6

Ultrafast laser-induced magnetisation dynamics of TbFeCo thin films

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Abstract
Laser-induced ultrafast magnetisation dynamic process in TbFeCo thin films has been studied by time-resolved magneto-optical Kerr effect (TRMOKE) at polar geometry. The measurements have been performed under different laser fluences and helicities. The ultrafast magnetisation behaviour induced by the circularly polarized laser pulses has been examined with different combinations of the helicity and the initial magnetisation direction.

Introduction
The ultrafast spin dynamics has become one of the hottest topics for today's magnetism [1-6]. Recently studies suggested that circularly polarised femtosecond laser pulses could be used to excite and control the spin dynamics in magnets by the way of the inverse Faraday effect [7]. The all-optical induced magnetisation reversal in magneto-optical recording media GdFeCo films has been observed. GdFeCo is a soft magnetic material with coercivity fields of the order of 100 Oe and usually used as a MO readout layer. TbFeCo has the similar magneto-optical properties as that of GdFeCo but with a much higher magnetic anisotropy and higher coercivity fields up to a few kOe. The ultrafast dynamics, especially with circularly polarised laser excitation, of the TbFeCo thin film has not been studied yet. This paper is to report our time-domain investigation on optical-induced magnetisation dynamics in the TbFeCo thin films using pump-probe polar magneto-optical Kerr effect.

Experiment
The results presented in this paper are mainly obtained from a 20 nm $Tb_{19}Fe_{66}Co_{15}$ thin film which presents a strong perpendicular anisotropy with a coercivity field 3.9 kOe measured by vibrating sample magnetometry (VSM). A typical time-resolved polar magneto-optical Kerr (TRMOKE) setup is used for all-optical pump-probe measurements in the TbFeCo film. An ultrafast Ti:sapphire laser with pulse width 150 fs, central wavelength 800 nm, and repetition rate 1 kHz was used. The polarisation of the pump beam has been varied between linear and circular using a $\lambda/4$ waveplate for 800nm wavelength while the polarisation of the probe beam stayed linear. The pump pulses came to the sample at an angle of incidence of 10° and the probe pulses at normal incidence. Both pump and probe beam were focused onto the same spot on the sample using two lenses with different focal length and positioned with the help of a CCD camera setup. The spot diameter was around 150 micro metres for the pump and 50 micro metres for the probe. The rotation of the polarisation and change of the reflectivity of the reflected probe beam was detected. To maintain the same initial magnetic state, a magnetic field H_{ext} = 0.5 T, which is 1000 Oe higher than the sample coercivity at room temperature was applied perpendicular to the sample plane.

Results and discussion
The opto-magnetic effect and the induced birefringence effect have the same dependence on pump helicity. It is difficult to separate them within the first picosecond. However the induced birefringence only lasts at the first instant while pump pulses present and then vanishes as pump pulses disappear.

Therefore any deviation from the thermal effect after the first picosecond may come from opto-magnetic effect. With the direction of magnetic field fixed, experiments were performed under different pump beam fluence with right ($\sigma+$) and left ($\sigma-$) circular polarisation at each fluence. Now we are concentrated on the dynamic process after the first picosecond where only thermal effect and possible opto-magnetic effect remain. The thermal effect are insensitive to the helicity of the pump, while the nonthermal effect changes phase between right- and left-handed circularly polarisation. Therefore the thermal, $M_{thermal}$, and nonthermal, $M_{nonthermal}$, effects on the magnetisation can be separated by analysing the sum and difference of the experimental data under different pump helicity, respectively. The analysed sum and difference of data are presented in Fig1 (a) and (b), again with left panel zooming at short time scale and the right panel extends to 400 ps. Fig1 (a) presents the time evolution of nonthermal effect obtained by taking the difference between the $\sigma+$ and $\sigma-$ data so that the thermal effect on magnetisation has been cancelled out. For the two cases with lower pump fluence, the time evolution of the nonthermal effect overlaps and goes back to its original state immediately after the rapid change during the overlap of the pump and probe around the zero delay, giving no indication of any opto-magnetic effect after the 1st picosecond. As the pump fluence

