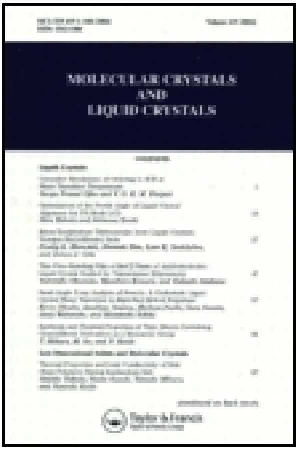

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Phase Modulation of Wave by a Polymer Dispersed Liquid Crystal Film with Nanosized Smectic Droplets: Theoretical Treatment

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The model for propagation of a plane wave through a polymer dispersed liquid crystal film with nanosized droplets of bistable smectic liquid crystal is proposed. The analytical expression for polarization-independent phase shift is obtained and analyzed.

Keywords: composite films; ferroelectric; phase shift

1. INTRODUCTION

The electrooptical properties of polymer dispersed liquid crystals (PDLC) have been the subject of much investigation [1,2]. The PDLC films have attracted interest for large number of applications such as switchable windows, diffraction gratings, optical shutters, displays, telecommunications, etc. In the PDLC films liquid crystal (LC) droplets are embedded in a hard polymer matrix. Under external control field the LC droplet directors (optical axes) are reoriented and different electrooptical effects take place.

The films with micron- and submicron-sized droplets are switched electrically from a light-scattering mode to a transparent one [1]. In the film with nano-sized droplets the scattering is small [3–9]. Such film looks like a homogeneous medium with the averaged refractive index affected by the applied field. At normal illumination the light propagates through the PDLC film regardless of the polarization state.

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In the PDLC film with a fine disperse structure it is possible to obtain polarization-independent phase modulation. For this reason, such films are perspective for innovative optical elements for displays and telecommunications. The PDLC films with nematic LC droplets have millisecond time of switching. To achieve microsecond time of switching, the smectic LC can be used [1,10].

In the paper the PDLC film with cylindrically symmetric structure of bistable smectic LC droplet directors is considered. The polarization independent phase shift is investigated on the basis of the Foldy–Twersky approximation and anisotropic dipole approximation.

2. BASIC EQUATIONS

Let us consider a PDLC film with bistable smectic liquid crystal (SmC*) droplets with homogeneously oriented internal structure of plane-parallel smectic layers [11]. We assume, that the normals n to the smectic layers averaged over the volume of the PDLC film form a cone with angle $2\theta_o$ (Fig. 1). The top of this cone is located at the

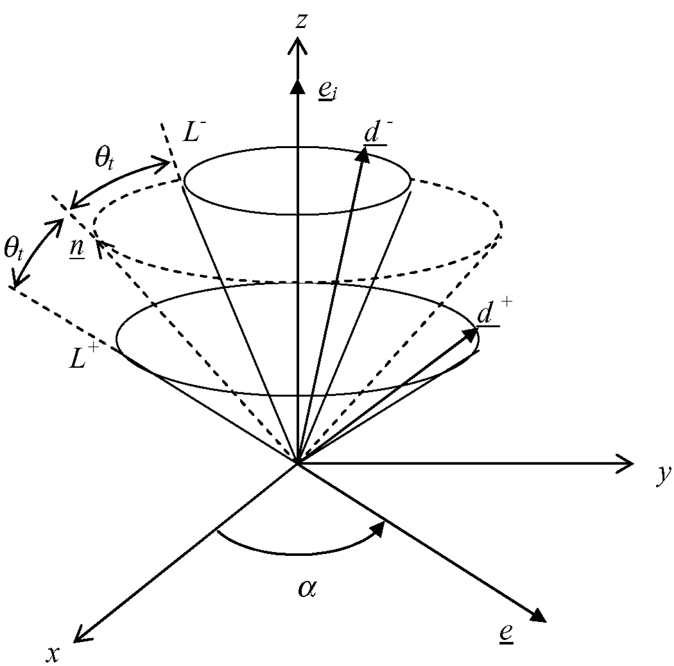

FIGURE 1 Schematic presentation of the director switching in the film. Notations are in the text.

