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An accurate optical method for measuring the azimuthal anchoring energy of nematic liquid crystals

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In this paper we report an accurate optical method for measuring the azimuthal director angle and the azimuthal anchoring energy for a nematic liquid crystal. The method is fully automated and provides a direct measurement of the azimuthal angle. The experimental procedure exploits the dependence of the reflectivity tensor on the surface director orientation. The measurement of the azimuthal angle does not require any knowledge of the optical parameters of the nematic material or of the substrate, and provides an absolute accuracy better than 0·2° in the whole range 0°–360° and a sensitivity of 0·01°. If the optical parameters of both the nematic sample and the substrate are known, the surface polar angle can also be obtained from the experiment.

1. Introduction

Nematic liquid crystals (NLC) are anisotropic fluids and their macroscopic properties are described by a unit vector field $\mathbf{n}(\mathbf{r})$ which is called *the director* [1]. $\mathbf{n}(\mathbf{r})$ represents the local average orientation of the molecular long axes. The surface alignment $\mathbf{n}_s$ of the director is determined by the competition between surface and bulk interactions. In the absence of external torques, the director is aligned along those directions (*easy axes*) which minimize the anchoring energy $W(\mathbf{n}_s)$ [2]. $W(\mathbf{n}_s)$ is a function of the surface polar angle θ_s and of the surface azimuthal angle ϕ_s, respectively (see figure 1), and represents the work which is needed to rotate the director from the easy axis towards the actual surface orientation. If θ_s is held fixed and equal to the easy polar angle θ_e, $W(\theta_s, \phi_s)$ becomes a function of ϕ_s only, and is called the azimuthal anchoring energy. In the continuum theory [1], the equilibrium director field $\mathbf{n}_{eq}(\mathbf{r})$ is obtained by minimizing the total free energy which is given by the sum of the bulk free energy [3] and of the anchoring energy. Therefore, knowledge of the anchoring function $W(\theta_s, \phi_s)$ is needed in order to make definite predictions about the equilibrium configuration of the director field. Many different experimental methods have been used to measure the anchoring energy. The more accurate methods consist of an optical measurement of the polarization state of either transmitted [4–15] or reflected [16–20] light. In all these cases, a known torque is applied on the director and the consequent rotation of the director at the surface is measured. This torque can be generated either by applying external fields (magnetic, electric) or by exploiting the completion between different surface orientations (hybrid cell [5]).

So far, attention has been mainly focused on measurements of the surface polar angle and of the corresponding polar anchoring energy [4–9, 16–18]. In typical experiments, the NLC is sandwiched between two solid plates and the bulk direction field is characterized by a splay–bend distortion with a constant azimuthal angle and a varying polar angle. The polarization of the transmitted and reflected light is related to the surface polar angles by relatively simple theoretical expressions. Then, from the measurement of the polarization state of the transmitted or reflected light, one can obtain the surface director polar angle.

The same approach can be used to obtain the surface azimuthal angle, but in this case the measurements in transmitted light are more complex [10–15]. In a typical transmission experiment one measures the polarization of a monochromatic beam which is transmitted through a nematic layer where a twist director distortion is generated. The calculation of the dependence of the

