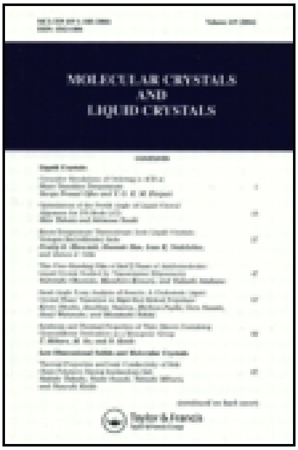

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Thermal and Orientational 2D +1 Spatial Optical Solitons in Dye Doped Liquid Crystals

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Thermal and Orientational 2D+1 Spatial Optical Solitons in Dye Doped Liquid Crystals

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We investigated the behavior of a beam experiencing the Optical Freedericksz effect while traveling through a nematic liquid crystal confined in a capillary and doped with a dye. The source is a fiber that delivers a narrow and well collimated beam. For two ranges of input power the beam is no longer diverging nor focusing and it propagates straightly, over a long distance compared to the Rayleigh range of the initial beam. The transverse profile of these beams are studied and found to be constant. The collision behavior of these modes is reported. It is shown in this paper how all the experiments performed lead us to think in terms of spatial 2D + 1 soliton.

Keywords Spatial solitons, doped liquid crystals

INTRODUCTION

Historically the solitary waves were discovered in fluids quite early [1]. This concept has now become a long story. "Soliton" is a wave that is defined by some rules. It should be (1) a traveling wave, (2) carrying an energy that is finite and localized, (3) stable, (4) display elastic behavior during collision, and (5) as the beam carries on more energy that the solitary wave should do, it splits in several solitons [2].

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The name soliton comes from this particle-like behavior. A spatial optical soliton is an electromagnetic wave with its energy localized in space. The $2D + 1$ notation refers to the symmetry; the energy is confined in a 2D transverse plane and propagates in the third direction. To excite a soliton you need a nonlinear response from the material.

Up until now, the solitons observed in liquid crystal have not been optical. They are mostly observed in hydrodynamic, defect motion, pretransitional effects, etc. [2]. It is worth noting that the optical solitons and the nonlinearly induced waveguides are two very similar concepts [3]. Different groups have worked on the nonlinear waveguides. However, it seems that they have not observed optical solitons. The first group that has observed a behavior in the class of solitons is the Libchaber's group [4, 5]. Although their work was focussed more on the instabilities than on the solitary waves, they nicely modelized the electromagnetic wave propagation problem [6–8]. Their experiments were performed using a geometry in which the nonlinear interaction between the light and liquid crystal occurs across a long distance. In this article, we report observations made on a similar geometry, but differently sized and using a different material. The system is sized to fit the optical fiber devices, and we used a dye doped liquid crystal in order to reduce the input power required to generate nonlinear effects, taking advantage of the reduced optical Freedericksz threshold value [9]. In our first observations in this reduced geometry, we reported a specific mode of propagation [10]. We confined the 5CB mixed with some anthraquinone dye in a capillary tube and shined it with a tapered fiber. We saw a specific shape of the beam for a range of input beam powers: a narrow tube with some brushes. In the present paper, we report on a similar experiment undertaken with the same mixture and a differently sized source. The main result is the observation of a second specific mode of propagation. The experiments described here lead us to the conclusion that both modes are spatial optical solitons, or at least quasisolitons. This means that these modes should fulfill the rules announced above. The first one is quite obvious; we will focus on the second one in studying the beam profiles. We also focus on the collision. The stability will be briefly considered. Finally, the last rule is not fulfilled since, as the carried energy is increased, different modes of propagation occur and the nematic mixture turns to the isotropic phase.

This paper is organized in three main parts. The experimental setup is described in the first part, the results are gathered in the second part, and finally a brief phenomenological approach is proposed in the third part.

SETUP

The setup we have been working with is depicted in Figure 1. The inner face of a capillary is treated in order to get a planar alignment of the liquid crystal and then filled with the material. The inner diameter of the capillary is 250 μm. The source is a cleaved single mode fiber inserted into the capillary in such a way that the emerging beam is travelling through the capillary parallel to its axis. At the output of the fiber, the beam width has a diameter of around 3 μm and is smaller than in the case of a tapered fiber as used in the previous experiment (diameter ~ 10 μm). It is referred to in this article as the source beam or pump beam.

