Benchtop time-resolved magneto-optical Kerr magnetometer

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We present here the construction and application of a compact benchtop time-resolved Kerr magnetometer to measure the magnetization precession in magnetic thin films and lithographically patterned elements. As opposed to very expensive femtosecond lasers, this system is built upon a picosecond pulsed injection diode laser and electronic pulse and delay generators. The precession is triggered by the electronic pulses of controlled duration and shape, which is launched onto the sample by a microstrip line. We used polarized optical pulses synchronous to the electronic pulses to measure the magneto-optical Kerr rotation. The system is integrated in a conventional upright microscope configuration with separate illumination, imaging, and magneto-optical probe paths. The system offers high stability, relative ease of alignment, sample changing, and a long range of time delay. We demonstrate the measurements of time-resolved dynamics of a Permalloy microwire and microdot using this system, which showed dynamics at two different time scales. © 2008 American Institute of Physics. [DOI: 10.1063/1.3053353]

I. INTRODUCTION

The burgeoning interests and applications in nanoscience and technology have seen the invention of many nanocharacterization tools in recent years. Magnetic microscopy has evolved with the same trend and today a spatial resolution of better than 50 nm can be routinely obtained by force and x-ray microscopies to image magnetic domains in micro- and nanomagnets.1,2 The recent advancements of magnetization and spin dynamics and spin electronics have generated intense interest in imaging the dynamics at fast time scales with high spatial resolution. Time-resolved magneto-optical Kerr effect (TRMOKE) microscope,3–7 Brillouin light scattering and spatially resolved ferromagnetic resonance microscope10 have evolved within this process. The TRMOKE microscope provides a very high spatio-temporal resolution and prevails above its competitors when “spatial × time resolution” is considered as a figure of merit.11 Aided by the recent advancements of cavity enhancement of MOKE11,12 and near field MOKE,12 it shows a bright future of resolving the dynamics of single nanomagnets in a high density array such as obtained in a patterned magnetic media.13

Magneto-optical effects, namely, the Faraday14 and Kerr15 effects, were discovered in the 19th century, but they continue to be extremely useful techniques for nondestructive investigation of magnetic properties of ferromagnetic materials such as magnetic domain imaging16 and in studying the precessional dynamics of magnetization.17 The basic phenomenon of MOKE is the rotation of the plane of polarization of a plane polarized light upon reflection from the surface of a magnetic material. A linearly polarized light is reflected as an elliptically polarized light and the Kerr rotation and ellipticity give a measure of the magnetization of the sample. The magneto-optical interaction introduces an orthogonal component (k) in the electric field vector of the reflected light both in and out of phase to that of the incident light (r). The in-phase component contributes to the Kerr rotation and the out-of-phase component contributes to the Kerr ellipticity. Several theoretical efforts have been made to understand the origin of magneto-optical effects in ferromagnet with approaches including band theory of metals18 and macroscopic theory considering off-diagonal terms in the dielectric tensor.19,20 On the other hand, the experimental detection and analysis of the MOKE signal have attracted more attention in recent times due to the technological relevance.21,22

There are three important MOKE geometries, namely, the longitudinal, polar, and transverse MOKE, which are defined according to the relative orientation of the plane of incidence with the magnetization vector M in the sample as shown in Fig. 1. In the longitudinal effect [Fig. 1(a)] the magnetization vector M lies in the plane of the sample and is parallel to the plane of incidence, while in the polar effect [Fig. 1(c)] M lies perpendicular to the plane of the sample. In both longitudinal and polar cases upon reflection linearly polarized (p- or s-polarized) light is converted into elliptically polarized light. The major axis of the ellipse is slightly rotated with respect to the principal plane and is referred to as the Kerr rotation as shown in Fig. 1(d). The flatness of the ellipse is quantified as the Kerr ellipticity. The Kerr rotation (θk) and ellipticity (εk) can be expressed as θk+iεk=k/r, when k<<r.23 The transverse MOKE [Fig. 1(b)] occurs only for p-polarized light and when M lies in the plane of the sample but perpendicular to the plane of incidence. In this case the reflected light remains linearly polarized, but the
amplitude of the reflected light changes as the magnetization vector $\mathbf{M}$ changes sign from $+\mathbf{M}$ to $-\mathbf{M}$. The measurement of Kerr rotation is performed by analyzing the polarization state of the reflected light.\(^{23}\) This is done either by using a crossed polarizer arrangement set at the extinction or by using an optical bridge detector consisting of a polarized beam splitter (PBS) and two photodiodes. The difference in the signal between the two photodiodes is proportional to the Kerr rotation.\(^{24}\) The PBS is placed at $45^\circ$ to the reflected light so that when a linearly polarized light (in the absence of Kerr rotation) passes through the PBS the intensity of light in two orthogonal components of polarization is identical that gives rise to a “balance” in the bridge. The Kerr rotation modifies the intensities in the two orthogonal components of polarization and gives rise to a finite electronic signal at the output of the optical bridge detector. For some samples such as nickel, Kerr ellipticity is much larger than Kerr rotation and in these cases the ellipticity is converted into rotation by introducing a quarter-wave plate before the analyzer.