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polarization of the transmitted light on the surface azimuthal angles requires a somewhat complex numerical analysis based on the Berreman transmission matrix [21]. This requires a complex fitting procedure to obtain the surface angles from the experimental results. The theoretical analysis becomes much simpler if the director is everywhere parallel to the plates of the cell and the characteristic length L_{dis} of the bulk twist distortion is very much greater than the optical wavelength λ (the Mauguin regime). In this case, if the polarization plane of the incident beam (normal incidence) is parallel (or orthogonal) to the orientation of the director at the first solid–nematic interface, it remains parallel (or orthogonal) to the local director field everywhere. Then, the polarization plane of the outgoing transmitted beam is parallel (or orthogonal) to the director orientation at the second interface. This theoretical result suggests a simple experimental method: the nematic layer is placed between two polarizers and they are rotated until the intensity of the transmitted light vanishes [12]. This occurs if the transmission axis of the first polarizer is parallel (orthogonal) to the director orientation at the first surface and the analyser is orthogonal (parallel) to that at the second interface. Barbero *et al.* [12] showed that the Mauguin regime corresponds to the zero order contribution of an expansion of the Berreman matrix in the small parameter $\alpha = \lambda/L_{\text{dis}}$. They showed that the first order correction to the Mauguin regime is not negligible in most practical situations and simulates an apparent surface rotation of the director which depends strongly on the phase shift $\delta = 2\pi(n_e - n_0)d/\lambda$ between the extraordinary and ordinary optical beams. The first order correction is very large ($\sim\pi/4$) if δ is an even multiple of π, but vanishes if δ is an odd multiple of π. Then, Barbero *et al.* proposed measuring the surface director angle by setting the temperature or the thickness of the NLC layer in such a way as to satisfy the condition $\delta = 2m\pi$. More recently Faetti and Lazzari [14] performed detailed investigations of the properties of a monochromatic beam transmitted by a twisted nematic layer, and compared the experimental results with the numerical predictions of the Berreman theory and with the predictions of the Barbero *et al.* α-expansion. They showed that, except for the special case of a very weak azimuthal anchoring, the quadratic contributions in the small parameter α cannot be neglected. For instance, in the case of a 5CB nematic layer in an external magnetic field of 1 T, the higher order contributions can simulate an apparent rotation of the director at the surface of some degrees. Of course, a direct comparison between the experimental results and the exact theoretical predictions obtained from numerical integration of the Berreman equations makes it possible, in principle, to extract the actual surface director rotation from the experimental data. However, this procedure is long and provides results of poor accuracy except in the case of very weak anchoring energies.

A special and interesting behaviour occurs if the director twist is uniform everywhere in the NLC layer. This happens if the director twist is produced by competition between two different orientations of the easy axes on the two plane surfaces of the NLC layer. In such a special case, the bissectrice of the two surface easy axes is a twofold symmetry axis for the system. In a recent paper, Polossat and Dozov [15] proposed a simple method with transmitted light which exploits only this special symmetry property of a uniformly twisted NLC cell. The main drawback of this technique is that the parameter which is directly measured is the difference between the azimuthal angles at the two interfaces of the NLC layer. Then, the azimuthal angle on one surface can be obtained only if the angle on the other surface is known. This occurs, for instance, if the director is strongly anchored at one of the two interfaces of the NLC layer.

The previous analysis shows that the standard transmission methods for measuring the azimuthal anchoring energy are somewhat complex and require some caution in the analysis of the experimental data. On the other hand, the Polossat and Dozov method is simple and direct, but it does not allow one to separate the effects due to the two interfaces of the NLC layer. In contrast, the measurements in reflected light are simple and provide a direct determination of the azimuthal anchoring energy at a single NLC interface. The principle of the reflection method has been already described by Faetti *et al.* [19]. A linearly polarized monochromatic beam impinges at normal incidence on the interface between an isotropic medium and a nematic liquid crystal. Due to the difference of the reflection coefficients for the ordinary and the extraordinary optical beams, the polarization plane of the reflected beam is rotated with respect to that of the incident beam. For a uniform director alignment of the NLC, the rotation of the polarization plane is related to the surface director angle by a simple theoretical expression. In this case, too, the presence of a sub-surface director twist ($\alpha \neq 0$) gives a correction contribution to the previous theoretical expression. However, the first correction terms are quadratic in the small parameter α and are a hundred times lower than the corresponding second order corrections to the transmission matrix. This is due to the fact that the relevant optical length which enters the correction terms in the transmission expression is $\lambda/\Delta n$, where $\Delta n \sim 0{\cdot}2$ is the anisotropy of the refractive indices of the NLC, while it is $\lambda/n \ll \lambda/\Delta n$ for the reflection expression. Then, the reflectivity matrix is much less sensitive to the bulk director distortion. A direct comparison between the experimental results obtained using the transmission and the reflection methods has been given in [14]. The main drawback of the reflection method is due to the fact that the cell containing the NLC must have a wedge shape in order to separate the optical beams reflected by the different interfaces (air–glass, glass–nematic, nematic–glass and glass–air). In a typical experiment, a magnetic field **H** is applied in order to disorient the surface director, and the consequent variation of the reflected light intensity after passage through a crossed analyser is measured. The resulting accuracy of the measurement of the azimuthal rotation $\Delta\phi_s$ was estimated to be 0·3°–0·4°. This uncertainty can be appreciably reduced by making successive measurements with different orientations of the polarizer with respect to the surface director [19]. This experimental procedure is time-consuming and tedious. Furthermore, it is important to remark that the intensity of the reflected light between crossed polarizers depends on both the azimuthal director angle and the polar director angle. Therefore, the previous reflection method cannot be used to measure the anchoring energy in those experimental situations where both the azimuthal and the polar director angles are changing simultaneously [8].

