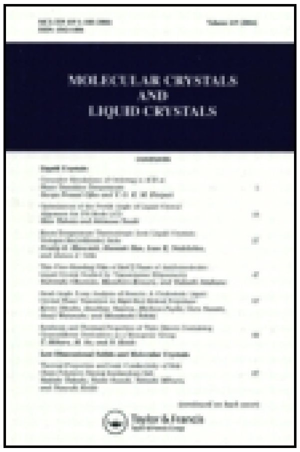

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A NEW OPTICAL METHOD TO MEASURE ANGULAR TILTS FOR PLANAR ANCHORED NEMATIC LIQUID CRYSTALS

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Abstract We present a new optical method to measure the small tilt angles of quasi-planar anchored nematics. We use an hybrid nematic cell which contains twin domains of different birefringence for non zero tilt. We measure the small rotation of the cell which equalize the twin domains birefringence, at a common border. This rotation is proportional to the tilt. The calibration constant can be calculated from the knowledge of the elastic constants anisotropy and the refractive indices, or independently measured from a known tilted anchoring plate. The method is linear in angle, i.e. sensitive and independent of the sample thickness. Comparative measurements of tilt on PVA and SiO are presented and discussed, using this method and other optical measurements of birefringence.

INTRODUCTION

During the last years a great deal of effort was devoted to determine the molecular orientation of nematic liquid crystal (NLC) on solid surfaces[1-4]. Sometimes liquid crystal molecules are oriented inside the planar surface (planar orientation). Sometimes the molecules can be slightly tilted from the plane. The control and measurement of small tilt angles are of great importance in many practical applications, in supertwisted nematic displays for instance. Several methods for measuring the tilt angle have been proposed. There exist indirect methods like the threshold displacement of Freedericksz transition[5] technique which requires an external field and a complicated analysis. A simpler method , to estimate the tilt angle, is to measure directly the birefringence of the NLC contained in a cell, with a compensator for instance. Usually, the cell is composed by two uniform pretreated plates which induce a uniform quasi planar anchoring. The measured birefringence depends on the tilt angle of the nematic director and on the thickness of the cell. A precise absolute measurement is not easy, since the local thickness is delicate to determine with sufficient accuracy. The wedge method[6] allows the determination, with accuracy, of the local thickness of the cell but it requires special plates, with well defined straight edges, and is not very convenient since conducting electrodes are in short circuit. The method of total reflexion[7] is accurate on the determination of the liquid crystal tilt angles but the samples need to be relatively thick and homogeneous.

More generally, one can deduce the texture tilt from the inspection of conoscopic figures where the probe light propagates at all possible angles in the sample, i.e. at varying extraordinary index and thicknesses. To design an optical birefringence method sensitive to the tilt, and independent of the sample thickness, one has to work in a geometry where ordinary and extraordinary waves propagate along the same direction, i.e. it is necessary to work close to normal incidence. In this case, the maximum sensitivity of the tilt variation of extraordinary index is achieved when the (uniform) texture is oriented at 45° from the normal. The index change is linear in tilt. This is not generally the case for small tilt angles, where this orientation is around 90°. We can obtain in this case the same linear sensitivity by using a non homogeneous liquid crystal texture, with orientation varying from parallel to perpendicular to the light beam, i.e. by using an "hybrid" cell. In this case, a small surface tilt around 90° is equivalent to a small rotation of an uniformely oriented cell around 45°. Using an hybrid cell, we describe in the present paper a new and simple optical method to determine the tilt angle of nematic liquid crystals close to a solid planar boundary with a reasonably good precision. The method uses the twin domains which appear spontaneously in the hybrid nematic cell. The idea is that the two twins domains, in presence of tilt, show a difference of birefringence linear in tilt. The equalization of the relative optical path difference of light between the two domains close to their common border allows the elimination of the unknown, but identical, cell thickness at their contact border. The proposed optical method is sensitive, since the birefringence is linear in angle and independent of the thickness of the cell. It does not need to use a compensator, nor does it require an external field. On the other hand this method requires the knowledge of the elastic constants anisotropy and the refractive indices of the NLC, or an independent calibration with an anchoring of known tilt.

