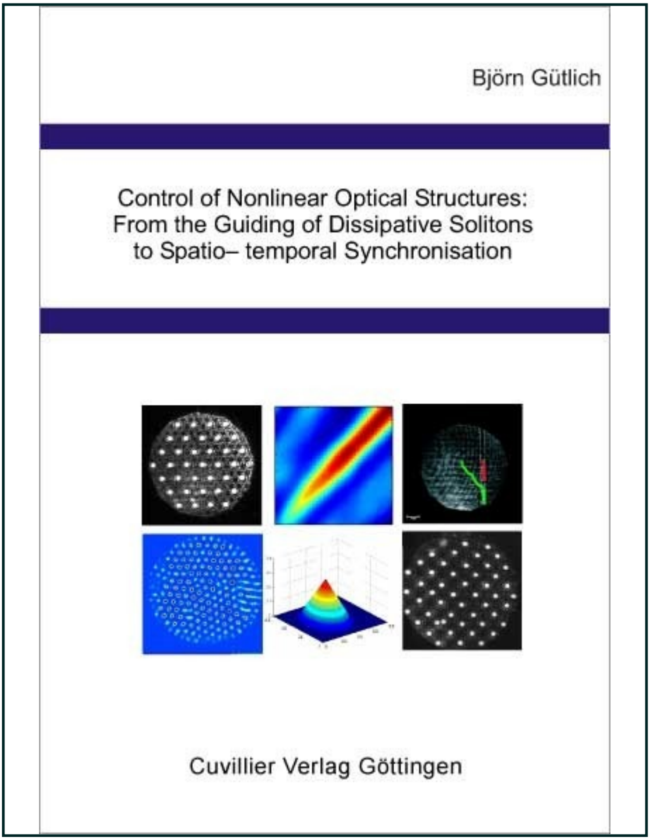
Björn Gütlich (Autor)

Control of Nonlinear Optical Structures: From the Guiding of Dissipative Solitons to Spatio– temporal Synchronisation



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1 Introduction

At present, the optical transmission and storage of optical data is rapidly gaining in importance for the everyday life of society. Yet, the eminent advantages of all-optical information processing, namely fast and highly parallel processing, cannot be appropriately exploited because the state of the art requires sequential electronic interfaces. For the development of all–optical information processing, nonlinear photonics will be the key, as concepts, where *"light is guiding light"*, can only be provided by nonlinear optical materials, which mediate the interaction of photons. If this goal is to be achieved a paradigmatic shift from the early notion of optical nonlinearities as being harmful to the development of methods exploiting the highly diverse nonlinear phenomena is decisive. Intensive research aiming at the implementation of all–optical concepts for switching, routing, and processing of optical information needs to take two directions: Firstly, the already excellent features of nonlinear optical materials must be improved further. Secondly, the phenomena observed in nonlinear optical systems such as the self– organised formation of spatio– temporal structures need to be explored. Moreover the control of these nonlinear phenomena poses the crucial challenge for the realisation of this task. Apart from this, the understanding of self–organised pattern formation and its control is of fundamental interest due to its universality. Self–organised pattern formation is common to many different nonlinear systems in chemistry, biology, physics, and even sociology [1–3]. Even though the microscopical reasons for the occurrence of these nonlinear effects are as diverse as the systems themselves, generalised models can be found describing an incredible number of systems nonetheless. In this context, nonlinear optical systems prove to be especially well suited models, as both theoretical and experimental handling of these extremely versatile systems is comparably easy. Based on the universality of nonlinear phenomena, the principles of spatio–temporal optical pattern formation and its control can advance the knowledge about nonlinear systems in general.

