Optical transmittance of ferronematic materials in the visible range

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A kind of ferronematic materials composed of 4-cyano-4'-pentylbiphenyl nematic liquid crystal and oil-based Fe_3O_4 magnetic fluid was prepared by using ultrasonic agitation. The influence of wavelength of incident light, concentration and thickness of samples and externally magnetic field strength on the transmittances of pure magnetic fluids and as-prepared ferronematic materials were obtained. The transmittances of pure magnetic fluids and ferronematic materials increase gradually with the incident wavelength and slightly with the magnetic field, but decreases with the volume fraction of magnetic particle and sample thickness at certain wavelength. For the ferronematic materials, their transmittances also increase with the volume fraction of nematic liquid crystal. The maximum relative enhancement in transmittance is achieved to be around 190% at the wavelength of 500 nm in our experiments.

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1. Introduction

Magnetic fluid (MF) is composed of small single-domain magnetic particles wrapped by a kind of surfactant and dispersed in organic or inorganic carrier liquids [1]. Since the homogeneous MF was fabricated in the 1960s, the methods for fabricating magnetic colloids have been optimized and diversified gradually, which result in better properties of MF due to its improved quality. Meanwhile, many applications based on MF have been implemented in the fields of mechanics, acoustics and optics. And the more fascinating is their successful penetration in the fields of biology and biotechnology, for instance, drug delivery [2, 3], magnetic resonance imaging [4, 5] and thermal dissipative centers in hyperthermia [6]. Some devices have been commercially available. Later, the dramatic development of photonic devices evokes the renewed study of the distinctive optical properties of MF, such as optical transmission [7, 8], thermal lens effect [9, 10], magnetochromatics [11], Mie scattering [12, 13] and Raman effect [14]. Based on these optical properties, many potential applications of MF to photonic devices have been proposed by researchers and some prototype photonic devices have been demonstrated in the laboratory, for instance, MF optical switch [15], MF tunable optical grating [16] and MF coarse wavelength-division multiplexing [17], which implies that MFs are promising optical functional materials with nanostructures.

Nematic liquid crystals are smart materials. The external electrical/magnetic fields and shear stresses can influence the physical properties of nematic liquid crystals considerably. Moreover, it has been observed that many properties of liquid crystals can be improved and enhanced by doping ferromagnetic grains [18-20]. This kind of composites is now called as ferronematic materials and belongs to a class of complex and smart materials, which shows the perspective for a variety of new technological developments.

Ferronematic materials can be obtained by simply mixing MFs and nematic liquid crystals. Few results about the optical transmittance of ferronematic materials have been reported, though the multiple-parameter-dependent optical transmittance of pure MFs has been widely investigated [22-29]. Because optical transmittance has a great impact on the performance and efficiency of the corresponding photonic devices, it is worth researching the optical transmittance of ferronematic materials in detail. In addition, optical transmittance is deeply related to the structure formation within ferronematic materials or MFs under externally applied magnetic field. It is also an effective means to study the agglomeration dynamics of magnetic nanoparticles within the soft materials and is crucial to the photonic applications. This work will experimentally investigate the influence of externally magnetic field strength, wavelength of incident light, sample thickness and concentration on the optical transmittance of pure MFs and as-prepared ferronematic materials.

2. Experimental details

The oil-based Fe_3O_4 MF with volume fraction of 5.62% was provided by Ferrotec Corporation (Chuo-ku, Tokyo, Japan). The 4-cyano-4'-pentylbiphenyl ($C_{18}H_{19}N$) nematic liquid crystal (5CB) was provided by Shijiazhuang Huarui Scientific and Technological Co., Ltd (Shijiazhuang, Hebei, China). To investigate the optical transmittance of MFs with different concentrations of magnetic particles, the MF was diluted with the liquid paraffin carrier (provided by Sinopharm Chemical Reagent Co., Ltd, Shanghai, China) with ultrasonic agitation of about 2 h. The pure MF samples with four different concentrations of magnetic particles are prepared and referred as samples a, b, c and d. Their volume fractions of magnetic particles are 0.47%, 0.52%, 0.57% and 0.62%, respectively, as shown in Table 1.