THE MODEL

a) Principle

We prepare an hybrid aligned nematic cell using the plate to be tested, expected to give a quasi planar anchoring, and a counterplate resulting in an infinitely strong homeotropic alignement (perpendicular to the plane - fig.1). In this cell, two twin textures are possible with a total angular distorsion of $\pi/2\pm\psi$ ($\psi>0$ is the small surface tilt angle). These two textures are separated by disclination lines, which draw well defined borders. For these two textures the surface energy is the same while the volume energy is slightly larger for the $+\psi$ configuration. The coresponding configuration for the tilt angle $+\psi$ is expected to be metastable with a hopefully large enough decay time if ψ is small. On the average, the averaged birefringence of an hybrid cell compares roughly with the one of a uniform cell, of tilt

$\frac{\pi}{4}\pm\frac{\psi}{2}$, i. e. the twins should present a difference of birefringence (calculated later)

linear in ψ. The value of the birefringence depends only on ψ and not on d, for large enough anchoring strength, and cell thickness. In what follows, both surface anchorings are assumed infinitely strong.

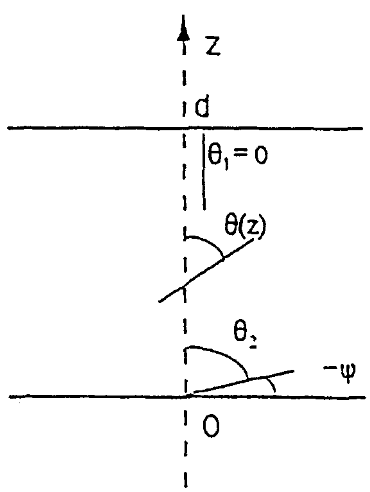

Figure 1 : An hybrid cell with homeotropic alignment ($\theta_1=0$) on the upper plate. θ_2 is the angle of the nematic director with the z axis at the lower plate.

The natural thing to do now is to measure the absolute optical path difference of each twin texture close to a common border. This path difference is just the product of d times the averaged birefringence. The ratio of the measured path differences across the border is now independent of d. We shall use this procedure to calibrate our measurements.

In practice, it is simpler to observe the contrast between the twin domains, versus the tilt angle of the incoming light beam on the sample. In case of a small tilt ψ, the necessary rotation is linear in ψ, with a calibration factor which can be calculated from the nematic material parameters or measured directly if ψ is known on a test plate.

b) Calculation

We calculate the birefringence of an hybrid cell. Consider the cell of fig.1 composed of two parallel glass plates separated by spacers of equal thickness d. We call $\theta(z)$ the angle of the nematic director with the z axis chosen normal to the cell boundaries. The tilt angle on the upper plate is $\theta_1=\theta(d)=0$ (homeotropic alignment). $\theta_2=\theta(0)$ gives the tilt angle of the lower plate while ψ is $\theta_2-\frac{\pi}{2}$ (fig. 1). In absence of external field the equilibrium state is determined only by the curvature elasticity of the nematic material and the anchoring at the boundary surfaces. For bend and splay distortion the profile of the director was calculated [8] using the Euler-Lagrange equations associated with the total free energy of distortion :

$$(1-K\sin^2\theta)(d\theta/dz)^2=C^2 \tag{1}$$

with

$$C=I(\theta_1,\theta_2)/d \tag{1a}$$

where $K=1-(K_1/K_3)$ is a measure of the anisotropy of the curvature elastic constants, K_1 being the splay constant K_3 the volume bend constant and C an integration constant determined by the boundary conditions[8].

In case of normal incidence, the path difference between the ordinary and the extraordinary waves for the above described cell is given by[6] :

$$\Delta l=n_0 d\left[\frac{J(\theta_1,\theta_2)}{I(\theta_1,\theta_2)}-1\right] \tag{2}$$

where

$$J(\theta_1,\theta_2)=\int_{\theta_1}^{\theta_2}\sqrt{\frac{1-K\sin^2\theta}{1-R\sin^2\theta}}\,d\theta \tag{2a}$$

$$I(\theta_1,\theta_2)=\int_{\theta_1}^{\theta_2}\sqrt{1-K\sin^2\theta}\,d\theta \tag{2b}$$

$$R=1-\left(\frac{n_o}{n_e}\right)^2 \tag{2c}$$

n_o and n_e are the ordinary and extraordinary refractive indices respectively.

If we know the thickness d of the cell from an independent measurement, the optical path difference Δl depends only on the angle θ_2 i.e. on ψ, a measurement of the optical path difference can give the value of ψ. Figure 2 shows the variation of the birefringence with the tilt angle of the nematic director on the lower plate, for homeotropic alignement on the upper plate of the cell.

