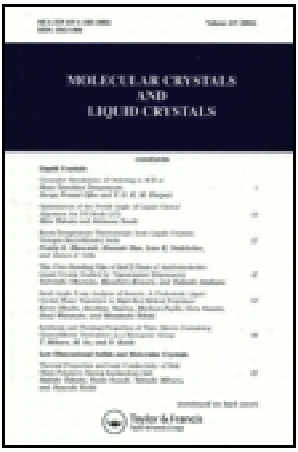

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Pattern Formation in the Two Electro-Hydrodynamic Systems Coupled Through free Lateral Boundaries

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PATTERN FORMATION IN THE TWO ELECTRO-HYDRODYNAMIC SYSTEMS COUPLED THROUGH FREE LATERAL BOUNDARIES

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Abstract The interaction between the two convective systems separated by free lateral boundaries and the pattern formation have been studied. We have prepared a cell, where two identical convective subsystems with small aspect ratios are placed in the direction of the roll axis and coupled through the free lateral boundaries and the liquid crystal placed in-between. It is found that the evolution of convection in one subsystem is affected by the state of the other subsystem through the free boundaries. Moreover, the entrainment of the spatial pattern is observed.

INTRODUCTION

In convective phenomena such as the electro-hydrodynamic (EHD) instability in nematic liquid crystals, a stationary state with no macroscopic flow becomes unstable and a macroscopic flow structure with one-dimensional period appears above a critical value of the external control parameter. Since liquid crystals are anisotropic in its optical properties, one can observe such flow structure as a two-dimensional pattern, called the Williams domain, easily by a polarizing microscope. The instability in convective systems depends on the aspect ratio, Γ, which is defined as the ratio of the horizontal to the vertical sizes of the system. In the systems with a small aspect ratio (say, $\Gamma \sim 1$), the lateral boundary condition of the system influences seriously the pattern formation.[1,2]

In the previous study, we made the free lateral boundary cell.[3,4] In that cell, a strip-shaped electrode was lithographically coated on the upper plate, and another one on the lower plate, and then the electrodes were crossed. Therefore, the electric field was applied only to a restricted area of the liquid crystal between the electrodes. Since the aspect ratios of this restricted area were much smaller than that of the part in which nematic liquid crystals were enclosed (about 200), the lateral boundary of the convective system was free but not constrained. Moreover, by using two strip-shaped electrodes on one plate, we could prepare a cell consisting of two identical EHD subsystems, which were separated from each other by the free lateral boundaries and the liquid crystal placed in-between. Since the aspect ratio of the subsystems is small and the lateral boundary is free, the subsystems influence each other. In the previous paper,[4] we investigated the pattern formation in the coupled system consisting of the two identical subsystems disposed horizontally (Figure 1), and found the entrainment of the spatial pattern due to the interaction between the subsystems. It is expected that the interaction changes drastically by varying the geometric configuration of the subsystems. So the knowledge of the pattern formation in other configurations is required.

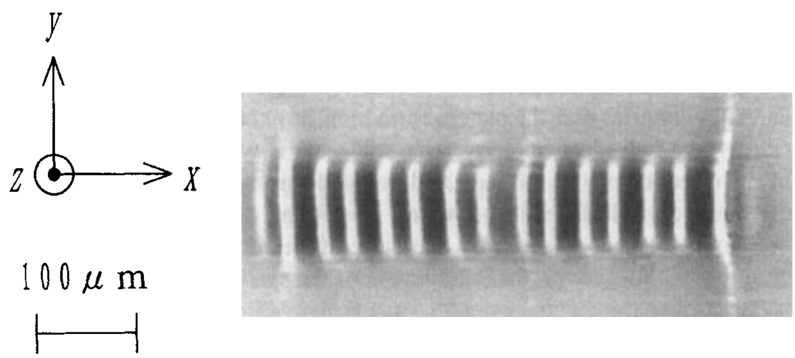

FIGURE 1 A typical Williams domain observed in the coupled system where the two subsystems are disposed horizontally.

EXPERIMENTAL

The interaction between the two convective systems was investigated in the following system. The nematic liquid crystal ZLI-1831(MERCK) was sandwiched between two glass plates (about 1×1 cm^2). Two parallel narrow electrodes being 100 μm wide were coated at a distance of 45 μm on the lower glass plate, while the other one is 200 μm wide on the upper glass plate (see Figure 2). To align the Williams domain parallel to the y-axis, the polyimide-coating and the rubbing treatment were adopted on the surface of the glass plates. Thus, two identical convective subsystems were disposed parallel to the y-axis and coupled through the liquid crystals placed in-between. Hereafter, we call these subsystems as the upper and the lower subsystems. The aspect ratios of each subsystem were $\Gamma_x = 4$ and $\Gamma_y = 2$, the cell thickness being 50 μm (as for x and y, see Figure 2).

