Manipulation and Removal of Defects in Spontaneous Optical Patterns

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Defects play an important role in a number of fields dealing with ordered structures. We demonstrate theoretically and experimentally the possibility of an active manipulation of defects in terms of an externally induced motion. We focus on the spontaneous formation of two-dimensional spatial structures in a nonlinear-optical system, a liquid crystal light valve under single optical feedback. For a particular parameter setting, a spontaneously formed hexagonal intensity pattern contains several dislocation-type defects. A scheme based on Fourier filtering allows us to restore spatial order in a selectable part of the pattern. Starting without control, the controlled area is progressively expanded, such that defects are swept out of the pattern.

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Defects are local deviations from a given ordered structure and have attracted large interest in many areas of physics [1]. The most prominent example is condensed matter physics [2,3]. This extends to adjacent areas, such as spin lattices and liquid crystals [4], but also to spontaneous structure formation, e.g., convection patterns [5].

Defects are catalogued in different classes depending on their topology [1]. Here we focus on stable point defects in two dimensions, known as dislocations. These break the discrete symmetry of the periodic structure locally. Dislocations are robust entities which cannot be removed by smooth local alterations of the pattern. They can only be created or annihilated in pairs and, correspondingly, they are assigned a *topological charge* [1].

The spatial order that we consider here develops spontaneously through self-organization and is studied in many branches of science [6]. Spontaneous patterns are also observed in numerous nonlinear-optical systems [7]. When the stress parameter exceeds a first threshold, ordered patterns appear which then give way to disorder after a second transition. Such disordered states may be purely spatial and/or spatiotemporal (*optical turbulence*) in nature and are often undesired since disorder reduces spatial correlations. In certain instances, these secondary transitions have been shown to be mediated by defects [6,8]. Here we regard a Kerr-type nonlinearity in a so-called *single-feedback* setup [9], where stationary hexagonal patterns form at a given threshold of the laser (pump) intensity. Above a second threshold, patterns become increasingly disordered, with defects appearing at random locations [10,11].

The aim of this Letter is to demonstrate the possibility to actively manipulate and (re)move defects. The intention is not to replace defects with other spatial structures, but to change their locations and progressively move them outside the region of interest. Since removing defects leads to the restoration of the ordered state, a key ingredient is a technique to control spatiotemporal disorder. In the regime of spontaneous disorder, the hexagonal state survives, but is unstable or marginally stable. Our scheme of control allows us to select this particular solution out of the infinite set of coexisting (dynamical) solutions and stabilize it. We stress that our method actively manipulates topological defects in 2D while previous techniques simply replace them with other structures as, e.g., in delayed systems [12] and in 2D laser models [13].

Our approach is based on the control scheme introduced in [13] where the growth of structures which do not belong to the desired, well-ordered *target state* is discouraged. This is achieved by adding an all-optical feedback (control) loop with a spatial Fourier filter blocking the discrete number of modes which constitute the *target pattern*. The remaining *control signal* is fed back negatively into the system. Consequently, the system is driven towards the target state, and the control signal vanishes when the ordered state is reached. In contrast to other approaches with persistent perturbations, this control is minimally invasive, preserving the properties of the original system [14]. Note that the control signal is continuous both in space and time, an important requisite for a local manipulation of defects. The control scheme has first been tested numerically [13], and then used in several experiments to control spatiotemporal chaos [15,16].

To manipulate defects in patterns, the control scheme described above is modified. Since we do not intend to replace a disordered pattern with a regular one at once, we apply the control to a gradually increasing part of the spontaneous structure. Because defects are topologically robust objects, they should not vanish instantaneously. Instead, they can annihilate with corresponding partners or move towards regions where the control signal is not operating. Consequently, defects should be swept out by the front separating the controlled, ordered part of the pattern to the uncontrolled and disordered spatial region.

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In order to achieve this, the control scheme is extended by introducing a mask, which selects the controlled area. Hence, in this configuration we act in real space and in the Fourier domain simultaneously.

In our single-feedback experiment, the optical Kerr-type nonlinearity is provided by a so-called liquid crystal light valve (LCLV). This device has an intensity-sensitive *write side* (photoconductor layer) and a reflective *read side* with variable refractive index (liquid crystal layer) [17]. An intensity profile at the write side is transformed into a corresponding phase profile of a light wave, which is reflected by the LCLV read side [18].

The LCLV is put into a feedback loop: A uniform laser beam is phase modulated and reflected by the LCLV read side. The modulated beam is then fed back to its write side. The free space propagation transforms spatial phase modulations into intensity modulations. Different configurations of LCLV feedback systems have successfully been used to investigate spontaneous optical patterns [10,11,18,19]. In this particular realization, pattern formation is based solely on diffractional coupling.

The experimental setup is presented in Fig. 1. A cw-Nd:YAG laser ($\lambda = 532$ nm) acts as a light source (not shown in the scheme). The expanded laser beam is phase modulated and reflected by the LCLV, and then guided to the write side by means of beam splitters (BS), mirrors (M), and lenses (L). The lenses L1, L2, and the aperture P form a spatial low pass filter. The dove prism D accounts for the correction of residual misalignments. The transverse intensity distribution is recorded with a camera (charge-coupled device).

