Nonlinear Complex Photonic Structures

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ABSTRACT
We introduce a new induction approach based on liquid crystal spatial light modulators that allows generation of arbitrary lattice structures. In this context, we demonstrate formation of complex nondiffracting photonic lattices, structures and superlattices. Our technique additionally enables an intuitive way of randomization, offering the necessary conditions for Anderson localization. We further use the high nonlinear response of these systems to experimentally demonstrate soliton oscillations in a parabolic potential landscape.

Keywords: Nonlinear photonic structures, spatial solitons, nondiffracting beams, photorefractive effect, holographic multiplexing.

1. INTRODUCTION

Due to their technological importance, artificial photonic crystals with their unique transmission and reflection spectra have become a very active topic of research. Typically, photonic crystals are realized by recent 3D structuring techniques on nano scale. However, light itself can be highly useful to structure materials artificially. Materials that change their properties due to nonlinear light-matter interaction provide the necessary link in order to control and guide light by light itself. In particular, the optical induction of photonic lattices in photorefractive materials allows achieving highly reconfigurable refractive index distributions [1]. They have been utilized to demonstrate intriguing linear as well as nonlinear effects [2], *e.g.* discrete and vortex spatial solitons as well as Bloch oscillation, Zener tunnelling, or Anderson localization [3].

While up to now only rather simple lattice geometries have been studied, we introduce a new induction approach based on liquid crystal spatial light modulators that allows generation of arbitrary lattice structures. In this context, we demonstrate formation of complex nondiffracting photonic lattices, structures and superlattices. Our technique additionally enables an intuitive way of randomization, offering the necessary conditions for Anderson localization. We further used the high nonlinear response of these systems to experimentally demonstrate soliton oscillation in a parabolic potential landscape.

2. NONDIFFRACTING BEAMS FOR OPTICAL INDUCTION

In order to optically induce two-dimensional refractive index modulations, we employ so-called nondiffracting beams [4] where the transverse intensity distribution is modulated while the distribution in direction of propagation is constant. Manipulating the ring shaped spatial spectrum of a nondiffracting beam, the choice of the field distribution recovers a useful tool to extend the gallery of intensity modulations with respect to coherent interference. Depending on the underlying coordinate system, the structural variety reaches from periodic (square, hexagonal symmetry: Graphene-like, kagome patterns) over quasi-periodic (Penrose structure) to curvilinear modulations, including Bessel, Mathieu and Weber beams [5,6].

To experimentally implement these particular field distributions we employ highly dynamic LCOS based spatial light modulators. In this manner, specifically designed diffraction patterns based on numerical field calculations of the respective nondiffracting beams allow for the generation of corresponding light fields in a volume of interest where a properly positioned photorefractive crystal enables the next step. That is, via the photorefractive effect the medium converts incoming intensity distributions into corresponding local refractive index changes. In this manner, longitudinally elongated photonic patterns covering a huge structural variety are feasible via optical induction [7]. These photonic patterns can show nonlinear response, even at very low power rates.

3. OSCILLATING WEBER SOLITON

Particularly, the Weber nondiffracting beam [6] exhibits a curvilinear transverse intensity distribution which is quadratically modulated along each parabola and is expected to feature transverse acceleration. Using this particular two-dimensional beam, the resulting optically induced potential for a fundamental soliton mimics the shape of a square potential for a bound particle well. Thus, we expect to observe oscillating soliton dynamics.

In our contribution, we show that a fundamental soliton with an additional transverse momentum follows an oscillating trajectory around the potential minimum as predicted numerically by Kartashov *et al*. [8]. This is the first experimental observation of stable spatial soliton oscillations in photonic potentials. We induce a photonic Weber structure in a photorefractive SBN crystal and demonstrate the existence and stability of the fundamental

978-1-4799-0683-3/13/$31.00 ©2013 IEEE

soliton in this photonic structure. Since a transverse phase gradient leads to a soliton oscillation with respect to the propagation distance, we also investigate the dynamics by recording the transverse position of the soliton for different propagation lengths. Figure 1 presents the intensity (a) and the phase distribution (b) of a nondiffracting Weber beam. The corresponding refractive index modulation is shown in Fig. (c), offering oscillating dynamics of a spatial soliton, as illustrated in Fig. 1(d).

