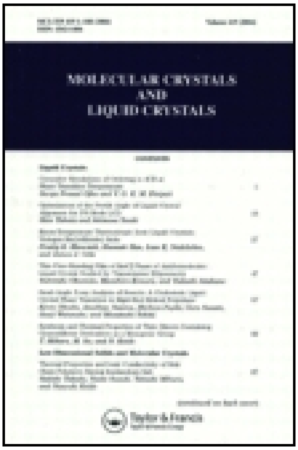

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl18

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Version of record first published: 24 Sep 2006.

To cite this article: M. Kreuzer, W. Balzer & T. Tschudi (1991): Formation of Spatial Structures in Bistable Optical Elements Containing Nematic Liquid Crystals, Molecular Crystals and Liquid Crystals, 198:1, 231-237

To link to this article: http://dx.doi.org/10.1080/00268949108033398

Mol. Cryst. Liq. Cryst., 1991, Vol. 198, pp. 231–237
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Printed in the United States of America

Formation of Spatial Structures in Bistable Optical Elements Containing Nematic Liquid Crystals

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(Received August 15, 1990)

We present experimental results on bistable elements with liquid crystals as nonlinear element showing that temporally nonstationary spatial structure formation occurs if the element is driven with a cw laser source. One necessary condition for this behavior is an illuminated area larger than the spatial resolution of the LC-cell.

During the past years, much work has been performed on the arrangement and analysis of optical bistable elements.[1,2] The 'classical' setup consists of a feedback structure, usually an optical resonator, containing a material having an intensity-dependent refractive index.

We set up an experiment using low-molecular mass nematic liquid crystals as nonlinear medium. The liquid crystal shows a dispersive nonlinearity due to the optically induced reorientation of the molecules. We are concerned here with systems where the response time of the material τ_{mat} is much larger than the time constant τ_{cav} of the feedback system.

Due to the interference properties of light, in two-dimensional optical systems spatial coupling can assume positive as well as negative sign and is periodic with the induced optical path change. This implies that under certain conditions one or more stationary states of such systems may correspond to spatially structured modulation distributions. Thermally driven index fluctuations act as an intrinsic noise source that can be controlled, e.g. by use of external fields.[5] For other systems, as neuronal networks and hybrid-optical feedback systems, introduction of a noise source can change the dynamic behavior of the system dramatically.[3,4] The complete measurement setup is shown in Figure 1.

In this case, the resonator was of the plane-plane type with a mirror spacing of

[1] This work was performed within a program of the Sonderforschungsbereich 185 Darmstadt-Frankfurt, FRG: Nonlinear Dynamics.

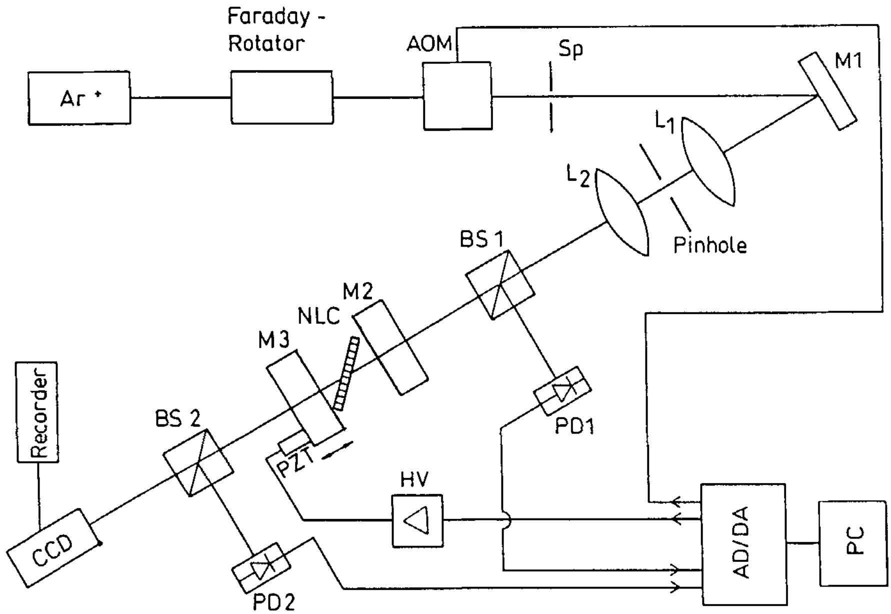


FIGURE 1 Experimental setup.

