Photonic ratchet superlattices by optical multiplexing

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We present a method based on incremental holographic multiplexing to create a refractive index ratchet distribution into a photorefractive crystal as an example for the generation principle of such complex multiperiodic lattices. The implemented technique follows a finite optical series expansion of the desired index modulation. To analyze the induced lattice, we determine the phase retardation of a probe beam at the back face of the crystal by digital holography analysis. Our result depicts a first example to optically explore the fascinating phenomena of ratchet resembling systems.

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The optical induction process features a highly promising technique to reversibly generate photonic lattices [1–3], used to excite intriguing effects in the linear or nonlinear regime, such as Bloch oscillation and Zener tunneling or Anderson localization, as well as localized structures and vortex solitons [4–6]. One demand for this method is a properly formed lattice beam that includes all the characteristics of the desired refractive index structure. Hence, to develop two-dimensional (2D) photonic lattices, the need for a transversely modulated periodic or quasiperiodic but longitudinally translation invariant intensity distribution has to be satisfied. In recent years, nondiffracting light fields [7,8] performed the role of the perfect induction beam in experiments [9]. A huge lineup of nondiffracting beams exhibiting an enormous structural variety of transverse periodic and quasiperiodic patterning was discovered and experimentally implemented [10,11]. Despite this multitude of variance—and proper coherent superpositions extend that lineup additionally—there is still a limitation of the structural variety, especially in terms of multiperiodicity. Furthermore, the investigation of arbitrary nondiffracting beams [12,13] does not yet provide a satisfying implementation due to a limited transverse resolution and an insufficient longitudinal stability of the intensity patterns. Hence it is still challenging to optically induce multiperiodic structures in photorefractive media employing one lattice inducing beam. But precisely these multiperiodic systems feature fascinating optical phenomena due to beneficial band structures, for instance, effects in analogy to quantum mechanics such as Klein tunneling [14] or photonic Zitterbewegung [15,16].

The most intuitive way to design structures with a multiperiodicity is to superimpose specific periodic patterns that in a summation resemble the intended pattern. In this Letter, we suggest a method of optical photonic lattice induction that is derived from the incremental multiplexing technique (IMT). This technique is well-known in the field of optical data storage [17] and enables the optical induction of variously designed multiperiodic photonic structures as well as lattice crossovers. Representatively, we show the optical induction of a one-dimensionally (1D) modulated refractive index ratchet lattice via IMT. These highly regarded functional structures find intriguing applications in research fields such as biological microscopic machinery and Bose–Einstein condensation [18], as well as quantum mechanics in solid-state or atomic physics systems [19], due to their ability for long-distance mass transport caused by a low-amplitude potential.

The development of a ratchet structure can be interpreted as an optical series expansion implemented via IMT. In this way, 1D modulated nondiffracting wave fields are employed as lattice inducing beams of similar transverse structure but varying structural size for each expansion term. Hence, we optically implement a Fourier series expansion of a ratchet function f_r to the tenth expansion order according to the formula

$$f_r(x) = \sum_{j=1}^{10} (-1)^{j-1} \frac{\sin(2\pi jx/g_1)}{j}, \qquad (1)$$

where g_1 is the lattice period of the first order term and x is the direction of the 1D modulation. In Fig. 1(a), the transverse intensity patterns of the 1D lattice beams for one expansion sequence are depicted. The procedure resembles a summation of all intensity terms as shown in Fig. 1(b).

As the structurally various transverse intensity patterns of nondiffracting beams are generally a consequence of complexly interfering partial waves, the need for a coherent light source is essential for the lattice beam formation. On the other hand, coherence constricts a simple (incoherent) summation of intensities of different light fields and leads to phase sensitive modulations as well as to undesired interference. Consequently, the single lattice beams have to contribute in an incoherent manner, which can, for instance, be accomplished by a successive illumination of a photosensitive material in order to locally structure the refractive index. This idea was implemented formerly [17,20] using volume hologram multiplexing techniques to enhance the amount of optically stored data per volume, for instance by angular or phase-coded multiplexing [21]. Employing a photorefractive material, exactly IMT denotes an overlay of several

