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Dynamics of dissipative structures and the transition to turbulence in a nematic liquid crystal

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It has been observed for the first time that the domain oscillations of a nematic liquid crystal subject to a transverse DC electric field are self-organized in space as concentric and spiral phase waves. The formation of the phase wave sources has been described. The transition of the hexagonal convective structure to turbulence has been investigated by the temporal Fourier analysis method. It has been found that a route to turbulence passes through a continuous widening of peaks in the power spectrum of light intensity transmitted through the cell.

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1. Introduction

Recently, there has been a significant growth of interest in investigations of the transition from a spatial ordering state to a disordering one and turbulence in non-equilibrium systems [1, 2]. Thermal convection, Couette flow and electrohydrodynamic convection in liquid crystals are well-known examples of such systems [2]. In the electrohydrodynamic convection of the nematic liquid crystal typical pictures of the dissipative structure of Williams domains, fluctuating Williams domains, grid patterns and dynamic scattering modes are observed successively with increasing AC electric field [3, 4].

For a DC electric field the successive transitional patterns and a domain symmetry differ significantly from the case of an AC electric field. At certain values of the DC electric field grid patterns consisting of many coupled triangle-like grids (we will call this grid pattern the hexagonal pattern) have been observed [5, 6]. On increasing the voltage further coherent domain oscillations arise [5, 6]. The behaviour of these oscillations in a DC electric field have not been extensively studied up to now. Recently, for the first time we have found a new type of domain oscillation in a DC electric field, which are self-organized in space as concentric and spiral phase waves. In this paper, the formation of the phase wave sources in the hexagonal convective structure and the transition to turbulence on increasing the DC electric field have been investigated. The dynamic characteristics of this system have been studied by the temporal Fourier analysis of the laser beam intensity transmitted through the cell.

2. Experimental

The nematic material 4-methoxybenzylidine-4′-*n*-butylaniline (MBBA) with its negative dielectric anisotropy was used in our experiments. The nematic layer was sandwiched between two parallel glass plates coated with tin oxide electrodes. The

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plates were rubbed to obtain strong planar boundary conditions. The lateral dimensions of the cell were 0·5 cm × 1·5 cm. The main experiments were performed with the nematic layer thickness of 25 μm, so that the aspect ratios were 200 × 600. The mica spacers with $10 \leqslant d \leqslant 80\,\mu$m were used to obtain the dependence of the oscillation frequency f on the layer thickness d. The cell temperature was stabilized at $25 \pm 0{\cdot}2$°C. A DC electric field of up to 30 V was applied across the nematic layer. All observations were made with an Amplival Pol.U polarized microscope. It is known that due to the modulation of the optic axis of the nematic in the external electric field the extraordinary transmitted light beam is focused and its intensity depends on the local variation of the birefringence $\Delta n(\mathbf{r}, t)$ [7]. To obtain the space averaged temporal characteristics of the dissipative structure, the intensity of transmitted light through all of the area of the cell was measured with a spectrophotometric adapter SFN-10 (LOMO, Leningrad). The analogue voltage signal from the adapter was digitized with a frequency of 20 Hz and stored. The temporal power spectrum of the light intensity fluctuations was obtained by the fast Fourier transformation technique [8, 9] of the 16384 experimental points. The power spectra were measured with step in the voltage ΔU of 0·2 V. All measurements were made after holding at each voltage U for 30 min. The signal/noise ratio was of the order of 10^3. A photocamera was used to study the spatial characteristics of the wave patterns.

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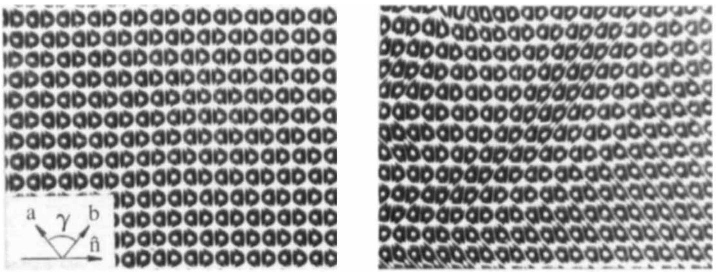
3. Results and discussion

3.1. *Microscope analysis*

Figure 1 (*a*) shows a micrograph of the stationary hexagonal domain structure. The crystallographic axes of this structure make the angles 125° and 55° relative to the initial orientation of director $\hat{\mathbf{n}}$. When the voltage is increased slightly above U_c, this structure becomes unstable and domain oscillations of very low frequency appear in the hexagonal pattern (see figure 1 (*b*)). In the figure, the voltage is given as the ratio to the critical voltage U_c of 8 V for the appearance of the hexagonal pattern. These oscillations occur as a periodic deformation of the triangle-like domains along the crystallographic axes of the hexagonal domain structure.

