Optical invariants of LCD "splay" retardation films

S. V. Belyaev, N. V. Malimonenko, J. S. Yu

Information & Electronic Materials Research Institute, LG Chemical Ltd. Research Park, 104-1, Moonji-dong, Yusong-gu, Daejeon, 305-380, Korea
Tel.: 82-42-866-2364, Fax.: 82-42-862-6069, e-mail: belsv@hotmail.com

Abstract

Retardation liquid crystal films with a profiled titled optic axis (splay films) of both nematic and discotic types are used as compensation films for twisted nematic displays (TN-LCD). A new method is developed to characterize retardation vs. inclination (retardation profile) of splay films by three parameters: "full retardation" $d{*}\Delta n$, "in-plane retardation" R_o and "retardation difference" R_d. Splay films with the same retardation profile but with different tilt profile (retardation invariants) are discovered. Splay films with different structure parameters but belong to the same retardation invariant have the same compensation opportunities for TN-LCD.

1. Introduction

Retardation films with local optical axis tilt profile (splay films) of both nematic and discotic types are considered. These films are polymerized liquid crystal films with combined homeoplanar surface alignment (at one surface – planar, or homogeneous alignment with low tilt angle as 0°-10°, at other surface – "homeotropic", or close to perpendicular alignment with high tilt angle as 70°-90°). The main destination of these films is a light leakage compensation at TN-LCD inclination in on-voltage regime. As result TN-LCDs viewing angles are broaden. Negative birefringent discotic Fuji films [1-4] and positive birefringent nematic films [5-7] are proposed for this purpose.

The compensation mechanism is due to similar local optical axes tilt profile (liquid crystal director profile) of mentioned films and TN-LCD near boundary. Therefore, TN-LCD and splay film have the same Retardation vs. Inclination (retardation profile) and a compensation is most effective. So, a retardation profile of splay film is an important characteristic for a compensation. On the other hand, a retardation profile of splay film can be used, in principle, for investigation its local optical axes tilt profile. Typical retardation profile of splay (nematic and discotic) films is shown in Figure 1. The only difference between nematic and discotic splay films is the sign of retardation, for this reason our conclusions will refer for both types of films. But for definiteness we will start with splay nematic films, which have positive retardation profile.

We consider here splay films which are not twisted, therefore a retardation profile is asymmetric in splay plane with respect to inclination direction and symmetric in perpendicular plane. If all structure parameters of splay film are known (pretilt surface angles, tilt profile, thickness and birefringence) it is possible to calculate a retardation profile. At *inverse problem* solution (structure parameters calculation from a retardation profile) a set of splay films with different structure parameters is generated. In other words, during fitting process our software generates splay films with different structure parameters at the same low fitting error (solution set !). Therefore, these different films possess by the same Retardation vs. Inclination values. We have named these films as **optical invariants** and stated their structure peculiarities.

It is important also from practical point of view to know splay film structure parameters to manufacture splay films with needed retardation profile.