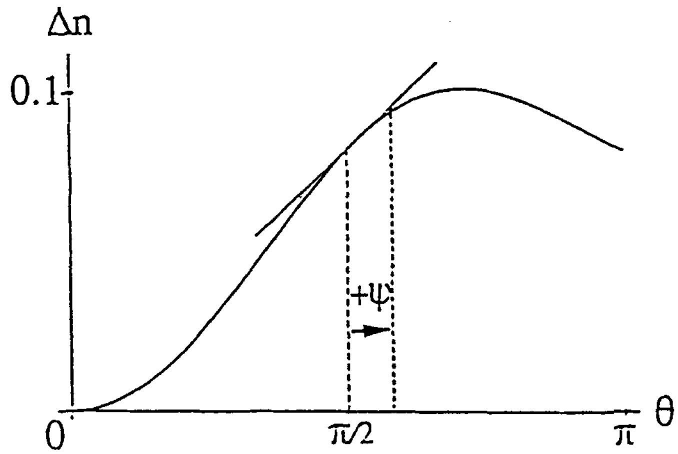

Figure 2 : Birefringence ($\Delta n = \frac{\Delta l}{d}$) versus the orientation of the nematic director at the lower plate for homeotropic alignment ($\theta_1=0$) at the upper plate.

The constants used are the one corresponding to the nematic 5CB, at 26.9°C, and a wavelength of light λ=.5461μm. These values given by the ref(9-10) are indicated on table I. Around θ_2=90°, one sees clearly that Δl is linear in $\psi=\theta_2-\pi/2$. The effective birefringence ~0.1 is half the value n_e-n_o~0.2.

TABLE I : The constants of 5CB from ref.(9-10)

T(°C)	K_{11}	K_{33}	n_o	n_e	λ(μm)	K	R
26.9	0.481($\times 10^{-6}$)	0.635($\times 10^{-6}$)	1.541	1.718	.5461	.243	.195

i)<u>The method of relative birefringence</u>

We consider two twin domains in the hybrid cell. The distribution of the nematic director of each twin domain is shown in fig.3 in normal incidence. These twin domains exhibit different birefringences. Let us call $\Delta l_{\pm\psi}$ the corresponding optical path difference for each twin domain with tilt angles $\pm\psi$ respectively. θ_1=0 while

$\theta_2=\pi/2\pm\psi$ for the domain with the $\pm\psi$ tilt angle respectively.

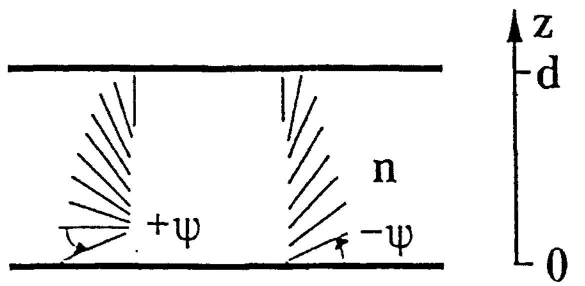

Figure 3 : The distribution of the nematic director n of the two twin domains with tilt angles $\pm\psi$.

The absolute optical path difference, $\Delta l_{+\psi}$ and $\Delta l_{-\psi}$ of each twin texture close to a common border, from eq.(2) are :

$$\Delta l_{\pm\psi} = n_o d\left[\frac{J(0,\frac{\pi}{2}\pm\psi)}{I(0,\frac{\pi}{2}\pm\psi)} - 1\right] = n_o d\left[\frac{J_{(\frac{\pi}{2}\pm\psi)}}{I_{(\frac{\pi}{2}\pm\psi)}} - 1\right] \tag{3}$$

where the unknown d is the same for the two domains. The relative optical path difference $\frac{\Delta l_{+\psi}}{\Delta l_{-\psi}}$ is now independent of d, since $J(\theta_1,\theta_2)$ and $I(\theta_1,\theta_2)$ are independent of d. By measuring the ratio of path differences of these two twin domains, one can determine ψ independently of d.

