Probing the local magnetization dynamics in large systems with spatial inhomogeneity

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Abstract.
We demonstrate the multifunctionality of our new femtosecond laser scanning Kerr microscope by studying the magnetization dynamics in a wedged Fe/Gd multilayer film exhibiting a spin reorientation transition (SRT). The microscope with a high temporal and spatial resolution of \(< 230\) fs and \(210\) nm, respectively, and large scanning ranges of \(8\) ns and \(320\) \(\mu\)m allows performing multi-parameter scans along the temporal, the three spatial, and the external magnetic field axes. From these scans we can measure local static and dynamic hysteresis loops at different delay times and positions along the wedge as well as construct spatio-temporal mapping of the magneto-optic signal at different fields. The results reveal a complex magnetization dynamics around the SRT.

1. Introduction to the experimental setup
Magnetic hetero- and nanostructures have been attracting a lot of attention from researchers and magneto-electronic industry due to their potential in future storage and switching devices. For applications the precise control of the switching behaviour on large lateral length scales is a pre-requisite. This, in turn, demands an instrument which can resolve the local static and dynamic magnetic properties at a high spatio-temporal resolution and scan over large positional and temporal ranges. We demonstrate that our newly developed femtosecond laser scanning Kerr microscope, equipped with a temporal and spatial resolution of \(< 230\) fs and \(210\) nm, respectively, and with large scanning ranges of \(8\) ns and \(320\) \(\mu\)m satisfies these requirements. Especially, we show how multi-parameter scans enable a comprehensive study of complex dynamic systems.

A Ti:sapphire oscillator generates laser pulses with a central wavelength of \(780\) nm, an output energy of ca. \(80\) nJ, a duration of ca. \(55\) fs and at a repetition rate of \(11\) M\(Hz\). A pump-probe technique is applied for magneto-optic Kerr effect (MOKE) experiments using the \(780\) nm pulses as the pump and frequency-doubled \(390\) nm pulses as the probe. A high precision linear stage enables a delay between the pump and probe pulses of up to \(8\) ns. Both beams are collinearly focused onto the magnetic sample, in the present work, by a microscope objective with a numerical aperture of 0.5. For imaging and fine focus adjustment we use a three-axis piezoelectric scanning stage with a travel range of \(320\) \(\mu\)m and a positioning resolution of \(1\) nm.
in all three axes. The temporal resolution is optimized by selecting optical components for minimal group delay dispersion (GDD) and adding negative GDD via prisms (pump beam) and chirped mirrors (pump beam). For a significant enhancement of the signal-to-noise ratio a double lock-in technique is used [1], where the pump and probe beams are modulated by an optical chopper at a frequency of 80 Hz and a photo-elastic modulator at 50 kHz, respectively. This detection scheme allows measuring the transient reflectivity $\Delta R$, the Kerr rotation $\theta_K$ and ellipticity $\epsilon_K$, and the pump-induced changes in $\Delta \theta_K$ and $\Delta \epsilon_K$. All experiments were made in the polar MOKE geometry which detects the magnetization component perpendicular to the sample plane $M_z$. A self-made control software enables us to perform multi-parameter scans along the three spatial axes, the delay time axis and the external magnetic field axis. Further details of the setup can be found in Ref. [2].

To demonstrate the capabilities of the instrument to study spatial variations in the static and dynamic magnetic properties we fabricated a wedge-shaped Fe/Gd multilayer system, where the bilayer composition for the thickest part was designed to be Fe(0.36nm)/Gd(0.36nm) to obtain a strong perpendicular magnetic anisotropy (PMA) there. The film thickness decreases to zero over a distance of about 100 µm; see Fig. 1 (a). Along this wedge the saturation magnetization $M_S$ and the magnetic anisotropy are expected to change as they are very sensitive even to small variations in the Fe/Gd bilayer thickness, the interface structure and the temperature [3]. Consequently, the magnetization reorients from out-of-plane to in-plane, thus giving a perfect playground to study the complex static and dynamic changes around the spin-reorientation transition (SRT) [4].