Electronic techniques such as pulsed inductive magnetometry\(^{25}\) and broadband ferromagnetic resonance magnetometry\(^{26}\) have developed in parallel to investigate the high frequency magnetization dynamics. However, the lack of spatial resolution has limited their applications to thin films and relatively large microstructures. Dynamics in magnetic nanoelements (nanopillars and magnetic vortex) due to spin transfer torque has been reported recently\(^{27,28}\) by the use of magnetoresistive methods, but it requires special sample fabrication and may not be considered as a purely nondestructive method. Optical probing combined with electronic pumping has a greater appeal due to better time resolution and for its nondestructive nature. To this end very few published efforts may be found\(^ {29}\) and a clear description of the technique and exploitation of its potential are lacking. For example, to investigate the dynamics of magnetic vortex and precession, which occur on different timescales, a long time delay with good time resolution is required simultaneously. In an optical pump-probe experiment this is difficult to achieve by a translation stage due to the unavailability of such long travel stages with sufficient spatial resolution and the difficulty in optical alignment. Finally, no effort has been made so far to develop a compact and user-friendly TRMOKE magnetometer (microscope) with potential for commercial exploitation.

Here, we have optimized the above aspects and built a TRMOKE magnetometer, which is compact, stable, provides time delays up to 40 ns with a resolution of 0.5 ps, and with a spatial resolution down to 600 nm. The optical detection is highly sensitive and allowed the measurement of in-plane translational motion of magnetic vortex core in a Permalloy dot 1 $\mu$m in diameter. We have demonstrated the dynamical measurements from both Permalloy dots and microwire, which showed magnetic vortex dynamics and precession of magnetization, respectively.

II. EXPERIMENT

We have started with building an upright MOKE microscope as shown in Fig. 2. A pulsed injection diode laser (PIL040 from Advanced Laser diode system) with central wavelength of 408 nm, pulse width of $\sim 42$ ps, spectral width of $\sim 7$ nm, repetition rate of up to 1 MHz, and peak power of $\sim 1.3$ W is used for the MOKE measurements. A prism pair is used for precompensating the temporal chirp in the laser beam. The laser beam is then linearly polarized with a polarizer with extinction coefficient $>10^5$:1. The mirror $M_1$ and the right angle prism $P_1$ fold the optical path along the downward normal of plane 2. The laser is focused onto the sample (in plane 1) at an oblique angle by an extra long working distance microscope objective of numerical aperture of 0.55. The laser spot and the sample are illuminated by a green light-emitting diode and are directly imaged in the back-reflected configuration by a high spatial resolution charge coupled device (CCD) camera (Hamamatsu model C4742–98) placed in plane 3. The CCD is used to place the

![FIG. 1. Schematics of (a) longitudinal, (b) transverse, and (c) polar MOKE geometries are shown. (d) Geometry of the Kerr rotation ($\theta_K$) and ellipticity ($e_K$) is shown. Here, $r$ is the Fresnel reflection coefficient, $k$ is the Kerr coefficient, and $\mathbf{M}$ is the magnetization of the sample.](image)

