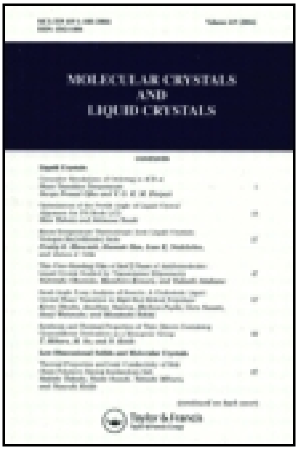

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Bulk Optical Fréedericksz Effect: Non Linear Optics of Nematics Liquid Crystals in Capillaries

M. Warenghem [a], J. F. Henninot [a] & G. Abbate [a b]

[a] Laboratoire de Physico-Chimie des Interfaces et Applications (LPCIA) Faculté des Sciences, Université d'Artois, SP 18, F.62307, LENS Cedex, FRANCE

[b] INFM unità di Napoli and Dip. di Scienze Fisiche, Università di Napoli, FEDERICO II Pad. 20, Mostra d'Oltremare I, 80125, NAPOLI, ITALY

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BULK OPTICAL FRÉEDERICKSZ EFFECT: NON LINEAR OPTICS OF NEMATICS LIQUID CRYSTALS IN CAPILLARIES

M. WARENGHEM, J.F. HENNINOT, G. ABBATE°,
Laboratoire de Physico-Chimie des Interfaces et Applications (LPCIA)
Faculté des Sciences, Université d'Artois
SP 18; F.62307, LENS Cedex; FRANCE
° INFM unità di Napoli and Dip. di Scienze Fisiche;
Università di Napoli; FEDERICO II Pad. 20, Mostra d'Oltremare
I 80125 NAPOLI, ITALY

We investigated the behavior of a beam experiencing the Optical Fréedericksz effect while traveling through a nematic liquid crystal confined in a capillary and doped with a dye. The source is a specially tapered fiber that delivers a narrow and well collimated beam. We present the results we obtained with two different nematics, having different birefringence and aligned in two different ways along with the capillary wall. In the case of an alignment normal to the wall (radial escaped structure), we observed an optically induced displacement of the homeotropic central part of the structure and even a splitting of it. In the case of a planar alignment (fully axial structure), we observed a self focusing and a « selfwaveguiding » behavior, different from the usual filaments. We also give an experimental evidence of the difference between the Fréedericksz threshold and self trapping threshold. In both cases, the light acts on a larger volume than the so far reported non linear optics experiments, therefrom the title. Our results are compared with those obtained in a similar geometry and a pure nematic by other authors. Finally, the non linear behavior of the liquid crystal is discussed.

INTRODUCTION

Up to now the experiments in the nonlinear optics of liquid crystals (LC) have been performed on films and the results of the light-matter interactions have been observed outside of the material and either the far or near field of the impinging beam are considered. A review of the works done in the field is beyond the scope of this paper, however, the reader can refer to the existing reviews [1 - 2] or to some chapters of general text books on liquid crystals [3,4]. The major groups working in this field have published most of their recent results in the previous OLC proceedings [5]. A geometry different from a film was first considered few years ago: it consists in a cylindrical one and the pump beam is traveling along with the axis of the cylinder. Some interesting behavior was reported and focusing, undulation and filamentation was observed [6] and then explained [7 - 10]. Although the calculations are scaled with respect to the transverse size of the used tube and the given explanations look universal, we planed to explore an identical geometry with different dimensions. In addition, it is interesting by itself to check whether the Bulk Optical Fréedericksz Effect acts in the same way in a pure nematic and in a dye doped mixture. Besides the liquid crystal characteristics, the pertinent parameters the effect depends on are the film thickness and the boundary conditions: the thickness is extremely large compared with the beam size and the radial size of the capillary is large as well. As a result, the main torque acting on the director is the optical torque and one expect the observed phenomenon to be dependent mainly on the bulk liquid crystal parameters, therefrom the title. Finally, we stress the support that this kind of experiments can give to the theoretical studies of defects behavior in LC confined in capillaries.

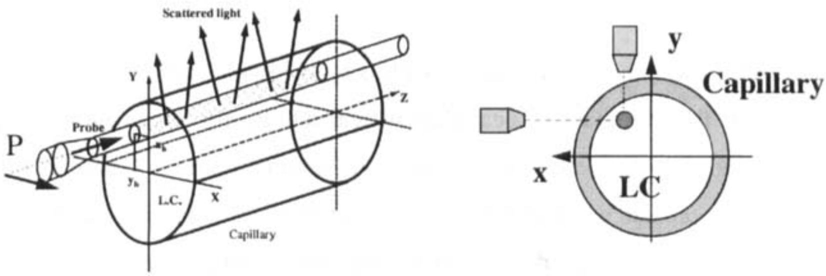
This paper is organized in three main parts: in the first one, we explain how we performed the experiments and in the next two, the results obtained in two different geometries, namely the so called radial escaped geometry and a planar axial one. From the Fréedericksz effect point of view, the first one is a non threshold geometry whereas the second is a threshold one.

So let us first describe the experimental set-up.