The shaded box in Fig. 1 contains the control loop. A fraction of the light wave is coupled out by beam splitter BS2. It passes the Fourier filter ($4f$ arrangement of the lenses L3, L4), containing a mask FM in the Fourier plane, which blocks the target modes. The remaining wave is reflected by mirror M4 and, after passing the filter a second time, is reinjected into the system. The phase of this control wave is adjusted by the phase shifter PS in order to achieve destructive interference, i.e., negative feedback of the control signal. The space mask S allows the selection of the area to which this control is applied. It is located in a plane, which is imaged onto the LCLV write side.

For the present experiment, the spatial low pass filter (L1, L2, P) is used to block all wave numbers above the first critical band. This makes the transition to spatial disorder smoother and makes it easier to choose the amount of disorder in the spontaneous structure [10]. The pump intensity was set to about 6 times the pattern threshold intensity. In the uncontrolled system, a distorted hexagonal pattern is observed (see Fig. 2, first image at $t = 0$), showing a slow dynamics on a time scale of approximately some hundred milliseconds. The structure consists of several ordered domains, separated by single or strings of defects. Care was taken to match the orientation of the target pattern with the spontaneous pattern in the region where the control is first applied.

After the system has reached an asymptotic disordered state, the space mask S is opened gradually from the left to the right side. Snapshots of the recorded sequence are shown in Fig. 2, where the front between controlled and uncontrolled regions is indicated by a gray line. Eye inspection of the images already shows how hexagonal order is gradually restored.

The ordering effect of our procedure becomes even more apparent when we extract the defect locations from the recorded images (Fig. 2). A hexagonal pattern consists of three independent Fourier modes, each corresponding to a stripe pattern. Each of the stripe patterns can show defects in the form of dislocations, i.e., of stripes ending somewhere in the pattern. Depending on the direction of the ending stripe, the defect is assigned a positive or negative topological charge. Consequently, a hexagonal pattern can contain six different types of defects, corresponding to the six possible Burgers vectors of unit length [2,3]. As long as we restrict the analysis to the topological properties only, domain boundaries can be regarded as strings of dislocations [3].

With the exception of a few defects which remain anchored to local inhomogeneities, the defects are indeed swept to the right-hand side by the control signal, and are finally pushed out of the active area. During this motion, mutual annihilation of pairs of defects takes place as well as the temporary creation of a few new defect pairs.

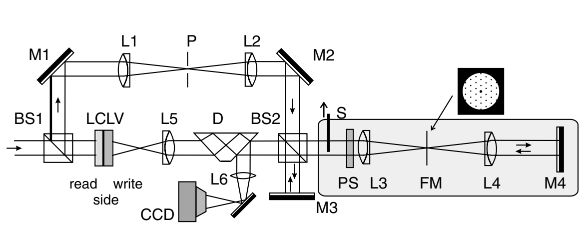

FIG. 1. Scheme of the experimental setup; details are given in the text.

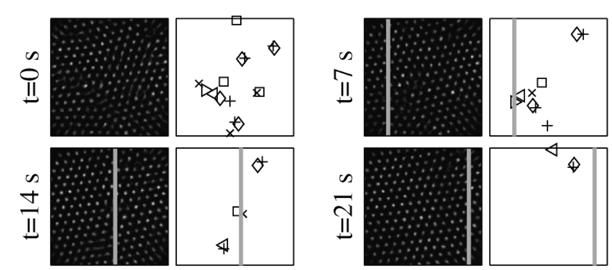

FIG. 2. Experimental sweeping of defects at the times indicated. Each panel contains the intensity distribution on the left and the extracted defect locations on the right. The gray line indicates the front separating the controlled from the uncontrolled part. Different marker types correspond to different hexagonal modes, where □, +, and ▷ indicate one charge, ◇, ×, and ◁ indicate the opposite topological charge, respectively.

The effect of the control does not appear to be strictly limited to the left-hand side part of the pattern that is directly exposed to the control signal. The number of defects in the uncontrolled area significantly decreases even when the control front is relatively far away. This can be associated to the long range spatial coupling: The hexagonal pattern is self-sustained by diffractional coupling throughout its extent. The restored order in the controlled part now promotes order even in the uncontrolled, disordered part, causing a reduction of the number of defects there.

We also observe that defects belonging to different hexagon modes tend to stay close to each other. This becomes evident by plotting all detected defect locations of the sequence into a single plot. The left panel of Fig. 3 illustrates that the defects have moved on definite paths.

In the investigation of model systems, Pismen, Tsimring, and others [20] have shown that two dislocations of different modes tend to form bound states, so-called penta-hepta defects. An experimentally observed penta-hepta defect is shown in Fig. 3. According to [20], attracting as well as repelling forces can exist between different penta-hepta defects and the motion of such defects depends very much on the embedding spatial structure. Hence, we infer that the inhomogeneities in our experiment strongly influence the defect motion.