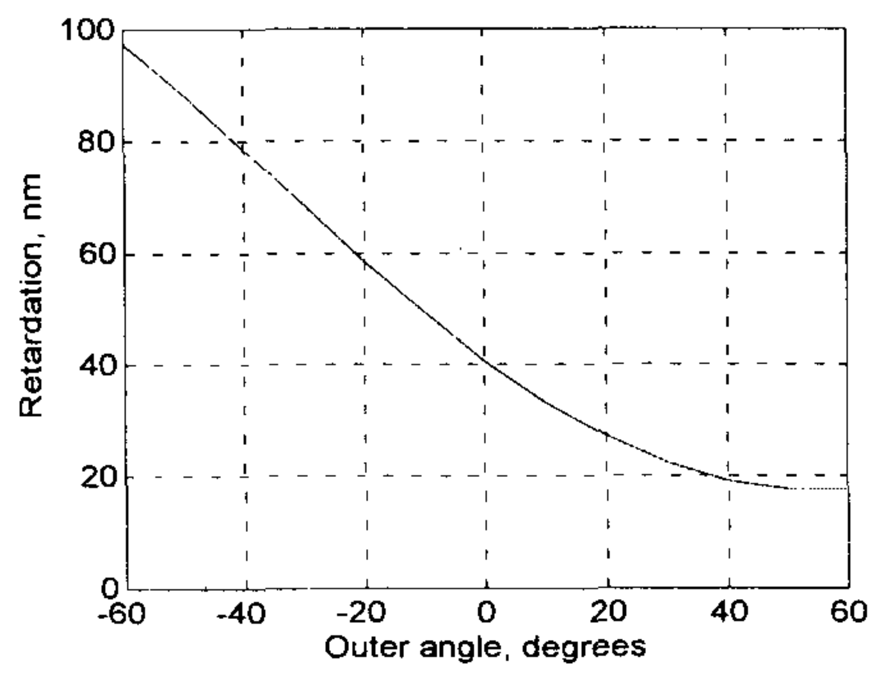


Figure 1. Typical retardation profile of splay (both nematic and discotic) films.

2. Retardation profile calculation

For propagation of light at angle φ with respect to principal axis of uniaxial media, we have effective birefringence Δn_{eff}, which is given by the equation :

$$\Delta n_{eff} = \frac{n_e \cdot n_o}{\left(n_e^2 \cdot \cos^2 \varphi + n_o^2 \cdot \sin^2 \varphi\right)^{1/2}} - n_o \qquad (1)$$

For the case Δn<<1 using Taylor expansion (1) may be derived:

$$\Delta n_{eff} = (n_e - n_o) \cdot \sin^2 \varphi = \Delta n \cdot \sin^2 \varphi \qquad (2)$$

Due to the smallness of Δn the two waves in uniaxial media have the same direction. Applying form (2) for sublayer with constant pretilt angle ψ (Fig.2), we can write for retardation vs. inclination R (Θ) :

$$R = \frac{d \cdot \Delta n_{eff}}{\cos(\theta)} = \frac{d \cdot \Delta n \cdot \sin^2(\gamma)}{\cos(\theta)} = \frac{d \cdot \Delta n \cdot \cos^2(\theta + \psi)}{\cos(\theta)} \qquad (3)$$

where θ - inner angle of light direction, ψ - tilt angle for optical axis (for LC director) and γ - angle between light ray and optical axis, $\gamma = \frac{\pi}{2} - (\theta + \psi)$

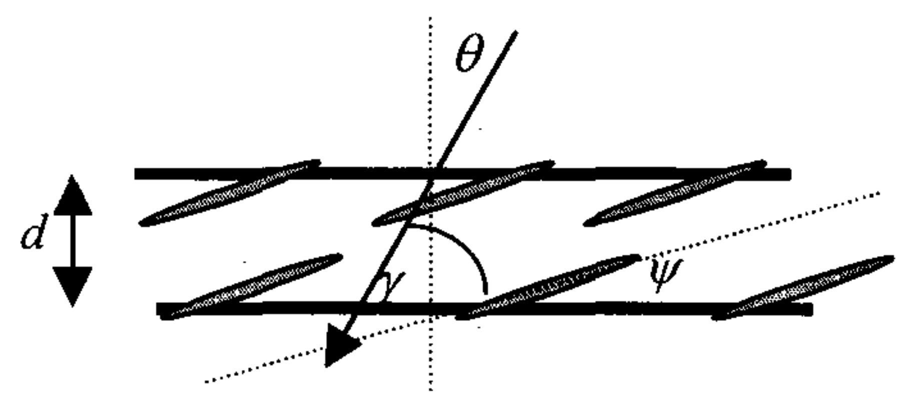


Figure 2. Sublayer with constant pretilt angle.

