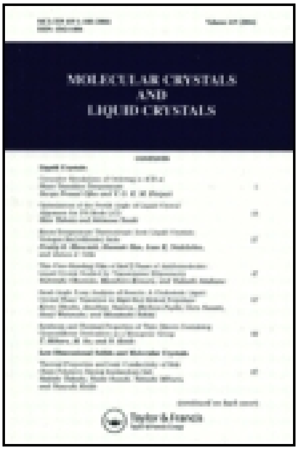
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Experimental study about pattern selection processes under spatially-periodic external force in the electroconvection system is reported. Specific formation processes of periodic patterns beyond the threshold were observed due to the external forces and wavenumbers. The convection pattern was either entrained into the external periodic force or maintained with the intrinsic spontaneous wavenumber (the fastest growing one), depending on magnitudes of mismatches such as difference between the wavenumber of the entrained pattern and the spontaneous wavenumber. We call it the entrainment (or spatial synchronization) of wavenumbers. The spatial entrainment and desynchronization were investigated in detail by changing applied frequencies and voltages.

Keywords: electroconvection; pattern selection; entrainment

INTRODUCTION

Periodic structures like crystal lattices and layer structures in smectic liquid crystals had attracted our interests for long time as one of the ordered states appearing in nature. In a convection system with increasing the control parameter a fastest growing mode with a wavelength q_s^{-1} is developed beyond a primary instability point and spontaneously leads to a periodic structure called "rolls". It is known as a typical dissipative structure in nonlinear nonequilibrium open system, unlike the above mentioned microscopic and equilibrium structures. Electroconvections in nematics thus have been studied as research object about dissipative structures and nonlinear dynamics in spatially-extended system because of some advantages about experiment, e.g., short time scale and easy visibility of convective structure, of which linear mechanism was well explained by Carr-Helfrich mechanism.[1,2]

It is known, on the other hand, that an external periodicity leads to commensurate-incommensurate structures, e.g., ferroelectric crystals[3] and epitaxial growth processes. In convection system, similarly, periodic external force by spatially-modulated control parameter causes other structure with more complex periodicity[4-6] and temporally oscillatory behavior.[7] Thus, competition between the intrinsic modes and the externally applied periodicity induces rich phenomena on pattern formation due to strong nonlinearity of the macroscopic open system.

In the common electroconvection system using spatially uniform control parameters, the pattern dynamics has been rather well studied, and continuous translational symmetry of the system breaks with a roll pattern formation. As usual, applying the stress beyond a threshold, small domains of the rolls pattern appear locally forming defects, and then, motion and pair-annihilation of defects occur due to phase gradients and/or Peach-Köhler force and imperfection disappears. This is called the pattern selection process which for uniform systems has been well studied. The systematic investigation of this process gives us the Busse balloon which describes a full nonlinear aspect near the convective onset.[8] It is expected that the Busse balloon may be strongly modified in spatially heterogenous external stress. Therefore as a first step in order to proceed in this direction as well as spatial entrainment, we have been investigating the pattern dynamics using spatially modulated control parameters.

In the present paper we report experimental results about the wavelength competition phenomena, i.e., "entrainment" of spatial patterns into the periodic external force in the electroconvection. Entrainment is a specific phenomenon in nonlinear systems. However, so far, many works have been done for temporal entrainment (synchronization) and only very few works are devoted to spatial entrainment in open systems.

EXPERIMENTAL

The standard nematics *p*-methoxybenzilidene-*p*'-*n*-butylaniline (MBBA) doped with tetra-*n*-butyle-ammonium bromide (TBAB) of 0.01wt% was filled between two parallel glass plates.

