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Magnetically modulated optical transmission of magnetic fluid films

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Abstract

The optical transmission of the magnetic fluid film under perpendicular magnetic fields was investigated by measuring the transmitted intensity of the normally incident light through the film. The transmittance I/I_0 of the magnetic fluid film was observed to decrease with the increase of the magnetic field strength H due to the reduction in the area occupied by the relatively optically transparent liquid phase. Moreover, under a given H , the transmittance decreased exponentially with the increasing film thickness L , i.e. $I/I_0 = \exp(-L/\delta)$, where the δ denotes the attenuation distance. It was further found that the δ varies with the magnetic field strength and the concentration of the fluid, but is independent of the sweep rate of the field.

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1. Introduction

Magneto-optics of magnetic fluids has recently attracted sustained interests due to the richness of this relatively unexplored phenomena. Within the research area, the study of optical transmittance of magnetic fluid films under external magnetic fields is growing all over the world because of the feasibility of optical devices such as the optical switch [1], the magnetic field sensor [2] and modulators [3] etc. It is indicated that the transmittance of the magnetic fluid film can be manipulated by adjusting the magnetic field strength [1,4]. In addition, the temperature [5] and wavelength effect [6] on the transmittance were also reported. The physical mechanism accounting for the variation in the resultant transmittance is indicated to be directly

attributed to the evolution of the structure in the magnetic fluid film under magnetic fields [2]. By taking account of the variations of the effective concentration and the area ratio of the liquid phase in the magnetic fluid film under magnetic fields, the resultant magnetic field dependence of the optical transmission can be predicted [2].

In our previous studies [7,8], it was found that the structural patterns could be affected by the control parameters, such as the field strength, the sweep rate of the field, the film thickness and the concentration of the magnetic fluid. This implies that the transmittance of the magnetic fluid film should also be determined by these control parameters. Even today, the relationship between the transmittance of the magnetic fluid film and the control parameters is still not understood well. In this study, we systematically investigate the influences of the film thickness, the concentration, and the sweep rate on the magnetically modulated transmittance of magnetic fluid films.

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2. Experimental details

The magnetic fluid was prepared with the chemical coprecipitation technique. The magnetic particle of the ferrofluid is Fe_3O_4 with a size around $118 \text{ \AA}$ [9,10]. The fluid was then injected into glass cells to form magnetic fluid films. A pair of solenoids was used to provide a magnetic field perpendicular to the plane of the magnetic fluid film. Throughout the experiment, the temperature was kept at 24.3°C . To measure the optical transmission of the magnetic fluid, an unpolarized parallel light ray with a wavelength of 1557 nm was perpendicularly incident to the film, and the transmitted light was guided, by an optical fiber, to the spectroscopy to measure the transmitted intensity. By dividing the measured transmitted intensity I of the magnetic fluid film under a given field by that, I_0 , of the bare glass cell, the transmission of the film was obtained. The structures of the magnetic fluid film under fields were observed with an optical microscope and then photographed with a CCD camera.

3. Results and discussion

Due to the formation of columns agglomerated by magnetic particles, the optical transmittance of the film can be modulated by external magnetic fields [2]. For the magnetic fluid film of a given thickness, the transmittance I/I_0 of the film was observed to decrease with the increasing magnetic field H . A typical I/I_0-H curve of the magnetic fluid film is shown in Fig. 1. As the film thickness L was increased, the I/I_0-H curve moved to the region of lower transmittance. This movement in the I/I_0-H curve is attributed to the elongation of the traveling path as the light passes the films. The inset in Fig. 1 plots the film-thickness dependence of transmittance under various H 's in the log-linear scale. It was found that the transmittance follows the relation $I/I_0 = \exp(-L/\delta)$, where δ denotes optical attenuation distance and the value of the $-1/\delta$ for a fixed H was the product of the $\ln 10$ and the slope of the corresponding $\log(I/I_0)-L$ curve shown in the inset. According to the experimental data, the various δ 's resulted under various H 's. Here, the δ ranged from 80 to $50 \mu\text{m}$ as the H increased from zero to 300 Oe .

In addition to the magnetic field and the film thickness, the transmittance of the magnetic fluid film was also observed to be dependent on the concentration of the fluid because of the enhancement in the optical scattering as light passes through the film of a higher concentration. This implies that the attenuation distance δ should be reduced for a magnetic fluid film of higher concentration. To check this, the $\log(I/I_0)-L$ curves were measured for the magnetic fluid films of various concentrations under either zero or nonzero magnetic

Fig. 1. Transmittance versus magnetic field strength for various film thickness L 's. The inset shows the film-thickness dependent transmittance of the magnetic fluid film in log-linear scale.

fields. For the zero field, it was found that the slope, s , of the $\log(I/I_0)-L$ curve changes with the concentration of the fluid, as shown in Fig. 2(a). Thus, the attenuation distance δ is indeed a function of the fluid concentration via the relation $\delta = -1/(s \ln 10)$. Through a careful analysis of the results in Fig. 2(a), the δ was found to decrease from 279 to $38 \mu\text{m}$ as the concentration increased from 0.17 emu/g ($= 0.30\%$ in volume fraction) to 1.08 emu/g ($= 1.93\%$). This phenomenon was also observed for a nonzero field, say 120 Oe , as shown in Fig. 2(b). It is worth noting that the $\log(I/I_0)-L$ curve under 120 Oe is steeper than the corresponding curve under zero field for a given concentration. Hence, a smaller value is for the δ under a higher field strength. This result is consistent with that shown in the inset of Fig. 1.

Finally, the influence of the field sweep rate on the magnetically modulated transmission of the magnetic fluid films was investigated. The I/I_0-H curves for magnetic fluid films with 0.17 emu/g of 130 and $200 \mu\text{m}$ in thick were probed at various dH/dt 's and are shown in Figs. 3(a) and (b), respectively. It is clear that the I/I_0-H curves for various dH/dt 's coincide with each other for a given film. To discover the origin of the phenomena in Fig. 3, the structural patterns were examined. It was observed that the columns are

Fig. 2. Transmittance as functions of the thickness of the magnetic fluid films with various concentrations under (a) zero field and (b) 120 Oe.

Fig. 3. Magnetic field dependent transmittance of the magnetic fluid films with thickness of (a) 130 μm and (b) 200 μm at various field sweep rates dH/dt .

distributed randomly all over the film even H up to 300 Oe. Furthermore, the $(A - A_{\text{col}})/A - H$ curves of a film at these dH/dt 's were also found to overlap, where A_{col}

denotes the total area of the cross section of the columns within a certain area A of the magnetic fluid film. Thus, under a given H , a fixed area was achieved for the optically transparent liquid phase in the film at various dH/dt 's. This led to a coincidence of the $I/I_0 - H$ curves of the magnetic fluid film at various dH/dt 's. The inference was obviously consistent with the experimental results shown in Fig. 3. On the other hand, the overlap of the $I/I_0 - H$ curves for the various dH/dt 's implies that the attenuation distance δ is independent of the sweep rate.

4. Conclusion

The transmittance of the magnetic fluid films can be reduced by increasing the magnetic field strength, the film thickness and the concentration of the fluid, but is independent of the field sweep rate. Also, the optical attenuation distance of the magnetic fluid film can be manipulated via varying the field strength and the concentration. Further investigations reveal that the structural patterns are dominant to the transmittance of the magnetic fluid films.

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