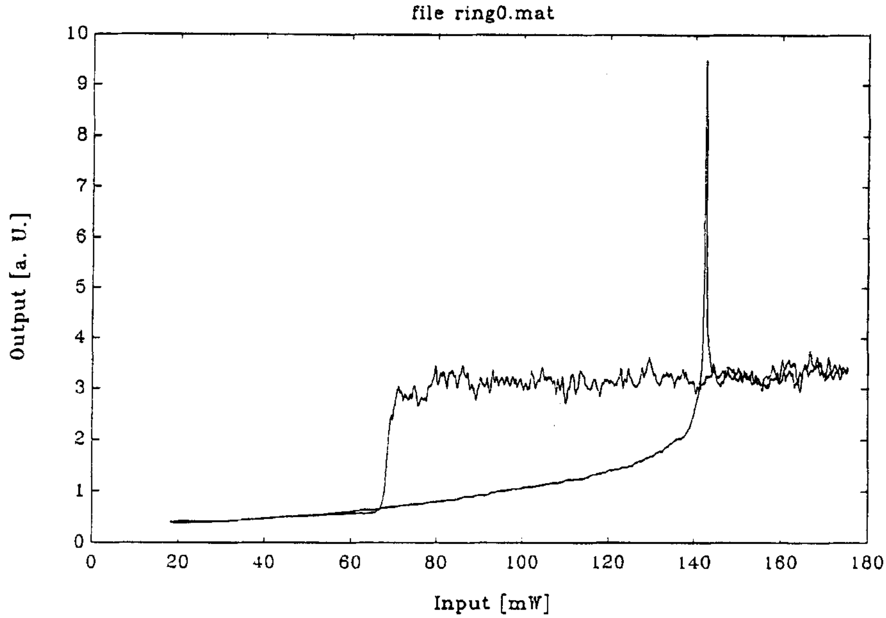
4 cm which could be fine-tuned by a piezoelectric actuator. Control and data acquisition of the setup was done by a computer.

As expected the behavior of single pixel bistability changes when the illuminated area exceeds the spatial resolution of the system. Figure 2 shows two hysteresis curves of a bistable element for different spot diameters.

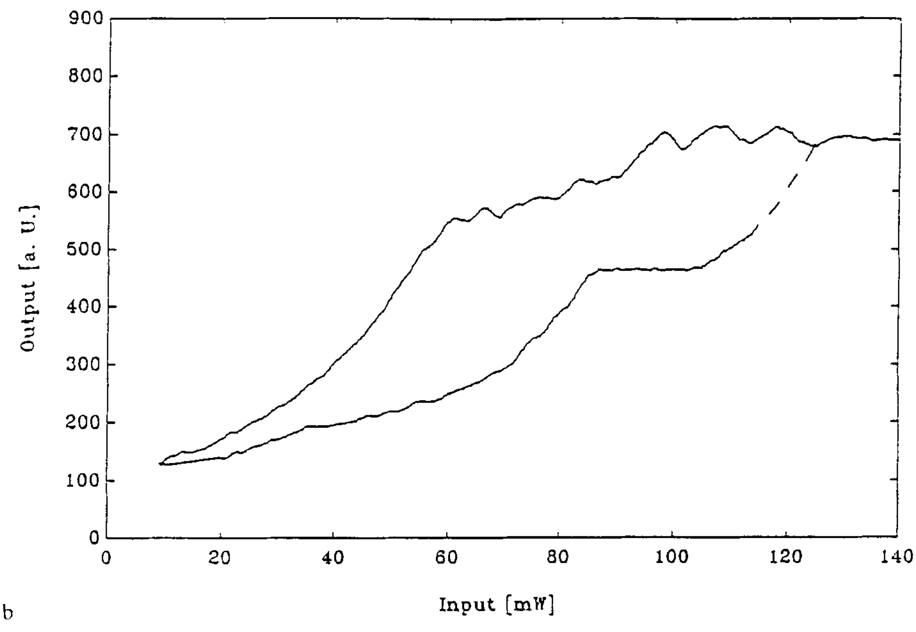
While the curve in Figure 2(a) shows single pixel switching, in the curve in Figure 2(b) the effect of the coexistence of bistable substructures can be seen. After the first switching a sequence of structure formation (at dashed line in Figure 2(b)) took place. An interesting fact was that the process of structure formation seems to follow scenarios which are, once a threshold power is reached, independent of beam power or small manipulations of mirror alignment. Figure 3 shows states of a sequence of spatial distributions in the farfield. The rightmost distribution appears to be a stable end state of the system.