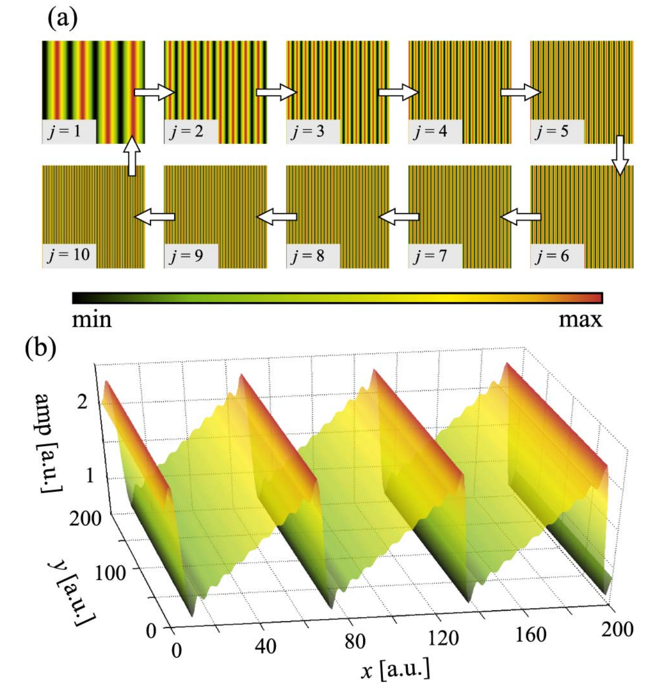

Fig. 1. (Color online) (a) Illumination sequence consisting of 10 cosine lattice beams with harmonic intensity modulation periods. (b) Pseudo-3D surface plot of the simulated intensity summation of all involved lattice beams forming a 1D ratchet distribution.

index gratings and was already applied to build up double-periodic photonic lattices showing two different Bragg angles [22]. Following this approach, we consecutively illuminate an externally biased photorefractive cerium-doped strontium barium niobate (SBN) crystal of dimensions $15 \times 5 \times 5$ mm^3 with the set of 10 lattice beams, each for a particular illumination time τ_j, where j denotes the jth beam according to the jth expansion term [cf. Fig. 1(a)]. The illumination time τ_j corresponds to the weighting of each expansion term of the series. For IMT the precondition $\tau_j \ll T_\mathrm{e}^\mathrm{w}$ has to be fulfilled [20], where T_w and T_e are the respective writing and erasure time constants, which are of the order of tens of minutes for the used SBN crystal. While each particular lattice representing one of the expansion terms is written, the residual lattices get exponentially erased; thus the refractive index change due to writing (Δn_w) or erasure (Δn_e) develops as

$$\Delta n_\mathrm{w}(t) = \Delta n_\mathrm{sat}[1 - \exp\,(-t/T_\mathrm{w})],$$
$$\Delta n_\mathrm{e}(t) = \Delta n_0 \exp\,(-t/T_\mathrm{e}). \quad (2)$$

In Eq. (2) Δn_sat denotes the maximal change of refractive index and $\Delta n_0 = \Delta n(t = 0)$. After various repetitions of the illumination sequence $j = 1, 2, 3\ldots$, the refractive index holds a spatial modulation including the summation of the intensities of the used lattice beams according to the particular weighting relations.

To implement a refractive index ratchet via IMT, we employ a setup according to the schematic illustrated in Fig. 2. An expanded continuous-wave solid-state laser

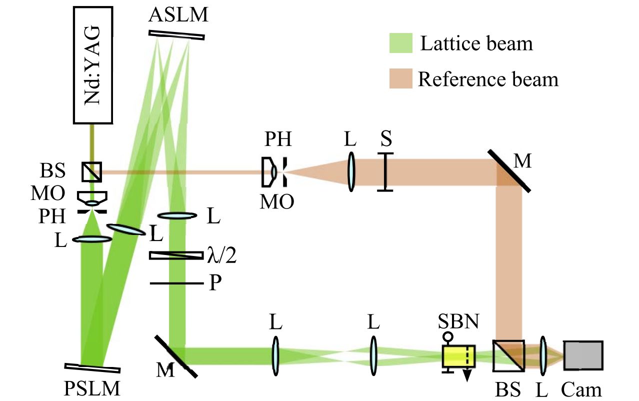

Fig. 2. (Color online) Setup of the presented method of IMT. ASLM: amplitude spatial light modulator, BS: beam splitter, Cam: camera, L: lens, $\lambda/2$: phase retardation plate, M: mirror, MO: microscope objective, P: polarizer, PH: pinhole, PSLM: phase spatial light modulator, S: shutter, SBN: Cer-doped strontium barium niobate crystal.