In this paper we present a new automated experimental method which avoids this tedious procedure and allows us to obtain a very accurate and direct measurement of the surface azimuthal rotation. The present method allows us to separate without any ambiguity the effects of the azimuthal director angle from those of the polar angle. The measurement of the azimuthal angle does not require knowledge of the optical parameters of the NLC and of the substrate. If the characteristic geometric and optical parameters of the contacting media are known, the method also provides a simultaneous and independent measurement of the surface polar angle θ_s. This method can be used to make both static and dynamic measurements of the surface director angles. The incident beam passes through a polarizer which rotates at the angular frequency ω. The reflected intensity is modulated at a frequency 2ω between a maximum (or minimum) value which occurs when the incident polarization is parallel to the surface director and a minimum (or maximum) which occurs when the incident polarization is orthogonal to the surface director. The reflected beam is collected by a photodiode and the oscillating output signal is sent to the AD-interface of a home computer. The output signal is the sum of a constant term and a sinusoidal function of time at the angular frequency 2ω. The phase of the oscillating signal is related directly to the surface azimuthal angle, while its amplitude is related to the polar director angle. Both these parameters (amplitude and phase) are accurately measured making the Fourier transform of the output signal at the frequency 2ω. This kind of procedure provides a sensitivity on the variation of the ϕ-angle of the order of 0·01° and an absolute accuracy of the order of 0·2° in the whole angular range 0°–360°. The accuracy on the measurement of the polar angle is usually much lower and depends greatly on the nature of the interface and on the θ_s-value.

Our paper is organized as follows. In §2 we describe the principle and the basic equations of the reflectometric method. In §3 we describe the experimental apparatus and show a typical experimental result concerning the azimuthal director angle at a SiO–nematic interface. Section 4 is devoted to conclusions.

2. The principle of the reflectometric method

The principle of the reflectometric measurements has been already described in previous papers [18, 19], we thus here recall only the basic features. Consider a monochromatic beam which propagates along the z-axis and impinges at normal incidence on the plane interface ($z=0$) between an isotropic medium and a NLC sample. We denote by x and y two orthogonal axes in the surface plane and assume the director is uniformly aligned everywhere with the azimuthal and polar angles ϕ_s and θ_s, respectively (see figure 1). To be general enough, the isotropic medium can be layered along the z-axis as occurs in the important practical case where a thin isotropic layer of SiO or a thin polymeric layer is interposed between a glass plate and a NLC sample. Due to the anisotropy of the NLC, the reflection coefficients r_0 and r_e for the ordinary and the extraordinary polarization of the incident beam are two different complex numbers. In the special case of a homogeneous non-adsorbing isotropic medium of refractive index n, the reflectivity coefficients are real numbers given by:

$$r_0=\frac{n_0-n}{n_0+n} \tag{1}$$

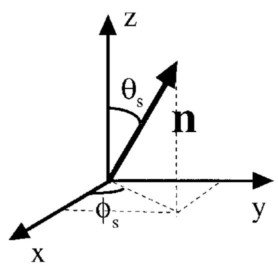

Figure 1. Orientation of the director at the interface ($z=0$) between a nematic liquid crystal medium and an isotropic medium, ϕ_s and θ_s are the azimuthal and the polar angles of the director, respectively.