Each transition is accompanied by a sharp increase in total transmitted intensity as Figure 4 shows. The onset of pattern formation can be understood if we consider the fact that an illuminating laser beam has radially-symmetric nonuniform intensity distribution. Thus, by increasing input intensity the central part of the illuminated area will reach the switching threshold first. Following this local switching process, the threshold conditions for the whole area will change, due to the change of intensity distribution by a lenslike action of the modulated area and due to elastic coupling in the medium. Thus, threshold conditions for the whole area will be locally modified and may initiate subsequent local switching processes or switching waves that terminate as the system reaches a stable pattern.

We examined the influence of several external parameters on structure forma-



a



b

FIGURE 2 Hysteresis curves of bistable element (cell thickness 100 μm) with different illuminated areas: a) spot size 70 μm b) spot size 300 μm.

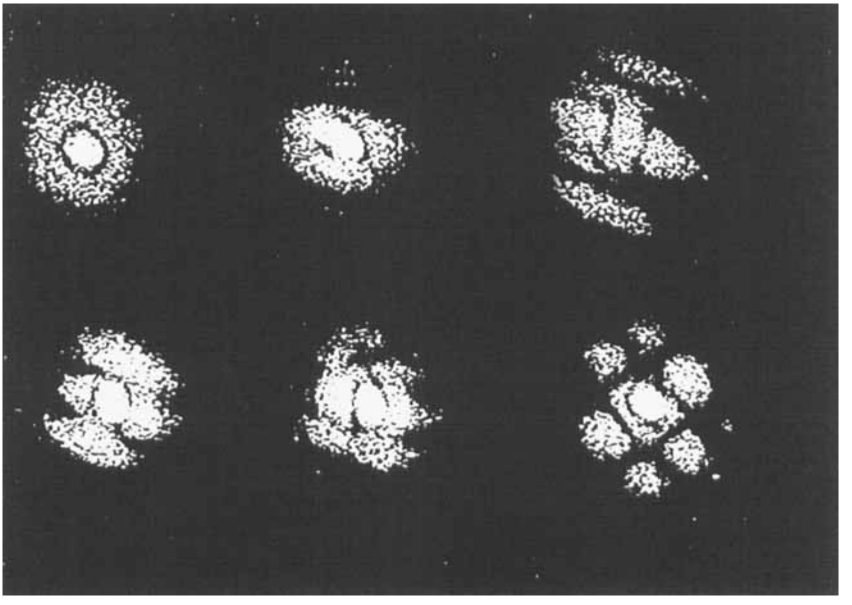


FIGURE 3 Sequence of patterns from a structure-forming bistable element.

