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PATTERN FORMATION OF CHOLESTERIC FINGER UNDER A MAGNETIC FIELD

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Abstract The effect of magnetic field on the growth of the cholesteric finger pattern has been investigated experimentally. It is found that the cholesteric finger grows along the applied magnetic field and the growth velocity of the finger is enhanced by the magnetic field. The preferred direction of the finger growth is discussed by considering the interaction energy between the director and the magnetic field.

INTRODUCTION

In recent years, much attention has been paid to the cholesteric finger pattern[1-8] appearing in a large pitch cholesteric liquid crystal sandwiched between glass plates with homeotropic anchoring. The cholesteric finger, that is the isolated domain of cholesteric phase embedded in the nematic phase, exists under a certain condition in which the anchoring force of the homeotropic agent competes with the winding force of cholesteric liquid crystal. Since the alignment of molecules can be varied by an electric and/or a magnetic fields, the appearing pattern of the cholesteric finger is influenced by the external fields. In the absence of the magnetic field, Ribiere *et al.*[3] constructed a phase diagram of the appearing pattern by changing the cell gap and the applied voltage for the liquid crystal with positive dielectric anisotropy. According to their study,[3] there are five regions in the phase diagram, and they numbered the regions in the phase diagram from I to V, where the effect of chiral force becomes stronger with increasing the number. Quite recently, the present authors have found an expanding concentric pattern in the narrow region between the regions IV and V.

Several investigations on the pattern formation of the cholesteric finger under the electric field have been described in the literature.[1-9] However, very little is known about the influence of the magnetic field on the growth of the finger pattern,[1] in spite that the alignment of the molecules can be varied by the magnetic field. Since the diamagnetic anisotropy of the rod-like molecule of the liquid crystal is positive, the molecules tend to align along the magnetic field. When the magnetic field is perpendicular to the glass plates, it plays the same role as the homeotropic agent. In such a geometry, no intrinsic change for the appearing pattern by the application of the magnetic field was observed.[1] In the present study, therefore, the magnetic field is applied on the cell in the direction parallel to the glass plates. In this geometry, a preferred direction of molecules is parallel to the glass plates. Thus, it is expected that the morphology of the appearing pattern can be varied by the magnetic field.

EXPERIMENTAL SET-UP

The liquid crystal used in the present study was a mixture of a nematic liquid crystal(Merck ZLI-2452) with positive dielectric anisotropy and a little amount of chiral molecules(Merck S-811) with the weight ratio 99.4:0.6. The pitch of the mixture was 15μm at 25°C. The mixture was confined between two ITO-coated glasses separated by spacers whose thickness was 16μm. To obtain a homeotropic alignment, a surfactant(Merck ZLI-3334) was coated on the surface of glass plates. The ac electric field with 1kHz was applied on the cell. Since the dielectric anisotropy of the molecules is positive, the electric field exerts the force on the molecules to establish the homeotropic alignment and suppresses the appearance of cholesteric phase. To observe the pattern formation under the magnetic field, a polarizing microscope was set in an electromagnet(Toei Kogyo TEM-WER3). The direction of the magnetic field is parallel to the glass plates and perpendicular to the electric field. The strength of magnetic field was monitored by a Hall generator. All the experiments were done at room temperature.

TABLE I Relation among the stability of the phases and the appearing pattern.

	I	II	III	IV	IV'	V
nematic	stable	stable	metastable	metastable	metastable	unstable
cholesteric	unstable	metastable	stable	stable	stable	stable
pattern	no pattern	finger (shrink)	finger	dendritic finger	concentric pattern	finger print

RESULTS AND DISCUSSION

Under no magnetic field, it is known that there are six regions in the phase diagram.[3,9] The relation among the appearing pattern and the stability of the nematic and the cholesteric states is summarized in Table I. Firstly, we tried to construct an H-V phase diagram of the appearing pattern by changing the voltage V and the strength of the magnetic field H. In the experiment, we applied the voltage 15V to the cell at first to establish the homeotropic alignment of nematic state(region I). Then the voltage was decreased quickly to a certain value of interest and the appearing pattern was observed. The magnitude of the magnetic field was kept at a constant value throughout one series of experiment. By repeating the same procedure for different amplitudes of the magnetic field *H*, we obtained the *H*-*V* phase diagram (see Figure 1).

