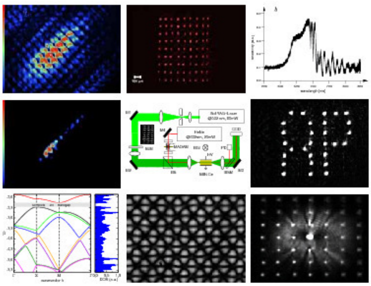
Denis Träger (Autor)

Optical Spatial Solitons and Nonlinear Optics in Complex Photonic Structures

Denis Träger

Optical Spatial Solitons
and Nonlinear Optics in
Complex Photonic Structures



Cuvillier Verlag Göttingen

https://cuvillier.de/de/shop/publications/1919

1. Introduction

Nature as the object of study does not only define the boundaries for scientific research. On the contrary, in many prominent cases researchers have learned from the huge variety of inventions done by nature and can do so in the future. This is not only true in engineering — consider for example the very stable hollow-core structure of blades of grass and the corresponding architecture of high artificial towers — but especially the very active field of optics profits from nature's ingenuity. So-called *photonic structures* which are periodic structures that are able to influence light propagation are known to produce for example the beautiful colour spectra in certain butterfly's wings [1].

While biology can be accounted as direct archetype for scientific developments like photonic structures, another topic of this thesis is farther away from its well-known equivalent in nature. The first documented observation of a different and novel type of wave phenomena — which has been denoted with the term *soliton* later — was made by the Scottish engineer John Scott Russell (1808-1882) already in 1834. While riding along a channel observing a transport ship moving quickly on the water and stopping abruptly, a water wave detached from the bow of the vessel and moved along the channel. Unlike the expected behaviour of quick decay the wave moved virtually without changing its shape. Russell reported that he had followed this robust wave along the waterway until it finally diminished after propagating for as long as about three kilometres. He named this discovery *Wave of Translation* and presented it to the public in 1844 at the *Fourteenth meeting of the British Association for the Advancement of Science* [2]. The nonlinear properties of matter — in this case the system consisting of water in combination with the boundaries of the canal — are responsible for the uncommon behaviour of the water wave. Nowadays, we are appalled by the tremendous destructive force a *Tsunami* wave develops, which from the physical point of view is simply the same phenomenon — a large temporal soliton propagating in the ocean and releasing its energy when arriving at the coastline. As we concentrate on optical solitons in this thesis, to read more on solitary waves in general we recommend the book *Waves Called Solitons* [3].

The field of optical research and technologies has been identified as the future technology of the 21st century by National Science Foundation (NSF) already in 1998 which is written down in the study *Harnessing Light - Optical Science and Engineering for the 21st Century* that was produced by the newly formed *Committee of Optical Science and Engineering* (COSE) [4]. A few years later in 2002 the German ministry of education and research (BMBF) published a corresponding booklet *Förderprogramm Optische Technologien (Optische Technologien – Made in Germany)* outlining the research programme in the same field [5]. All these activities indicate the high rating of the relevance of optical research for the future of science — and even led to the declaration of the *Century of the Photon*, following the *Century of the Electron*.

The advancement of optical research and technologies would not have been possible without the invention of the laser in the 1960s which is one of the central developments of the last decades not only for optical sciences. These brilliant, stable light sources that can emit high output power paired with excellent beam quality are the key for quite different applications ranging from pointing devices, data transmission over material processing to nonlinear optics. For example, lasers of different type and power are used for material processing in different media: A wide range of applications from cutting steel to complicated surgery in the human eye is possible. Consequently, when working with such powerful tools special care has to be taken as potential damaging effects of even faint laser radiation on the body and especially the human eye are known since long ago [6] teached in special compulsory seminars. For example, to avoid possible hazard only low-power sealed semiconductor lasers are used in devices for end customers to read and write optical discs, like music players and computers.

