig. 2 yielding the same result.

Thus, this all-optical method is capable of reproducing the magnetization dynamics after the system has been driven out of the equilibrium by an optical excitation that is equivalent to a 100 ps magnetic field pulse.

IV. Conclusion

By all-optical pump and probe method, we demonstrated that the photo-excitation could effectively excite coherent spin waves in the magnetic material. An intense (pump) optical beam excites the medium due to an ultrafast laser-induced heating and a less intense (probe) beam monitores this photo-excited state through the magnetooptical Kerr effect. Time-domain measurements on the consequently excited precession give information on the magnetic anisotropy, switching and damping phenomena. The ultrafast magnetic response of $Gd_{23.1}Fe_{71.9}Co_{5.0}$ MAMMOS structures was measured under near actual read/write temperature condition. Precession frequencies of several gigahertz and relaxation times in the nanosecond range were observed under various external magnetic fields. The experimental data are in good agreement with our calculations on the basis of the Landau–Lifshitz–Gilbert equation.

References

[1] H. Awano, S. Imai, M. Sekine, M. Tani, N. Ohta, K. Mitani, N. Takagi, H. Noguchi, and M. Kume, *IEEE Trans. Magn.*, vol. 36, pp. 2261–2265, 2000.
[2] J. Hohlfeld, T. Gerrits, M. Bilderbeek, H. Awano, N. Ohta, and T. Rasing, *Trans. Magn. Soc. Jpn.*, vol. 25, pp. 202–205, 2001.
[3] J. Hohlfeld, T. Gerrits, M. Bilderbeek, T. Rasing, H. Awano, and N. Ohta, *Phys. Rev. B*, vol. 65, p. 012 413, 2002.
[4] M. van Kampen, C. Jozsa, J. T. Kohlhepp, P. LeClair, L. Lagae, W. J. M. de Jonge, and B. Koopmans, *Phys. Rev. Lett.*, vol. 88, p. 227 201, 2002.
[5] T. Gerrits, H. A. M. van den Berg, J. Hohlfeld, L. Bar, and T. Rasing, *Nature*, vol. 418, p. 509, 2002.
[6] T. J. Silva, P. Kabos, and M. R. Putfall, *Appl. Phys. Lett.*, vol. 81, p. 2205, 2002.