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Retrieving pulse profiles from pump-probe measurements on magnetization dynamics

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A method for back-tracing magnetic field pulses in pump-probe-type magnetization dynamics measurements is presented. Solving vectorially the Landau–Lifshitz–Gilbert equation for our field-induced measurement geometry yields field pulse profiles fulfilling the theoretical expectations on a 100 ps timescale. Applying the method to our earlier, all-optical-type pump-probe measurements, the claim that the optical pulse triggers an ultrafast anisotropy field pulse gets a direct proof: we derive a pulse consisting of a delta-peak type, full width at half maximum < 5 ps impulse on top of a very fast rising step-like profile. Application of the method to other, less trivial pump-probe schemes can contribute to the development of novel type magnetic recording technologies. © 2004 American Institute of Physics. [DOI: 10.1063/1.1667440]

Studies of fast (subnanosecond) magnetization phenomena with a diffraction limited spatial resolution are nowadays possible via pump-probe-type magneto-optical measurements.^{1–5} Using femtosecond pulsed lasers in a stroboscopic way, one can explore the temporal evolution of the local magnetization of thin layers and microstructures as a *vectorial* quantity reacting to external influences such as intense short heat pulses,² fast pulsed magnetic fields,^{5,6} or a combination thereof.

At the same time, the needs of the current recording technology push our interest toward studying nanosecond magnetic and magneto-optic phenomena of confined structures. It has become clear that achieving stable switching conditions in the precessional regime, requires fine tuning of the field pulses to a high degree of precision.^{3–7} Therefore, an important problem is the characterization (amplitude, rise/fall time, duration, flatness, etc.) of the magnetic field pulse itself at the position of the micromagnetic entity under consideration.

Our approach is separating the Landau–Lifshitz–Gilbert (LLG) equation of magnetization motion into its vectorial components and applying the obtained system onto different experimental data. In this article, we present the back-tracing of field pulses in the case of our recent vectorial measurements on field-induced precessional dynamics and earlier all-optical studies on gigahertz precession.² In principle, there is no direct obstacle for extending the model and calculus to more complex cases.

A pump-probe-type setup based on the measurement of the magneto-optical Kerr effect (MOKE) versus time is shown in Fig. 1. Each pump pulse (magnetic or laser pulse) is followed by a second, weak probing laser pulse. The probe beam has a well-defined incident polarization that can be compared to the final polarization of the beam after being reflected from the sample surface. The time difference (“delay time”) between the arrival of the pump and probe pulses is controlled during the experiment with a mechanical delay line.

In our studies on field-induced precessional dynamics, we use as pump source magnetic field pulses generated by current pulses running through a microscopic coplanar waveguide structure (200 nm thick, 50 μm wide Au stripes on GaAs). The waveguide is electrically coupled to a commercial pulse generator (rise/fall times of typically 120 ps). The pulse generator is triggered by the monitor signal of the built-in photodiode of a mode-locked Ti:Sa laser (80 MHz, 100 fs pulses at 780 nm, 0.05 nJ/pulse). The electrical pul-

FIG. 1. Experimental pump-probe setup. Top left inset: microscopical photograph of an actual sample, top view.

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segenerator is switched on and off by an external 10 kHz square wave, that is also used to trigger the lock-in amplifier. The MOKE signal measured by a polarizer/analyzer combination, can be linearly transformed into magnetization units.

The waveguide structure was covered by an electrically insulating SiN_x layer, prior to sputter deposition of a 30 nm Permalloy (Py) layer. Discs of 4 to 50 μm diameter were structured by a lift-off technique. A photograph of a microscopic sample is shown as an inset in Fig. 1. Field pulses at an amplitude up to 350 A/m are used; this value is well below the coercivity of our Py “dots” (650 A/m). Therefore, we cannot achieve switching of magnetization during these measurements.

