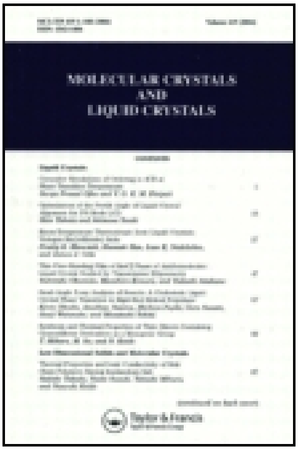

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Propagation of Polarized Light Through the Pdflc Monolayer

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Propagation of Polarized Light through the PDFLC Monolayer

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On the basis of the amplitude-phase screen model an analytical expression for the coherent transmittance of the polymer-dispersed ferroelectric liquid crystal (PDFLC) monolayer normally illuminated by linearly polarized plane wave has been obtained. Within the framework of the anomalous diffraction approach the conditions for coherent transmission quenching have been determined. It is shown that for the PDFLC monolayer on the basis of bistable smectic liquid crystals it is possible to provide a coherent transmittance equal to zero and unity for two stable states of droplet directors in electric field. The influence of polydispersity for the γ-size distribution of droplets on the quenching conditions of coherent transmission has been investigated.

Keywords: polymer-dispersed liquid crystal, ferroelectric, contrast ratio

INTRODUCTION

The search for ways of increasing the contrast of PDFLC materials is an urgent problem of the liquid crystal (LC) optics in developing various electro-optical devices: optical shutters, light modulators, projection systems, displays, etc.

One of the ways of increasing the contrast ratio of the PDFLC is the determination of the conditions (concentration, size, optical constants of droplets and the tilt angle of the LC director) under which the maximum and the minimum value of the coherent transmittance for two different stable states of the LC droplet directors are attained.

In the present paper the PDFLC monolayer is considered . Particular emphasis is placed upon the determination of the quenching conditions for coherent transmittance[1]. The results have been obtained in the single-scattering approximation with the use of the anomalous diffraction approach (ADA)[2].

First, we consider a monodisperse layer where coherent transmission quenching is most pronounced, and then the influence of polydispersity on the quenching conditions has been investigated.

AMPLITUDE-PHASE SCREEN MODEL ANOMALOUS DIFFRACTION APPROACH

Let the PDFLC monolayer be illuminated along the normal to its surface by a linearly polarized plane wave. Consider electric components of the transmitted wave which are parallel and orthogonal to the polarization plane of the incident wave. We designate them as VV- and VH-component, respectively [3], and for each component we write the local amplitude transmission coefficients using the amplitude-phase screen (APS) model [4]:

$$T_a^{VV}(\underline{x}) = \begin{cases} 1, \underline{x} \in A_1, \\ V_j^{VV}, \underline{x} \in A_2 = \bigcup \sigma_j, \end{cases} \tag{1a}$$

$$T_a^{VH}(\underline{x}) = \begin{cases} 0, \underline{x} \in A_1, \\ V_j^{VH}, \underline{x} \in A_2 = \bigcup \sigma_j, \end{cases} \tag{1b}$$

where A_1 and A_2 are, respectively, the unshaded and shaded regions in the monolayer plane; $A_1 + A_2 = A$ is the monolayer area; σ_j is the j-th droplet projection on the monolayer plane; V_j^{VV} and V_j^{VH} are complex transmissions of equivalent screens identified with the j-th droplet depending on its shape, size, optical constants and internal structure.

