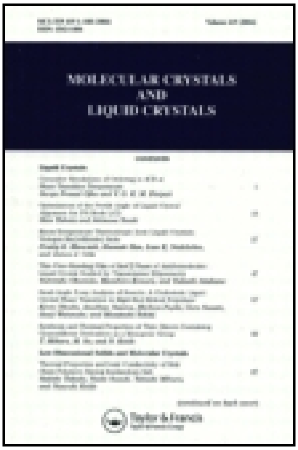

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Observation of Liquid Crystal Alignment in Capillaries Using a New Experimental Approach

Olivier Duhem [a], Jean-Francois Henninot [a], G. Abbate [b] & Marcwarenghem [a]

[a] Laboratoire de Physico-Chimie des Interfaces et Applications (LPCIA), Université dn'Artois, Faculté Jean Perrin, SP 18, 62307, LENS, France

[b] Dip. di Scienze Fisiche, Univ. di Napoli FEDERICO II, Pad. 20, Mostra D'Oltremare, I-80125, NAPOLI, Italy

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Observation of Liquid Crystal Alignment in Capillaries Using a New Experimental Approach

OLIVIER DUHEM[a], JEAN-FRANÇOIS HENNINOT[a], G. ABBATE[b] and MARC WARENGHEM[a,]*

[a] *Laboratoire de Physico-Chimie des Interfaces et Applications (LPCIA), Université d'Artois, Faculté Jean Perrin, SP 18, 62307 LENS, France;*
[b] *Dip. di Scienze Fisiche, Univ. di Napoli FEDERICO II, Pad. 20, Mostra D'Oltremare, I-80125 NAPOLI, Italy*

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In this paper, we report an original fringe pattern observed in the light scattered by a nematic liquid crystal confined in a capillary. Using a fiber properly tapered, it has been possible to obtain a very well collimated and narrow beam that has been driven in a capillary filled with a nematic liquid crystal. This source beam is scattered by the liquid crystal and this scattered light exhibits a fringe pattern. This pattern is experimentally studied and an explanation is given. It is shown how the pattern is correlated with the liquid crystal structure, and in turn how this pattern can be used as a structure explorer.

Keywords: Capillaries; liquid crystal; optical polarizing

INTRODUCTION

The possible configurations for the director of liquid crystals confined in a capillary have been investigated theoretically by several authors, mainly in the frame of defect studies [1–8], orientational transition studies [9, 10] or in an optical point of view [11]. Experimental evidences of some possible structures have been reported [2, 4, 5, 7] using mainly techniques consisting in a visual inspection of the capillary through an optical polarizing microscope. Such an inspection gives a general aspect of the structure and is

*Corresponding author.

generally sufficient to confirm the theoretical model. However, the observed light has traveled through the whole section of the cylinder and therefore carry on informations integrated over that section. What is observed is somehow a conoscopic pattern. It do not give local informations on the structure.

In this paper, we propose an other approach based on the analysis of an original fringe pattern. A narrow collimated beam travelling in the liquid crystal parallel to the capillary axis is scattered, this scattered light presents a modulation along with the capillary axis, it looks like a fringe pattern. This pattern is correlated with the birefringence at the place where the light is scattered and thus yields to informations on the structure that are more local than that reported so far.

The technique used to obtain a well collimated beam is described in the first part: a fiber properly tapered is used to feed the capillary. In a second part, the original fringe pattern is shown and the circumstances under which it occurs are detailed. In a third part, a rapid explanation is given, based on a simple light scattering model. Finally, the potentiality of structure exploration of such an approach is discussed.

1. Collimation of a Beam Using a Tapered Fiber

As it is schematically shown in Figure 1a, the beam emerging out of a normally cleaved fiber is divergent and that spreading is numerically expressed through the numerical aperture NA or an angle of aperture (Θ_f, Fig. 1) the value of which depends on the indices of the core, the cladding and the external material. The monomode propagation can be depicted using the gaussian model in which the energy is supposed to propagate as a gaussian beam with a radius ω_0 different from the core radius **a**, but correlated with it [12]. As the wave is emerging out of the fiber, the gaussian beam propagates freely and the numerical aperture of that beam is connected to its waist as usual in the gaussian optics. By reducing the radius of the core (tapering), we induce a spreading of the energy: the associated gaussian beam radius is larger and as a result of the usual diffraction, the divergence is smaller (Fig. 1b). In fact, in the region where the geometry of the fiber is affected, the energy is no longer guided within the core. As this ≪expanded≫ beam reaches tranversally the limit of the cladding, it can be either reinjected in the cladding and the core or be expelled out of the cladding, depending on the index of the surrounding material. For an external index lower than the cladding one, the energy is totally reflected into the fiber and turns propagating in a multimode regime. On the

