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Polarization properties of bent-type optical fibre probe for magneto-optical imaging

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Summary

Quantitative evaluation of magneto-optical parameters is necessary in order to apply scanning near-field optical microscope (SNOM) technology to the study of magnetism on the mesoscopic scale. For this purpose, quantitative knowledge of polarization transmission properties through an optical fibre probe is required. We therefore determined the Stokes parameters of the bent-type optical fibre probe that is used as a cantilever for atomic force microscope operation in our SNOM system. As a result, it is found that the degree of polarization is maintained in the light emitted from the probe, although the probe acts as if it were a wave plate. This anisotropic polarization state of the light emitted from the probe was compensated for by using a Berek compensator placed in front of the fibre coupler.

Introduction

Recent progress in magnetic and magneto-optical (MO) recording technology to realize ultrahigh density storage has required development of the observation and evaluation technologies of magnetism on the mesoscopic scale. For this purpose, various different techniques have been developed: the Lorentz electron microscope (Chapman *et al.*, 1995); the spin-polarised scanning electron microscope (Koike & Hayakawa, 1984); the magnetic force microscope (Rugar *et al.*, 1990); the spin-polarised scanning tunnelling microscope; and the scanning near-field optical microscope (SNOM) (Betzig *et al.*, 1992a,b).

It has been anticipated that MO-SNOM will be a powerful tool not only for MO imaging, but also for quantitative investigation of magnetic properties on the sub-wavelength scale. In previous papers this group reported an MO imaging technique using a SNOM employing a bent-type optical fibre probe operated as an atomic force microscope (AFM) cantilever and succeeded in the MO imaging of Bi:DIG (Mitsuoka *et al.*, 1998; Nakajima *et al.*, 1998) and Pt/Co (Ishibashi *et al.*, 1998) using the crossed polariser technique and the polarization modulation technique, respectively. It is expected that the polarization modulation technique will be capable of obtaining quantitative MO parameters. For this purpose, one requires an ideal polarization property for a light transmitted from the aperture of the probe. Most previous works which employed straight fibre probes and lateral shear force feedback system paid attention only to the extinction ratio of the emitted light from the probe, as this parameter provides sufficient information for the purpose of imaging. However, in order to obtain quantitative MO parameters, accurate polarization transmission properties of the optical fibre probe are required, which in turn will provide information to achieve an exact compensation. This is especially necessary in our system, because polarization properties experience disturbance caused by both tapering and bending.

In this paper we report on the polarization properties of the bent-type fibre probes using the Stokes parameters that provide an analytical description of the polarization states, including parameters such as the degree of polarization and the optical retardation.

Experimental

The Stokes parameter was measured to investigate the polarization properties of the fibre probe for our SNOM system. Our SNOM for MO imaging is based on a commercially available AFM unit (model SPI3700, Seiko Instruments). The details have been described elsewhere (Chiba *et al.*, 1995). The single mode optical fibres, whose core and cladding are 3·2 and 125 μm in diameter, respectively, are pulled to form the tip and then bent by irradiation with a CO_2 laser. The bend angle is about 80°

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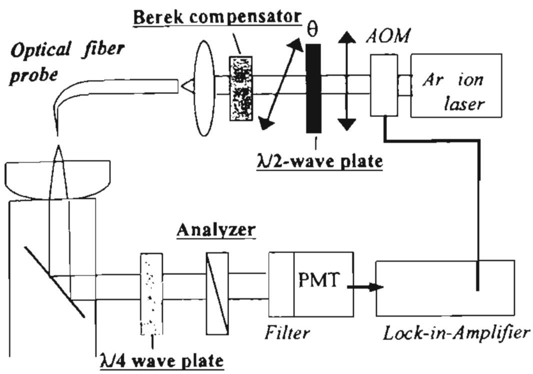

Fig. 1. A schematic diagram of the system for measuring the Stokes parameters.

and the point is 0·5 mm away from the apex of the tip. By coating the side of the tapered probe with 100–150 nm thick aluminium film an aperture is fabricated at the apex of the probe. An aperture size of ≈ 80 nm was obtained.