Main objectives of this dissertation

The experimental implementation and characterisation of control methods for spatio–temporal optical structures and the context of their potential application will be at the centre of the research reported on here. For the experimental control of spatio–

temporal optical structures we have chosen a so called single feedback system as a model system which uses a liquid crystal light valve as optical nonlinearity [4–17]. During the last decade the spatio–temporal structures, which can be observed in this specific system, have been explored in detail and well–functioning theoretical models exist for this system. As the principal behaviour of this system is therefore well known, the issue of controlling the nonlinear phenomena observed can be addressed. Previous to this thesis, control already was studied using methods involving invasive and non– invasive Fourier space control [18–21], and control was applied to symmetric patterns in real space by forcing with incoherent intensity distributions [22–25].

Dissipative optical solitons existing in the LCLV single feedback system are particularly interesting objects for all optical information processing because they possess robust shape- preserving properties and binary features. Yet, spontaneous interactions, drift motions etc. are challenging potential applications of solitary structures in all–optical routing, switching or storing of optical data. Fourier space control methods have already been successful in controlling the positions of dissipative optical solitons relative to each other [15, 26–29]. Fourier control can, however, not achieve an absolute position control necessary for the implementation of the potential applications. In context of this thesis, a main scope therefore will be the realisation and testing of a control method, which will allow to statically and dynamically control the absolute positions of dissipative optical solitons. By using an open loop control method we will impose amplitude parameter gradients onto the system allowing to implement such an absolute position control. Starting from a characterisation of the action of the control method onto the nonlinear system, the implementation of static control schemes allowing the realisation of artificial robust position traps and of a robust and complete addressing scheme for the dissipative optical solitons needs to be studied. In the context of position control, the dynamical response of the dissipative solitons in relation to varying parameter gradients is essential to characterise the trapping quality of the control. Furthermore, dynamical control schemes are required allowing the arbitrary dynamic repositioning of groups or individual dissipative optical solitons and the control of their drift motions.

Another intriguing phenomenon observed in nonlinear system is the mutual entrainment of the evolution of weakly coupled nonlinear systems called synchronisation. The synchronisation of chaos has mainly been studied at the hand of one–dimensional oscillators or with networks of coupled one dimensional nonlinear oscillators yet. Synchronisation essentially can be interpreted as a control scheme where the chaotic dynamics of one nonlinear system controls the dynamic of other chaotic systems. Here we will extend the one–dimensional concept of temporal chaos synchronisation to a spatio- temporally extended and continuous system with a non–local nonlinear coupling mechanism. For this purpose, the spatio–temporal synchronisation of two independent, unidirectionally coupled optical LCLV single feedback systems, which show spatio–temporal complexity is studied. Apart from initial theoretical reports on the possibility of realising spatio–temporal synchronisation in optical systems these are experiments pioneering this field. Therefore, appropriate coupling schemes to study spatio-temporal synchronisation need to be developed and the onset of spatio–temporal synchronisation needs to be characterised. For this purpose, methods known from one dimensional oscillators have to be adapted to the spatio–temporal system. The influence of experimental imperfections onto spatio- temporal synchronisation must be studied, and a comparison to the initial theoretical results obtained in a different system as well as to numerical simulations of the LCLV system are required to cross–check the influence of different imperfections with theory. If one intends to realise the technique of encrypted communication using spatio–temporal synchronisation of spatio–temporal complexity suggested in theory, sufficiently high cross– correlations of the systems are necessary. If these are not achieved in experiments, strategies, which increase the degree of spatio–temporal synchronisation, need to be developed.

All in all, the control methods explored here will contribute to the growing number of schemes enabling the control of nonlinear optical systems. Thus, both the knowledge about the complexity of nonlinear optical systems and the potential applicability of nonlinear optical methods in context of photonics for the 21st century is progressed.