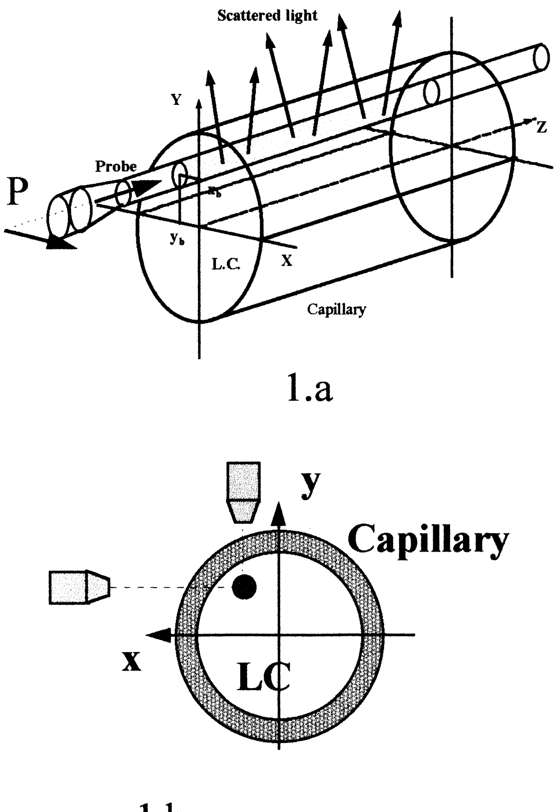

FIGURE 1 Setup. (a) Side view, (b) cross section.

The polarization of this beam can be adjusted using either a normal polarizer or 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 placed and oriented in different directions. It can emit in a direction parallel to the capillary axis (oz, Figure 1), placed roughly in the middle of the capillary and displaced accurately in the section of the capillary (ox, oy, Figure 1). It can also be displaced along with the capillary axis, allowing the source to enter the liquid crystal more or less deeply (oz, Figure 1). This setup is installed on a polarizing microscope in such way that the capillary axis lies parallel to the microscope stage. The observations are made by means of the microscope illumination light or by just collecting the light coming from the source beam that is scattered by the liquid crystal in the oy direction (Figure 1b) [11]. We also set up a second microscope in the perpendicular direction (ox, Figure 1b) to spot the source beam properly and to observe the system from another point of view.

The material used in this experiment is a mixture of the well-known 5CB doped with a small amount of an anthraquinone dye (AQ1) in concentrations of 0.2% w/w. The real part of the doped nematic refractive indices were measured and are not different from the pure host. The ordinary index of the mixture is found to be 1.53, which means a good index matching and, in terms of numerical aperture, the beam entering the liquid crystal is slightly divergent. It is now well known that it is possible to observe the Optical Freedericksz Transition with a mW laser [9] in these doped materials.

As already mentioned, the inner face of the capillary is treated to induce a planar alignment of the director on the capillary wall, parallel to its axis. The beam therefore experiences propagation through a homeotropic material wherever it is located in the capillary. In a Freedericksz transition point of view, this configuration is definitely a threshold one. It is very similar to a homeotropic thin film illuminated under normal incidence, apart from the totally different boundary conditions that make this geometry attractive. Although this geometry is the same as the one studied by the Libchaber's group [4, 5], the differences should be noted. 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 local heating. This absorption makes all the variables of the system z dependent, and due to the weak concentration we should say *slightly* dependent. In addition, the range of energy explored is probably different in terms of ratio input energy/Freedericksz threshold energy.

EXPERIMENTAL RESULTS

In this section, we will focus on some specific points of our observations connected to the "rules" evoked in the introduction. We first describe the different events we have observed, how the energy is confined (beam profiles), and the behavior of the solitons in collision. Finally, we report on miscellaneous observations.

Sequence of Events

As the input power is increased, the beam profile changes within the liquid crystal material. For input powers lower than around 3 mW, the beam has a normal, slightly diverging shape. Due to the dye absorption, it is no longer visible after roughly 400 μm (Figure 2a). Within a narrow range of powers around 3 mW, the beam becomes straight, narrow, and travels over a distance (mm) much longer than the previous 400 μm (Figure 2b). For reasons which will be explained later in the text, we call this mode "thermal soliton." For higher powers up to roughly 5 mW, the beam shape is quite complex. For a range of powers around these 5 mW, a second specific mode of propagation occurs. The beam is again straight and narrow and looks narrower than in the low power mode. Two sets of brushes are visible, one at the output of the fiber and the other at the end of the straight line. As the input power is varied, the length of the straight line changes reversibly (Figure 2c). This mode of propagation is referred to in this article as the "orientational soliton." Multiple foci are also visible as the power is increased. This event is similar to one already reported [4, 5]. For larger powers, the beam shape changes, and it becomes inflated on its medium part. Sometimes, it is possible to see rays fanning out of the source fiber that appear to be totally reflected within the medium. The envelope of these reflections gives rise to the characteristic inflated shape. We call this the "flame" regime. For higher powers, the nematic goes into the isotropic phase.