On increasing the voltage up to 1·2 U_c, a system of undamped oscillating domain blocks results, where concentric expanding waves are generated. The dynamics of the wave generation during the one domain oscillation period T is shown in figure 2 (*a*). The triangle-like domains located along one crystallographic direction are merged and



(*a*) (*b*)

Figure 1. Hexagonal domain structure: (*a*) stationary domains at $U_c = 8$ V, (*b*) oscillating domains at 1·1 U_c. The angle between the crystallographic axes **a** and **b** is $\gamma \approx 70°$. (Magnification × 100.)

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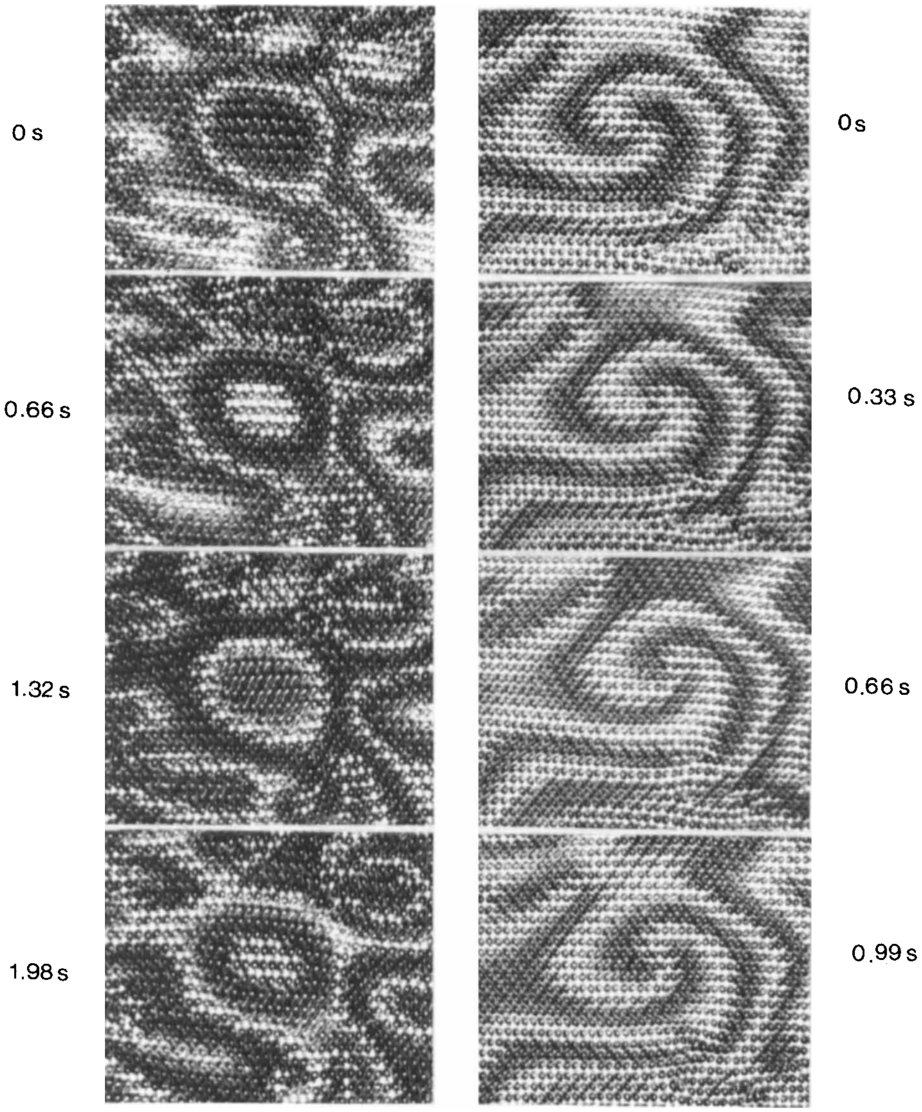

