Improved time-resolved magneto-optical Kerr effect technique and dynamic magnetization reversal mechanism of perpendicularly magnetized $L_1_0$ FePt films

X. D. Liu$^1$, Z. Xu$^2$, R. X. Gao$^1$, Z. F. Chen$^1$, T. S. Lai$^{1*}$, J. Du$^3$, and S. M. Zhou$^2*$

$^1$State-Key Laboratory of Optoelectronic Materials and Technologies, and Department of Physics, Zhongshan (Sun Yat-Sen) University, Guangzhou 510275, China

$^2$Department of Physics, Fudan University, Shanghai 200433, China

$^3$National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China

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Abstract

The dynamic coercivity cannot be measured rigorously by the conventional time-resolved magneto-optical Kerr effect technique because the irreversible deviation of the transient magnetization is accumulated. In order to remove the accumulation effect, the alternating magnetic field is employed and synchronized with the femtosecond laser pulse. Since the sample is reset before each single laser pulse, the accumulation effect of the irreversible deviation of the transient magnetization is removed. For perpendicularly magnetized $L_1_0$ FePt films, the dynamic magnetization reversal process is accomplished by the nucleation of reversed domains and the pinned domain wall motion.

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*Electronic mail: stslts@mail.sysu.edu.cn; shimingzhou@yahoo.com
Femto-second (fs) laser induced ultrafast spin dynamics has been studied extensively for magnetic films because of its importance in basic research and potential applications in heat assisted magnetic recording [1, 2, 3, 4, 5, 6, 7]. Upon applications of fs laser, hot electrons are firstly excited. Afterwards, spins are in non-equilibrium state because of interactions among electrons, phonons, and spins. The transient temperatures of electrons, spins, and phonons can be revealed by transient reflectivity and Kerr rotation. In order to reveal the laser-induced magnetization reversal process, dynamic hysteresis loops were usually measured by the time-resolved magneto-optical Kerr effect (TR-MOKE) technique [1, 2, 3, 8, 9]. The dynamic coercivity $H_C$ is normally much smaller than that of the static state, that is to say, the magnetic films become magnetically soft. In studies of CoPt$_3$ films, at the delay time longer than 600 fs $H_C$ is equal to zero, which was explained in terms of the paramagnetism of CoPt$_3$ films [10].

Hysteresis loops are often used to study the magnetization reversal mechanism. The temperature should be fixed during measurements. In the TR-MOKE measurements, however, the temperature of the sampling location undergoes sharp rise and slow recovery. The magnetic anisotropy constant is reduced due to the thermal effect after the fs laser excitation. An additional magnetic field may be induced by the linear polarized fs laser [11], leading to the orientation change of the effective magnetic field. Therefore, the transient magnetization may irreversibly deviate from the original equilibrium state when the magnetic field is smaller than the saturation one [3]. As pointed out by Zhang and Roth et al, due to the irreversible deviation the evolution of $H_C$ with the delay time cannot be rigorously detected in the conventional TR-MOKE technique [12, 13]. To reveal the real-time evolution of the dynamic coercivity, it is necessary to re-initialize the magnetization state after single laser pulse shot. In this work, a photo-magnetic synchronized TR-MOKE technique is developed based on a home-built alternating magnetic field (AMF). As a result, the real-time evolution of dynamic hysteresis loops is measured.

In our experimental setup, the AMF is generated in 2 mm magnetic gap of an electromagnet with a nanocrystal-film-wound core that has a response frequency of 100 kHz. The inductive reactance of the electromagnet is cancelled by a suitable capacitor so that the electromagnet is resonant electrically at 1.14 kHz. The electromagnet is driven by a sinusoidal current in the amplitude of 60 A and can generate a 1.14 kHz sinusoidal AMF with an amplitude of up to 8.0 kOe. The AMF is measured by a Hall sensor with a response frequency
of 10 kHz and sampled synchronously. The driving power supply is externally synchronized by fs laser pulse train from a Ti:sapphire laser amplifier with a repetition rate tuned at 1.14 kHz, a pulse duration of 150 fs and an energy of 0.5 mJ/pulse. A programmable electrical time delayer with a time resolution of 25 ns is used to control the delay time $t_1$ between the fs pulse train and the AMF. The laser pulses go through a standard pump-probe setup and are split into strong pump and weak probe pulses. The pump pulses pass through an optical delay line so that the delay time $t_2$ of the probe pulse with respect to the pump pulse can be scanned with a fs resolution. The pump and probe pulses are incident nearly normally and focused to a same area on the sample. The pump spot size is at least two times larger than the probe one, where the former one is 200 $\mu$m. The pump fluence is at least ten times more than that of the probe. Polar Kerr rotation of the probe reflected from the sample surface is measured by a balance optical bridge and subsequently readout by a lock-in amplifier referenced at the frequency of an optical chopper which modulates the probe beam at 340 Hz.