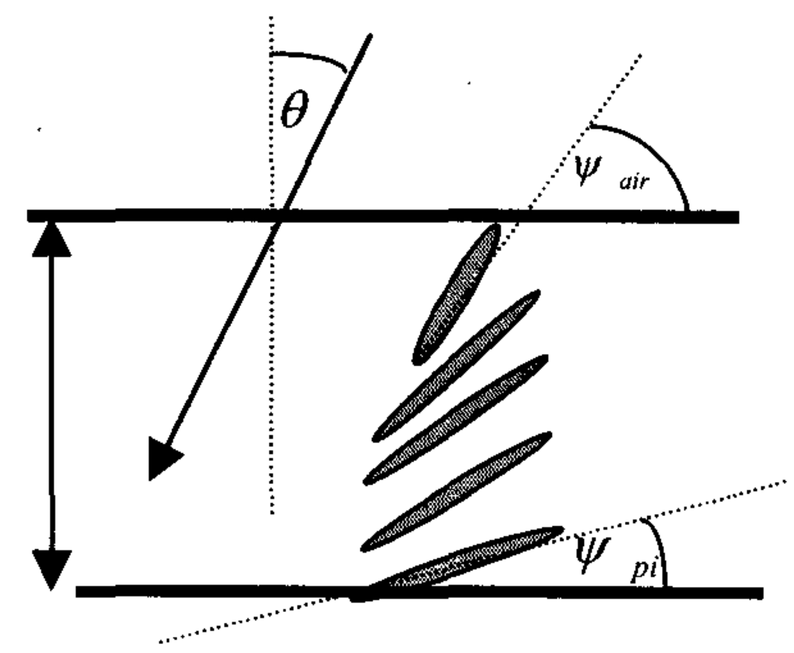


Figure 3. Splay film LC director structure.

Considering splay film as finite number of sublayers with constant inclination, the total retardation for splay film is a sum of sublayers retardation. To calculate the total retardation R (θ) of splay film vs. incidence inner angle θ, we need to integrate the equation (3) along thickness coordinate z:

$$R(\theta) = \int_0^d \frac{\Delta n}{\cos(\theta)} \cdot \cos^2(\theta + \psi(z)) \cdot dz \qquad (4)$$

In general case we suggest the tilt angle varies with the coordinate z by the form:

$$\psi(z) = (\psi_{air} - \psi_{pi}) \cdot \left(\frac{z}{d}\right)^{\xi} + \psi_{pi} \qquad (5)$$

Where ψ_{air} and ψ_{pi} – are pretilt angles at splay film surfaces and ξ - *profile* parameter.

If the splay (K_{11}) and bend (K_{33}) elastic constants of liquid crystal are equal, *profile* parameter ξ is equal 1, and we have linear profile of tilt angle. If not, we have deviation from linearity, which can be enlarge significantly near transition temperature to smectic phase.

In case of linear distribution (ξ=1) the integral can be resolve "manually", and we obtain known formula [7] for a retardation of splay film with constant gradient of tilt angle:

$$R(\theta) = \frac{\Delta n \cdot d}{\cos(\theta)} \cdot \left[\frac{1}{2} + \frac{\sin(2(\psi_{air} + \psi_{pi})) - \sin(2(\psi_{air} + \psi_{pi}))}{4 \cdot (\psi_{air} - \psi_{pi})}\right] \qquad (6)$$

In general case of arbitrary ξ and in a case of high birefrinence Δn we used Jones matrix method to calculate a retardation profile from splay film structure parameter.

3. Optical invariants

In general case of arbitrary ξ the expression (4) for propagation of light at angle -θ can be considered in following form using trigonometric expansion:

$$R(-\theta) = \Delta n \cdot \int_0^d \left[\frac{\cos^2(\psi(z) - \theta)}{\cos(\theta)}\right] dz = \qquad (7)$$

$$= \Delta n \cdot \int_0^d \left[\frac{\cos^2(\psi) \cdot \cos^2(\theta) + \sin^2(\psi) \cdot \sin^2(\theta) + 0.5 \cdot \sin(2\theta) \cdot \sin(2\psi)}{\cos(\theta)}\right] \cdot dz$$

Or in other terms :

$$R(-\theta) = \frac{1}{\cos(\theta)} \cdot \left[R_0 \cdot \cos^2(\theta) + (d \cdot \Delta n - R_0) \cdot \sin^2(\theta) + \frac{\sin(2\theta)}{2} \cdot R_d\right] \qquad (8)$$

Here we have made the denotations :

$$R_0 = \Delta n \cdot \int_0^d \cos^2(\psi(z)) \cdot dz \qquad (9)$$

and

$$R_d = \Delta n \cdot \int_0^d \sin(2 \cdot \psi(z)) \cdot dz \qquad (10)$$

R_o – is the retardation of splay film at normal direction or "in-plane" retardation (compare with (4)).

We can clear the physical sense of R_d parameter, if we find, using (8), the difference in retardations at two opposite inclination angles R(-θ) - R(θ):

$$R(-\theta) - R(\theta) = 2 \cdot \sin(\theta) \cdot R_d \qquad (11)$$

At θ=30°, R_d = R(-30°) - R(30°)

So, R_d characterizes the asymmetric properties of splay film.