I. SETUP

The set up we have been working with is quite simple and it is depicted on Figure 1. The inner face of a capillary is treated to get the alignment we want, then filled with the material we choose and illuminated with a source. A fiber which was tapered under specific conditions then cleaved provides a beam the width of which is smaller than the taper diameter (~10μm). Depending on the taper geometry, the different indices of refraction of the fiber and of the used liquid crystals, the outcoming beam can be very well collimated [11]. Such a tapered fiber, fed with the green line of an Ar^{+} cw laser, is referred as the source in the following. It should be stressed that the geometry of the taper and the way the source is introduced in the capillary allows to select the mode that will emerge out of the fiber. In addition, the polarization of this beam can be adjusted either with a normal polariser or with a three loops system. After all the optical components, the available power at the output of the taper is in the range of 0 to 6 mW. By means of different micropositioning stages, this source can be oriented to emit in a direction parallel to the capillary axis (oz, Fig. 1), placed roughly in the middle of the capillary and displaced accurately in the section of the capillary (ox, oy, Fig. 1). Finally, it can be also displaced along with the capillary axis, allowing the source to enter the liquid crystal more or less deeply (oz, Fig.1). We performed all the experiments with 250 μm internal diameter capillaries and a source with a diameter around 10 μm.

This set up is installed on a polarizing microscope in such way that the capillary axis lies parallel to the microscope stage. We made the observations by means of the microscope lamp light or just collecting the light coming from the source beam and scattered by the liquid crystal in the oy direction (Fig.1b). This is what we call « leakography »[12]. We also set up a second microscope in the perpendicular direction (ox, Fig.1b) to spot the source beam properly and to observe the system from another point of view.



1.a 1.b

FIGURE 1. Setup; 1.a: side view ; 1.b: section view.

A fringe pattern that reveals the evolution of the polarization of the beam during its propagation can be seen in the scattered light. We showed that these fringes are visible only when both ordinary and extraordinary rays are excited and the fringe spacing is inversely proportional to the local birefringence [11]. In the present paper, this result is used to determine whether the input beam polarization excites simultaneously the ordinary and extraordinary components or not: the observation of a fringe pattern reveals that the input polarization excites both.

The LC's that have been used are either the well known 5CB or a mixture of OS53 and OS33 from Merck. The first material has a birefringence of about 0.2 whereas for the second mixture it is one order of magnitude lower (~0.02). The ordinary index of the 5CB is 1.53, the mixture index is equal to that of the fiber core, namely 1.46, which means a quasi perfect index matching and, in term of numerical aperture, the beam entering the liquid crystal is slightly divergent for the 5CB and almost not for the mixture. We doped these LC's with small amounts of an anthraquinone dye (AQ1) in different concentrations, up to 0.7% w/w. The real part of the doped nematics refractive indices were measured and are not different from the pure hosts. It is now well known that it is possible to observe the Optical Fréedericksz Transition with a mW laser [13] in these doped materials. The way to align the doped LC's is described in the two next sections devoted to the experimental results and the interpretations.

II. RADIAL ESCAPED STRUCTURE

We first treated the inner face of the capillary to align the director normal to this surface, using lecithin. The obtained configuration is the well known radial escaped structure [14 - 15]. The correct alignment is checked by a direct visual inspection of the capillary (Figure 2).

For our purpose, the Optical Fréedericksz Transition (OFT) can be reduced to its two main features. The first one is the existence of an optical torque which forces the director to align parallel to the optical electric field and the second is the fact that this reorientation occurs above a threshold intensity in the case of a director initially aligned perpendicularly to the optical field. Balancing the optical torque with the surface and bulk elastic torques, it is possible to picture out what is supposed to occur in term of Optical Fréedericksz Transition (OFT). So let us first describe a qualitative scenario.

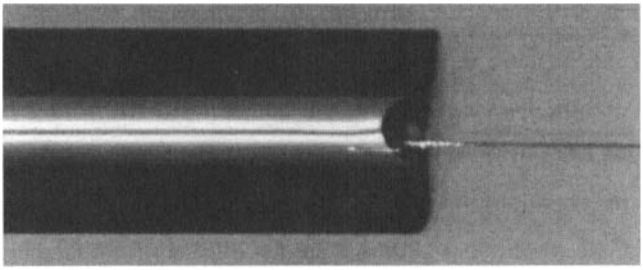


FIGURE 2. Photograph showing the capillary filled with nematic: the central homeotropic zone is clearly visible. On the right, it can be seen the taper (source) not yet entered the capillary. (Internal diameter of the capillary : 250μm).

II.1 BOFE and Radial escaped structure: what is expected?

In this section, we consider only our experimental situation where the source beam is linearly polarized in the oxz plane (Fig. 1) and displaced along with the ox axis. All other situations are more complex in term of OFT and have been disregarded in this paper. First, the initial alignment of the director with respect to the optical field depends on the position of the source beam with respect to the central axis of the capillary. For a beam located at the external part of the capillary (Fig. 3), nothing special should occur, the director being already aligned parallel to the optical field. As the beam is displaced towards the center (Fig. 4a), one expect a reorientation of the director without any threshold, the director being initially tilted with respect to the optical field. Such a reorientation should be revealed by a shift of the homeotropic[1] zone which is in the middle part of the capillary in absence of any perturbation (Fig. 4b). Such a drift do not generate conflictual situations in term of defects, even pictured in the oxy plane (Fig. 4c) ; given the size of the capillary, the induced distortions can be easily elastically damped. As the beam is right in the center of the homeotropic zone (Fig. 5a), both boundary and optical field act in the same sense and one should have a situation as depicted in figure 5b. If one considers a two dimensional picture (i.e. in the section of the capillary), things are a bit more tricky: one can expect the creation of two defects or more distorted zones (Fig. 5c).

