Nonlinear Photonic Structures

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Abstract: In photonics, the investigation of structured nonlinear systems is an active and vivid research area. Their ability to control the dispersion and diffraction properties of light allows tailoring light in its spectral, temporal, and spatial features. Manipulating the spatial features, i.e., overcoming diffraction, is an actual and challenging issue that is of utmost importance for further information processing tasks. With this contribution, we highlight some of the most recent publications in this field. Among others, we discuss the progress in complex photonic lattice generation as well as the guiding and control of discrete spatial solitons—entities that no longer spread during propagation. We also emphasize the importance of photonic lattices as optical analogies to quantum mechanical systems and review current results on Anderson localization of light.

Index Terms: Nonlinear photonics, photonic lattices, band gap structures, spatial solitons, parity-time (PT) symmetry, Anderson localization.

Driven by the increasing requirements for digital information transmission and processing bandwidth, photonics research continuously provides new concepts for the engineering, guiding, or storing of light. In particular, the introduction of an artificial periodicity of the refractive index of a material and thus a structured potential can lead—in analogy to semiconductors—to dramatically modified propagation properties due to the appearance of band gap structures. In this context, many groups have published significant results during the last year, and in this contribution, we will review some of these works that advanced discrete spatial optics considerably.

In the field of artificial materials, photonic crystal structures with their artificial periodicity of the dielectric constant or the refractive index, respectively, and their unique transmission and reflection spectra revealing band gaps provide maybe the most influential concept in order to tailor light propagation. Whereas in the last 15 years special emphasis was set on the control of the spectral features of light, recently, the spatial features of light and its spatial frequencies came into view. By using materials that change their refractive index properties due to light whereupon light itself reacts on the modified material environment, this approach even allows for the control of light by light itself. Nonlinear effects to tailor the refractive index of the material are an indispensable ingredient of the success of this technique. Among them, photorefractive crystals are promising examples and, after illuminating with structured low intensity lattice writing light waves—a technique known as optical induction of photonic lattices [1]—can be used as an ideal model system to demonstrate a multitude of groundbreaking propagation effects [2].

In the course of 2011, several novel strategies have been presented [3] in order to overcome simple lattice geometries like hexagonal lattices studied in these systems so far. Among others, the

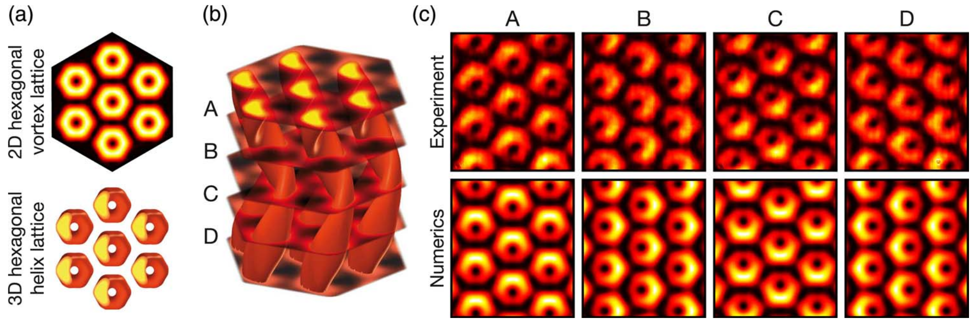

Fig. 1. (a) Intensity distribution of the 2-D hexagonal vortex lattice and top view of the corresponding 3-D helix lattice, (b) plot of the isointensity surfaces of the hexagonal helix lattice at 60% of the maximum intensity, and (c) comparison of experimental (top row) and numerical (bottom row) images for the planes A–D marked in (b).

idea to control the phase relation of different components in the spectrum of discrete nondiffracting beams led us to the demonstration of nondiffracting kagome [4] and graphene lattices [5]. Also, an analysis of nonlinear wave dynamics in the latter ones has been provided [6].

In the same way, the creation of 3-D helical lattices was a challenge for discrete photonics until we found a modification to the optical induction approach and used 2-D vortex lattices as a basis for the first construction of helix lattice waves [7]. Fig. 1 exemplarily illustrates the hexagonal helix lattice and its connection to the corresponding 2-D vortex lattice [7]. The analysis of different planes in the direction of propagation clearly verifies the helical structure of the complex 3-D intensity distribution.

The impressive capabilities of such photonic lattices have been underlined once more by the presentation of a structure allowing for a negative Goos-Hänchen shift [8]. While this application already illustrates the significant influence of structured materials on light and light propagation, the introduction of defects into an otherwise periodic potential adds other important features as an analysis of nonlinear beam deflection in lattices with negative defects shows [9]. In addition, the experimental realization of a true reflectionless potential that facilitates complete transmission for incident beams and, at the same time, supports localized modes is very interesting [10].

