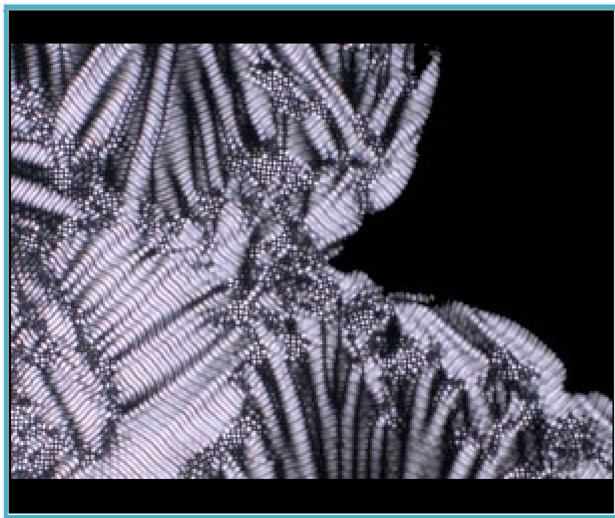


Electrically driven convection in liquid crystals

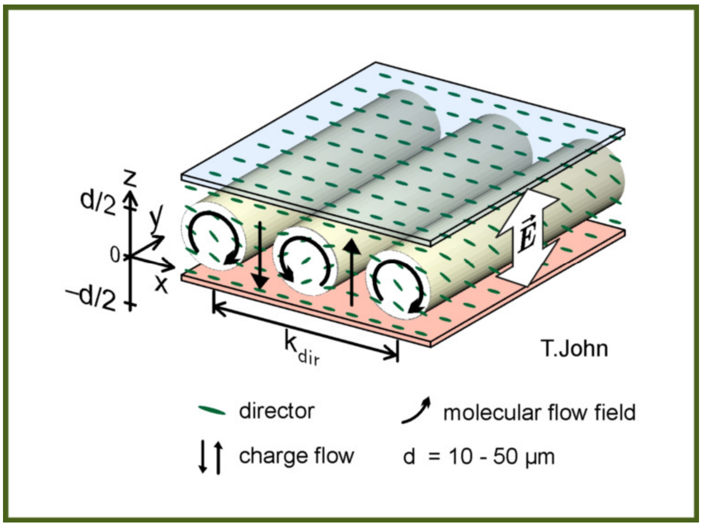
Jana Heuer, Thomas John, Dirk Pietschmann, Ralf Stannarius

Introduction

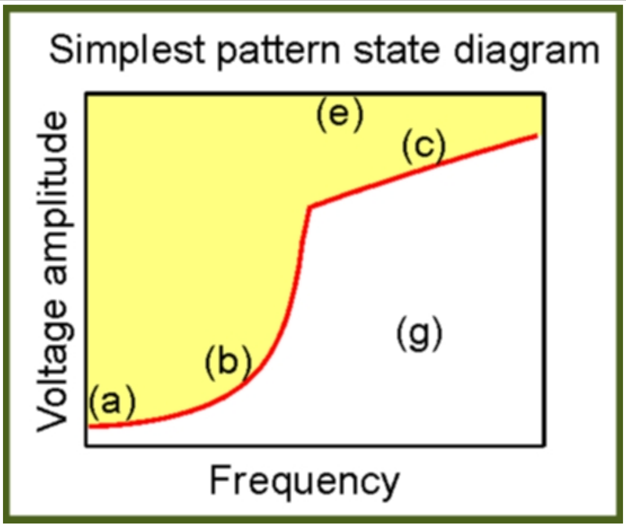
Electro-hydrodynamic convection (EHC) in anisotropic fluids is a standard system for dissipative pattern formation. A large variety of electroconvection patterns in an external electric ac field has been reported. Different combinations of the anisotropies of conductive and dielectric material constants result in distinct types of EHC structures. In the classical EHC studies, liquid crystals with positive conductivity anisotropy and negative or weakly positive dielectric anisotropy have been used. Both the spatial (normal rolls, grid patterns) and temporal properties (stationary, harmonic, subharmonic, travelling patterns) of these systems are multifaceted and have been investigated thoroughly in the course of the last 30 years. Beside the rich experimental results, an extensive model based on the Carr-Helfrich mechanism has been developed that yields not only a linear stability analysis but also a weakly nonlinear description. It explains the temporal behaviour of the electroconvection system.