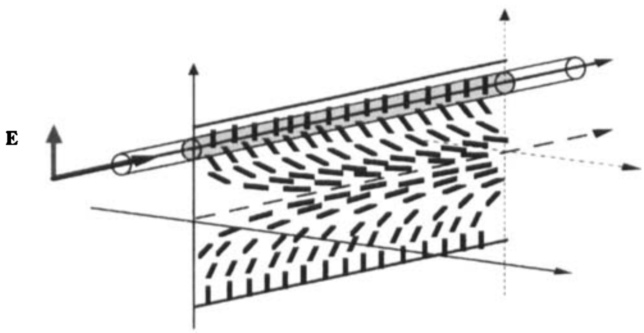


FIGURE 3. As the source is on the external part of the NLC, the director is properly aligned with respect to the optical field and no reorientation is expected.

Such a splitting might take place only in the case of a perfect symmetry, where the beam is exactly centered on a completely aligned nematic. In all other slightly asymmetric situations one can expect a shift of the homeotropic zone as explained before which costs less in energy than defects creation.

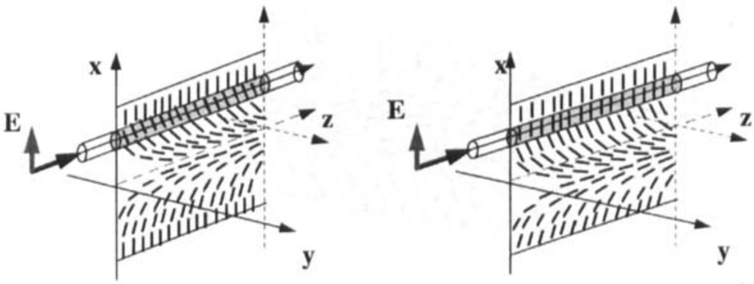
Actually, this sketch has to be completed, accounting for the presence of the dye: there will be some non negligible thermal effects. As long as the isotropic phase do not appear, the qualitative scenario is still correct. However, due to the absorption, depending on the dye concentration, the optical field intensity decreases along the z-axis, until it drops down below a threshold value. One therefore expects that the drift of the central homeotropic zone exists over a finite length, which depends on the dye

[1] Let's call homeotropic a director alignment parallel to the light propagation direction

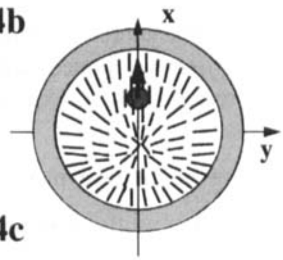
concentration. We now present the experimental results we obtained with this material.

II.2 BOFE and Radial escaped structure: experimental observations.

All the above described scenario was effectively observed: almost no change as the source is very close to the capillary wall, the drift of the central homeotropic zone

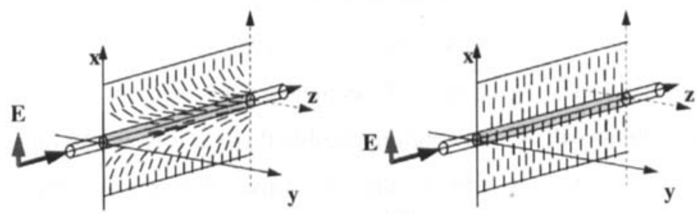


4a 4b

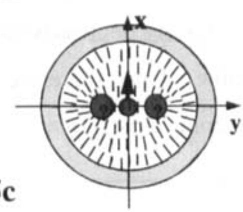


4c

Figure 4.
a: initial alignement
b, c: expected alignement.
The central homeotropic zone should drift away from the beam.



5a 5b



5c

Figure 5.
a: initial alignement
b, c: expected alignement.
The central homeotropic zone can be split in two zones.

for an intermediate position of the source (Fig. 6) or the splitting of this zone as the source is right in the middle of the capillary (Fig.7). The response time of the reorientation is of the order of magnitude of the second. It is worth noticing that in the latter case, it seems that it is still a non threshold effect: this is probably due to the fact that in the tube-like volume covered by the source beam, the director is not strictly parallel to the capillary axis, especially in the outer part of the beam.

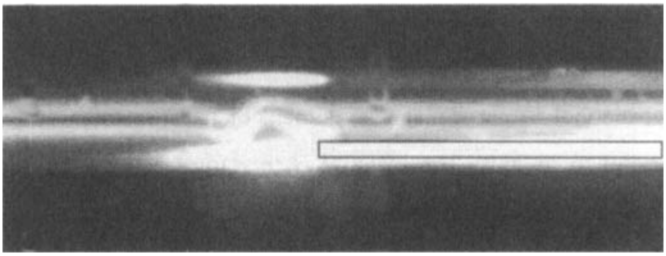


FIGURE 6. Light induced deformation of the central homeotropic zone in a radial escaped structure: the source is artificially marked. It looks close to the capillary wall due to the lens effect of the capillary, it is in fact in between the center of the capillary and its wall. The bright spot that can be seen in the upper part is a ghost also due to the cylindrical optics. Linear polarization in the plane of the figure.