Thus, the coherent transmittance of the PDFLC monolayer T_c will be determined as

$$T_c = \left|\left\langle T_a^{VV} \right\rangle\right|^2 + \left|\left\langle T_a^{VH} \right\rangle\right|^2, \tag{2}$$

where the mean values of $\left\langle T_a^{VV} \right\rangle$ and $\left\langle T_a^{VH} \right\rangle$ are found by integrating Eqs.(1),

$$\left\langle T_a^{VV} \right\rangle = \frac{1}{A}\int_A T_a^{VV}(\underline{x})d\underline{x} = 1 - \eta(1 - \overline{V^{VH}}), \tag{3a}$$

$$\left\langle T_a^{VH} \right\rangle = \frac{1}{A}\int_A T_a^{VH}(\underline{x})d\underline{x} = \eta\overline{V^{VH}}. \tag{3b}$$

Here η is the overlap coefficient of the monolayer equal to the ratio of the projection area of all the droplets on the monolayer plane to the area where they are distributed, i. e. $\eta = A_2 / A$; $\overline{V_{VV}}$ and $\overline{V_{VH}}$ are the averaged (over sizes, orientations of droplets, etc.) transmissions of equivalent screens.

For the wave scattered in the incidence direction, transmissions of the equivalent screens are described by [4]

$$V^{VV} = 1 - \frac{2\pi}{k^2\sigma} f_{VV}(0), \tag{4a}$$

$$V^{VH} = \frac{2\pi}{k^2\sigma} f_{VH}(0), \tag{4b}$$

where $k = 2\pi/\lambda$, λ is the light wavelength; $f_{VV}(0), f_{VH}(0)$ are the VV- and VH-components of the vector amplitude of scattering for an individual droplet at a zero scattering angle.

In the case of monodisperse identically oriented droplets, the coherent transmittance of the PDFLC monolayer is found on the basis of Eqs. (2)-(4) without averaging in Eqs.(4),

$$\mathrm{T}_c = 1 - Q\eta + \frac{Q^2 \mathrm{L}}{2}\eta^2, \tag{5}$$

where

$$Q = \frac{4\pi}{k^2\sigma} \operatorname{Re} f_{VV}(0) \tag{6}$$

is the extinction efficiency factor [1]. The value L is equal to

$$\mathrm{L} = \frac{1}{2}\left(1 + \frac{\operatorname{Im}^2 f_{VV}(0)}{\operatorname{Re}^2 f_{VV}(0)}\right) \cdot \left(1 + \frac{|f_{VH}(0)|^2}{|f_{VV}(0)|^2}\right). \tag{7}$$

Equation (5) shows that T_c has a minimum if and only if $QL > 1/\eta_{\max}$ ($\eta_{\max}$ is the maximum overlap coefficient of a PDFLC monolayer) which equals $T_{\min} = 1 - 1/(2L)$ at $\eta = 1/(QL)$.

If $L = 0.5$, the coherent transmittance at the minimum vanishes, i. e. quenching of coherent component of the radiation passed through the monolayer takes place [1]. The extinction efficiency factor Q_0 and the value of η_0 at which $T_c = 0$ should satisfy the relation $\eta_0 = 2/Q_0 < \eta_{\max}$.

Let the droplets in the form of ellipsoids with semi-axes a,b,c, along the axes x,y,z, respectively, be oriented with their large semi-axes a along the x-axis (see Fig.1 which, for the sake of simplicity, shows one droplet). The plane (x,y) is the monolayer plane; the z-axis assumes the direction of the normal to the layer; $\underline{k},\underline{e}$ are, respectively, the wave vector and the unit polarization vector of the incident wave.

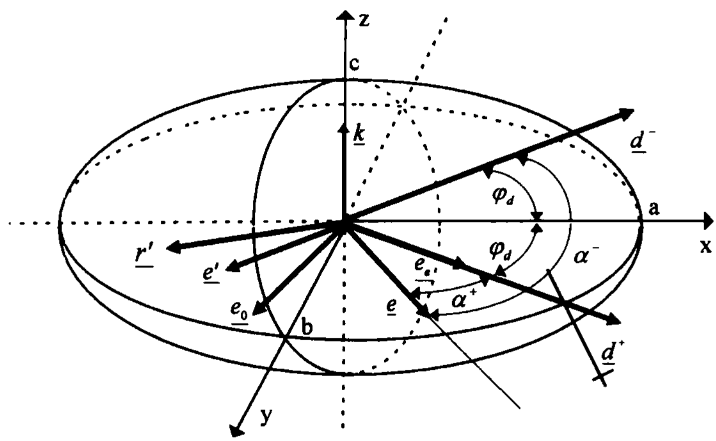

FIGURE 1 Schematic representation of droplet illumination conditions. Notations are in the text.