Beam Profiles

Using an image processing, it is possible to get the intensity profiles of the beam for the different events of interest at different locations, namely close to the output of the fiber and far away from it. The obtained results are

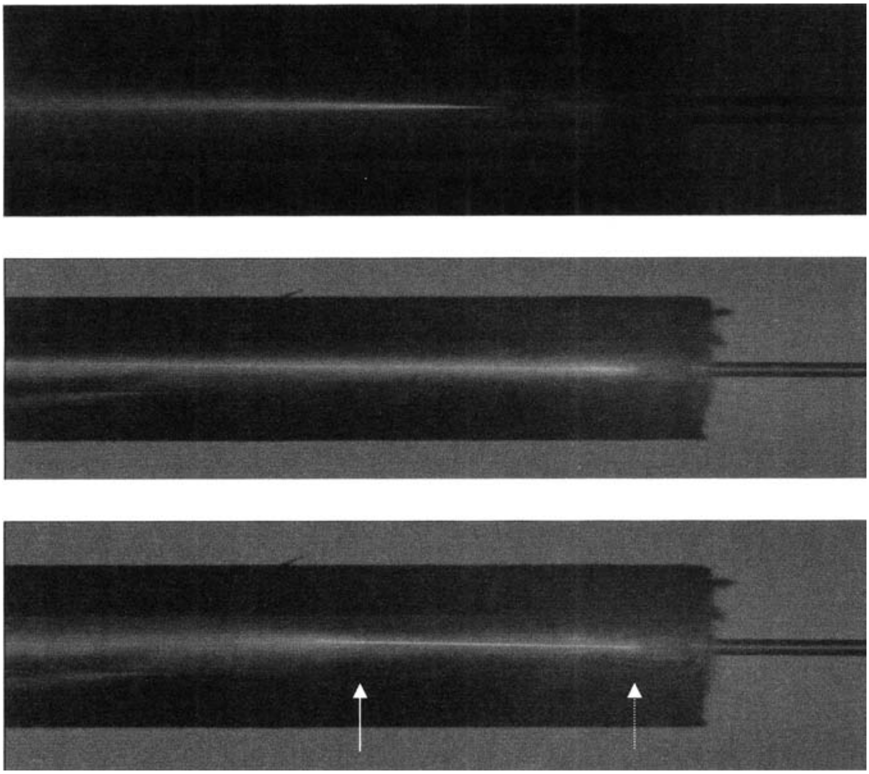

FIGURE 2 Observed modes of propagation: (a) Normal diverging beam (input power < 3 mW). (b) First mode: the beam is visible over a distance at least twice as long as in 2a. (c) Second mode: brushes (not visible here) at the beginning (dotted arrow) and at the end (arrow). The length between the arrows depends on the input power.

shown in Figure 3. From these profiles, it is obvious that the corresponding energy is confined in the radial region and has a constant shape along with the propagation.

It should be noticed that the profiles shown in Figure 3 concern the collected light, which is the light scattered by the liquid crystal, and not the actual beam. Although both are correlated, the relationship between them is not simple: the actual nonuniform beam intensity reorients the liquid crystal nonuniformly. In turn, it scatters the light nonuniformly, and the camera collects that scattered light through the capillary meniscus. Even assuming that expressing the scattered light as a function of the actual pump intensity distribution is possible, the reverse (i.e., to get the actual intensity profile from the photograph) looks unlikely.