In the case of small tilt angles ψ one can linearize eq. 3 as :

$$\frac{\Delta l}{d}\Big|_{\pm\psi} = \frac{\Delta l}{d}\Big|_0 \pm c_\psi \psi \tag{4}$$

$$\text{with } c_\psi = n_o\left[\left(\sqrt{\frac{1-K}{1-R}}\right) I\left(\frac{\pi}{2}\right) - J\left(\frac{\pi}{2}\right)\frac{\sqrt{1-K}}{2}\Bigg/ I\left(\frac{\pi}{2}\right)\right] \tag{4a}$$

c_ψ is a function of the elastic anisotropy and the refractive indices of the nematic. Writing, as usual, $\Delta l/d=\Delta n$ the effective birefringence of the texture, eq.3 gives immediately :

$$\Delta n^*_{\pm\psi} = \frac{\Delta n_{\pm\psi}}{\Delta n_0} - 1 = \pm\mu\psi \tag{5}$$

with

$$\mu = \frac{c_\psi}{\Delta n_o} = \frac{\sqrt{(1-K)(1-R)}}{J\left(\frac{\pi}{2}\right) - I\left(\frac{\pi}{2}\right)} - \frac{J\left(\frac{\pi}{2}\right)\sqrt{1-K}}{I\left(\frac{\pi}{2}\right)\left(J\left(\frac{\pi}{2}\right) - I\left(\frac{\pi}{2}\right)\right)} \tag{5a}$$

Δn_o is the birefringence for $\psi=0$ ($\theta=\pi/2$).μ depends on the elastic constants anisotropy and the refractive indices of the NLC. Using the same values of table I for 5CB, we have calculated $\Delta n^*_{\pm\psi}$. In figure 4 the solid points correspond to the exact formula derived from eq.3 and the solid line illustrates the approximate linear relationship. The linear approximation is satisfactory within 10% up to $\psi=12°$.

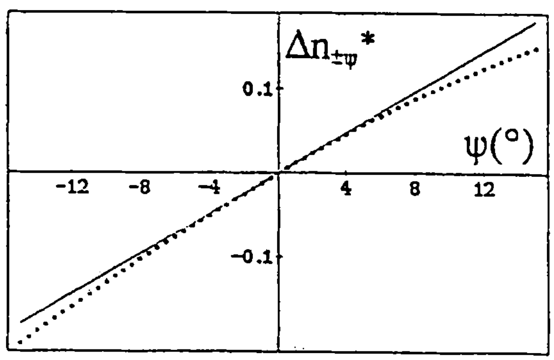

Figure 4 : The solid line corresponds to eq. 5 while the solid points correspond to the exact formula derived from eq.3. The calculation has been done for 5CB at the temperature T=26.9°C.

In the linear approximation we derive the simplified expression for the tilt angle ψ:

$$\psi = \frac{1}{\mu}\left[\frac{\Delta n_{+\psi} - \Delta n_{-\psi}}{\Delta n_{+\psi} + \Delta n_{-\psi}}\right] = \frac{1}{\mu}\left[\frac{\Delta l_{+\psi} - \Delta l_{-\psi}}{\Delta l_{+\psi} + \Delta l_{-\psi}}\right] \tag{6}$$

From (6). and the knowledge of μ, we see that the simple measurement of $\Delta l_{\pm\psi}$ gives the tilt ψ. This method would require the use of a compensator to measure the optical path differences. In practice we can use it for calibration, but we propose a simpler procedure, as follows :

ii) Birefringence equalization by rotation of the sample.

Up to now, we have just considered path differences for normal incidence. The effective birefringence must also depend linearly on the incidence angle, since the hybrid cell is roughly equivalent optically to a $\pi/4$ uniformly tilted plate. One expects now an equalization of the birefringence for the twin domains for a certain angle of incidence of light on the boundaries of the cell, linear in ψ. We first calculate the path difference between the ordinary and extraordinary waves in case of oblique incidence and then the path difference between the two twin domains. We treat the NLC as a stack of thin birefringent layers. Each layer is supposed to present uniaxial symmetry. The nematic director of two successive layers at distance dz is turned through a small angle $d\theta$. Because of the oblique incidence, we will have successive refraction of the extraordinary wave at each layer. The direction of the normal to the ordinary wave remains the same following the line OA (fig.5). The direction of the normal to the extraordinary wave changes with increasing depth of penetration into the layer of the NLC and it is propagated along the curve OB.