The experimental observation is performed with a µm thin transparent glass cell wherein the nematic liquid crystal is sandwiched. Applying an electric AC field normal to the cell will lead to an accelaration of the charges that exist due to impurity. In the inhomogenous director field these carges will separate into charge clouds. The flow field driven by this ionic flow couples to the director deflection. Thus, convection rolls arise that are visible by means of the shadowgraph method in the polarazing microscope. The pattern appears above a certain threshold voltage with different wave numbers that depend on the excitation frequency.

Sketch of the convection and director patterns in a planar cell

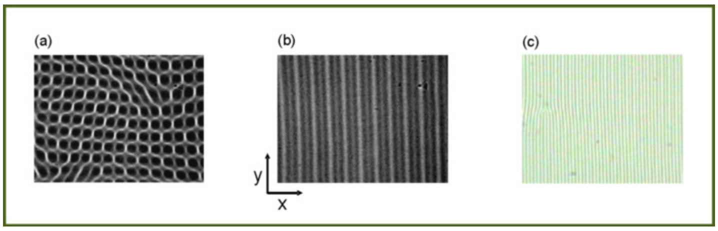


Literature:
e. g. L. Kramer, W. Pesch: *Electrohydrodynamic instabilities in nematic liquid crystals* in: Pattern Formation in Liquid Crystals, p. 221, editors A. Buka, L. Kramer (Springer, NY, 1996).

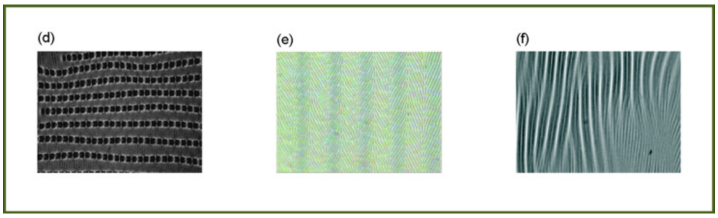


(a): oblique conduction rolls
(b): normal conduction rolls
(c): normal dielectric rolls
(e): higher instabilites
(g): ground state, no convection rolls

EHC patterns near the threshold voltage:



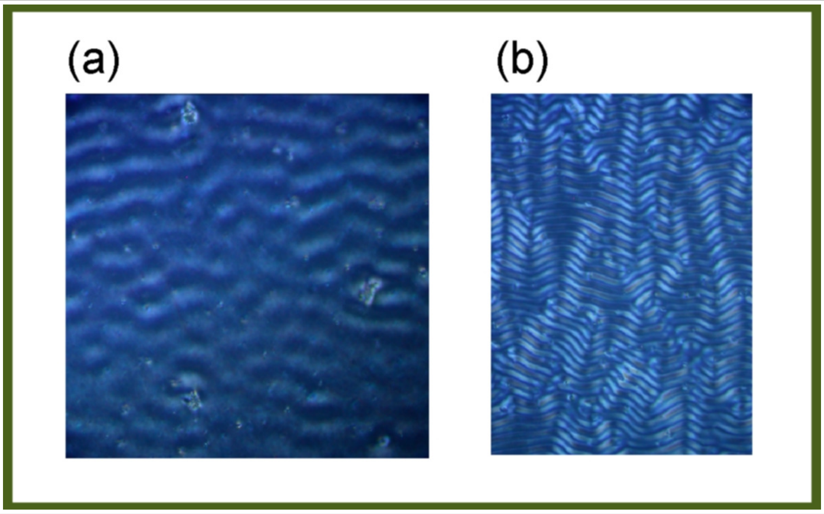
At higher voltages the pattern becomes more complex:

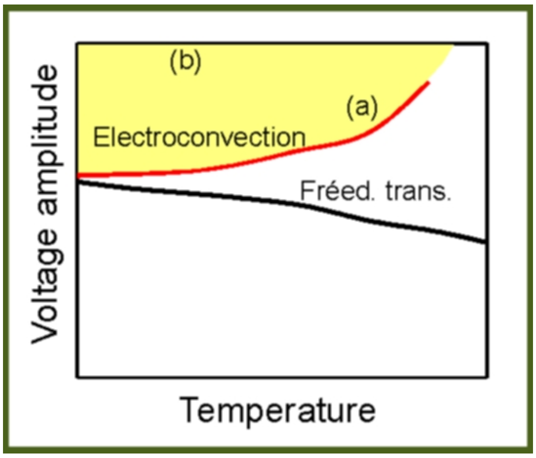


Unusual electroconvection of bent-core nematics

In the materials studied in our group, the signs of the conductivity and dielectric anisotropy are different from the standard EHC materials. The observed patterns differ significantly from the classical types. Partially these patterns can be described within the Carr-Helfrich mechanism, but in some cases novel or adapted models have to be discussed.