Assume that all droplets have a uniform planar orientation of LC directors along the vector of $\underline{d}$; $\underline{d}$ is the droplet director which can assume two stable states $\underline{d}^+$ and $\underline{d}^-$ characterized by the tilt angle φ_d. Such a structure is realized in PDFLC layers on the basis of bistable smectic LC [5,6]. The droplet director switches from the state $\underline{d}^+$ to the state $\underline{d}^-$ and back due to the change of polarity of the electric field normally applied to the layer.

To determine the components of the vector amplitude of scattering entering into Eqs. (6), (7), we introduce the unit vector $\underline{e}'$ orthogonal to the polarization plane of the incident wave (see Fig.1). Then [3]:

$$f_{VV} = \underline{e}\underline{\underline{S}}\underline{e}, \tag{8a}$$

$$f_{VH} = \underline{e}'\underline{\underline{S}}\underline{e}, \tag{8b}$$

where $\underline{\underline{S}}$ is the amplitude matrix 2×2 at a zero scattering angle. Let us find it with the use of the ADA assuming that $k >> 1$ and $|n - n_p| << 1$ [7]; n is an ordinary n_0 or extraordinary n_e refractive index; n_p is the refractive index of the binding polymer.

For the $\underline{d}^+$-state the extraordinary and ordinary waves into which the incident wave is broken inside a droplet will be polarized in the principal plane $(\underline{k}, \underline{d}^+)$ and orthogonal to it along the unit vectors $\underline{e}_e$ and $\underline{e}_0$, respectively, (see Fig.1).

Due to the optical softness (close values of n_0, n_e to n_p) both waves propagate approximately in the same direction of the incident wave $\underline{k}$ (refraction and reflection by the droplet surface is negligibly small). Then all the vectors $\underline{e}, \underline{e}', \underline{e}_e, \underline{e}_0, \underline{d}^+$ and $\underline{d}^-$ lie in the monolayer plane (x,y).

In the basis $(\underline{e}_e, \underline{e}_0)$ the $\underline{\underline{S}}$-matrix has a diagonal form

$$\underline{\underline{S}} = \begin{pmatrix} S_e & 0 \\ 0 & S_0 \end{pmatrix}. \tag{9}$$

Here S_e and S_0 are the scattering amplitudes for the extraordinary and ordinary waves at a zero scattering angle. Within the framework of the ADA [7]

$$S_0 = \frac{k^2}{2\pi}\int_\sigma (1 - e^{i\Delta_0(\underline{r}')})d\underline{r}', \tag{10a}$$

$$S_e = \frac{k^2}{2\pi}\int_\sigma (1 - e^{i\Delta_e(\underline{r}')})d\underline{r}', \tag{10b}$$

where integration is carried out over the droplet section $\sigma = \pi ab$; $\Delta_0(\underline{r}')$ and $\Delta_e(\underline{r}')$ are phase shifts for the ordinary and extraordinary waves passed through the droplet in the $\underline{k}$-direction specified on the section σ at the point with the radius -vector $\underline{r}'$ (see Fig. 1).