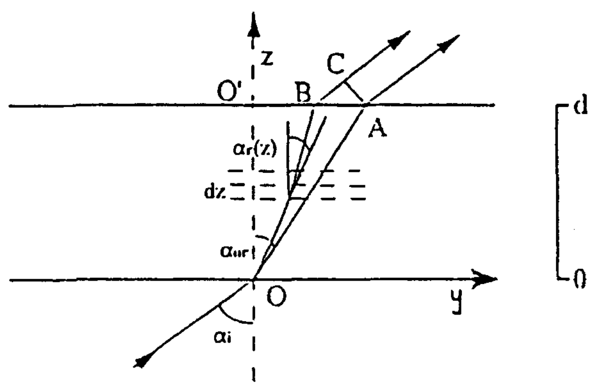

Figure 5 : Phase difference between the ordinary and the extraordinary waves transmitted by the nematic liquid crystal confined in a hybrid cell. α_i is the incidence angle. α_{or} the refraction angle for the ordinary wave and α_r is the refraction angle for the extraordinary wave.

Let us call $\alpha_r(z)$ the refraction angle which is a function of the incidence angle α_i and of the tilt angle θ (z). For each layer, the angle of refraction is obtained from the system of equations:

$$\sin\alpha_i = n_r \sin\alpha_r \tag{7a}$$

$$\frac{1}{n_r^2} = \frac{\cos^2\alpha}{n_o^2} + \frac{\sin^2\alpha}{n_e^2} \tag{7b}$$

where α is the angle between the extraordinary wave normal and the nematic director.

The refraction angle for the ordinary wave α_{or} depends only from the angle of incidence. The total optical path difference Δl between the two waves is :

$$\Delta l = l_{OB} + l_{BC} - l_{OA} \tag{8}$$

where :

$$l_{OB} = \int_o^B n_r \, dl = \int_{o'}^B n_r \sin\alpha_r \, dy + \int_o^d n_r \cos\alpha_r \, dz$$

$$= \int_{o'}^B \sin\alpha_i \, dy + \int_o^d \left(n_r^2 - \sin^2\alpha_i\right)^{1/2} dz \tag{8a}$$

$$l_{BC} = n_{air}(BC) = \sin\alpha_i \left((O'A) - (O'B)\right) = d\sin\alpha_i \tan\alpha_{or} - \sin\alpha_i \int_{o'}^B dy \tag{8b}$$

$$l_{OA} = n_o \, d / \cos\alpha_{or} \tag{8c}$$

so one obtains from eq.8

$$\Delta l = \int_o^d \sqrt{n_r^2 - \sin^2\alpha_i} \, dz - n_o \cos\alpha_{or} d \tag{8d}$$

combining this equation with eq.1 and eq.7b we derive the final expression for the path difference :

$$\Delta l_{\pm} = \frac{d}{I} \int_0^{\theta_2} \sqrt{1 - K\sin^2\theta} \left(\frac{n_o^2}{1 - R\sin^2(\theta \pm \alpha_i)} - \sin^2\alpha_i \right)^{1/2} d\theta \; - \; n_o \cos\alpha_{or} d \tag{9}$$

where $I \equiv I(\theta_1 = 0, \theta_2)$ is given by (2b).

From eq. 9 one can deduce the birefringence between the two twin domains :

$$\frac{\Delta l_{+\psi}-\Delta l_{-\psi}}{d}=\frac{1}{I(0,\frac{\pi}{2}+\psi)}\int_0^{\pi/2+\psi}\sqrt{1-K\sin^2\theta}\left(\frac{n_o^2}{1-R\sin^2(\theta+\alpha_r)}-\sin^2\alpha_i\right)^{1/2}d\theta\ \ldots$$

$$-\frac{1}{I(0,\frac{\pi}{2}-\psi)}\int_0^{\pi/2-\psi}\sqrt{1-K\sin^2\theta}\left(\frac{n_o^2}{1-R\sin^2(\theta-\alpha_r)}-\sin^2\alpha_i\right)^{1/2}d\theta \qquad (10)$$

Using the data of table I for 5CB, we have calculated the effective birefringence $\Delta n=(\Delta l_{+\psi}-\Delta l_{-\psi})/d$ for various angles of incidence. To simplify, we have just considered the case where the incidence angle α_i,comparable to ψ, is small compared to 1 radian, i.e. we have used the approximation $\cos\alpha_i\sim 1$. Δn is shown on fig.6. versus the two parameters ψ and α_i.