Outline of this dissertation

This thesis is structured as follows: In chapter 2 we will introduce and briefly review principal concepts enabling the control of nonlinear systems in general and nonlinear optical systems in particular. We will put an emphasis on the open loop control method of external forcing, which is mainly applied here. Furthermore, the reader will be introduced to the concept of spatio–temporal synchronisation from the perspective of open loop control. The third chapter is dedicated to the spontaneous evolution of spatio–temporal structures caused by light propagation in nonlinear optical media. Starting from a brief review of modulation instabilities of coherent beams, we will then discuss the formation of optical solitons propagating in different nonlinear optical materials and their potential impact for all–optical controlling of optical data flows. Concluding this chapter experimental results on the control of the first and secondary thresholds of modulation instability of partially incoherent optical beams propagating in nonlinear optical media by tuning the coherence properties of the beams will be presented. These experiments are important for implementing controlled interaction behaviour of propagating solitons, as modulation instability is a crucial prerequisite for the formation of propagating optical solitons, and their mutual interactions are strongly influence by their coherence properties [30,31]. In chapter 3 the fascinating concept of self–organised optical pattern formation induced by the introduction of a feedback scheme, either provided by a nonlinear optical cavity or a nonlinear single feedback mirror configuration, will be discussed. We will concentrate on the single mirror feedback configuration, which will mainly be studied here, by introducing a simplified single feedback scheme, its theoretical foundation, and possible experimental configurations. The introduction to dissipative optical solitons forming in optical cavities or single feedback systems will conclude this chapter. Chapter 5 is dedicated to the detailed discussion of single feedback systems with liquid crystalline nonlinearities. We will particularly discuss the theory and experimental realisation of a liquid crystal light valve (LCLV) single feedback system, which we will use as model experiment for the control of nonlinear optical structures. In this context, the observation of a novel structure in the LCLV, namely dark dissipative solitons which exist in the vicinity of saturation in phase–only mode, will be presented.

Results on the imposing of external amplitude parameter gradients to implement static and dynamic position control of dissipative solitons existing in the LCLV single feedback system will be reported on in chapter 6. After characterising the response of the nonlinear system to the external control, the realisation of a compensation method for experimental imperfections is demonstrated. The implementation of static position control with square hexagonal and cone shaped parameter gradients is presented [29], and the influence of changing slope, and spatial scale of the parameter gradients onto the motion of the feedback solitons is studied. The demonstration of dynamical control schemes, where the interaction of drifting dissipative solitons with different static parameter gradients is also studied complete this chapter [32, 33]. Chapter 7 treats the experimental realisation of spatio- temporal synchronisation [34]. The spatio- temporal synchronisation of two independent nonlinear feedback system exhibiting spatio–temporal complexity will be studied with a unidirectional coupling scheme and varying coupling strengths. First time experimental evidence of spatio– temporal synchronisation of spatio–temporal complexity will be presented using different methods analysing the degree of spatio–temporal synchronisation. The influence of spatial non–uniformity onto spatio–temporal synchronisation is studied numerically and in an experimental setup with reduced influence of inhomogeneities. Finally this thesis ends in chapter 8 with a summary of the achievements and an outlook.

2 Control methods for nonlinear optical systems

The first descriptions of what we call *control of a nonlinear system* today dates back into ancient times. Originally, the term of '*chaos*' derives from the work of the ancient Greek philosopher Plato. Today it is commonly used to characterise a disordered system state with erratic motions observed in context of nonlinear systems. Besides using the term in the sense of unpredictability, Plato also uses the term 'chaos' in the sense of emptiness or a void. Later the meaning of the word changed from unpredictability and void to disorder, the latter being the meaning associated with the term 'chaos' today. In the imagination of ancient times the possibility of controlling of such a chaotic state remained to the domain of a transcendent divinity.

