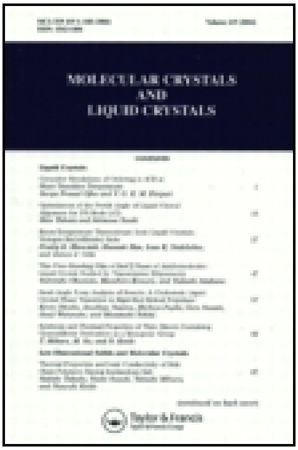

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Polarization independent phase modulation by a film with nano-sized droplets of liquid crystal

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POLARIZATION INDEPENDENT PHASE MODULATION BY A FILM WITH NANO-SIZED DROPLETS OF LIQUID CRYSTAL

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On the basis of the Foldy-Twersky integral equation in the Rayleigh approximation the analytical expression for polarization independent phase shift in polymer dispersed liquid crystal films with nano-sized liquid crystal droplets is obtained. A fair good agreement between theory and experimental data is finally established.

Keywords: liquid crystal dispersion; nematic; phase modulation

1. INTRODUCTION

Polymer dispersed liquid crystal (PDLC) materials are applied to produce electrooptical devices with controlled optical characteristics [1,2]. They consist of liquid crystal droplets (LC) embedded in a polymer matrix sandwiched between two glass or plastic transparent plates covered with transparent electrodes. The PDLC films with fine (nano-sized) droplets are promising materials for the development of the polarization-independent phase modulators of light [3]. These films are of great interest for various applications, in particular, for telecommunication systems [3,4]. This paper considers a method to relate morphological characteristics of a PDLC film

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including nano-sized liquid crystal domains with the optical phase shift of the transmitted wave and the final relation itself. The method is based on the Foldy- Twersky integral equation to describe light transfer through a layer. The scattering characteristics by a single liquid crystal droplet were found in the Rayleigh approximation to give an expression to calculate the dependence of the optical phase shift on the applied voltage. Finally the comparison with experiments is carried out and a satisfactory agreement with the obtained data is found.

2. BASIC EQUATIONS

Consider a film with nano-sized liquid crystal droplets. Let us assume that the film is illuminated by a plane wave normally to the film surface. The configuration of LC molecules inside each droplet is considered to have a cylindrical symmetry. Orientation of the droplet directors is random when there is no applied field. Applied field reorients the directors towards its direction if a LC has a positive anisotropy. In a strong field all droplet directors are aligned in the same direction parallel to the film normal. For oriented droplet directors the cylindrical symmetry axis corresponds to the direction of the applied field. Under these conditions, the problem on the propagation of the coherent field component [5] is reduced to a scalar case. The extinction coefficient and phase of the transmitted wave will not depend on the polarization state of the incident wave.

The coherent transmitted field $\langle E \rangle$ can be found from the Foldy-Twersky integral equation [5]

$$\langle E \rangle = E_0 \psi(z)/_{z=l}, \tag{1a}$$

$$\psi(z) = \exp(ikz)\left\{1 - q\langle S(0)\rangle \int_0^z \exp(-ikz_s)\psi(z_s)dz_s\right\}, \tag{1b}$$

where E_0 is the amplitude of the incident wave (E_0 is a real quantity for linearly polarized light, and a complex one for elliptical polarized light); $\psi(z)$ is the coherent light field inside a film at the depth z for the unit amplitude of the incident wave; l is the film thickness; $q = 2\pi k^{-2} N_v$, N_v is the number of LC droplets per unit volume; $k = 2\pi/\lambda_p$, λ_p is the wavelength of the incident light in the polymer matrix; and $\langle S(0)\rangle$ is the amplitude scattering function [6] at zero scattering angle averaged over droplet sizes and orientations of their directors.

By solving equation (1b), we can find

$$\langle E \rangle = E_0 \exp(iKl), \tag{2a}$$

$$K = k + iq\langle S(0)\rangle, \tag{2b}$$

where K is the effective propagation constant.

From Eqs. (2a) and (2b) it follows that the PDLC film is similar to a homogeneous plate with a complex refractive index $\tilde{n}$:

$$\tilde{n} = \frac{K}{k} = 1 + i\frac{2\pi}{k^3}N_v\langle S(0)\rangle. \tag{3}$$

The complex refractive index $\tilde{n}$ is determined by the averaged scattering function $\langle S(0)\rangle$ at zero scattering angle. Using the Rayleigh approximation we obtained [6,7]:

$$\langle S(0)\rangle = -\frac{ik^3}{4\pi}\langle v\rangle\left[\frac{n_{do}^2}{n_p^2} - 1 + \frac{n_{de}^2 - n_{do}^2}{3n_p^2}(1 - S_f)\right], \tag{4a}$$

where $\langle v\rangle$ is the mean volume of a droplet; S_f is the order parameter of the film [8]; n_p is the refractive index of the polymer; n_{do} and n_{de} are, respectively, the ordinary and extraordinary refractive indices of droplets averaged over the droplet volumes [9]

$$n_{do}^2 = n_{iso}^2 - \frac{1}{3}(n_e^2 - n_o^2)S_d S, \tag{4b}$$

$$n_{de}^2 = n_{iso}^2 + \frac{2}{3}(n_e^2 - n_o^2)S_d S, \tag{4c}$$

$$n_{iso}^2 = \frac{2n_o^2 + n_e^2}{3}. \tag{4d}$$

Here S_d is the droplet order parameter; S is the molecular order parameter [8]; and n_o, n_e are the ordinary and extraordinary refractive indices of the liquid crystal.