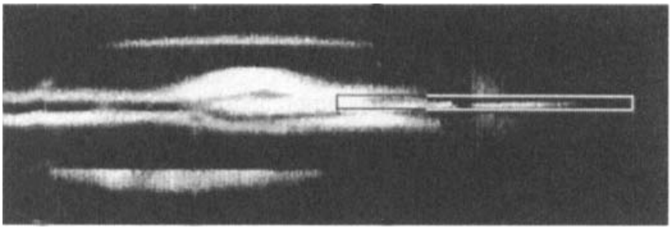


FIGURE 7. Same configuration as in the Figure 6, the source is now placedright in the center of the capillary. The light induced reorientation results in a splitting of the homeotropic zone. The two branches of the distorted zone are not exactly lying in the plane of the figure.

We were also able to optically displace the point defects which can exist in such a structure. We will not enter in these details now, we only underline the perspectives opened by this capability in the study of LC defects.

We now focus on the second geometry, in which the director is aligned parallel to the capillary axis.

III. FULLY AXIAL STRUCTURE.

We treated the inner face of the capillary using the usual technique of the polyvinyl alcohol to get a planar alignment of the director on the capillary wall, parallel to its axis. The material is therefore seen by the beam as an homeotropic material wherever it is located in the capillary.

Although this geometry is the same as the one studied by the Libchaber's group [6 - 10], it should be noticed some differences. Both the radial size of the capillary and the beam size are smaller, though the ratio is quite the same, however we found different results. Thermal effects have to be considered for two reasons: the capillary is not cooled and the absorption of the dye is responsible for a local heating. This absorption makes all the variables of the problem z dependent. In addition, the range of energy explored is probably different in terms of ratio input energy/Fréedericksz threshold energy. Anyway a more comprehensive comparison, taking into account also a numerical modeling of the experiments, will be given in a forthcoming paper.

In a Fréedericksz transition point of view, this configuration is a definitely threshold one and it is very similar to an homeotropic thin film illuminated under normal incidence, apart the totally different boundary conditions, that make this geometry attractive. It is possible to roughly scale the Fréedericksz threshold. In the case of a very thin film compared with the beam radius, the radial dependence of the director can be disregarded and an exact variational calculation leads to a threshold value that scales as $1/d^2$, the inverse squared thickness. In the reverse case of a very thick film, the radial dependence is now crucial and an exact calculation is extremely unlikely. However, it has been shown that in the case of a ribbon shaped beam [1], the Fréedericksz threshold scales as: $\propto [1/d^2 + 1/\omega^2].K/\Delta\varepsilon$, with ω the characteristic transverse length of the ribbon. This result is also valid in a 2 dimensional configuration. An Italian group arrives at an identical conclusion in the case of planar waveguides [16]. A quite comprehensive numerical calculation on this geometry has been also published [17]. In our geometry, we are obviously confronted with this large thickness case with the condition that the thickness is actually extremely large. Therefore the intensity threshold will likely scale as $\propto [1/\omega^2].K/\Delta\varepsilon$, which means that when we consider a power threshold, the latter is dependent only on intrinsic parameters of the liquid crystal $P_{Fr} \propto K/\Delta\varepsilon$, at least in a first approximation. Again, it should be taken into account in our geometry the presence of dye and the presence of the capillary wall which stabilizes the structures and plays a major role in the non linearity of the nematic.

As in the first section, using some simple physical arguments, we propose to picture out what is expected to occur as the input power is increased.

III.1 BOFE and Fully axial structure: what is expected?

The dye was chosen to get a positive Kerr-like medium. This medium becomes non linear above a threshold power which we call the Fréedericksz threshold power P_{Fr}. As the input power equals the so called critical power or self trapping power P_{st}, the focusing property of the Kerr-like material just overcome the natural diffraction of the beam. For input powers larger than this P_{st}, the beam is actually self-focused. For higher powers, the beam can be confined in some tubes: we get the so called filamentation. Somehow the light has built up its own cylindrical waveguide. To these considerations which are usual in non linear optics, we have to add the liquid crystalline behavior. The non linearity is originated from the light induced director reorientation which optically results in a distribution of the effective extraordinary index which thus depends on the spatial coordinates and parametrically on the source intensity. The resulting non linear part of the index depends on both the radial distribution of the director and on the birefringence of the material and it cannot always be written as $n_2.I$ (I is the input intensity), especially for large reorientations which is exactly what it is observed here. As already stated in another paper [7], a nematic LC is a Kerr-like material only in a first approximation, in a small range of input powers. One can however keep working with the usual expression for the index with a non linear part (n_2) which we know to be potentially intensity dependent. We have to add the thermal fluctuations that make the material optically « unstable » either because the cavity is large compared to the usual coherence length or because the working temperature is close to a phase transition. Let us finally add some dye specificities. First the absorption induces a z dependence of the different parameters of the system, mainly the locally available power decreases along with the capillary axis. Second, we used the argon green line which is partly scattered by the liquid crystal and partly absorbed by the dye molecules and the excited molecules return it partly by fluorescing, in our case, in the red region. So by properly filtering, one can observe either the scattered green light, the red fluorescence of the dye or both.