(*a*) (*b*)

Figure 2. Dynamics of phase wave generation at 1·25 U_c: (*a*) concentric phase wave, (*b*) spiral phase wave. (Magnification × 50.)

transformed into ones like a linear Williams domain, which form a separate block ($t=0$). Then, the linear domains are divided into the initial triangle-like domains inside the block; however the ring-shaped concentric area that consists of the linear domains, remains around these triangle-like domains and begins to expand ($t=T/4$). After that, the linear domains are formed again, but in the other crystallographic direction ($t=T/2$) and a new concentric area is generated ($t=3T/4$). Thus, a period of wave generation is equal to the half-period of the linear Williams domain-like formation in the block. The shape of this concentric area keeps the domain block singular. It should be noted, that the propagating waves appear as the periodic changing of the linear domain orientation and do not include displacement of domains.

So, we have called this concentric area with the same linear domain orientation a phase wave and an oscillating domain block a leading centre. The wave front is a boundary between areas with different linear domain orientations. The propagation speed of the waves is of the order of $1\cdot5-2\times10^2\,\mu\mathrm{m\,s^{-1}}$ at an applied voltage of $1\cdot2\,U_c$. The wavelength is practically constant and is equal to about $100\,\mu$m for a range of applied voltages where phase wave propagation is observed. Unlike phase wave propagation in the rectangular convective structure (for an AC electric field) [10], the wavelength is isotropic in this system.

It has been established that the waves interact with each other and with the cell boundary as follows: (i) the waves do not interfere with each other; (ii) the waves do not reflect from the cell boundary; (iii) the waves are diffracted by defects of initial domain structure or dust particles, the size of which is comparable with the wavelength; (iv) the waves annihilate each other upon collision. These properties are known as auto-wave properties [11]. The wave sources are fixed in space but they are not stable in time: some of them are created, whereas others are destroyed. The leading centre disappears when in its vicinity there is another centre oscillating with a higher frequency. By the analysis of the wave pattern dynamics it has been found that a phasing of the leading centre oscillations takes place in the system. It has been observed that the rotating spiral waves form when the concentric wave fronts are broken by the defects of domain structure or dust particles (see figure 2 (*b*)). The rotation frequency of the spiral waves is of the order of 2 Hz at $1\cdot2\,U_c$. The centres of the spiral waves are distributed in space at random. Note, that only spiral waves with an even number of sleeves (in general, with two sleeves) are observed experimentally. Two neighbouring sleeves have a different orientation of linear domains. These two kinds of wave pattern coexist in the system from $1\cdot2\,U_c$ up to $1\cdot5\,U_c$.

Above $1\cdot6\,U_c$ wave propagation is not observed. The domain blocks are arranged in space in staggered order, where two neighbouring domain blocks oscillate with opposite phases, as shown in figure 3 (*a*). On increasing the voltage the triangle-like domains are destroyed (see figure 3 (*b*)) and with further increase of the voltage a transition to the turbulence (or dynamic scattering modes) occurs at about $2\cdot0\,U_c$. Note, that the number of domain blocks grows and their size decreases with voltage. This voltage dependence of linear domain size in blocks L is shown in figure 4.

It has been observed that the character of the domain patterns do not change with the thickness of the nematic layer. However, the frequency of the domain oscillations are inversely proportional to the thickness of the nematic layer (see figure 5).

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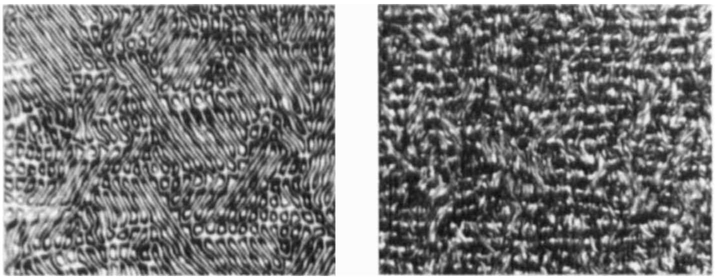

(*a*) (*b*)

Figure 3. Oscillating hexagonal domain structure at (*a*) $1\cdot65\,U_c$ and (*b*) $1\cdot9\,U_c$. (Magnification × 100.)