In our case of uniform planar orientation of LC directors in the droplet,

$$\Delta_0 = k(\frac{n_0}{n_p} - 1)h = 2kc(\frac{n_0}{n_p} - 1)\sqrt{1 - \frac{\sigma'}{\sigma}}, \tag{11a}$$

$$\Delta_e = k(\frac{n_e}{n_p} - 1)h = 2kc(\frac{n_e}{n_p} - 1)\sqrt{1 - \frac{\sigma'}{\sigma}}, \tag{11b}$$

where h is the path of the ray into the droplet in the $\underline{k}$-direction at point $\underline{r}'$; σ' is the ellipse area on the ellipsoid surface within which h is constant. The last expressions take into account the fact that when the radiation propagates along the z-axis, for ellipsoids the relation $\sigma' = \sigma(1-(h/2c)^2)$ takes place [8]

Substitution of Eqs. (11) into Eqs. (10) leads to integrals of the form

$$\int_0^1 (1 - e^{i\nu\sqrt{1-\xi}})d\xi = 2K(i\nu), \tag{12}$$

where $\xi = \sigma'/\sigma$; K is the Hulst function [7],

$$K(i\nu) = \frac{1}{2} + \frac{e^{-i\nu}}{i\nu} + \frac{e^{-i\nu}-1}{(i\nu)^2}. \tag{13}$$

The values of ν in Eqs. (12), (13) for the ordinary and extraordinary waves are given, respectively, by

$$\nu_0 = 2kc(\frac{n_0}{n_p} - 1), \tag{14a}$$

$$\nu_e = 2kc(\frac{n_e}{n_p} - 1). \tag{14b}$$

As the result, we have

$$S_0 = \frac{k^2\sigma}{\pi} K(i\nu_0), \tag{15a}$$

$$S_e = \frac{k^2\sigma}{\pi} K(i\nu_e). \tag{15b}$$

Taking into account that in the basis $(\underline{e}_e, \underline{e}_0)$ the unit vectors $\underline{e}, \underline{e}'$ have expressions: $\underline{e} = (\cos\alpha^+, \sin\alpha^+)$, $\underline{e}' = (-\sin\alpha^+, \cos\alpha^+)$, and α^+ is the polarization angle in the $\underline{d}^+$-state (angle between $\underline{e}$ and $(\underline{k}, \underline{d}^+)$), from Eqs. (15), (9), (8), we find finally,

$$f_{VV}(0) = \frac{k^2\sigma}{\pi}\left\{K(iv_e)\cos^2\alpha^+ + K(iv_0)\sin^2\alpha^+\right\}, \tag{16a}$$

$$f_{VH}(0) = \frac{k^2\sigma}{2\pi}\left\{K(iv_0) - K(iv_e)\right\}\sin 2\alpha^+. \tag{16b}$$

Substituting Eqs. (16) into Eqs. (6), (7), we determine the coherent transmittance for the $\underline{d}^+$-state.

For the $\underline{d}^-$- state the coherent transmittance is determined on the basis of Eqs. (16), but instead of α^+ one has to substitute the value of the polarization angle α^-. It is equal to $\alpha^+ + 2\varphi_d$ (see Fig.1).

As can be seen from Eqs. (16), (14), the coherent transmittance of the PDFLC monolayer for the ellipsoidal droplets does not apparently depend on the droplet sizes (semi-axes a,b) in the monolayer plane. The values of a,b influence the overlap coefficient of the monolayer (in the monodisperse system: $\eta = N\pi ab / A$, N is the number of droplets in the monolayer).

QUENCHING OF COHERENT TRANSMITTANCE: MONODISPERSION

The values of Q and L at which $T_c = 0$ were obtained above by analyzing Eq. (5). Here, investigating the conditions for coherent transmittance quenching of

PDFLC monolayer within the framework of the ADA for monodisperse identically oriented droplets, we assume that in the $\underline{d}^+$-state the polarization angle $\alpha^+ = 0$. Then, from Eqs. (6), (7), (16), we find