We have proposed a novel mechanism that leads to patterns that are qualitatively different from those of the conventional EHC. In this context we investigated a bent-core (banana-shaped) liquid crystal with a positive dielectric and a negative conductivity anisotropy [Tamba2007]. The orientation and optical behaviour of the observed patterns are no longer describable within the classic model. In contrast to the common EHC, the pattern evolves from a distorted ground state above the so-called splay Fréedericksz transition. Moreover, the convection rolls are oriented along the initial director easy axis. The usual stripe patterns are perpendicualr to this axis or slightly tilted. Because of these qualitative differences, we derived a new basic mechanism that adapts the Carr-Helfrich theory and is based on a twist instability causing a modulation in the cell plane after a splay Fréedericksz transition. Our model predicts qualitatively correct the threshold behaviour and optical characteristics of the observed electroconvection patterns [Stannarius2007,Heuer2008].

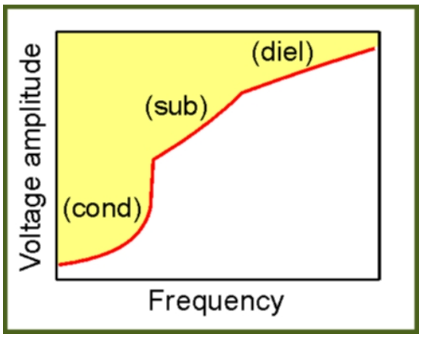




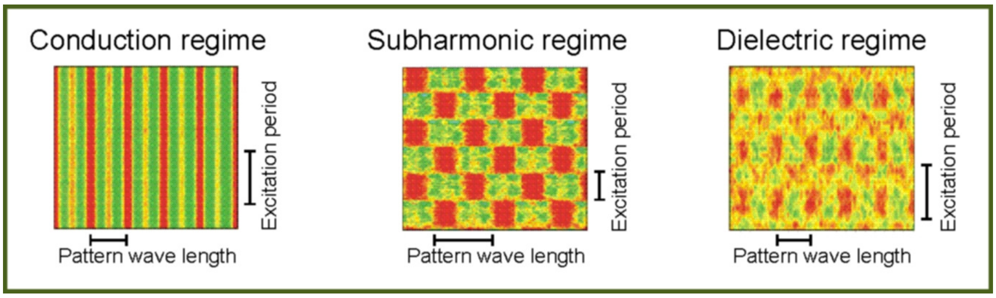
M.-G. Tamba, W. Weissflog, A. Eremin, J. Heuer, R. Stannarius: *Electro-optic characterization of a nematic phase formed by bent core mesogens*, Eur. Phys. J. E **22**, 85 (2007).
R. Stannarius, J. Heuer: *Electroconvection in nematics above the splay Fréedericksz transition*, Eur. Phys. J. E **24** 27, (2007).
J. Heuer, R. Stannarius, M.-G. Tamba, and W. Weissflog. *Longitudinal and normal electroconvection rolls in a nematic liquid crystal with positive dielectric and negative conductivity anisotropy*. Phys. Rev. E, **77** 056206, (2008).

Subharmonic patterns

In EHC experiments different regimes can be observed that are distinguishable clearly due to their spatio-temporal behaviour. Their occurance depends on the excitation wave form and the excitation frequency. The classic EHC studies, using sinus and square waves, described two dynamic pattern regimes: Conduction rolls have stationary director fields whereas in dielectric patterns the director deflections change with the periodicity of the excitation. We found a new regime with a dynamics that leads to a system response with twice the period of the excitating voltage [John2004]. Necessary for the occurrence of these novel patterns are particular asymmetries of the applied wave form [John2005,Stannarius2005,Heuer2006]. Antisymmetry, time reversal symmetry and dichotomy of the excitation wave forms suppress the subharmonic regime. A new rigorous method to compute the optical properties of electroconvection patterns has been implemented on the basis of FDTD (Finite Difference Time Domain) approaches [Bohley2005]



e.g. sawtooth excitation:



Space-time plots of the three pattern regimes (pseudocolor presentation of the optical transmission intensity)

