

Magnetization dynamics in NiFe thin films induced by short in-plane magnetic field pulses

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The magnetization dynamics in a thin NiFe film was investigated by applying short in-plane magnetic field pulses while probing the response using a time-resolved magneto-optical Kerr effect setup. In-plane magnetic field pulses, with duration shorter than the relaxation of the system, were generated using a photoconductive switch and by subsequent propagation of current pulses along a waveguide. The field pulses with typical rise and decay times of 10–60 and 500–700 ps, respectively, have a maximum field strength of 9 Oe, by which Permalloy elements of 16 nm thickness and lateral dimensions of $10 \times 20 \mu\text{m}$ were excited. The observed coherent precession of a ferromagnetic NiFe system had precession frequencies of several GHz and relaxation times on a nanosecond time scale. The dynamic properties observed agree well the Gilbert's precession equation and the static magnetic properties of the elements © 2001 American Institute of Physics. [DOI: 10.1063/1.1359462]

I. INTRODUCTION

The study of spin dynamics in magnetic media has gained more and more interest in the last few years, as the writing speed of data on magnetic media is increasing rapidly and because of the rapid rise of the magnetic random access memory (MRAM) technology on the basis of the magnetic tunnel effect. As soon as writing times of less than 1 ns are reached, spin precession effects will play a dominant role here. There have been various experimental studies of ultrashort spin dynamics in ferromagnetic media,^{1–3} showing magnetization collapse and recovery on ultrasfast (ps) time scales. However, all these studies employed ultrashort intense laser pulses that heated the electrons far above equilibrium temperature. Though of great fundamental interest, such studies do not address the issues that are relevant for the writing process of magnetic information in recording media. The write field pulse pulls the magnetic spin system out of its equilibrium state. The relaxation process to its new equilibrium state is determined by the rate of the energy dissipation of the media, i.e., by the Gilbert's damping constant. The study of this magnetization dynamics can best be done by using magnetic field pulses, that are shorter in time than the typical relaxation-time constants of the system.

Here, we report on investigations on the spin dynamics of a ferromagnetic system following excitation by 10–60 ps rise time, 500–700 ps decay time in-plane magnetic field pulses, being much shorter than the magnetic relaxation time. Thus the magnetic response of the system at large pump-probe delays was solely governed by the magnetic properties of the sample. The response was probed by a time-resolved magneto-optical Kerr effect (MOKE) experiment detected with balanced photodiodes.⁴ We will show that our experimental approach is optimally suited to study the spin

dynamics of a weak ferromagnetic system. Similar experiments were used to probe the dynamics by a polar field pulse⁵ in a single coil.

The great interest of using in-plane field pulses to study the dynamics of a ferromagnetic system lies in its impact on the writing process of MRAM, for which the timing and shape of the in-plane field pulses are of decisive importance for the speed, the reproducibility, and the energy consumption of the writing procedure. The design of our device is done in a way that in principle we can generate pulses of arbitrary shape.

Experiments using in-plane field pulses have already been reported previously. However, the field pulses in these experiments were generated by pulse generators⁶ and only the rise times were shorter than the relaxation time of the system.

II. EXPERIMENT

The short magnetic field pulses were generated by using a GaAs photodiode in combination with two copper electrodes structured into a coplanar waveguide. Figure 1 shows a photograph of the device. The inset of Fig. 1 shows a close-up photograph of the photoconductive switch (Auston switch⁷). A 100 fs laser pulse is used to pump the switch, which is designed in a finger structure that enlarges the area for the excitation of carriers and thus the total current. The gap between the electrodes is $15 \mu\text{m}$. As the pump laser beam hits the device under a certain angle, the electrodes would cause some dark area within the photoswitch. This would result in a larger resistance and would decrease the generated current. Therefore we introduced 10-nm-thin electrodes as first conducting layer on the GaAs substrate, which were separated $5 \mu\text{m}$ from each other. The thickness of these electrodes is chosen to be smaller than the skin depth of the incoming laser beam. Light can travel through into the GaAs

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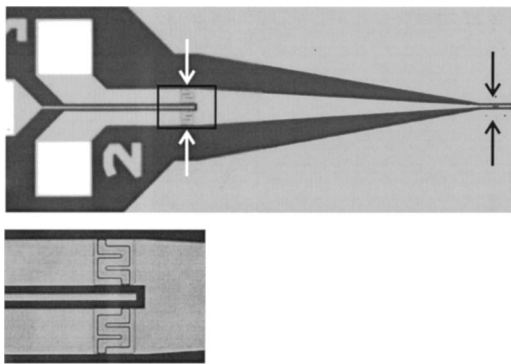