Different methods have been reported recently for simultaneous measurements of multiple components of the magnetization vector.^{5,6} We use a vectorial scheme as follows. A laser objective (NA 0.38) focuses a wide, aperture-filling perpendicular laser beam on the sample. Since there is a 15° difference between the angle of incidence of the top-bottom (A,C), respectively left-right (B,D) regions of the beam, they probe different ratios of the three components of the magnetization vector. Using a four-quadrant photodetector, these four sections of the reflected laser beam are measured with independent lock-in amplifiers. After normalization to the dc intensities, we can see that $M_z \propto (A+B+C+D)$, $M_y \propto (A+B-C-D)$, and $M_x \propto (A-B+C-D)$. In the present experiments, we use the setup simplified to two quadrants (A,C) and two components (M_y, M_z).

The all-optical experimental setup uses, instead of magnetic field pulses, intense ultrashort laser pulses combined with a double-modulation measurement technique described in detail in Ref. 2. Measurements were done on a large variety of (mostly unstructured) thin layers of ferromagnetic metals; the results presented here were obtained on a polycrystalline, 7 nm thin Ni layer on a Si/SiO₂ substrate with an in-plane easy axis for the magnetization vector.

Next, we present an analysis used to trace back the applied field pulses (electrically or optically induced ones) from the observed precessional motion of $\vec{M}$. The dynamics is described by the LLG equation

$$\frac{d\vec{M}(t)}{dt} = -\gamma\mu_0(\vec{M} \times \vec{H}_{\text{eff}}) + \frac{\alpha}{M_s} \left(\vec{M} \times \frac{d\vec{M}(t)}{dt} \right), \quad (1)$$

where γ is the gyromagnetic ratio, α is the (dimensionless) damping parameter, and M_s is the saturation magnetization of the magnetic layer.

In the case of our **field-induced magnetization measurements**, we have the pulse field $\vec{H}_p(t) \equiv H_p(t) \cdot \hat{y}$ and the bias field $\vec{H}_{dc} \equiv H_0 \cdot \hat{x}$ both in the film plane (xy), and perpendicular to each other. The demagnetization field is oriented opposite to the M_z component of the magnetization and equal in amplitude with it, $\vec{H}_{\text{demag}} \equiv M_z \cdot \hat{z}$. We also assume a weak perturbation, thus, $M_x = \text{const} = M_s$. With these considerations, Eq. (1) can be separated for the three directions and simplified to the following form:

FIG. 2. Vectorial measurement of field-induced precessional dynamics. (a) 0.5 ns (short) field pulse, $M_y - M_z$ plot. (b) 1.5 ns (long) field pulse, $M_y - M_z - \Delta t$ plot. Magnetization values are normalized to M_s . In both cases, an external DC field of 2.4 kA/m is applied along the x -axis.

$$\dot{M}_x = 0,$$

$$\dot{M}_y = -\gamma\mu_0(M_s + H_0)M_z - \alpha\dot{M}_z, \quad (2)$$

$$\dot{M}_z = -\gamma\mu_0(M_s \cdot H_p(t) - M_y H_0) + \alpha\dot{M}_y.$$

The goal is to determine from these equations the field pulse $H_p(t)$ when measuring one of the two components (M_z or M_y). Solving Eq. (2) for H_p yields

$$H_p(t) = -\frac{\alpha^2 + 1}{\gamma\mu_0} \dot{m}_z - \alpha(M_s + 2H_0)m_z - \gamma\mu_0 H_0 (M_s + H_0) \int_{-\infty}^t m_z dt \quad (3)$$

for the case of measuring M_z , and

$$H_p(t) = -\frac{\alpha^2 + 1}{\gamma^2 \mu_0^2 (M_s + H_0)} \ddot{m}_y + \frac{\alpha(M_s + 2H_0)}{\gamma\mu_0 (M_s + H_0)} \dot{m}_y + H_0 \cdot m_y \quad (4)$$

for the case of measuring M_y , with $M_i = m_i \cdot M_s$.

The geometry of the **all-optical measurements** is slightly different. In particular, $\vec{H}_p$ is oriented perpendicularly to the film plane, due to the temperature-dependence of the shape anisotropy: $\vec{H}_p(t) = H_p(t) \cdot \hat{z}$. This yields a slightly more complicated transformation, to be published in full detail elsewhere.

In all the above cases we can obtain a formula for the field pulse that contains only the measurement data, its derivatives and/or integrals, and some free parameters.

