Three-dimensional optically induced reconfigurable photorefractive nonlinear photonic lattices

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We experimentally investigate the formation of reconfigurable three-dimensional (3D) nonlinear photonic lattices in an externally biased cerium doped strontium barium niobate photorefractive crystal by a spatial light modulator-assisted versatile simplified single step optical induction approach. The analysis of the generated 3D nonlinear photonic lattices by plane wave guiding, momentum space spectroscopy, and far field diffraction pattern imaging is presented, which points to the embedded potential of these 3D structures as reconfigurable platform to investigate advanced nonlinear light-matter interaction in periodic structures.

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Envisaging a wide range of potential photonic applications, a great deal of research and investigations are prevalent in the design, fabrication, and optimization of various three-dimensional (3D) photonic crystal structures, which are characterized by the modulation of refractive index along all three dimensions [1]. Nonlinear photonic lattices formed by a periodic modulation of the refractive index in nonlinear optical media are subject of active research owing to their versatile promising applications [2–4]. In view of fascinating nonlinear effects such as discrete spatio-temporal solitons and quantum tunneling, based on the interplay of nonlinearity and various lattice geometries as well as periodicities, different approaches are adapted to form two-dimensional (2D) photonic lattices, most often in nonlinear photorefractive media [2–8]. However, 3D reconfigurable photorefractive photonic structures that are able to show advanced nonlinear features such as slow and stopped light have not yet been realized (to our knowledge). In this Letter, we report what we believe to be the first time demonstration of the fabrication and analysis of well-defined reconfigurable 3D photorefractive nonlinear photonic lattices in externally biased cerium doped strontium barium niobate (SBN:Ce) photorefractive material by a spatial light modulator (SLM)-assisted versatile single step optical induction approach by means of computer engineered phase patterns.

It has been shown that, by the interference of multiple beams as well as by the multiple exposure of two beam interference, all fourteen 3D Bravais lattices can be generated [9,10]. Unlike conventional multiple beam interference, where a complicated optical setup needs to be implemented, recently, the actual techniques make use of the discrete diffractive optical elements, the single prism based approach, or the spatial light modulator assisted approach [11–13]. Taking advantage of the wavelength sensitivity of a particular photorefractive medium, optically induced photonic lattices can be generated at very low power levels. Making use of the versatility of programmable SLM [8,13,14], based on computer-generated reconfigurable phase engineered patterns, we have simplified the conventional multiple beam interference technique for 3D photonic structures. The computer engineered phase pattern, representing the phase information extracted from the overall complex amplitude of the irradiation profile of the interference pattern for a particular 3D photonic lattice structure, is sent to a programmable phase-only SLM. This phase engineered pattern spatially modulates a plane-wave incident on the SLM, generating the required lattice-forming beams. Various 3D lattice-forming geometries for different reconfigurable 3D periodic lattices with variable periodicity are experimentally investigated in real time by this versatile approach. To exploit the full potential of the approach, the experimental realization of 3D hexagonal photonic lattices through our SLM-assisted optical induction approach is presented, where the lattice beam geometry consists of a normally incident central beam surrounded by angularly displaced six side beams. The irradiance profile of seven plane-waves interference is given by

$$\mathbf{I}(\mathbf{r}) = \sum_{j=1}^{7} |\mathbf{E}_j|^2 + \sum_{i\neq j}^{7} \mathbf{E}_i \cdot \mathbf{E}_j \exp[\mathrm{i}(\mathbf{k}_i - \mathbf{k}_j)\cdot \mathbf{r} + \mathrm{i}\psi_{ij}], \quad (1)$$

where $\mathbf{E}_j$, $\mathbf{k}_i$, $\mathbf{r}$, and ψ_{ij} are the complex amplitudes, the wave vectors, position vector, and the initial phase of the interfering beams, respectively. The interfering beams are linearly polarized in the direction relative to the *c* axis of the recording photorefractive medium oriented as per the lattice orientation requirement. The wave vectors of the side beams could be given by

$$\mathbf{k}_m = k[\cos(q_m\pi)\sin\theta_i, \sin(q_m\pi)\sin\theta_i, \cos\theta_i], \quad (2)$$

where $q_m=2(m-1)/6$, m is from 1 to 6, and $k=2\pi n_{\mathrm{eff}}/\lambda$. Considering SBN:Ce, for an extra ordinarily polarized (*e*-polarized) wave, $n_{\mathrm{eff}}^2=n_e^2-n_e^4 r_{33}E_{\mathrm{sc}}$ is the effective refractive index of the medium experienced by it, whereas for an ordinarily polarized

(o-polarized) wave the refractive index n_e and electro-optic coefficient r_{33} will be, respectively, replaced with n_o and r_{13} [6]. The angle between the central beam and the side beams is given by θ_i and λ is their wavelength. For the simulations $\theta = 12°$ is taken, which is experimentally variable as per the lattice geometry and periodicity requirement, by means of lattice wave demagnification-optics as well as by engineering the modulating phase pattern, within the span of available pixel resolution of SLM. E_{sc} is the space charge field under the influence of optical field from light intensity distribution and the electric field from externally applied bias voltage [5–8]. Figure 1(a) gives the simulated three-dimensional intensity distribution of the interference pattern. Phase engineered pattern for forming hexagonal lattice seven-beam geometry is given in Fig. 1(d).