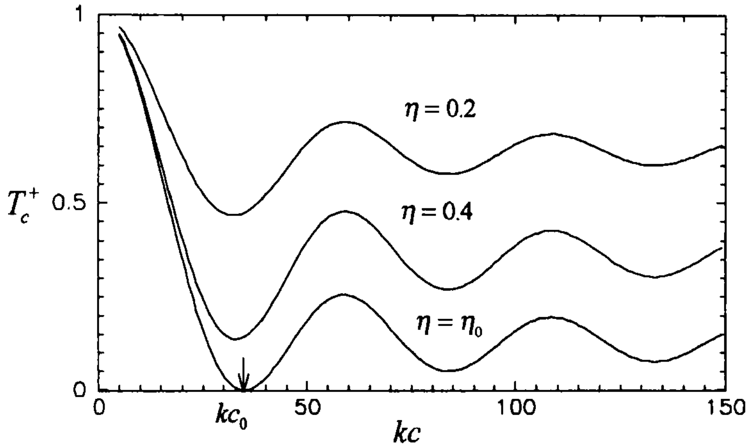

FIGURE 2 Coherent transmittance versus the size parameter. $\alpha^+ = 0$; $n_e = 1.65$; $n_p = 1.55$; $\forall n_0$. The arrow shows the value of kc_0 at $\eta = \eta_0 \approx 0.64$ where $T_c^+ = 0$ is implemented.

$$Q^+ = 4\,\mathrm{Re}\,K(i\,v_e), \tag{17a}$$

$$L^+ = \frac{1}{2}\left(1 + \frac{\mathrm{Im}^2\,K(i\,v_e)}{\mathrm{Re}^2\,K(i\,v_e)}\right). \tag{17b}$$

Consequently, $T_c^+ = 0$ if

$$\mathrm{Im}\,K(i\,v_e) = 0, \tag{18a}$$

$$\eta_0 = \frac{1}{2\,\mathrm{Re}\,K(i\,v_e)} < \eta_{\max}. \tag{18b}$$

Both values v_e and v_0 are real for nonabsorbing droplets. Then, we write for the real and the imaginary parts of the Hulst function,

$$\mathrm{Re}\,K(i\,v_e) = \frac{1}{2} + \frac{1}{v_e^{\,2}} - \frac{\sqrt{1+v_e^{\,2}}}{v_e^{\,2}}\cos(v_e - arctgv_e), \tag{19a}$$

$$\mathrm{Im}\,K(i\,v_e) = \frac{\sqrt{1+v_e^2}}{v_e^2}\sin(v_e - arctgv_e). \tag{19b}$$

From Eqs. (18), (19), we obtain that $T_c^+ = 0$ at several values of the monolayer overlap coefficient

$$\eta_0 = \left(1 + \frac{2(1+\sqrt{1+v_l'^2})}{v_l'^2}\right)^{-1} < \eta_{\max}, \tag{20}$$

where v_l' are the roots of the equation $v_e - arctgv_e = \pi l, l = 1,3,5,\ldots$ The minimum value $\eta_0 \approx 0.64$ is realized at $l = 1$ and $v_1' \approx 4.49$. The sizes of droplets c_0 at which $T^+{}_c = 0$ should satisfy the relation (see Eq. (14b))

$$kc_0 \approx \frac{4.49}{2|n_e / n_p - 1|}. \tag{21}$$

Figure 2 shows the dependence of T_c^+ on kc at various values of η. It is seen that an increase in the droplet concentration leads to a decrease in the coherent trransmittance at all sizes of droplets in the PDFLC monolayer.

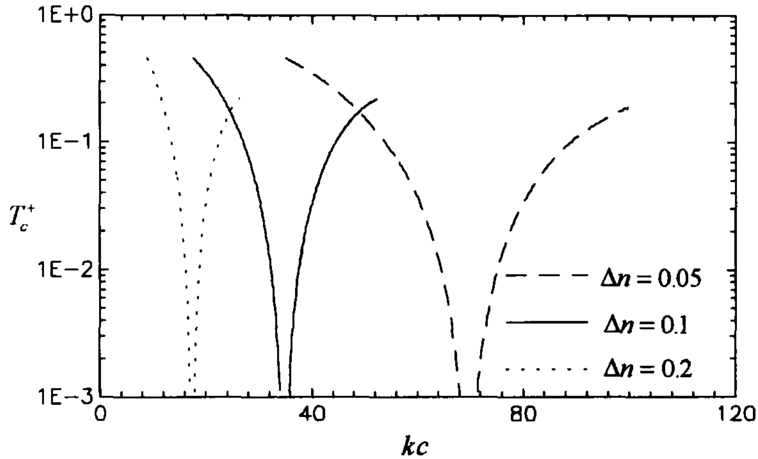

FIGURE 3 Coherent transmittance versus the size parameter in the vicinity of zero minima ($T_c^+ = 0$) at different optical anisotropies Δn ($n_0 = n_p = 1.55$).