In Fig. 2, two measurements are shown with electrically induced field pulses of ~ 500 ps (a) and ~ 1500 ps (b), respectively. Typical results are in agreement with theoretical predictions, e.g., Ref. 8. In the case of the long pulse measurement [Fig. 2(b)], the precession starts to damp out after the first step (the rise of the field pulse). However, the magnetization does not reach the new equilibrium before the falling edge of the pulse exerts a new torque on it.

Applying Eqs. (3) and (4) to recover the original field pulse profile, necessitates double differentiation and integration of the measured datasets. In case of a real measurement with finite noise, the differentiation needs adequate smoothing of the data, while the integration induces a slope in the

FIG. 3. Short (a) and long (b) field pulses back-calculated from the measurements shown in Fig. 2. Note the timescale difference between (a) and (b). The long-pulse measurement on (b) is overlapped with an image of an oscilloscope display showing the 1.5 ns *electric* pulse, on the same timescale.

dataset whenever there is an inaccuracy in centering the precessional data around zero. Taking care of these two problems, very acceptable results are obtained for short and long field pulses (Fig. 3). In Fig. 3(a) the profiles derived from the two independent magnetization components almost completely overlap, illustrating that the procedure yields unambiguous results. As a further comparison, we paste in a screen capture of a fast oscilloscope showing the electrical pulse entering an ideal 50- Ω impedance matched probe [Fig. 3(b)]. The arrows point to fine pulse details shorter than the time scale of the oscillation period, that are similar on both long pulse images, indicating the high accuracy of the method. The amplitude of the obtained field pulse (350 A/m) also corresponds in order of magnitude to the values obtained through a finite element method simulation. A damping parameter of $\alpha=0.01$ can be deduced, in good agreement with other values obtained for thin Py layers.⁶

A typical all-optical polar measurement is shown in Fig. 4(a). Laser pulses of ~ 100 fs are used, and a bias field of 200 kA/m is applied at an angle of 35° with respect to the

FIG. 4. All-optical-type measurement (a) and its back-calculated pulse field (b).

surface normal to induce a canted orientation of $\vec{M}$, and assure a sufficient in-plane field as well. Due to the applied bias field that is considerably larger than in the presented field-induced measurements, the precession frequency is also higher: $\omega = \gamma \mu_0 \sqrt{H_0(H_0 + M_s)} = 2\pi \cdot 9.98$ GHz.

In order to apply our back-tracing procedure, first the laser-induced reduction of the magnetic moment (ΔT , solid line) has to be separated from the orientational effect ($\Delta \theta$, dashed line). Assuming that ΔM_z for $t < 1$ ps is dominated by the first effect, and considering a slow recovery of the temperature of the Ni film after 1 ps, provides the dashed line as an estimate of the orientational contribution to the measurement. This is used as an input for deriving the effective pulse profile.

The earlier claim that the optical pulse triggers an ultrafast anisotropy field pulse² is substantiated by the derived pulse profile shown in Fig. 4(b): an extremely fast delta-like pulse (full width at half maximum < 5 ps) superposed on a step-like background with a rise time < 5 ps. The derived pulse shape depends slightly on the exact procedure used to separate the amplitude and orientation of the transient magnetization. However, independent of those details, a delta-like pulse always appears, with a rather unique value for its integrated area. A completely unambiguous profile would be achieved when performing a vectorial measurement. Finally, we stress that similar behavior was observed on a large number of systems (Ni and Py thin films, different substrates, film thicknesses, anisotropy, and applied fields) presented in Ref. 2.

In conclusion, our vectorial magnetization measurements depict a field-induced dynamics behavior that is in good agreement with the expectations. The calculus we describe was successfully applied to back-calculate the magnetic field pulses just above the strip line. The method is shown to work for more complicated cases as well, wherein the pulse profile cannot be determined by other means. Applied to our former all-optical experiments, the method demonstrates that the laser pulse triggers an ultrashort anisotropy field pulse. We suggest further applications to other, less trivial pump-probe schemes, such as multiple field pulses⁵ or field pulses combined with a laser heating pulse, of relevance for novel type technologies in magnetic recording.

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