Local magneto-optical Kerr effect imaging by scanning near-field optical microscope in reflection-mode

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A method for local magneto-optical Kerr effect imaging based on a home-made scanning near-field optical microscope working in reflection mode is presented. Shear force detection is carried out by using a symmetric piezoelectric bimorph sensor, which provides an easy way not only for probe-surface distance control but also for imaging. Polarization-preserving fiber probes used as a local optical detector are fabricated with a heating-pulling technique and the probes' polarization properties are measured. Shear force topographic and near-field magneto-optical images of magneto-optical disk taken with the proposed method are shown.

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The performance of magnetic materials is ultimately determined by their properties such as the local magnetic domain structure and its dynamic characteristic. The characterization of magnetic materials with high lateral resolution is thus important for both fundamental researches and modern technologies[1]. Many microscopic methods have been developed for the measurement of magnetic domainses and magnetization. For example, Lorentz-mode transmission electron microscopy (TEM)[2] and scanning electron microscopy with polarization analysis (SEMPA)[3] can be used for probing magnetic domains and magnetization with high resolution. However, such methods require expensive electron optics devices and vacuum conditions which limit the range of applications. Based on atomic force microscopy (AFM) widely employed in the nanometer-scale investigation, magnetic force microscopy (MFM) is useful for magnetic imaging[4]. However, MFM cannot measure the magnetization of materials directly, detecting only the magnetic stray fields near the surface. In addition, external magnetic fields are hardly applied to avoid affecting the electron motions in TEM and SEMPA. In MFM technique, measurements in external magnetic fields should be carefully treated in case of the damage on the magnetized cantilever. Furthermore, the magnetic tip will influence the magnetic structure under investigation, especially when the samples are soft magnetic materials. Classical magneto-optical microscopy based on Kerr or Faraday effect is an appropriate way to investigate magnetic domains in the present of external magnetic fields. The resolution of classical optical microscopy is, however, limited to the diffraction limit, which is approximately half a wavelength of the illuminating light[5].

Scanning near-field optical microscopy (SNOM) is one of the advanced optical microscopy methods, in which a sub-wavelength-size probe is placed in close proximity to a sample surface and raster scanned to form an optical image[6−8]. The resolution of SNOM that breaks the diffraction limit is determined by the probe size and probe-surface distance, both of them should be much smaller than the wavelength of light[9]. Utilizing Kerr and Faraday effects, a number of different configurations of near-field magneto-optical imaging systems are built, including aperture-transmission[10,11], aperture-reflection[12−14], and apertureless SNOMs[15]. In most of these systems, the probe-surface distance control is realized by fixing an optical fiber probe to one arm of a tuning fork, which is first proposed by Karrai *et al.*[16]. This technique works well but it requires great preparation for each probe. In addition, the high quality (Q) factor limits the scan speed to relatively low values. Those disadvantages result in the difficulties in performing experiment upon near-field magneto-optical imaging.

In this letter, we propose a method for local magneto-optical Kerr effect imaging based on a home-made SNOM working in reflection mode. Shear force detection is carried out using a symmetric piezoelectric bimorph sensor[17]. Polarization-preserving fiber probes used as local optical detector are fabricated with a heating-pulling technique and their polarization properties are measured. Shear force topographic and near-field magneto-optical images of magneto optical disk taken with the method are shown.

A schematic of the experimental arrangement is shown in Fig. 1. The home-made SNOM operating in reflection mode was used. The probe-surface distance regulation was carried out by employing a piezoelectric bimorph sensor, which consisted of two thin piezoceramic layers attached to a common center electrode that is connected to the ground. One of the piezo layers used as a dither piezo was electrically connected to a reference signal of the lock-in amplifier. A constant sine wave voltage was applied to it to drive the bimorph to vibrate parallel to the surface. The other layer, a detection piezo generated a maximum induced piezo voltage when the bimorph was driven at its resonance frequency. The induced voltage was enhanced by a preamplifier and then demodulated by means of the lock-in amplifier. When the probe neared the surface, the oscillation of the sensor was damped due to the tip-surface interactions, resulting in a decrease in the output signal of the lock-in amplifier. The decreased signal was compared with a set-point of the feedback circuit and the resulting difference was used to control the tip-sample distance while imaging.

