Journal of the Korean Physical Society, Vol. 55, No. 3, September 2009, pp. 1259∼1262

Temperature Dependence of the Optical Transmission of a Magnetic Fluid with an Applied Magnetic Field

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(Received 25 August 2008)

The physical origin of the temperature dependence of the optical transmission of a magnetic fluid under an applied magnetic field is studied in this paper When a magnetic field is applied parallel to the plane of a magnetic fluid thin film, magnetic chains form in the same direction as the magnetic field, which suppresses the optical transmission. We observed that the optical transmission could be tuned by varying the ambient temperature of the magnetic fluid thin film. The design and the experimental results are also analyzed.

PACS numbers: 78.66.-w, 85.70.Sq, 75.30.-m
Keywords: Magnetic fluid, Magnetic chains, Optical transmission, Thermal agitation

I. INTRODUCTION

A magnetic fluid (MF) is a homogeneous colloidal suspension of single domain ferromagnetic particles wrapped by a surfactant in a suitable carrier liquid. The quality of a MF has undergone great improvement thanks to fast-developing nanoscale technology and material science, which results in better optical properties of the MF. The optical properties of a MF, which include the refractive index tunability [1–3], magneto chromatics [4,5], magneto-optic effect [6–15], *etc.*, benefit from the magnetism of solid ferromagnetic matter and the fluid behavior of liquid matter. With the help of these unique properties, many MF-based photonic devices have been proposed, such as MF light modulators [16], MF optical switches [17,18], MF gratings [19], *etc.* Because the optical transmission of a MF greatly influences the properties and the efficiency of these photonic devices, it is worth researching the optical transmission of a MF under different conditions.

The optical transmission of a MF has been shown to be deeply related to its structural patterns under external fields. Yang *et al.* have proven that the magnetic-field-dependent optical transmission originates from an agglomeration of magnetic particles that reduces the area of the liquid phase [20]. Because thermal agitation can suppress agglomeration [21], the optical transmission varies with the ambient temperature around the MF. Based on this principle, we carried out experiments to investigate the temperature dependence of the optical transmission of a MF under an applied magnetic filed. In this paper, we report the design and the experimental results, and we discuss the physical origin of the temperature dependence of the optical transmission of a MF under an applied magnetic filed.

II. EXPERIMENTS AND DISCUSSION

A schematic of the experimental arrangement is shown in Fig. 1. In the experimental setup, a MF thin film is put between a pair of solenoids, which is used to apply magnetic field with its direction parallel to the plane of the film. The sample investigated here is water-based MF, which has ferromagnetic particles, Fe_3O_4, with an average diameter of 10 nm and a volume concentration of 6.47% and which is sealed in a 3.3 cm × 1.7 cm glass cell with a thickness of 7 μm to form a MF thin film.

The magnetic field is controlled by using a combination of a signal generator that provides a square-shaped wave and a driving circuit that is on or off. The field strength detected by using a teslameter is adjustable by changing the amplitude of the square-shaped wave. In our experiment, the amplitude of the magnetic field was 40.9 mT.

Laser light with a wavelength of 650 nm and a polarization direction perpendicular to the direction of the magnetic field is incident perpendicular to the film. In this case, the incident light is ordinary light. The transmitted intensity is detected in the direction of light propagation. A silicon photovoltaic cell, which converts the optical signal into an electric signal is used to detect the