However, whatever the relationship between both intensity profiles, it is the same whether we check a point next to the output of the fiber or far from it. As a conclusion, the constancy of the profiles we have observed for the scattered intensities holds on for the actual beam intensity profile, and the soliton law on the conservation of the energy looks fulfilled. One can argue that the conservation does not hold for a long propagation distance. Actually, this has to be compared to the Rayleigh range of the input Gaussian beam. In our case, this Rayleigh range is around 15 μm and the conservation is observed for distances larger than 500 μm, which means that the soliton is observed over distances larger than 30 times the Rayleigh range. This is much larger than the soliton observed, for instance, in the photorefractive materials [12]. It should be also stressed that our observation

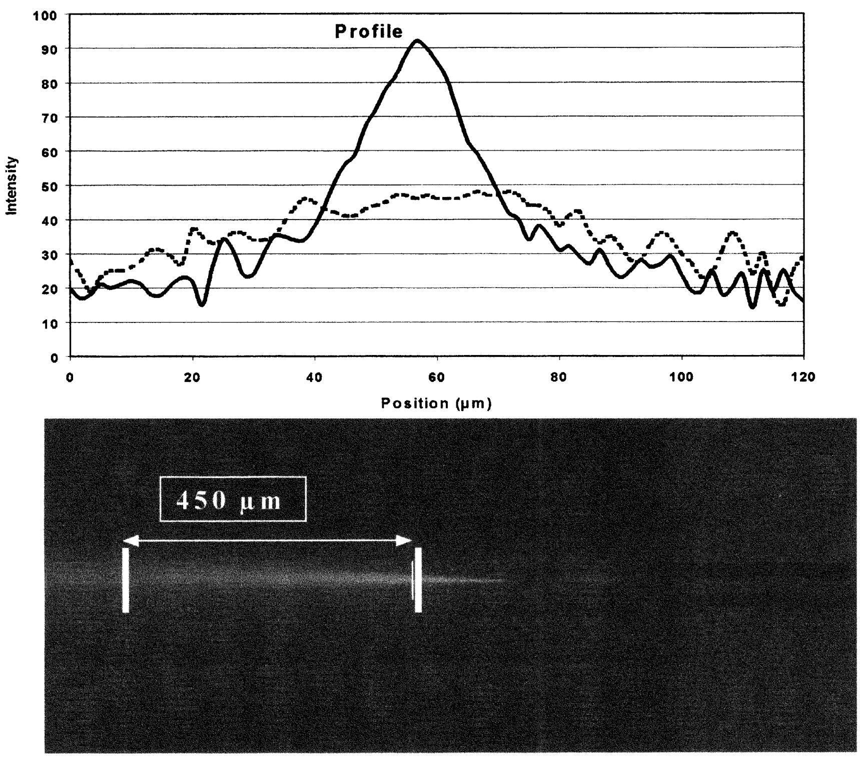

FIGURE 3 (a) Intensity profiles of the scattered light for a normal diverging beam. The dotted line profile corresponds to the leftmost section on the photograph, the solid line to the rightmost one. (b) Intensity profiles of the scattered light for the "thermal" soliton. The dotted line profile corresponds to the leftmost section on the photograph, the solid line to the rightmost one. A similar result is obtained with the profiles of the "orientational" soliton.

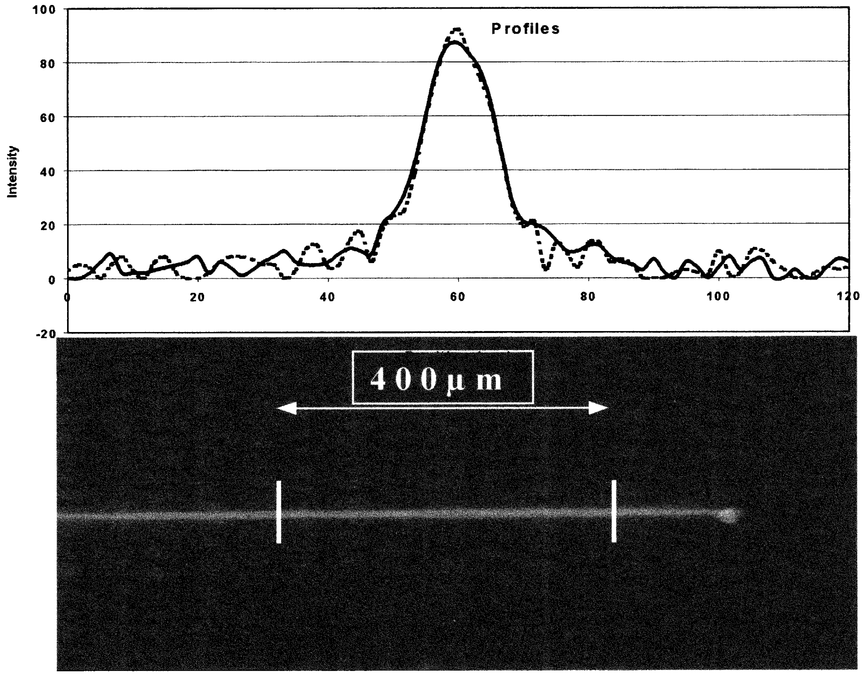

FIGURE 3 (*continued*)

concerns a purely optical soliton. In the photorefractive materials, it takes an applied voltage to excite the soliton, and the transverse size depends on the applied voltage [13].

