Light modulation by polymer-dispersed liquid crystal films with small nematic droplets

Valery A. Loiko, Alexander V. Konkolovich, and Polina G. Maksimenko

B.I. Stepanov Institute of Physics of the National academy of sciences of Belarus
Nezalezhnasti Avenue 68, 220072, Minsk, Belarus
Tel: +375(17)2842894, fax: +375(17)2840879; e-mail: loiko@dragon.bas-net.by

Abstract

Light propagation through a polymer-dispersed liquid crystal film with nanosized nematic liquid crystal droplets is considered under the Rayleigh-Gans approximation. Multiple light scattering is taken into account by means of the Foldy-Twersky integral equation. Polarization state of the coherent component of the transmitted light is investigated for films with bipolar droplets. Conditions for circular and linear polarization implementation are obtained and discussed. The results are compared with known experimental data.

1 Introduction

Polymer films with encapsulated liquid crystal (LC) droplets are promising materials for various electro-optical devices, where light modulation is required. Typically droplets of submicron-to-micron sizes are used. Recently films with small droplets as compared with the wavelength of incident light have attracted particular attention of researchers. These films possess weak light scattering and enable one to control the polarization and phase of transmitted light in the visible and infrared regions.

A polymer-dispersed liquid crystal (PDLC) film is a polymer film with embedded LC droplets [1]. This film is placed between two transparent plates with deposited transparent electrodes. We consider liquid crystals with positive birefringence and bipolar structure of molecular arrangement inside the droplets [1, 2]. Each droplet is characterized by an axial vector. This vector is commonly called by a droplet director. It determines the direction of the droplet optical axis. Under applied voltage, LC molecules are reoriented to be aligned along the direction of the electric field and the optical axis of a droplet is rotated (an LC droplet is reoriented). Thus one can change optical properties of a PDLC film by varying the applied voltage. Numerous devices, such as light modulators, optical shutters, TV projection systems, displays, colour filters, polarizers, etc., are developed on this principle. No rigorous theory relating parameters of a PDLC film, applied voltage, and characteristics of transmitted light has been developed yet. Researchers deal with models, which are valid for specific kinds of the films. Typically the transmittance of PDLC films is considered [1, 3].

We investigate the polarization state of light transmitted through a PDLC film with nanosized nematic droplets. Particular attention is paid to the conditions providing linear or circular light polarization.

2 Model to describe polarization state

Consider a PDLC film with small nonabsorbing nematic LC droplets randomly distributed in a polymer binder. Let this film be illuminated by a monochromatic linearly polarized plane wave normally to its surface along *z*-axis. The *x*- and *y*-axes are in the plane of the film. The droplet directors are partially oriented along the *x*-axis. The azimuth angles of the droplet directors are uniformly distributed over the interval $[-\varphi_d^{\max}, \varphi_d^{\max}]$.

An important characteristic of a PDLC film is the distribution of LC molecules inside droplets. As mentioned above, each LC droplet is characterized by an axial vector called by the director of a droplet. To describe the alignment of LC molecules, we use order parameters [1], namely *S* is the molecular order parameter of an LC; S_d is the order parameter of a droplet (it describes the alignment of LC molecules inside the droplet); S_x, S_y and S_z are the components of the order parameter tensor of the PDLC film [4]. These components show the orientation degree of droplet directors in the laboratory coordinate system. Light scattering by a single LC droplet is described under the Rayleigh-Gans approximation. Multiple scattering of waves is taken into consideration by means of the Twersky theory [5].

Components $E_{e,o}$ of the coherent transmitted field can be written as follows:

$$E_{e,o} = a_{e,o} \cos \Phi_{e,o} , \tag{1}$$

where $a_{e,\ o}$ are the amplitudes and $\Phi_{e,\ o}$ are the phases of the extraordinary and ordinary waves, respectively. They depend on the PDLC film parameters [4, 6]:

$$a_{e,o} = \exp(-\frac{1}{2}\gamma_{e,o} l)\begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix}, \tag{2}$$

$$\Phi_{e,o} = \frac{klc_v}{2}\left(\frac{2n_o^2 + n_e^2}{3n_p^2} - 1 + \frac{2\left(n_e^2 - n_o^2\right)}{3n_p^2} SS_d S_{x,y} \right). \tag{3}$$

Here $\gamma_{e,\ o}$ are the extraordinary and ordinary extinction indices, respectively; l is the thickness of the film; α is the polarization angle of the incident light; k is the module of the wave vector of the incident light in the polymer; c_v is the volume concentration of the LC in the film; n_e and n_o are the refractive indices of the LC; n_p is the refractive index of the polymer. Using Eqs. (1) - (3), one can investigate characteristics of light transmitted through a PDLC film with small LC droplets.

