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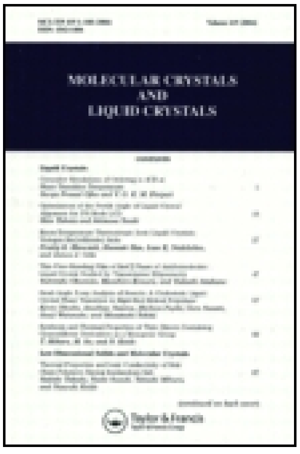

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Multiple Light Scattering from Polymer-Dispersed Liquid Crystals

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MULTIPLE LIGHT SCATTERING FROM POLYMER-DISPERSED LIQUID CRYSTALS

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Abstract Measurements and Monte Carlo simulations of the angular distribution of light scattered from wedge-shaped Polymer-Dispersed Liquid Crystals (PDLCs) are reported. The simulation model is based on two length scales: the scattering mean free path and the transport mean free path. The simulation reproduces the experimental angular distribution of multiply scattered light as a function of sample thickness if the angular distribution in each scattering event is taken as a Mie distribution or as a Lorentzian in the cosine of the scattering angle. The experimental parameters are in the intermediate range where models based on either single or diffusive scattering do not apply.

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INTRODUCTION

Žumer and Doane[1,2] were the first to model light scattering from Polymer-Dispersed Liquid Crystals (PDLCs). Their single scattering theories have been compared successfully with experiments on PDLCs containing low volume fractions of liquid crystal (LC). PDLCs of practical interest, however, often contain high contents of LC, so that multiple scattering must be taken into account[3,4]. If one wants to model such systems, one has to resort to a simpler description of the scattering events. A model of this type which applies to scattering near the forward direction, has been proposed by Kelly and Wu[4]. Here we report a scattering model that is applicable to all scattering angles and all values of the cell thickness d. For large values of d, we recover diffusive transport of light. Our experiments on PDLCs of display interest can neither be described by single scattering nor by diffusive scattering. We will show that our simulation model provides an accurate description of the light-scattering behavior. The model contains two length scales: the scattering mean free path ℓ_{scat}, which is a measure for the extinction of the beam, and the transport mean free path,

$$\ell_{trans} = \ell_{scat}/(1 - \langle\cos\beta\rangle) \tag{1}$$

where β is the scattering angle in a scattering event; ℓ_{trans} describes the distance a photon travels before the memory of its original direction is lost.

EXPERIMENTAL

PDLC samples have been prepared by radiation curing of a mixture of 80% TL205 and 20% PN393 (Merck Ltd). The curing dose was 13 mW/cm^2; the curing wavelength was 365 nm. Two wedges have been prepared: wedge A, cured at 25°, and wedge B, cured at 15°C. Different curing temperatures yield different scattering characteristics (see Figs. 1 and 2). The wedge shape allowed the study of scattering properties as a function of cell

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thickness.

The samples are illuminated by a perpendicular collimated beam, having a divergence of $\pm 0.5°$. The beam diameter at the measuring spot is 1.5 mm. The angular distribution of the light scattered from the center of the illuminated area is determined by a measuring microscope rotating around the measuring spot. The field of view of the microscope at the measuring position is a disk perpendicular to the optical axis of the detection unit, with a diameter of 0.25 mm. The collection half-angle, θ_0, of the detection system which samples the scattering distribution, is adjusted to $\theta_0 = 1°$ for the measurements of the angular dependence. For contrast measurements, the divergence of the incoming beam was $\pm 1°$ and the transmittance within a collection half-angle $\theta_0 = 2.6°$ around the forward direction was measured.

SIMULATION MODEL

In the simulation, scattering of light is modeled as scattering of typically 10,000,000 particles, commonly called photons. Similar models have been published before[4,5]. The distance between scattering events is taken randomly from an exponential distribution characterized by a scattering mean free path ℓ_{scat}. The value of ℓ_{scat} is obtained from an independent measurement of the direct transmission (see Fig. 1a). The scattering distribution in a scattering event is taken to be a Lorentzian function of $(1 - \cos\beta)$:

$$L(1 - \cos\beta) \propto 1/[1 + a^2(1 - \cos\beta)^2] \ , \tag{2}$$

or a Gaussian in the scattering angle β, $G(\beta) \propto \exp(-b^2\beta^2)$. The parameters a and b are found straightforwardly from the value of $\langle\cos\beta\rangle$, which must be such that the simulation results fit the experiment in the diffusion regime. As an alternative we used a Mie[6] scattering distribution which is very close to the Lorentzian.

RESULTS

A comparison between experiment and simulation is given in Figs. 1 and 2. In Fig. 1a the exponential decay of the direct transmittance with cell thickness is plotted for the two wedges. The scattering mean free paths that have been used in the simulations are the decay lengths found from this figure. In Fig. 1b we plot the contrast, which is the ratio of the transmittance in the transparent state and in the scattering state within a collection half-angle of 5.2 °. Scattering in the transparent state was negligible. In Fig. 2 the scattering distribution is given for a few values of the sample thickness. Figs. 1b and 2 show the good fit between the results from the experiment and the simulation.