Therefore, retardation profile of splay film can be fully characterized by 3 retardation parameters: **d*Δn, R_o and R_d.**

Our next step is to find all splay films (all structure profiles) possessing by a fixed retardation profile. For this purpose we need to solve two equations (9) and (10) to find combination of all structure parameters (ψ_{air}, ψ_{pi} ,ξ), which fit to the same retardation profile or the same combination of d*Δn, R_o and R_d.

For definiteness let us accept parameter d*Δn = 1 and R_o=0.5. Solution of equation (9) gives us the surface in coordinate system ψ_{air} ,ψ_{pi} , ξ,. It is more convenient to show (Fig.4) this surface as the lines corresponding to certain ξ on plane ψ_{air} ,ψ_{pi}.

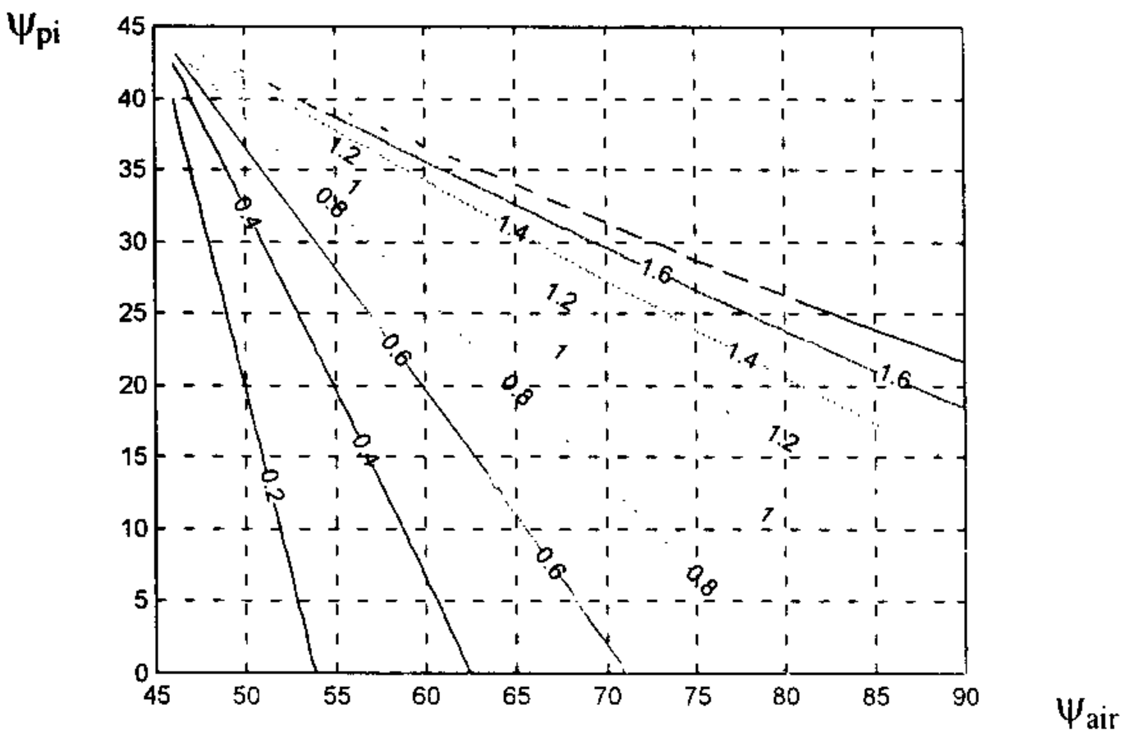


Figure 4. Contour map of profile parameter ξ as a function of two pretilt angles ψ_{air} and ψ_{pi} . Solution of equation (9) at d*Δn = 1 and R_o=0.5.

Solution of equation (10) at fix R_d gives the other surface in the same coordinate system ψ_{air} ,ψ_{pi} , ξ,.

An intersection of two surfaces gives us the solution of our task. To find intersection, we calculated R_d for all solutions of equation (9) and draw the lines with constant R_d level. In Figure 5 we add series of curves with fix R_d on plane ψ_{air} ,ψ_{pi}.