Figure 1 shows a schematic diagram of a measuring system for the Stokes parameters. Light from an Ar ion laser with a wavelength of 488 nm is modulated by an acousto-optic modulator (AOM) to achieve the lock-in detection and coupled into the end of an optical fibre probe. The polarization property of the light emitted from the aperture was measured in a far-field region without samples in order to obtain the polarization effect of the fibre probe separately, avoiding any interaction between the aperture and samples.

As shown in Fig. 1, a half-wave (λ/2) plate, a quarter-wave (λ/4) plate and an analyser are inserted in the optical path to determine the Stokes parameters. Furthermore, in order to compensate for the anisotropic polarization state of the beam emitted from the probe, the Berek compensator is placed in front of the fibre coupler. The Stokes parameters are given by

$$S_0 = I_x + I_y \tag{1}$$

$$S_1 = I_x - I_y \tag{2}$$

$$S_2 = 2I_{xy} - S_0 \tag{3}$$

$$S_3 = 2I_{qxy} - S_0 \tag{4}$$

where I_x, I_{xy} and I_y are intensities measured with an analyser at angles of 0 (x axis), 45° and 90° (y axis), respectively, and I_{qxy} is the intensity measured with a quarter wave plate. Therefore, S_0, S_1, S_2 and S_3 represent the intensities of the light, the polarised light along the x axis, the polarised light at 45° and the circularly polarised light, respectively. The degree of polarization, P, is given by

$$P = (S_1^2 + S_2^2 + S_3^2)^{1/2}/S_0 \tag{5}$$

An MO disc using a Pt (0·8 nm)/Co (0·3 nm) multilayer with a thickness of 15 nm as a recording layer was employed for the measurement. Using a magnetic-field modulation method marks were recorded with a length of 10 mm and a width of 1 mm. MO spectra of the Pt/Co multilayer were recorded using an MO spectrometer; from these spectra Faraday rotation and Faraday ellipticity at 488 nm were determined to be 0·74° and 0·47°, respectively.

Results and discussion

Figure 2 shows the Stokes parameters, normalized with S_0 and the degree of polarization, versus the rotation angle of the polariser for (a) ideal linearly polarised light (b) light emitted from the aperture of a bent optical fibre without tapering and (c) that from a bent optical fibre probe. In the case of ideal linearly polarised light, S_1 and S_2 vary as a sine curve with the rotation angle and S_3 is zero at all angles, as shown in Fig. 2(a). In both Fig. 2(b) and (c), in addition to S_1 and S_2, S_3 is also varying as a sine curve. It is found that optical anisotropy is obviously induced by bending. This result indicates that the bent optical fibre and the bent optical probe act as if they were a wave plate, as reported previously (Mitsuoka *et al.* 1998; Nakajima *et al.* 1998; Ishibashi *et al.* 1998), although the difference in polarization properties between the bent optical fibre and the bent optical fibre probe is not clear. Furthermore, it is surprising that the degree of polarization is almost maintained after transmission from the aperture of a bent optical fibre probe.

The Stokes parameters of a light which penetrates a wave plate having a retardation angle δ and an azimuth α are given by

$$S_1 = \cos 2a \cos 2(\theta - a) - \cos\delta \sin 2a \sin(\theta - a) \tag{6}$$

$$S_2 = \sin 2a \cos 2(a - \theta) - \cos\delta \cos 2a \sin 2(a - \theta) \tag{7}$$

$$S_3 = \sin\delta \sin 2(\theta - a) \tag{8}$$

where θ is the azimuth of an incident light. These equations indicate that S_1, S_2 and S_3 vary as sine curves. The angle of retardation, δ, and the azimuth, α, are determined from an amplitude and a phase shift of S_3, respectively. Therefore, the retardation can be compensated for and a linearly polarised light can be reproduced by using the compensator. Figure 3 shows that the Stokes parameters of the bent optical fibre probe were compensated for by the Berek compensator placed in front of the fibre coupler. The amplitude of S_3 is reduced to < 0·1 while S_1 and S_2 vary as a sine curve. This result indicates that the retardation induced by the probe is compensated for, and that the linearly polarised light is emitted from the aperture. The quantitative analysis of MO imaging can be discussed by the use of an ideal linearly polarised light as follows.