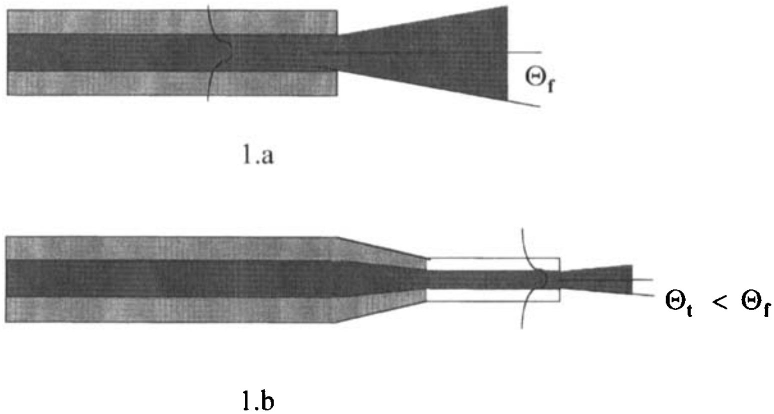


FIGURE 1 Divergence of a beam emerging out of a normal cleaved fiber (1.a) and out of a tapered cleaved fiber (1.b).

contrary, in case of an external indice higher than the cladding one, the energy is partially expelled out of the fiber and a small amount of it is reinjected into the fiber. In any case, the propagation is again almost monomode after a few millimeters in the narrow part: therefore it is sufficient to have that part long enough to ensure the fundamental mode to be prominent [12, 13]. The polarisation at the output of the taper depends on the modes propagating and is not well known, however, one can use a three stage looped-fiber polarization controller to adjust it and to get any elliptical, circular or linear and in any direction [14]. In our experiments, we have used a usual fiber (core diameter: 3 μm; cladding diameter: 125 μm); typically, the narrow part is 1 mm long for a diameter of 20 μm.

2. Fringe Pattern Observed Using ≪Leakography≫

As an optical device is embedded in Liquid Crystal matrice, any light leaking out of the device is scattered by the LC and becomes visible. The observation and analysis of such scattering is what we call ≪ Leakography ≫ [15, 16]. The principle is shown on the Figure 2. While studying the leakage of a taper using this technique, we have observed a fringe pattern as shown on the Figure 3. The geometry associated with this Photo is shown on the Figure 4. The first explanation that comes to mind is an interference between the radiative modes generated in the region where the fiber becomes narrower and the guided mode. Such an explanation is probably wrong. Actually, the guided mode is probably monomode and has a very simple electric field distribution whereas the radiative modes are really complex and

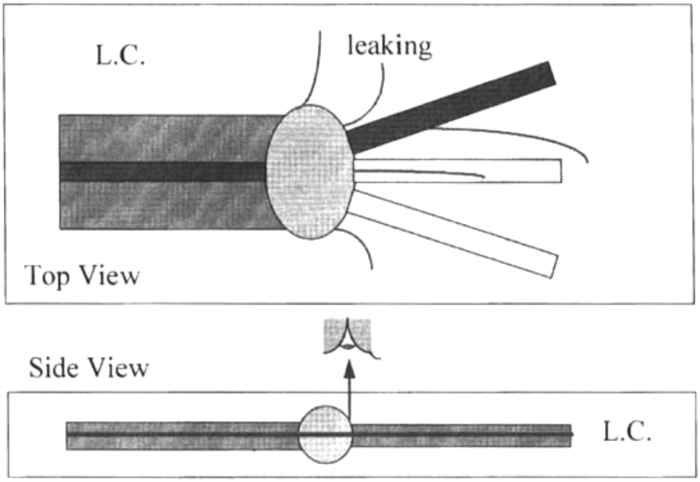


FIGURE 2 Principle of ≪Leakography≫: a device is embedded in a liquid crystal bucket; any light leaking out of the device (symbolized by dark curves) is scattered by the liquid crystal matrice and becomes easily visible from the top.

