Demonstration of Optically Controlled Beam Steering in Dynamic Photonic Lattices

Christian R. Rosberg, Ivan L. Garanovich, Andrey A. Sukhorukov, Dragomir N. Neshev, Wieslaw Krolikowski, and Yuri S. Kivshar
Nonlinear Physics Centre and Laser Physics Centre,
Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS),
Research School of Physical Sciences and Engineering
Australian National University, ACT 0200 Canberra, Australia
Home page: http://www.rsphysse.anu.edu.au/nonlinear
E-mail: crr124@rsphysse.anu.edu.au

We demonstrate experimentally all-optical beam steering in modulated photonic lattices produced by three wave interference in photorefractive crystals. We show that high spatial resolution can be achieved by combining dynamic beam steering with nonlinear self-localization.

OCIS codes: 190.4420; 190.5940; 060.1810

Optically-induced photonic lattices[1] represent a powerful tool for studies of fundamental properties of nonlinear light propagation in periodic structures[2,3]. The generic advantage of the optical induction technique is the possibility to create reconfigurable and tunable structures in real time. One-dimensional optical lattices created by *two* interfering beams are inherently symmetric in the transverse direction (x) and invariant in the propagation direction (z). By introducing a third interfering wave in the (x, z) plane which breaks the symmetry and induces lattice modulation along both x and z [see Fig. 1(a) and (b)], it is possible to achieve controlled steering and switching of nonlinearly localized beams, as recently suggested theoretically[4,5].

In this work, we present the first experimental demonstration of optically controlled beam steering in dynamically modulated lattices, and show that nonlinear beam self-focusing allows to compensate for diffraction and increase the spatial resolution for practical applications. We use a modulated lattice created in a biased photorefractive SBN crystal by *three* interfering plane waves [Figs. 1(a-c)] and study an experimentally accessible case of moderate lattice strength and modulation, where a nonlinear self-localized probe beam extends over a few lattice sites.

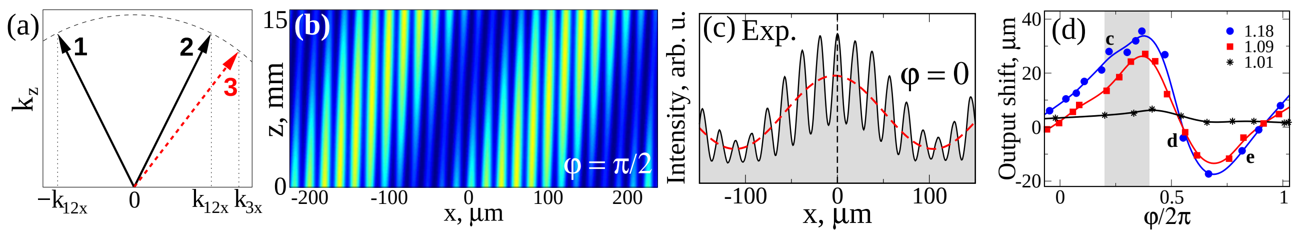

Fig. 1. (a) Schematic of the k-vector configuration in a modulated optical lattice. Beams 1 and 2 define a straight lattice, while the symmetry breaking control beam 3 introduces transverse (x) and longitudinal (z) lattice modulation as shown in (b) for $k_{3x} = 1.18k_{12x}$ and relative phase $\varphi = \pi/2$. Probe beam input position is $(x, z) = (0, 0)$. (c) Experimental transverse optical lattice intensity profile at $z = 0$ for $\varphi = 0$. (d) Measured shift of linear probe beam output vs. φ for three different values of k_{3x}/k_{12x}. Shading marks the region with maximized figure of merit. The control beam power is $I_3 = 4I_{12}$.

The interference pattern of the three lattice-writing plane waves is defined as $I_p(x, z) = |A_L|^2$, where $A_L = A_3 \exp[i\beta_3 z + ik_{3x}x - i\varphi] + 2A_{12}\exp(i\beta_{12}z)\cos(k_{12x}x)$, and the x and z coordinates are normalized to the characteristic scales x_s and z_s, respectively. φ is the relative phase between the third wave and the other two waves, and the propagation constants $\beta_j = Dk_j^2$ define the longitudinal wavevector components. Here $D = z_s\lambda/(4\pi n_0 x_s^2)$ is the diffraction coefficient, n_0 is the average refractive index of the medium, and λ is the wavelength in vacuum. Figure 1(b) shows an example of such a modulated lattice. Changing the phase of the third beam φ causes the lattice pattern to shift in both transverse [cf. Fig 1(c)] and longitudinal directions. The lattice also depends on the inclination angle and power of the third beam, characterized by the parameters k_{3x}/k_{12x}, and I_3/I_{12}, where $I_3 = |A_3|^2$ and $I_{12} = |A_{12}|^2$.

