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Magnetic field dependence of Cotton–Mouton rotation for magnetic fluid films

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Abstract

The azimuthal distribution of the transmitted intensity of a linearly polarized laser beam through a 6 μm -thick magnetic fluid film was measured under various magnetic fields H normal to the direction of the light propagation to study the magnetic field dependent Cotton–Mouton (C–M) effect of the sample. Here, the azimuthal angle η is the angle between the transmission axes of the polarizer and the analyzer. For obtaining the most significant variation in the polarization of the incident light, the angle between H and the polarization of the incident light θ is set to be 45° . The I – η curves were found to be symmetric with relative maximum at $\eta_{I=\text{max}}$ around 0° and minimum at $\eta_{I=\text{min}}$ around 90° . Furthermore, these curves showed a gradual shift up to $\Delta\eta = 1.55^\circ$ with respect to the curve under zero magnetic field as H increased to 250 Oe. All the details will be discussed in this report. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Cotton–Mouton rotation; Magnetic fluid film; Elliptical polarization

1. Introduction

Birefringence induced by the application of a magnetic field perpendicular to the propagation of the light in an isotropic medium is known as Cotton–Mouton (C–M) effect, in which an elliptical polarization occurs with a linearly polarized incident light. In magnetic fluids, the birefringence is believed to be due to the spatial anisotropy caused

by the alignment of the particles under a magnetic field [1,2]. Some experimental results revealed that the ferrite particles agglomerate to form short chains in magnetic field films as a magnetic field H applied along the film surface [2–5]. C–M rotations for some of these systems were obtained indirectly by calculating from the measured transmittance and the maximum and minimum transmitted intensity through the samples under a given magnetic field. In this work, we prepared the high-quality ferrofluid for the investigation of the structure of the sample under parallel magnetic fields. Furthermore, the azimuthal distribution of the transmitted intensity of a linearly polarized

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Fig. 1. Setup of the experiment for investigating the Cotton-Mouton effect of the magnetic fluid film.

laser beam through a $6\text{ }\mu\text{m}$ -thick high-quality magnetic fluid film under various magnetic fields was performed to study the influence of the magnetic field on the C–M effect. The measurement of the azimuthal distribution of the transmitted intensity used here affords a direct observation of the C–M rotation.

2. Experimental details

The saturated kerosene-based ferrofluid ($M_s = 12.98\text{ emu/g}$) with a volume concentration about 27.8% used in this work was prepared by the coprecipitation technique. To obtain a transparent sample for the study of the Cotton–Mouton (C–M) effect, the magnetic fluid was sealed in a $4\text{ cm} \times 1\text{ cm}$ rectangular glass cell to form a $6\text{ }\mu\text{m}$ -thick film.

In this work, the setup of the C–M effect is shown in Fig. 1. A He–Ne laser beam (wavelength = 632.8 nm) was linearly polarized by a polarizer and then was incident normally to the magnetic fluid film. The magnetic field here was generated by a pair of solenoids and applied to the film perpendicular to the propagation of the light. The angle θ between the transmission axis of the polarization of an incident light and the applied magnetic field can be adjusted by rotating the magnetic field. To examine the polarization of the transmitted light through the film, an analyzer was used to measure the azimuthal distribution of the transmitted intensity. The azimuthal angle η , the angle between the

Fig. 2. Nearly perfect periodic long-chain structure for the magnetic fluid film under a parallel magnetic field.

two transmission axes of the polarizer and the analyzer, was determined by rotating the transmission axis of the analyzer with the aid of a stepping motor with a resolution of 0.01° . Finally, a PMT tube was used to detect the intensity of the transmitted light through the sample. It is noted that the instrument was aligned very carefully to obtain symmetric I – η curves for various magnetic fields through the experiments.

3. Results and discussions

It is well known that the C–M effect is due to the spatial anisotropy caused by the alignment of the magnetic chains for the magnetic fluid under a parallel magnetic field. Thus, the formation of the magnetic chains should be investigated. As applying a parallel magnetic field H to the magnetic fluid film, it was observed that many aligned discrete magnetic short chains were formed by the agglomeration of the magnetic particles. With keeping increasing H , these short chains started to combine with each other to become longer discrete chains until H reaching a critical magnetic field ($\sim 60\text{ Oe}$ for this system). As H exceeds this critical value, a periodic long-chain structure can be found for the magnetic fluid thin film. A typical image of the periodic long-chain structure was shown in Fig. 2. Owing to the long-chain structure, a strong spatial anisotropy is induced for the magnetic fluid under parallel magnetic fields. It was also found in the experiment that these long chains moved closer

Fig. 3. I - η curves under various applied magnetic fields H from zero to 250 Oe at $\theta = 45^\circ$. The angle $\eta_{I=\min}$ for each curve is indicated by an arrow.

to each other as increasing the applied magnetic field. This indicates that the spatial anisotropy can be modulated by an applied magnetic field.

For investigating the influence of the magnetic field-dependent periodic long-chain structure in the magnetic fluid on Cotton–Mouton effect, the I - η curves for the transmitted light of a linearly polarized incident light under various applied magnetic fields H were measured. To obtain the most significant variation in the polarization of the incident light through the magnetic fluid, the angle between H and the polarization of the incident light is set to be 45° . For a zero magnetic field, the I - η curve was symmetric with a relative maximum intensity at $\eta_{I=\max} = 0^\circ$ and zero intensity at $\eta_{I=\min} = 90^\circ$ and -90° . The symmetric I - η curves under nonzero magnetic fields were also obtained with a translational shift by a $\Delta\eta$ ($\equiv |\eta_{I=\min}(H) - \eta_{I=\min}(H=0)|$) with respect to the zero-field curve. In order to decide the C–M rotation $\Delta\eta$ precisely, the I - η results at η around -90° were enlarged and shown

in Fig. 3. The value of $\Delta\eta$'s, which were indicated by arrows in Fig. 3, increased gradually up to 1.55° as H increased to 250 Oe. This significant variation in $\Delta\eta$ may be attributed to the periodic long-chain structure in the magnetic fluid film. In addition, the minimum intensity $I_{\min}$ occurred at $\eta_{I=\min}$ in the I - η curve was found to be nonzero under $H \neq 0$ and increased as raising H . The existence of $I_{\min} \neq 0$ suggests obviously that the transmitted light is not linearly but elliptical polarized under magnetic fields. Moreover, the fact of the magnetic field dependent $I_{\min}$ implies that the configuration of the elliptical polarized transmitted light is affected by the applied magnetic field simultaneously. These phenomena may suggest that a phase separation should be taken into account in the birefringence effect for a magnetic fluid thin film with the periodic long-chain structure.

4. Conclusions

In conclusion, a method for direct measurement of the Cotton–Mouton rotation $\Delta\eta$ was developed in this study. Besides, we also found some interesting results. A fairly significant Cotton–Mouton rotation $\Delta\eta = 1.55^\circ$ was observed for our sample with a nearly perfect periodic long-chain structure under $H = 250$ Oe at $\theta = 45^\circ$. For further quantitative analysis, more experimental data such as transmittance and an adequate theory by considering the observed phase separation for the system are required in the future.

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