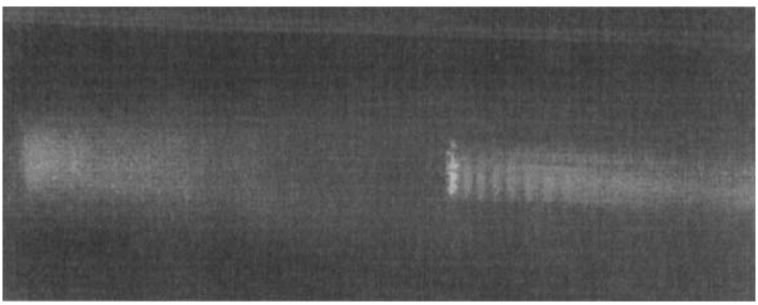


FIGURE 3 First observation of the fringes. The liquid crystal is confined in between the two artificially marked lines (internal diameter of the capillary, 250 μm; (photograph from a ccd camera on microscope)).

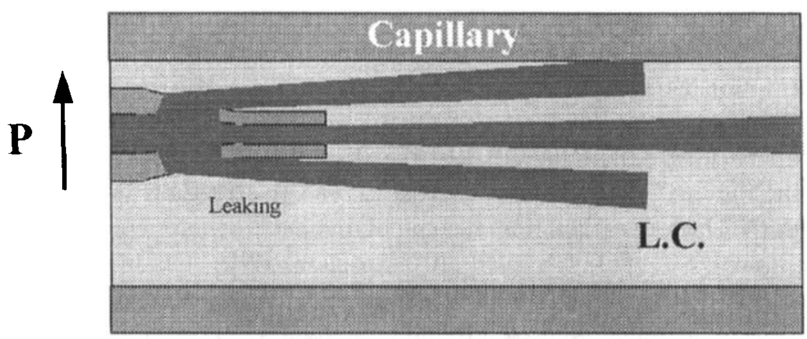
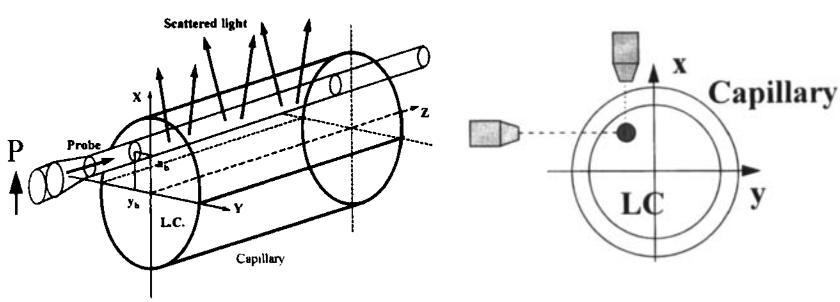


FIGURE 4 Schematic view of the geometry yielding to the Photograph shown on Figure 3.

the field distribution as well. Therefore a simple fringe pattern is very unlikely. Moreover, these contributions have very different intensities and can hardly give a pattern with such a large visibility. To understand the origin of these fringes, we have performed a systematic study of this pattern. The set up we have used is described on the Figures 5. We have devised a taper (the source in the following) that delivers a very well collimated and narrow beam (probe beam, in the following) as explained in the previous section. This source can be translated through the section of the capillary by means of translation stages specially suited for fiber micropositionment. We have observed this beam through leakography, it means we had a look on the scattered light through a microscope, and we looked at it in both directions as shown on the Figure 5b. The inner face of the capillary is treated to get an homeotropic alignment therefore we are left with the so called radial escaped structure [1,2]. This has been checked by straight visual inspection through a polarizing microscope. The Figure 6 shows what we have observed while probe beam is localised close to the inner face of the capillary. Fringe pattern is clearly visible all along with the probe beam propagation. As this probe beam is moved away from the external side of the capillary, the fringe spacing is larger, and the pattern is visible only at the beginning of the path and also in a second part of the path (Fig. 7). As the probe beam is still farther from the side, a beam separation can be observed (Fig. 8). As the probe beam is right in the center of the capillary, the probe beam looks again propagating straightly and no fringe pattern is visible.



5.a 5.b

FIGURE 5 Set-up: the position (x_b, y_b) of the probe beam can be varied using micropositioning stages (5.a). A polarizer is inserted in the fiber to control the polarization state at the entrance of the beam in the liquid crystal. The scattering is observed simultaneously through two microscopes as shown on 5.b.