beginning of the laboratory coordinate system (x, y, z). The plane (x, y) coincides with the forward surface of the film, and z-axis coincides with the normal to the PDLC film, e_i is the unit illumination vector, e is the unit polarization vector of the incident wave, and α is the polarization angle (the angle between e_i and x-axis). Under the control field, the orientation of droplet directors in the film is changed. For bistable smectic liquid crystal in the one stable state the directors of droplets d^+ form a cone L^+, and in the other stable state the directors d^- form a cone L^-. The angles between droplets directors in states L^+ and L^- and z-axis equal: $\theta^+ = \theta_o + \theta_t$ and $\theta^- = \theta_o - \theta_t$, respectively. Here θ_t is the tilt angle of the director with the normal to the planes of smectic layers in the droplet. At normal illumination of the PDLC film by the linear polarized plane wave, the problem of determination of transmitted coherent field is described in the frame of a scalar theory [4,12].

To determine the transmitted coherent field $\langle E \rangle$, the Foldy–Twersky approximation is used [4,13]. In this approximation:

$$\langle E \rangle = E_i \exp(ikl) t \exp(-i\Phi). \tag{1}$$

Here E_i is the amplitude of the incident wave; $k = 2\pi/\lambda_p$; λ_p is the wavelength of the incident light in the polymer matrix; l is the film thickness; t is the module of the amplitude transmittance; Φ is the change of the wave phase coursed by the scattering on droplets.

Values t and Φ are determined by the equations:

$$t = \exp(-q\mathrm{Re}\langle S(0)\rangle l), \tag{2}$$

$$\Phi = q\mathrm{Im}\langle S(0)\rangle l. \tag{3}$$

Here $q = 2\pi k^{-2} N_v$, N_v is the number of LC droplets per unit volume; $\langle S(0)\rangle$ is the size- and orientation-averaged amplitude of scattering at zero scattering angle.

If the size of LC droplet is less than the wavelength of the incident light, using an anisotropic dipole approximation we find.

$$\langle S(0)\rangle = -\frac{ik^3\langle v\rangle}{4\pi}\left(\frac{\varepsilon_o}{\varepsilon_p} - 1 + \frac{\Delta\varepsilon}{2\varepsilon_p}\langle \sin^2\theta^{+;-}\rangle\right), \tag{4}$$

where $\langle v\rangle$ is the mean volume of droplets; ε_o is the dielectric constant of the LC for the ordinary wave; ε_e is the dielectric constant of the LC for the extraordinary wave; $\Delta\varepsilon = \varepsilon_e - \varepsilon_o$: ε_p is the dielectric constant of the polymer matrix.

Let us determine the phase shift $\Delta\Phi$ as the difference of wave phases for two stable states L^+ and L^-:

$$\Delta\Phi = \Phi^+ - \Phi^-. \tag{5}$$

In view of equations (3), (4), we write:

$$\Delta\Phi = \frac{1}{4}\frac{\Delta\varepsilon}{\varepsilon_p}klc_v\{\langle\sin^2\theta^-\rangle - \langle\sin^2\theta^+\rangle\}, \quad (6)$$

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

Assuming uniform distribution by the angles θ_o, θ^+, and θ^-, we have:

$$\langle\sin^2\theta^{+;-}\rangle = \frac{1}{2}\left(1 - \cos(2(\theta_o \pm \theta_t))\frac{\sin 2\theta_m}{2\theta_m}\right), \quad (7)$$

where θ_m is the maximum deviation angle. Then

$$\Delta\Phi = -\frac{1}{4}\frac{\Delta\varepsilon}{\varepsilon_p}klc_v\frac{\sin 2\theta_m}{2\theta_m}\sin 2\theta_o \sin 2\theta_t. \quad (8)$$

The minus in equation (8) shows, that at positive optical anisotropy of LC ($\Delta\varepsilon > 0$) the phase velocity at L^+ state is less, than at L^- state. As follows from equation (8), for any chosen values of parameters l, c_v, θ_m, $\Delta\varepsilon$ and ε_p, the maximum values of $|\Delta\Phi|$ is implemented at $\theta_o = \theta_t = 45°$, i.e. at the transition of planar cylindrically symmetric structure of droplet directors to the homeotropic one.

