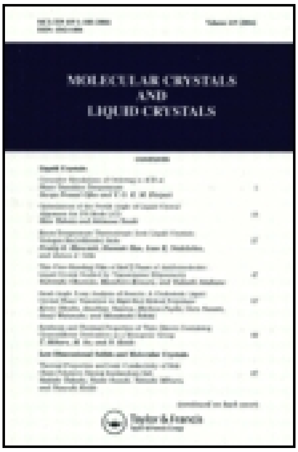

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B. GÜTLICH [a] , M. Kreuzer [a] , R. Neubecker [a] & T. Tschudi [a]
[a] Institute of Applied Physics, Darmstadt University of Technology, Hochschulstraβe 6, Darmstadt, 64289, Germany

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Manipulation of Solitary Structures in a Nonlinear Optical Single Feedback Experiment

B. GÜTLICH, M. KREUZER, R. NEUBECKER
and T. TSCHUDI

Institute of Applied Physics, Darmstadt University of Technology,
Hochschulstraße 6, 64289 Darmstadt, Germany

Interest in spatial solitary structures originates from their characteristics to enable a locally self-confined switching between a dark background state and a bright spot. We report on the control and addressing of solitary structures in a single feedback experiment with a liquid crystal based reflective optically addressable spatial light modulator (OaSLM) as nonlinearity. In general the lateral positions of solitary structures are strongly influenced by mutual spot interaction and system inhomogeneities. Pinning, drifting and spontaneous disappearance of solitary spots determines the system behavior. For photonic applications these effects must be minimized. A control method based on a Fourier filtering method was studied in order to position solitary spots. Numerical and experimental results show that solitary spots can be aligned to periodic grids of hexagonal or square geometries.

Keywords: solitary structures; control; nonlinear optics; information technology

INTRODUCTION

In the last years spatial solitary structures have attracted much attention in the scientific community. In a simple picture, solitary structures may be described as bright spots on a dark background surface. Solitary spots appear in extended nonlinear optical systems such as single feedback experiments or nonlinear resonators, if diffractive broadening induced by propagation is balanced by a self-focussing nonlinearity [1]. Additionally the system must show a bistability, which allows a locally confined switching between two stationary states like a dark state and a bright state. Due to their binary and self-sustaining character, it is possible to interpret solitary structures as information channels. In combination with their flexibility in addressing, the features of solitary structures can be used to realize innovative concepts of all–optical information routing or switching. Such applications have not yet been realized in optical networks and therefore demand totally new concepts and technologies. In this context, one of the main tasks is to find methods to control the positioning of solitary structures, which without control are mostly determined by a spontaneous dynamics. Up to now solitary structures have for example been observed in systems with spatial light modulators [2], in liquid crystal materials [3], atomic vapors [4], photorefractive crystals [5] and saturable absorbers [6] as nonlinearities.

EXPERIMENTAL SETUP

The Nonlinearity

In the system under investigation a reflective optically addressable spatial light modulator (OaSLM) is used as saturable Kerr-like nonlinearity. The OaSLM consists of a planarly aligned nematic liquid crystal layer (LC), dielectric mirrors and a photoconducting layer sandwiched between ITO coated glass substrates. The hybrid device, which is operated with an AC bias voltage applied over the ITO electrodes, can be divided into two functional sides, a read and write side. According to the intensity distribution at the photoconductive write side the birefringence of the LC read side is spatially modulated. An incoming plane read wave is reflected at the internal dielectric mirror and leaves the OaSLM modulated in its phase and polarization state. In the near future it may be possible to replace the hybrid OaSLM with novel liquid crystal materials. For example dye-doped liquid crystals [7] have sensitivities high enough for our purposes.

The Single Feedback

The OaSLM is operated in a single feedback configuration (Fig. 1). As light source a linearly polarized, frequency doubled Nd:YAG laser

(λ = 532nm, P= 100mW) is used. The expanded laser beam is reflected by the read side of the OaSLM, being modulated in its phase and polarization state. The modulated light field propagates freely over a given distance L. During the propagation the spatial phase modulation transforms into an intensity distribution. The propagated wave front is imaged to the write side of the OaSLM by mirrors and lenses, thus closing the feedback loop.