The minimum for T_c^+ equal to zero corresponds at $\eta_0 \approx 0.64$ to the first minimum on the curve for T_c^+ versus kc. Note that at $\alpha^+ = 0$ the coherent transmission does not depend on the ratio n_0 / n_p (see Eqs. (17), (14b)).

The coherent transmittance T_c^+ in the vicinity of kc_0 is given in Fig. 3. An increase in optical anisotropy of droplets $\Delta n = n_e - n_0$ leads to a shift of the minimum towards smaller kc. This can be easily seen from Eq. (21) assuming $n_p = n_0$. The minimum width becomes smaller with increasing Δn.

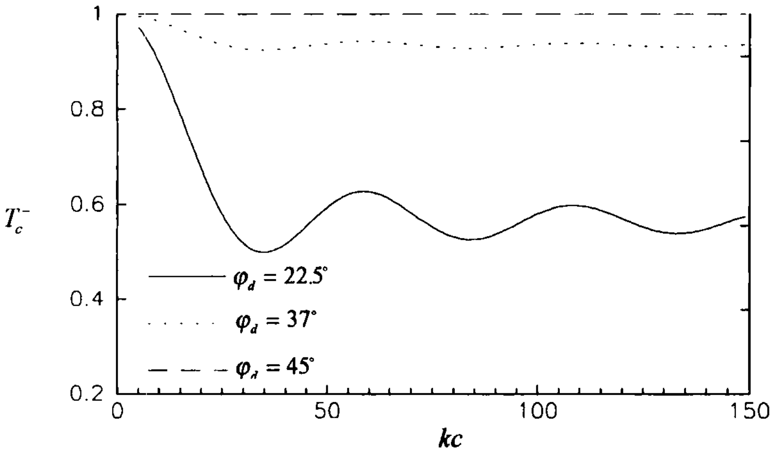

FIGURE 4 Coherent transmittance versus the size parameter at various tilt angles φ_d. $n_0 = n_p = 1.55$; $\Delta n = 0.1$; $\eta = \eta_0 \approx 0.64$.

As can be seen from Eqs. (16), (5)-(7), at $n_0 / n_p = 1$ and $\varphi_d = 45^\circ$ the coherent transmittance in the $\underline{d}^-$-state T_c^- is equal to unity independent of η and droplet sizes. Thus the PDFLC monolayer becomes completely transparent, switching from the $\underline{d}^+$-state to the $\underline{d}^-$-state. Such a behavior is due to the disappearance of the refractive index gradient for the ordinary ray if the incident wave is normally polarized to the principal plane $(\underline{k}, \underline{d}^-)$[6].

The dependence of T_c^- on kc at various tilt angles φ_d is given in Fig. 4. It can be seen that an increase in φ_d corresponds to an increase in transparency of the monolayer at all sizes of droplets.

At larger values of φ_d oscillations of T_c^- become weaker. For a tilt angle $\varphi_d > 22.5^\circ$ the coherent transmittance $T_c > 0.5$.

Thus, it is possible to select such values of the droplet concentration ($\eta_0 \approx 0.64$) and size (see Eq. (21)), the polymer refractive index ($n_p = n_0$), and the tilt angle ($\varphi_d = 45^\circ$) at which the coherent transmittance of the PDFLC monolayer for the $\underline{d}^+$- and $\underline{d}^-$-states are equal to zero and unity, respectively.