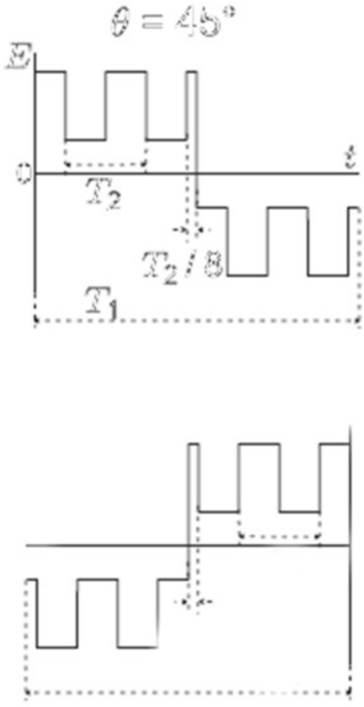
T. John and R. Stannarius. *Preparation of subharmonic patterns in nematic electroconvection.* Phys. Rev. E, 70 025202(R), (2004).
T. John, J. Heuer, and R. Stannarius. *Influence of excitation wave forms and frequencies on the fundamental time symmetry of the system dynamics, studied in nematic electroconvection*, Phys. Rev. E **71**, 056307 (2005).
R. Stannarius, J. Heuer, and T. John. *Fundamental relations between the symmetry of excitation and the existence of spatiotemporal subharmonic structures in a pattern-forming dynamic system*, Phys. Rev. E **72**, 066218 (2005).
C. Bohley, J. Heuer, R. Stannarius. *Optical properties of electrohydrodynamic convection patterns: rigorous and approximate methods*, J. Opt. Soc. Am. A **22**, 2818 (2005).
J. Heuer, T. John, and R. Stannarius. *Reentrant EHC Patterns Under Superimposed Square Wave Excitation*, Mol. Cryst. Liq. Cryst. **449**, 11 (2006).

Instability thresholds under time-reversed excitation wave forms

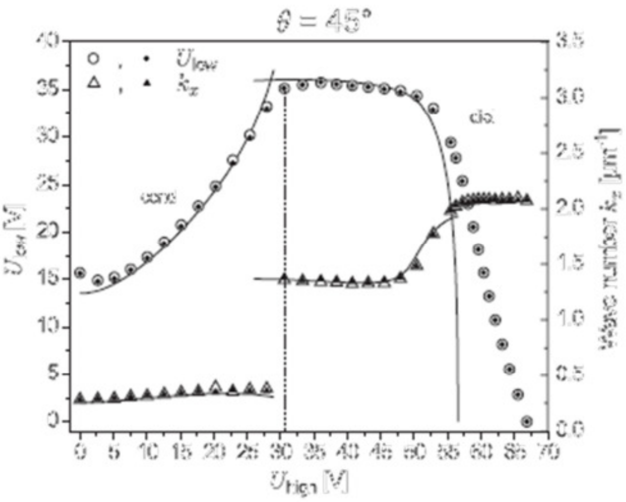
Standard model (Carr-Helfrich)

Dynamic patterns that are described by differential equations of two or more dynamic variables in general exhibit different trajectories of these variables when the excitation wave form is changed. This leads in general to different thresholds for the instability of the ground state, even in a linear stability analysis (Floquet analysis) [Stannarius2009]. It has been demonstrated by a linear stability analysis of a simple two-variable model for EHC, and confirmed in experiments [Heuer2008], that this dissipative pattern forming system belongs to a special class of systems that is insensititve to such a time reversal. The reason lies in the special structure of the underlying differential equation system, which contains a matrix that has the same temporal dependence in all off-diagonal elements [Heuer2008].

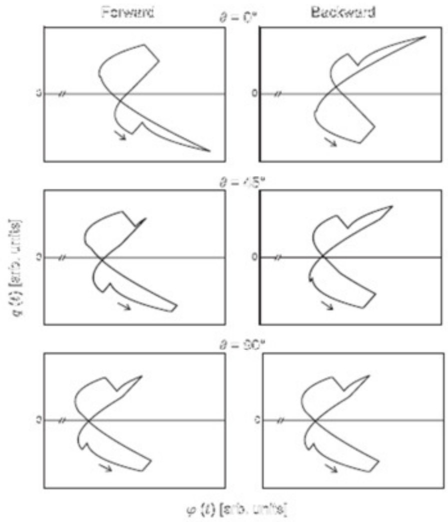
The test of the mathematical modeling was performed in experiments with superimposed square wave functions. The trajectories of the two dynamic variables (charge density amplitude q and director deflection amplitude φ) differ for time mirrored functions (see figures below). The thresholds and onset wavelengths are identical, within experimental uncertainty, for both excitations.