and

$$r_e = \frac{n(\theta_s) - n}{n(\theta_s) + n} \tag{2}$$

where

$$\frac{1}{n^2(\theta_s)} = \frac{\cos^2 \theta_s}{n_0^2} + \frac{\sin^2 \theta_s}{n_e^2} \tag{3}$$

where n_0 and n_e are the ordinary and extraordinary refractive indices of the NLC. More complicated expressions for r_0 and r_e are obtained in the case where a thin SiO layer or polymeric layer is interposed between the glass plate and the NLC. In such a case, the reflectivity coefficients are complex numbers that also depend on the thickness and the refractive index of the thin layer.

If the incident beam is polarized by a linear polarizer at the angle α_0 with respect to the x-axis, the electric field $\mathbf{E}^r$ of the reflected beam satisfies the simple relations:

$$E_e^r = r_e \cos(\alpha_0 - \phi_s)\mathbf{E}^i \tag{4}$$

$$E_0^r = r_0 \sin(\alpha_0 - \phi_s)\mathbf{E}^i \tag{5}$$

where E_e^r and E_0^r are the components of the reflected electric field with the extraordinary and the ordinary polarization, while $\mathbf{E}^i$ is the amplitude of the incident electric field. If the polarizer rotates with angular frequency ω, the polarization angle $\alpha_0 = \omega t + \phi_0$ is a linear function of time t. Then, the intensity of the reflected beam is a periodic function with frequency 2ω:

$$I^r(t) = I_0[a + b \cos 2(\omega t + \phi_0 - \phi_s)] \tag{6}$$

where I_0 is the intensity of the incident beam and

$$a = \frac{|r_0|^2 + |r_e|^2}{2} \tag{7}$$

$$b = \frac{|r_e|^2 - |r_0|^2}{2}. \tag{8}$$

If the reflected beam passes through a crossed analyser which rotates consistently with the polarizer, the intensity of the transmitted beam becomes:

$$I_{\mathrm{ort}}^r(t) = I_0 c[1 - \cos 2(\omega t + \phi_0 - \phi_s)] \tag{9}$$

where

$$c = \frac{|r_0 - r_e|^2}{8}. \tag{10}$$

The two oscillating signals in equations (6) and (9) contain direct information about the surface director angles ϕ_s and θ_s. The ϕ_s-azimuthal angle is related directly to the phase of the oscillating signals, while the θ_s-polar angle is related to their amplitudes. Indeed the amplitudes b and c in equations (6) and (9) depend on the extraordinary reflectivity coefficient r_e which, in turn, is a function of θ_s. For instance, in the special case of a homogeneous isotropic substrate, r_e is given by the simple form in equation (2).

Note that the measurement of the azimuthal angle using the present method is very direct and does not require any knowledge of the optical parameters of the bounding media (NLC and substrate). Furthermore, a variation of the polar director angles does not affect the measurement of the azimuthal angle. On the contrary, the surface polar angle can be obtained only if the optical parameters of the substrate and of the NLC, and the geometric structure of the interface are known. The θ_s measurement using the method between crossed polarizers [equation (9)] requires also the knowledge of the intensity I_0 of the incident beam. The need for this knowledge can be avoided when only one polarizer is present [equation (6)] if the ratio b/a between the oscillation amplitude and the d.c. component is measured.

Each of the two signals in equations (6) and (9) could be used to measure the azimuthal director angle. In the case where only one polarizer is present, the output signal is the superposition of a constant $I_0 a$ and of an oscillating signal of amplitude $I_0 b$. Then, if $a \gg b$, small fluctuations of the intensity of the incident beam produce a noise $I_0(t)a$ which can reduce appreciably the accuracy of the phase and amplitude measurements. In this special case ($a \gg b$), the measurement between crossed polarizers would be preferred.