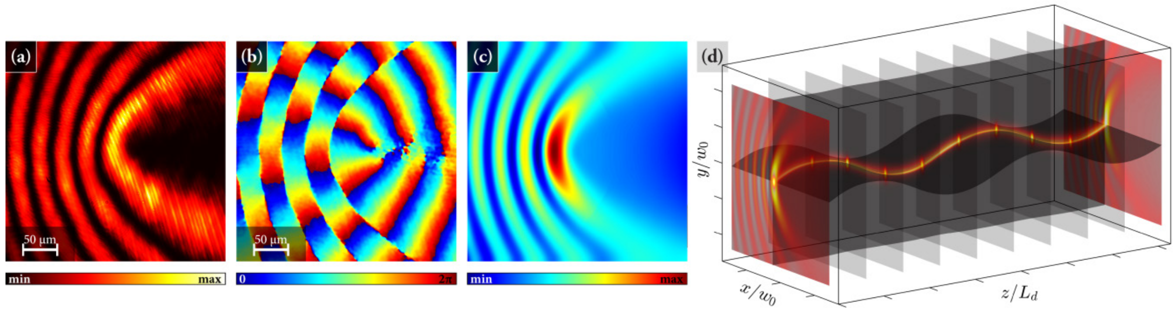

Figure 1. The photonic Weber lattice. (a) Experimentally realized intensity and (b) phase distribution of the nondiffracting beam. (c) Simulated induced refractive index modulation. (d) 3d numerical simulation of the oscillating soliton in the photonic Weber lattice.

The presented results indicate that the field of the spatio-temporal soliton dynamics in photonic structures still holds many fascinating new results of general interest for the soliton community which can be further investigated by using the flexibility provided by the presented experimental methods.

4. RANDOMIZED PATTERNS AND ANDERSON LOCALIZATION

As one of the most fascinating effects in solid state physics, Anderson localization (AL) [8] specifies an increased probability of a wave function in a randomly affected potential to be localized in the vicinity of its initial position. This effect was primarily predicted for electron waves in condensed matter. However, since the effect generally bases on wave phenomena, AL also occurs in various systems and has been discovered for waves differing from electron wave fields in several 1D or 2D systems. A randomized field distribution of the spatial spectrum is an eligible way to achieve nondiffracting wave fields with fully disordered intensity modulations in real space.

In this regard, we present our recent results on experimental realizations of two-dimensional Anderson Localization in an optically induced randomized photonic structure.

We suggest an advancement of the method to generate complex photonic systems via optical induction in photorefractive materials with respect to the first demonstration of AL in photonic lattices [3] implementing for the first time complex and statistical nondiffracting beams [7]. Designing the ring-shaped Fourier spectrum of a nondiffracting beam randomly, the structural size – the *photonic grain size* – becomes a control parameter that can be adapted in an intuitive way. In combination with nondiffracting beams of regular symmetries such as periodic, quasi-periodic as well as curvilinear transverse intensity modulations, we developed a tool to reversibly induce complex photonic refractive index landscapes of various shapes and degrees of randomness. Figure 2(a) shows a randomized intensity distribution of a particular nondiffracting writing beam, which can be translated into a refractive index modulation via the photorefractive effect. In Fig. 2(b), a randomized diamond potential is shown, leading to transverse localization. It is compared to discrete diffraction in a periodic diamond lattice [cf. Fig. 2(c)]. In detail, Fig. 2(d) presents a logarithmic plot of the intensity profiles through the localization center, depicting the fundamental difference between propagation in periodic media with and without disorder, respectively.