3. RESULTS

The dependence of the module of polarization-independent phase shift $|\Delta\Phi|$ on the angle θ_o at different values of the tilt angle θ_t for smectic LC is presented in Figure 2. The calculations are carried out at the refractive indexes of LC $n_o = 1.524$ ($n_o^2 = \varepsilon_o$) and $n_e = 1.722$ ($n_e^2 = \varepsilon_e$); the polymer refractive index $n_p = n_o$; the wavelength of the incident light $\lambda = 0.6328\,\mu m$; the volume concentration of LC droplets $c_v = 0.075$; the maximum deviation angle of the normals n to the smectic layers $\theta_m = 5°$; the film thickness $l = 20.1\,\mu m$ (in such a case the maximum value $|\Delta\Phi| = 90°$ is achieved at $\theta_o = \theta_t = 45°$). For values $\theta_o = 0°$ and $\theta_o = 90°$ phase shift $|\Delta\Phi|$ is equal to zero, as the states L^+ and L^- at propagation of a plane wave through a PDLC film are physically indiscernible. These results illustrate the sensitivity of $|\Delta\Phi|$ to the change of the tilt angle.

Note that at the chosen parameters of a film and LC, the value of the coherent transmittance T_c is close to unity. The modulation of the coherent transmittance at the mean sizes of LC droplets, varying in the range from 50 nm to 100 nm, does not exceed five percents.

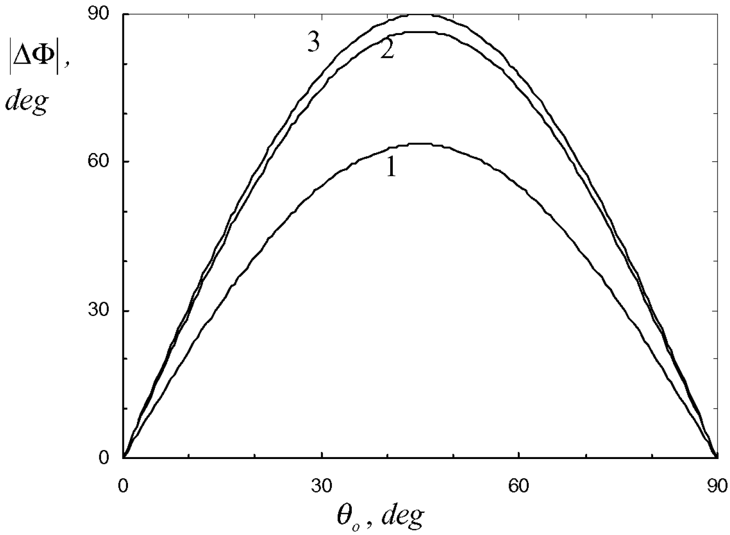

FIGURE 2 Dependence of the module of polarization independent phase shift $|\Delta\Phi|$ on the angle θ_o at different values of the tilt angle $\theta_t \cdot n_p = n_o = 1.524$, $\Delta n = 0.198$, $\lambda = 0.6328\,\mu m$, $l = 20.1\,\mu m$, $c_v = 0.075$, $\theta_m = 5°$, $\theta_t = 22.5°$ (curve 1); $\theta_t = 37°$ (curve 2); $\theta_t = 45°$ (curve 3).

4. CONCLUSION

A model to describe propagation of a coherent field in the PDLC film has been considered. It is based on the Foldy–Twersky integral equation to solve the problem of propagation of a linear polarized wave through such a film with nanosized droplets of bistable smectic liquid crystal. In the framework of this model at the independent scattering regime, the equation for field-controlled phase shift is obtained. This equation can be modified at the implementation of the dependent scattering regime in the film.

The presented results are obtained for smectic liquid crystal droplets. They can be used at development of phase modulators on a base of a PDLC film with nanosized bistable smectic LC droplets for innovative photonic devices.

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