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Observation of discrete quadratic surface solitons

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Abstract: We report the first observation of discrete quadratic surface solitons in self-focusing and defocusing periodically poled lithium niobate waveguide arrays. By operating on either side of the phase-matching condition and using the cascading nonlinearity, both in-phase and staggered discrete surface solitons were observed. This represents the first experimental demonstration of staggered/gap surface solitons at the interface of a semi-infinite nonlinear lattice. The experimental results were found to be in good agreement with theory.

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1. Introduction

The interplay between discreteness and nonlinearity has led to a host of new phenomena in physical sciences. This has been most pronounced in the area of optics where high-quality discrete structures can be fabricated and the optical power levels required to induce nonlinear effects can be easily achieved [1]. Discreteness has resulted in the prediction of new classes of spatial solitons and other phenomena that have no counterparts in continuous systems [2-4]. And indeed, many of these processes have been observed in a variety of Kerr, quadratic, photorefractive and liquid crystal media [5-8].

Thus far, the arrays used for discrete optics experiments have been fabricated by a variety of techniques, some of which lend themselves to small and controllable index differences at the array boundary with continuous media. This feature can now facilitate new experimental studies in the area of nonlinear surface guided waves which received a great deal of theoretical attention in the 1980’s and early 1990’s [9-12]. The theoretical feasibility of guiding waves along an interface between two media, at least one of which exhibits a self-focusing nonlinearity was discussed extensively. Yet, in spite of these efforts, no successful experiments have been reported along these lines. Part of the problem was to find media combinations whose linear index difference was of the order of the maximum index change allowed by self-focusing nonlinearities, i.e. typically $10^{-4}$ and less. For the weakly guiding arrays currently in use, such small index differences are available at the interface between the array and the host medium. This can in turn facilitate the observation of interface solitons as recently suggested by our group [13]. Theory has already shown that such interface guided waves do exist at the boundary between arrays and continuous media [13], and in fact they have been observed for the first time in self-focusing Kerr lattices [14].

Discrete quadratic solitons have been previously demonstrated inside arrays governed by the “cascading” quadratic nonlinearity [6]. One of the unique features of this nonlinearity is that it can change from effectively self-focusing to defocusing depending on the wavevector mismatch conditions. Thus both signs of the nonlinearity are accessible in the same sample just by, for example, changing the temperature. This property has been used to demonstrate both in-phase and staggered (adjacent fields are $\pi$ out of phase with each other) spatial solitons in these arrays [6]. In this paper we show theoretically and experimentally that both types of quadratic surface discrete solitons exist for both signs of the cascading nonlinearity.

We note that this represents the first observation of gap surface solitons in arrays with defocusing nonlinearity as earlier predicted [13, 15].

2. Theory

The system shown in Fig. 1 was modeled by employing a coupled mode formulation for quadratic nonlinear media [3, 6].
In our system, the adjacent waveguides comprising the array are weakly coupled by their evanescent fields. Given the fact that the second harmonic (SH) \( \text{TM}_{00} \)-modes are strongly confined, the coupling process between the SH fields is negligible. Therefore, here we only consider coupling between the modal fields of the fundamental wave (FW). In physical units, the pertinent coupled mode equations describing the wave dynamics in a semi-infinite array are given by the following:

\[
\begin{align*}
\frac{i}{\hbar} \frac{\partial u_n}{\partial z} + cu_n + \gamma u_n^* v_n &= 0, \quad \text{for } n = 0 \\
\frac{i}{\hbar} \frac{\partial u_n}{\partial z} + c(u_{n+1} + u_{n-1}) + \gamma u_n^* v_n &= 0, \quad \text{for } n \geq 1 \\
\frac{i}{\hbar} \frac{\partial v_n}{\partial z} - \Delta \beta v_n + \gamma u_n^2 &= 0, \quad \text{for } n \geq 0
\end{align*}
\]

where \( u_n \) and \( v_n \) are the FW and SH modal amplitudes in the \( n \)th waveguide respectively, \( c \) is the linear coupling constant and \( \gamma \) is the effective quadratic nonlinear coefficient. Furthermore, \( \Delta \beta = 2\beta(\omega) - \beta(2\omega) \) is the wavevector mismatch between the FW and SH.

Stationary solutions of the form \( u_n = f_n \exp(i\mu z) \) for the FW and \( v_n = s_n \exp(2i\mu z) \) for the SH were numerically determined by applying Newtonian relaxation techniques. Here \( \mu \) is the soliton eigenvalue and is related to a nonlinear change in the propagation constant \( \Delta k^\text{NL} = c\mu \). In-phase solitons are possible when \( 2\Delta k^\text{NL} + \Delta \beta > 0 \), while staggered solitons exist for \( 2\Delta k^\text{NL} + \Delta \beta < 0 \) [3]. The power versus nonlinear wavevector shift diagrams for both the in-phase and staggered surface soliton families obtained are shown in Fig. 2 and Fig. 3, respectively, along with the corresponding typical intensity profiles. Throughout this study we use the parameters typical of the experiments. More specifically, the coupling length in this array is taken to be 25 mm and the quadratic nonlinear coefficient is 18 pm/V [6].
Fig. 2. (a) Surface soliton existence curves for in-phase solitons for $36\pi$ (red curve) and $-15.5\pi$ (blue curve). (b), (c) Intensity profiles for low, and high powers for FW (blue) and SH (red), in the case of positive mismatch $36\pi$, respectively, and (d) Intensity profiles for high powers for FH (blue) and SH (red), in the case of negative mismatch $-15.5\pi$. The SH powers of both solitons are overlapped for large nonlinear wavevector shifts.