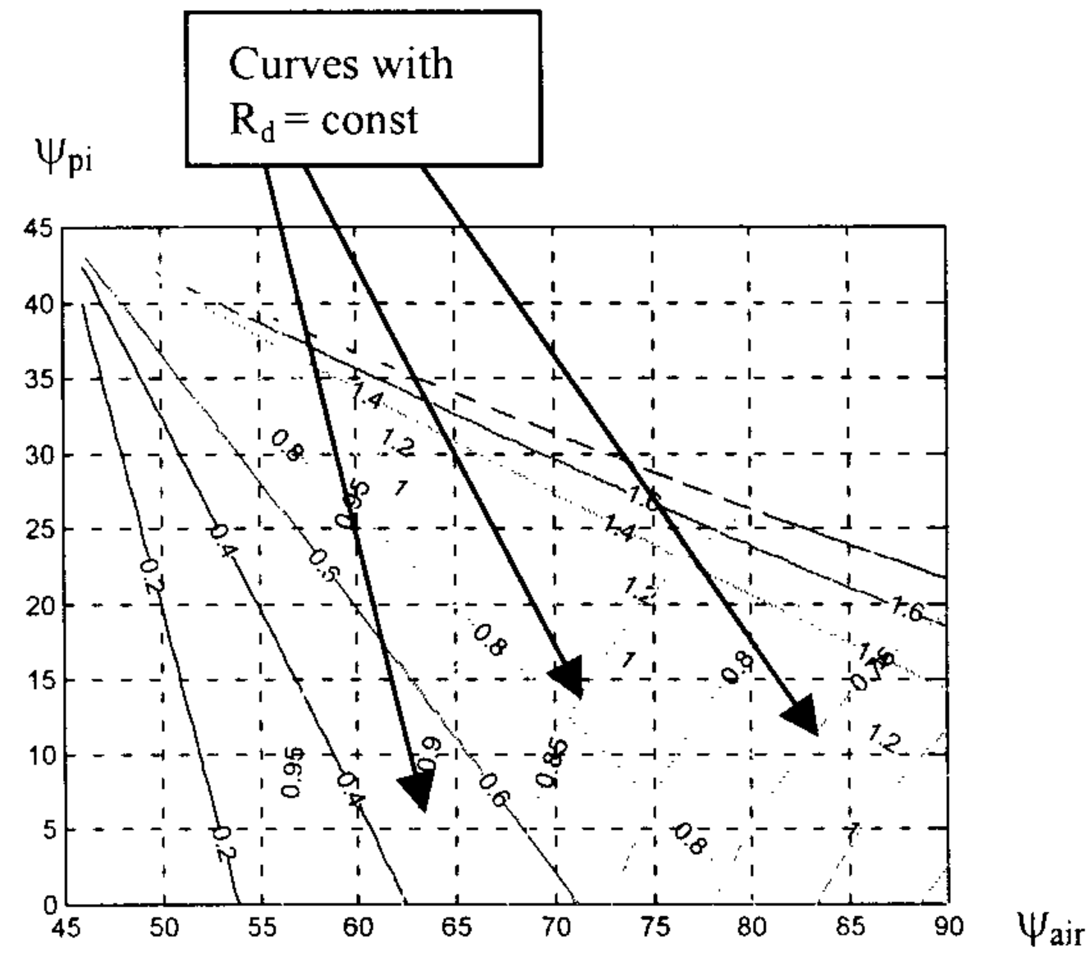


Figure 5. Contour map of *profile* parameter ξ and retardation *difference* R_d as a function of two pretilt angles ψ_{air} and ψ_{pi} .

So, we have curves with constant retardation difference R_d on the surface with constant R_o=0.5. All splay films with parameters ψ_{air} ,ψ_{pi} ξ , which belong to one curve with fixed R_d possess by the same retardation profile. We name these splay films an **optical invariant**.

In Figure 6 we show LC director profiles for a set of splay films with the same retardation profile, these films belong to one optical invariant.