Collision

In order to check the behavior of these modes of propagation as they are encountering each other, another experiment has been undertaken. It consists of injecting two beams within the capillary with some weak angle, as shown on the Figure 4a.

Both source fibers are fed with the same Ar^+ laser (i.e., the same energy), and the solitons are excited simultaneously in the material. During the adjustment of the set-up, special attention has been paid to make sure that both beams encounter each other. For all the experiments done, the same behavior has been observed for the "thermal" solitons. As shown in Figure 4b, the two beams appear to ignore each other.

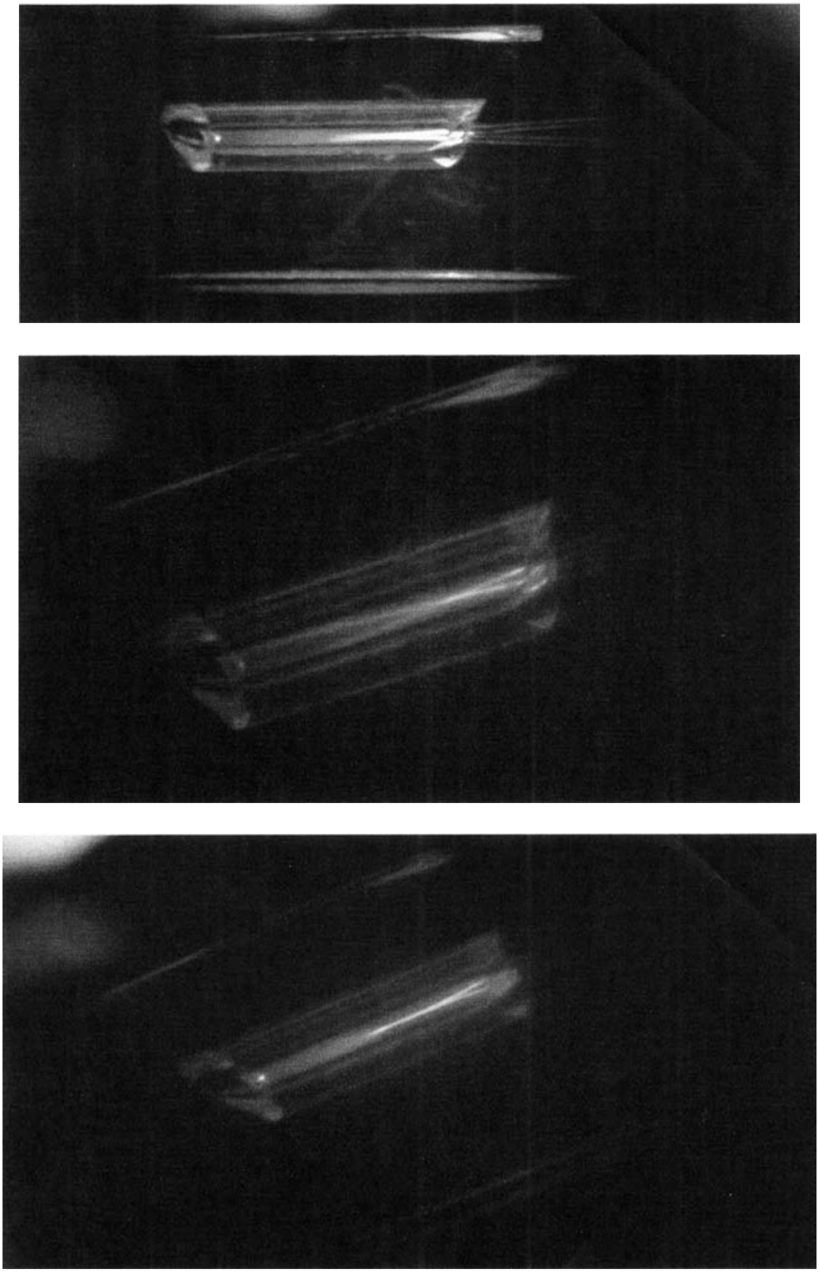

FIGURE 4 (a) General view of the soliton collision experiment. The two source fibers are visible on the right hand side of the capillary. (b) Interaction between two ‘‘thermal’’ solitons. They almost ignore each other. (c) Interaction between two ‘‘orientational’’ solitons. They spiral around each other.