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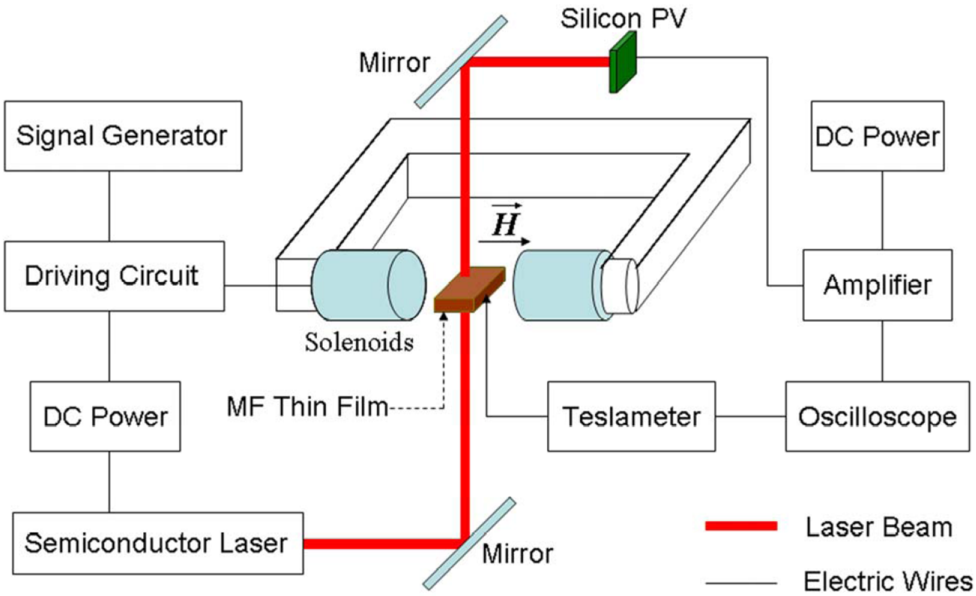

Fig. 1. Schematic of the experimental setup for analyzing the temperature dependence of the optical transmission of a MF under an applied magnetic filed.

transmitted light intensity, which can be observed using an oscilloscope. An amplifier is utilized to amplify the output signal of the silicon photovoltaic cell and to input the amplified signal into the oscilloscope. The electric signal of the applied magnetic field is also shown on an oscilloscope connected to the teslameter. The ambient temperature is changed by using an electric heater around the MF thin film, and a thermocouple is used to detect the changing temperature.

At first, when the magnetic filed is not applied, the MF is isotropic and shows little absorption so that the transmitted intensity and the electrical signal shown on the oscilloscope are both at a high level. Then, when a magnetic field is applied, magnetic chains form in the MF, which results in the absorption of the incident light. Thus, some of the light will not be allowed to pass through the MF thin film so that the electrical signal is shifted to a low level.

The results for optical transmission under an external magnetic field for different temperature conditions are shown in Fig. 2 and Fig. 3, from which we can see that the transmittance increases with increasing temperature. It is worth noting that MF needs some response time to form magnetic chains [21,22] so that in Fig. 2, the transmittance needs some time to be steady. In Fig. 3, the transmittance is the electrical signal at half-decay time divided by the largest electrical signal (at time zero). The experimental data are fitted by using an exponential growth curve. The following will focus on the physical origin of such experimental results.

The theoretical formula describing the transmittance of ordinary light is given as [23]

$$Tr_{ordinary} = \exp\left\{-2\pi\left(\frac{d}{\lambda}\right)\phi_M\left[\frac{4\cdot(4\pi\sigma/\omega)}{[(\varepsilon+1)-\langle N\rangle(\varepsilon-1)]^2}+\frac{C_2}{2}\left(\frac{\langle a\rangle}{\delta}\right)^4\right]\right\}, \tag{1}$$

where d is the thickness of the film (7 μm), λ is the wavelength of the incident laser (650 nm), ϕ_M is the volume fraction of the MF (6.47%), σ is the electric conductivity of the solute particles in the MF (2.98×10^{15} esu), ω is the frequency of the incident laser (2.90×10^{15} Hz), ε is the ratio of the dielectric constants of the solute particles and the solvent of the MF (0.05625), $\langle N\rangle$ is the mean depolarizing factor in the direction of the magnetic field (0.28), C_2 is the constant for normalization, δ is the skin depth (4.02×10^{-8} m), and $\langle a\rangle$ is the mean radius of the magnetic chains. The values in brackets are the parameters for the experiment.