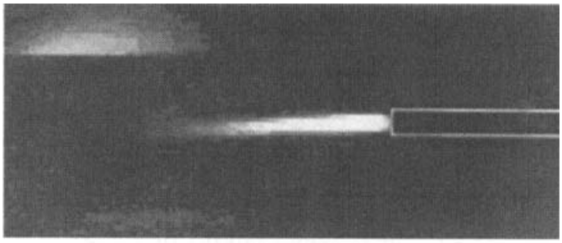
We now report the experimental results

III.2 BOFE and Fully axial structure: experimental results and interpretation.

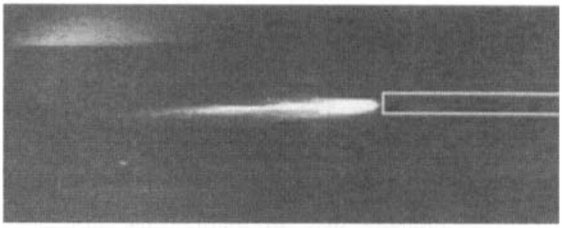
We worked with two different materials (5CB and mixture of OS33 + OS53) doped with the AQ1 dye to have the Fréedericksz threshold as low as possible and to bring to the fore the main features of the BOFE in dye doped LC. The results being notably different for the two mixtures, we present our results in two separated paragraphs.

III.2.1. a. Mixture OS33 + OS 53: experimental results.

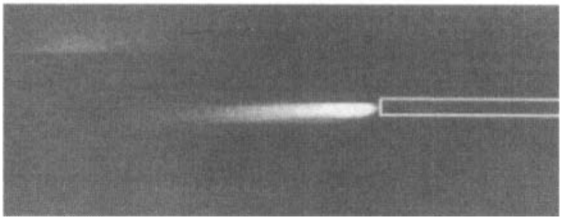
For this material, we increased the input power from 0 to 6mW at different rates. One can consider two different regimes, low rate and high rate. In this preliminary work, we did not focus on the quantitative aspect, so we do not give a numerical value for the increasing power rate limiting both regimes, this limit being readily understandable as it is explained hereafter. As the input power is increased fast enough, the beam focuses sharply and then relaxes practically immediately (high rate regime; Figure 8). If the power is changed more slowly (low rate regime), the focusing is practically invisible, looking even not existing, at least in the limits of our set-up accuracy. In fact, we cannot stabilize the focusing, whatever the power increase rate is.



8a



8b



8c

FIGURE 8: 8.Sequence observed for the mixture (OS33 + OS53 + AQ1; 5/100) for increasing input powers. Photographs digitalized from a video recording, time interval between photos: 5 video frames.

8a: the input power is lower than the Fréedericksz threshold and no focusing occurs.

8b: Larger input power, the induced gradient is large enough to have a self trapping threshold smaller than the input power and a transient focusing is visible.

8c: After a while and even for a larger input power, the reorientation of the nematic becomes effective over the whole capillary section and in turn the self trapping threshold has increased, becoming larger than the actual input power: no more focusing is observed.

III.2.1.b. Mixture OS33 + OS 53: interpretation.

An explanation can be given, based on simple physical considerations. The crucial point is the low birefringence of this material (0.02) which means that it takes a large gradient of the director distribution to obtain a large value of the non linear part n_2 of the index. The optical field first reorients the central part of the beam, it takes milliseconds to do that. The elastic director reorientation over the radial direction is a more longer process due to the large radial size. A rough estimation of the relaxation time ($\tau \propto \eta/K.r^2$, with η the viscosity and r the capillary radius, here 125 μm) gives an order of magnitude of seconds for this process. As a result, after the input power becomes larger than the Fréedericksz threshold at t_0 ($P(t_0) = P_{Fr}$), the director is reoriented in the central part but not in the lateral part and there is a short lapse of time (Δt ~ s) during which the gradients and therefore the non linear index n_2 are large enough to induce focusing i.e. the power is larger than the self trapping power ($\exists$ t, $P(t_0 < t < t_0 + \Delta t) > P_{st}$). However, in a first approximation, the self trapping threshold power P_{st} is inversely proportional to the non linear index [18] and as soon as the radial relaxation process makes the gradients and thus n_2 smaller, P_{st} increases, becomes larger than P(t) and the beam diverges. This result can be interpreted as an experimental evidence (the first at our knowledge) of the distinction between the Fréedericksz and the self trapping thresholds. To stabilize the focusing, it is necessary to increase the orientational gradients either by playing with the boundary conditions (a smaller capillary, different anchoring energies etc) or by enlarging the birefringence. We chose the second possibility.

III.2.2.a. 5CB + AQ1: experimental results.