In order to realize the spatially periodic modulation of the external force, interdigitated transparent electrodes was photolithographically coated on one of the glass plates of the cell as shown in Fig. 1. The two different interdigitated regions are composed as the electrode and electric field with different amplitude $\Delta V = V_A - V_B$ is applied between these two, where the voltages applied to A and B in Fig. 1 are V_A and V_B respectively. Then, the control parameters are defined as

$$\varepsilon_A = (V_A^2 - V_c^2) / V_c^2 \tag{1}$$

and

$$\varepsilon_B = (V_B^2 - V_c^2) / V_c^2, \tag{2}$$

where V_c is the threshold voltage of the electroconvection. Thus the control pa-

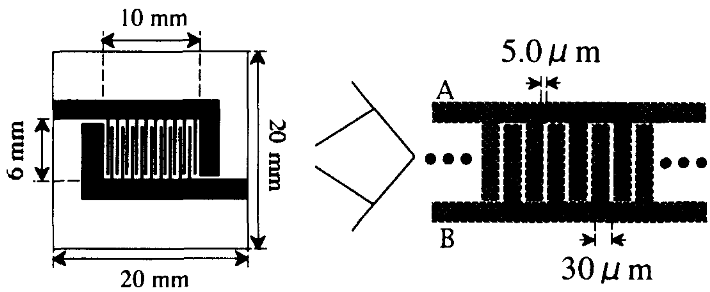

FIGURE 1 Glass plate with interdigitated electrodes.

rameter was modulated periodically in a direction defined as x. Averaged control parameter

$$\varepsilon_0 = (\varepsilon_A + \varepsilon_B) / 2 \tag{3}$$

and amplitude of the periodic external force

$$\Delta\varepsilon = |\varepsilon_A - \varepsilon_B| / 2 \tag{4}$$

were also defined. The other glass plate was coated uniformly.

In order to obtain a uniform planar alignment of the director of the nematics, the top and bottom contact surfaces of the glass plates were rubbed in x-direction after the treatment by a surfactant polyvinyle alcohol (PVA). Since the space between the two plates was 50μm and x-length of the area was 10mm and y-length 6mm, the aspect ratios of the system Γ's were obtained as $\Gamma_x = 200$ and $\Gamma_y = 120$. The sample cell was kept in a thermally insulated container whose temperature was maintained within 30 ± 0.05°C.

One of the other advantages of the electroconvection is possible to the precise control of the wavenumber of convective patterns. The spontaneous wavenumber can be for example controlled by frequency of applied voltage. Figure 2 shows the dependence of the spontaneous wavenumber q_s on the frequency f of the applied voltage for $\varepsilon_A = \varepsilon_B = 0.10$ (i.e., $\Delta\varepsilon = 0$ and $\varepsilon_0 = 0.10$). The solid line shows the wavenumber k_e of the external force. The difference between $q_s(f)$ and k_e, which increases with the frequency of the applied voltage, corresponds to a kind of the mismatch strength, that is, "frustration" of the pattern. Thus we defined the mismatch parameter as $Q_{fr}(f) = |q_s(f) - k_e| / k_e$.

RESULTS AND DISCUSSION

We conducted the similar experiment for the dynamics of the pattern selection

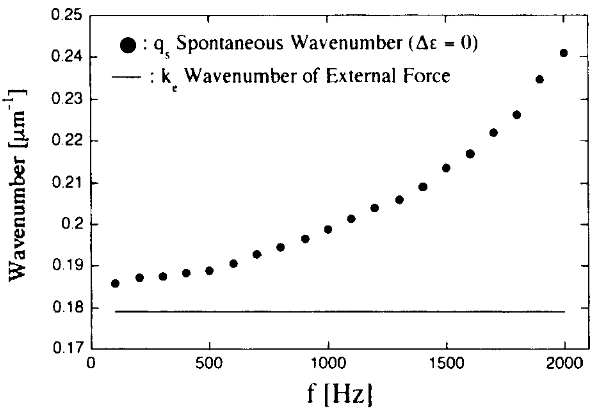

FIGURE 2 Dependence of spontaneous wavenumber q_s on frequency f of applied voltage for $\Delta\varepsilon = 0$ and $\varepsilon_0 = 0.10$. The thick line indicates the wavenumber of the periodic force.