Using the polarization modulation technique, the MO signals are obtained by detecting intensities of light modulated by a photo-elastic modulator (PEM) at a frequency of p. In principle, the p and $2p$ components of the detected signals correspond to the Faraday ellipticity and Faraday rotation, respectively, if an ideal polarization property is maintained during transmission through the fibre probe. The Faraday ellipticity and Faraday rotation are

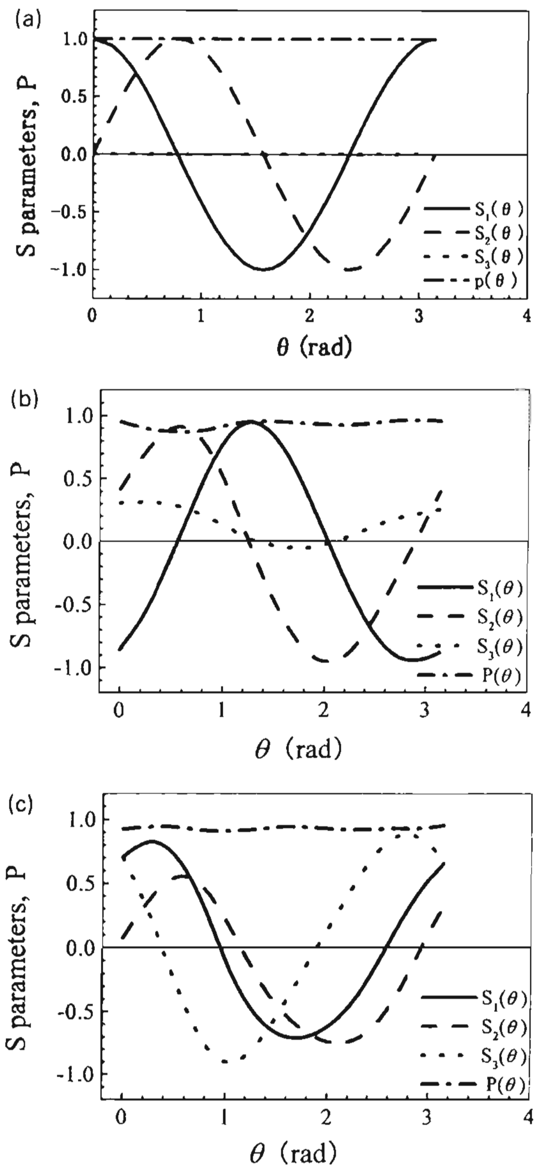

Fig. 2. The Stokes parameters, normalized with S_0 and the degree of polarization, versus the rotation angle of the polariser for (a) ideal linearly polarised light, (b) light emitted from the aperture of the bent optical fibre and (c) that from the bent optical fibre probe.

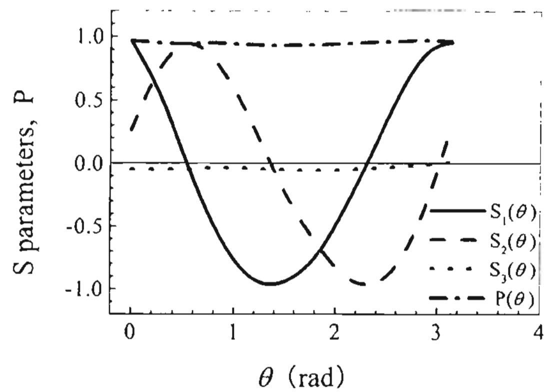

Fig. 3. The Stokes parameters of the bent optical fibre probe compensated for by the Berek compensator.