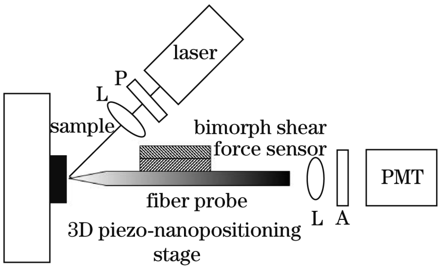

Fig. 1. Schematic of the SNOM setup. P: polarizer; A: analyzer; L: lens; 3D: three-dimensional; PMT: photomultiplier tube.

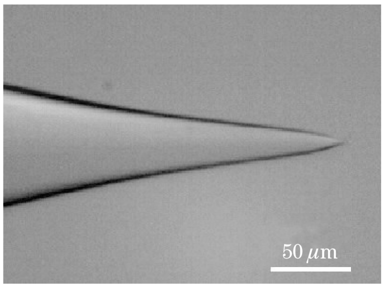

Fig. 2. Optical micrograph of the polarization-preserving fiber probe produced by our heating-pulling method.

Polarization-preserving single-mode fiber probe (BT-SG80-1310, Beijing Glass Research Institute) was fabricated with a heating-pulling method developed in our laboratory. Figure 2 gives an optical micrograph of the polarization-preserving fiber probe produced by this method.

The sample was illuminated by a p-polarized coherent light (λ = 635 nm) from far field. Considering the problem of the setup geometry, the angle of the incident light was set at about 45° to the normal of the sample surface. The optical signal was collected in near-field of the sample by the polarization-preserving single-mode fiber probe. The collection of the light was analyzed by the PMT (CR131, Hamamatsu, Japan) equipped with the polarization analyzer. A closed loop piezoelectric 3D positioning stage (PI517.3CL, Physik Instrument, Germany) was employed as the scanner providing movements with nanometer resolution.

For polarization measurements, uncoated fiber probes were used in order to avoid the depolarization effects related to metal-coated SNOM probes. Those uncoated probes were pre-selected by measuring their polarization properties at the wavelength used in the experiment. The measurement of polarization properties was done with two incident light in different linearly polarized directions. One is parallel to the fast axis, and the other is parallel to the slow axis of the fiber. By turning the analyzer, changes in the light intensity were recorded. Figure 3 displays two typical normalized light intensity curves, where the squares represent the results when the polarization of the incident light is parallel to the fast axis of the fiber and the triangles show that when the polarization is parallel to the slow axis. It is easy to find that the extinction ratio is about 15:1 for the polarization direction parallel to the fast axis, and is only about 2:1 for the polarization direction parallel to the slow axis.

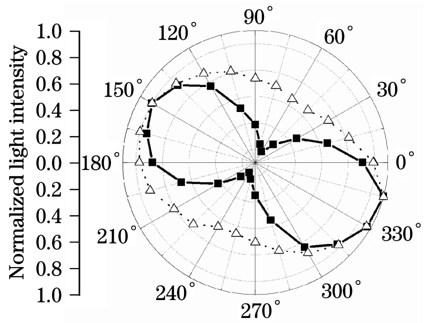

Fig. 3. Relation between the normalized light intensity of the polarization-preserving fiber probe and the polarization direction of the analyzer. The squares represent the results when the polarized direction of the incident light is parallel to the fast axis of the fiber. The triangles show that when the polarized direction is parallel to the slow axis.

Generally, linearly polarized light become depolarized when it passes through the probe tip. In our experiment, only fiber probes with the polarization extinction ratio larger than 15 were used.