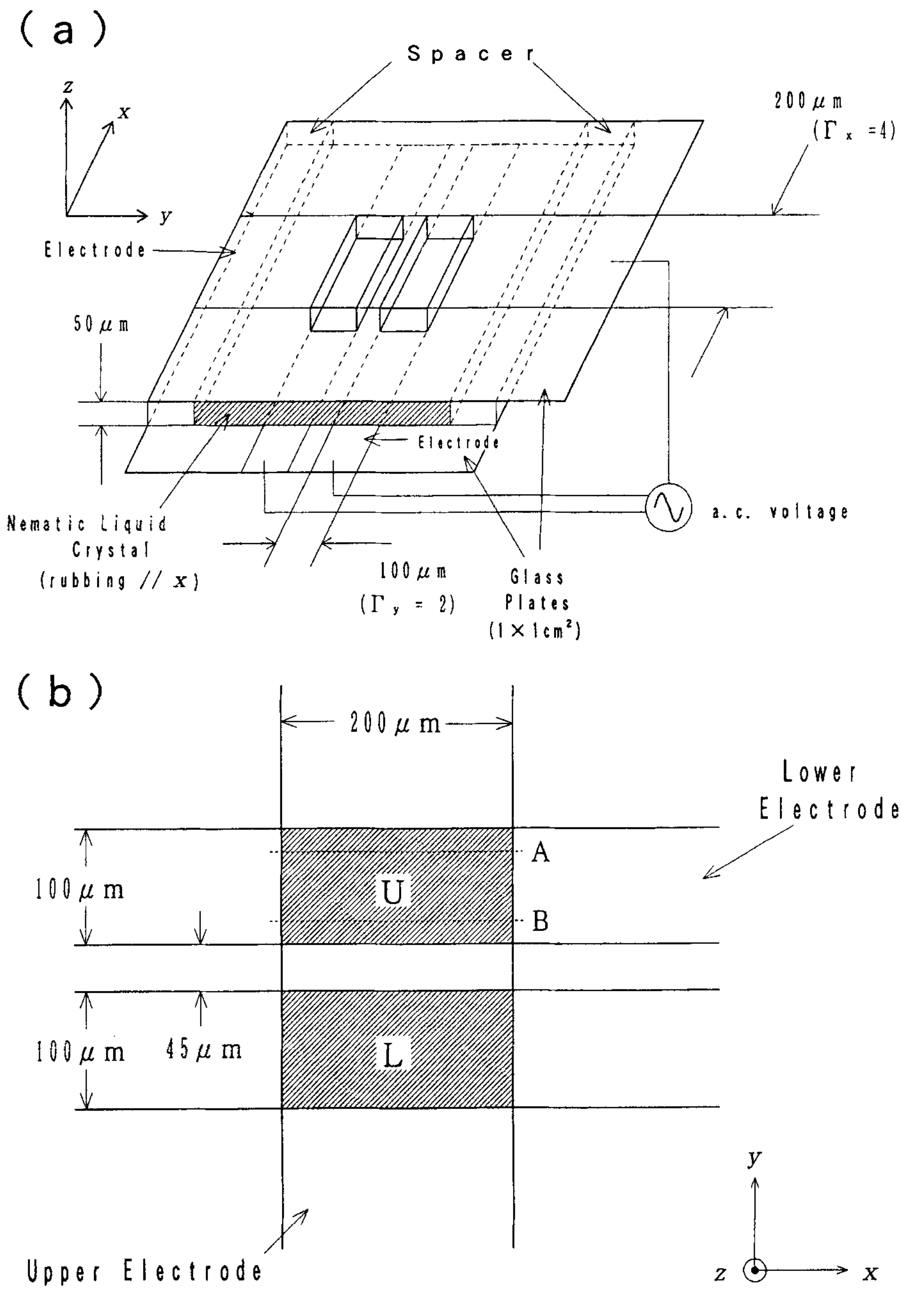

FIGURE 2 The cell for preparing two coupled convective systems. The rubbing direction is along x. "U" and "L" indicate the upper and the lower subsystem, respectively.

