Velocity of an electric-field-induced synclinic solitary wave invading the anticlinic liquid crystal phase

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The electric-field dependence of the velocity of synclinic fingers invading the anticlinic phase is determined by a time-of-flight technique. The time delay for a rapid increase in the transmitted optical intensity through the sample is measured between two points as a function of their separation along the trajectory of the solitary wave. The data are quantitatively consistent with the rapid velocities deduced from a previous measurement [Liq. Cryst. **27**, 249 (2000)], demonstrating that the previous data were not affected by multiple nucleation sites occurring at higher fields.

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In both the chiral anticlinic (also known as the smectic-C_A^*) and synclinic (also known as the smectic-C^*) liquid crystalline phases the director tilts by a polar angle θ with respect to the smectic layer normal [1–4]. In the chiral synclinic phase the azimuthal orientation of the $\hat{c}$ director—the $\hat{c}$ director is the projection of the nematic director $\hat{n}$ into the smectic layer plane—is nearly the same in every layer, except for a very small layer-to-layer rotation $\Delta\varphi$ associated with the long, chiral-induced, helical pitch [1]. Similarly, the layer polarization $\vec{P}$, which is perpendicular to the molecular tilt plane, varies by the same small amount $\Delta\varphi$ from one layer to the next. In the anticlinic phase, on the other hand, the azimuthal orientations of $\hat{c}$ and $\vec{P}$ change by approximately π in adjacent layers [2,5]. If a sufficiently large electric field is applied parallel to the smectic layer plane in the anticlinic phase, thereby coupling to the layer polarization, regions of synclinic phase nucleate and propagate into the anticlinic phase as solitary waves parallel to the smectic layers [6]. The width of the synclinic fingers is typically $1-10$ μm, which depends upon the liquid crystal and cell preparation, and the velocity of the solitary waves is a strong function of the applied field [6]. In a simple model that involves elasticity, coupling between the polarization and applied field, and layer-layer interactions that stabilize the synclinic phase, Wang and Taylor [7] and Li *et al.* predicted [6] that the propagation velocity v is proportional to the reduced field E_r, where $E_r=(E-E_{th})/E$ and where the threshold field E_{th} for the onset of solitary waves is given by $E_{th}=2U/P$. Here U corresponds to the strength of the anticlinic interactions. Zhang *et al.* optically measured v vs E_r by noting that, when the cell is placed between appropriately oriented crossed polarizers and illuminated, the image of the anticlinic regions is dark and that of the synclinic regions is light [8]. They imaged a cell onto a fast photodiode detector masked by a long slit of length L and approximately one finger in width, and measured the rise time $\overline{\tau}$ of the optical intensity (averaged over hundreds of pulses) as the image of the field-induced solitary wave traversed the slit. By associating the quantity $L/\overline{\tau}$ with the velocity v of the solitary wave, they extracted v vs E_r, finding v to be approximately linear in E_r only for small E_r. For $E_r \gtrsim 0.05$, however, they found that the velocity increases much more rapidly than linearly in E_r. The data analysis in Ref. [8] was predicated on the assumption that the image of the solitary wave traverses the slit by entering at one end of the slit and leaving at the other, and that no other nucleation site is present within or near the region imaged by the slit. However, it is entirely possible that additional nucleation sites occur at higher fields, with a concommitant growth of the overall synclinic region by *multiple* solitary waves. In such a case the additional synclinic nucleation sites would result in an image of synclinic regions filling the entire length of the slit in a considerably shorter time period $\overline{\tau}$ than would have occurred had there been only a single solitary wave traversing the slit, thereby incorrectly suggesting an anomalously large solitary wave velocity. To circumvent this potential artifact we report on results that utilize a ''time-of-flight'' approach. An enlarged image of the liquid crystal cell is probed by a pair of matched detectors connected to optical fibers whose centers are separated by a virtual distance x (i.e., the separation in the liquid crystal cell) along the smectic layer. Sudden application of a dc reduced electric field $E_r>0$ results in a solitary wave, the image of which is sensed first by one detector, and then a time Δt later by the downstream detector. This is a single-shot measurement. The velocity of the solitary wave is taken as the reciprocal of the slope of Δt vs x for a given applied field E. Thus, *if* additional synclinic nucleation sites were induced at higher fields, Δt would begin to decrease at larger x as the solitary waves emanating from the spurious nucleation sites would reach the second detector before the initial solitary wave could reach that detector. In effect, the signals at the two detectors would become uncorrelated, each related to the location of the two closest nucleation sites. Thus, detailed results from such a measurement would allow us to evaluate the validity of the results of the slit experiment [8], i.e., whether the data represent a single or multiple solitary waves traversing the slit. Our central result from the time-of-flight measurement is that Δt is not only approximately linear in x, indicating the absence of additional nucleation sites and thus validating the method of Zhang *et al.*, but