An exemplary ancient description of controlling of a chaotic state can be found in the first chapter of the book of Genesis, where an account of the origin of the world is given. The text describes the state of the earth at the beginning as *'tohobohu'*, which is the Hebrew word for chaos in the Platonic meaning often translated as 'being without form and void'. This chaotic state of the world is described to be transformed into an ordered state by the creative 'spoken word' of a deity[1]. The main conceptual ideas necessary for the implementation of control of a chaotic system are already contained in this process. The first ingredient necessary for controlling of a chaotic state is a control *intention* and a control *mechanism.* In the example the controller – the Biblical deity – expresses its intention in the 'spoken word'. At the same time the 'spoken word' defines the target state of the control it also acts as the controlling mechanism in our ancient example because the initial system state is transformed into an ordered state due to the 'spoken word'. The control mechanism itself must be defined as extremely small, as the spoken word cannot be a considerable intervention in the system earth. At the same time this smallest conceivable intrusion into the system accomplishes the attaining of the target state. Finally the Biblical deity compares the final state of the system with the initial control intention, evaluates the final state as being 'very good' and thus comes to

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[1] Genesis 1,2-4: "And the earth was *tohobohu* (without form, and void); and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters. 3 And God said, Let there be light: and there was light. 4 And God saw the light, that it was good."

the conclusion that no further control is necessary[2].

Even though this ancient report on the control of chaos must clearly be viewed as a primarily theological text, it nonetheless anticipates some important aspects of chaos control used in scientific context today. The extremely small intrusion 'spoken word' for example could be interpreted as an anticipation of using the famous *butterfly effect* of nonlinear science for the control of a nonlinear chaotic system. The evolution of chaotic nonlinear systems in contrast to linear systems is known to dependent strongly on the initial conditions of the system. A prominent example for a chaotic nonlinear system is the evolution of the weather. Although the deterministic equations for thermodynamical quantities in the atmosphere, which are relevant for the description of the weather, in principle are known, the weather evolution nonetheless shows the characteristics of deterministic chaos due to nonlinear coupling of the model equations for the atmosphere. Therefore, the weather evolution cannot be simply projected into the future, and a tiny change of initial conditions can dramatically alter the future weather conditions on a large scale. Referring to the famous *butterfly effect*, the flap of a butterfly's wings in New York's Central Park eventually could cause the evolution of a hurricane in the Gulf of Mexico. This very basic feature of nonlinear physical systems can, besides giving rise to the unpredictability of the systems, also be used as a means of control for these systems. A small intrusion in the nonlinear system acting at the right time and in the right position can conform the evolution of the nonlinear system to the intention of the control. The challenge in this approach to control, however, is to overcome the fundamental unpredictability of chaotic nonlinear systems. Even though the detailed individual system evolution of nonlinear chaotic systems remains unpredictable, the progress in nonlinear science meanwhile allows to predict and characterise the principal behaviour of many microscopically extremely differing nonlinear systems. Starting from the ongoing exploration of hydrodynamical turbulence, nonlinear processes are studied at hand of systems in biology, chemistry, engineering, physics, and optics today [35].

In contrast to systems which are one-dimensional in space or time or which can be constructed as a network of discrete, one dimensional systems the evolution of spatially extended continuous systems is often dominated by nonlocal effects such as diffraction or diffusion, which cause a continuous nonlocal spatial coupling. At the same time these nonlocal effects create the vast variety of the observed transverse structures as well as making the categorising of the observed spatio–temporal dynamics, and in consequence also its control, more complicated [1–3]. Therefore, the simultaneous control of the complete transverse space is often necessary for the implementation of control in spatially extended and continuous systems [36].

Optical systems which are in the scope of this thesis are particularly well suited to

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[2] Genesis 1,31: "And God saw every thing that he had made, and, behold, it was very good."

study these spatio–temporal dynamics and the implementation of spatio–temporal control. In contrast to other physical systems the dominant system parameter - the optical field - is directly observable in its amplitude and phase and both quantities can be easily manipulated. Therefore, a direct control of the complete optical field is feasible. Furthermore, optical fields have the inherent advantage that transverse control operations can be processed in parallel as opposed to sequentially. The Fourier transformation in particular is performed all optically and in parallel at the speed of light by a simple lens. Consequently, the realisation of different operations such as convolutions or calculations of correlations can also be accomplished with plain all-optical schemes. So, the demand for simultaneous control of the complete transverse space can be easily met in an optical system. These fundamental advantages of optical experiments are the basis for the successful theoretical and experimental implementation of methods for the control of spatio–temporal complexity.