FIG. 1. A photograph of the waveguide, used in our experiment. From the $65 \times 65 \mu\text{m}$ photoswitches (white arrows), the tapering concentrates the current onto the $10 \mu\text{m}$ signal line (black arrows). The thin $10 \times 20 \mu\text{m}$ film is placed at the end of the tapering. Around the signal line, two big ground flats are placed as a waveguide. The inset shows a close-up photograph of the photoswitches. Between the finger structure, another light electrode can be seen. This is a thin copper electrode that should prevent shadow effects from the larger electrodes.

and excite carriers there. Consequently, the resistance due to dark areas within the switch is reduced. This technique makes it possible to change the angle of incidence of the pump beam without changing the resistance of the photo-switch.

Figure 1 shows a photograph of the complete waveguide structure. There are two photoswitches, which can be used as one switch only, or can be used in a pump-pump-probe experiment, where the voltage on the electrodes can be arbitrary. By applying opposite voltages and pumping the switches at different times, one can in principle shorten a pulse already generated^{8,9} and produce arbitrary pulse shapes. Here we restrict ourselves to the excitation of a single switch only. We designed the device according to a model^{10,11} which describes the propagation of the current pulse on the signal line. It describes the attenuation and dispersion due to the surface impedance of a coplanar strip line, including the dielectrics surrounding it.

The generation of large magnetic field pulses clearly depends on the generated current. The magnetic field close to the surface is proportional to the current density inside the conductor: $H = I/2w$, where w is the width of the conductor. In our case, we chose w to be $10 \mu\text{m}$. The large photoswitches provide a large current, as the total current depends on the carrier density times the area of the photoswitch. The combination of large photoswitches and small signal lines requires the introduction of a tapering. The latter was designed in such a way that the impedance of the waveguide would not change, by keeping the ratio between the middle line and the spacing constant.¹⁰ A change in impedance would cause reflections on the signal line, which will broaden the current pulse and lower the maximum obtainable field.

Figure 2 shows a scheme of our experimental setup. The magnetic response of the system due to the field pulse was probed by a standard time-resolved pump-probe setup. With the probe beam we measured the linear MOKE signal by means of the balancing diodes and lock-in technique. Focusing was done by a long working distance microscope objec-

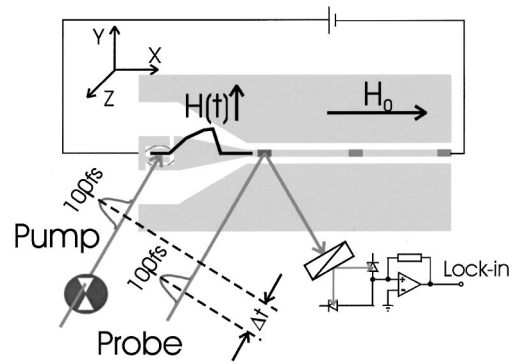


FIG. 2. Scheme of the waveguide with the signal line and the magnetic thin film lying on it. The 100 fs pump pulse generates the current pulse, which is concentrated in the tapering. The response of the system is measured by the 100 fs probe beam.

tive (numerical aperture 0.3) to a spot size of $5 \mu\text{m}$ on the NiFe film. The use of a long working distance objective was necessary to avoid screening of the pump beam.

III. RESULTS AND DISCUSSION

Figure 3 shows the time-resolved magneto-optical response of a NiFe film element that is subjected to an in-plane bias field of 94 Oe and, perpendicular to that, an in-plane pulse field of 9 Oe at the peak. The figure shows a damped oscillation with a period of about 400 ps and a damping of the order of 1 ns. This dynamics can well be described in terms of the Landau-Lifshitz equation with the Gilbert damping term

$$d\mathbf{M}/dt = \gamma(\mathbf{M} \times \mathbf{H}) - \alpha(\mathbf{M} \times d\mathbf{M}/dt). \quad (1)$$

The value of γ is given by $-g\mu_B/h$, where μ_B and g are the Bohr magneton and the spectroscopic splitting factor, respectively. The Gilbert damping of the system is represented by α . In our fits to the measured precessions, we took $\gamma = 17.6 \times 10^6 (\text{Gs})^{-1}$ and estimated $\alpha = 0.008$. In Eq. (1) \mathbf{H} denotes the total field within the system.