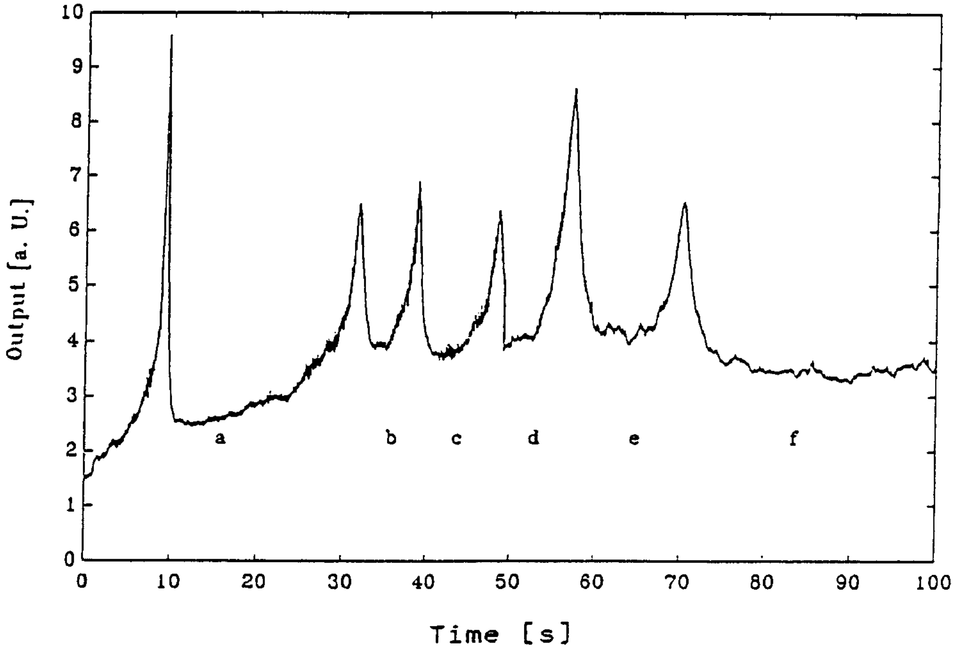


FIGURE 4 Temporal development of transmitted intensity.

tion. With input intensity, there is a first threshold for the stable formation of the 'ring' structure of Figure 3. With slighly higher intensity, sequences similar to the one shown in Figure 3 start. For constant input power, the sequences are, once this threshold intensity is reached, not dependent on input power. Higher intensities only accelerate the speed at which the sequence runs. Stabilization of a intermediate pattern can be achieved by lowering the input power after the state has been formed. Figure 5 shows three typical metastable patterns.

An important question is what relative contribution to the structures comes from the transfer characteristics of the resonator, and what contribution is due to the modulation transfer properties of the nonlinear medium. The system, including the elastic coupling in the medium can be described by a nonlinear heat-conduction-like differential equation for the induced phase shift where the diffusionlength L_D^2 is proportional to d^2 (d: thickness of the LC-cell). This leads to the conclusion that structures smaller than the cell thickness can not appear as a stable state. The ideal bistability, shown in Figure 2a and predicted for the case of plane waves, is only a special case when the spatial resolution of the system supresses the formation of spatial structures.

Figure 5 shows the pattern for two thicknesses indicating that higher resolution of the medium increases sharpness and modulated area while retaining the structure itself. This is equivalently increasing the beam diameter. A change in resonator length by a factor of ten (which accordingly decreases resonator imaging resolution) also did not change pattern appearance, indicating that elastic coupling in the medium is the dominating effect for the given resonator type.

More details of structure formation and transitions between metastable patterns can be understood observing the intensity distributions in the near-field. Figure 6 shows the metastable structures in the plane of the output-mirror of the resonator corresponding to the farfield structures of Figure 5.

Assuming the process of structure formation as a process of self organization, the stable end pattern (6d) relate to the fact that this is the best space filling pattern of smallest structures, which can be resolved by the system.

The fact that scenarios seem to be largely independent on boundary conditions can be understood assuming that there is a route of patterns the system has to follow; each pattern allows or 'prepares' certain subsequent transitions.

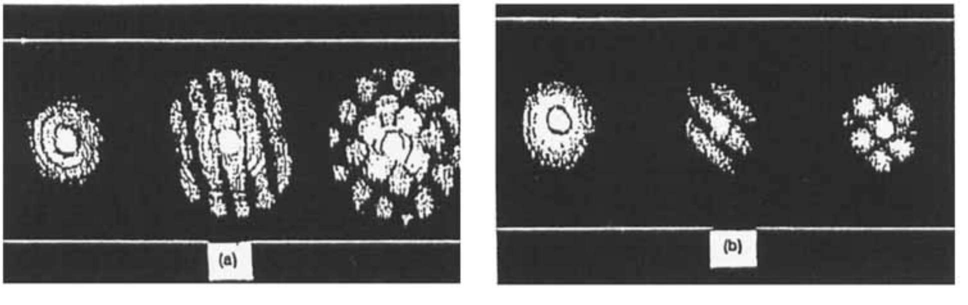


FIGURE 5 Metastable pattern in the far-field for a) cell thickness 50 μm, b) cell thickness 100 μm (spatial resolution decreased by a factor of 4).