process under the external periodic force to the one under spatially-uniform force. Figure 3 shows typical processes of the periodic pattern formation for making the applied voltage jump from $\varepsilon_0 = 0$ and $\Delta\varepsilon = -1$ to 0.10 and 0.01 at $t = 0$sec. For lower range of the frequency of the applied voltage, marked with the symbol × as shown in Fig. 3(a), a defect-free periodic pattern appears whose wavenumber does not change from its beginning. For middle range of the frequency, marked with the symbol • as shown in Fig. 3(b), although defect-free patterns appear at beginning as a quasi-steady state, waiting for a while, a few isolated defects form. Then, defects climb out and the wavenumber increases slightly. Namely pattern selection dynamics through defect motions is observed. For higher range of the frequency, marked with the symbol □ as shown in Fig. 3(c), a defect-free pattern does not appear at beginning, and pattern selection occurs through formation, motion and pair-annihilation of defects similarly to the case of spatially-uniform force ($\Delta\varepsilon = 0$) mentioned above. Figure 4 shows the phase diagram for these three types of the behavior in $\Delta\varepsilon$ - Q_{fr} plane.

In order to investigate the dynamical behavior of the patterns we detailedly measured the dynamical change of the wavenumber. Figure 5 shows the dependence of the wavenumber on the amplitude of the periodic external force $\Delta\varepsilon$ for $\varepsilon_0 = 0.10$ and $Q_{fr}(f = 1400\text{Hz}) = 0.168$. The cross shows the initial wavenumber q_i, i.e., the wavenumber of the initial periodic pattern observed at $t = 1$sec immediately after the jump of the applied voltage, and the open circle the final wavenumber q_f, i.e., the wavenumber of the final pattern observed at $t = 300$sec. For

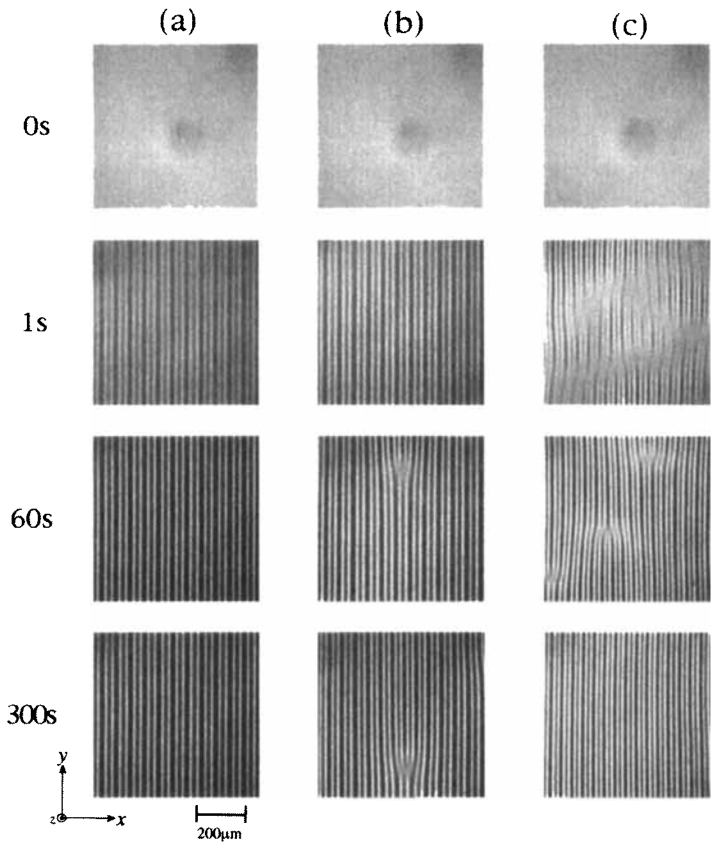

FIGURE 3 Typical processes of periodic pattern formation for making applied voltage jump from $V_A = V_B = 0V$ to $\varepsilon_0 = 0.10$ and $\Delta\varepsilon = 0.01$ at 0sec. (a) $f = 600Hz$, (b) $f = 1400Hz$, (c) $f = 2000Hz$.