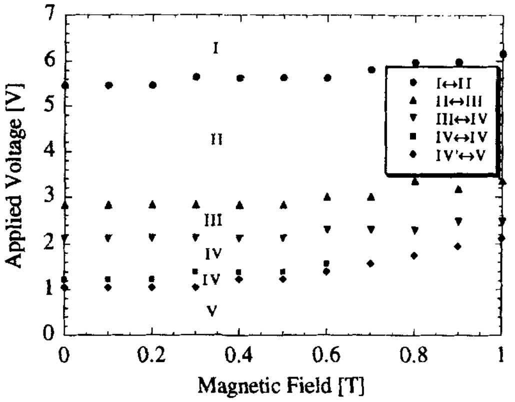

FIGURE 1 Magnetic field-voltage phase diagram of the appearing pattern.

It is natural that all the threshold voltages increase with the increase of the magnetic field because the magnetic field reduces the effect of electric field which suppresses the appearance of cholesteric phase. Concerning the concentric pattern observed in the region IV',[9] the range of voltage becomes narrow as the increase of magnetic field, and then the concentric pattern disappears at *H*=0.7T.

The growth of finger pattern is observed in the regions III and IV.[3,9] In the region III, the elongation of fingers proceeds with undulating their shape. In the region IV, on the other hand, the growth of finger pattern proceeds with splitting their tips and the dendritic finger pattern appears. Then we investigated the effect of the magnetic field on the growth of the cholesteric finger. In this experiment, we applied 15V on the cell to obtain the homeotropic alignment(region I). Then the system was quenched into the region III by decreasing the applied voltage down to 2.3V. The magnetic field dependence of the finger pattern in the region III is shown in Figure 2. All the photographs were taken at the same time 30 sec after the quenching. Under no magnetic field(Figure 2(a)) the cholesteric fingers nucleated from the imperfection of the cell (located in the center of the photograph) and grew up into the different directions. The direction of growth may be governed by the condition of the cell. Under the magnetic field of 0.2T(Figure 2(b)), the finger indicated by the arrow grew up into the direction parallel to the magnetic field.

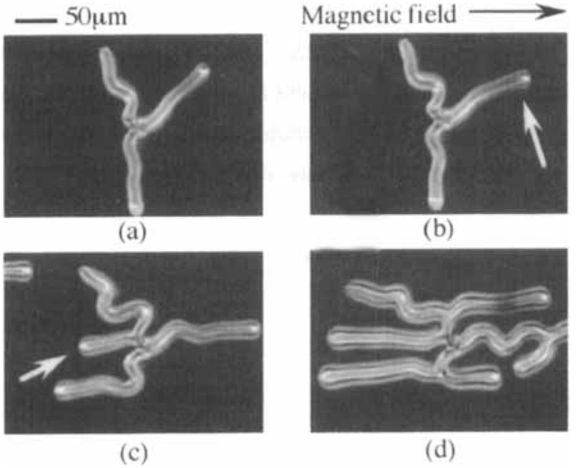

FIGURE 2 Pattern formation in the region III under the magnetic field. The strength of the magnetic field are (a)0T, (b)0.2T, (c)0.4T and (d)0.6T.

In addition, the velocity of the tip of the finger indicated by the arrow was faster than that of the other fingers that grew up along the direction perpendicular to the magnetic field. Under the magnetic field of 0.4T(Figure 2(c)), every finger grew up into the direction parallel to the magnetic field. Moreover a new tip of finger, indicated by the arrow in Figure 2(c), nucleated from the curved point of the finger. Under the magnetic field of 0.6T(Figure 2(d)), the side branching of the finger frequently happened and the growth velocity of the finger was faster than that under the magnetic field of 0.4T. Then we measured the magnetic field dependence of the growth velocity. In this experiment, we chose such a finger that the growth direction of the finger is parallel to the magnetic field.

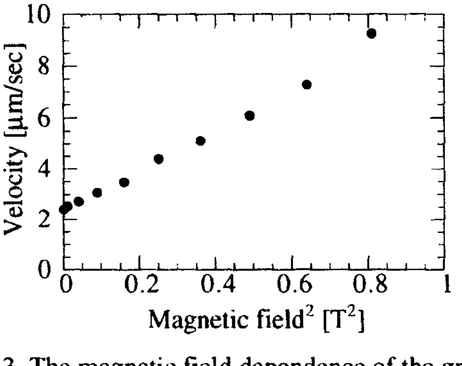

FIGURE 3 The magnetic field dependence of the growth velocity.

Since the driving force should come from the anisotropy of magnetic susceptibility, the velocity of the finger tip may be expanded in terms of H^2 as

$$v=a_0(E)+a_2(E)H^2+a_4(E)H^4+\cdots\cdots. \quad (1)$$

It is seen from Figure 3 that the velocity is a linear function of H^2 at weak magnetic fields, as was expected. With respect to the coefficient a_0, the dependence of a_0 on the applied voltage was investigated by Ribiere *et al.*[4] in detail.