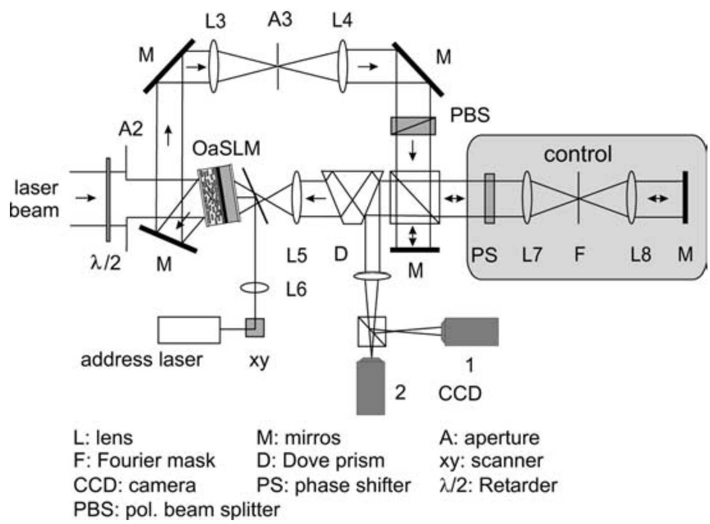

Figure 1: Experimental setup: Feedback loop with optically addressable spatial light modulator (OaSLM). A control arm is (grey shaded part) added to the feedback.

Above a threshold of the input intensity the plane wave solution becomes modulationally unstable against perturbations with a critical spatial wave number k_c and the systems spontaneously forms two dimensional structures in the transverse plane. Far and near field of the evolving structures are recorded by imaging a small fraction of the signal to a CCD camera.

When a linear polarizer is inserted into the feedback loop, additionally, the polarization modulation is transformed into an intensity modulation. As consequence, the system shows bistability and thus the existence of solitary structures is enabled. The OaSLM itself provides a self–defocusing nonlinearity. A symmetry in the model equations allows to simulate a self–focusing nonlinearity by using a negative propagation length L in the setup. This can be achieved by imaging a plane in front of the OaSLM read side onto its write side. A detailed description of the feedback and of the theoretical model used for simulations of the system can be found in the references [8,9].

In order to control the spontaneous structure formation process, a control arm is added to the feedback loop described so far. The control signal is derived from the given light wave with a spatial Fourier filtering technique, and then is coupled back into the system (Fig. 1).

Single solitary spots can be addressed on distinct positions by shining short and focused address pulses with a diode laser and a xy-scanner onto the write side of the OaSLM.

ADDRESSING SOLITARY STRUCTURES

At first, solitary structures were addressed in the system by shining an incoherent and spatial inhomogeneous light pulse with a large transversal extension onto the write side of the OaSLM. Induced by the addressing pulse, the system switches to the homogeneous bright solution in large parts of the active area. When the excitation pulse is off, solitary structures slowly form on random positions. During the transient time these solitary structures interact with each other. Spots move spontaneously, very close spots merge, others lock at certain distances to each other and some simply disappear. Finally after several seconds, a steady state forms which can be stationary for up to half an hour (Fig. 2).

It turns out that the solitary spots are finally located more likely on some favorite positions. This becomes particularly clear by averaging over 50 steady state images, showing that the spontaneously forming spots are pinned by inhomogeneities of the system.

The interaction between the solitary spots themselves can be observed by switching on spots on positions forming a square grid with an address laser and a xy- scanner. The closer the spots are the more the initially square configuration of the spots becomes distorted by

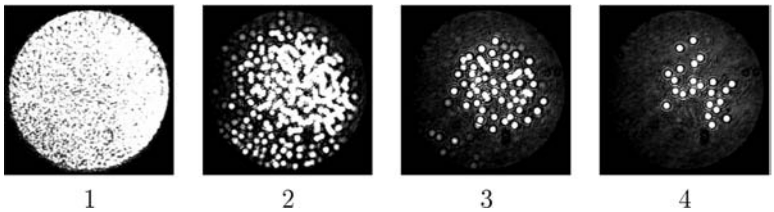

Figure 2: Addressing solitary structures with an incoherent and inhomogeneous light pulse. The system in large parts switches to the bright solution (image(1)). Solitary spots form, interacting with each other ((2)-(3)). After some seconds, a steady state forms (4). The diameter of the active area is $d = 8\text{mm}$.

the spot–spot interaction. As a reason for the interaction behavior the motion of solitary spots along phase gradients has been proposed [1, 6]. The overdamped motion of a spot with index j along these phase gradients can be written in terms of an interaction potential $V_j(r, t)$ [9]:

$$V_j(r,t) = -\sum_{i,i\neq j} V_i(r - r_i(t))A(r,t), \; i = 1, 2, \ldots, \tag{1}$$

where the index i denotes the respective spots, $r_i(t)$ its time dependent position. $A(r, t)$ accounts for a global potential originating from the profile of the incident wave. $V_i(r - r_i(t))$ describes the interaction between spots. The contribution of spot interaction to the potential can be explained by self-diffraction rings which can be observed around solitary structures (Fig. 3). The phase of the light field connected to these diffraction rings results in an alternation between domains of attraction and repulsion. A minimal spot distance exists and it can be expected that neighboring spots lock on the diffraction rings.