beam with wavelength $\lambda = 532$ nm is phase modulated by a computer controlled spatial light modulator (PSLM). The phase pattern given to the PSLM and the displayed pattern of the following amplitude modulator for spatial frequency filtering (ASLM) are chosen to implement particular nondiffracting beams according to the certain expansion terms. The PSLM is additionally used as a shutter with a sufficient high temporal resolution of a few microseconds. An external field of 1.6 kV/cm is applied to the SBN crystal parallel to the c-axis, and the propagation direction of the lattice beam is along the $d_z = 5$ mm crystal direction perpendicular to the c-axis. To encounter a small electro-optic coefficient and to avoid an interaction between refractive index change and index-changing beam, the lattice-writing beams are polarized perpendicular to the c-axis (ordinary polarization). The lattice period of the first grating is $g_1 = 150$ μm, which is also the length of the ratchet period. In general, limiting factors of the ratchet period are the pixel pitch of the PSLM, the magnification factor of the imaging optics, and the number of multiplexed expansion terms. For our setup and the specific realization of 10 expansion terms, the smallest possible lattice period is approximately 12 μm. To undergo these limitations, systems including strongly focusing microscope objectives are one simple approach. In turn, smaller grating periods effect a reduced longitudinal elongation of the nondiffracting beam area.

We further fix the net illumination duration of all terms to $\sum_{j=1}^{10} \tau_1/j = 20$ s. Hence, the duration of the first term results in $\tau_1 = 6.83$ s and each illumination time is given by $\tau_j = \tau_1/j$. To probe the induced structure, we send an extraordinarily polarized plane wave through the index-structured crystal and superimpose it with an equally polarized but tilted reference beam. In this manner, a digital hologram of both interfering waves is recorded via imaging lenses and a camera. Subsequently, the hologram is numerically analyzed receiving the transverse phase and amplitude information at the back face of the crystal pervaded by the wave field [23]. Similarly, we measured the transverse spatial phase of the probing wave propagating through the medium of homogeneously distributed refractive index. By subtracting these data from the results

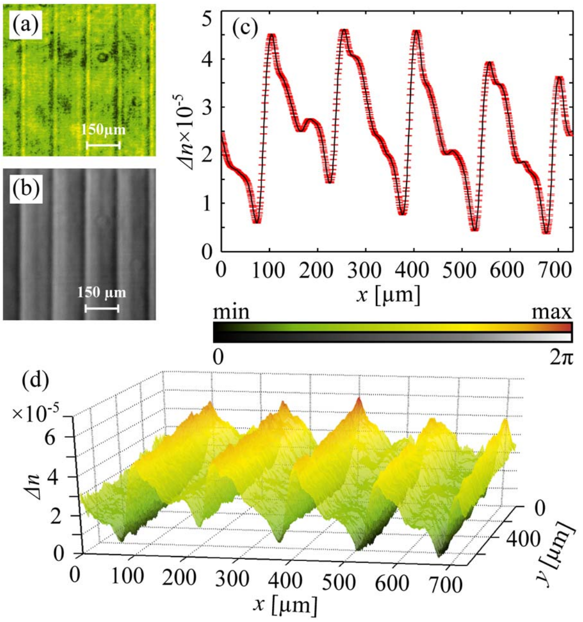

Fig. 3. (Color online) Analysis of a ratchet lattice induced by IMT. (a) Intensity, (b) corrected phase, (c) refractive index change determined by the average of all lines in (b) and statistical error, (d) pseudo-3D surface plot of refractive index change.

of the induced ratchet, we estimated a corrected phase distribution to get information solely about the phase retardation effected by the multiperiodic index structure.

The result of the incremental multiplexing process is shown in Fig. 3. Intensity and phase distributions of a guided plane wave are depicted in Fig. 3(a) and (b), respectively. Especially the spatial phase shown in Fig. 3(b) resembles the aspired refractive index structure, verifying a succeeded induction process of the 1D refractive index ratchet distribution. Taking the corrected phase into account, the refractive index change Δn can be determined by $\Delta n = \lambda\Delta\varphi/(2\pi d_z)$. Hence, exploiting the result of $\Delta\varphi$, Fig. 3(c) shows the plot of the mean and error of the refractive index change, calculated by averaging over all lines of $\Delta\varphi$ [cf. Fig. 3(b)]. To present the 2D index distribution more descriptively, Fig. 3(d) depicts a pseudo-3D surface plot of Δn originating from the measurements of $\Delta\varphi$ at the back face of the SBN crystal.

In conclusion, we presented the optical induction of a 1D refractive index ratchet distribution into a photorefractive SBN crystal by implementing the IMT and demonstrated the analysis of the index modulation emerging from phase measurements via digital holography techniques. Our results prove a high functionality of this multiplexing technique to induce multiperiodic photonic structures. Moreover, the presented generation of a photonic ratchet structure opens up the attractive opportunity to experimentally study impressive photonic phenomena in analogy to different physical systems resembling ratchet characteristics.

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