Numerical simulations of the progressive removal of defects in a spatially disordered stable structure have been implemented by using the LCLV model originally introduced in [19] and used later in [16]. All parameters of the fully quantitative model have been chosen in accordance to the experiment. Simulations above the pattern forming threshold, however, did not reach stable spatially disordered configurations.

In order to represent more faithfully the experimental observations, we have simulated inhomogeneities as localized dips in the pump laser intensity. These local imperfections were of variable number, location, size, and depth. A large variety of stable or long term metastable disordered configurations formed by patches of hexagonal patterns were obtained up to 3 times above threshold. Remaining differences with the experimental observation of metastable disordered structures higher above threshold are explainable by the simplified modeling of the inhomogeneities. With random initial conditions, a variety of spatially disordered structures were found, where defects tend to anchor in the vicinity of the local inhomogeneities. Figure 4(a) shows a stable (or long term metastable) disordered structure observed 3 times above pattern formation threshold.

The Fourier control scheme was implemented numerically in a way that the area where control acts on the spontaneous structure can be chosen. Figures 4(b) and 4(c) show the progressive sweeping of the defects while the domain which corresponds to the target state grows to finally occupy the entire area. In spite of the presence of pronounced local inhomogeneities, an ordered hexagonal structure is restored and stabilized at the end of the procedure [see Fig. 4(d)].

In agreement with the experimental results, we observe in the numerics progressive annihilation of dislocations ahead of the moving control front. In simulations with strong local inhomogeneities (such as the ones reported here), we also observed a lag between the moving front and temporally surviving defects. This, again, is in agreement with experimental measures. By an appropriate choice of the space mask, we succeeded in preliminary simulations to move only an individual defect with negligible effects on others.

In conclusion, we have shown how defects can be swept out of spontaneous optical patterns by using a control technique based on Fourier filtering. The control is applied to a varying part of slightly disordered hexagons. Agreement is found between experiments on a LCLV single-feedback system and numerical simulations on the full model. We emphasized the role played by local inhomogeneities in stabilizing spatial disorder by pinning the defects. This disorganizing effect of inhomogeneities, which are difficult to eliminate in real experiments, can be overcome by our control technique.

Our control technique is independent of the nature of the nonlinearity and has been applied successfully

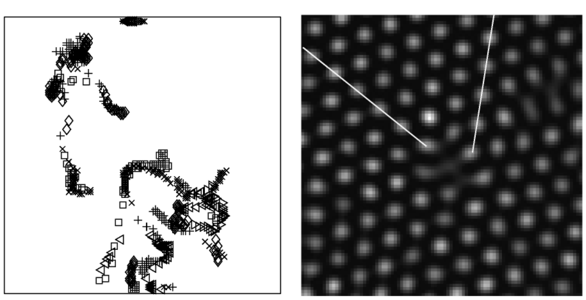

FIG. 3. Left panel: All defect locations, detected during the sequence of the moving control front (cf. Fig. 2). Right panel: Experimental example of a penta-hepta defect, where two rolls of different modes end close to each other (as indicated).

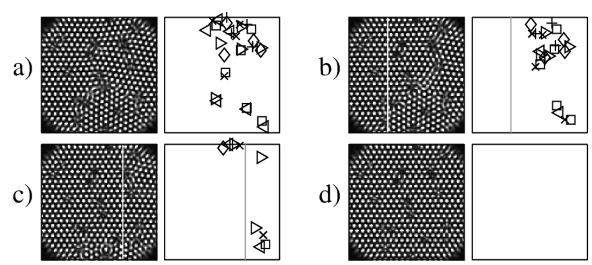

FIG. 4. Numerical simulation of progressive removal of defects at times $t = 0$ (a), $t = 28$ (b), $t = 44$ (c), and $t = 80$ (d), where t has been normalized by the LCLV response time. The vertical bar signals the position of the control mask moving from left to right. Each panel contains the intensity distribution on the left and the location of defects on the right.

to stabilize unstable patterns in models of saturable absorbers, lasers [13], and optical parametric oscillators (OPO) [21]. Presently, we are applying and modifying our elimination technique to systems with defects other than pattern dislocations. These include, for example, domain walls and vectorial defects in models of OPO devices [22].

We expect our control scheme to work in a variety of experiments in optics and other sciences such as chemical reaction-diffusion or fluid-dynamical systems where stable defects have been observed. There are two options for an implementation: an all-optical realization which is possible in systems that can be manipulated by light, for instance photosensitive chemical reactions [23], or convection experiments by means of local laser heating [24]. Here, the light waves used for detection and for actuation may need to differ in wavelength and/or intensity. A transformation between both can be performed by optically addressed spatial light modulators, such as LCLVs [17]. This scheme allows one to perform the Fourier filtering optically, the limiting factors now due to the used modulators.

For other pattern forming systems, a numerically calculated Fourier control signal can be fed back via an appropriate technique specific to the experimental realization. In these cases, the control response should be limited by the speed of the camera used in the detection of the spatial profiles. Even with high-resolution digital cameras, this can be faster than ten frames per second. Such a time scale is much shorter than that of diffusion of heat or of chemical species that determine the dynamics of spatial structure evolution.

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