The schematic representation of the experimental setup is shown in Fig. 2. A linearly polarized beam at $\lambda = 532$ nm wavelength, derived from a frequency-doubled Nd:YAG laser, is spatially phase modulated using a high resolution programmable SLM, giving rise to the required lattice-forming wave, which is imaged to the input face of 5-mm-long photorefractive $Sr_{0.60}Ba_{0.40}Nb_2O_6$ (SBN:Ce) crystal using a high-NA telescope. SBN:Ce is biased by an externally applied electric field of 1.5 kV cm^{-1}. Beam path A in Fig. 2 is used for the recording and analysis of the photonic lattices whereas beam path B is used only for momentum space spectroscopic analysis [8,14,15]. We experimentally investigated 3D lattice formation using o-polarized as well as e-polarized lattice wave. Taking the beams all together, the power of the lattice wave was ~40 μW. In the case of e-polarized wave, lattice-forming beams themselves are affected by the refractive index modulation induced by them and so they experience nonlinear effects also during lattice formation [6,8].

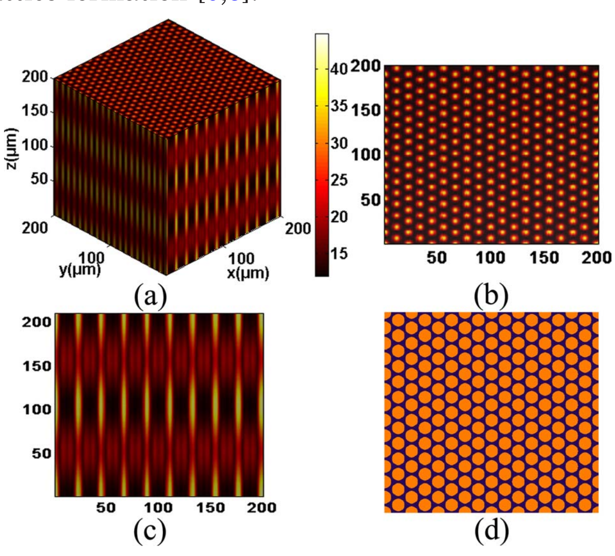

Fig. 1. (Color online) (a)–(c) Computer simulation of the light intensity distribution by the interference of lattice-forming beams. (a) 3D interference pattern formed by seven-beam configuration. (b), (c) Light intensity distribution, respectively, in the x-y and x-z planes. (d) Computed phase engineered pattern to generate seven lattice-forming beams.

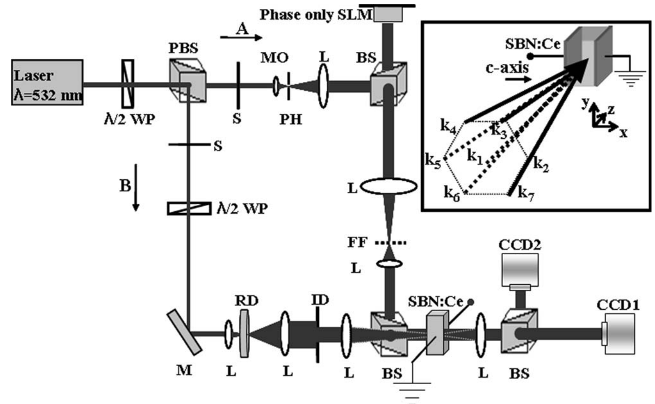

Fig. 2. Schematic representation of experimental scheme for the generation and analysis of 3D nonlinear photonic lattices in an externally biased SBN:Ce. PBS, polarizing beam splitter; S, shutter; MO, microscope objective; PH, pin-hole; L, lens; BS, beam splitter; FF, Fourier filter; M, mirror; RD, rotating diffuser; ID, iris diaphragm. Beam-launching scheme is given in inset.

Three different experimental tools are used to analyze the 3D nonlinear photonic lattices, giving full insight into the 3D nature of the lattice. First, the generated photonic lattices are probed by means of an e-polarized broad plane wave (~1:10 in comparison to lattice wave intensity) [5,8,14]. Figures 3(a)–3(d) give the images of guided wave intensity acquired using CCD1, qualitatively mapping the refractive index modulation induced by the lattice-forming wave and effectively imaging the photonic lattice in that direction. The x-y (0001) plane of the generated hexagonal photonic lattice structure had a lattice period of ~14 μm and in transverse direction the lattice period