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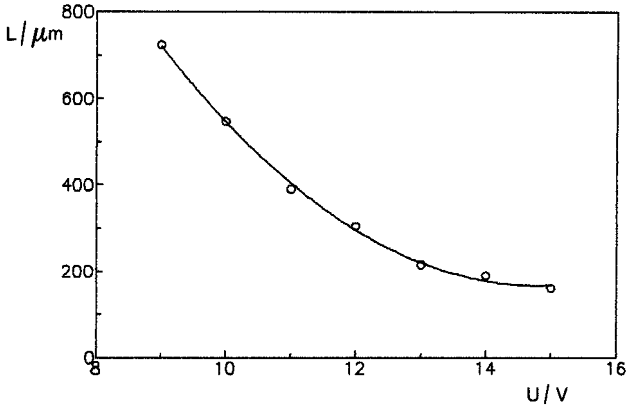

Figure 4. Voltage dependence of the linear domain size L in the blocks.

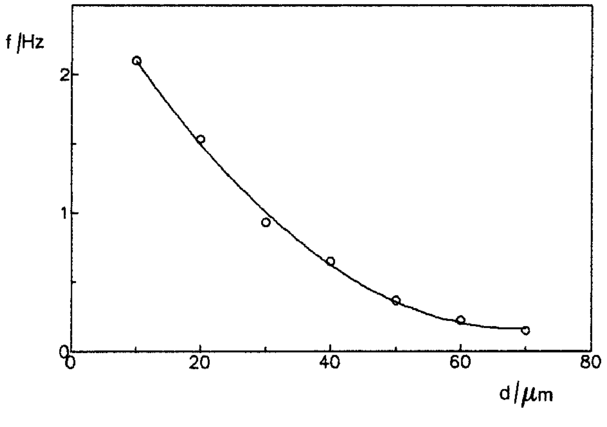

Figure 5. Dependence of the oscillation frequency f on the nematic layer thickness d.

3.2. *Temporal Fourier analysis*

Typical power spectra of the laser beam intensity transmitted through the cell are shown in figure 6. It is well known that stationary convective flows appearing in the nematic above the threshold of electrodynamic instability, lead to the static deformation of the director [7]. So, due to the stationary nature of the hexagonal convective pattern and space average some noise, connected only with temperature fluctuations and fluctuations of the nematic director, exists in the power spectrum. A small peak with frequency f of about 0·3 Hz corresponding to domain oscillations appears in the power spectrum on increasing the voltage (see figure 6 (*a*)). The narrow peak indicates that the director disturbance is close to sinusoidal. With the change of the applied voltage above $1{\cdot}2\,U_c$ the amplitude of the fundamental peak drastically increases and several of its harmonics $2f$, $3f$, etc., arise in the power spectrum, as shown in figure 6 (*b*). The increase in the fundamental peak amplitude is the result of the growth of oscillating regions in the stationary hexagonal structure. The multiple harmonics seem to be connected with the non-sinusoidal (or polyharmonic) character of the director field disturbance. Since the propagation of phase waves occurs as the periodic reorientation of the domain in space, their frequency is equal to that of linear domain