Table 1. Pure MF samples with different concentrations of magnetic particles.

Sample	a	b	c	d
Volume fraction of magnetic particle	0.47%	0.52%	0.57%	0.62%
Volume ratio of pure MF to liquid paraffin	1 : 11	1 : 9.80	1 : 8.90	1 : 8

To investigate the optical transmittance of ferronematic materials with different concentrations of magnetic particles, one milliliter of 5CB and four milliliters of any one of sample a, b, c or d are mixed to obtain samples a-5CB, b-5CB, c-5CB and d-5CB, respectively. The volume fractions of 5CB of these samples are the same (20.00%). The volume fractions of magnetic particles for samples a-5CB, b-5CB, c-5CB and d-5CB are 0.37%, 0.42%, 0.45% and 0.50%, respectively, as shown in Table 2.

Table 2. Concentrations of samples a-5CB, b-5CB, c-5CB and d-5CB.

Sample	a-5CB	b-5CB	c-5CB	d-5CB
Volume fraction of magnetic particle	0.37%	0.42%	0.45%	0.50%
Volume fraction of 5CB	20.00%	20.00%	20.00%	20.00%
Volume ratio of samples a, b, c or d to 5CB	4:1	4:1	4:1	4:1

Similarly, a series of samples with constant concentration of magnetic particle and different concentrations of 5CB are prepared and shown in Table 3. They are denoted as samples MF-5CB, MF-5CB(2), MF-5CB(3) and MF-5CB(4). The volume fraction of magnetic particle is fixed at 0.47%. Their volume fractions of 5CB are 10.00%, 12.52%, 14.29% and 16.72%, respectively.

Table 3. Concentrations of samples MF-5CB, MF-5CB(2), MF-5CB(3) and MF-5CB(4).

Sample	MF-5CB	MF-5CB(2)	MF-5CB(3)	MF-5CB(4)
Volume fraction of magnetic particle	0.47%	0.47%	0.47%	0.47%
Volume fraction of 5CB	10.00%	12.52%	14.29%	16.72%

The ferronematic materials and MFs were injected into the rectangular glass cells with different thicknesses to form the experimental samples. The experimental setup used for measuring the transmittance of the samples was schematically illustrated in Fig. 1. An illuminator emitting visible light was employed as the white light source. A pair of solenoids was used to provide a magnetic field perpendicular to the surface of the sample film. The strength of magnetic field can be adjusted by varying the magnitude of the supply current. The propagation direction of the incident light was parallel to the applied magnetic field. Because the incident light is unpolarized, the Faraday effect can be neglected. The optical transmittance spectrums were measured by a grating spectrometer. During the experiments, the ambient temperature was kept at 22 ºC.

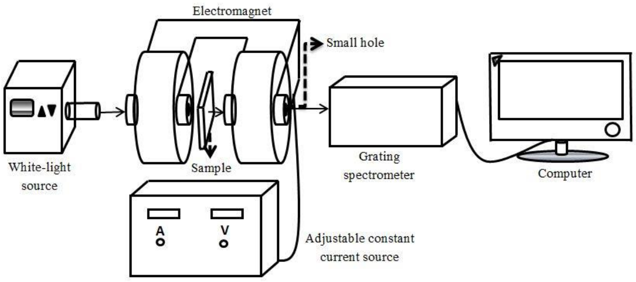

Fig. 1. Schematic of the experimental setup for measuring the transmittance of pure MFs and ferronematic materials.

3. Results and discussion

Fig. 2 shows the transmittance of pure MFs with different magnetic particle concentrations at zero magnetic fields as a function of incident wavelength in the visible range. From Fig. 2, we can see that the transmittances of samples a to d increase gradually with the incident wavelength. Besides, the sample with high volume fraction of magnetic particle has low transmittance under the same wavelength. These are due to the increased scattering and absorption for the high concentration sample.

Fig. 2 also indicates that the wavelength- and magnetic-particle-concentration dependent transmittances for the ferronematic samples (samples a-5CB, b-5CB, c-5CB and d-5CB) are very similar to those of the pure MF samples. In addition, the transmittance of the ferronematic samples is higher than those of the corresponding pure MF samples. This is probably assigned to the decrease of magnetic particle concentration through doping 5CB. Then, the effect of scattering and absorption decreases.