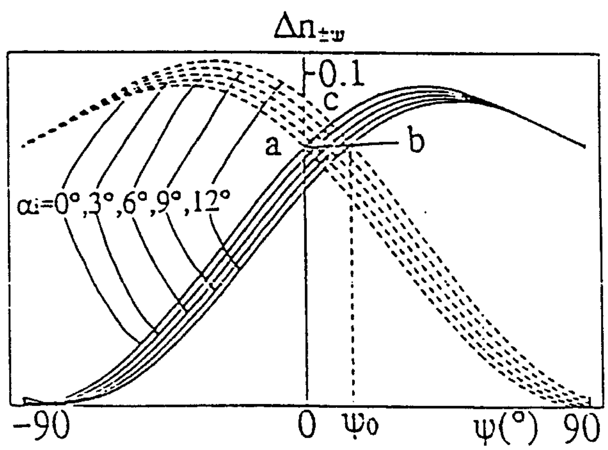

Figure 6 : Absolute birefringence of the twin domains as a function of the tilt angle ψ for different angles of incidence α_i. The ψ axis is referred to the solid lines curves group while for the other group the sign of ψ must be changed. The intersection of the curves corresponding to the same angle α_i are on the straight line ab.

Each group of curves correspond to a texture $\pm\psi$. For the same incidence angle α_i, the two curves $\pm\psi$ intersect, i.e. correspond to the same index, for a given value of ψ. This correspondance $\alpha_i\rightarrow\psi$ is indicated by the dashed line on fig.6 which represents the intersection of all the $\pm\psi$ curves for values of α_i from 0 to 12°, by steps of 3° (line ab). For $\alpha_i=12°$, one finds $\psi_o=14°.7$. As the α_i and ψ values are small, ab is a straight line, and the ratio ψ/α_i for equal contrast between the two domains is $\psi/\alpha_i=\Gamma=14.7/12=1.23$. This ratio can be calculated easely by expanding the equation 6. In the vicinity of $\psi=0$ and $\alpha_i=0$ in the linear approximation, one obtains :

$$\frac{\Delta I}{d}\Big|_{\pm\psi,\pm\alpha_i}=\frac{\Delta I}{d}\Big|_{0,0}\pm c_\psi\psi+c_\alpha\alpha_i \tag{11}$$

The expression of c_α is given by :

$$c_\alpha=\frac{1}{I\left(\frac{\pi}{2}\right)}\left[1-\sqrt{1-K}-\frac{K-R}{\sqrt{KR-R^2}}\tan^{-1}\left(\frac{R}{\sqrt{KR-R^2}}\right)+\frac{R-K}{\sqrt{KR-R^2}}\tan^{-1}\left(\frac{R\sqrt{1-K}}{\sqrt{KR-R^2}}\right)\right] \tag{11a}$$

The equal birefringence condition gives immediatly :

$$\psi=\frac{c_\alpha}{c_\psi}\alpha_i=\Gamma\alpha_i \tag{12}$$

As c_α and c_ψ, Γ depends only on the anisotropy of elastic constants, and on the refractive indices.

If one measures the angle of incidence a_i for equal contrast between the two domains, from eq.12 one can deduce the value of the tilt angle ψ.

EXPERIMENTAL SET-UP

The experiments were performed with cells prepared from two pretreated glass plates. We have used silane coated glass plates to get an homeotropic alignment on the upper surface of the cell. The other plate of the cell was coated by two different methods :

- PVA (Poly Vinyl Alcohol) coating, rubbed after polymerization with a soft cloth. The rubbing was performed always in the same direction, from 30 to 100 times. With this treatment we obtain a quasi planar orientation ($\theta\sim\pi/2$, $\psi\sim0$).

- Evaporation of SiO (50Å) under 74° with the normal to the substrate [11]. This gives a small tilt angle, with the disadvantage to induce a bistable anchoring on the surface.

To check the new method, the thickness of each cell was measured, in absence of liquid crystal, by the observation of Newton's rings[12]. The cells were filled by capillarity with the nematic liquid crystal, pentyl cyano biphenyl (5CB), at

26.9°C. The experimental set-up is a Leitz polarizing microscope with a rotating Feodorov's stage. The zero orientation of the Feodorov stage is checked as follows : We measure the stage rotation (i.e.the incidence angle) at which the twin domains present equal contrast. Then, we rotate the stage by 180° and we remeasure this angle. One finds a half difference of 0.1°, which represents the zero angle residual tilt of the stage compared to the microscope axis. Our data are corrected from this zero offset, which compares with the angular resolution of the set-up.