Fig. 3. (a) Surface soliton existence curves for staggered solitons for a mismatch of $-15.5\pi$ (red curve) and $36\pi$ (blue curve). (b), (c) Intensity profiles for low, and high powers for FH (blue) and SH (red), in the case of negative mismatch $-15.5\pi$, respectively, and (d) Intensity profiles for high powers for FH (blue) and SH (red), in the case of positive mismatch $36\pi$. The SH powers of both solitons are overlapped for large nonlinear wavevector shifts.
A number of interesting features are predicted for these quadratic surface solitons. Different from the infinite arrays case, these surface self-trapped states exist only when their power exceeds a critical level - a direct consequence of the semi-infinite geometry of the lattice. This is a feature common to surface solitons at the interface between continuous media, also found recently for surface solitons propagating due to self-focusing and self-defocusing nonlinearities in Kerr media [13,15]. As the soliton power increases the fields become progressively more confined in the n=0 channel. The fraction of power carried by the SH is decreased as $\Delta k^{NL}$ increases.

Furthermore, just as found for discrete solitons in infinite 1D media, the solitons consist of coupled FW and SH fields. In addition to the expected staggered solutions, in-phase solitons were also found under negative phase mismatch conditions for $2\Delta k^{NL}+\Delta \beta > 0$, i.e. with self-focusing nonlinearities. See the blue curves in Fig. 2(a) for the existence curves and the field distributions in Fig. 2(d). Note that this family of solitons can only be excited if the SH is considerably stronger than the FW. Similarly in regions of positive phase-mismatch, both stable in-phase and staggered (for $2\Delta k^{NL} +\Delta \beta < 0$, i.e. a self-defocusing nonlinearity for the blue curves in Fig 3(a) and the fields in [ 3(d)] surface solitons are predicted to exist. This mirrors the case predicted for infinite quadratically nonlinear 1D arrays [3]. We emphasize that in all cases the branch associated with the SH wave in the existence curves [see Figs. 2(a) and 3(a)] does not depend on the value of phase-mismatch $\Delta \beta$. This can be formally proved based on the fact that the waveguides are uncoupled for the SH wave.

Finally, we note that stability analysis of Eqs. (1) indicates that the predicted surface solitons are stable in the regions where the slope of the curve is positive, in accordance with the Vakhitov-Kolokolov criterion [16].

3. Experiment

The arrays used here consist of channels formed by Ti diffused into the surface of LiNbO₃ as shown in Fig. 1. Phase-matching for second harmonic generation is achieved by periodic poling of the lithium niobate (PPLN) ferroelectric domains along the propagation direction. This poling extends beyond the array but in that region the periodicity required for efficient SHG is different from that required for the channels and the generation of the second harmonic is very weak and can be neglected. There is no Ti in-diffused outside of the array, therefore the array boundary corresponds to an interface between the 1D waveguide array and a semi-infinite half-space.

The samples contained four waveguide arrays each consisting of 101 coupled channel waveguides with propagation along the X-axis. The spacing between the arrays was sufficiently large (> 100µm) that the region beyond each array boundary can be considered as a half-space. Seven cm long waveguides were formed by titanium in-diffusion into the Z-cut surface. TM₀₀-mode waveguide losses were 0.2dB/cm for the FW at $\lambda =1550$ nm and 0.4dB/cm for its SH. The center-to-center channel separations was $d = 16$ µm resulting in a coupling length of $L_c =25$ mm for the FW TM₀₀ mode. These were determined from the output intensity distribution under single waveguide excitation conditions [17,18]. The sample was periodically poled with a period of 16.75 µm by electric field poling to achieve phase-matching between the TM₀₀ modes for SH generation at temperatures elevated to the range of 200-250°C. The required wave-vector mismatch was adjusted by varying the sample temperature $T$. In our experiments the relation between the phase-mismatch $\Delta \beta L$ and sample temperature $T$ was measured to be $\Delta \beta L=8.1(234-T$ °C) [17].