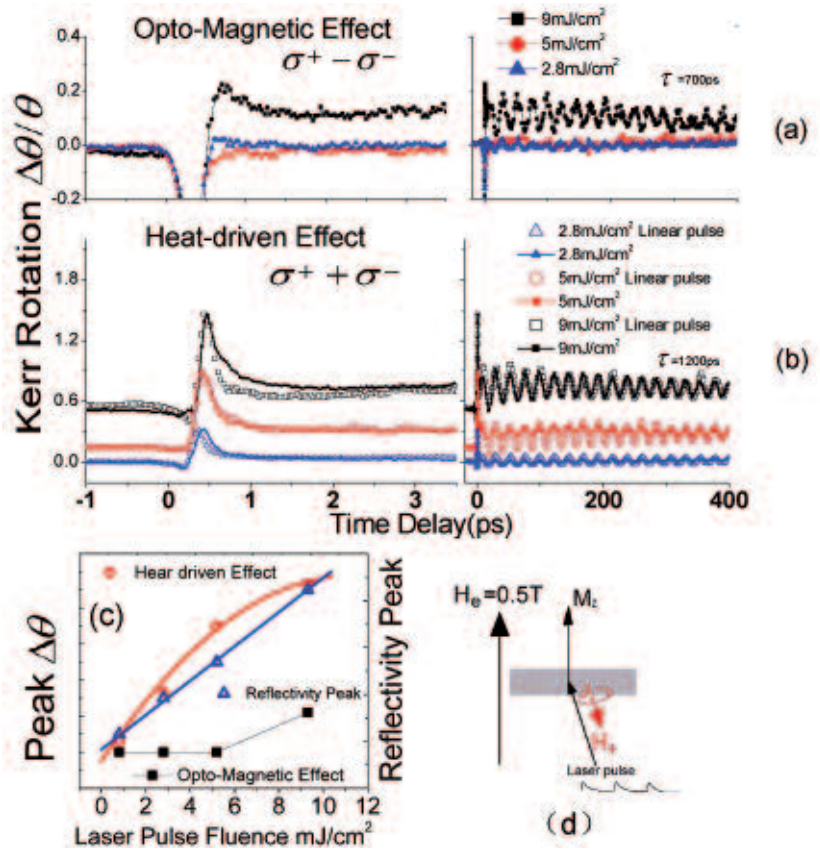

Figure 1. (a) The difference between the data under right (σ+) and left (σ–) pump pulses at different pump fluence. (b) The solid lines is the sum of the data under right (σ+) and left (σ–) pump pulses at different pump fluence. The hollowed lines are responses excited by the linearly polarized laser pulse at the same energies. (c) The peak amplitude in heat-driven effect (red circles), the change in Mz between the magnetic state at delay time of 1 ps and its original state in opto-magnetic effect (black dots), the peak amplitude of reflectivity (blue crosses) are plotted as a function of pump fluence. (d) The schematic representation of the experimental geometry used.

is increased to around 9 mJ/cm^2, the nonthermal effect doesn't go back to the original state immediately but stay in a different magnetisation state and gradually switch back under the applied 0.5 T magnetic field. The observed phenomena can be explained under the assumption that a high density laser pulse can affect the magnetisation spins in a nonthermal way via the inverse Faraday effect which can be phenomenologically described as an axial magnetic field [7,8,9]. The sign of this induced field depends on the laser helicity and the amplitude increases as the laser fluence. In this work, the initial magnetisation is saturated by a 0.5 T external magnetic field and the pump beam comes to the sample with an angle of incidence of 10°, which is schematically represented in Fig 1(d). The right circularly polarized pulses act as a pulse field H+ to switch the TbFeCo magnetisation from its heated state. This opto-magnetic switching behaviour completes within the pump pulse duration and then the magnetisation reverse back at a relaxation time of about 700 ps. The solid curves in Fig 1(b) present the time evolution of the thermal effect data obtained by taking the sum between the σ+ and σ– data to get rid of optical effects, and compared with the directly measured heat-driven dynamics (hollow dots) excited by the linearly polarized pump of the same pulse energy for three different pump fluence. Three pairs of time domain data overlap with each other extremely well for every single pump fluence. The good agreement proves the quality of the experimental data and backs up our suggestion for the indication of opto-magnetic effect in the highest fluence data in Fig 1(a). The magnetisation recovery time after the ultrafast demagnetisation under 9 mJ/cm^2 pump fluence is found to be 1200 ps, much longer than the 700 ps relaxation time of the opto-magnetic case. This is reasonable since the former is a heat-driven effect and recovery of magnetisation relies on the cooling rate of the lattice system, which is a slow process; while the latter is a magnetisation precessing process and the switching time is dependent on the damping mechanism of the material system. The precessional motion was not obvious in the time evolution data in Fig 1(a). It may be due to the strong ringing at 42 GHz frequency which presents in all the time-domain data. The period of this ringing has no magnetic field dependence and no film thickness dependence. It exists no matter what the polarisation the pump beam is but more profound under linearly polarised pump excitation. The origin of this ringing is not known. To examine the dependence of the heat-driven and opto-magnetic effects on the laser excitation fluence, the change in magnetisation between the magnetic state at 1 ps delay time and its original state in Fig 1(a) is plotted versus the pump fluence and shown in Fig 1(c), so is the peak amplitude of the heat-driven data in Fig 1(b) and the peak amplitude of reflectivity data. From the heat-driven curve one can tell that the sample is almost totally demagnetised at 9 mJ/cm^2, which is the condition for opto-magnetic effect to take place. There is no sign of opto-magnetic effect for data taken at lower pump fluence because the spin system was not hot enough. 9 mJ/cm^2 is the highest pump fluence can be applied without damaging the sample surface and opto-magnetic effect has only been observed at this highest pump fluence.

Conclusion

The laser-induced ultrafast dynamics of magnetisation of $Tb_{19}Fe_{66}Co_{15}$ film (20nm) has been investigated by TRMOKE measurements. By comparing the responses from different laser helicities and excitation fluence, the opto-magnetic effect has been observed in time domain under the highest excitation fluence applied. This opto-magnetically induced magnetisation switching completes within the first picosecond and the relaxation time is found to be 700 ps. This relaxation time is much shorter than the recovery time of heat-driven demagnetisation, which is found to be 1200 ps. This demonstrates different mechanisms responding for these two processes involved.

Acknowledgements

XZ and JW would like to thank the Laser Loan Pool for the loan of the femtosecond laser system, and useful discussions with Prof R Chantrell. JWC would like to acknowledge the support from the National Basic Research Program of China through Grant No. 2009CB929201 and the National Natural Science Foundation of China through Grant Nos. 50671119, 50721001, and 50831002.

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