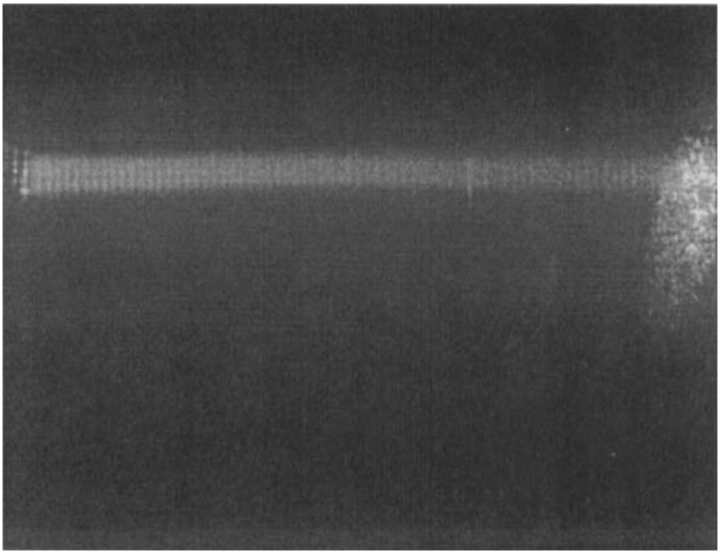


FIGURE 6 Fringes observed as the probe beam is close to the inner face of the capillary; (length of the visualized part: 1mm; photograph from a ccd camera on microscope).

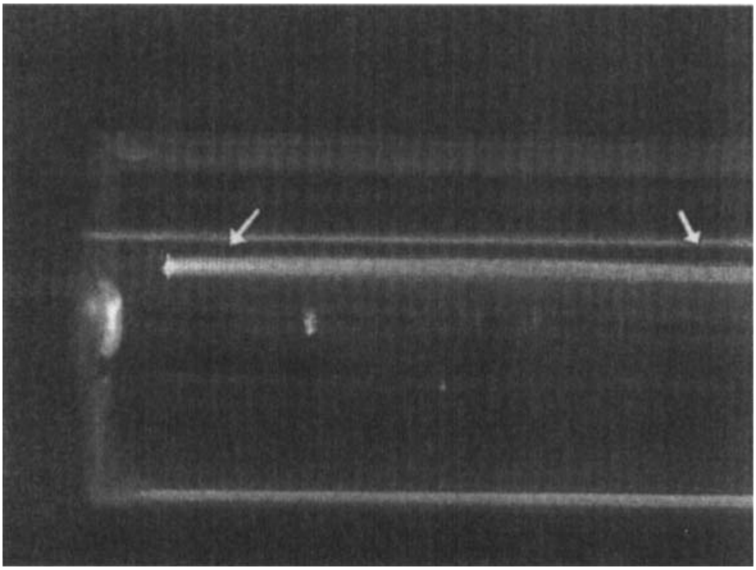


FIGURE 7 Same configuration as the Figure 6, with the probe beam displaced towards the center of the capillary. The fringes are visible only at the beginning and at the end of the probe beam (arrows); (photograph from a ccd camera on microscope).

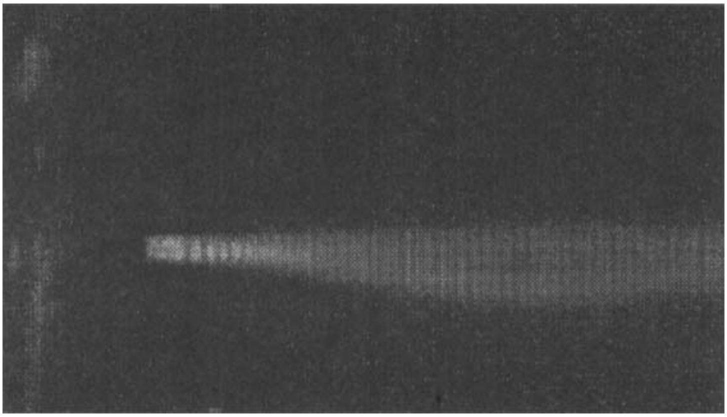


FIGURE 8 The probe beam is now close to the center, in a part where the liquid crystal director is tilted. A beam separation is visible; (photograph from a ccd camera on microscope).