A 5-MHz train of bandwidth limited 9-ps-long pulses at a wavelength of 1557 nm was produced by a modified Pritel fiber laser [17,18]. The pulses were stretched, amplified in a large area core fiber amplifier, and then recompressed in a bulk grating compressor to give up to 4 kW of peak power in nearly transform limited pulses 7.5-ps-long. The recompressed pulses were spatially reshaped into elliptical Gaussian beam with 4.3 µm width (full width at half maximum, FWHM) and 3.5 µm height which corresponds to the measured intensity profile of the fundamental mode of a single channel waveguide. In all experiments the n=0
channel was excited. The sample was heated in an oven both to minimize photorefractive effects and to adjust the wave-vector mismatch with temperature \( T \). The experimental set-up used is shown in Fig. 4.

![Experimental set-up diagram](image)

**Fig. 4.** Experimental set-up: MO-microscope objective; PPLN-periodically poled lithium niobate; Pol-Polarizer; \( \lambda/2 \)-half-wave plate.

The output of the array was observed with separate cameras for the FW and the SH, and quantified by measuring temporally averaged output intensities and total powers.

Figure 5 shows the observed FW discrete diffraction pattern obtained at low powers. It is in good agreement with the theoretical pattern generated from Eqs. (1) of Ref. [13].

![Diffraction pattern graphs](image)

**Fig. 5.** Linear diffraction when only \( n=0 \) is excited, experiment (blue) and theory (red).

The evolution of the output intensity distributions versus input peak power of the fundamental for single channel excitation \( (n=0) \) is shown in movies in Fig. 6 (positive phase mismatch) and Fig. 7 (negative phase mismatch). Increasing the input peak power leads in both cases to localization into surface solitons, as predicted theoretically. At peak powers of 600W for the focusing case and 500W for the defocusing case the localization is essentially complete. The observed intensity decay into the array from the boundary out to distances typical of the low power discrete diffraction pattern is a direct consequence of the pulsed excitation used which contains a continuum of powers. That is, not the full pulse is trapped as a surface soliton in the boundary channel and the weaker parts of the pulse appear as part of a modified linear discrete diffraction pattern. We want to mention here that we controlled the input powers with a combination of a polarizer and a half-wave plate, and thus the power scaling is sinusoidal. The weak second harmonic component is localized almost completely in the \( n=0 \) channel, in agreement with theory in Fig. 2(b) and 2(c) and 3(b) and 3(c).
Fig. 6. The evolution of the output intensity distribution with increasing input peak power of the fundamental for single channel excitation (n=0) (positive phase mismatch = +36\pi)

Fig. 7. The evolution of the output intensity distributions versus input peak power of the fundamental for single channel excitation (n=0) (negative phase mismatch = -15.5\pi)

An important problem is to verify which field distributions were generated, staggered or in-phase for each sign of the cascading nonlinearity. Theory has shown the ratio of the FW to SH powers are very different in the two cases. In order to compare experiment approximately with theory, the assumed hyperbolic secant temporal profile was decomposed into cw temporal slices and the pulse response was simulated by adding the slices together. A fourth order Runge-Kutta method was then used to propagate the fields under the influence of Eq. (1). Comparing the measured and the calculated ratios of the FW to SH powers at the output, clearly the observed surface solitons were the staggered ones for negative and the in-phase ones for positive mismatch since the experimentally measured power ratio FW/SH was much bigger than unity. It would be necessary to also input the appropriate SH field in order to excite the other surface solitons.

Using the same numerical approach, the output intensity distributions across the array were calculated versus input peak power for both positive (+36\pi) and negative (-15.5\pi) phase mismatches for in-phase and staggered solitons respectively. A sampling of these results, along with the corresponding experimental data is shown in Fig. 8 and Fig. 9:
Fig. 8  Measured (left-hand-side) and calculated (right-hand-side) output field distributions for single channel excitation for two input power levels corresponding to partial collapse into a surface soliton for FH (first row) and full collapse into a surface soliton for FH (second row) and SH (last row). Phase mismatch = +36π (self-focusing nonlinearity). The red curves represent theoretical results (at 435 W and 441 W) and the blue experimental data (at 430 W, and 600W) FW input powers.
Fig. 9. Measured (left-hand-side) and calculated (right-hand-side) output field distributions for single channel excitation for two input power levels corresponding to partial collapse into a surface soliton for FH (first row) and full collapse into a surface soliton for FH (second row) and SH (last row). Phase mismatch = -15.5π (self-defocusing nonlinearity). The red curves represent theoretical results (at 310 W and 321 W) and the blue experimental data (at 420 W, and 580 W) FW peak input powers.

In fact there is good qualitative agreement between experiment and theory considering the non-ideally hyperbolic secant temporal profile of the input beam and the coupling efficiency estimated from low power throughput experiments [17,18]. If a coupling efficiency of 50% is assumed into the input channel, the resulting quantitative agreement is also good.

4. Summary

In summary, discrete quadratic solitons guided by the interface between a 1D array and a semi-infinite medium have been predicted theoretically and observed experimentally. Two of the four predicted soliton types were generated by exciting the first channel with a beam at the fundamental frequency. The additional solitons not observed will probably require the excitation of both fundamental and second harmonic fields. Finally, the results reported here represent the first observation of staggered discrete surface solitons in any periodic system.

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