We model the propagation of an extraordinarily-polarized probe beam by a parabolic equation for the normalized beam envelope $E(x, z)$, $i\partial E/\partial z + D\partial^2 E/\partial x^2 + \mathcal{F}(x, z, |E|^2)E = 0$, where the function $\mathcal{F}$ is proportional to the optically-induced change of refractive index. Due to the strong electro-optic anisotropy of the SBN crystal, this term almost vanishes for the lattice-writing beams polarized orthogonal to the c-axis of the crystal because of the very small effective nonlinear coefficient. The extraordinarily-polarized probe beam, on the other hand, experiences a high nonlinearity with $\mathcal{F}(x, z, |E|^2) = -\gamma(I_b + I_p(x, z) + |E|^2)^{-1}$, where I_b is the constant dark irradiance, $I_p(x, z)$ is the lattice interference pattern, and γ is a nonlinear coefficient proportional to the applied DC field. To match our experiments, we use $\lambda = 0.532\mu$m, $n_0 = 2.35$, $x_s = 1\mu$m, $z_s = 1$mm, $I_b = 1$, $\gamma = 2.36$, and $d = 20.0\mu$m is the period of the non-modulated lattice (for $A_3 = 0$). The crystal length is $L = 15$mm. In experiment, a Gaussian probe beam with a full width at half maximum (FWHM) of 25μm (along the x direction and extended in y) is launched into the crystal, parallel to the z axis ($k_x = 0$). The front and back faces of the crystal are imaged onto a CCD camera to capture the probe beam intensity distributions. A second imaging system is used to monitor the input position of lattice fringes and probe beam, the latter of which is fixed at $x = 0$.

First, we characterize the effect of the modulated lattice geometry on the propagation of a low-power ($\sim 25nW$) probe beam (linear regime) for three different angles of the modulating beam, in the case of strong lattice modulation, $I_3 = 4I_{12}$. In Fig. 1(d) we plot the shift of the beam center of mass vs. the modulating beam phase φ which is tuned by passing the third beam through a thin glass plate with a variable tilt. For $k_{3x} = 1.01k_{12x}$ the beam shift is virtually zero throughout the entire phase scan [stars in Fig. 1(d)]. The insensitivity to φ results from the lattice being fully symmetric when beams 2 and 3 in Fig. 1(a) are parallel ($k_{3x} = k_{12x}$). As the angle of the third lattice-forming wave is increased, the lattice becomes asymmetrically modulated, and the beam shifts [squares and circles in Fig. 1(d)], depending strongly on the value of φ. Thus, not only the local asymmetric distortion of the lattice, which in this case tends to shift the beam towards positive x, but also the broader effective modulation geometry plays an important role for the beam propagation dynamics.

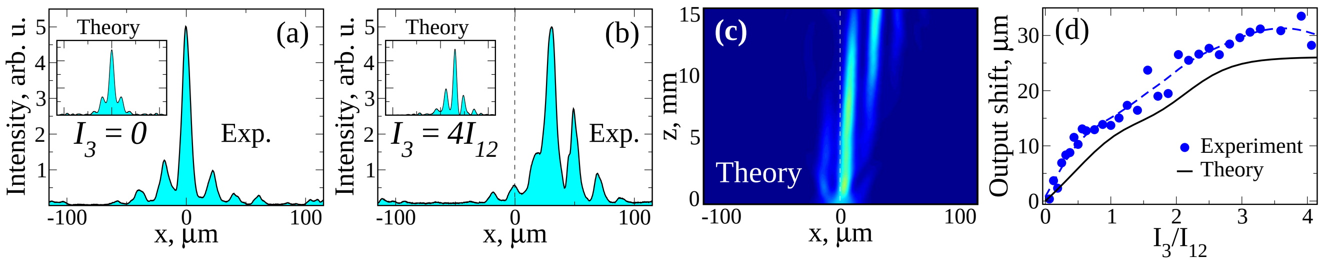

Fig. 2. (a,b) Experimental and theoretical (inset) nonlinear probe beam output in straight ($I_3 = 0$) and modulated ($I_3 = 4I_{12}$) lattice, respectively. (c) Numerical simulation of nonlinear beam propagation corresponding to (b). (d) Nonlinear probe beam output shift vs. control beam power. In (b-d), $k_{3x} = 1.18k_{12x}$ and $\varphi/2\pi = 0.22$.

We quantify the spatial steering resolution by a figure of merit $F = |\Delta x| / W$, where Δx and W are the shift and the width of the output beam, respectively. In Fig. 1(d) gray shading marks the region in which F exceeds 0.5 for the largest modulation angle $k_{3x} = 1.18k_{12x}$. Focusing now on this case ($\varphi/2\pi = 0.22$), we show in Fig. 2 that increasing the power of the probe beam to 1.5μW leads to strong self-focusing and enhanced beam localization [Fig. 2(a)] while preserving a large beam shift [Fig. 2(b)]. As a result, the figure of merit is increased by approximately a factor of two compared to the linear case. The experimental observations agree well with numerical simulations, shown in Fig. 2 as the beam profile insets in panels (a) and (b), and the top view of the propagation dynamics in panel (c). In Fig. 2(d) we trace the experimental (dots) and theoretical (solid line) nonlinear beam shift as a function of the lattice modulation power. We find that the beam shift gradually increases and, in experiment, saturates at approximately $\Delta x = 30\mu$m for $I_3/I_{12} > 3$.

In conclusion, we have demonstrated experimentally all-optical steering of nonlinear self-localized beams in modulated optically-induced lattices, and described how the effect depends on inclination angle, phase, and power of the modulating lattice beam. The characterization allowed us to optimize the steering performance and achieve high spatial resolution with a figure of merit exceeding unity.

References

1. N. K. Efremidis *et al.*, Phys. Rev. E **66**, 046602 (2002).
2. J. W. Fleischer *et al.*, Nature **422**, 147 (2003).
3. Yu. S. Kivshar and G. P. Agrawal, *Optical Solitons: From Fibers to Photonic Crystals* (Academic Press, San Diego, 2003).
4. Y. V. Kartashov, L. Torner, and D. N. Christodoulides, Opt. Lett. **30**, 1378 (2005).
5. I. L. Garanovich, A. A. Sukhorukov, and Yu. S. Kivshar, Opt. Express **13**, 5704 (2005).