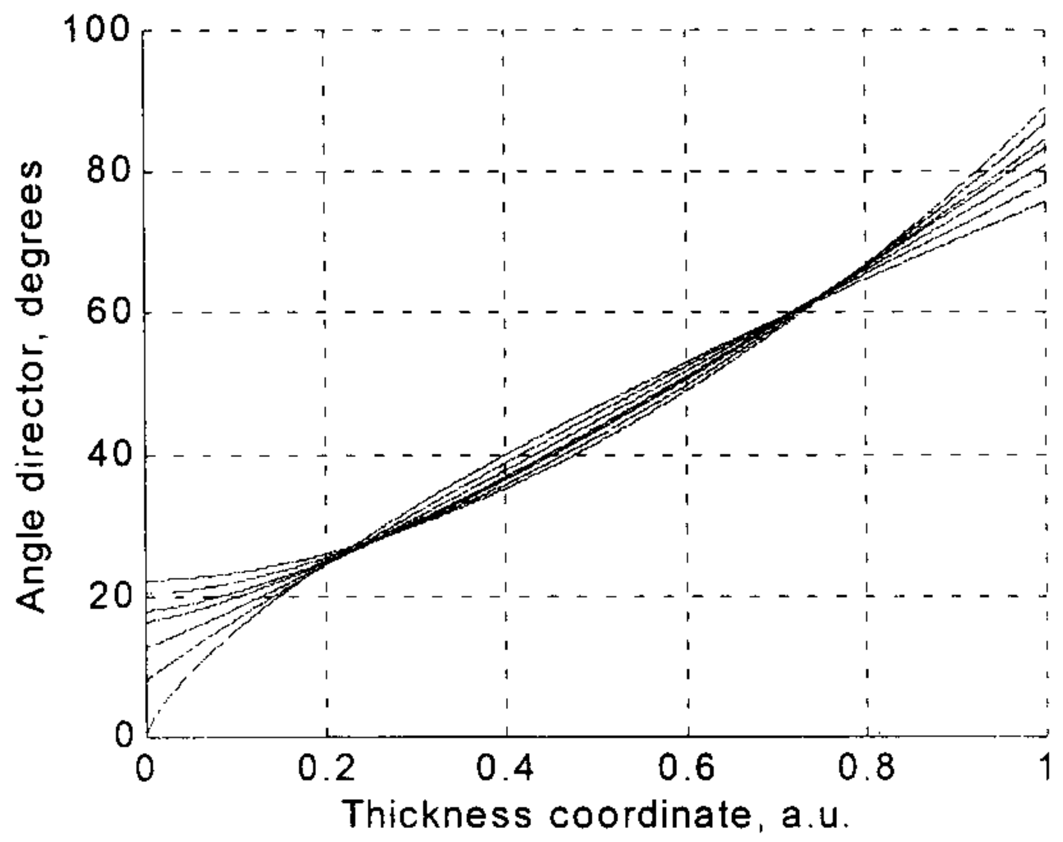
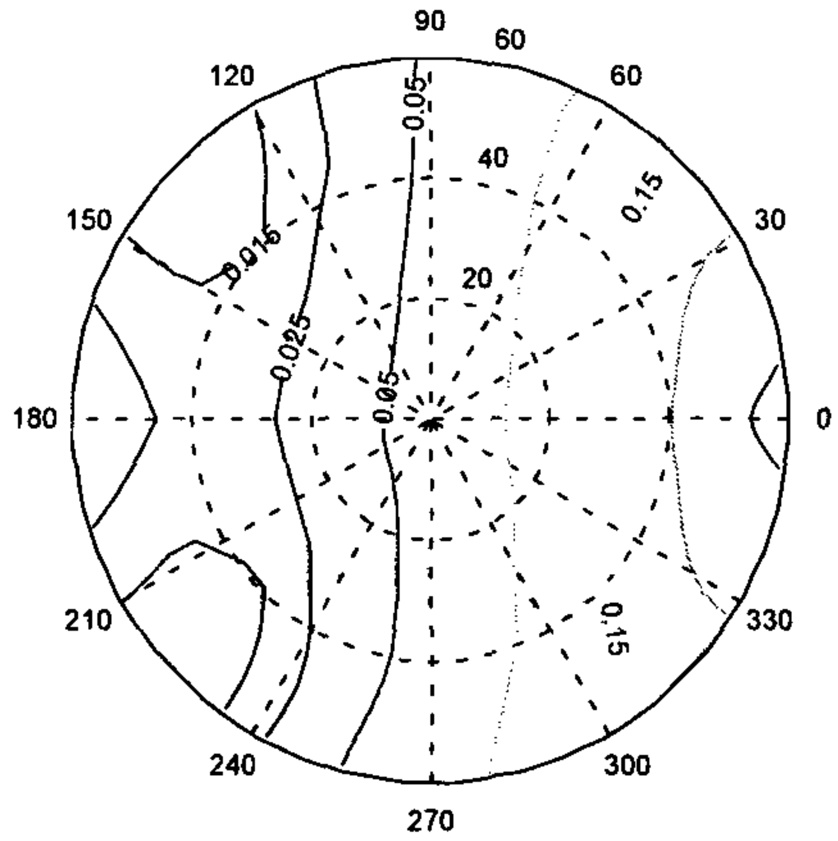


