Magnetically-modulated refractive index of magnetic fluid films

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We developed a setup to probe the refractive index of the magnetic fluid films under external magnetic fields. This setup possesses a high resolution of 0.0001 in the measured refractive index. It was found that the refractive index of the magnetic fluid depends linearly on the concentration of the dilute magnetic fluid under zero field. For a given magnetic fluid film, the refractive index increases with the increasing field strength over a critical value, and then becomes saturated as the field reaches around 200 Oe. It is noteworthy that the magnetically modulated refractive index of the magnetic fluid films could have great potential in electro-optical applications. © 2002 American Institute of Physics. [DOI: 10.1063/1.1531831]

Magnetic fluids have attracted a great deal of attention of researchers, not only because of their versatile structural patterns under external magnetic fields,^{1–5} but also because of their remarkable magneto-optical properties, such as birefringence,^{6–11} field-dependent transmission^{9,12,13} and magnetochromatics.^{14,15} The work to clarify the physical origins of these characterizations of the magnetic fluids has been vast. Investigations reveal that many potentially electro-optical devices, for example, the optical switch,^{16–19} the tunable grating,^{20,21} or the optical waveguide,^{22–24} can be designed and developed by utilizing the magneto-optical characteristics of the magnetic fluids. Hence, the study of magnetic fluids has become more and more popular in both the academic and the industrial areas of research and development.

Although the optical characterizations of the magnetic fluids have been examined for decades and novel phenomena have been discovered, reports on the refractive index of the magnetic fluid are still rare. To explore it, we established an experimental setup, wherein the critical angle of the total reflection at interface between the magnetic fluid and the reference prism can be determined precisely to measure the refractive index of the magnetic fluid films. Since the properties of the magnetic fluid can be modulated by external magnetic fields, it is worth investigating the effects of a magnetic field on the refractive index of the magnetic fluid films.

Figure 1 is a cross-sectional drawing, schematically illustrating the system used to measure a refractive index of the magnetic fluid film. The magnetic fluid used here is water- or kerosene-based Fe_3O_4 , which was injected into a glass cell with an area of $4 \times 4 \text{ mm}^2$ and a depth ranging from several to hundreds of micrometers. The magnetic fluid film was covered with a triangle prism made of ZnSe, silicon, or other compounds with a high refractive index. Thus, there exists a PM interface between the prism and the magnetic fluid. An external magnetic field H was provided by a

FIG. 1. Experimental setup for detecting the refractive index of magnetic fluid films under magnetic fields.

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solenoid and was perpendicular to the film surface. The deviation of the applied magnetic field within the sample region is around 0.5%. The temperature was maintained at 24.3 °C by using a circulating water system. The resolution of the temperature is 0.1 °C.

The light source employed in this work is a laser diode that generates an IR light of 1.557 μm . Since the IR light emitted from the laser diode is divergent instead of parallel, a convex lens was placed in front of the laser diode to produce a parallel light when the originally divergent IR light passed through the lens. The incident angle θ_i into the prism is controlled by a stepping motor with a resolution of 0.01°. An optical fiber was used to guide the ray DE in Fig. 1 to a photodetector to sense the intensity of light. Since the diameter of the optical fiber is much smaller than that of the light ray DE, it was necessary to probe the spatial distribution of the intensity to obtain a real intensity for the light ray DE. The position of the outward light DE corresponding to a given θ_i was located through a coarse scan, followed by finely moving the optic fiber around this position to scan the spatial distribution of the intensity inside the light beam DE. The relatively scanning angle θ_D of the optical fiber with respect to a fixed normal line at point D corresponding to a certain incident angle was controlled by another stepping motor with a resolution of 0.01°.

When the parallel IR light ray AB was incident into one side of the prism with an incident angle θ_i , the light experienced refraction at point B and then reflected from the magnetic fluid at point C, as shown in Fig. 1. The reflected light had refraction occurring at point D and then left the prism. The refractive angle at point B is denoted by θ_r , and the incident and the reflective angles at point C are θ_{ic} and θ_{rc} , respectively. The θ'_i and θ'_r stand for the incident and the refractive angles at point D. According to the reflective and Snell's law, the following relations are obtained:

$$\sin \theta_i = n_p \sin \theta_r, \quad (1)$$

$$\theta_{ic} = \theta_{rc}, \quad (2)$$

$$\theta'_i = \theta_r, \quad (3)$$

$$\theta'_r = \theta_i, \quad (4)$$

$$\text{and } \theta_{ic} + \theta_r = \pi/4, \quad (5)$$

where n_p represents the refractive index of the prism. In this case, the total reflection occurs at point C with a condition of $\theta_{ic} = \theta_c$, where θ_c is the critical angle, at which a total reflection occurs. At point C, we also have

$$n_p \sin \theta_c = n_{MF}, \quad (6)$$

where n_{MF} denotes the refractive index of the magnetic fluid film. With Eqs. (1)–(6), the refractive index of the magnetic fluid n_{MF} can be derived to be

$$n_{MF} = \frac{1}{2} (\sqrt{2n_p^2 - 2 \sin^2 \theta_{it}} - \sqrt{2} \sin \theta_{it}), \quad (7)$$

where θ_{it} is the value of θ_i corresponding to the occurrence of the total reflection on the PM interface. Here, the intensity of the light DE for various θ_i is measured to find the θ_{it} . With the resolution of 0.01° in θ_i , the resolution in n_{MF} is 0.0001 via Eq. (7).