Today, already the major part of long-range data transmission for telephony as well as Internet traffic is handled via optical links. In general, it is based on fiber optics where modulated infrared carrier beams are coupled into fibers. The main problems arise at the interfaces of the long fiber cables — to be able to reconfigurably route signal beams from one fiber to another the vision of *all-optical networks* comes into play. Currently, the signals are routed by manual fiber patching, via mechanical or electrical switches or they are decoded into electrical signals, processed and afterwards encoded optically again. The conceptional idea of all-optical networks bases on routing exclusively steered by light. For this vision to become reality, optical sciences have to deliver powerful tools for fast and reliable optical data communication. Especially research on *nonlinear optical phenomena* is necessary as nonlinear effects have the potential to be used for signal routing by steered interaction of optical beams as well as by artificial periodic structures. In this thesis, I present a variety of different nonlinear optical phenomena that we investigated in the last few years.

1.1. Objectives of this Work

The topics of this work cover a range from optical spatial solitons and optically induced periodic structures to synthetic photonic crystals. A variety of linear and nonlinear optical phenomena in photorefractive and other media is considered. Photorefractive crystals and especially Strontium Barium Niobate (SBN) have disclosed themselves to be very convenient means to study nonlinear optical phenomena with low experimental demands. Therefore, the photorefractive effect plays a dominating role in the major part of this work.

For this thesis work, the choice of topics was led by the idea to invent and explore new concepts for guiding light and steering its propagation in different bulk and structured media. Self-focusing of optical spatial solitons as starting point is an intrinsic stabilisation technique for light beams that allows for self-consistent propagation without external intervention and offers interesting waveguiding features. To be able to exploit steered interaction especially in complex configurations of solitons that can be used as waveguides, studies of the behaviour of these objects in parallel arrangements has to be performed. Discussion of many different scenarios and testing of their feasibility for optical communication application awaited fulfilment.

As photonic structures can strongly influence light propagation by means of their periodicity their fundamental characteristics are important to understand. Different methods are known for artificial structuring of matter like material deposition or removal comparable for example to semiconductor technology. Nevertheless, a novel and convenient technique called optical induction produces periodic refractive index structures in photosensitive media like photorefractive crystals for example. Both types of periodic structures are able to exhibit linear and nonlinear properties and can be investigated with a variety of methods to learn more about these nonlinear effects in general and search for corresponding applications. With these fundamental optical systems we have an excellent test-bench for nonlinear optical phenomena in general that serves to learn as much as possible about nonlinear effects, their exploitation and the the choice of parameters in particular with regard to possible applications.

1.2. Structure of the Thesis

The ability to reversibly modulate the refractive index of a material just by the influence of light is very important for the study of a large variety of optical effects without requiring any permanent change of material properties. Chapter 2 serves as a general mainly theoretical introduction to the field of nonlinear optics and the specific topics presented in this work. These span from nonlinear optics in general via self-focusing effects and optical spatial as well as photorefractive solitons including their interaction features. Furthermore, the basic principles of periodic structures and photonic crystals including their linear and nonlinear properties are discussed. Additionally, in Appendix A the numerical simulation of nonlinear beam propagation and soliton formation is sketched while in Appendix B the calculation of optical band structures is outlined.

Then in Chapter 3, I start with the introduction of requirements for studying experimentally complex configurations of optical spatial solitons in photorefractive media. Since the first discovery of these objects complexity of the investigated interaction scenarios is constantly growing and we have been able to make some important contributions to this very active field. *Generation and stability* of soliton arrays covers a large part of this chapter as this is a key feature for potential applications. Furthermore, intrinsic and especially steered *interaction* is very important in large configurations of solitons and makes them ideal candidates for different applications in optical data communication. The natural refractive index modulations self-induced by photorefractive solitons allow for *guiding of light beams* of different wavelength in the solitary waveguides as well. Apart from guided red light beams, we have shown that the *waveguiding features* are present even for infrared light that is being widely used in today's telecommunication systems. *Steering* of the beams by light and interaction of photorefractive solitons can be exploited to form optical couplers and switches as discussed as well.