"Forward" excitation wave form. The wave form is asymmetric with respect to time reversal, its time mirror (right) differs from the forward wave form when the phase shift θ is not zero or multiple integers of 90°.



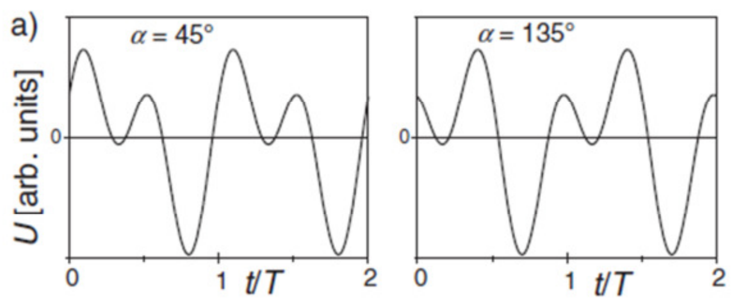
Thresholds and pattern wavelengths of the electroconvection pattern for forward (open symbols) and backward (solid symbols) excitation with square waves in a 1:4 frequency ratio [Heuer2008]



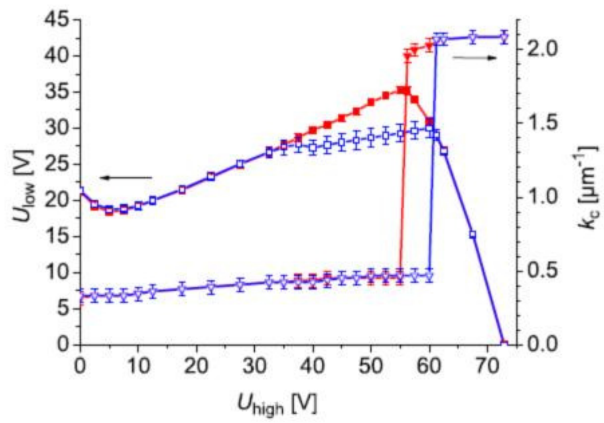
Trajectories of the system variables (charge q and director deflection φ) for different phase shifts θ between the high and low frequency components. The trajectories for 0° coincide, since the wave form only changes sign under time reversal. The 90° trajectories also coincide because the wave form is symmetric, the 45° trajectories differ noticeably, while the thresholds remain unchanged [Heuer2008].

Beyond the standard model

The experiments were later extended to superimposed harmonic waves, and it was found that in the vicinity of the cutoff frequency separating conduction and dielectric regimes, the thresholds as well as the critical wavelengths differ [Pietschmann2010]. This was observed earlier, and a so-called weak electrolyte model was developed by Treiber and Kramer to account for charge dissociation and recombination processes. The breakdown of the classical EHC model is reflected in our experiments in the different cut-off frequencies, pattern thresholds and critical wavelengths in that region. Similar experiments with time reversed excitation functions have been performed in Faraday wave experiments [Pietschmann2013], where the thresholds were also found to be independent of the time-direction of the excitation.



Superimposed sine waves with frequency ratios 1:2 and phase shifts corresponding to a forward/backward pair. The threshold voltages and pattern wave lengths show a clear mismatch in the vicinity of the so-called cutoff frequency [Pietschmann2010]. In that region, the standard EHC model is obviously incorrect for the description of the pattern onset (see pattern stability diagram on the right hand side).



R. Stannarius. *Time-reversal of parametrical driving and the asymptotic stability of the parametrically excited pendulum*. Am. J. Phys., **77** 164, (2009).
J. Heuer, T. John, and R. Stannarius. *Time reversal of the excitation wave form in a dissipative pattern forming system*. Phys. Rev. E, **78** 036218, (2008).
D. Pietschmann, Th. John, and R. Stannarius. *Nematic electroconvection under time-reversed excitation*. Phys. Rev. E, **82** 046215, (2010).
D. Pietschmann, R. Stannarius, C. Wagner, and Th. John. *Faraday waves under time-reversed excitation*. Phys. Rev. Lett, **in press**, (2013).