It is essential to compare the difference of the conventional and the improved TR-MOKE techniques. In the conventional technique, the DC magnetic field is employed. On the one hand, at every data point of the Kerr loop, the sample is excited by multiple laser pulses. When the magnetic field is smaller than the saturation one, the transient magnetization may deviate from the equilibrium by each fs laser pulse, which can be accomplished by either the precession of the transient magnetization or the nucleation of the reversed domains [3, 16]. The precession may be caused by the thermal effect on the magnetic anisotropy constant and/or the angular momentum transfer. After the recovery procedure, the transient magnetization finally approaches another state different from the starting state due to the irreversibility. Between consecutive laser pulses, irreversible deviation of the transient magnetization is accumulated. On the other hand, the DC magnetic field of the specific data point in the Kerr loop changes directly from that of the preceding data point by a step $\Delta H$. The starting state of a specific data point before the laser pump is evolved from the ending state of the preceding data point. Therefore, the deviation of the transient magnetization is also accumulated during consecutive measurements of subsequent data points. In a word, the so-called magnetic softening is induced by the accumulation effect of the irreversible deviation of the transient magnetization.

In order to understand the improved technique, we take the loop at $t_2 = 200$ picosecond
(ps) as an example, as shown in Fig. 1. At the data point "A" of the Kerr loop, multiple laser pulses are applied. For each single laser pulse, one period of the alternating magnetic field is swept. At $t_1 = 0.125$ ms, where $H_A = 2.0$ kOe, a single pump pulse is applied. After the time delay of $t_2 = 200$ ps, the Kerr signal of the probe laser is detected. Although the magnetic field still changes during the pump-probe measurements, the magnetic field is almost constant during the detection of the Kerr rotation from the probe pulse since the range of $t_2$ is at least six orders smaller than the period ($T$) of $t_1$. It should bee pointed out that at the beginning of each period, the sample is saturated and that at the data point "A", *before excitation of each laser pulse the sample is reset to the corresponding state of the static Kerr loop without laser pump*. Therefore, the accumulation effect is removed from either the preceding laser pulse or the preceding data point. Above procedure is repeated to obtain the dynamic Kerr loop by scanning $t_1$ from 0 to $T$.

It is significant to compare the dynamic hysteresis loops measured by the two techniques on a 6 nm thick perpendicularly magnetized $L1_0$ Fe$_{0.5}$Pt$_{0.5}$ film, as shown in Fig. 2. At first, the static coercivity is 2.9 kOe and 3.3 kOe in the Kerr loops measured with the dc and alternating magnetic fields as a result of the thermal activation effect, respectively [14, 15]. Secondly, with either approach the saturated Kerr rotation initially decreases sharply and then recovers slowly with increasing $t_2$. Thirdly, as shown in Figs. 2(b)-2(e), $H_C$ measured by the conventional approach is reduced seriously by the accumulation of the irreversibly deviation of the transient magnetization, as analyzed above. The irreversibility of the deviation is also verified from the Kerr loops at $t_2 = -5.0$ ps, or 877 µs where although the saturated transient magnetization is almost completely recovered, $H_C$ is still equal to zero. As shown in Figs. 2(f)-2(j), however, $H_C$ observed by the improved technique does not decrease much with $t_2$. At small and large $t_2$, the dynamic Kerr loops are almost squared and the dynamic coercivity is almost the same as the static value. At the intermediate $t_2$ of 600 ps, the dynamic Kerr loop is slightly slanted. In particular, at $t_2 = 200$ ps the dynamic coercivity is smaller than the static value, as shown in Fig. 1(a).