As already mentioned, another possibility to strongly influence light propagation is given by *periodic structures* which are discussed in Chapter 4 to 6. Due to appliance in optical systems, these structures are called photonic structures or even denoted as *photonic crystals* to stress the similarity with crystals in solid state physics. Investigation of the fundamental properties of such periodic structures is facilitated enormously by the optical induction technique which allows for easy reconfiguration of their geometric parameters. In Chapter 4, I present our investigations on a variety of different lattice geometries to find the most promising for further linear and nonlinear studies.

Based on our findings, we identified specific lattice structures with special linear features like a full photonic bandgap. Their nonlinear features are responsible for example for solitonic localisation that we have measured and will be discussed in Chapter 5 of this work. Furthermore, we implemented novel experimental techniques to excite Bloch waves in such bandgap structures. These investigations deliver important results for further research and development of photonic devices. A step further is done with synthetically produced photonic crystals that are discussed in Chapter 6. We have investigated the nonlinear response in four-wave-mixing experiments by localisation of light in one-dimensional photonic structures and discuss the results.

In the framework of this thesis a number of publications have originated that are listed in Appendix C and cited in the Bibliography. Most of them originated from cooperations with national and international partners and include a significant amount of articles in peer-reviewed journals as well as talks and poster presentations at national and international conferences and workshops. Finally, I appreciate the ideational and financial support by the *Konrad-Adenauer-Stiftung e. V.* that facilitated the major part of my thesis work.

2. Light Propagation in Nonlinear Optics

Nonlinear optics has gained attention in the past years due to rising demands especially from the telecommunication market. For several reasons the exploration of fundamental nonlinear optical effects is of special interest. On the one hand, the available bandwidth is limited by losses and perturbations of optical signals while high bandwidth is of central importance for optical data communication systems. Furthermore, the field of basic research profits from the increasing knowledge on nonlinear effects in general. In particular, nonlinear coupling of waves in space and time occurs as a fundamental mechanism. And finally and most importantly, to be able to benefit from nonlinear effects in order to counterbalance disturbing phenomena, both of them have to be identified.

Light-matter interaction in the field of nonlinear optics is able to change the material's refractive index and influence light propagation. As photorefractive materials serve as a universal tool for the study of optical effects throughout this thesis, at the beginning of this chapter this type of nonlinearity is described. Both, optically induced photonic structures as well as optical spatial solitons are based on photorefraction. With the optimization of four-wave-mixing efficiency in synthetically produced 'real' photonic crystals another fascinating field is discussed in Chapter 6. In following introductory section of the thesis, the underlying physics for this broad range of different nonlinear optical phenomena is discussed on the basis of a general introduction to nonlinear optics given there.

2.1. Nonlinear Optics

In general, a nonlinear response to an electromagnetic field in the optical wavelength range is the basis for nonlinear optical phenomena. The propagation of an optical wave is governed by the nonlinear wave equation

$$\Delta \boldsymbol{E} - \frac{1}{v^2}\nabla_t^2 \boldsymbol{E} - \frac{1}{\epsilon_0 c^2}\nabla_t^2 \boldsymbol{P} = 0\,. \tag{2.1}$$

Here, the material's reaction is quantified by the polarisation $\mathbf{P}$ (with the group velocity v, the speed of light c and the dielectric constant ϵ_0). While linear optics is fully described by the polarisation being directly proportional to the first order of the electric field strength $\mathbf{E}$

$$\mathbf{P} \propto \mathbf{E}\,, \tag{2.2}$$

for the description of nonlinear effects the electric field has to be written as a power series incorporating higher orders of the electric field $\mathbf{E}$. This nonlinear behaviour is reached when the intensity of the light beam becomes strong enough so that the electric charge distribution can be influenced by higher order terms of the electric field times the corresponding susceptibility. In general, developed into a power series the polarisation then becomes the form