This agreement over the whole range of measured thickness values is obtained by using a Lorentzian in $(1 - \cos\beta)$ (see eq. 2) as the angular distribution in each simulated scattering event. Although a Gaussian function of β may be made to fit either for $d \approx \ell_{scat}$ (where the external scattering distribution is dominated by the small-angle scattering in the scattering events) or for $d \gg \ell_{trans}$ (where only ℓ_{trans} is of importance) it cannot be made to fit for the entire d range. This is explained in Fig. 3. A Mie function for spheres of 2 μm with a refractive index that is 0.13 higher than the refractive index of the medium is very close to the Lorentzian. Preliminary microscopy data[7] show that the size of the droplets in similar samples is indeed 2-3 μm. The Mie interpretation of our light scattering experiments suggests a volume fraction of spheres of 40 %. In the experiment, the droplet concentration is much higher (roughly 80 %). The effective values that arise

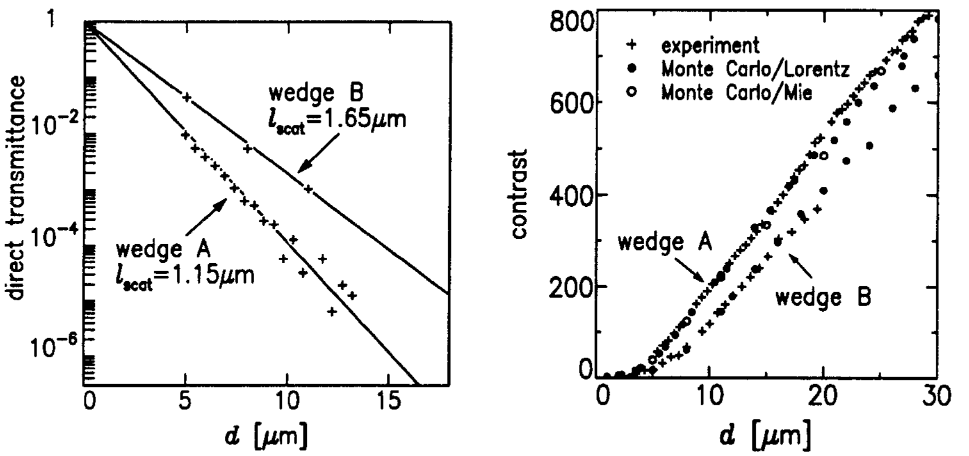

FIGURE 1 Transmittance of unscattered light (Fig. 1a) and contrast (Fig. 1b) as a function of cell thickness for wedges A and B. In the diffusion regime ($d > 50\mu m$) no experimental data are available.

from a multiple Mie scattering simulation express the fact that inter-droplet scattering is modeled as scattering between droplets and an effective medium. Comparisons of this type should be considered with caution: at or near the droplet border the director need not change abruptly and within the droplets complicated director patterns may exist. The relevant light scattering parameters are ℓ_{scat} and ℓ_{trans}. The relation of these parameters with the morphology is useful and must be explored further, but it is of a qualitative nature.

CONCLUSION

The good fits in Figs. 1b and 2 show that a simple simulation model is successful in describing multiple scattering in PDLCs. The simulation may easily be extended to include any specific features of actual devices.

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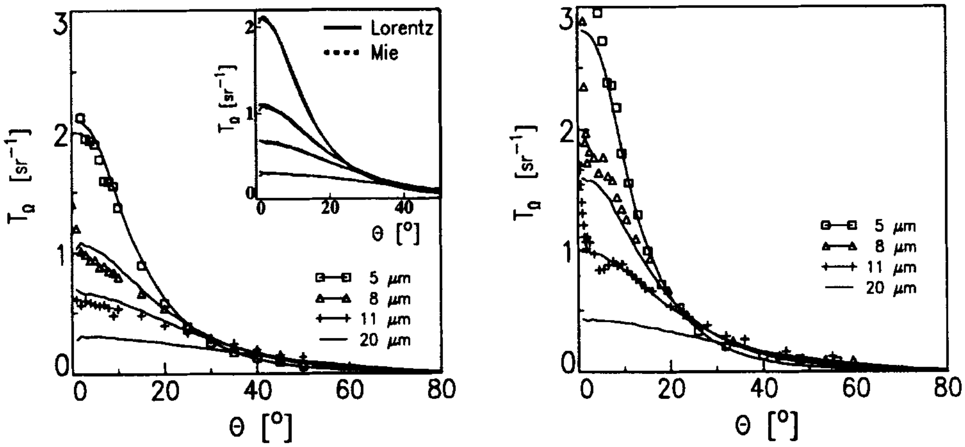

FIGURE 2 Angular distribution of scattered light: the transmittance per solid angle as a function of scattering angle for various values of sample thickness for wedges A (2a) and B (2b). In the inset we compare the scattering distribution of the cell for simulations using a Lorentzian and a Mie distribution in each scattering event. Direct transmission is included in the experimental data, but not in the simulation results.

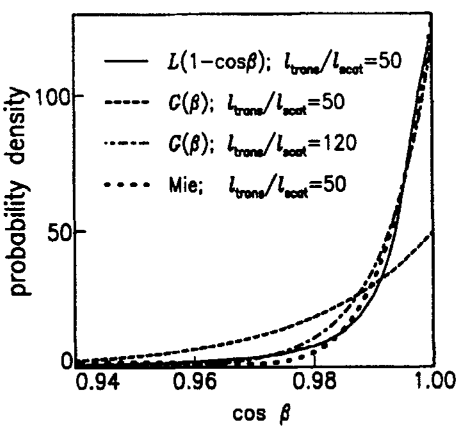

FIGURE 3 Probability distribution of scattered light as a function of scattering angle β in a scattering event, normalized such that the integral over $\cos\beta$ yields unity. A Gaussian function deviates strongly from the Lorentzian of eq. 2 or the Mie distribution described in the text, if these distributions have the same value of ℓ_{trans}/ℓ_{scat} (or of $\langle\cos\beta\rangle$).

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