For the so-called "orientational" soliton, a different but reproducible behavior has been observed. The two beams attract each other, adopting a structure that is not readily visible in Figure 4c—the beams interlace each other. The behavior of the "thermal" soliton is consistent with the required elastic collision (our rule 4 in this article's introduction), which is not directly the case for the "orientational" one. However, it has been shown that solitons can behave as observed in our geometry [14] and we can still claim that even the "orientational" mode of propagation is a quasisoliton.

Miscellaneous Observations

In this section, we report on some experimental results of general interest. In addition to the previous one, they lead us to nickname the low power mode "thermal" soliton and the high power one "orientational," as will be discussed in the next section.

1. The same experiment has been performed in the planar cell of liquid crystal and similar modes have been observed, in slightly different conditions of input power.
2. As the source is wider (tapered fiber, 10 μm diameter), the "thermal" mode has not been observed, whereas the "orientational" one still can be excited.
3. The "thermal" mode has not been reported in the experiments performed with a material whose index is almost constant with the temperature [4]. We have performed the experiment with the pure 5CB and have not been able to excite the "thermal" mode.
4. The used dye has its maximum absorption in the red region of the spectrum: we have unsuccessfully tried to excite the soliton by pumping with an He-Ne laser beam.
5. Finally, it should be stressed that the "thermal" mode is almost insensitive to the polarization of the input beam.

These observations enhance the important role played by the temperature gradients present in the capillary.

DISCUSSION

The results reported here are from experiments performed with a dye doped material and, as already stated, the dye absorption induces temperature gradient in the system. They have to be compared with that one performed with a pure material and a thermal stabilization of the setup [4, 5]. The role of the temperature gradients in a liquid crystal system and the thermal nonlinearity have been already considered [15]. In our geometry, for input powers such as the liquid crystal that are not yet or only slightly reoriented, the beam experiences the ordinary index of the mixture or an extraordinary index slightly different from the ordinary one. For the material used, the value of that index is increasing with the temperature; the material is focussing because the temperature is higher at the center of the beam than in the external part. The role of the temperature gradient is to enhance the focussing property. On the contrary, as the input power is large enough to induce a large reorientation, the beam experiences an extraordinary index that decreases as the temperature increases. As a result, the role of the temperature gradient is to flatten the index profile, or in other words to weaken the focussing property of the material. Without entering deeply in any theoretical model, these considerations allow us to understand that for the low power mode, the index profile is more acute than the one induced for the large power mode.

By numerically solving the elastic equation and inserting a realistic temperature profile, it is possible to simulate the index profiles for different input powers. It is found in this very naive scenario that in the central part of the capillary, the index profile can be either Gaussian or parabolic depending on the input power. Such specific profiles are known to drive specific modes of wave-guides [3]. This rough phenomenological approach is consistent with our observations.

One question still remains: for the "thermal" soliton, the role played by the temperature gradient is undoubtedly essential, but is the reorientation, however slight, compulsory to excite the soliton? Is the thermal nonlinearity of the ordinary principal index sufficiently large enough to induce the wave-guide? This question is considered in another paper [16].

CONCLUSIONS

Using a geometry that allows the interaction of light/matter to take place over a long distance, two specific modes of propagation in dye doped liquid crystal have been observed. The dye doped liquid crystal is confined in a capillary and a beam emerging out of a fiber enters into it, traveling parallel to the capillary axis. For a range of low powers, the beam is no longer diverging and it looks like a narrow straight line, propagating over a long distance into the material. For another range of powers, slightly higher, a second mode of propagation occurs, and the beam looks like a narrow straight line the length of which is reversibly correlated to the input energy. The profiles of energy of these two modes of propagation have been studied and found to be constant over a long distance. The low power modes elastically collide with each other, whereas the high power modes have a more complex interaction. These features are those of spatial solitons. The nonlinear mechanisms responsible for this are the thermal indexing and the Janossy effect. For the low power soliton, it is proposed that the thermal effect plays the major role, whereas the orientational nonlinearity is prominent for the high power soliton, therefore we use the terms "thermal" and "orientational" solitons. For the former case, there is no experimental evidence for the existence or nonexistence of a small reorientation as the "thermal" soliton is excited. Further experiments are under way to answer this question. A semianalytical and numerical approach is developed in another paper, showing that it is possible to excite the soliton with no reorientation.

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