For local magneto optical Kerr effect imaging, a small piece of magneto-optical disk (MOD, P1002E, Plasmon Inc., USA) with perpendicular magnetization as a test sample was observed in our first experiment. The MOD was a 3.5-inch plastic disk and the capacity was 1 GB. We split the disk mechanically in order to expose the ferromagnetic material which was sealed beneath the plastic to the surface. The surface profile of the sample consists of grooves with the periodicity of 1.6 μm and depth of approximate 100 nm. Magnetic bits with a width of about 1 μm were written along the grooves[18]. Figure 4 gives shear force topographic and near-field magneto-optical images of the MOD obtained at a scan rate of about 1 Hz and a set-point of 0.96. The scanning area of the image is 10×10 (μm). The scanning direction is perpendicular to the incident plane. In the topographic image of Fig. 4(a), the elevated areas of the surface are brighter than the grooves and some fine structures can be clearly observed, showing that the image almost truly reflects the features of the sample surface. Figures 4(b) and (c) are the magneto-optical images taken at the minimum and maximum light intensities, respectively, by rotating the polarization direction of the analyzer. Stripes are also observed and have an obvious similarity to the topographic structure, as shown in Fig. 4(b). The optical image contrast is mainly due to the differences in reflectivity between the top and bottom positions. It should be pointed out that the magnetic bits are not resolved in the image taken under this condition. However, the magnetic bits on the grooves are clearly visible in Fig. 4(c). Figure 4(d) is a line profile at the position indicated by the line AA' in Fig. 4(c). The resolution, defined as the lateral displacement with a change of 10%–90% of the vertical variation, is estimated to be smaller than 300 nm, which is smaller than half the wavelength of the incident light. The results are similar to those obtained by Meyer *et al.*, who performed the Kerr effect measurement of the same sample by conventional Kerr microscope and SNOM, respectively[19]. In fact, the SNOM resolution can be further improved by using a metalized fiber probe.

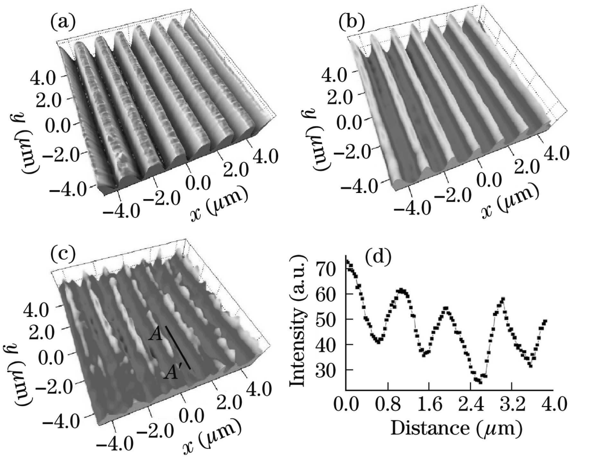

Fig. 4. (a) 3D topographic image of the MOD; (b), (c) magneto-optical images of the MOD taken at the minimum and maximum light intensities, respectively, by rotating the polarization direction of the analyzer; (d) line profile at the position indicated by the line AA' in (c).

The origin of the near-field magneto-optical image contrast can be simply derived based on magneto-optical Kerr effect. In the first-order approximation, Kerr rotation angle ϕ can be given by

$$\phi = \phi_K + i\varepsilon_K. \quad (1)$$

The intensity of collection light I is then written as

$$I(\pm M) = I_0 \sin^2(\alpha \pm \phi_K) + I_B, \quad (2)$$

where $\pm M$ is the magnetization intensity, ϕ_K is the real part of the complex Kerr rotation angle, α is a small angle that makes two crossed polarizers misaligned for distinguishing the sign of the rotation angle, I_B is the background intensity that cannot be eliminated due to the quality of the polarizer and the fiber. Usually, α and ϕ_K are small, so light intensity is proportional to M. It is well appropriate for local magnetic domain imaging and magnetization curves collection[20].

In conclusion, we demonstrate a method for local Kerr effect imaging by home-made reflection mode SNOM. Shear force detection is carried out by using a symmetric piezoelectric bimorph sensor, which provides an easy way to control probe-surface distance and imaging. Polarization-preserving optical-fiber probes used as local optical detector are fabricated with a heating-pulling technique and the Prokes' polarization properties are investigated. Shear force topographic and near-field magneto-optical images of magneto optical disk taken with the proposed method are shown. The results suggest that the home-made reflection-mode SNOM combined with magneto-optical Kerr effect is reliable and suitable for local magnetic domain imaging.

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