MEASUREMENTS

For every cell the following procedure is used. The cell thickness is measured in absence of NLC from Newton fringes. To count the fringes, we distort the sample to establish the optical contact between the plates. and get the zeroth order fringe. Then the sample is mounted on the Feodorov's stage. We fill the cell with the NLC. Twin domains are formed. All these domains are separated by disclination lines which move while the NLC is entering the cell. They draw well defined borders between the two textures. If the tilt angle ψ of the twin domains is smaller than ~10°, the large enough metastable $+\psi$ texture appears stable and measurements can be performed. For tilt angles larger than ~15°, or for too small domains, we observe that the $+\psi$ texture desappears quickly and does not permit measurements. We chose for instance a PVA plate rubbed thirty times. The thickness of the cell is d=2.32µm. We measure the absolute optical path difference ($\Delta l_{\pm\psi}$) of each domain with a tilt compensator (Leitz M). We find $\Delta l_{+\psi}$=196.0nm and $\Delta l_{-\psi}$=185.9nm. Proceeding further we tilt the cell until the twin domains present equal birefringence and we measure the tilt angle (α_i) of the cell at this position. We find α_i=1°.70 ±0.05 averaged from four measurements. From the measured values of $\Delta l_{\pm\psi}$ we calculate the tilt angle ψ using the previously described methods :

1) Absolute measurement of birefringence.

From eq.3 and using the value of the thickness d. the obtained tilt angle is ψ=2°.5±0.5.

2) The relative birefringence variation.

From eq.6 and the calculated value of the constant μ=0.012 ψ is found equal to 2°.2±0.1 ;

3) The rotation method.

From eq.12 using the measured value of the rotation α_i and the calculated value of the ratio constant Γ= 1.23, we obtain ψ=2°.1±0.1.
The values of ψ given by the three methods are nearly the same but the accuracy is better for the relative birefringence and the rotation methods. This is due to the fact that in these cases we need not measure the thickness of the cell. The rotation method is in addition much simpler. In the case of rubbed PVA, we observe that the tilt angle increases and decreases with the number of rubbing. This variation will be studied in a next work.

Finally, we have observed that for some samples, the tilt angle seems to change a little with the cell thickness d. The observed general trend is a decrease of ψ for a large d. This variation can be explained by the existence of a finite and relatively weak anchoring : when the extrapolation length L which defines this anchoring[13] compares with d, one expects such a variation. The optical method remains correct, but the measured angle is no more characteristic of the plate alone. To avoid this effect it is necessary to use a cell with a large enough thickness so that the condition d>>L is satisfied. This could be a drawback of the method for very weak anchoring.

The measured values of the tilt ψ for different types of substrates and for the three measurement methods are summarized in table II . For PVA coated surface, we observe only two twin domains while for SiO evaporated surface four domains are observed. They are constituted by the twin domains with an azimuthal angle ϕ=±7°. For each domain, to determine ϕ, we twist the microscope stage to obtain the maximum of extinction. Each twin domain corresponds to one of the two ±ϕ surface anchoring directions of the nematic.

TABLE II : The tilt angle ψ (degrees) calculated for different samples from the three methods.

	PVA number of rubbing			SiO (74°) thickness (Å)	
	30	50	100	40	55
absolute birefringence	2.5	10.3	5.8	4.5	2.9
relative birefringence	2.2	11.2	5.7	4.4	3.
equalization of the birefringence between the twin domains	2.1	11.2	5.7	4.5	3.2

CONCLUSION

We have described a new optical method to measure angular tilts for planar anchored nematic. An hybrid cell with twin domains is made, using the planar plate to be investigated and an homeotropic counter-plate. This cell is rotated until the twin domains present the same birefringence. The molecular tilt angle is proportional to the measured rotation angle of the cell, for tilt angles $\psi<15°$. The coefficient of the proportionality can be calculated from the elastic constants anisotropy and the refractive indices of the NLC or can be measured independently for a given NLC material. The application of this method is simple. The angular accuracy in measuring the tilt angle depends on the angular resolution of the rotating stage, 0.1° in our case. The method does not work for too weak anchorings.

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