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The use of bowed reverse twist disclination lines for the measurement of long pitch lengths in chiral nematic liquid crystals†

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A novel method is described for the measurement of long pitch lengths in chiral nematic liquid crystals using the bowing of reverse twist disclination lines in 90° twisted nematic devices. The method has been used to measure pitch lengths of up to 50 mm, significantly longer than previously possible using existing methods.

1. Introduction

Chiral nematic liquid crystals possess a director with a helical rotation in space described by the pitch length P, the distance over which the director rotates by an angle of 2π. They can show a pitch length of less than 0.1 µm and, by diluting these materials into a standard nematic liquid crystal, mixtures with a range of pitch lengths from 0.1 µm to an infinite value can be formulated. The relationship between P and the concentration x (by weight) of the chiral nematic liquid crystal in the mixture is given by:

$$P^{-1} = x(HTP) \qquad (1)$$

where HTP is known as the *helical twisting power* of the chiral additive. Similar results can be achieved with non-liquid crystalline chiral additives providing the concentrations used are small.

Dilute mixtures with long pitch lengths are used in many commercial liquid crystal display devices. For example, it is normal to use chiral nematic liquid crystal materials with $P \approx 200\,\mu m$ to remove the twist degeneracy [1] inherent in twisted nematic LCDs [2], and materials with $P \approx 20\,\mu m$ to induce the higher twist angles found in supertwisted nematic LCDs [3].

The standard method for measuring pitch lengths up to 1 mm involves the use of a thick layer of liquid crystal of smoothly varying thickness confined between two surfaces treated to produce parallel planar anchoring. This so-called Grandjean–Cano wedge [4] geometry shows a series of parallel disclination lines orthogonal to the direction of increasing layer thickness when observed using a polarizing microscope. These disclination lines correspond to a sudden change of π in the total twist angle across the layer and occur when the liquid crystal layer thickness d is related to the pitch length by:

$$d_m = (2m-1)\frac{P}{4},\ m = 1, 2, 3, \ldots\ldots\ldots \qquad (2)$$

and P can therefore be calculated from the observed values of d_m. However, the sensitivity of this method is limited to $P \leqslant 1$ mm by the practical difficulties involved when using layers thicker than 0.25 mm.

2. Reverse twist disclination lines

Twisted nematic (TN) LCDs are constructed using orthogonal planar alignments on the two surfaces defining the liquid crystal layer, and the degeneracy between $+\pi/2$ and $-\pi/2$ twist angles results in reverse twist domains. These domains are eliminated in practical TN LCDs by using a long pitch ($P \approx 200\,\mu m$) chiral nematic mixture to remove the degeneracy [1]. Longer pitch materials can also remove the degeneracy, but their efficiency is limited by the pinning of the reverse twist disclination lines on spacer particles, dirt or other defects within the liquid crystal layer.

However, by using TN devices containing randomly dispersed spacer particles to define the layer thickness, pinning sites for the disclinations are introduced resulting in information that yields a new and more sensitive method of measuring long pitch lengths. E7, a standard nematic liquid crystal mixture ($P=\infty$) was introduced into a standard 15 µm thick test TN device containing randomly dispersed spacer particles, and any

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Figure 1. TN device containing E7 between crossed polarizers.

influence on the alignment of flow from the filling process was eliminated by thermal cycling through the isotropic phase. Figure 1 shows a typical result after allowing several hours for the liquid crystal to reach equilibrium. The disclinations have shrunk to become virtually linear between the spacer particles in order to minimize the line tension associated with the disclination [5].

3. Bowed reverse twist disclination lines

This simple situation is changed when a similar device is filled with a long pitch chiral nematic material. Figure 2 shows TN devices filled with chiral nematic liquid crystals formed by diluting a sample of E70A doped with 0.06% CB15 into E7, such that the final mixtures contain 0.012, 0.0053, 0.0027 and 0.0013% of the chiral dopant CB15. The most obvious feature is that the reverse twist lines are now bowed, with the smaller radius of curvature being associated with the shorter pitch length, consistent with E7 showing a virtually infinite radius of curvature. This bowing is caused by the introduction of the chiral dopant which favours one sense of twist but is prevented from forming a single twist domain by the pinning of the disclination lines. The disclination therefore increases its length and bows, driven by the chirality, until equilibrium is reached.