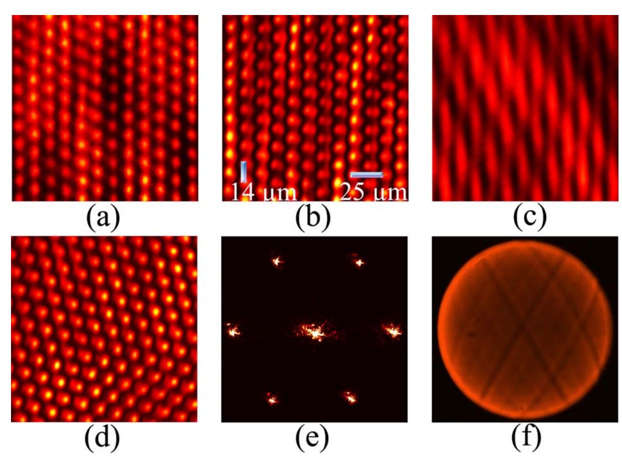

Fig. 3. (Color online) 3D nonlinear photonic lattices in self-focusing photorefractive media. (a) x-y plane of the photonic lattice formed by o-polarized lattice wave. (b), (c) Image of photonic lattice formed by e-polarized lattice wave respectively in the same direction as in (a) and perpendicular to it. (d) x-y plane of the photonic lattice using lattice wave generated by rotating the phase pattern by an angle 45° about z axis in comparison to (b). (e) Far-field diffraction pattern of photonic lattice in (a) imaged using CCD camera. (f) Momentum space spectroscopic image of 3D photonic lattice generated by o-polarized lattice wave rotated by 90° about z axis with respect to the crystal c axis, as compared to photonic lattice image of (a).

is measured to be ~25 μm. To ensure the 3D lattice formation, the image of the *x*-*z* plane, which is perpendicular to the (0001) plane, is also taken after rotating the crystal by 90°.

Second, an important experimental tool used for the analysis of 3D photonic lattices is momentum space (*k*-space) spectroscopy. In line with the structural analysis of 2D photonic lattices formed by coplanar beams, through mapping the Bragg reflection planes in momentum space [8,14,15], we extended this technique to the analysis of full 3D structures induced by noncoplanar lattice-forming beams. CCD2 was kept at the focal plane of the output lens, capturing the image at the Fourier plane. The *k*-space mapping serves as a very simple but efficient tool giving vital information about the generated photorefractive 3D lattices in terms of their structure, orientation, and its anisotropic nature as depicted in Fig. 3(f). Because of the orientation anisotropy of SBN:Ce, the horizontal dark lines relative to the direction of the crystal *c* axis are missing in the images, as observed also in 2D Brillouin-zone spectroscopy [8,14].

Finally, the far-field diffraction pattern [12] of 3D lattice was imaged (Fig. 4) using a digital camera, while the lattice was illuminated by a plane wave. The diffraction patterns in both directions again substantiate the 3D photonic lattice formation inside the photorefractive media. Further, the nonlinear beam coupling from the central beam to the side beam in the direction parallel to the crystal *c* axis, along which the external field is applied [16], which is taken place during the lattice formation, is also prominently visible (diffracted side beam with higher intensity) in the far-field diffraction pattern of the photonic lattices formed by *e*-polarized lattice wave.

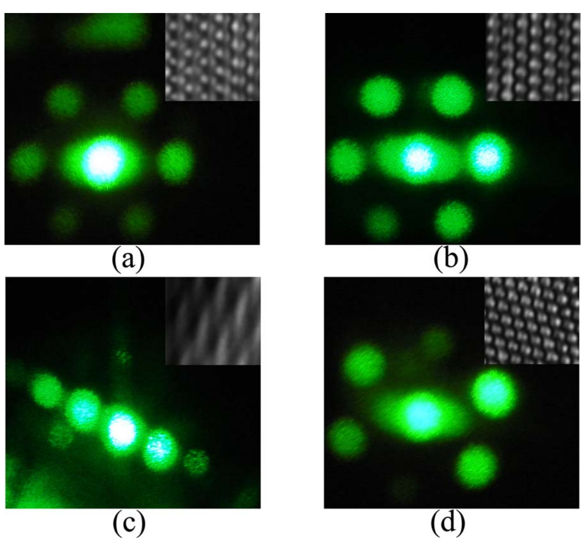

Fig. 4. (Color online) Far-field diffraction patterns of generated photonic lattices (respective lattices in inset). (a), (b) *x*-*y* plane of photonic lattices formed by *o*-polarized lattice wave and *e*-polarized lattice wave, respectively. (c) *x*-*z* plane of photonic lattice formed by *e*-polarized lattice wave. (d) *x*-*y* plane of the photonic lattice using lattice wave generated by rotating the phase pattern by an angle 45° about *z* axis in comparison to (b).

In conclusion, we have experimentally demonstrated for the first time (to our knowledge) [17] the generation of well-defined reconfigurable 3D photorefractive nonlinear photonic lattices in an externally biased SBN:Ce crystal by an SLM-assisted versatile simplified single-step optical induction approach. The formation of these 3D nonlinear photonic lattices in photorefractive media is analyzed and verified using various experimental tools. The experimental investigation of these 3D photonic structures focuses to their embedded potential as reconfigurable platform in the field of advanced nonlinear light-matter interaction in periodic structures.

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