3 Polarization of transmitted light

Using Eq. (1), we analyze characteristics of polarization states of transmitted light. In general case, light is elliptically polarized. Define ellipticity η as a ratio of the minor semiaxis of the polarization ellipse to the major one and azimuth ξ as the angle between the major semiaxis and x-axis, counted from the x-axis counterclockwise.

$$\eta = \sqrt{\frac{\left(a_e \sin\xi\right)^2 + \left(a_o \cos\xi\right)^2 - a_e a_o \sin 2\xi \cos\Delta\Phi}{\left(a_e \cos\xi\right)^2 + \left(a_o \sin\xi\right)^2 + a_e a_o \sin 2\xi \cos\Delta\Phi}}, \tag{4}$$

$$tg 2\xi = 2\frac{a_e a_o}{a_e^2 - a_o^2}\cos\Delta\Phi . \tag{5}$$

Here $\Delta\Phi$ is the phase shift between the extraordinary and ordinary components:

$$\Delta\Phi = \frac{lkc_v}{3}\frac{\left(n_e^2 - n_o^2\right)}{n_p^2}\frac{\sin\left(2\varphi_d^{\max}\right)}{2\varphi_d^{\max}}\left(1 - S_z\right)SS_d . \tag{6}$$

Consider conditions providing the linear polarization of transmitted light. Light is linearly polarized, when at least one of the following conditions is fulfilled:

i. Polarization angle α is equal to 0 or $\pi/2$. In this case, the transmitted light retains the initial polarization state.
ii. Phase shift $\Delta\Phi$ between extraordinary and ordinary waves is equal to 0. Then the transmitted light is polarized as the incident light as well.

iii. Phase shift $\Delta\Phi$ is equal to π. In this case, the light is linearly polarized. The polarization angle is determined as follows:

$$\xi_{lin} = \operatorname{atan}\left(\exp\left(\frac{-k^3}{8\pi\langle V\rangle} g\left(\frac{2n_o^2 + n_e^2 - \left(n_e^2 - n_o^2\right)SS_d}{3n_p^2} - 1 + \frac{2\pi\varphi_d^{\max}}{lkc_v \sin\left(2\varphi_d^{\max}\right)}\right)\right)\tan^{-1}\alpha\right) + \frac{\pi}{2}. \quad (7)$$

Here $\langle V\rangle$ is the mean volume of LC droplets; g is the function determined by the droplet shape, size, and configuration of LC molecules inside the droplet [4]. Function g can be calculated analytically for several special cases, but in general it should be computed numerically. To simplify the problem, we assume that the LC droplets are of spherical shape. In the case of very small LC droplets, angle ξ_{lin} linearly depends on angle α ($\xi_{lin} = \pi - \alpha$).

The dependence of angle ξ_{lin} on mean droplets radius $\langle R\rangle$ and polarization angle α is shown in Fig. 1.