The line tension E_L, or energy per unit length, is related to some combination of the elastic constants and the strength of the disclination line, though the precise details are somewhat uncertain [5]. We will therefore make the following simple assumption for the line tension:

$$E_L = \pi^2 k \tag{3}$$

where k is the average elastic constant. The twist energy F per unit volume of a layer of thickness d and twist angle ϕ is known from the continuum equation:

$$F = \frac{k_{22}}{2}\left(\frac{\phi}{d} - \frac{2\pi}{P}\right)^2. \tag{4}$$

The difference in energy ΔF per unit area between the two twist domains ($\phi = \pm\pi/2$) is therefore given by:

$$\Delta F = \frac{2\pi^2 k_{22}}{P}. \tag{5}$$

The equilibrium condition is found by minimizing the total energy (E_L+ΔF) and it can readily be shown that the following simple result holds for long pitch lengths,

$$P = 2R \tag{6}$$

where R is the radius of curvature of the bowed disclination line, and a single elastic constant has been assumed ($k_{22}=k$).

Using the measured radii of curvature from figures 1 and 2 the pitch lengths have been calculated and a plot of P^{-1} against concentration is linear, figure 3, as anticipated by equation (1). This yields an *HTP* of $9.3\,\mu^{-1}$ for CB15, slightly larger than the value of $8.8\,\mu^{-1}$ found for the CB15-doped E70A sample using a Grandjean–Cano wedge.

4. Sensitivity and accuracy of the method

The traditional Grandjean–Cano wedge can be used to measure pitch lengths of less than 1 mm, but the thick liquid crystal layer necessary uses a significant quantity of liquid crystal material. The new method can easily measure a pitch length of 10 mm, and as it uses a thin cell, the quantity of sample required is small. Even longer pitches of around 50 mm have been measured by the new method using standard 15 µm thick test TN devices.

Sensitivity is limited by two constructional details of the TN devices used, as well as the difficulty of observing radii of curvature larger than 100 mm. The first of these constructional details is that the TN test devices have rubbed polyimide alignment, which has a pretilt angle of around 1–2°. This pretilt slightly favours the twist domain with a uniform director tilt across the layer, and it can be shown that the energy difference ΔF_P per unit area between the two twist domains due to a pre-tilt of θ_P is given by:

$$\Delta F_P = \frac{2k_{11}\theta_P^2}{d}. \tag{7}$$

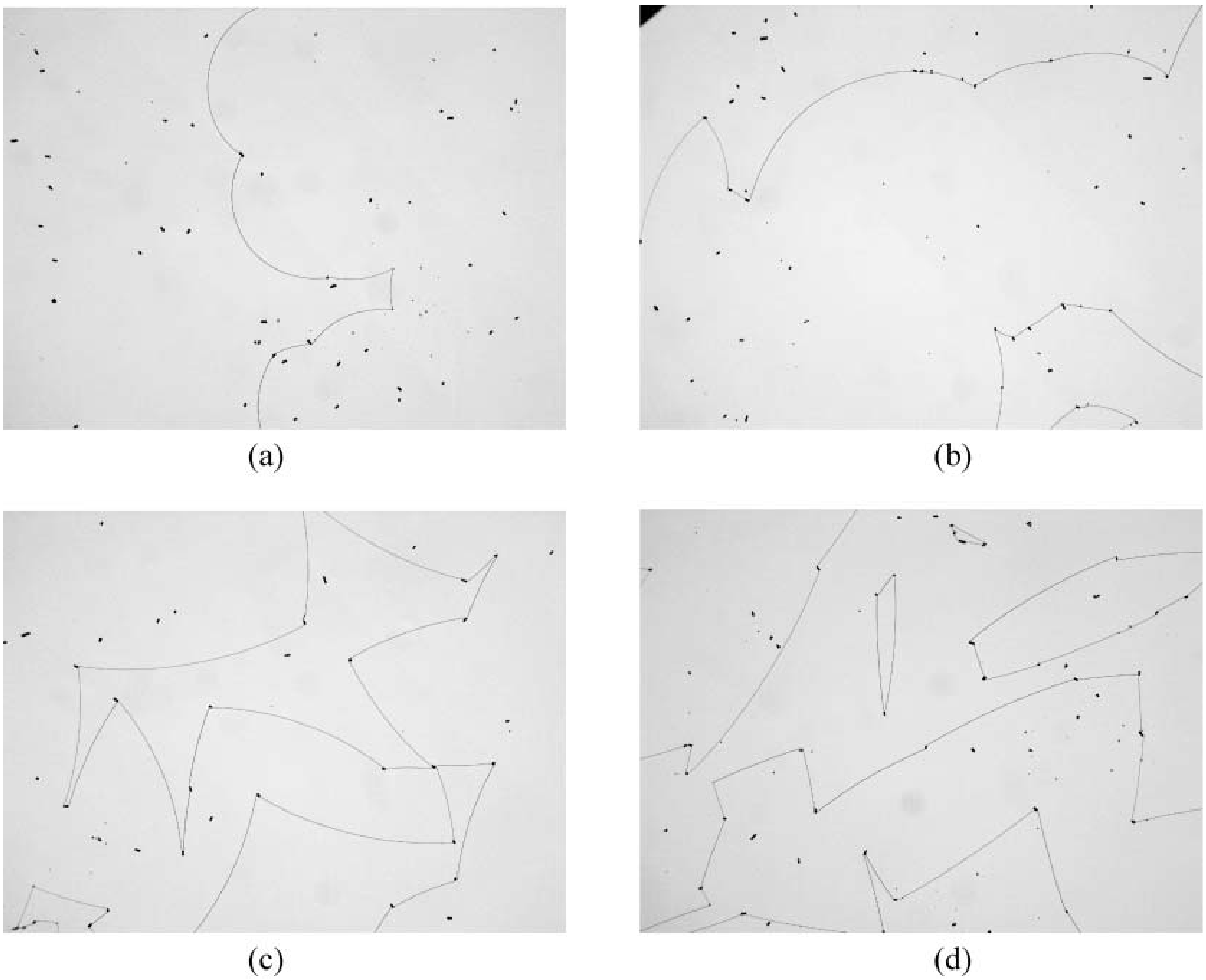

Figure 2. TN devices containing nematic liquid crystal material doped with (*a*) 0.012, (*b*) 0.0053, (*c*) 0.0027, (*d*) 0.0013% of CB15, observed using crossed polarizers.

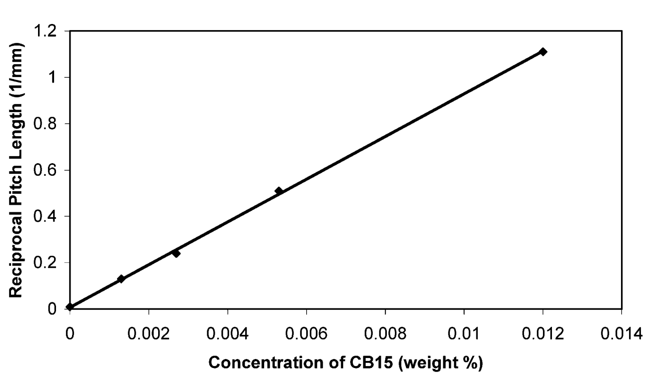

Figure 3. Concentration dependence of reciprocal pitch length.

An estimate shows that this limits the sensitivity of pitch measurement to around 50 mm, but the use of lower, or even zero pretilt would increase this figure.

The second constructional limitation arises from the error in the angle between the alignment directions. If this *pretwist* has a magnitude of ϕ_P, the two domains have twist angles of ($\phi_P \pm \pi/2$), producing an energy difference ΔF_T per unit area between the two domains of:

$$\Delta F_T = \frac{\pi k_{22} \phi_P}{d}. \tag{8}$$

Direct measurement of the twist angle from the guiding of polarized light in the standard TN test devices suggests that $\phi_P < 0.5^0$. Observation of the disclination lines in the E7-filled device suggests that, unless there is significant compensation between the pretilt and pretwist, the pretwist is actually less than $0.1°$. Pretwist is likely to be variable between devices, but should be no larger than $0.1°$ for measurement of pitches up to 50 mm; measurement of even longer pitches will require either smaller pretwist or its precise measurement using nematic liquid crystals with infinite pitch.

The simple form assumed for the line tension in equation (3), together with the one-elastic constant approximation, will limit the accuracy of the method. However, comparison of the *HTP* measured using this method with that determined using a Grandjean–Cano wedge, and measurement of radii of curvature for disclination lines of different orientation, for example in figure 2 (*c*), suggest that these errors are less than around 10%. A more sophisticated model for the line tension would reduce this error.

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