Dissipative Structures in Liquid Crystals

Yoshiki Hidaka* and Shoichi Kai

Department of Applied Quantum Physics and Nuclear Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan
**E-mail address: hidaka@ap.kyushu-u.ac.jp*

(Received September 6, 2014; Accepted January 29, 2015)

Key words: Liquid Crystal, Electroconvection, Dissipative Structure, Nonequilibrium Open System

1. Liquid Crystal

A liquid crystal (LC) consists of rod-shaped organic molecules which align in one direction like pencils packed in a box. Therefore, the physical properties measured parallel to the molecular orientation are different from those measured perpendicular. This character called anisotropy is originally known as that of solid crystals. Because center of mass positions of the molecules, however, are randomly distributed like conventional liquids, it has fluidity. Due to these characteristics, LCs simultaneously show both properties of liquids and crystals.

LCs have been now-a-day used for various applications in modern technology, e.g. electronic displays called liquid crystal displays (LCDs) for TV and a mobile phone. The orientation of LC molecules can be easily changed by application of electric fields due to the anisotropy and softness like liquids. Owing to the orientation change, polarization of incident light through a LC cell can be changed due to its optical anisotropy, i.e. electrically induced birefringence or electro-optical effect. By application of these properties LCD has been successfully developed. Originally invented LCD nearly half century ago, however, used a different phenomenon in LC as follows.

By applying alternating electric fields to LC with negative dielectric constant, flow occurs accompanied with dragging of impurity ions, such as called the electrohydrodynamic effect. Even developed turbulence can occur for high electric fields. Turbulence causes a strong scattering of light, because the orientation of LC becomes random owing to the turbulence. G. H. Heilmeier invented the world's first LCD using this effect and named its phenomenon "dynamic scattering mode" (DSM) (Heilmeier, 1968). However, this type of LCD could not be commercialized because of slow time response and high electronic power-consumption.

2. Electroconvective Pattern

The electrohydrodynamic effect in LC induces a stripe pattern due to convective roll structures for lower voltage than that for DSM (see Fig. 1(a)). This pattern is called the Williams domain, because R. Williams found this phenomenon (Williams, 1963). Williams was a Heilmeier's colleague, and Heilmeier made the DSM-type LCD with inspiration from this Williams' discovery. When Williams found this phenomenon, he could not elucidate that convection made it. However, the subsequent researches revealed that each white line in the stripe pattern corresponds to an electroconvective roll structure visualized by the optical anisotropy of LC. The mechanism of the electroconvection of LC called the Carr-Helfrich effect (Carr, 1969; Helfrich, 1969), is summarized as follows. With no electric field, uniform orientation of LC molecules is a stable state. However, the orientation is not completely uniform, but fluctuating around the stable state. With applying an alternating electric field, spatially nonuniform distribution of impurity electric charges is produced, because the spatial fluctuations of the molecular orientation induce electric currents parallel to the electrodes (perpendicular to the electric field) due to the anisotropy of electric conductivity.

Under sufficiently low electric fields, both the orientational fluctuations and the nonuniform distribution of electric charges decay immediately. However, under higher electric fields than a certain threshold, drag of the nonuniform distribution of space charges by the electric filed induces flow of LC molecules. Since the flow gives torques, the orientational fluctuations do not decay but grow. Then, the nonuniform distribution of electric charges does not decay but grow and create more charge as well as deformation torque of orientation. Steady convection starts by this feedback process.

It is important that this feedback mechanism affects only to a fluctuation with a specific wavelength corresponding to the distance between electrodes. Therefore the electroconvection appears as a periodic roll structure described above. The top-view of this periodic roll structure is a stripe pattern, i.e. the Williams domain. Such periodic roll structures by convection have been studied in thermal convection in normal fluids heated from below. Both in thermal convection in normal fluids and electroconvection in LCs, energy is continuously supplied to the system and dissipated as friction heat accompanied with the convective flow. Such a system, where continuous supply and dissipation of energy takes place, is called nonequilibrium open system, and observed structures, e.g. periodic roll structure and turbulence, are called *dissipative structure*. Structures like various crystals in equilibrium systems, on the other hand, are