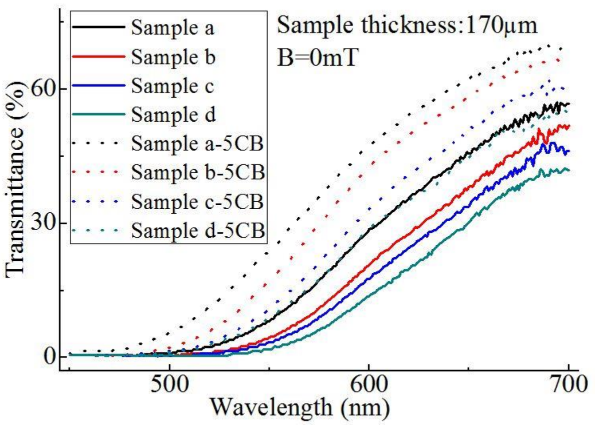

Fig. 2. Transmittance of pure MFs and ferronematic materials as a function of incident wavelength in the visible range.

To further investigate the influence of 5CB concentration on the transmittance of ferronematic samples, the transmittance of samples MF-5CB, MF-5CB(2), MF-5CB(3) and MF-5CB(4) are also measured and the experimental results are shown in Fig. 3. From Fig. 3, we can see that the transmittance of samples MF-5CB to MF-5CB(4) increases gradually with the incident wavelength. Moreover, the samples with high volume fractions of 5CB have high transmittance under the same wavelength. Table 3 shows that all the ferronematic samples have the same volume fraction of magnetic particles (0.47%) but have different 5CB volume fractions. This indicates that the increase of the 5CB concentration decreases the scattering and absorption of the ferronematic samples.

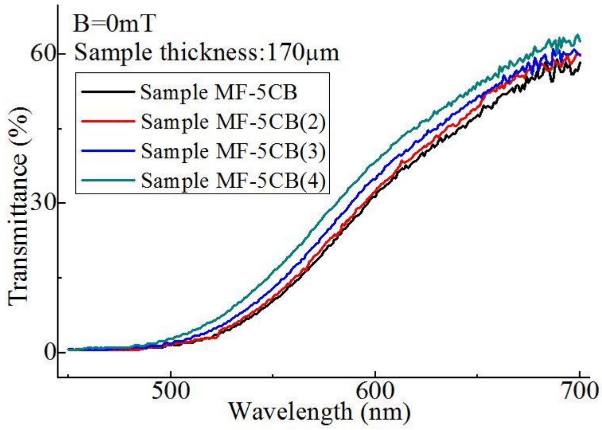

Fig. 3. Transmittance of ferronematic samples with fixed magnetic particle volume fraction and different volume fractions of 5CB as a function of incident wavelength in the visible range.

To quantify the enhanced optical properties, the relative enhancement of transmittance is defined as $T_R = \left[T_{MF+5CB(i)} - T_a\right] / T_a \times 100$. Herein, $T_{MF+5CB(i)}$ and T_a are the transmittance under certain wavelength for samples MF-5CB to MF-5CB(4) and sample a (all of these samples have the same volume fraction of magnetic particle, i.e. 0.47%, but different concentrations of 5CB), respectively. T_R as a function of incident wavelength in the visible range is calculated and plotted in Fig. 4. From Fig. 4, we can see that T_R increases at first and then decreases with the wavelength of the incident light. The maximum T_R occurs around wavelength of 500 nm. Comparing with the transmittance of sample a, the relative enhancement of transmittance of the ferronematic samples MF-5CB to MF-5CB(4) can reach about 190%.