Two main factors determine the agglomeration or dispersion process of the magnetic chains: magnetic attraction and thermal agitation. The former factor means that with increasing magnetic field, more and more magnetic particles agglomerate in the MF while the latter factor means that with increasing temperature, more and more magnetic particles disperse in the MF [21]. In our experiment, the amplitude of the magnetic field remains

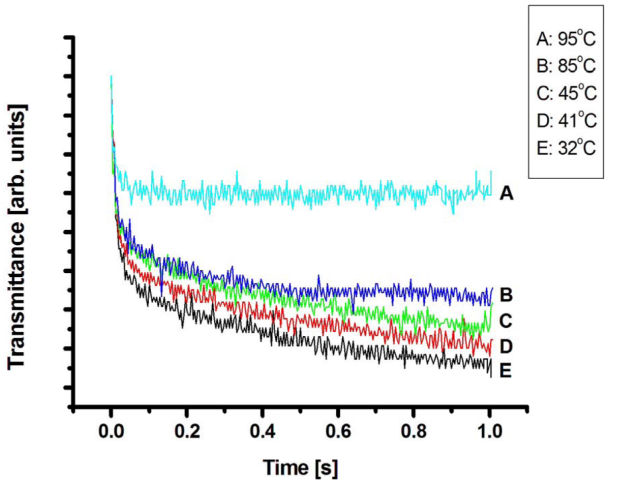

Fig. 2. Transmittance as a function of time for a MF sample under different temperature conditions. The transmittance is the electrical signal at any time divided by the largest electrical signal (at time zero).

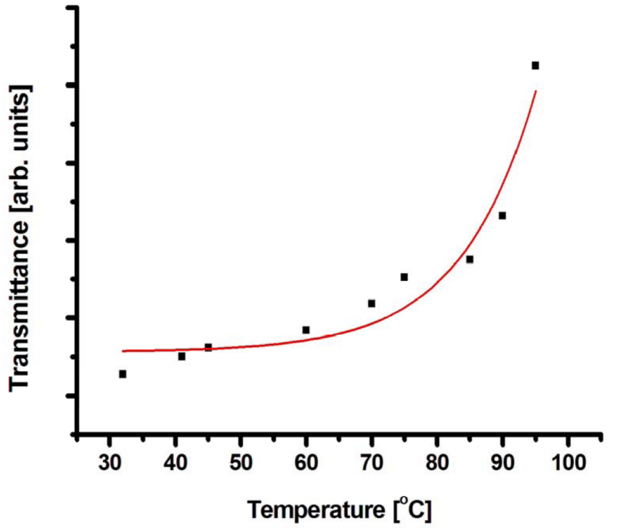

Fig. 3. Exponential growth of the fitted transmittance with temperature. The transmittance is the electrical signal at the half-decay time divided by the largest electrical signal (at time zero).

unchanged while the temperature keeps rising so that the latter factor plays a major role. That is to say, the higher the temperature, the harder it is for magnetic chains to be formed so that the mean radius of the magnetic chains, a, is inverse proportional to the temperature. The mean depolarizing factor in the direction of the magnetic field, N, reflects the shape of the magnetic chains. When there is no magnetic field, all the particles disperse in the carrier liquid randomly so that N is $1/3$, which is the largest value of N. With increasing magnetic field strength, the particles agglomerate to form magnetic chains so that N decreases. In a magnetic field with fixed strength, more particles will disperse into the carrier liquid with increasing temperature, which has been discussed above, so that N increases. Thus, are from Eq. (1) that the combined effect of the mean radius of the magnetic chains, a, and the mean depolarizing factor in the direction of the magnetic field, N, causes the transmittance to increase with increasing temperature. Thus, the transmittance exhibits an exponential growth with the temperature, which matches with the experimental results.

III. CONCLUSION

In conclusion, the effect of thermal agitation is enlarged by rising the temperature when the amplitude of the magnetic field is unchanged, which suppresses the magnetic chains that are formed. Thus, the optical transmission is enlarged. From a theoretical analysis, we see that the transmittance fits an exponential growth with the ambient temperature around the MF, which is in good agreement with the experimental results.

ACKNOWLEDGMENTS

We are grateful to the National Basic Research Program “973” of China (No. 2007CB307000), the National Natural Science Foundation of China (No.10574092).

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