$$\begin{aligned} \mathbf{P}(\mathbf{E}) &= \left[\epsilon_0\chi^{(1)}\mathbf{E} + \epsilon_0\chi^{(2)}\mathbf{E}\mathbf{E} + \epsilon_0\chi^{(3)}\mathbf{E}\mathbf{E}\mathbf{E} + \ldots\right] \\ &= \epsilon_0\mathbf{E}\left[\chi^{(1)} + \chi^{(2)}\mathbf{E} + \chi^{(3)}\mathbf{E}\mathbf{E} + \ldots\right] \end{aligned} \tag{2.3}$$

with the nonlinear coefficients $\chi^{(n)}$ being tensors of rank $n+1$, respectively, which denote the different orders of the optical susceptibility. Typically, the most important nonlinear terms $\chi^{(2)}EE$ and $\chi^{(3)}EEE$ are several orders of magnitude smaller than $\chi^{(1)}E$, the linear one [7]. The fact that even in strong nonlinear materials this results in nonlinear coefficients differing by at least one order of magnitude from the linear susceptibility will be assumed further on. As a consequence, to excite nonlinear effects, much higher amplitudes of the electric field are needed than in the linear case. On the other hand, the characteristic of an excited nonlinear response is at least of a squared or cubed form, which makes these effects specifically interesting for potential applications as such effects allow for nonlinear characteristics of new devices and additionally for smaller dimensions.

The classification of nonlinear optical effects is based on the order in the series of the polarisation. The 'classical' *linear effect* does not change with the strength of the electric field and is nothing else than the intrinsic refractive index of the material. The associated second-rank tensor is given as $\chi^{(1)}$. As there is no refractive index change observable due to optical fields, the regime is called *linear optics* (or classical optics).

In the case of second order nonlinear effects $\chi^{(2)}$, a tensor of rank 3 is controlling the material answer. Second order effects need non-centrosymmetric materials to occur, for example crystals without inversion symmetry. Here, the refractive index change is proportional to the linear electric field amplitude in contrast to linear optics. This second order term is responsible for different effects like second harmonic generation, sum- and difference-frequency generation as well as optical parametric amplification and oscillation processes. The corresponding effect studied here for $\chi^{(2)}$ is denoted as the *linear electro-optic effect* or *Pockels-effect*. Although it is called *linear* electro-optic effect it remains a nonlinear effect where the dependence of the polarisation on the electric field is stressed:

$$\mathbf{P} \sim \chi^{(2)}\mathbf{E}\mathbf{E}\,. \tag{2.4}$$

Third order nonlinear effects require $\chi^{(3)}$, a tensor of rank 4, and can exist in centro- as well as in non-centrosymmetric media. In spite of the linear field amplitude, here the refractive index change is proportional to the squared electric field, that is the optical intensity:

$$\mathbf{P} \sim \chi^{(3)}\mathbf{E}\mathbf{E}\mathbf{E} = \chi^{(3)} I\mathbf{E}\,. \tag{2.5}$$

Many different nonlinear optical effects are intensity-dependent as there are third-harmonic generation as well as Raman and Brillouin scattering and of course all relevant refractive index changes including the photorefractive effect. As the nonlinear response of the material is proportional to the optical field it is denoted as Kerr nonlinearity. For a broader overview on nonlinear optical effects we refer to [8].

Our main object of study — the photorefractive nonlinearity — is not only related to simply one nonlinear phenomenon. As we show later in this chapter, the second order Pockels-effect dominates the refractive index change in photorefractive media, while on the other hand the generation of optical spatial solitons in two dimensions is governed by a saturable Kerr-nonlinearity, the third order effect, resulting from charge carrier redistribution.

2.1.1. Self-Focusing in Nonlinear Media

The presence of nonlinear effects allows to balance out phenomenons that normally lead to disturbed linear propagation of optical beams in matter.