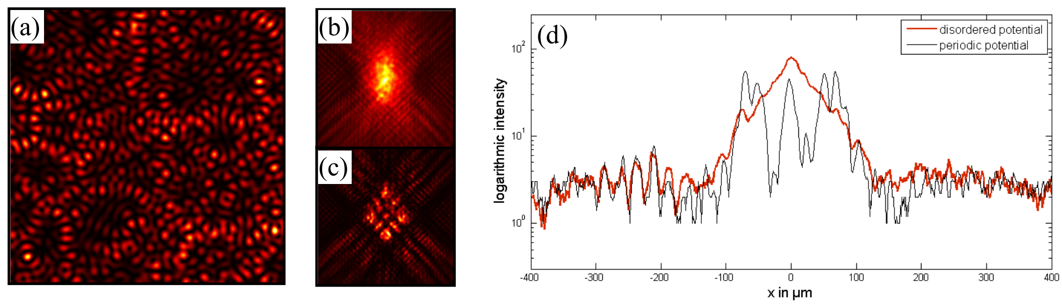

Figure 2. Anderson localization in optically induced refractive index potentials. (a) random 2D intensity distribution of nondiffracting writing beam; transmission for (b) disordered and (c) periodic diamond patterns averaged over many realizations, (d) central intensity profiles of the averaged probe beam in periodic and disordered potentials.

The presented technique paves the way for the investigation of light localization at the interface between index modulation and homogeneity as well as at defect sites under the influence of randomization as it has recently been investigated theoretically [10]. Moreover, it proves the high flexibility of our experimental approach and illustrates the universal nature of Anderson localization.

5. PHOTONIC MULTIPERIODIC AND DEFECT STRUCTURES

The generation of multiperiodic structures is highly desirable since remarkable optical as well as nonlinear effects in analogy to quantum mechanics may evolve in these systems, for instance Klein tunneling or Zitterbewegung [11,12]. However, the optical induction of multi-periodic structures is still challenging, as lattice beams showing multiple transverse wave vectors are inherently modulated in the direction of propagation. Moreover, no convincing general concept to optically induce lattices holding local defects has been introduced up to now, even though defect bearing structures are one of the most intriguing topics in the regime of nonlinear photonic systems. In this context, new states of light confinement and localization appear in the linear as well as nonlinear regime of light propagation in defect photonic structures [13].

As a general concept, we extract a specific set of parameters for the creation of such a structure from computational simulations by summing up individually weighted refractive index changes corresponding to 2D intensity distributions. To generate these superstructures experimentally [14], we combine the so-called incremental multiplexing technique established in the field of holographic data storage and the optical induction via nondiffracting beams. In Fig. 3, results of an induced 2D photonic ratchet present a successful multiplexing procedure where the field distribution of a plane probe wave significantly indicates the ratchet characteristic.

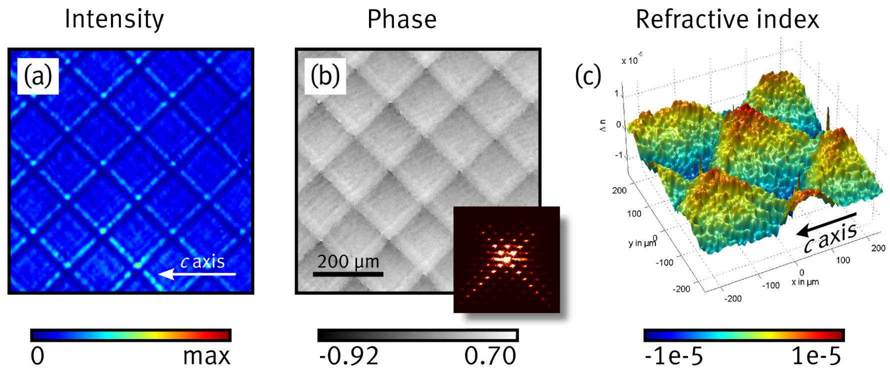

Figure 3. Experimental results of 2D photonic ratchet structure. (a) Intensity, (b) phase distribution of the plane probe wave in real space. Inset of (b) illustrates far field diffraction spectrum. (c) Refractive index landscape in 2D ratchet shape [14].

6. CONCLUSION

We presented numerous results regarding the optical induction of complex photonic structures in a photorefractive crystal. A large selection of diverse writing beams combined with several techniques enables us to generate photonic structures in most diverging shapes, ranging from periodic and quasi-periodic, to curvilinear as well as multiperiodic characteristics, such as two-dimensional ratchet structures.

Developing a highly sophisticated experimental setup, we could demonstrate so far unexploited oscillating dynamics of a soliton in a parabolic potential landscape. Additionally, by introducing a randomized writing beam, we are able to disturb any regular pattern in order to initiate Anderson localization.

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