Sinusoidal electric fields were supplied by synthesizers (NF 1940) and amplifiers (NF 4005). The temperature of the cell was fixed at 50 °C during the experiments by a hot stage (Linkam TH-600PR). A TV camera mounted on a polarizing microscope sent the image signal to an image processing system (Carl Zeiss, Vidas Plus), where the image was digitized into 256 gray levels of the 512×512 pixels area. The maximum of sampling rate of the images was 25 Hz and the total number of frame amounted to 24. The-root-mean-squared value of the voltage applied to the upper and the lower subsystems are denoted as V_U and V_L, respectively.

In all experiments, we adjusted the objective lens so that one could observe the virtual image, where all bright lines, showing the positions of the roll axis, were of the same brightness.[5] We observed the formation process of the Williams domain after applying an ac electric field stepwise above the critical value from zero field.

RESULTS AND DISCUSSION

Figure 3 shows a typical Williams domain observed in the coupled system (V_U, V_L = 27.5 V and frequency, f = 4.2 kHz). There are eight bright lines, namely, 8 convective rolls in each subsystem. By varying the amplitude and the frequency of the applied electric field, the number of stable rolls changes. There are four kinds of stable convective states, namely 4-roll, 6-roll, 8-roll and 10-roll states.

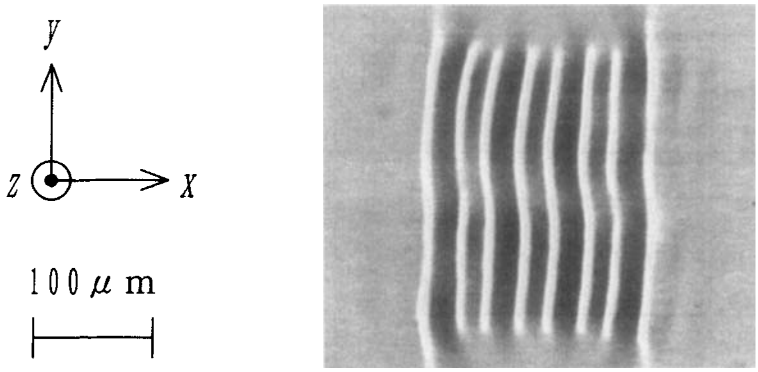

FIGURE 3 A typical Williams domain observed in the coupled system where the two subsystems are disposed vertically. The applied ac voltages were $V_U = V_L$ = 27.5 V and the frequency was f = 4.2 kHz in both systems.

If the aspect ratio for the direction of the roll axis is small enough, the temporal oscillation of the spatial pattern occurs, when the stability of the stationary spatial pattern breaks down above a threshold of the external control parameter.[3,6] In the present system, a similar oscillatory pattern sometimes appears when the two subsystems are coupled, even if each subsystem is in the stationary roll state under electric fields less than the critical value of the angle-deflective oscillation[3] in the non-coupled system. It is thought that this phenomenon takes place, because the effective aspect ratio of the whole system for the direction of the roll axis becomes large by the coupling between the subsystems.

We observed the evolution process of the Williams domain in the upper subsystem in the following procedure. V_L = 27.5 V was applied only to the lower subsystem first, and then 8-roll pattern formed. After the 8-roll state was stabilized after about 5 minutes, V_U = 29.0 V was applied stepwise to the upper subsystem. In both voltages, frequency, f, was set to 4.2 kHz. The temporal evolution of the Williams domain was monitored at two lines crossing the Williams domain parallel to the x-axis in the upper subsystem. We call the lines located at the upper and the lower part of the upper subsystem "line A" and "line B", respectively, as shown in Figure 2(b). Figures 4(a) and (b) show the temporal evolution of the intensity of image on the line A and B, respectively. The abscissa indicates the position, x, on the lines, and the ordinate the intensity of the image. The one-dimensional image intensity profiles in a sequence of 24 frames which were sampled at the interval of Δt (sec) are shown from the bottom to the top in a chronological order. The voltage, V_U, was applied stepwise to the upper subsystem at the time when the first frame was sampled. In the upper side of the upper subsystem, the 10-roll state appears initially. As time goes on, the 10-roll state becomes unstable, and the 8-roll state is finally stabilized. In the lower side of the upper subsystem, on the other hand, the stable 8-roll state appears directly. The 10-roll state does not appear due to the influence of the 8-roll state in the lower subsystem. If there is no convection in the lower subsystem, the 10-roll state appears uniformly in the upper subsystem and then it changes to the stable 8-roll state. In this case the temporal evolution of intensity is the same as that shown in Figure 4(a).