The latter conditions can be reversed to give $T_c^+ = 1$ and $T_c^- = 0$. In this case, the values of η_0, φ_d remain unchanged, but $n_p = n_e$ and the droplet size c_0 will be determined similarly to Eq. (21) by substituting n_0 instead of n_e.

QUENCHING OF COHERENT TRANSMITTANCE: POLYDISPERSION

The quenching of coherent transmission is a cooperative interference effect [1]. It takes place when (i) the VV-component of the wave scattered in the $\underline{k}$-direction (this wave is the sum of waves scattered by all droplets) is equal to the incident wave in the amplitude and opposite to it in the phase, (ii) the VH-component is equal to zero. Obviously, the quenching of coherent transmittance is most pronounced in the case of the monodisperse layer. A real PDFLC layer is polydisperse, therefore it is necessary to evaluate the influence of polydispersity on the quenching conditions of coherent transmittance.

Consider a monolayer of droplets differing in sizes. To determine the coherent transmittance we should average Eqs. (16) over the size c.

Then, analysis of the quenching conditions for coherent transmittance in the polydisperse monolayer and analysis of the switching from the $\underline{d}^+$- to the $\underline{d}^-$-state will be analogous to the monodisperse system with the mean values of the real and the imaginary part of the Hulst function (Eq. (13)).

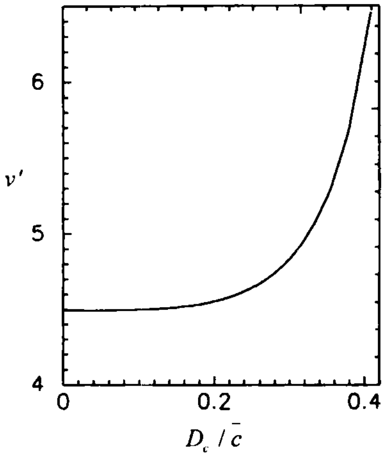

FIGURE 5 The solution ν' of equation (24) which determines the modal size c_m^0 for coherent transmittance quenching.

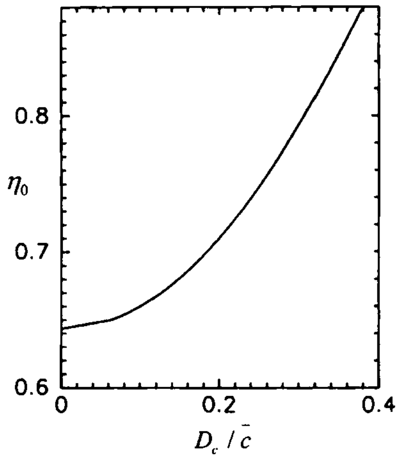

FIGURE 6 The overlap coefficient η_0 of PDFLC monolayer at which coherent transmittance is quenched.

For the γ -size distribution of droplets [9]

$$\psi(c) = \frac{\mu^{\mu+1}}{\Gamma(\mu+1)} \cdot \frac{c^{\mu}}{c_m^{\mu+1}} e^{-\mu \frac{c}{c_m}}, \tag{22}$$

where c_m and μ are, respectively, the mode and the distribution parameter, we obtain at $\mu > 1$ the following expressions for the mean values of the real and the imaginary part of Eq. (13)

$$\overline{\operatorname{Re} K(i\,v)} = \frac{1}{2} + \frac{\mu}{(\mu-1)v_m^2} - \frac{\mu^{\mu+1}\sqrt{1+v_m^2}}{v_m^2(\sqrt{\mu^2+v_m^2})^{\mu}} \times \times \cos[\mu arctg\frac{v_m}{\mu} - arctg v_m] , \tag{23a}$$

$$\overline{\operatorname{Im} K(i\,v)} = \frac{\mu^{\mu+1}\sqrt{1+v_m^2}}{(\mu-1)v_m^2(\sqrt{\mu^2+v_m^2})^{\mu}} \sin[\mu arctg\frac{v_m}{\mu} - arctg v_m] . \tag{23b}$$

The value of v_m in Eqs. (23) is analogous to Eqs. (14) where instead of size c the modal size c_m should be used. The modal size is related to the mean size $\bar{c}$ by the relation $c_m = \mu\bar{c}/(\mu+1)$.