We also increased the input power from 0 to 6mW at different rates. For this material, as opposed to the previous one, we have been able to stabilize the different events, whatever the rate was. This does not means that the radial reorientation process do not exist, it just means that after the director distribution reached the steady state, the non linear index is still large enough to have a self trapping threshold P_{st} smaller than the pump power. Again, we present now only a qualitative discussion of our findings. As the power is increased, we observe the sequence of the following events: focusing, shortening of the focal distance, the appearance of a « self wave-guiding » structure and finally the appearance of the isotropic phase. These different stages are shown on figures 9. Let us details these events.

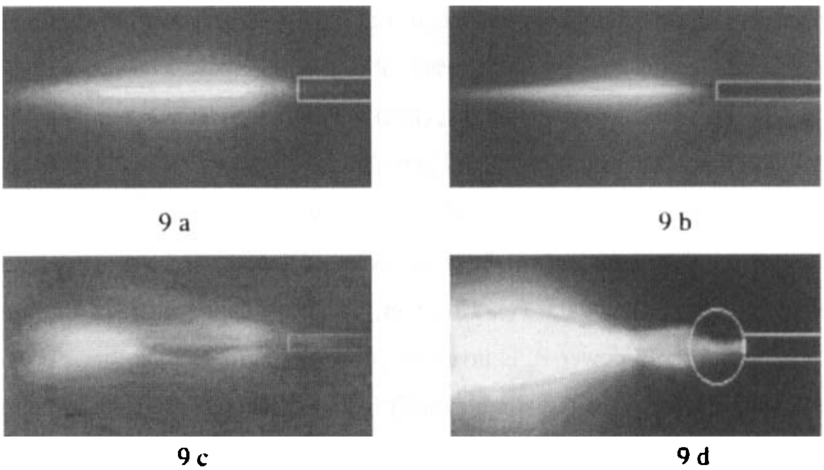


FIGURE 9. Sequence observed for the mixture (5CB + AQ1; 1/100) for increasing input powers. Photographs digitalized out from a video recording.

9a: The input power (1mW) is larger than the Fréedericksz threshold, the beam is slightly focused.

9b: Larger input power (1.2 mW), the focus is shorter.

9c: Stable configuration of the beam propagation for input powers larger than 1.4 mW. As the input power is increased, the length of the medium part is increased as well.

9d: For powers larger than 5mW, the isotropic phase appears, artificially marked on this photo.

The two first events are similar to these already observed in a pure nematic[6]. Although we did not measure it carefully[2], the focusing occurs above a threshold (roughly measured ≈ 0.6 mW). As the « focal point » (O, Fig. 10) is quite close to the taper

(f estimated to be lower than ten microns, P ≈ 1.3 mW) a quite well stable structure appears, shown on Figure 9c. Due to a practically inevitable overexposure of the camera, what is actually viewed is sketched on Figure 10. It consists in some green « brushes » (a, b Fig. 10) and a narrow, linear, well marked, mostly red and stripped tube (c, OO', Fig. 10). The length of this tube is monotonically dependent on the pump power: as the power is increased or decreased, the length of the tube (l, OO', Fig. 10) increases or decreases. This tube appears almost totally red: the fluorescence is prominent whereas the scattering is very weak. This red light is strongly linearly polarized. Some darker strips can be seen in this tube revealing an internal structure. Viewed from the second microscope, the tube looks the same as viewed from the upper microscope, apart a central narrow dark line. In all our experiments, this tube looks perfectly straight, we did not observe any undulations: this is probably due to the way our source beam enters the liquid crystal. This structure is stable for tens of minutes and then destabilizes, the effect becoming observable again after the whole sample has been cooled down.

There are two different sets of « brushes »: first, a bundle emerging out from the end of the tube, linearly polarized along with the capillary axis (b, Fig. 10) and second, two beams emerging one from the starting point of the tube and the second from the end (a, from O and O', Fig. 10), both with

[2] The distinction between the self trapping and Fréedericksz threshold is not experimentally obvious as the results presented in the previous section demonstrates it.

the same angle of emergence with respect to the capillary axis. These beams are almost circularly polarized. While observing the capillary using the second microscope (viewing the oyz plane, Fig. 10), it turns out that the « a » brush system is developed on a cone with an irregular distribution of intensity, whereas the « b » system keeps propagating almost in the plane oxz.

As the input power is increased, up to around 5mW, the isotropic phase appears in such a way that it can not be missed (Fig. 9d). Within the isotropic bulb, the beam is slightly divergent (normal numerical aperture of the taper) and then entering the nematic phase, it is focused due to the curvature of the interface nematic/isotropic.