![FIG. 2. (a) Schematic diagram of the MOKE microscope in the upright configuration. (b) Top view of the schematic of the sample mount placed within the pole pieces of the electromagnet.](image)
laser spot at the desired position on the sample. The focused laser spot has a diameter of ~600 nm. The back-reflected laser beam was collected by the microscope objective and recollimated before the right angle prism P2 and mirror M2 fold the beam back into plane 2 and send it to a differential photodiode detector, which consists of a PBS and two biased silicon photodiodes. The difference signal between the two photodiodes corresponds to the longitudinal MOKE. The pair of right angle prisms is easily replaced by a 50:50 beam splitter and additional folding mirrors in the back-reflected beam path to measure the polar MOKE. An in-plane magnetic field is applied by a cross-pole electromagnet [Fig. 2(b)] whose orientation can be continuously varied by adjusting the currents in the pair of coils in the two cross arms of the electromagnet. For the static hysteresis loop measurements, we have set the repetition rate of the pulsed laser diode at 100 kHz from its internal clock and measured the Kerr rotation in the reflected beam by a lock-in amplifier with a reference signal from the output trigger of the laser diode. In Fig. 3(a) we show the scanning electron microscope (SEM) images of a Permalloy microwire (12 μm wide, 100 μm long, and 50 nm thick) and array of microdots (1 μm diameter and 50 nm thick) deposited on a microstrip line structure that has been used for the static and the microwire loop. The dynamic measurements need the launching of an ultrafast magnetic field pulse to the sample. We have used an electronic pulse generator (model 10,060A from Picosecond Pulse Labs) with rise time of 55 ps, variable duration from 100 ps to 10 ns, and +10 V maximum signal to achieve this. The high frequency voltage pulse is launched onto the samples by a microstrip line (Au on GaAs) with 18 μm track width and 100 nm thickness. The induced precessional motion is probed by measuring the magneto-optical Kerr rotation of the probe laser as a function of the time delay between the optical and electronic pulses. The cross-pole electromagnet has limited aperture for sample mount, and a cross type sample mount placed at 45° relative to the pole pieces allows the optimum use of the limited available space. As shown in Fig. 4(a), two semirigid coaxial cables are pressure mounted on the bond pads of the microstrip line, which results in low capacitance and therefore correct impedance matching between the pulse generator and the stripline with 50 Ω characteristic impedance. The microstrip line has a folded structure [Fig. 4(b)] to accommodate relatively long structure and large bondpads. The transmitted pulse through the microstrip line is measured by a 20 GHz sampling oscilloscope (HP 83480A) and compared with the direct pulse from the picosecond pulse generator. The measured rise time of the transmitted pulse is 60 ps as opposed to 55 ps for the incident pulse. The peak-to-peak jitter is about 10 ps. The amplitude of transmission is about 95% without any significant ringing or reflection as shown in Fig. 4(c), showing a good impedance match between the electronics with the microstrip line. The synchronization between the electronic and optical pulses is obtained by the use of a variable electronic delay generator (PDL30A, Colby Instruments, USA) with total delay of 40 ns at 0.5 ps time step. The synchronization scheme is shown in Figs. 5(a) and 5(b). The output trigger of the picosecond laser diode corresponds to the pulsed injection to the lased diode and is used to trigger the variable electronic delay generator whose output consequently triggers the picosecond pulse generator. The output pulse from the picosecond pulse generator is fed to the 50 Ω terminated microstrip line structure. All cables used are of high band-
width (>18 GHz) with SMA connectors. The laser pulse is emitted 157 ns after the output trigger from the laser power supply. The internal delays of the variable delay generator and the picosecond pulse generator are 19.22 and 90 ns, respectively. These delays added with the delays generated by the cables allow us to set the zero delay near one end of the variable delay generator, and hence a maximum delay of ~33 ns is obtained during the experiment. There is further scope of increasing this delay range to ~40 ns by rack-mounting the electronics next to the microscope and thereby shortening the cables. The synchronization is initially obtained by replacing the sample by a fast Si p-i-n photodiode with 50 ps rise time (Thorlabs model DET02AFC) and by comparing the delays in the pump and probe paths on the 20 GHz sampling oscilloscope. In order to measure the very small Kerr rotation due to the magnetization dynamics, a modulation scheme is used. We have gated the picosecond pulse generator at a much lower frequency (2–10 kHz) compared to the repetition rate of the laser and measured the Kerr rotation with a lock-in amplifier referenced at the gate frequency of the picosecond pulse generator. The sample is scanned under the focused laser spot by a three-axis piezo-electric scanning stage (Thorlabs model MDT693). The whole system requires an areal space of approximately 1.2 × 0.7 m² including the optics and electronics.