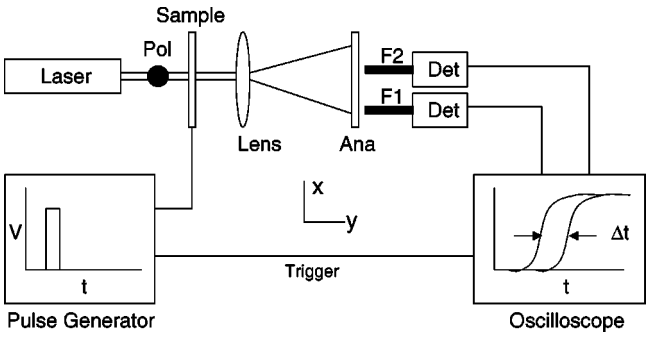

FIG. 1. Experimental apparatus. Smectic layers lie in the *x*-*y* plane. The image of liquid crystal is enlarged by factor of 35 at the two optical fibers F1 and F2, placed behind the anlyzer (ana).

that the measured velocities are quantitatively consistent with those of Ref. [8] as well.

A pair of indium-tin-oxide-coated glass slides was first cleaned and then spin-coated with the polyimide RN1266 (Nissan Chemical Ltd.) The slides were then baked and rubbed unidirectionally with a cotton cloth using a dedicated rubbing machine to facilitate planar alignment of the liquid crystal. The slides were placed together, separated by a pair of Mylar spacers of nominal thickness 5 μm, and cemented. The cell was placed into a temperature-controlled oven and filled with the liquid crystal TFMHPOBC [4-(1-trifluoromethylhexyloxycarbonyl) phenyl 4'-octyloxybiphenyl-4-carboxylate] in the isotropic phase. The cell was slowly cooled through the smectic-*A* into the smectic-C_A^* (i.e., the anticlinic) phase to ensure a well aligned sample.

The cell was mounted on an optical table with the rubbing direction parallel to the *z* axis. The sample was illuminated by light from an Ar-ion laser at wavelength 488 nm and polarized along the *z* axis (Fig. 1). A lens of focal length $f=2.5$ cm was placed after the sample a distance slightly larger than its focal length, creating a real image of the illuminated spot that was magnified by a factor of 35 at the analyzer. Two multimode optical fibers, each of diameter 500 μm and surrounded by a protective sheath of thickness 1.24 mm, were placed immediately behind the analyzer, such that one fiber was mounted to a fixed post and the other mounted to a precision translation stage. The vertical positions of the fibers were carefully adjusted so that both fibers were at the same position *z*; in this way both fibers sampled the same fingers propagating along the *x* axis. Note that each optical fiber sampled a diameter in real space of 500 μm, corresponding to a virtual distance of (500/35) μm$\approx$14 μm in the liquid crystal cell. Light from the fibers was fed into a pair of matched photodetectors that had rise times of a few tens of μs. The output signals from the two detectors were then fed into a fast digital storage oscilloscope.