More importantly, with the improved method the evolution of the dynamic Kerr loops with $t_2$ can better reflect the dynamic magnetization reversal process. At small negative magnetic fields, the magnetization reversal process is induced by the nucleation of reversed domains instead of the precession [16]. This is because as shown in Fig. 3, the transient Kerr rotation does not oscillate as a function of $t_2$ when the external magnetic field is smaller than
the saturation field. The nucleation process is in turn determined by the external magnetic field, the nucleation field, and the delay time $t_2$. After the fs laser excitation, the temperatures of the lattice and the spins are raised, thereby leading a reduction of the nucleation field. At $t_2$ smaller than 50 ps, however, the nucleation of the reversed domains cannot happen due to its large timescale. At $t_2$ of hundreds of picoseconds, the nucleation effect becomes more prominent. Since the large negative magnetic field favors to induce the nucleation, the reduction of the Kerr rotation is increased at more negative magnetic field. At $t_2$ of nanoseconds, the temperatures of the lattice and the spins recover and the nucleation field is increased, thereby weakening the nucleation effect. Accordingly, the dynamic Kerr loops are squared at small and large $t_2$ but slanted at intermediate $t_2$. Moreover, at all $t_2$ the sharp reduction of the transient Kerr rotation occurs at the switching field of the static Kerr loop as marked by the dot line in Fig. 2. For the FePt film, the static magnetization reversal process is accompanied by the pinned domain wall motion (not shown). Although the pinning field may be reduced, the variation of the switching field cannot be observed in the $t_2$ region of several hundreds of picoseconds because the pinned domain wall motion happens in the timescale of nanoseconds. More remarkably, although the transient magnetization is mostly reversed as demonstrated by the negative transient Kerr rotations near $t_2 = 400$ ps when the magnetic field, such as -3.0 kOe and -3.4 kOe, is smaller than the switching field, it is still recovered, as shown in Fig. 3. Finally, it should be pointed out that $H_C$ observed by the conventional TR-MOKE technique also strongly depends on the pump fluence. At small fluences, it may be equal to the static value. This is because the additional magnetic field induced by the linearly polarized laser and the thermal effect become small, leading to a negligible deviation of the transient magnetization from the equilibrium position and the reduction of $H_C$ is suppressed.

In conclusion, in order to measure the dynamic coercivity rigorously, the conventional TR-MOKE technique is improved. The fs laser pump and the alternating magnetic field are synchronized, in which the magnetic field is controlled by modifying $t_1$. Before each fs laser pulse, the sample is reset magnetically, thereby leading to the elimination of the accumulation effect of the irreversible deviation of the transient magnetization. With the improved TR-MOKE technique, the dynamic magnetization reversal process of the perpendicularly magnetized $L1_0$ FePt film is better revealed. It consists of the nucleation of reversed domains at small negative magnetic fields and then by the pinned domain wall motion at the
switching field. The dynamic coercivity changes non-monotonically as a function of \( t_2 \) with a minimum at intermediate \( t_2 \) whereas the switching field almost does not change.

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FIGURE CAPTIONS

Figure 1 Typical dynamic polar Kerr loop measured by the improved TR-MOKE (a), and schematic pictures of AC magnetic field within one period (b) and the delay time between the pump and probe pulses (c). The data point "A" in (a) corresponds to that of \(( t_A, H_A )\) in (b). In (b) and (c), the time relationship between the alternating magnetic field and the pump pulse, and that between the pump and probe pulses are demonstrated. The scale of \(t_2\) is exaggerated greatly for clarity.

Figure 2 Polar dynamic Kerr loops measured by the conventional (left column) and the improved (right column) TR-MOKE techniques with 0.5 ps (b, g) and 50 ps (c, h) and 600 ps (d, i) and -5 ps, i.e., 877 \(\mu\)s (e, j). In comparison, the Kerr loops measured by DC (a) and alternating (f) magnetic fields without pump fluence are given. The inset numbers refers to the delay time \(t_2\). \(\theta_{KS0}\) refers to the corresponding saturation Kerr rotation at the static state.

Figure 3 Transient polar Kerr rotation versus the delay time \(t_2\) at negative magnetic fields.
FIG. 1:
FIG. 2:
FIG. 3: