Demonstration of surface soliton arrays at the edge of a two-dimensional photonic lattice

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We demonstrate surface soliton arrays at the interface between a homogeneous medium and an optically induced two-dimensional semi-infinite photonic lattice. These are nonlinear Tamm-like surface states localized in one but extended periodically in the other transverse dimension. Both in-phase and staggered out-of-phase soliton arrays are observed, and the experimental results are corroborated by numerical simulations. © 2008 Optical Society of America

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Recently, self-trapped nonlinear surface states (surface solitons) have attracted a great deal of interest in optical discrete systems [1]. For instance, one-dimensional (1D) bright in-phase (IP) surface solitons (fields in phase in adjacent channels with propagation constants located in the semi-infinite gap) at the edge of a waveguide lattice with a self-focusing nonlinearity have been predicted and demonstrated in experiment [2,3]. Likewise, out-of-phase (OP) surface gap solitons (fields with a π phase difference between adjacent channels with propagation constants in a "true" photonic bandgap) have been established with a self-defocusing nonlinearity [4–7]. These studies extend the analogy between optical surface waves and localized surface Tamm states into the nonlinear regime. Theoretical studies of such surface solitons have been carried on in the two-dimensional (2D) domain [8–10], where many interesting aspects of nonlinear surface waves are expected to occur. In fact, 2D surface solitons have also been successfully demonstrated in experiment [11,12].

At the interface between a homogeneous medium and a 2D semi-infinite photonic lattice, such as those created in [11,12], it is natural to ask if a train of 2D surface solitons (surface soliton arrays) can propagate along the interface. Although soliton trains have been generated in a 2D waveguide lattice before [13,14], they were excited inside the uniform lattice but not at the edge of the lattice. To our knowledge, surface soliton arrays have never been demonstrated in experiment. (In theory, arrays of 2D surface solitons were proposed, but they was based on the transverse modulation instability of 1D solitons at the surface of a 1D waveguide lattice [15]). In this Letter, we report what we believe to be the first observation of surface soliton arrays propagating along the edge of an optically induced 2D waveguide lattice. Different from previous experiments on surface solitons, we launch a tightly focused stripe beam (akin to a quasi-1D plane wave) at the interface between a uniform medium and a semi-infinite 2D waveguide lattice. Both IP and OP (staggered) surface solitons are observed with the self-focusing and self-defocusing nonlinearities, respectively. The difference between these two types of surface solitons is clearly
illustrated in our experiment by phase measurement as well as by monitoring the Fourier spectrum. Numerical simulations find good agreement with experimental observations.

The experimental setup is similar to that used for generation of a single 2D surface soliton [11]. An interface between a uniform medium and a semi-infinite 2D waveguide lattice is optically induced by an ordinarily polarized lattice beam with a gridlike intensity pattern that remains nearly invariant through a 10 mm long Ce:SBN (strontium-barium niobate) photorefractive crystal [Fig. 1(a)]. A cylindrically focused probe beam is at 488 nm wavelength and extraordinarily polarized. The probe beam has a FWHM ~14 μm at input [Fig. 1(b)], and it undergoes linear diffraction to ~70 μm in the homogeneous regime of the crystal [Fig. 1(c)]. The probe beam is launched at the interface between the homogeneous and periodic (lattice) regimes and propagates collinearly with the lattice beam. The first Bloch band structure of the 2D square lattice is illustrated in Fig. 1(d), and the experimentally recorded Fourier

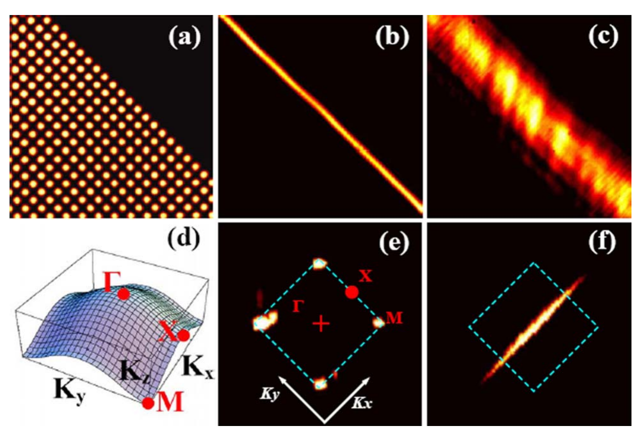

Fig. 1. (Color online) Shown in top panels are the (a) lattice pattern, (b) the probe beam at input, and (c) linear output. Bottom panels show the (d) first Bloch band structure within the first BZ, the k-space spectra of the (e) lattice beam, and that of the (f) probe beam. High-symmetry points are marked with dots and the first BZ with dashed lines.

(k-space) spectrum of the lattice beam and that of the probe beam are shown in Figs. 1(e) and 1(f), respectively. Clearly, the initial stripe beam is narrow enough so that its spectrum extends across the first Brillouin zone (BZ).

First, we apply a positive voltage to turn the crystal into a *self-focusing* medium [11] and demonstrate the IP surface soliton arrays. The excitation scheme is similar to that used for the demonstration of discrete soliton trains inside a uniform 2D square lattice [13] except that the stripe beam is now launched along the lattice surface, parallel to one of the lattice principal axes. Typical experimental results are presented in Fig. 2, where Fig. 2(a) shows the lattice pattern with the location of input probe beam marked by a straight (blue) line. When the nonlinearity is absent (taking advantage of the noninstantaneous response of the crystal [11]), linear propagation of the probe beam is shown in Fig. 2(b). Strong discrete diffraction and coupling of the probe beam up to the fourth waveguide channel from the surface is clearly visible. Under the same experimental condition, the probe beam couples only to the nearest lattice sites when it excites a waveguide inside and far away from the lattice boundary, suggesting possible surface-enhanced reflection [3,11]. With a proper level of high nonlinearity (at a bias field of 2.0 kV/cm), the probe beam evolves into a surface soliton train [Fig. 2(c)], localized in one transverse direction but extended periodically in the other orthogonal direction owing to the periodic modulation of the waveguide lattice. Such an array of surface solitons established under the self-focusing nonlinearity belongs to the IP surface solitons with modes bifurcated from the Γ point of the first Bloch band but located in the semi-infinite gap. This is confirmed by monitoring the phase structure (interference measurement between the soliton beam and a tilted broad beam), and part of the zoom-in interferograms are shown in Fig. 2(d). The IP relation between stripes trapped in adjacent channels is evident. Furthermore, the spatial spectrum of the probe beam obtained from linear [Fig. 2(e)] and nonlinear [Fig. 2(f)] propagations indicates that, when the surface soliton train is established the spectrum reshapes and most of the power tends to concentrate to the central region of the first BZ (i.e., near the Γ point) where the probe beam would otherwise undergo normal diffraction.

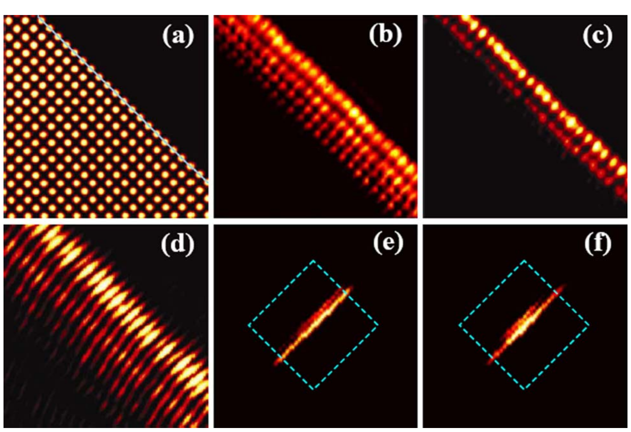

Fig. 2. (Color online) Experimental demonstration of IP surface soliton train. (a) Lattice pattern with location of input stripe beam; (b) linear and (c) nonlinear output patterns of the stripe beam; (d) zoom-in interferogram of (c) with a tilted plane wave; and (e), (f) the k-space spectra corresponding to (b) and (c), respectively.

Next, we apply a negative voltage to turn the crystal into a *self-defocusing* medium and demonstrate the OP surface soliton arrays. The excitation scheme is similar to that used for the demonstration of discrete gap soliton trains [14], except that the stripe beam is now launched between the first two rows of the lattice surface where the index change is maximum. Figure 3(a) shows the lattice pattern and the location of the input probe beam. With a proper level of nonlinearity (at a bias field of −1.5 kV/cm), self-trapping of the stripe beam is also realized [Fig. 3(b)], although the surface soliton train is less localized as compared with that of [Fig. 2(c)]. This surface soliton train differs significantly from the IP soliton train shown in Fig. 2 in both the phase structure and spatial spectrum. Phase measurement shows that the surface soliton train has an OP relation between stripes trapped in adjacent channels [Figs. 3(c) and 3(d)] but remains IP along each stripe parallel to the lattice edge, a characteristic feature of the Bloch modes at the X point of the first band of a square lattice [16]. Spectrum measurement reveals that from linear propagation [Fig. 3(e)] to nonlinear self-trapping [Fig. 3(f)], the stripe beam reshapes its spectrum so that most of power tends to concentrate into the region near the X point where the stripe beam would experience anomalous diffraction. Thus, both the phase and spectrum suggest that the surface soliton train arise from Bloch modes at the interior X point of the first band [17]. We also mention that the spectrum shown in Fig. 3(f) has only one pronounced peak near one (upper right) X point but extended nearly uniformly across the other (bottom left) X point, simply because the excitation occurs at the interface between the homogeneous regime and the semi-infinite lattice.

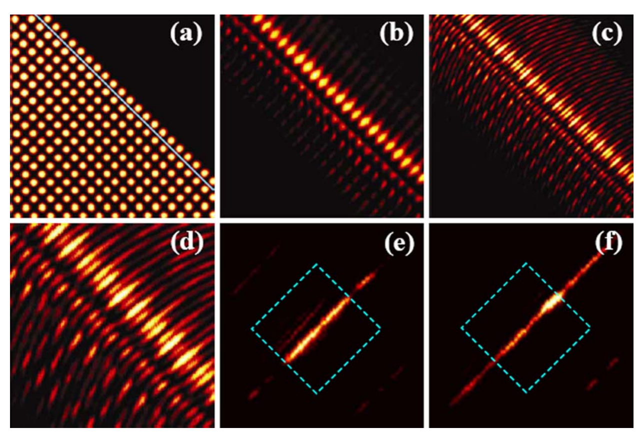

Fig. 3. (Color online) Experimental demonstration of OP surface soliton train. (a) The lattice pattern with location of input stripe beam; (b) nonlinear output pattern of the soliton train; (c) interferogram of (b) with a titled broad beam; (d) zoom-in version of (c); and (e), (f) the k-space spectra corresponding to linear and nonlinear propagation, respectively.

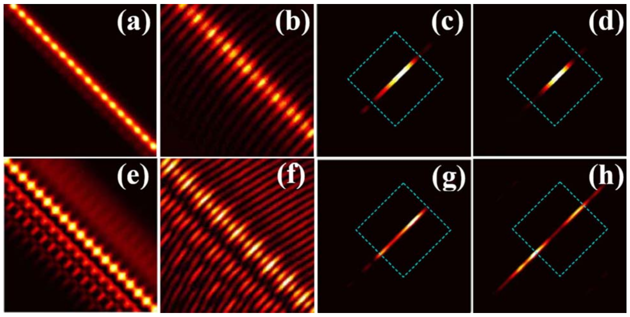

Fig. 4. (Color online) Numerical results of IP (top) and OP (bottom) surface soliton train corresponding to Figs. 2 and 3. From (a) to (d) are the intensity pattern of the soliton beam (after 10 mm propagation), the interferogram, and the linear and nonlinear k-space spectra. Dashed squares mark the first BZ.

Finally, the above observations are corroborated by our numerical simulations with parameters close to those from experiment. Numerical results after 10 mm of propagation (corresponding to the crystal length) are shown in Fig. 4. Again, difference in phase relation and spectrum reshaping can be seen clearly between IP and OP surface soliton trains.

Before closing, we mention that the term *surface soliton train* is used here loosely, as the observed 2D surface arrays do not arise from the transverse modulation instability of the stripe soliton as in [15]. In fact, the instability occurs at higher powers or for the case when the stripe beam is excited far from the lattice edge at the same level of nonlinearity, suggesting a stabilizing effect of the surface or a threshold power for surface solitons. Nevertheless, the term surface soliton train is used as a periodic nonlinear Tamm-like surface state, which could also be viewed as a bound state of the 2D surface solitons observed in [11]. For the IP train it looks like a juxtaposition of many single surface solitons, while the energy should be adjusted owing to the interaction between the nearby soliton states; for the OP train, it is more than a juxtaposition of single 2D surface gap solitons owing to its phase structure (i.e., IP for all peaks along the same stripe parallel to the lattice surface). This difference relates directly to the k-space reshaping to the M versus X points of the first band. The variety and stability of the soliton bound states may stimulate further study in other nonlinear surface systems.

In summary, we have demonstrated the formation of discrete surface soliton arrays at the interface between an optically induced 2D photonic lattice and a continuous medium. These are Tamm-like optical nonlinear surface states localized in one transverse dimension while propagating invariantly along the surface in the longitudinal direction. Although the electronic Tamm surface states are well known in solid-state physics, the area of optical surface waves seems to be enriched by many new ideas, such as nonlocal surface solitons [18], polychromatic surface solitons [19], and spatiotemporal surface light bullets [20]. Now that surface states have been successfully demonstrated in a number of experiments in nonlinear optics, we expect many interesting surface phenomena could be explored in an optical setting with reconfigurable photonic structures.

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