Figure 6. LC director profiles for splay films with the same retardation profile. d*Δn=1; R_o=0.5; R_d=0.775; ξ= 0.7 – 1.9

At splay film inclination in other azimuth than splay plane a polarization plane rotation is induced for input beam. In this case it is quite difficult to find a similar simple analytical description of splay films optical properties. For this reason we used Jones matrix method to compare splay films from same optical invariant at an inclination in all azimuths. The calculated iso-transmission curves are shown in Figure 7 for splay films between two crossed polarizers. These films belong to the same optical invariant, but with rather different structure parameters. The same iso-transmission picture is possible to see.



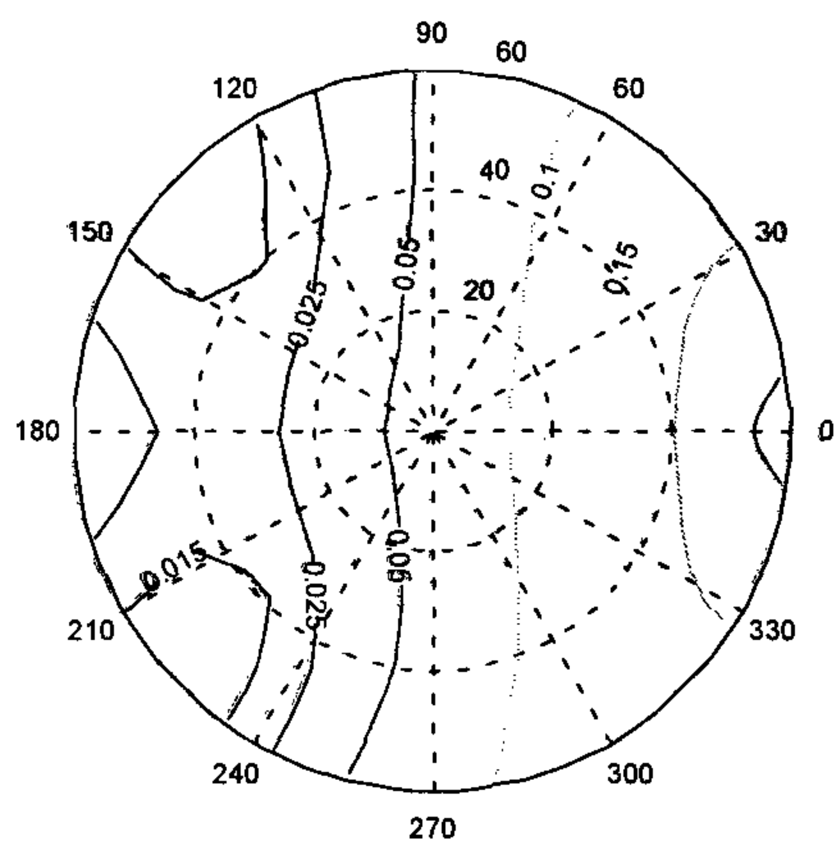


Figure 7. Iso-transmission curves of two splay films from same optical invariant ($\Delta n^*d = 1$, R_o=0.5, R_d=0.8), but with different structure parameters. Upper: $\psi_{pi}=7°$, $\psi_{air}=75°$, $\xi=0.8$ Down: $\psi_{pi}=19.5°$, $\psi_{air}=82°$, $\xi=1.4$. Crossed polarizers, splay plane is parallel to input polarizer transmission axis

3. Conclusions

Retardation vs. inclination (retardation profile) of splay retardation films both nematic and discotic can be fully characterized by three parameters: "full retardation" d*Δn, "in-plane" retardation R_o and retardation difference R_d. These parameters are possible to measure from experiment.

A set of splay films exists with the same retardation profile, but different structure parameters (pretilt surface angles, tilt profile, thickness and birefringence). We named these sets as optical invariants.

Splay films with different structure parameters but belong to the same retardation invariant have the same compensation opportunities for TN-LCD.

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