the whole range of $\Delta\varepsilon$, the initial pattern always occurs with the same wavelength as the external periodicity, that is, the convective pattern is entrained. For large amplitude of the periodic external force such as $0.03 \leq \Delta\varepsilon \leq 0.05$ the pattern is totally entrained for its whole stage. Non-entrainment has been obtained for $\Delta\varepsilon < 0.03$ at final stages. The final wavenumber q_f increases with decreasing $\Delta\varepsilon$,[9] and extrapolated value $q_f = 0.21\mu m^{-1}$ at $\Delta\varepsilon = 0$ is nearly equal to spontaneous

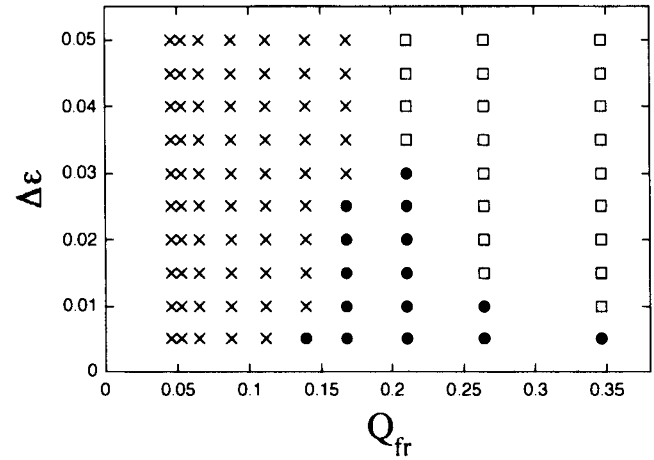

FIGURE 4 Phase diagram for three types of pattern formation process in Q_{fr} - $\Delta\varepsilon$ plane. The cross indicates the stable case shown in Fig. 3(a), the closed circle (b) and the open square (c).

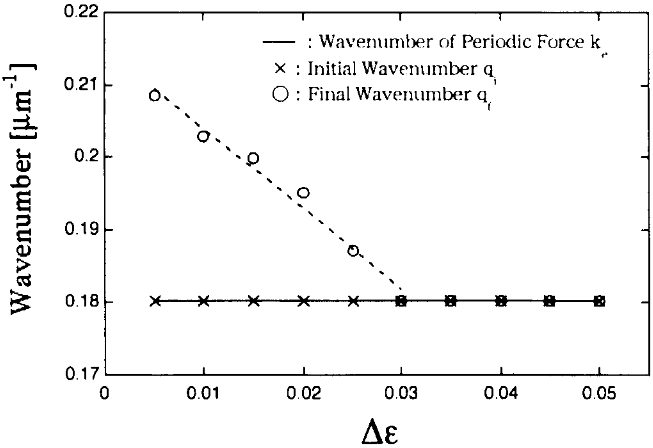

FIGURE 5 Dependence of initial wavenumber q_i (cross) measured at t = 1sec immediately after jumping applied voltage and final wavenumber q_f (open circle) measured at 300sec on amplitude of periodic external force $\Delta\varepsilon$ for constant $\varepsilon_0 = 0.10$ and $Q_{fr}(f = 1400\text{Hz}) = 0.168$. The dotted line indicates linear fitting $q_f = a\,\Delta\varepsilon + q_0$ for $\Delta\varepsilon \leq 0.03$, where $a = -1.1\mu\text{m}^{-1}$ and $q_0 = 0.21\mu\text{m}^{-1}$.

wavenumber q_s for $\varepsilon = 0.10$ ($f = 1400$Hz).