In particular, the occurrence of photonic band gaps in periodic structures offers unique possibilities to control the propagation of light. Since the pioneering work by Christodoulides *et al.* on discrete solitons in nonlinear photonic lattices [1], [2], many researchers have developed this field further. An important actual aspect is steering of discrete solitons. In 2011, a concept for positioning these localized structures based on linear defects has been introduced [11]. By dragging the defects, the attached solitons can be moved and positioned. Another work investigated two approaches for the control of soliton refraction in optical lattices [12] and could demonstrate the influence of both shape and position of individual waveguides on the soliton transmission.

Also, the interaction between solitons is of particular interest. Here, we want to highlight the detailed investigation of coupled dark-bright states, including corresponding experimental realizations [13]. The authors show that these two structures can coexist as a solitonic entity. Furthermore, it was demonstrated that two in-phase bright gap solitons—in contrast to solitons in homogeneous media—can repel each other while out-of-phase solitons show mutual attraction [14]. This anomalous interaction of spatial gap solitons in optically induced photonic lattices is also an important result since it emphasizes once more the importance of phase as a control parameter.

In the same sense, discrete vortex solitons being clusters of coupled bright states with distinct phase relations have been discussed for several years. In 2011, we contributed a work showing that surface vortex solitons in the two-beam counterpropagating geometry allow for a stable propagation of such vortex states, and we studied their orbital angular momentum transfer [15]. Configurations showing more than one phase singularity are referred to as multivortex solitons. Recently, researchers from the Australian National University introduced discrete multivortex solitons in a set of nonlinear oscillators and found stable multivortex solitons supporting complex vortex dynamics [16]. They revealed that the vortices in this configuration can show spiraling trajectories or even topological charge flipping providing an all-optical discrete vortex switch [17].

Localization in the temporal domain is an important and actual aspect of photonic lattices as well. Combined with a spatial localization, this leads to the concept of so-called light bullets being nondispersive and nondiffractive at the same time. While this idea has been discussed for years, at the end of 2010 finally a first experimental realization providing 3-D nonlinear light bullets in arrays of coupled waveguides has been published [18]. During 2011, the authors added a detailed discussion about the evolution dynamics of these intriguing entities of light [19].

Moreover, due to formal similarities to quantum mechanical systems, discrete photonic structures also can serve as a versatile platform for the demonstration of optical analogies to quantum mechanical effects like quantum interference [20]. In this scope, currently a lot of interest surrounds questions related to parity-time (PT) symmetry in optics [21]. This property has been analyzed in detail for honeycomb photonic lattices [22] and the authors found a dispersion relation identical to tachyons. Furthermore, solitons were found in PT symmetric nonlinear photonic lattices as well [23]. Utilizing PT symmetry considerations, researchers from the United States presented another particularly interesting structure that acts as a unidirectional invisible medium [24]. In this way, light coming from one side passes the medium completely undisturbed, while light incident from the opposite side is strongly affected.

However, PT symmetry is only one analogy photonic structures can provide. At the beginning of 2011, we presented an experimental study on Pendellösung oscillations and interband Landau-Zener transitions based on resonant coupling between high-symmetry points of 2-D photonic lattices [25]. Also, Rabi oscillations in subwavelength structures have been investigated [26], and anharmonic Bloch oscillations facilitating second-order coupling were observed [27].

All these publications underline the possibilities of discrete optics to visualize important effects and therewith to deepen the understanding in multiple physical areas. This is particularly true for the field of Anderson localization. Since the first experimental observation of light localized in a perturbed periodic lattice [28], many researchers investigated Anderson localization in optical systems and, during 2011, again, multiple intriguing results have been published—among them the finding of localization in porous media [29]. Furthermore, it has been shown that partially coherent waves can experience this localization effect [30].

In this field, we recently contributed, on the one hand, an analysis of Anderson localization near the boundaries of a photonic lattice [31] and, on the other hand, of the crossover from 2-D to 1-D configurations in the linear and the nonlinear regime [32]. Since Anderson localization heavily relies on statistics, the properties of the underlying lattice play an important role. Notably, the introduction of disorder into quasi-periodic lattices was found to enhance wave transport [33], while characteristically, mobility was expected to decrease with increasing disorder.

Another intriguing concept of random structures introduced in 2011 is the idea of amorphous photonic lattices [35]. These materials lack Bragg peaks but, nevertheless, show band gaps and therewith raise many open questions.

All these significant scientific results show that photonics research in general and the investigation of photonic lattice structures in particular is a very active and vivid field. Many researchers from all over the world contribute on a daily basis to the constant progress. Naturally, we could not honor all important contributions of the last year in this short review. However, we hope to stimulate further research in this area contributing to the successful history of nonlinear photonics.

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