A positive voltage pulse V at frequency $f=1$ Hz and duration 200 ms was applied to the liquid crystal cell; a portion of this voltage also was used as a trigger for the oscilloscope. The 800 ms duration of zero voltage between pulses was sufficient to allow the liquid crystal to fully relax back to a uniform anticlinic texture between pulses. For $E_r<0$, corresponding to $E<E_{th}$, a small optical signal was

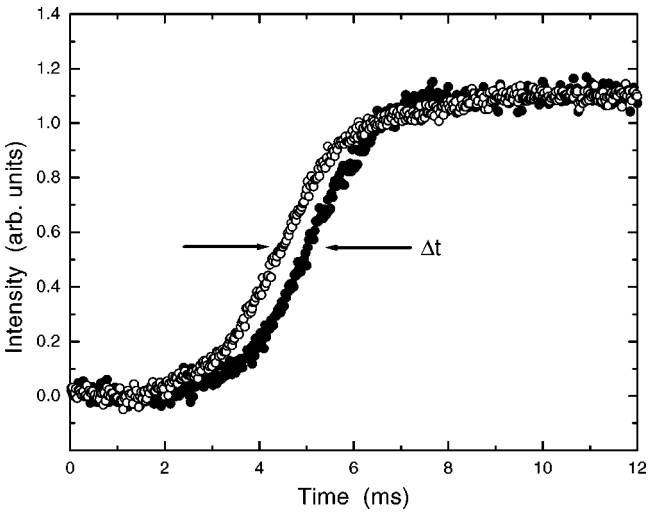

FIG. 2. Typical trace of the two optical signals, separated by a time $\Delta t=0.60$ ms. With a virtual fiber separation (in the cell) $x=(2980\ \mu\text{m}/35)=85\ \mu$m, we deduce a velocity $v\approx 14.2$ cm s^{-1}.

observed. This was due in part to an unwinding of the helical structure and a concommitant field-induced optic-mode-like distortion. For $E_r>0$ a sharp rise in intensity was observed at the first detector, followed by a similar rise occuring a time Δt later at the second detector. Figure 2 shows an example of the two traces with the two fiber casings abutting each other, i.e., corresponding to a virtual distance in the cell of $x=85$ μm, its minimum possible value. It is clear from Fig. 2 that the rise times τ of the two detector signals are identical, and that $\tau>\Delta t$, the temporal separation of the optical signals at the two fibers. However, if a single solitary wave had a width greater than 14 μm and its image were to completely fill the two optical fibers, the rise time τ always must be less than or equal to (14 μm/85 μm) $\Delta t=0.16\Delta t$. When the fiber casings abut each other, $\tau=0.16\Delta t$; for any larger fiber separation, the rise time $\tau<0.16\Delta t$. As is obvious from Fig. 2, however, this is not the case, as $\tau>\Delta t$. To understand the observed behavior we note that the finger widths are narrow, of order 1–2 μm, and thus many finger widths are needed to fill the diameter of the optical fiber. Polarizing optical microscope observations at slower velocities reveal that the many fingers nucleate at slightly different positions in the cell, not only along the smectic layer normal, but along the cell normal as well. Once nucleated, they travel together with the same velocity, with each solitary wave front at a slightly different position along the propagation direction. From the data in Ref. 2 we conclude that the measured rise time τ from each detector is washed out when the image of a *group of many* solitary waves is sensed. At a time Δt later the second detector senses the same group, with the *same relative shift* among the fingers. Thus, even a slow rise time τ does not affect our ability to measure the time-of-flight Δt. Finally, for completeness we note that the contribution to τ from modal dispersion in the fiber is negligible, and is well within the scatter from the detector response time.

