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SMALL-ANGLE LIGHT SCATTERING BY MONOLAYER OF LIQUID CRYSTAL DROPLETS IN POLYMER MATRIX

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ABSTRACT. A method for modeling the angular distribution of light scattered by a monolayer of liquid crystal droplets dispersed in polymer matrix is developed. It is based on the anomalous diffraction and interference approximations.

1. Introduction

Polymer dispersed liquid crystal (PDLC) films are composite materials consisting of liquid-crystal droplets dispersed in a solid polymer matrix. They are used as light modulators for photonics and optoelectronics applications. Controlled light scattering from liquid crystal (LC) materials is achieved by using electrically, magnetically, or thermally induced change in director orientation and molecular configuration to manipulate their optical properties[1,2]. Since liquid crystals are optically anisotropic materials, scattering problems are more difficult to solve for single LC droplets and droplet arrays as compared to optically isotropic particles. For this reason, solutions are generally obtained by approximate methods. Typically scattering by single anisotropic LC droplet is under consideration [2]. The known methods do not take into account ordering of droplets in the polymer film conditioned by their high concentration.

We propose a method for analyzing the angular distribution of light scattered forward by a single-layer PDLC film (monolayer) with droplet size larger than the light wavelength in the polymer matrix. The method is based on anomalous diffraction approximation and an interference approximation, which takes into account cooperative scattering effects for an ensemble of anisotropic LC droplets. We examine the intensities of the forward-scattered light components polarized parallel (vv) and perpendicular (vh) to the polarization of a linearly polarized plane wave normally incident on a PDLC film. A single layer of spherical LC droplets with cylindrical symmetry is considered. The internal structure of the droplets and their orientation in the layer are modeled by using a hierarchy of scalar and tensor order parameters [2,3], which substantially simplifies solution of direct and inverse scattering problems.

2. Basic relations

Let a PDLC monolayer be illuminated by a normally incident linearly polarized plane wave. The laboratory coordinate system xyz is defined by the incident polarization (x axis), the incident wave propagation direction (z axis), and the film plane (xy). Here we consider monolayers of large droplets. Ordinary refractive index of liquid-crystal and refractive index of polymer are nearly equal. Typical value of birefringence is about 0.2 [2]. Under these conditions, multiple scattering is negligible, and we can use interference approximation which takes into account the far-field interference of waves scattered by the droplets. The multiple-scattering contribution decreases with increasing droplet size as more light is scattered forward. Taking into account the far-field interference of waves scattered by the droplets, we write expressions for the intensities of the vv - and vh - components of the incoherent (diffuse) light transmitted through the film as follows:

$$I_{inc}^{vv} = \frac{E_i^2 N}{k^2 R^2} \sum_{l=1}^{m} P - l |f_l^{vv}(\mathbf{k}_s)|^2 + \frac{E_i^2 N}{k^2 R^2} \sum_{l,l'=1}^{m} P_l P_{l'} f_l^{vv}(\mathbf{k}_s) f_{l'}^{vv*} \big(S_{ll'}(\mathbf{k}_s) - 1\big) \ , \quad (1)$$

$$I_{inc}^{vh} = \frac{E_i^2 N}{k^2 R^2} \sum_{l=1}^{m} P - l |f_l^{vh}(\mathbf{k}_s)|^2 + \frac{E_i^2 N}{k^2 R^2} \sum_{l,l'=1}^{m} P_l P_{l'} f_l^{vh}(\mathbf{k}_s) f_{l'}^{vh*} \big(S_{ll'}(\mathbf{k}_s) - 1\big) \ . \quad (2)$$

Here R is distance to the observation point, $\mathbf{k}_s$ is the scattering vector of the scattering wave, N is the number of droplets within the illuminated area A, $S_{ll'}(\mathbf{k}_s)$ are the partial structure factors:

$$S_{ll'}(\mathbf{k}_s) = 1 + \Lambda \int_A \big(W_{ll'}(\mathbf{r}) - 1\big) \exp\left(i\mathbf{k}_s \cdot \mathbf{r}\right) d\mathbf{r} \ . \quad (3)$$

In the expressions above, E_i is the incident wave amplitude; k is the wavevector magnitude in the polymer; subscripts l and l' refer to LC droplet types that differ in terms of shape, size, internal structure, etc.; m is the number of distinct LC droplet types; P_l, $P_{l'}$ denote the partial surface concentrations of droplets of types l and l; Λ is the mean surface concentration of LC droplets; the pair distribution function $W_{ll'}(\mathbf{r})$ is the probability that droplets of types l and l' are separated by the relative position vector $\mathbf{r}$ in the xy plane; $f_l^{vv}(\mathbf{k}_s)$ and $f_l^{vh}(\mathbf{k}_s)$ are the vv and vh components of the scattering matrix in the $\mathbf{k}_s$ direction for LC droplets of type l; and the asterisk denotes the complex conjugate. According to expressions (1)(3), to analyze the angular distribution of scattered light, the scattering-matrix components $f_l^{vv}(\mathbf{k}_s)$ and $f_l^{vh}(\mathbf{k}_s)$ should be determined by solving the scattering problem for single LC droplets, and the partial structure factors $S_{ll'}(\mathbf{k}_s)$ should be found by calculating the pair distribution functions $W_{ll'}(\mathbf{r})$. General solution of these problems is a formidable task because of the complexity of external effects on the molecular configuration inside LC droplet. Consequently, the solutions to inverse scattering problems are also difficult to find. This motivates the use of approximate methods to obtain simplified solutions relating the angular distribution of light scattered by a PDLC monolayer to the orientational structure of the layer. We suppose that the droplet directors are preferentially aligned, within a cone, along a certain average direction.

To analyze the angular distribution of scattered light, we use an effective-medium approximation [2,3]. At this approach the effective ordinary n_{do} and extraordinary n_{de} refractive indices of the droplets are used. In the case of nematic droplets with moving poles, we found that

$$n_{do} = \frac{2n_o + n_e}{3} - \frac{1}{3}\Delta n S_d \ , \tag{4}$$

$$n_{de} = \frac{2n_o + n_e}{3} + \frac{1}{3}\Delta n S_d (1 - 2S_{fz}) \ . \tag{5}$$

Here $\Delta n = n_e - n_o$, n_e and n_o are the extraordinary and ordinary refractive indices of the LC, S_d is the scalar order parameter of droplets, S_{fz} is the z component of the tensor order parameter of the PDLC film.

At numerical simulation we consider a monolayer of identical nematic LC droplets with uniform distribution of their directors within a solid angle $\Delta\Omega$. The results for dependence of forward-scattered intensity distribution on the filling fraction, the droplet order parameter, and the droplet radius are obtained. For example, it is shown that the small variation of the order parameter S_d may cause a drastic change in the vh component of scattered light. The highest sensitivity to the molecular configuration in droplets is observed in the neighborhood of order parameter of droplet $S_d = 0$.

3. Conclusion

A method is developed for modeling and computing the angular distribution of light scattered forward by a single-layer polymer dispersed liquid crystal film. The obtained results show the dependence of the distribution of the scattered light on the droplet concentration, size, and the droplet and film order parameters.

The method provides a tool for examining the liquid-crystal droplet configuration. It can be used to study field- and temperature-induced phase transitions in LC droplets with cylindrical symmetry (bipolar, axial, and etc) by analyzing the angular distribution of forward-scattered light. The results can be applied in developing various devices (for example, amplitude and phase modulators, polarization converters, displays, etc.), with response due to changes in the LC configuration caused by the external factors.

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