Figure 6 shows the dependence of the initial wavenumber q_i (cross) and the final q_f (open circle) on $Q_{fr}(f)$ at $\varepsilon_0 = 0.10$ and $\Delta\varepsilon = 0.01$.[9] Entrainment is broken for large frustration ($Q_{fr} > 0.139$), and then the final wavenumber q_f increases with increasing Q_{fr} as $q_f = 0.18 + a(Q_{fr} - Q_{fr}^*)^\gamma$ with $a = 0.13$, $Q_{fr}^* = 0.14$ and $\gamma = 0.44 \pm 0.07$ and tends to saturate at about 0.23μm^{-1} for larger Q_{fr}. The spontaneous wavenumber $q_s(f)$ simultaneously increases linearly with Q_{fr} as shown by a dash-dotted line in Fig. 6 because of the definition $Q_{fr} = |q_s(f) - k_e| / k_e$. It has been expected that the final wavenumber q_f in non-entrainment case is equal to q_s. However, in the experimental result q_f does not coincide with q_s as shown in Fig. 6. The question how the q_f is decided is now arised which should be solved in future.

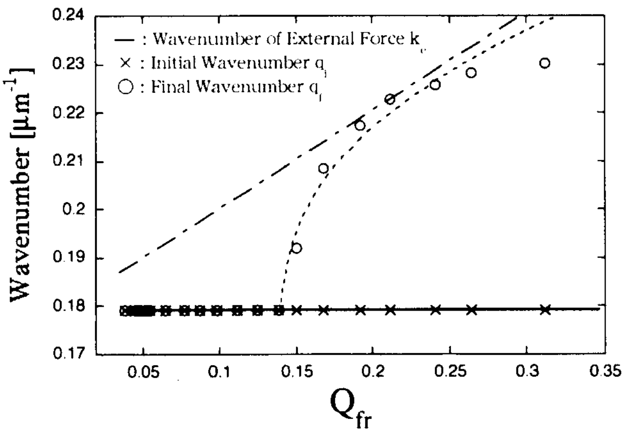

FIGURE 6 Dependence of initial wavenumber q_i (cross) and final q_f (open circle) on mismatch parameter $Q_{fr}(f)$ for constant $\varepsilon_0 = 0.10$ and $\Delta\varepsilon = 0.01$. The dotted line indicates least squares fitting $q_f = 0.18 + a(Q_{fr} - Q_{fr}^*)^\gamma$ with $a = 0.13$, $Q_{fr}^* = 0.14$ and $\gamma = 0.44 \pm 0.07$ for $Q_{fr} \geq 0.13$. The dash-dotted line indicates q_s.

Immediately after applying the periodic force, since the amplitude of the convection is small, the wavenumber of the convection may easily be entrained into the periodic force. However, if the amplitude of the periodic force is small or the difference between the spontaneous wavenumber and the wavenumber of the entrained pattern is large, entrainment is broken as far as the convective amplitude become large enough. As a result of non-entrainment, the wavenumber of the pattern becomes one between the spontaneous wavenumber and the forced one; $q_f(\Delta\varepsilon, Q_{fr})$.

According to recent theoretical works based on amplitude equations including spatially modulated terms, the variety of pattern dynamics has been proposed.[4,5] Some of them arise the entrainment into forced wavenumbers and an oscillatory behavior. The present results could be also understood in the same direction as them. The attempt is now in progress.

SUMMARY

Experimental study about pattern formation processes under spatially-periodic external force in the electroconvection system is reported. At initial stage of the formation process, the convection pattern is entrained into the spatially-periodic external force. When the amplitude of the external force is small or the mismatch between the spontaneous wavenumber and the wavenumber of the external force is large, the convective wavenumber shifts out of the wavenumber of the external force through the climb of defects. The final wavenumber of the convective pattern is thus different from the spontaneous wavenumber and depends on both the amplitude of the external force and the mismatch between the spontaneous wavenumber and the wavenumber of the external force.

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[9] It was confirmed that the final wavenumber q_f does not change for enough long time (about 6 hours).