Data were collected at two temperatures, viz., $T=111\,^\circ$C and $T=113\,^\circ$C. Figure 3 shows Δt vs x for several

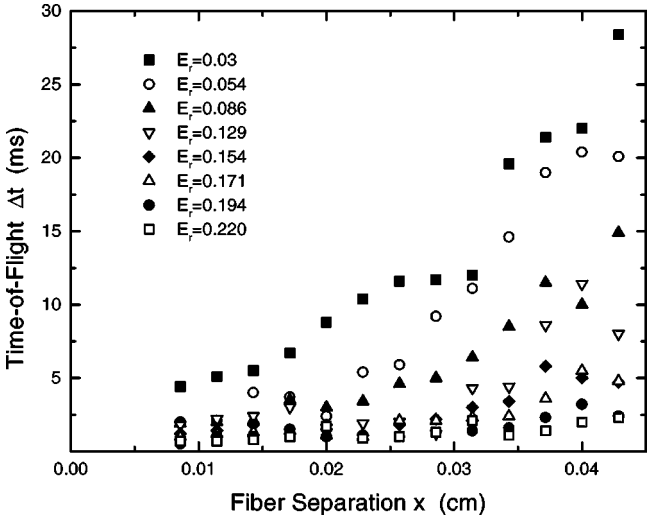

FIG. 3. Time-of-flight Δt vs virtual fiber separation x for several values of reduced field E_r at $T=113\,^{\circ}\mathrm{C}$: the symbol key is shown.

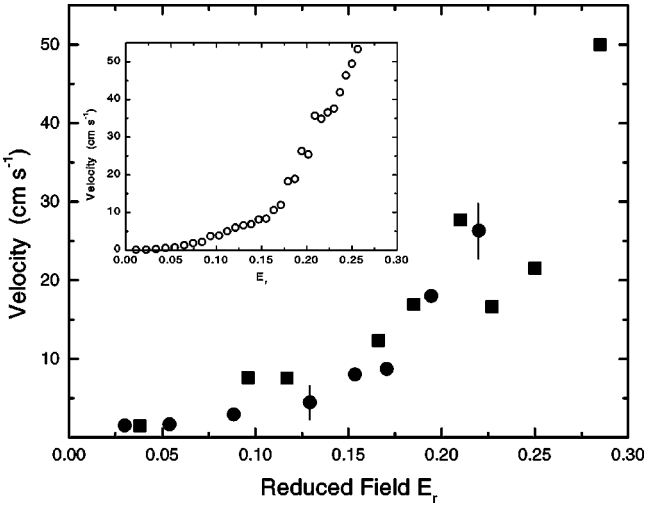

FIG. 4. Velocity v as a function of E_r obtained from a linear fit of the data in Fig. 3. ■ corresponds to $T=111\,^{\circ}\mathrm{C}$ and ● to $T=113\,^{\circ}\mathrm{C}$. Inset: Data from slit measurement of Ref. [8] taken at $T=113\,^{\circ}\mathrm{C}$.

different applied fields at temperature $T=113\,^{\circ}\mathrm{C}$. Each set of data is approximately linear in x, and was fitted to a straight line. The reciprocal of the slope corresponds to the velocity v of the solitary wave for reduced field E_r. It is important to note that no systematic decrease in slope was observed at higher fields, indicating the absence of spurious synclinic nucleation sites at higher fields. Occasionally a slight increase of slope was sometimes observed at lower field. This likely was due to the solitary wave crossing a line associated with a focal conic defect. The velocity v vs E is plotted in Fig. 4 for data obtained at the two temperatures. Despite the experimental uncertainty, the velocities clearly increase more rapidly than linearly with E_r. Moreover, data for v vs E_r are in good quantitative agreement with the open slit results of Ref. [8], which are shown in the inset.

The results of this time-of-flight experiment corroborate earlier reports of the rapid increase of solitary wave velocity as a function of reduced field. Spurious nucleation sites, *if* they were present, would exhibit a clear signature in the Δt vs x. The absence of such a signature therefore lays to rest the concern that the open slit measurements of Ref. [8] were artifactual owing to extra nucleation sites induced at higher fields. Unfortunately, this experiment cannot address the question of why the velocity is so highly nonlinear in E_r. Further experiments to explore this issue are being planned.

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