Generally speaking, the stable state changes by varying the external control parameter in the convective system. In the present system, as is mentioned above, there are four kinds of stable states and the number of roll changes by varying the amplitude and the frequency of the electric field. Under the constant frequency of applied electric field, the number of rolls increases when the amplitude of the electric field increases above a critical value. For the case of the coupled system, it is expected that the critical values of the external control parameter are modified due to the interaction between the subsystems. So we measured the values of critical voltages in the coupled system in the

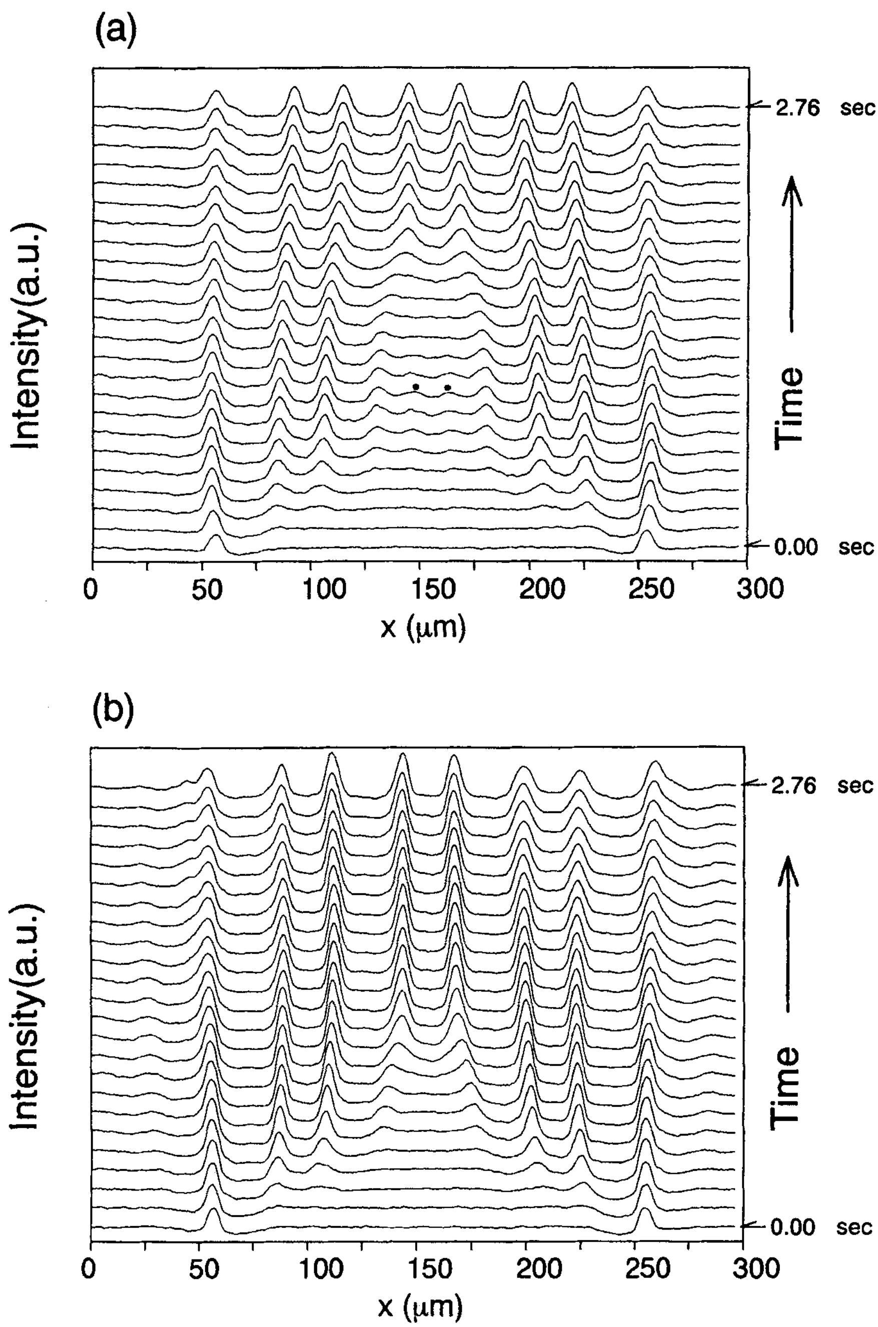

FIGURE 4 Evolution processes of the one-dimensional profile of the Williams domain in the upper subsystem. The sampling interval was $\Delta t = 0.12$ sec, i.e., the measuring time was 2.76 sec. The small closed circles show the positions of the peaks which disappear soon. In (a) the data were sampled along the line A in Fig. 2(b) and in (b) along the line B in Fig. 2(b).