Equations (6) and (9) have been obtained assuming that the director field is oriented everywhere along the same direction represented by the two surface angles θ_s and ϕ_s. This condition is certainly not satisfied when the anchoring energy is measured. In this latter case, a torque must be exerted to rotate the surface director from the easy axis. Then a distortion of the director field is present close to the interface and the reflected intensity is no longer given by the simple expressions in equations (6) and (9), but can only be obtained by using the exact Berreman reflection matrix. However, the corrections to equations (6) and (9) depend only on the square power of the small parameter $\alpha = \lambda / L_{\mathrm{dis}}$ and are completely negligible in standard experimental conditions [19, 18]. For instance, for a twisted NLC layer of 5CB with a twist characteristic length greater than $L_{\mathrm{dis}} = 2\,\mu\mathrm{m}$, the higher order contributions simulate an apparent rotation of the director at the surface which is smaller than 0·01°. For a detailed analysis of the effect of the twist distortion we refer the reader to [19], while for the case of splay–bend distortions we refer the reader to [18] and references therein.

3. Experimental apparatus and results

The experimental method we propose here is based on the measurement of the intensity of the reflected beam without a crossed analyser, see equation (6). The same experimental apparatus could be used with small technical changes to measure the intensity between crossed polarizers [see equation (9)]. The material which is used in the present experiment is the nematic liquid crystal 5CB which has a nematic–isotropic transition temperature $T_c = 35{\cdot}3°C$. The reflectometric method requires a wedge shape of the NLC cell to separate the beams reflected by its different interfaces. This is obtained by sandwiching the NLC between two glass plates separated by two mylar spacers of different thicknesses (typically $d_1 = 120\,\mu m$ and $d_2 = 240\,\mu m$) which give a wedge angle of about 0·4° [(see figure 2)]. The glass plate where the optical beam impinges will be here called the first glass plate of the nematic cell. The first glass plate (thickness $h = 1{\cdot}2$ mm) has a wedge shape with a similar wedge angle. Only the intensity of the beams reflected by the first air–glass interface (2 in figure 2) and by the first glass–nematic interface (1 in figure 2) are measured in the present experiment. Let us denote by x and y two orthogonal axes in the plane of the first glass–nematic interface, with the x-axis parallel to the wedge axis. The surfaces of the glass plates in contact with the NLC sample are previously treated by oblique evaporation of a thin layer (10 nm) of SiO at the incidence angle 60° in order to obtain a planar homogeneous alignment of the director along the z-axis. A uniform magnetic field **H** up to 0·75 T can be applied along the y-axis to generate an azimuthal external torque on the director. The nematic sample is placed in a thermostatic box which ensures a temperature stability better than 0·1°C.

The experimental optical apparatus is schematically shown in figure (3). A He–Ne laser beam is polarized by the linear polarizer P, passes through the optical lens L (focal length 1 m) and the tilting compensator C. The beam is then reflected by mirror M_1, passes through the rotating polarizer P_1 and is finally focused on the NLC sample. Polarizer P_1 rotates at a constant angular frequency $\omega = 1{\cdot}043$ rad s^{-1} ($\Delta\omega/\omega < 3 \times 10^{-4}$). The

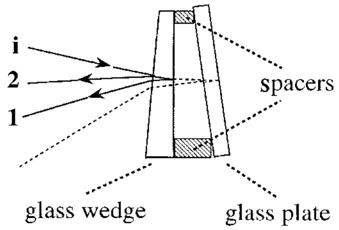

Figure 2. Schematic view of the nematic wedge cell and of the incident and reflected beams. i is the incident beam; 1 is the beam reflected by the first glass–nematic interface which is used for the measurement of the surface director angles; 2 is the beam reflected by the air–glass interface which is used as a reference beam.