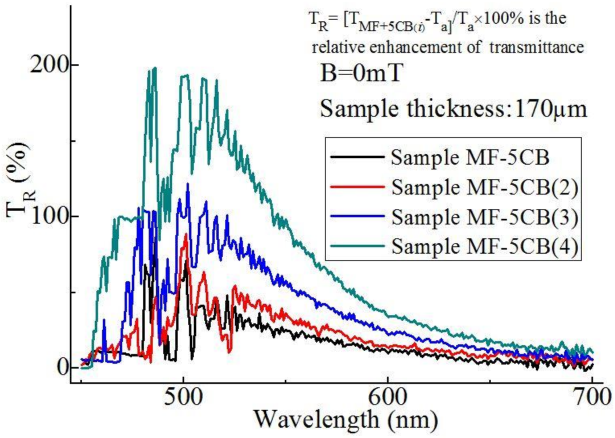

Fig. 4. Relative enhancement of transmittance of ferronematic samples with fixed magnetic particle volume fraction and different volume fractions of 5CB as a function of incident wavelength in the visible range.

Transmittance of samples a and MF-5CB with different thicknesses as a function of incident wavelength at zero magnetic field are shown in Fig. 5. From Fig. 5, we can see that thick samples have low transmittance at certain wavelength for both types of materials (samples a and MF-5CB). This is attributed to the elongation of traveling path as the light passes the films.

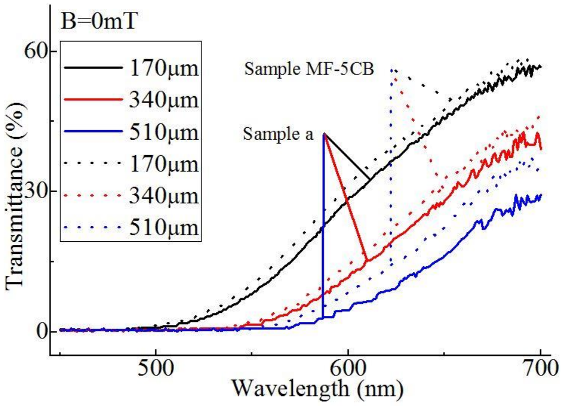

Fig. 5. Transmittance of samples a and MF-5CB with different thicknesses as a function of incident wavelength in the visible range.

To further investigate the influence of magnetic field on the transmittance of ferronematic samples, the transmittance of samples a, MF-5CB and MF-5CB(4) at different magnetic fields are measured and shown in Fig. 6. Fig. 6 indicates that the wavelength-dependent transmittance of the samples at certain magnetic fields is very similar to those of the samples at zero magnetic field. Besides, the transmittance slightly increases with the applied magnetic field at certain wavelength. Application of external magnetic field will induce magnetic particles aggregation, which will form columns elongated along the external magnetic field within MF and ferronematic samples that confined between two glass plates. This results in the reduction of area covered by the magnetic particles across the cross-section (perpendicular to the propagation of the incident light). Therefore, the increase of transmittance with magnetic field is due to the geometrical shadowing effect [30].

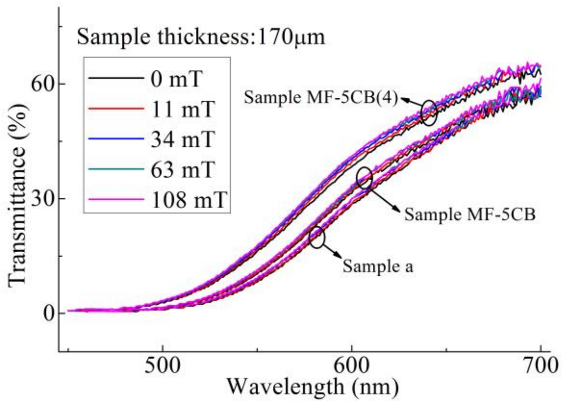

Fig. 6. Transmittance of samples a, MF-5CB and MF-5CB(4) at different magnetic fields as a function of incident wavelength in the visible range.

4. Conclusions

The optical transmittance of pure MF and ferronematic thin films as a function of incident wavelength in the visible range are investigated. The transmittances of pure MF and ferronematic samples increase gradually with the incident wavelength and decrease with the magnetic particle concentrations and thicknesses of the samples. Moreover, the transmittances of both kinds of samples increase slightly with the magnetic field strength at certain wavelength. For the ferronematic materials, the sample with high volume fraction of 5CB has a relatively high transmittance. The maximum relative enhancement of transmittance of our experimental samples is obtained to be around 190% at the wavelength for 500 nm.

Acknowledgments

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