following way. First the electric field was applied to the lower subsystem so that the N-roll state was formed. After the N-roll state in the lower subsystem was stabilized, the step voltage V_U was applied to the upper subsystem. For the sake of simplicity, the both frequencies were set equal. V_U was raised at the interval of about 35 mV, and the critical voltage V_U^c was defined as the voltage at which the number of rolls in the upper subsystem was increased. The relation between the state of the lower subsystem and the critical voltage of the upper subsystem is summarized in Table I. The V_U^c where the number of rolls changes from 4 to 6 is not influenced by the state of the lower subsystem. However, the V_U^c where the number of rolls changes from 6 to 8 for the 6-roll state of the lower subsystem is higher than for the 8-roll state. Moreover, for the V_U^c where the number of rolls changes from 8 to 10, the difference between the V_U^c for the 8-roll state of the lower subsystem and the one for the 10-roll state is still larger. We consider that because the lower subsystem in the 8-roll state leads the upper subsystem to the 8-roll state in the process as seen in figure 4, the upper subsystem does not become easily the 10-roll state, so the critical voltage, V_U^c, rises. In other words, the 8-roll state in the lower subsystem stabilizes the 8-roll state in the upper subsystem and suppresses the instability for the increase of rolls.

TABLE I Relation between the state of the lower subsystem and the critical voltage of the upper subsystem. N_L shows the number of the rolls in the lower subsystem. V_U^c shows the critical voltage of the upper subsystem at which the number of rolls changes.

N_L	4 (f= 1.4kHz, V_L = 8.71V)	6 (f= 1.4kHz, V_L = 9.21V)
V_U^c (4 to 6)	8.87 V	8.87 V
N_L	6 (f= 3.4kHz, V_L = 16.98V)	8 (f= 3.4kHz, V_L = 17.51V)
V_U^c (6 to 8)	17.69 V	17.31 V
N_L	8 (f= 4.2kHz, V_L = 27.52V)	10 (f= 4.2kHz, V_L = 28.60V)
V_U^c (8 to 10)	29.68 V	28.10 V

The increase of the difference between V_U^c for N_L and V_U^c for N_L+2 with increasing N_L may be explained as follows. In the experiment, as shown in Table I, N_L increases with the applied voltage. In the electro-hydrodynamic instability high voltages induce strong convection, i.e., in this case long rolls, which penetrate into the other subsystem and influence V_U^c.

CONCLUSIONS

We have prepared the cell, where two identical convective systems, of which aspect ratios are relatively small, are placed in the direction of the roll axis and coupled through the free lateral boundaries and the liquid crystal placed in-between, and investigated the interaction between these two subsystems in the pattern formation.

Two kinds of the entrainment of the spatial pattern was observed, when we studied how the pattern formed in the upper subsystem after the stationary pattern had already formed in the lower subsystem. The first is concerned with the pattern evolution process in the upper subsystem when the wave number of the ultimate pattern in the upper subsystem is equal to the one in the lower subsystem. The pattern of the upper subsystem settles down to the ultimate one gradually from the position near the lower subsystem by the entrainment of the lower subsystem. Secondly, the dependence of the critical voltage where the number of rolls in upper subsystem increases on the state of the lower subsystem is investigated. If the number of rolls of the upper subsystem is equal to the one of the lower subsystem, the critical voltage for escaping from that equal-roll state rises. We think that the higher voltage is necessary to increase the number of the rolls, because it is difficult for the upper subsystem to increase the number of rolls against the entrainment by the lower subsystem.

Since the two subsystems are completely equivalent, one can observe the same phenomena if their roles are exchanged.

REFERENCES

1. C. W. Meyer, G. Ahlers and D. S. Cannell, Phys. Rev. Lett., 59, 1577(1987).
2. J. Vinals, H. W. Xi and J. D. Gunton, Phys. Rev. A, 46, 918(1992).
3. Y. Hidaka, H. Orihara and Y. Ishibashi, J. Phys. Soc. Jpn., 61, 3950(1992).
4. Y. Hidaka, K. Shimokawa, T. Nagaya, H. Orihara and Y. Ishibashi, J. Phys. Soc. Jpn., 63, 1698(1994).
5. K. Kondo, M. Arakawa, A. Fukuda and E. Kuze, Jpn. J. Appl. Phys., 22, 394(1983).
6. C. Y. Yang, H. Itakura, S. Horie, Y. Tsuchiya and T. Kawakubo, J. Phys. Soc. Jpn., 55, 703(1986).