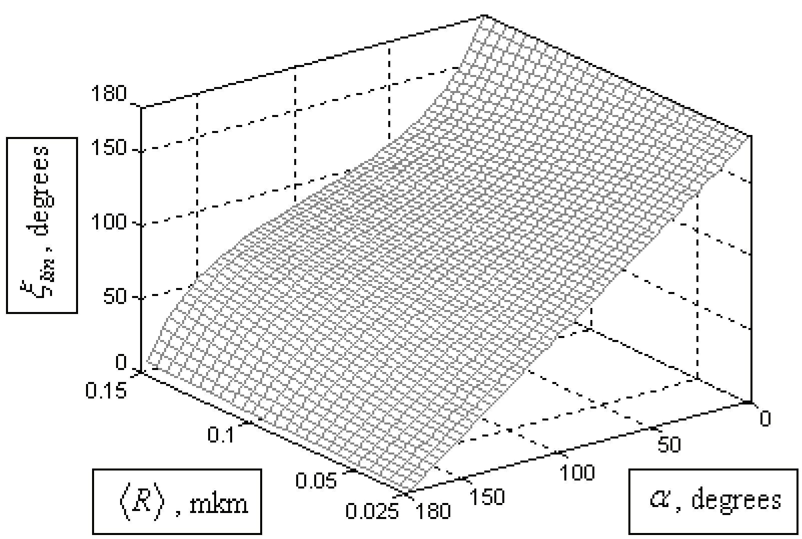

Figure 1: Polarization angle ξ_{lin} of transmitted light vs mean radius $\langle R\rangle$ of LC droplets and polarization angle α of incident light.

Now consider conditions providing the circular polarization of transmitted light ($\eta = 1$). The solution of Eq. (4) shows that the transmitted light is circularly polarized if phase shift $\Delta\Phi = \pi/2$ and the incident light is polarized at the angle:

$$\alpha_{circ} = \arctan\left(\exp\left(\frac{-k^3}{16\pi\langle V\rangle} g\left(\frac{2n_o^2 + n_e^2 - \left(n_e^2 - n_o^2\right)SS_d}{3n_p^2} - 1 + \frac{\pi\varphi_d^{\max}}{lkc_v \sin\left(2\varphi_d^{\max}\right)}\right)\right)\right). \quad (8)$$

Polarization angle $\alpha'_{circ} = \pi - \alpha_{circ}$ also provides circular light polarization. Figure 2 illustrates the dependence of the ellipticity on polarization angle α and on the strength of electric field E applied to the film. There are two polarization angles for each mean radius, when the ellipticity equals to unity. The ellipticity peaks correspond to the strength of the electric field, at which the condition of $\Delta\Phi = \pi/2$ is implemented. The mean radius of LC droplets can be estimated by the polarization angles.

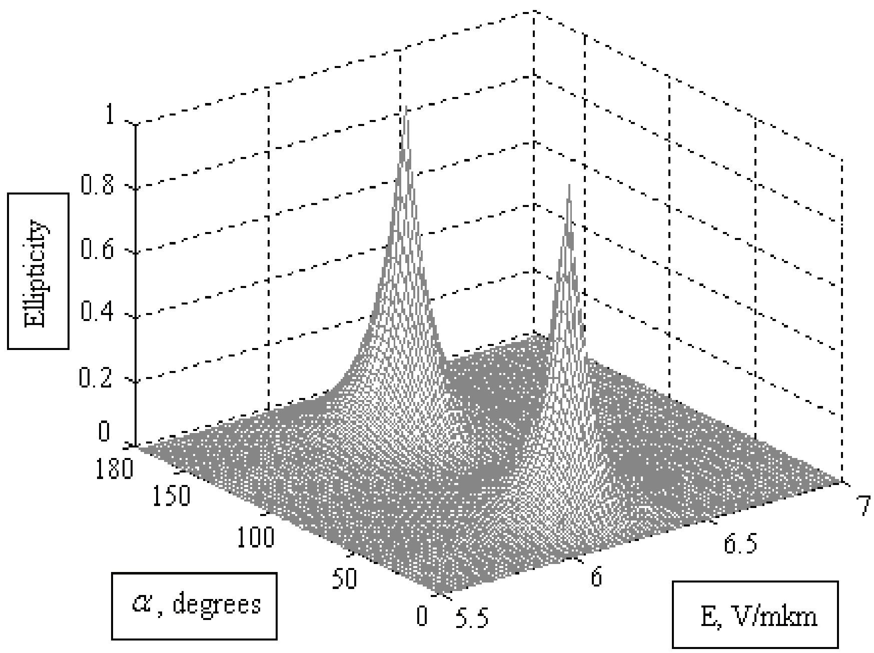

Figure 2: Ellipticity η vs polarization angle α of incident light and strength E of applied electric field.

4 Conclusion

The model to describe polarization state of light transmitted through a PDLC film with nanosized bipolar LC droplets is developed. Polarization characteristics of transmitted light are analyzed. The conditions providing circular and linear polarization of transmitted light are derived and investigated. The results can be used to estimate the mean radius of fine LC droplets in the film. There is a reasonable agreement between the theoretical data and the known experimental results.

References

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