given by (Sato, 1981)

$$\eta_F = I(p)/\{I(0)4\ J_1(\delta_0)\}C_\eta \quad (9)$$

$$\theta_F = -I(2p)/\{I(0)4\ J_2(\delta_0)\}C_\theta \quad (10)$$

where $I(0)$ is the intensity of the light, T is the transmittance, J_n is the nth order Bessel function and δ_0 is the retardation by the PEM. In the measurement, these values should be corrected by C_η and C_θ, which are factors affected by experimental set-ups such as optical elements or electrical devices.

Figure 4 shows MO images of a Pt/Co MO disc visualized with the p and $2p$ components of the detected signals, whose contrasts correspond to rotation angles of η_F and θ_F. Recorded marks having a shape characteristic of the magnetic field modulation method are clearly resolved. Figure 5 shows cross-section profiles of the images shown in Fig. 4. A resolution of ≈ 150 nm was obtained for both MO images using p and $2p$ components. Signal outputs, which are differences in voltage between a recorded and an unrecorded area, were obtained to be $I(p) = 75$ and $I(2p) = 90\ \mu V$ for η_F and θ_F respectively. Considering the factors C_η and C_θ, η_F and θ_F are obtained to be $288/I(0)$ and

Fig. 4. The MO images of a Pt/Co MO disc visualized with (a) the p and (b) the $2p$ components of the detected signals.

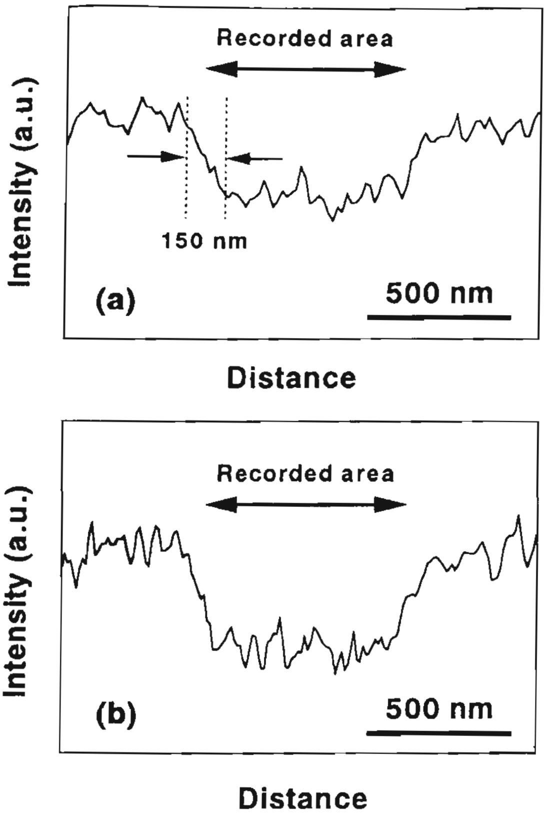

Fig. 5. Line scans of a mark recorded on a Pt/Co MO disc. (a) and (b) correspond to Fig. 4(a) and (b), respectively. A resolution of ≈ 150 nm was obtained.

692/I(0), respectively. This result is consistent with the rotation angles of η_F and θ_F measured by conventional Faraday spectroscopy. We are convinced that the evaluation of these values in MO imaging will be achieved, and investigations are continuing.

Conclusions

The Stokes parameters were measured in order to understand the polarization properties of a bent-type optical fibre probe. It was found that the probe acts as if it were a wave plate, and the degree of polarization is maintained after emission from the probe. The retardation induced by the probe was measured by the Stokes parameter S_3 and was compensated for by using the Berek compensator. An example of a quantitative analysis would be to apply the polarization modulation technique to a SNOM. We are convinced that this method contributes to the study of magnetism at the sub-wavelength scale and its applications.

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