A histogram of the steady state spot distances reveals this locking of spots onto the diffraction rings (Fig. 3). In the measurements one can observe a peak structure on top of a broad underground distribution. The peaks are due to the fact that the spots are pinned to the minima of the spot–spot interaction potential. The broad underground is due to inhomogeneities in the system which smear out

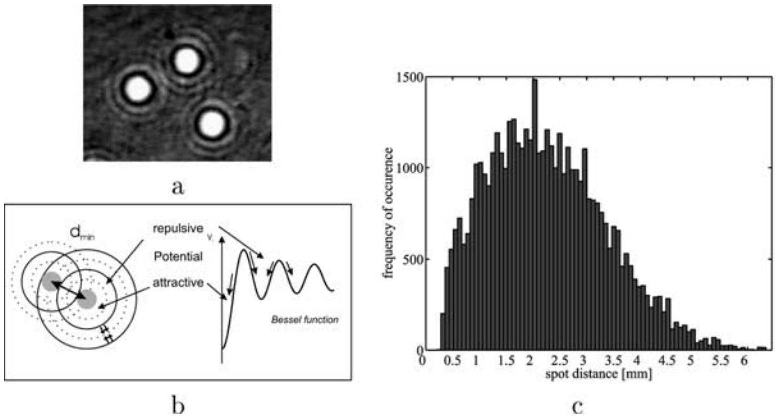

Figure 3: a) Close-up of solitary structures surrounded by diffraction rings, b) scheme of the interaction potential alternating between attraction and repulsion, c) histogram of the spot distances in steady states.

the contribution by the mutual spot interaction. Similar results have already been obtained in a feedback system with sodium vapor as nonlinearity [4].

CONTROL

For potential photonic applications of solitary structures the observed spontaneous dynamics is not acceptable and has to be controlled. Hence, the objective must be the control of the positions of the solitary structures. In practice, a positioning on grids with square or hexagonal geometry would be useful.

To realize such a positioning of solitary structures a Fourier control method was applied to the system. The Fourier control method works in the following way [10–13]: The deviation of the system from a target state is detected by amplitude masks in Fourier space. The control signal consists of these deviations and is subtracted from the original feedback signal. Optically these operations are simple. Experimentally a control arm was added to the feedback arm (Fig. 1). With the help of a beam splitter a fraction of the light wave is coupled into the control arm and passes the spatial Fourier filter. The

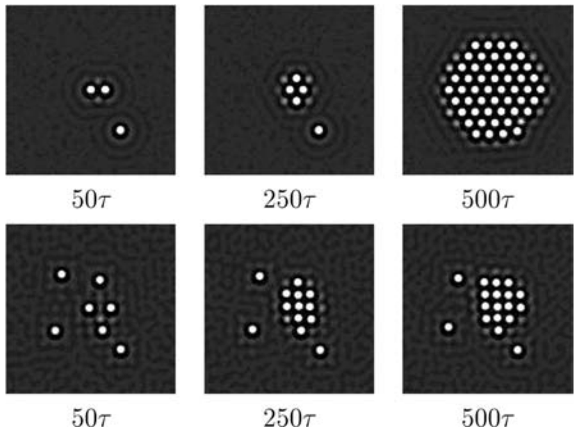

Figure 4: Numerical simulations with hexagonal (1. row) and square (2. row) control. The control forces solitary spots to arrange in accordance to the control grid. New spots get switched on at edges and on gap positions.

Fourier mask blocks the modes of the target state. After reflection the resulting control signal interferes destructively with the signal wave in the feedback loop.

In numerical simulations it showed that with the described Fourier control method indeed solitary spots can be ordered in accordance to grids with square and hexagonal geometry (Fig. 4). However, it turned out that the Fourier control induces the creation of new spots on neighboring positions. This results in the growth of patterned areas of solitary spots.

In experiments it has been confirmed that the solitary spots can be aligned to the control grid in hexagonal and square geometries (Fig. 5). The control masks used in the experiments blocked hexagonal and square modes at a spatial frequency of $k_{mask} = 13\text{mm}^{-1}$. The critical spatial frequency was $k_c = 19\text{mm}^{-1}$ in the free running experiments. It could not for sure be determined if the control switches on new spots, because the interferometric setup is very sensitive to vibrations. The vibrations can result in constructive superposition of control and feedback which automatically leads to the creation of

Figure 5: Experimental images of controlled solitary structures. Fourier control orders solitary structures on square and hexagonal grids.

new solitary spots.

CONCLUSION AND OUTLOOK

In measurements it showed that solitary structures without means of control are greatly influenced by mutual interaction and system inhomogeneities, leading to spontaneous motions. A control method based on Fourier filtering techniques provides a tool which allows to arrange the solitary structures on square and hexagonal grids. Induced by control new solitary spots evolve at gap and edge positions of the grids. In the future one aim must be to minimize these effects by an appropriate adaptation of the control method.

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