Actually, we have analysed the phenomenon with respect to the birefringence of the NLC, studied the polarisation of the scattered light, the dependence of the visbility of the pattern on the probe beam polarisation and its position in the capillary. Let us gather our experimental observations. The fringe spacing looks inversely proportional to the liquid crystal birefringence: the spacing measured as the probe beam is located at the external part of the capillary, where the alignment of the liquid Crystal is perpendicular to the beam propagation direction, is ten times larger for an eutectic mixture (OS 33 and OS53; Merck) than for the Nematic 5CB having a birefringence ten times larger (5CB : $\Delta n = 0.2$; mixture: $\Delta n = 0.02$). The scattered intensity is the sum of two different contributions: a constant one being polarised in a direction parallel to the capillary axis and a modulated one polarised in a direction perpendicular to the capillary axis. The visibility of the fringes depends on both the polarisation of the probe beam and its location in the capillary. Two general rules can be extracted from our observations: first, as the probe beam is on one of the two axis (*ox* and *oy*, Figs. 5 and 9), the visibility is extremely low, second for any other locations of the probe beam, the fringes are visible whatever the input polarisation is, except for two specific linear polarisations, namely one parallel to the diameter including the probe beam position and one perpendicular to it (Fig. 10, $E_{\text{in,ext}}$ and $E_{\text{in,ord}}$).

Obviously, these observations have to be correlated with the radial escaped structure, anyway, one can give a first interpretation of our observations with a minimum of calculations.

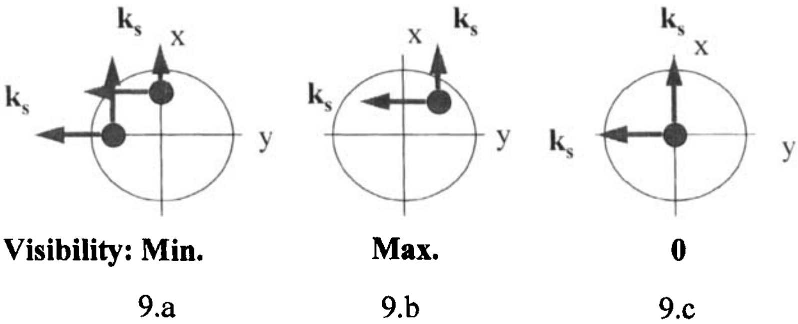


FIGURE 9 Visibility of the pattern; it is minimum as the probe beam is on one of the two diameters (9.a); maximum at 45 degrees away of them (9.b) and definitely zero right in the center. This is valid whatever the input polarization is $\boldsymbol{k}_s$ stands for the scattered wave vector.

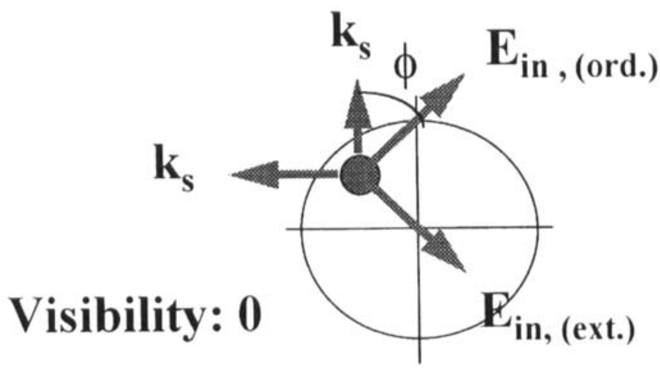


FIGURE 10 The visibility is zero as the input polarization of the probe beam is linear and excites either the ordinary or extraordinary beam in the liquid crystal. This is valid wherever the probe beam is in the capillary.

3. Interpretation

The explanation of the beam distortion is quite obvious if one considers the radial escaped structure: as the probe beam is close to the capillary boundary, it travels through an homogeneous birefringent material, whose the optical axis is perpendicular to the propagation direction. As the probe beam is placed in middle part of the capillary, it experiences a propagation through a tilted optical axis inducing a separation between the ordinary and extraordinary beam: the name birefringence comes from this separation!. The extraordinary beam travels through an inhomogenous and is bent due to the index gradient (the tilt angle of the director varies from the center to the external part of the capillary: radial escaped structure). The fringe pattern is visible only at the place where the two beams (ordinary and extraordinary) are overlapping. As the beam is travelling right in the middle of the capillary, it travels through an homeotropic material (isotropic-like) and no separation occurs.