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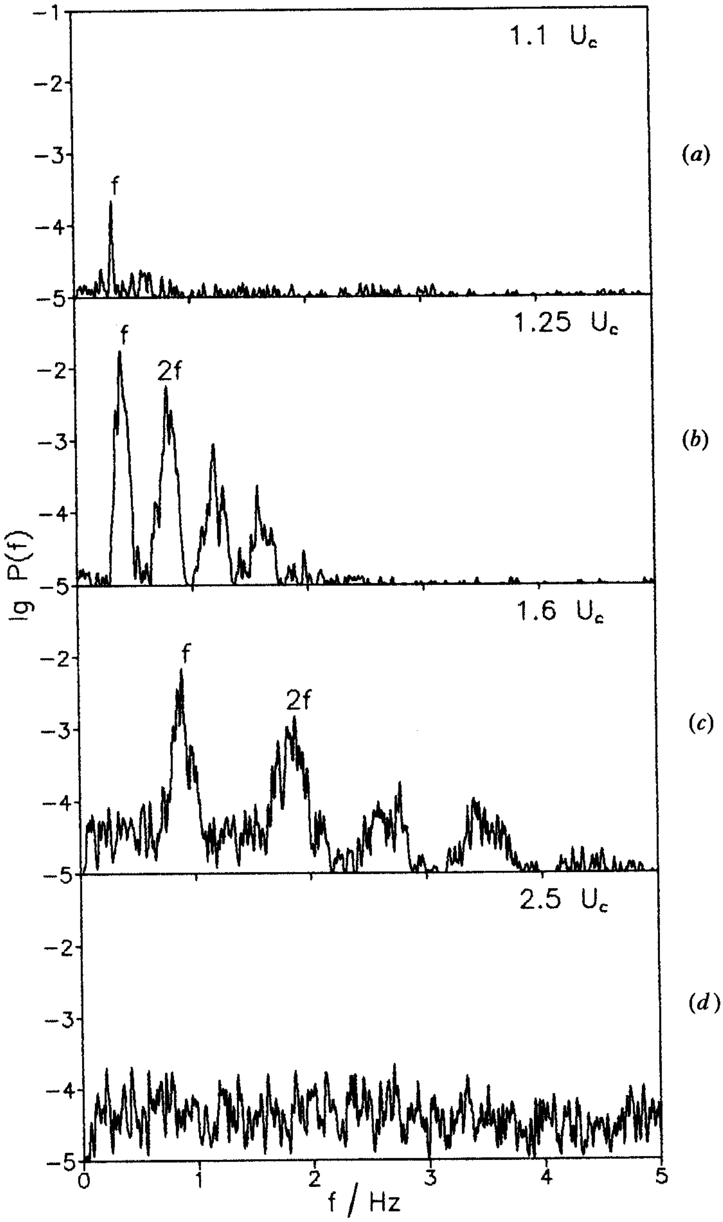

Figure 6. Typical power spectra of the light intensity transmitted through the cell for various applied voltages.

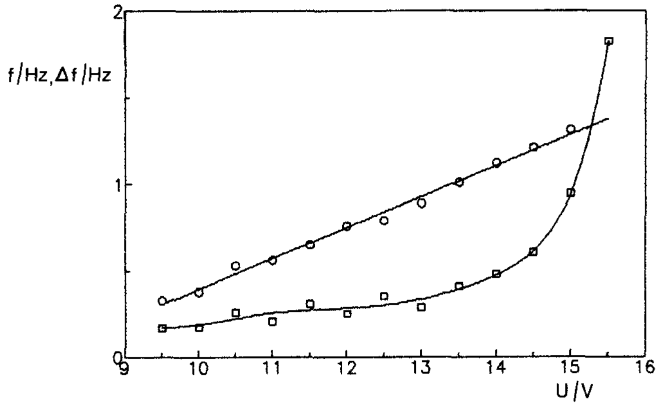

Figure 7. Voltage dependence of the oscillation frequency *f* and the effective width of the power spectrum Δf_{eff}. ○, *f*; □, Δf.

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orientation changing in blocks that are recorded by the adapter. With further voltage increase the peaks become a wide band at about $1{\cdot}5\,U_c$, as shown in figure 6 (*c*). The half-width is equal to 0·15 Hz at an applied voltage $1{\cdot}2\,U_c$ and 0·9 Hz at $1{\cdot}8\,U_c$. The widening of the power spectrum indicates the growth of the fluctuations. Above $2{\cdot}0\,U_c$ the power spectrum is continuous as shown in figure 6 (*d*). It is associated with the dynamic scattering mode state of the nematic, when the director oscillates non-periodically in time as well as in space.

In figure 7 the voltage dependence of the oscillation frequency *f* and effective width of the power spectrum

$$\Delta f_{\text{eff}} = (1/P_{\max}) \int P(f)\,df$$

are shown. This figure demonstrates the linear increase of the oscillation frequency and the dramatic growth of Δf_{eff} with voltage near the dynamic scattering mode threshold.

In conclusion, we have found phase waves in the oscillating hexagonal convective structure of the nematic. The typical patterns observed were concentric expanding and rotating spiral ones. These wave patterns are the result of self-organization in space of domain oscillations; wave propagation occurs as periodic domain reorientation. The transition to turbulence of the hexagonal convective structure has been investigated experimentally. It has been established that the route to the turbulence is accompanied by an increase in the domain oscillation frequency and the widening of the peaks in the power spectra.

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