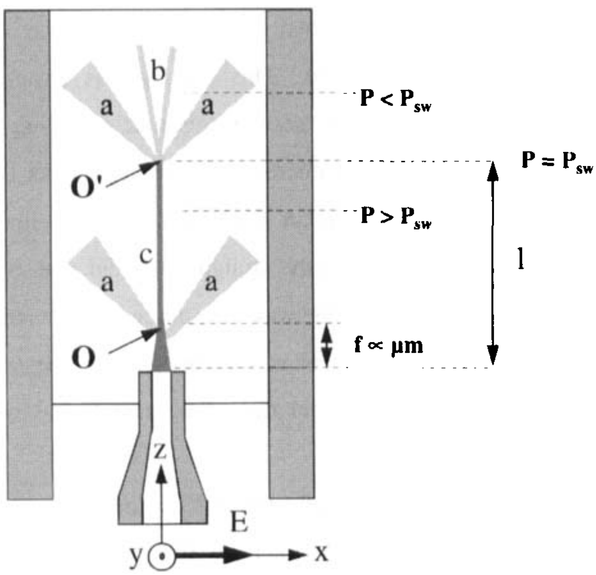


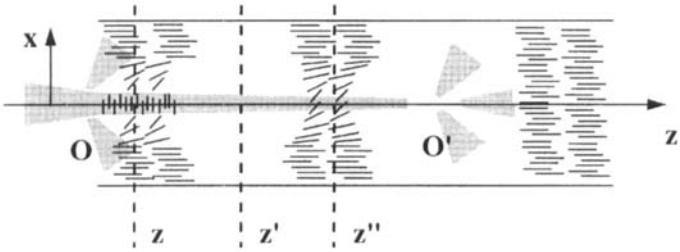
FIGURE 10. Schematic representation of the photograph 9c, which is overexposed to be able to see both the central part and the leaking beams, nicknamed « brushes ». Due to absorption, the local available power is z dependent.

III.2.2.b. 5CB + AQ1: interpretation.

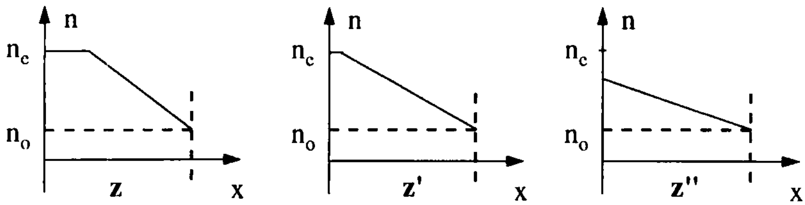
The first two events need no further explanations: they correspond to the expected behavior. However, we did not correlate the distance of the focusing point from the output of the taper (f, Fig. 10) with the pump power, this is worth to be done to compare the herewith considered doped mixture with the pure host behavior where a dependence have been found, which is linear or exponential for thin (100 μm) or thick (1000 μm), respectively [6]. The fourth event can be readily explained through simple geometrical optics. However, it contains interesting informations on the director distribution. The beam is emerging out of the fiber in an isotropic material the index of which is larger than the taper, as a result, it diverges slightly. As the beam enters the nematic phase, it is focused: this is due to the curved interface, but the angle of refraction through this interface depends on the director alignment. The director distribution can be estimated from measurements on such photograph (Fig. 9d).

More intriguing is the third event. First, looking at the fourth event, one can be sure that the tube is not a confined region where the material went to isotropic phase. However, there is obviously some heating due to the dye absorption: the central part of the tube is hotter than the external part. This affects the extraordinary index for a tilted director through the principal values $n_e(T)$ and $n_0(T)$. The thermal gradient induces a modification of the index gradient induced by the optical reorientation, which is not qualitatively relevant in the region between the most reoriented tube and the surroundings, but which could determine an index gradient structure internal to the tube. This heating should not affect qualitatively the light propagation until it remains local. This is indirectly confirmed by our observation reported above: after ten to twenty minutes, the effect is no longer visible: the heating of the sample is no more local, the birefringence decreases in the whole sample due to the temperature increasing, and the system behaves like the previous one, i.e. the focusing can not be stabilized any more. After a natural cooling down, the guiding structure can be retrieved. We can add to this that a large amount of the input energy is absorbed by the dye and expelled out through the fluorescence.

To meet the main experimental features of this tubular regime, namely a well organized, spatially stable and practically no scattering tube, we propose a simple picture based more on wave guiding than on nonlinear processes. This tube is originated right after the focus (O, Fig. 10) as the input power is larger than a specific power, which we call hereafter P_{sw}, sw for self waveguiding ($P_{sw} > P_{st} > P_{Fr}$). The region between the taper and this point O can be considered as a strongly focusing lens (large orientational gradients in both radial and axial directions), thus strongly aberrating therefrom the brushes (a, Fig. 10). At the point O, the energy is highly concentrated: one can therefore expect that the director is totally reoriented in this region (Figure 11). Let us assume, for the sake of simplicity, that in this region, the director is uniformly reoriented perpendicular to the capillary axis. This creates an optical channel in which the light cannot escape out of it due to the total internal reflection. So, if the light intensity is large enough to keep the nematic largely reoriented, this large reorientation keeps the light confined. Now, considering the dye absorption, even if confined in such a self waveguiding structure, the intensity decreases as it propagates along with the capillary axis. The optical torque therefore decreases and the director reorientation becomes smaller: first the radial size over which the director is totally reoriented becomes smaller (z and z', Fig. 11) and second the maximum angle of reorientation is lower than 90° (z '', Fig 11). The gradients become too small and the light is no longer trapped: this is the end of the tube where the power is equal to P_{sw}. After this point, we again find a perturbed zone with large radial and axial gradients, thus strongly aberrating, and



11a



11b

FIGURE 11. Schematic representation of the « tube ». This is a picture valid only in the plane of the input beam polarization, namely OXZ

11a: radial director distribution

11b: associated extraordinary index profile for different sections.