doi:10.5047/forma.2015.s010

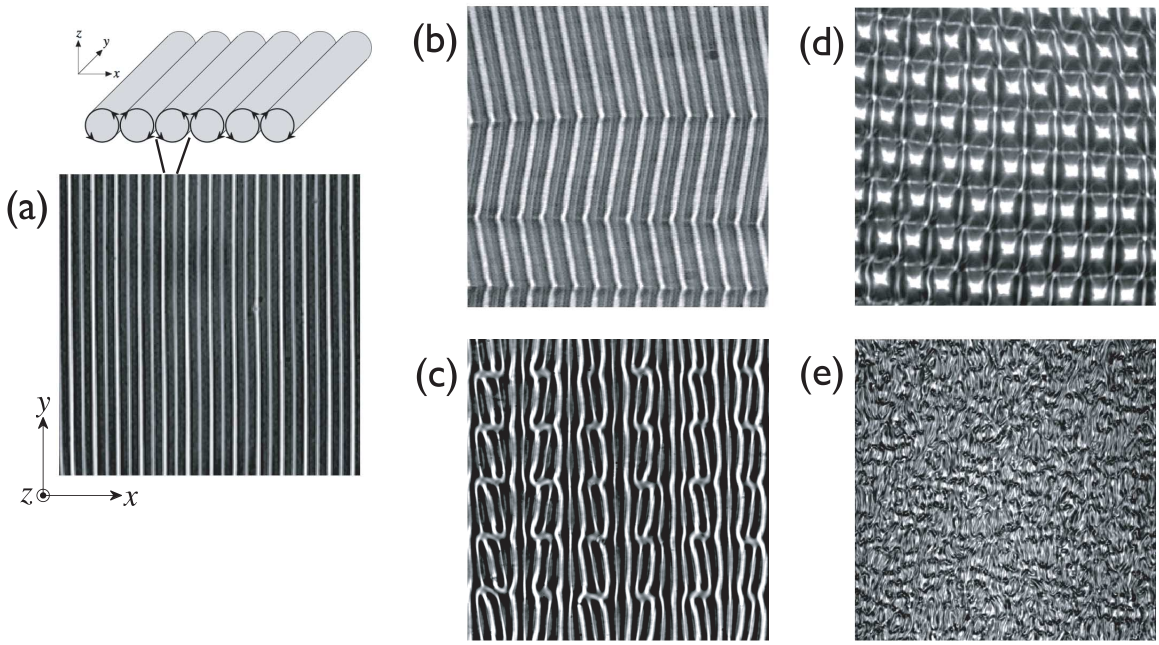

Fig. 1. Patterns observed in an electroconvective system of a LC. (a): Williams domain and the corresponding convective rolls. (b): Zigzag pattern. (c): Defect lattice. (d): Grid pattern. (e): Developed turbulence (dynamic scattering mode).

called equilibrium structures. Researches for equilibrium structures have a long history and they have been more or less understood. Researches of dissipative structures in nonequilibrium open systems has become more attractive because they are less understood. In addition, they are commonly observed in our environments including ourselves (living systems). It is therefore very important for us to understand those physics.

The above phenomenon, i.e. the stability of uniform orientation of LC molecules is broken by the feedback process under applied electric fields, is called electrohydrodynamic instability. For the instability, the wavevector of the periodic roll pattern is a unique unstable mode. In this way, a new state (periodic roll pattern in the present case) appears via instability. This is called bifurcation phenomenon where nonlinearity in the system plays an important role. The stronger the injection energy, the stronger the nonlinearity in the system, as well as the farther deviation from the equilibrium state. The strong nonlinearity induces subsequent bifurcations, and new unstable modes appear. Therefore, as the applied voltage in electroconvection is increased, observed patterns normally show more complex periodicities. The frequency of the applied voltage is another important bifurcation parameter because the frequency controls characteristic times in an electroconvective system. Accordingly, various patterns appear by changing frequency of the applied voltage as well as the intensity (shown in Figs. 1(b)–(d)). In any case, fully developed turbulence (DSM), as shown in Fig. 1(e), finally appears at high voltage. The above-mentioned electrohydrodynamic effect in LC is different from the mechanism of thermal convection, nevertheless there is a similarity between bifurcation in electroconvection of LC and that in thermal convection. This fact may suggest that there is a certain universality for many dissipative structures.