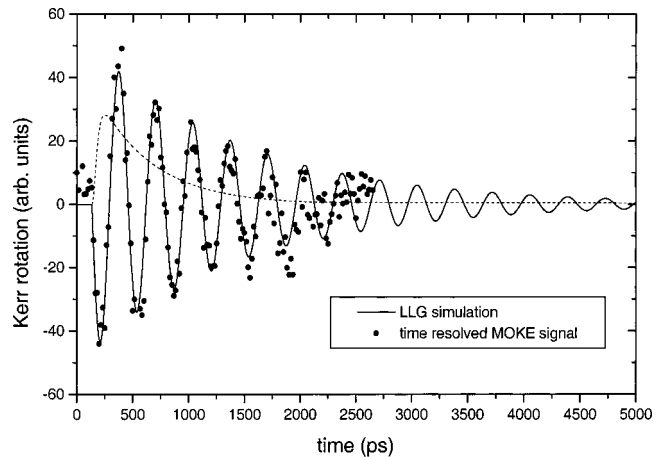


FIG. 3. Precession of the ferromagnetic NiFe system as measured by a time-resolved pump-probe MOKE experiment. For this measurement the bias field was 94 Oe. The solid line shows the LLG simulation for the given system. The dashed line shows the estimated magnetic field pulse.

$$\mathbf{H} = \mathbf{H}_{\text{ext}} + \mathbf{H}_s, \quad (2)$$

where \mathbf{H}_{ext} is given by the applied bias field (H_0) and the field pulse $h(t)$. $\mathbf{H}_{\text{ext}} = [H_0, h(t), 0]$. \mathbf{H}_s represents the shape anisotropy and includes both the magnetostatic shape and field-induced anisotropy contribution of the thin film element. The solid line in Fig. 3 is a simulation of the Landau–Lifshitz–Gilbert (LLG) equation showing excellent agreement with the experimental data. To simulate the precession of the NiFe system, we derived the static magnetic parameters of the elements from the magnetization curves measured by the longitudinal Kerr effect. Determination of the anisotropy constants of the thin film elements with lateral dimensions is of primary interest, as these contribute to the torque experienced by the dipoles. [cf. Eq. (1)+2]. Our thin film elements are oriented on the wafer such that the easy axis of the uniaxial anisotropy, induced during the film deposition, coincides with the long axis of the lateral geometries. The hard axis hysteresis loop of the thin film element can well be described by two uniaxial anisotropy constants, with values: $K1 = 5200 \text{ erg/cm}^3$; $K2 = -3000 \text{ erg/cm}^3$. These measurements give an effective anisotropy of 2 Oe along the long axis of the thin film.

The shape of the magnetic field pulse was estimated by fitting it to the dynamics of the system at different bias fields. It could well be represented by the simple formula

$$h(t) = h_0 [1 - \exp(-t/\tau_r)]^3 \exp(-t/\tau_f), \quad (3)$$

where τ_r , τ_f , and h_0 are the rise time, decay time, and the peak field value, respectively. By fitting this pulse shape to precessions, obtained for different bias fields, we determined $\tau_r = (35 \pm 25) \text{ ps}$, $\tau_f = (600 \pm 100) \text{ ps}$, and $h_0 = (9 \pm 1) \text{ Oe}$. The dashed line in Fig. 3 shows an estimation of the magnetic field pulse. The simulation was done using a pulse of 30 ps rise time and 600 ps decay time. In Fig. 3 it can be seen that the precession frequency decreases, during the decay of the magnetic field pulse. This is due to the fact the precession frequency is proportional to the total effective field, which can only be enhanced by the magnetic field pulses due to their orthogonal orientation to the bias and effective anisotropy field. In addition, the center of precession is shifted towards the direction of the field pulse during the field pulse. As the pulse decays the precession frequency decreases until it reaches its equilibrium state at which the frequency is determined by the bias field and the anisotropy of the film element. The stronger this effective bias field, the

higher the precession frequency is.¹² In these conditions, the precession axis coincides with the long axis of the element.

IV. CONCLUSION

We have shown that our technique, involving the combination of a photoswitch and a coplanar waveguide, is perfectly suited to study the spin dynamics in a soft ferromagnetic system. The setup produces short in-plane field pulses of large amplitude, which are short enough to study the dynamics of a magnetic system. We estimated the field pulse to have a rise time of 10–60 ps, a decay time of 500–700 ps, and a field strength of 8–10 Oe at the peak. We could also show that the device in principle is suited to produce very short pulses in a pulse time regime, which will be of much interest to future MRAM devices. Therefore, we plan to investigate the dynamics of ultrashort magnetization reversals of the ferromagnetic thin film elements by further improving the shape and strength of the magnetic field pulses.

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