Next we investigated the growth of the dendritic finger under the magnetic field. In this experiment the system was quenched from the region I to the region IV by decreasing the applied voltage into 1.75V. All the photographs were taken at the same time 15 sec after quenching(see Figure 4). As the magnetic field increases, the growth velocity increases especially for the direction parallel to the magnetic field. It is clearly shown that the magnetic field promotes the growth of the finger.

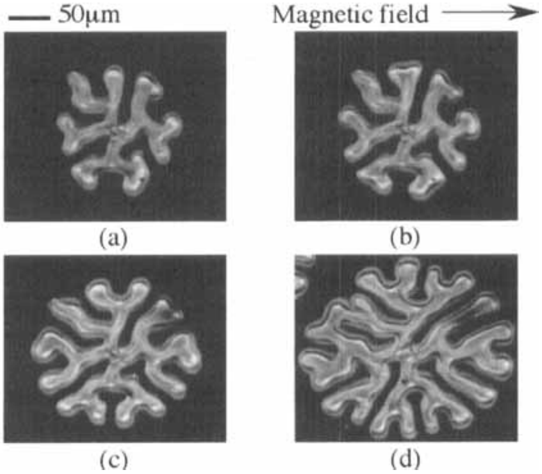

FIGURE 4 Pattern formation in the region IV under the magnetic field. The strength of the magnetic field are (a)0T, (b)0.2T, (c)0.4T and (d)0.6T.

Finally, let us consider the reason why the cholesteric finger elongates into the direction parallel to the magnetic field. We focus on the variation of the interaction energy density δf by the application of the magnetic field. Under the weak magnetic field $\delta\mathbf{H}$, δf can be expressed as

$$\delta f = -\frac{\chi_a}{2}\left[(\mathbf{n}_0 + \delta\mathbf{n})\cdot\delta\mathbf{H}\right]^2$$
$$= -\frac{\chi_a}{2}\left[(\mathbf{n}_0\cdot\delta\mathbf{H})^2 + 2(\mathbf{n}_0\cdot\delta\mathbf{H})(\delta\mathbf{n}\cdot\delta\mathbf{H}) + (\delta\mathbf{n}\cdot\delta\mathbf{H})^2\right] \quad , \qquad (2)$$

where χ_a is a diamagnetic anisotropy, $\mathbf{n}_0$ a director under the absence of the magnetic field and $\delta\mathbf{n}$ a small variation of the director from $\mathbf{n}_0$ due to the application of the magnetic field. Suppose that the glass plates of the cell is in a x-y plane and there is an infinitely long finger along the x-axis. When we apply the magnetic field of $\delta\mathbf{H}$=($H\cos\theta$, $H\sin\theta$, 0) on the cell, where H is a strength of the magnetic field and θ

an angle between the finger and the magnetic field, the variation of the free energy density is written as

$$\delta f = -\frac{\chi_a}{2}\left(n_x H\cos\theta + n_y H\sin\theta\right)^2$$
$$= -\frac{\chi_a H^2}{2}\left(n_x^2\cos^2\theta + n_y^2\sin^2\theta + 2n_x n_y\sin\theta\cos\theta\right) \quad (3)$$

where n_x, n_y and n_z are the components of $\mathbf{n}_0$. By calculating the averaged values of n_x^2, n_y^2 and $n_x n_y$, we are able to know θ dependence of the total variation of the interaction free energy. However, it is difficult to measure the configuration of director in the cholesteric finger in general. Then we obtained the following averaged values $\langle n_x^2\rangle=0.072$, $\langle n_y^2\rangle=0.042$ and $\langle n_x n_y\rangle=0$ from the numerical calculation performed in our pervious study.[10] (Due to the reason of symmetry, $\langle n_x n_y\rangle$ is zero.) Roughly speaking, the average of the director configuration is parallel to the axis of the finger. Consequently the total value of the variation of the interaction free energy becomes

$$\delta F = \int \delta f dv = -\frac{\chi_a H^2 V_0}{2}\left(0.042 + 0.03\cos^2\theta\right) \quad (4)$$

where V_0 is a unit volume around the finger. It is readily seen from Equation 4 that δF has a minimum at $\theta=0$ and π. Therefore it is intuitively understood that the preferred direction of the cholesteric finger is parallel to the magnetic field.

In conclusion, we have investigated the effect of the magnetic field on the growth of cholesteric finger pattern. It is found that the growth of finger is accelerated by the magnetic field especially for the direction parallel to the magnetic field. In the region III, moreover, the finger tends to elongate into the direction parallel to the magnetic field. The preferred direction of the finger can be understood by considering the interaction free energy between the director and the magnetic field.

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