The fringe pattern concerns the light scattered by the material, namely the liquid crystal. It can be understood how the phase shift due to the birefringence is contained in this intensity through few calculations [see for instance [7] and [17]]. Let us focus on the simplest case where the probe beam illuminates the outer part of the capillary, with an elliptical input polarisation. In that part, the probe beam experiences a propagation through an homogeneous birefringent material with an optical axis aligned perpendicular to the propagation direction. The scattering geometry is depicted on the Figure 11.

The scattered field is proportional to both the input one and the fluctuation part of the dielectric tensor (1) which is itself connected to the director fluctuation (2)

$$\vec{E}_S \approx \delta\varepsilon \cdot \vec{E}_i \tag{1}$$

$$\delta\varepsilon_{ij} \approx \varepsilon_a \cdot (n_i \cdot \delta n_j + n_j \cdot \delta n_i) \tag{2}$$

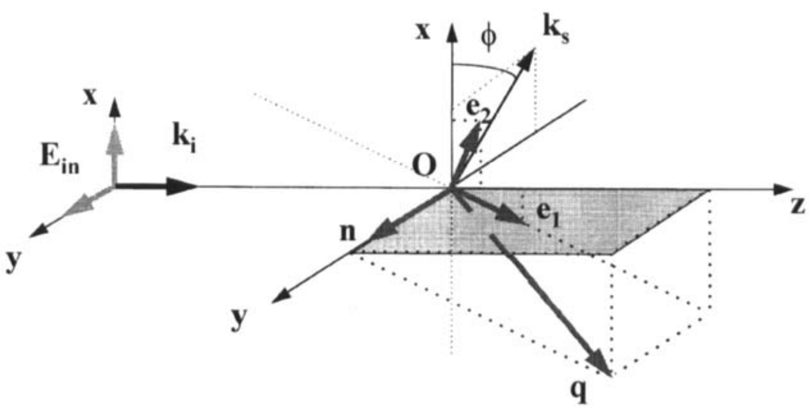


FIGURE 11 Scattering geometry. The oz direction is the capillary axis, the (oy, oz) plane is a diametral section of the capillary. The director direction corresponds to a probe beam close to the outer part of the liquid crystal. As the probe beam is shifted towards the center of the capillary, the director will be tilted in the plane (oy, oz), due to the escaped structure. Right in the center, the director is parallel to oz. The scattered wave vector $\boldsymbol{k}_s$ lies in the (ox, oy) plane. The so called de Gennes frame $(\boldsymbol{n}, \boldsymbol{e}_1, \boldsymbol{e}_2)$ is such as the vectors $\boldsymbol{e}_1$ and $\boldsymbol{e}_2$ lie in the (ox, oz) plane.

That fluctuations at the first order are such as:

$$\vec{n} \cdot \delta\vec{n} = 0 \tag{3}$$

as a result, the fluctuation part of the dielectric tensor reduces as:

$$\delta\varepsilon = \begin{bmatrix} 0 & \delta\varepsilon_1 & 0 \\ \delta\varepsilon_1 & 0 & \delta\varepsilon_3 \\ 0 & \delta\varepsilon_3 & 0 \end{bmatrix} \tag{4}$$

It is worth noticing that the null terms are at the same place in the tensor in our frame or in the de Gennes frame. For an input electromagnetic field $\boldsymbol{E}_i$, the scattered field $\boldsymbol{E}_s$ is given by:

$$\vec{E}_i = \begin{matrix} E_{i1} \\ E_{i2} \\ 0 \end{matrix} \qquad \vec{E}_S \approx \begin{matrix} \delta\varepsilon_1 \cdot E_{i2} \\ \delta\varepsilon_1 \cdot E_{i1} \\ \delta\varepsilon_3 \cdot E_{i2} \end{matrix} \tag{5}$$

If one consider the component of that field polarised parallel to the capillary axis (oz axis), one gets:

$$E_{\mathrm{II}} \approx \delta\varepsilon_3 \cdot E_{i2} \tag{6}$$

Whereas the component polarised perpendicular to the capillary axis is expressed as:

$$E_{\perp} = E_{S1} \cdot \mathrm{Cos}\,(\phi) + E_{S2} \cdot \mathrm{Sin}\,(\phi) \approx \delta\varepsilon_1 \cdot (E_{i2} \cdot \mathrm{Cos}\,(\phi) + E_{i1} \cdot \mathrm{Sin}\,(\phi)) \tag{7}$$