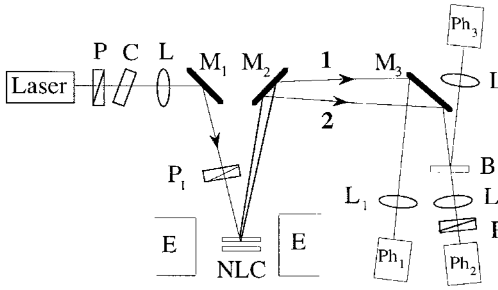

Figure 3. Schematic view of the optical reflectometric apparatus. P, P_1, P_2 = linear polarizers; L, L_1, L_2, L_3 = optical lenses; Ph_1, Ph_2, Ph_3 = photodiodes; C = tilting plate compensator, B = glass beam splitter, NLC = nematic LC cell, E = polar expansions of the electromagnet.

diameter of the laser spot on the NLC wedge is about 0·5 mm. The incidence angle of the laser beam on the interface between the first glass plate and the NLC is lower than 1°. As shown in [18, 19], this small incidence angle can be disregarded and one can assume a normal incidence. The reflected laser beams 1 and 2 in figure (3) are related to the reflections from the glass–NLC and the air–glass interfaces, respectively [see figure (2)]. Beam 1 contains the information about the surface director alignment, while beam 2 is used as a reference phase beam. Beam 1 is reflected by mirrors M_2 and M_3, and is focused by the optical lens L_1 on photodiode Ph_1. Beam 2 passes through the polarizer P_2 and is focused by lens L_2 on photodiode Ph_2. A third reference constant signal, which is proportional to the intensity of the incident light, is obtained by reflecting beam 2 on the glass beam splitter B at a small incidence angle (<2°) and focusing it on photodiode Ph_3. The NLC sample lies between the two polar expansions of a Brucker Electromagnet. The outputs of photodiodes Ph_1 and Ph_2 oscillate at the angular frequency 2ω. The phase of the signal of photodiode Ph_1 is linearly related to the surface azimuthal angle of the director according to equation (6), while that of photodiode Ph_2 is determined by the orientation of polarizer P_2.

Polarizer P and compensator C are introduced to compensate partially the effects due to the small rotation of the polarization plane and the optical dephasing introduced by mirrors M_1, M_2 and M_3. These mirrors were needed in the present experiment due to the geometric restrictions imposed by the dimensions of the optical table ($1{\cdot}5 \times 1{\cdot}2$ m^2) and by the position of the electromagnet on this table. In the absence of these space restrictions, one could eliminate the three mirrors and avoid polarizer P and compensator C. In this case one could use an unpolarized (or a circularly polarized) laser beam which passes through polarizer P_1 and is focused directly on the NLC cell. Then, one could collect directly the reflected beams 1 and 2 on two photodiodes Ph_1 and Ph_2 without using any mirror. In these conditions, the intensity of beam 2 reflected by the first air–glass interface would be independent of the orientation of polarizer P_1. On the contrary, in our experimental geometry, the mirrors change slightly the polarization state of the optical beams and, thus, the intensity of the optical beam which is collected by photodiode Ph_3 changes if polarizer P_1 is rotated. A similar modulation is also superimposed on the signal coming from the reflection at the glass–nematic interface and perturbs the measurement of the azimuthal angle. A partial compensation of these spurious effects is obtained by introducing polarizer P and compensator C and using the following procedure. First, polarizer P is oriented at 45° with respect to the incidence plane on mirror M_1 and the optical axis of the compensator is rotated at 45° with respect to polarizer P. Then, the compensator plate is tilted until a circularly polarized beam is obtained. Finally, the output signal of photodiode Ph_3 is measured when polarizer P_1 is rotating. In these conditions the output is the superposition of a constant signal and a small periodic modulation (about 10%) due to the presence of the mirrors. Then, the orientation of polarizer P, the optical axis and the optical dephasing of compensator C are slightly adjusted in such a way as to eliminate the periodic modulaton at frequency 2ω.