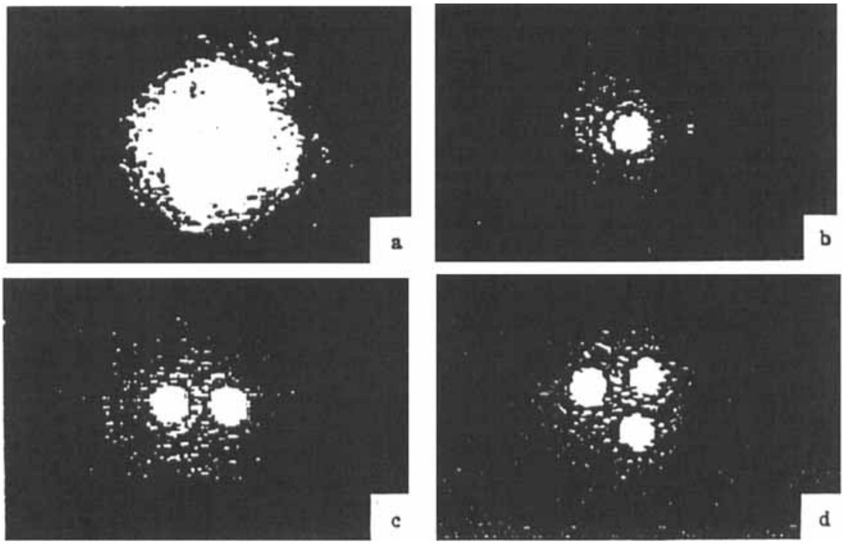


FIGURE 6 Original gaussian beam (a) and the intensity distributions (b–d) in the plane of the output-mirror of the resonator.

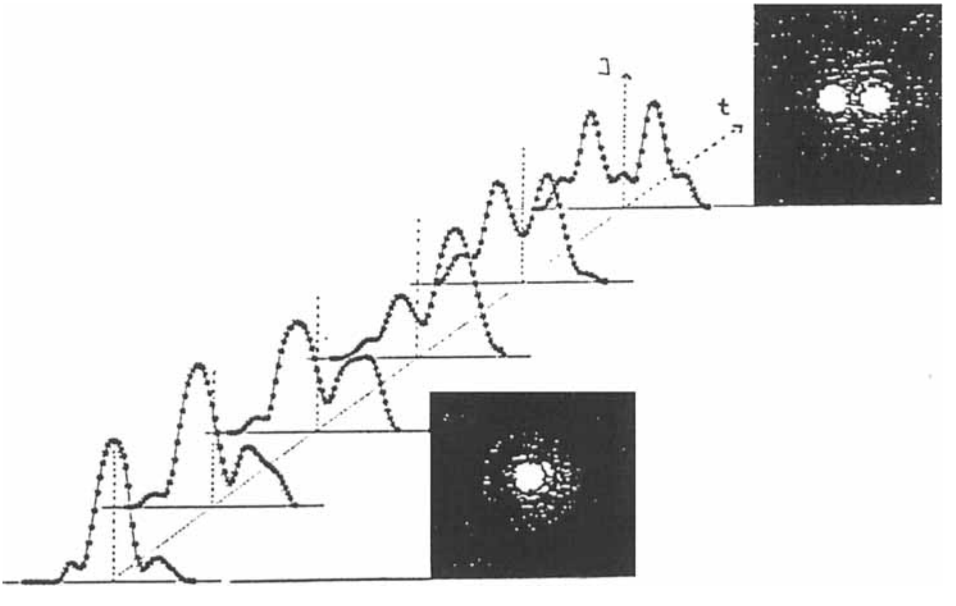


FIGURE 7 Transition between metastable structures.

Figure 7 shows the transition between two metastable pattern. The process starts at no predetermined point shifting the first structure out of the center. After a short overshooting of the second structure a new metastable pattern is formed. The transition shows that the intrinsic noise of the liquid crystalline medium seems to play a central role in this dynamic behavior by facilitating transitions between metastable patterns.

CONCLUSION

We have shown that it is possible to achieve self-induced structure formation in optical bistable elements, if spatial resolution is matched to illuminated area. Reaching a threshold intensity, sequences of metastable patterns are observed which are basically insensitive to external distortions and moderate misalignment. Over a wide range of intensities above threshold value, the type of sequence does not depend on the input intensity, while the sequence speed increases with power. The dynamic process, the symmetry breaking, and the fact that the stable end state is the best space filling pattern of smallest structures leads to the conclusion that this is a process of self organization.

Intrinsic noise of the liquid-crystalline medium seems to play the central role in the process of transitions between metastable structures.

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