From a historic perspective the interest in the control of nonlinear optical systems dates back to the discovery of the laser. The laser itself may be considered as a prototype of a nonlinear optical system. It consists of a nonlinear optical material placed into an optical cavity which provides a feedback mechanism. The nonlinear nature of the laser e.g. reveals itself in the transcritical bifurcation of the laser emission [35]. Most often, however, the nonlinear dynamics occurring in lasers are restricted to longitudinal modes in order to meet the demands of applications, namely high output power and uniform beam profiles. The whole range of complex nonlinear dynamics resulting in temporal and spatial instabilities which come into play if the laser dimensions are extended thus allowing for transverse modes, are generally considered to be unacceptable for application. The suppression of nonlinear characteristics to create a well defined laser output is no longer feasible in a spatially extended device like vertical cavity surface emitting lasers (VCSELs) [37,38]. Hence control methods for nonlinear spatial optical systems exhibiting spatio–temporally complex system states are required.

At present, it is widely discussed to not only consider optical nonlinearity as being harmful, but to use its benefits for the implementation of all optical concepts for information processing. Nonlinear systems as such provide an incredible richness of solutions and system states, which just are not accessible in the linear regime. If one thus intents to use the multitude of nonlinear effects instead of suppressing them, a main aim must be to develop control methods which allow to either impose or stabilise a system state of the nonlinear system predefined by the control intention.

Implementing such reliable control methods in nonlinear optical systems will allow an extension of optical information processing far beyond the linear limit. Particularly all optical concepts of optical information processing which follow the promising concept of '*light guiding light*' can only be accomplished if the nonlinearity of the systems is activated. Otherwise photon – photon interactions, which are at the heart of the concept of the concept of *light guiding light*, cannot be realised. Suggestions for potential applications of nonlinear optical systems range from all– optical routing and switching of optical information to optical data storage, methods of image recognition and data encryption. For these applications the control of nonlinear optical systems and their spatio-temporal complex dynamics becomes even more obviously indispensable. It will not be sufficient to only suppress unwanted temporal or spatial complexity, but the realisation of control schemes, which allow to address and select a certain target state, is required. Thus, the output needs not only be predictable but control moreover must define the system output at a given input to the nonlinear system in a reliable manner according to the intention of the user.

At this point we will refrain from categorising all potential control schemes for spatio-temporal nonlinear systems, which are likely as diverse as the rich spatio-temporal phenomena observed in these systems. A brief overview over the control methods for temporal and spatial chaos will be given instead. We will here define the basic conceptual ideas on control in particular which will be used in the context of this thesis. Corresponding to the main issue of this thesis we will put an emphasis on the spatio–temporal control of nonlinear optical systems.

2.1 Fundamental concepts for the optical control of nonlinear spatio–temporally complex systems

Spatio–temporal control can be *open loop* or *closed loop*. Open loop schemes impose a predefined temporal and/ or spatial signal onto the nonlinear system. These concepts hence function without a feedback mechanism to the nonlinear system. The open loop control signal therefore does not change if the controlled system evolves in an unpredicted manner due to the lack of a feedback mechanism with the actual state of the nonlinear system. In principle a preceding knowledge about the target state of the nonlinear system is not required for open loop control. For the application of open loop methods it is helpful, however, if the response of the system to the control signal can be predicted in a reliable manner. Open loop methods can also be suitable if the actual system state is difficult to measure in real time or if a closed loop scheme is difficult to realise. The action of open loop control in comparison to closed loop control is shown schematically in figure 2.1

A feedback of the control signal to the actual system state exists in closed loop schemes. The control signal derives from a comparison of the actual system state with the intended target state. In the control schemes an approach of either positive or negative control can be taken. In a *positive control* scheme the control signal, which often will be the target state, is added to the system. Thus the target state