2. Results and discussion

We first demonstrate the spatio-temporal mode of operation. The Fe/Gd wedge is scanned along its thickness gradient; see Fig. 1 (a). Combining this positional scan with the delay time $\Delta t$ scan, the results shown in Fig. 1 (b) have been obtained. Extracting the measurement points along the $\Delta t$ axis in Fig. 1 (b) for a fixed position on the wedge the pump-induced magneto-optic response $\Delta \theta_K$ can be plotted against $\Delta t$; see Fig. 1 (d). The oscillations shown in these curves are caused by an opto-thermically induced transient SRT from an in-plane to an out-of-plane magnetization [4]. The absorption of the pump pulse leads to an elevation of the temperature which reduces the magnitude of magnetization vector $|\vec{M}|$ and, therefore, weakens the demagnetizing field $H_{dem}$. The heat also reduces the intrinsic PMA of the Fe/Gd multilayer. However, if the effect of the heat-induced reduction of $|\vec{M}|$ is stronger, the transient SRT rotates the direction of the effective magnetic field $H_{eff}$ out of plane. This exerts a torque on the magnetization vector $\vec{M}$, which leads to a precession of $\vec{M}$ around $H_{eff}$. As the heat $H_{eff}$ relaxes slowly back into its original direction and $\vec{M}$ follows $H_{eff}$ with a damped precession. The SRT has been shown to be very sensitive to the film thickness [3]. As the thickness decreases along the wedge, the effect of $H_{dem}$ will gradually increase, making in-plane magnetization more favourable. Therefore, the rotation of $\vec{M}$ resulting from the heat-induced SRT will also become larger with decreasing thickness. This is reflected in the black, orange and blue curves in Fig. 1 (c) which show that the pump-induced magneto-optic response $\Delta \theta_K$ increases substantially with decreasing thickness. However, going further towards the thinner part, the oscillation amplitude of $\Delta \theta_K$ decreases drastically. This could be due to the reduction of the total magnetic moment within the probed region resulting from the volume reduction and/or due to the reduction of $M_S$ caused by the intermixing between Fe and Gd atoms.

The second mode of operation combines $\Delta t$ and external magnetic field $H_{ex}$ scans; see Fig. 1 (c). Note that $H_{ex}$ is applied perpendicularly to the sample plane. In Fig. 1 (e) the time-resolved $\Delta \theta_K$ signals obtained for different strengths of $H_{ex}$ are extracted from Fig. 1 (c). Using this data set one can study the field dependence of the precession frequency or the damping, which,
Figure 1. (Color online) (a) A schematic drawing of the Fe/Gd wedge, (b) the pump-induced changes in Kerr rotation $\Delta \theta_K$ measured at different delay times $\Delta t$ and different locations along the thickness gradient, (c) $\Delta \theta_K$ measured at different $\Delta t$ and different external fields $H_{ex}$, (d) $\Delta \theta_K$ plotted against $\Delta t$ at fixed positions marked in (a) and (b), (e) $\Delta \theta_K$ plotted against $\Delta t$ at fixed field values marked in (c), (f) $\Delta \theta_K$ plotted against $H_{ex}$ at fixed delay times marked in (c).

For instance, can be used to extract information about the anisotropy field. The second way of data evaluation is to plot $\Delta \theta_K$ against $H_{ex}$ for different values of $\Delta t$, which gives hysteresis loops of the pump-induced dynamic MOKE responses. In Fig. 1 (f) a remarkable change in the shape and size of the hysteresis with increasing $\Delta t$ is observable. The large response of $\Delta \theta_K$ in the loop measured at $\Delta t = 1349$ ps can be easily understood by considering the fact that at $\Delta t = 1349$ ps the maximum of the SRT induced oscillation appears for $H_{ex} = 0$. The reduction of $|\Delta \theta_K|$ with increasing $H_{ex}$ can be explained by the fact that a strong $H_{ex}$ aligns $\vec{M}$ perpendicularly to the sample plane, leaving no room for a SRT. With increasing $\Delta t$ the system returns to the equilibrium state leading to a decay of $|\Delta \theta_K|$, thus the hysteresis loop becomes smaller.

In the third mode of operation $H_{ex}$ and sample position scans are combined; see Figs. 2 (a) and (b). This mode is used to record local static and dynamic hysteresis loops at different locations; see Figs. 2 (c) and (d). Fig. 2 (d) shows a drastic reduction of the magnetic contrast over a distance of 25 $\mu$m confirming that the magnetic moment becomes reduced with decreasing layer thickness. Although not explicitly shown here, looking at hysteresis loops measured for thinner...
parts we could observe strong changes in their shape (from squared to skewed) confirming that in-plane magnetization is preferred for thinner parts. Fig. 2 (c) show a large increase of \( \Delta \theta_K \) between the sample positions, 5 \( \mu m \) and 18.5 \( \mu m \), indicating a transition from perpendicular to in-plane magnetization. In addition, the skewed shape and the reduced size of the loop measured for the sample position 30 \( \mu m \) suggest that \( H_{dem} \) is already too strong here to enable a SRT.

3. Summary
Studying the opto-thermally induced transient SRT in a Fe/Gd multilayer wedge, we have demonstrated different modes of operation of our femtosecond laser scanning Kerr microscope. Equipped with high spatio-temporal resolutions, large scanning ranges and the capability of performing multi-parameter scan, this microscope is a powerful tool for investigating the local magnetization dynamics in spatially inhomogeneous samples.

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