giving rise to an other set of brushes, one (a, Fig. 10) is expelled out of the tube the same way as at the entrance, which means a similarity between the director distributions at the points O and O'. The second set of brushes (b, Fig. 10) can correspond to special modes propagating in the tube. In a first naive picture, the tube is considered as a self built up waveguide with a constant core index surrounded with a graded index cladding as shown in Figure 11. The tube behaves as a graded index waveguide and probably only few modes are propagating in it. Actually, considering that the index gradient structure thermally induced in the inner part of the guiding tube is camel hump shaped, it is quite understandable that odd guided modes, yielding an output intensity profile with a central minimum, are favored with respect to the even ones, which inversely yield a central maximum. In addition to this, a more accurate model should take into account the non cylindrical symmetry of the system: the self built up waveguide has not the same index profile in the ox and oy directions: it is somehow a polarization maintaining waveguide.

For this tube we prefer not to use the term filamentation which seems to us not appropriate in accordance with the proposed mechanism. Actually, though this model is naive, it stresses on an interesting point: the plane section (parallel to the input polarization) of the nematic can be considered as two adjacent hybrid cells. Actually, as the field is large enough, the director in the central part is almost perpendicular to the capillary axis and can not be changed anymore: the optical torque plays the role of a surface torque and the structure of the film is ruled by the elastic theory together with the anchoring energies. The index profile now depends on the input intensity through the anchoring angle in the central part. However, for high optical field this angle can be almost 90 °, resulting in an index profile practically insensitive to a further optical intensity increase: the material is no longer non linear. Finally, it should be stressed that this behavior is due to the specific boundary condition and thus to the geometry.

CONCLUSIONS

In this paper, we report on some experimental results we obtained on nonlinear optics of dye doped liquid crystals confined in capillaries. Two different confinement geometries were considered: the radial escaped structure and the fully axial structure. A narrow and collimated beam induces a reorientation of the nematic LC. Depending on the geometry, it is either a non threshold process or a threshold one. In the case of the radial escaped structure, we have shown that it is possible to displace the homeotropic zone and also the point defects which can exist in such a structure. In the case of a fully axial structure, apart the focusing, we observed for high pump powers the appearance of a self wave guiding structure. We propose, on the basis of the main experimental features, a possible picture for this behavior: the high optical torque totally reorients the director in a small region the index of which becomes the LC extraordinary index and is therefore larger than that in the remaining part of the capillary, creating a waveguide. The light is thus trapped with an intensity large enough to maintain this large reorientation and in turn this large reorientation keeps the light trapped. This model should be now confirmed through numerical models and further experiments which are already underway.

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REFERENCES

1. N.V. Tabiryan, A.V. Sukhov, B. Ya Zel'dovich, Mol. Cryst. Liq. Cryst. 136, 1, (1986)
2. I.C. Khoo, Prog. Optics, 27, 107, (1988)
3. I.C. Khoo, S.T. Wu, « Optics and non linear optics of Liquid crystals », World Scientific, 1, Chap. 3 and 4, (1993)
4. I.C.Khoo, F. Simoni, « The Physics of Liquid Crystalline materials »,

Gordon&Breach, Chap. 14, (1991)

5. The proceedings of the OLC's have been published in special issues of Molecular Crystals & Liquid Crystals:
   OLC'95 (Le Touquet, France): Vol 282
   OLC'93 (Lake Balaton, hungary): Vol 251
   OLC'91 (Cocoa Beach, USA): Vol 222-223
   OLC'90 (Cetraro, Italy): Vol 207
   OLC'88 (Torino, Italy): Vol 179
   OLC'86 (Napoli, Italy): Vol 143
6. E. Braun, L. Faucheux, A. Libchaber, Phys. Rev. A, 48-1, 611, (1993)
7. E. Braun, L. Faucheux, A. Libchaber, D.W. McLaughlin, D.J. Muraki, M.J. Shelley, Europhys. Lett., 23 (4), 239, (1993)
8. D.W. McLaughlin, D.J. Muraki, M.J. Shelley, Physica D, 68, 116, (1993).
9. D.W. McLaughlin, D.J. Muraki, M.J. Shelley, X. Wang, Physica D, 88, 55, (1995)
10. D.W. McLaughlin, D.J. Muraki, M.J. Shelley, Physica D, 97, 471, (1996)
11. O. Duhem, J.F. Henninot, G. Abbate, M. Warenghem, Mol. Cryst. Liq. Cryst., in press
12 J.F. Henninot, M. Warenghem, N. Tabiryan, Mol. Cryst. Liq. Cryst., in press
13. I. Janossy, A.D. Lloyd, Mol. Cryst. Liq. Cryst., 179, 1, (1990)
14. P. E. Cladis, M. Kleman, J. de Phys. (Paris) 33, 591, (1972)
15. G.P. Crawford, S. Zumer, Int. Journ. Mod. Phys., 9 (18-19), 2469, (1995)
16 G. Abbate, F. Castaldo, L. de Stefano, Mol. Cryst. Liq. Cryst., 282, 269, (1996)
17. IC. Khoo, T.H. Liu, P.Y. Yan, Journ. Opt. Soc. Ame. B4, 115, (1987)
18. See for instance: R.W. Boyd, « Nonlinear Optics », Academic Press inc., chapt.6, (1992).