III. RESULTS AND DISCUSSIONS

The relatively weak power (average power=5.5 µW) of the puls injection diode laser is not sufficient to excite the precession of magnetization by direct optical pumping or by producing a pulsed magnetic field by optically triggering a photoconductive switch. Hence, electronic excitation and optical detection are most appropriate when using a picosecond injection laser diode. In the following we demonstrate the measurements of two samples showing dynamics at two different time scales. First we measure a Permalloy microwire deposited on a microstrip line structure as shown in Fig. 3(a). The laser spot was placed at the center of the sample and the time-resolved Kerr rotation is measured as a function of the bias magnetic field applied along the long axis of the wire as shown in Fig. 6(a). We applied a pulsed magnetic field of 80 Oe peak value, 55 ps rise time, and 4 ns duration. The pulsed field amplitude was high enough to cause a large angle reorientation of the in-plane magnetization of the sample from the long axis, which shows up as a large initial step followed by a ringing corresponding to the precession of magnetization (not shown). We have extracted only the ringing part to demonstrate the precessional dynamics here. The precessional part has been artificially shifted in time to match the zero delay for visual clarity. The fast Fourier transforms (FTTs) [panel 2, Fig. 6(a)] show a dominant single precession frequency, which shows a variation with the bias field as shown by the symbols in Fig. 6(b). Although in such confined magnetic samples a spatially varying precessional motion is expected, which will be described in detail elsewhere, the central part of the sample is spatially uniform and the precession frequency may be described by the ferromagnetic resonance mode frequency given by the Kittel’s formula

$$f = \frac{g \mu_B}{2 \hbar} \sqrt{(H_b + H_K)(H_b + H_K + 4\pi M_S)}.$$  

(1)

Here $H_b$ is the bias magnetic field, $H_K$ is the anisotropy field, and $4\pi M_S$ is the demagnetizing field for a flat plate with $H_b$ within the plane of the sample. The demagnetizing field considered here is a rough approximation for this confined structure and requires thorough micromagnetic simulations, which is beyond the scope of this paper. However the fitted curve shows good agreement with the experimental data with $g=2.2$, $H_K=20$ Oe, and $M_S=860$ emu/cm³, which are all appropriate for this sample.

In Fig. 7 we have demonstrated the time-resolved dynamics from a Permalloy dot of 1 µm width and 50 nm thickness (aspect ratio=0.05). The measurements are done at zero bias field and a pulsed field of 80 Oe peak value, 55 ps rise time, and 1 ns duration is applied in the geometry as shown in Fig. 7. The time-resolved signal shows a long lasting slow oscillation until 30 ns. The FFT spectrum extracts a frequency of 255 MHz, which is the characteristic frequency of vortex core oscillation for Permalloy dot studied here. The pulsed field amplitude is well below the vortex annihilation field for this sample and hence we observe only a gyrotric...
motion of the vortex core. A high frequency oscillation corresponding to the spin wave also appears in the time-resolved signal but is not prominent in the FFT spectrum due to the dominance of the vortex core oscillation.

Finally, the above system can be easily used to obtain scanning images of the dynamics by using the existing piezoelectric scanning stage as the conventional TRMOKE microscope. However, we also propose a single shot measurement of the dynamical images by using the time-gated high-resolution CCD camera. This technique may allow us to study localized rotational motion of vortices in the real space of a defective lattice consisting of randomly sized magnetic disks as expected in Ref. 33. Further extension of the expected results may lead to an electromagnetic wave guide in the artificial crystal of the magnetic vortex system such as two-dimensional photonic crystals.

IV. CONCLUSIONS

We have described the development and implementation of a benchtop time-resolved magneto-optical Kerr magnetometer, which combines electronic and optical methods of excitation and detection, respectively, while keeping the cost of development and the space requirement to the minimum. We have applied this technique to measure the time-resolved dynamics from a Permalloy microwire and a microdot showing typical precession of magnetization and gyrotropic motion of magnetic vortex core. We discuss scopes for further improvement of this microscope, which may lead to a commercial system for routine characterization of time-resolved dynamics of magnetic materials.

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