The obtained results allow one to analyze extinction and phase modulation of a wave transmitted through the film with fine droplets.

Let us investigate phase change caused by varying orientations of droplet directors in an external applied field. As mentioned above, the phase changes in this case do not depend on the orientation of a polarization vector of the incident wave. We define the polarization independent phase shift $\boldsymbol{\Delta\Phi}$ as the difference between the optical phase for a wave transmitted through the film with and without the applied field. Then:

$$\boldsymbol{\Delta\Phi} = kl[\mathrm{Re}\ \tilde{n}(S_f) - \mathrm{Re}\ \tilde{n}(S_f = 0)]. \tag{5}$$

The film order parameter is $S_f = 0$ without an electric field, whereas $S_f > 0$ while applying the electric field. At high electric field $S_f = 1$.

In view of Eqs. (3), (4a)–(4d), the magnitude $|\Delta\Phi|$ is:

$$|\Delta\Phi| = \frac{1}{6} k l c_v \frac{\left(n_e^2 - n_o^2\right)}{n_p^2} S S_d S_f, \tag{6}$$

where $c_v = N_v \langle v \rangle$ is the volume concentration of droplets in the film.

As a first approximation, we use the following expression for the order parameter [2]

$$S_f = \frac{1}{4} + \frac{3(e^2+1)}{16e^2} + \frac{3(e^2+1)(e^2-1)}{32e^3} \ln\left|\frac{e+1}{e-1}\right|. \tag{7a}$$

$$e = AE, \tag{7b}$$

where e is a reduced field [8], which is proportional to the applied field E, and A is determined by the size and shape of the droplets, the optical anisotropy of LC, and the elastic constants; it weakly depends on the order parameters S, S_d, S_f.

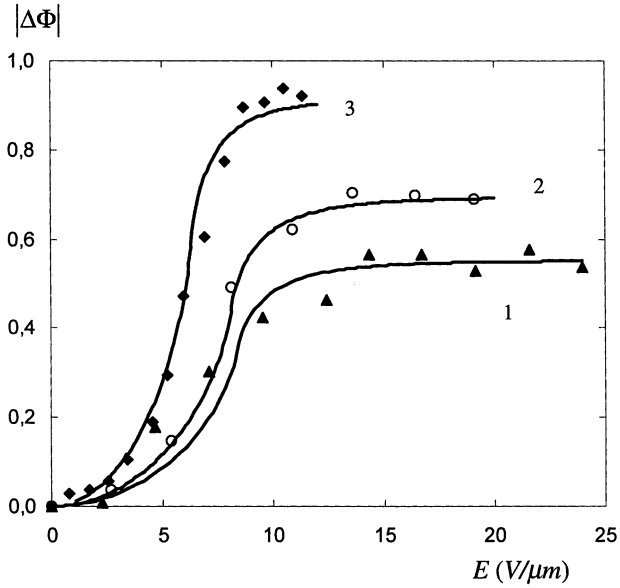

FIGURE 1 Dependence of the phase shift $|\Delta\Phi|$ versus electric field strength E. Theoretical results (curves) and experiments (symbols). $n_o = 1.511$; $n_e = 1.74$; $n_p = 1.524$; $S = 0.6$; $S_d = 0.7$. 1. $l = 13\,\mu m$, $c_v = 0.125$, $A = 0.12\,\mu m/V$; 2. $l = 23\,\mu m$, $c_v = 0.089$, $A = 0.124\,\mu m/V$; 3. $l = 36\,\mu m$, $c_v = 0.075$, $A = 0.16\,\mu m/V$.

3. COMPARISON WITH EXPERIMENT

The calculated dependencies of the phase shift (Eqs. (6, 7)) on the electric field strength E are compared in Figure 1 with the experimental data [10]. The measurements were carried out with a fiber-optic Mach-Zehnder interferometer at laser wavelength $\lambda = 0.6328\,\mu m$. The phase shift was determined by the shift of interference fringes. The experimental details are described elsewhere [11].

Figure 1 shows good agreement of the calculations with experimental data for chosen values of the order parameters. We used typical values for the order parameters $S$and S_d, and fitted c_v and A as free parameters. A more detailed comparison requires an additional information on the morphological and structural properties of the films which are not yet available. However the final result is quite satisfactory.

4. CONCLUSION

On the basis of the Foldy-Twersky integral equations we calculated the optical phase shift induced by a nematic PDLC film with nano-sized droplets. The theoretical results are in good agreement with the experimental data. They can be used to make a more detailed analysis of the dependence of polarization independent phase shift (controlled by an electric field) on the morphological and structural parameters of a film with nano-sized liquid crystal droplets. The developed method can be applied to analyze light extinction, absorption and scattering losses in the films.

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