FIG. 2. Symmetric spatial distribution for the intensity of the reflective light DE for various incident angles θ_i . The total reflection occurs on the PM (prism–magnetic fluid) interface at $\theta_i = 30.40^\circ$. With n_p being 2.4739 for $\lambda = 1.557 \mu\text{m}$, the $n_{MF} = 1.3545$.

Figure 2 plots a typical pattern for the spatial distributions of the light ray DE corresponding to incident light rays AB of various incident angles θ_i from 32.60° to 28.60°. The symmetry of each curve reveals that the instruments are well-aligned throughout this experiment. It was observed that the intensity of the light ray DE increases higher as θ_i is reduced, and then becomes saturated when the θ_i reaches to 30.40°.

According to the experimental architecture shown in Fig. 1, the reduction in θ_i leads to the increase in the incident angle θ_{ic} at the PM interface. Thus, as the θ_i is decreased, making θ_{ic} larger than the critical angle θ_c on the PM interface, the light BC was reflected almost totally, and the intensities of light rays DE remain nearly unchanged for smaller θ_i . Hence, the results in Fig. 2 imply that the total reflection on the PM interface occurs at $\theta_i (= \theta_{it}) = 30.40^\circ$. With n_p being 2.4739 for $\lambda = 1.557 \mu\text{m}$, and based on Eq. (7), the refractive index is 1.3545 for the investigated magnetic fluid with a concentration of 0.17 emu/g.

Figure 3 shows experimental results on the concentration-dependent refractive index (n_{MF} – M_s curve) of the diluted water-based Fe_3O_4 magnetic fluids under zero field. It is obvious that the refractive index of the magnetic fluid depends linearly on the concentration of the dilute water-based magnetic fluid under zero field. This linear relationship between the refractive index and the concentration is also found for the dilute kerosene-based Fe_3O_4 magnetic fluid, as shown in Fig. 3. One can measure the refractive index of concentrated magnetic fluids by replacing the prism by that with a high refractive index n_p .

To investigate the influence of the external magnetic field on the refractive index n_{MF} of the magnetic fluid films, the n_{MF} under various perpendicular magnetic fields are measured and shown in Fig. 4. For a given magnetic fluid film, for example, $M_s = 0.68 \text{ emu/g}$ and $L = 11.8 \mu\text{m}$, the refractive index did not vary as the field was increased from zero to 30 Oe. Further, the refractive index increased monotonously from 1.4352 to 1.4385 as the field strength rose from 0 to 30 Oe. Further, the refractive index increased monotonously from 1.4352 to 1.4385 as the field strength rose from 0 to 30 Oe. Further, the refractive index increased monotonously from 1.4352 to 1.4385 as the field strength rose from 0 to 30 Oe.

FIG. 3. Concentration-dependent refractive index of water- and kerosene-based magnetic fluids under zero field for a wavelength of 1.557 μm .

30 to 180 Oe, and then almost remained unchanged as the field strength reached 200 Oe. According to the observation of the structures in the magnetic fluid film under external fields, there is no column formation in the film until the field is over 30 Oe. More columns are formed as the field increases further. An image of a typical structure in the magnetic fluid film 11.8 μm thick under a perpendicular field of 120 Oe is shown in the inset of Fig. 4. When the field strength is higher than 200 Oe, no newly-formed column appears. These results imply that the magnetically tunable refractive index of the magnetic fluid film is perhaps due to the light scattering by the column formation in the film under external fields.

For the magnetic fluid films of various thickness, a similar trend was also obtained the $n_{\text{MF}}-H$ curve, as shown in

FIG. 4. Magnetic field dependence of the refractive index of the magnetic fluid films of various thicknesses. The inset shows the structure pattern in the magnetic fluid film under external magnetic field, which is outward to the sheet.

Fig. 4. It is noted that the refractive index of the magnetic fluid film is independent of the film thickness under zero field, whereas a higher saturated value of the refractive index is achieved for a thicker magnetic fluid film. This means that the variation in the refractive index of the magnetic fluid film with the magnetic field is enhanced as the film becomes thicker. In addition, the desired variation in the refractive index with the field for practical optical applications can be achieved by suitably setting the thickness of the magnetic fluid film.

In conclusion, we established an experimental setup to precisely measure the refractive index of the magnetic fluid films under either zero or nonzero magnetic fields. It was found that the refractive index of the magnetic fluid can be manipulated by adjusting the concentration and finely tuned by controlling the magnetic field strength. These results lay out the significant information for developing potential applications in electro-optical devices by utilizing the magnetically-modulated refractive index of the magnetic fluid films.

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