The intensities that are actually observed are the moduli of that fields, thermally averaged:

$$I_{S\mathrm{II}} \approx \langle|\delta\varepsilon_3|^2\rangle \cdot |E_{i2}|^2 \tag{8}$$

$$\begin{aligned} I_S \perp &\approx \langle|\delta\varepsilon_1|^2\rangle \cdot |E_{i2} \cdot \mathrm{Cos}(\phi) + E_{i1} \cdot \mathrm{Sin}(\phi)|^2 \\ &= \langle|\delta\varepsilon_1|^2\rangle \cdot \Big[\mathrm{Cos}^2(\phi) \cdot |E_{i2}|^2 + \mathrm{Sin}^2(\phi) \cdot |E_{i1}|^2 + 2 \cdot \mathrm{Sin}(\phi). \\ &\cdot \mathrm{Cos}(\phi)\mathrm{Ree}(E_{i2} \cdot E_{i1}^*)\Big] \end{aligned} \tag{9}$$

Obviously, the parallel component is constant with respect to z, whereas the perpendicular one is modulated due to the cross term $E_{i2} \cdot E_{i1}^*$. These two components are phase shifted, and the phase shift is given by:

$$\varphi = \varphi_{\text{ini}} + \varphi(z) \tag{10}$$

where the first term corresponds to the initial phase shift at the entrance of the probe beam in the capillary-it can account for any elliptical polarisation, the second one accounts for the free propagation of the probe beam in the liquid crystal (for instance, in an homogeneous medium, it writes: $2\pi/\lambda . \Delta n . z$, where Δn is the actual birefringence).

The results can be pictured out in an optical point of view in saying that both ordinary and extraordinary input components will give rise to two scattered beams. In such a geometry, the ordinary component (E_{i1}, in 5) will only give an extraordinary beam ($\delta\varepsilon_1 \cdot E_{i1}$ in 5) whereas the extraordinary input beam (E_{i2}, in 5) will have two scattered components, one in the direction ox ($\delta\varepsilon_1 \cdot E_{i2}$ in 5) and the oz direction ($\delta\varepsilon_3 \cdot E_{i2}$ in 5). While averaging, a cross term of the two components in the xy plane will remain, carrying a phase difference: everything works as if one have to sum up the amplitudes and not the intensities.

In the expression (9) the cross term, which is responsible for the fringe pattern, will vanish under two different conditions: for a ϕ angle equal to 0 or 90 degrees or for one of the two components E_{i1} or E_{i2} equal to zero. The first corresponds to a probe beam located on one of the two lines of ≪ no visible pattern ≫ (Fig. 9), and the second corresponds to a probe beam linearly polarised with the polarisation direction parallel or normal to the director (only one ordinary or extraordinary-beam excited). This is consistent with the observations reported above.

DISCUSSION

Having understood the origin of these fringes, they can be used to analyse the structure of a liquid crystal in more complex confinements. Mainly, two rules have to be exploited in such an analysis. First, the existence of the fringe pattern, connected with the polarisation and the general structure as developed above; shortly, both ordinary and extraordinary beams have to be excited simultaneously to observe the pattern. Secondly the fringe spacing is inversely proportional to the local birefringence: that spacing can easily be measured at different points of the probe beam, using any image processing. A constant spacing reveals a constant birefringence, in other words a uniform director distribution, on the contrary any distortion in the director distribution will result in an non constant fringe spacing. It is worth noticing that such an analysis can be done on a slowly varying process such as reorientation: a comprehensive study of the spacing versus time and position in the capillary can give very interesting informations on the transient structure.

Finally, it should be noticed that this observation is similar to what has been observed in a birefringent fiber while looking at 45 degrees from the optical axis of the fiber: the fiber is feed with a circularly polarised light and during its guided propagation, it becomes linearly polarised at 45 degrees from the principal lines: in that case no light is scattered along with the electric field direction and a dark spot is observed [12]. The process involved is in that case the Rayleigh scattering whereas in our observation it is the dynamic scattering of nematics.

In both cases, scattering allows to visualize the propagation in a birefringent material and the evolution of the polarisation during the propagation: guided in the case of the birefringent and free propagation in our case.

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