Polarizer P_2, in front of photodiode Ph_2, is introduced in order to obtain a reference signal oscillating at the same frequency 2ω of the measuring signal and with a phase which can be suitably adjusted by rotation of polarizer P_2. The two output signals of photodiodes Ph_1 and Ph_2 are amplified and sent to the numerator inputs of two high precision (0·1%) analogic dividers. The third constant reference signal coming from photodiode Ph_3, which is proportional to the intensity of the incident beam, is amplified and sent to the denominator input of the same dividers. This procedure provides two different signals at the outputs of the analogic dividers which oscillate at the angular frequency 2ω and are insensitive to variations of the intensity of the incident beam. The first is proportional to the intensity of the beam reflected by the glass–nematic interface [equation (6)], the second is an oscillating signal which provides a reference for the phase. These two signals are sent to the inputs of the analogic–digital interface of a PC which is synchronized with the rotation of polarizer P_1. Two (or more) periods of the oscillating signals are acquired at each time with more than 300 measured points for each period. Then, the d.c. components and the amplitudes and phases of the two oscillating signals are obtained from the Fourier transform at the frequency 2ω and the corresponding phase difference $\Delta\phi$ is measured. In order to reduce possible effects due to variations of the rotation frequency of the polarizer, two successive synchronism signals are acquired and the period $T_0 = 2\pi/\omega$ is measured at each time and used to set the frequency parameter 2ω for the Fourier transform. From equation (6), we see that the azimuthal rotation of the director at the surface is related to the measured variation of the phase difference by

$$\Delta\phi_s = \frac{\Delta\phi}{2}. \tag{11}$$

The errors due to neglect of the director distortion in equation (6) are completely negligible in the present experiment (<0·01°). The main sources of uncertainty in the measurement of the surface director angles are related to technical problems such as imperfect rotation of polarizer P_1, imperfect positioning of the incident laser beam at the centre of the rotating polarizer and incomplete compensation of the effects of the mirrors. All these effects can produce a spurious modulation of the experimental signals that affects the measurement of amplitudes and phases. The direct calculation of these error sources is practically impossible, and thus, we have estimated the effective uncertainty in the azimuthal angle using a direct calibration procedure. To do this, we rotated the NLC cell with a precision motorized rotating state which ensures an accuracy better than 0·01°. In the whole angular range 0°–360°, we found that the azimuthal rotation measured by our optical apparatus agreed with the effective rotation of the rotating plate within 0·2°. Therefore, 0·2° represents the absolute accuracy which can be reached with the present apparatus, while the sensitivity is estimated to be about 0·01°. Note that the discrepancy between the measured rotation and the effective rotation depends on the value of the angle $\Delta\phi/2$ between the surface director and the transmission axis of polarizer P_2. In particular, this discrepancy is a maximum for $\Delta\phi/2 = 45°, 135° \ldots$, but is reduced to less than 0·02° for $\Delta\phi < 6°$. Therefore, to have the best accuracy, polarizer P_2 is rotated in such a way that there is a zero phase-shift between the measuring and the reference signals. Then, the magnetic field is switched on and the phase difference $\Delta\phi$ is measured at each acquisition time. Figure 4 shows a typical dependence of $\Delta\phi_s$ on time t when a 0·75 T magnetic field is switched on at $t = 0$ and switched off at time $t = 4h$ for a temperature $T = 31$°C. The surface azimuthal angle reaches the value of 5·8° almost instantaneously and after this starts to increase slowly and continuously with time. According to the analysis reported in [22], only the 5·8° sharp variation is related to the anchoring energy of the NLC, while the slow increase of ϕ_s is due to a slow variation of the easy axis connected with absorption phenomena. The same kind of slow dynamic response is clearly

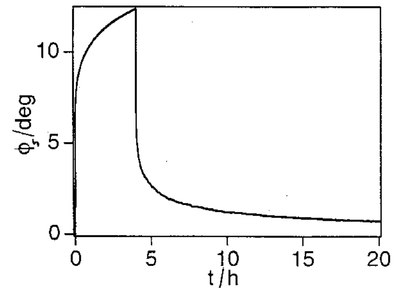

Figure 4. Typical time-variation of the azimuthal surface director angle when a 0·75 T magnetic field is switched on at time $t=0$ and switched off at time $t=3$ h.