Then, by analogy with Eqs. (18) and Eqs. (19) we obtain that the required condition of quenching is

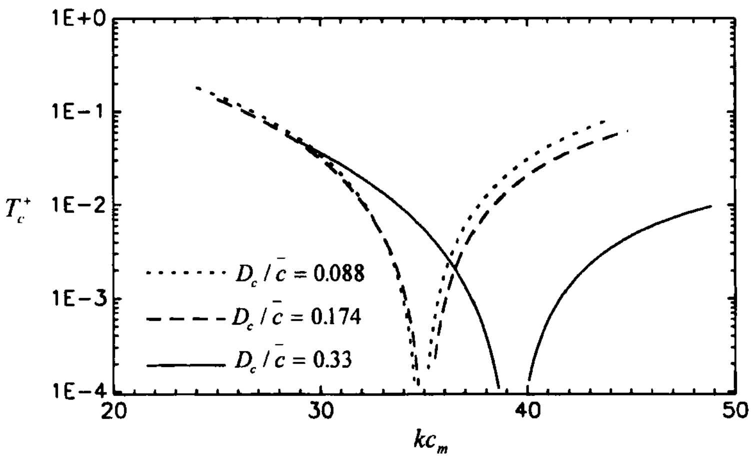

FIGURE 7 The dependence of coherent transmittance in $\underline{d}^+$-state on the modal size parameter at various variation coefficients. $n_e = 1.65$; $n_p = 1.55$; $\forall n_0$.

$$\mu arctg\frac{v_m}{\mu} - arctgv_m = \pi l\,, \qquad (24)$$

$l = 1,3,\ldots$. The last equation has a solution for v_m if $\mu > 2l + 1$. The solution of the last equation v' at $l = 1$ depending on the variation coefficient $D_c / \bar{c} = 1/\sqrt{\mu + 1}$, ($D_c = \sqrt{D_c^2}$, D_c^2 is the variance coefficient of size c) is given in Fig. 5.

The modal size c_m^0 at which $T_c = 0$ depends on the distribution width. It can be determined from the data of Fig. 5 by means of the relation: $kc_m^0 = v' / (2|n_e / n_p - 1|)$. The overlap coefficient η_0 also depends on the distribution width of the size c droplets, increasing for wider distributions (see Fig. 6). The least value of $\eta_0 \approx 0.64$ is attained in the monodisperse system ($D_c / \bar{c} = 0, \mu \to \infty$).

The dependencies of T_c^+ on kc_m in the vicinity of kc_m^0 at various values of $D_c / \bar{c}$ are given in Fig. 7. The position of the zeroth minimum with increasing polydispersity (increasing variation coefficient) is shifted towards large kc_m and the minimum becomes wider. For the γ-size distribution of droplets with $D_c / \underline{c} > 0.5$, the quenching of coherent transmittance is not observed.

The dependencies of T_c^+ and T_c^- on the size parameter, which are shown in Figs. 3,4 for the monodisperse layer, are preserved qualitatively for the polydisperse monolayer. If $n_p = n_0$, $\varphi_d = 45^\circ$ and the conditions for coherent transmisttance quenching in the $\underline{d}^+$-state have been found, the values of $T_c^+ = 0, T_c^- = 1$ are provided. Equalities $T_c^+ = 1, T_c^- = 0$ are also possible as in the case of the monodisperse layer.

CONCLUSIONS

The results obtained can be used to optimize the contrast ratio of PDFLC layers. The value of the dispersion LC phase concentration in the PDFLC monolayer, at which the maximum contrast ratio for the coherent component of light is implemented, corresponds to sufficiently high values of the monolayer overlap coefficient ($\eta_0 \geq 0.64$). The value of η_0 can probably be decreased at an oblique incidence of light.

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