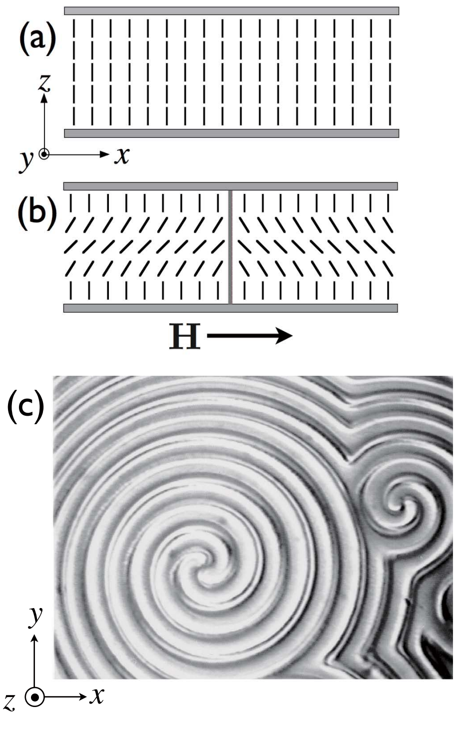

Fig. 2. (a): Schematic picture of a homeotropic orientation system of a LC. Bars indicate the averaged direction of LC molecular orientation, called a director. (b): Wall formed by the Fréedericksz transition. (c): Spiral wall pattern under a rotating magnetic field.

3. Pattern Formation by Forced Rhythm

The LC also has magnetic anisotropy via the magnetic susceptibility. Let us consider the uniform orientation of the director (which shows the averaged direction of LC molecule orientation shown in a bar in Fig. 2(a)) in the z-

direction in the absence of magnetic fields. Applying then a magnetic field beyond a certain threshold in the x-direction to the LC system, the director of LC molecules inclines to the x-direction as shown in Fig. 2(b). This inclination instability is called the Fréedericksz transition, but it is not a dissipative structure (although during inclination it transiently dissipates energies). Regarding inclination of the director, another symmetric orientation can be possible. That is, the director can incline to the opposite $(-x)$ direction because of an equal energy state. Therefore, an interface, which separates the two states ($+x$ and $-x$), can exist in the system as shown in Fig. 2(b). Now, let the direction of the magnetic field rotate in the $x-y$-plane. The inclined director shows precession motion (rotation) by the rotating magnetic field which plays a role as a periodic external force. The motions of the walls accompany the precession rotation, and finally characteristic patterns can be formed like either target or spiral as shown in Fig. 2(c) (Nasuno *et al.*, 1995). A wall formed by the Fréedericksz transition disappears in steady state with the static magnetic field, but remains steady as a dynamical interface with the rotating magnetic field.

Therefore, LC with rotating magnetic field is also a nonequilibrium open system, where target and spiral patterns appear as dissipative structures. Such target and stripe patterns are already well-known as dissipative patterns which were observed in oscillating chemical reaction systems called the Belousov-Zhabotinsky (BZ) reaction. Concentration of reaction materials spontaneously oscillates in the BZ reaction, and all chemicals are gradually consumed in time and the reaction system finally reaches to equilibrium state. In a spatially extended system, the reaction system can be regarded as a continuously distributed oscillatory system and at any location all oscillators combine each other with diffusion of chemicals. Phase differences among those oscillators show either target or spiral patterns depending on conditions. It is interesting to stress here that quite similar patterns can be observed in completely different systems such as LC systems and chemical reaction ones. Thus, there may be certain universality for formation of dissipative structures independent of detailed mechanisms. To understand such universality is an ultimate goal of physics of nonequilibrium open systems.

References

Carr, E. F. (1969) Influence of electric fields on the molecular alignment in the liquid crystal p-(anisalamino)-phenyl acetate, *Molecular Crystals*, **7**, 253–268.

Heilmeier, G. H. (1968) Dynamic scattering in nematic liquid crystals, *Appl. Phys. Lett.*, **13**, 46–47.

Helfrich, W. (1969) Conduction-induced alignment of nematic liquid crystals: basic model and stability considerations, *J. Chem. Phys.*, **51**, 4092–4105.

Nasuno, S., Yoshimo, N. and Kai, S. (1995) Structural transition and motion of domain walls in liquid crystals under a rotating magnetic field, *Phys. Rev. E*, **51**, 1598–1601.

Williams, R. (1963) Domains in liquid crystals, *J. Chem. Phys.*, **39**, 384–388.