observable on switching off the magnetic field. Once the surface rotation $\Delta\phi_s$ is measured, the azimuthal anchoring energy coefficient W_ϕ can be obtained using the theoretical expression [19]:

$$W_\phi = \frac{2(K_{22}\chi_a)^{1/2}}{\sin 2\Delta\phi_s}\mathbf{H} \qquad (12)$$

where K_{22} is the twist elastic constant and χ_a is the diamagnetic anisotropy of the NLC. Equation (12) has been obtained assuming the anchoring energy to be given by the simple Rapini–Papoular form in agreement with previous experimental results [22]. Using the experimental values $K_{22}=2{\cdot}2\times10^{-7}$ dynes [23] and $\chi_a=0{\cdot}97\times10^{-7}$ [24] and the value $\Delta\phi_s=5{\cdot}8°$, we get the azimuthal anchoring coefficient $W_\phi=1{\cdot}110^{-2}$ erg cm^{-2} which is a typical value for this kind of substrate [22].

The present experiment concerns the measurement of the azimuthal anchoring energy. However, the same optical apparatus could also be used to measure the polar anchoring energy. In such a case, the magnetic field has to be oriented at an angle $\beta\neq0$ with respect to the easy axis in the plane xz formed by the normal to the glass–NLC surface and the easy axis. At switch on of the magnetic field, the director polar angle changes. This variation induces a corresponding variation of the ratio b/a between the oscillating and the constant component of the measuring signal. If the optical parameters of the substrate and the NLC are known, the surface director rotation can be directly deduced from the experimental value of b/a. The principle of this measurement of the polar angle is essentially the same as the method which was proposed originally by Langevin-Cruchon and Bouchiat [25] and used by Faetti and Palleschi [18] to measure the director alignment and the polar anchoring energy at the nematic–vapour and the nematic–isotropic interfaces. Therefore, we refer the reader to these papers for details on the accuracy of this kind of measurement. Here we emphasize only that the accuracy of the measurement of the polar angle depends greatly on the kind of interface which is investigated and on the value of the polar angle θ_s. The better accuracy is reached in the case where the bounding medium is a well known isotropic *homogeneous* medium. In this case, the reflection coefficients are given by equations (1) and (2) and the lowest accuracy is reached for the homeotropic ($\theta_s=0$) or the planar orientation ($\theta_s=\pi/2$), whilst the accuracy is greatest if the director angle is tilted at an angle $\theta_s=\pi/4$. The presence of a thin SiO layer can reduce strongly the accuracy of the measurement of the polar angle. Indeed, in such a case, the reflectivity coefficients depend greatly on both the thickness of the SiO layer and its refractive index. Both these parameters are generally known with a poor accuracy. Furthermore, the roughness of the SiO surface introduces a further important parameter which is not easy to assess. Therefore, as far as the polar anchoring at a SiO–nematic interface is concerned, the classical transmission methods provide a better accuracy [4–7].

4. Conclusions

A simple and accurate experimental method for measuring the azimuthal surface director angle at the interface between a solid isotropic plate and a nematic liquid crystal has been described. The method is fully automated and is based on reflectometric measurements. An oscillating signal is detected and its phase and amplitude are measured. The phase depends only on the azimuthal director angle, while the amplitude is related to the polar angle. The principal advantage of this method is that the surface azimuthal angle can be measured accurately without any knowledge of the material parameters of the NLC and of the substrate. Furthermore, in constrast to the previously reported reflectometric method [19], the effect of a variation of the azimuthal angle is completely separated from that of variation of the polar angle. Therefore, this method can also be used to make measurements of the director azimuthal angles in those special cases where both the azimuthal and the polar director angles are changing simultaneously during the measurement [8]. The method provides also a simultaneous measurement of the surface director polar angle if the physical parameters of the interfacial media (refractive indices, geometry) are well known. In the present experimental conditions, the method ensures an absolute accuracy on the surface azimuthal angle of 0·2°; this is greatly increased when small azimuthal rotations have to be measured, as usually occurs for measurements of the azimuthal anchoring energy. The accuracy on the polar angle is lower and depends greatly on the nature of the interface and on the value of the surface polar angle θ_s.

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