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Staggered and unstaggered solitons in quadratically nonlinear lithium niobate waveguide arrays

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Abstract: We report the first observation of staggered and unstaggered quadratic discrete solitons in arrays of coupled waveguides. Intensity profiles, powers and stability of the solitons were measured in good agreement with theoretical predictions.

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1. Introduction

The interesting properties of nonlinear wave propagation in discrete systems that are due to the band structure of the dispersion relation have been discussed theoretically [1] and investigated experimentally [2]. Many elegant experiments have been performed recently in optical systems by implementing discreteness in the form of arrays of coupled optical channel waveguides [3]. An optical nonlinearity modifies via an intensity-dependent phase velocity the coupling between adjacent waveguides and for specific input conditions the formation of discrete spatial solitons is possible. To date, spatial discrete solitons based on the Kerr and the photorefractive nonlinearity have been observed. Theoretically also the existence of discrete solitons in quadratic nonlinear media was predicted [4]. In contrast to the Kerr and photorefractive solitons observed previously, quadratic solitons consist of two or three different frequency components coupled by the optical second-order nonlinearity near the phase-matching condition of a quadratic nonlinear mixing process. Here we report the first observation of staggered and unstaggered discrete quadratic spatial solitons and the measurement of their intensity profiles, powers, existence conditions and stability behavior in very good agreement with the theoretical predictions.

2. Sample and experimental setup

Channel waveguide arrays (each consisting of 101 guides) were fabricated on 70-mm-long z-cut $LiNbO_3$ wafers by diffusing titanium stripes into the substrate. The center-to-center spacing between the array's channels varies from 14 to 16 μm yielding linear coupling lengths l_c in the range from 9.5 to 25.6 mm for TM_{00} modes at a fundamental wave (FW) with wavelengths near 1550 nm. TM_{00} modes at the second-harmonic (SH) frequency are strongly localized with negligible field overlap between the channels and experience no linear coupling. To implement efficient phase-matching between the FW and the SH TM_{00} modes at temperatures near 230°C, a uniform QPM grating was written in the sample by electric field poling. The sample was heated in an oven to temperatures higher than 180°C to prevent photorefractive index changes and to adjust the wave-vector mismatch. Low power measurements of discrete diffraction patterns of single and broad beam excitations confirmed the excellent linear properties of the arrays. This proved to be a crucial requirement for the soliton experiments.

The experiments were performed using a source, operating at a wavelength of 1557 nm, consisting of a Pritel fiber laser producing a 5 MHz train of bandwidth limited 9-ps-long pulses, stretched in a chirped grating, amplified in a large core EDFA from Keopsys, and then recompressed in a bulk compressor to give 4 kW of peak power in nearly transform limited pulses, 7.5 ps long. Only the FW was launched and we relied on propagation into the medium to generate the necessary SH part of the soliton. Elliptically shaped Gaussian beams, 3.9 to 4.4 waveguides wide, were used to excite with 50-60 % coupling efficiency the array. The output of the sample was observed with cameras for the FW and the SH and with power detectors.

3. Soliton characteristics

We increased the input power and observed the output FW and SH. For a positive wave-vector mismatch $\Delta\beta L$ (focusing nonlinearity) and an excitation of the array with the same phase in all waveguide modes the beam first narrows with increasing power as shown in Fig. 1(a). The eventual broadening and splitting of the beam for powers exceeding the soliton power requires more investigations for full understanding. When the output beam width equals the width of the input beam a soliton propagates. Typical FW and SH intensity profiles of a soliton are shown in Fig. 1(b). A linear diffracting beam is shown for comparison. Solitons with in-phase modes in the individual waveguides are called “unstaggered” solitons and could not be excited for negative $\Delta\beta L$ because that region corresponds to a defocusing nonlinearity. Instead, the defocusing nonlinearity broadens an unstaggered beam monotonic increasingly with increasing input powers which was observed experimentally, see Fig. 2(a) for an example of a broadened beam.

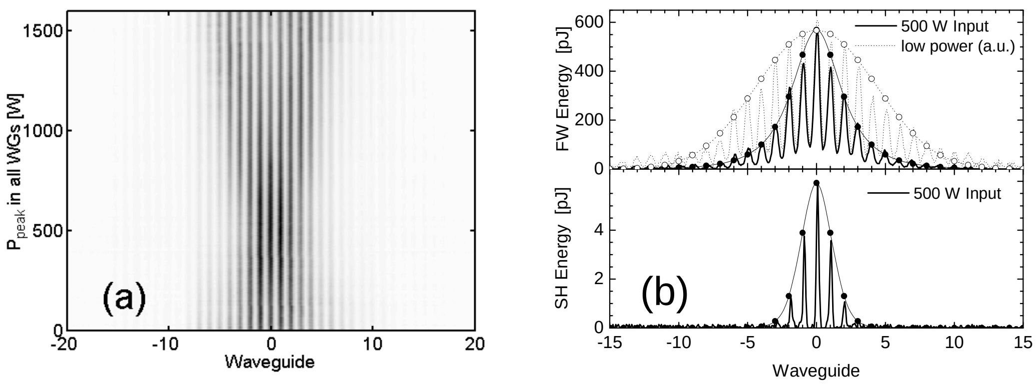

Fig. 1: Output from an array with a coupling length of 15.7 mm, unstaggered excitation, $\Delta\beta L=140\pi$. (a) Output beam profile versus input peak power. (b) FW and SH energy profile of an unstaggered soliton for an input peak power of 500 W. The envelopes show calculated soliton profiles.

With a tilted input beam we excited the array waveguides with modes with phase differences of π between adjacent waveguides. Now we observed for appropriate powers soliton formation for $\Delta\beta L<0$. Such solitons with phase differences of π between adjacent waveguides are called “staggered” solitons. Fig. 2(b) shows an example of a staggered soliton. Theory predicts them to exist only for a defocusing nonlinearity and indeed they could not be observed for $\Delta\beta L>0$. Instead a staggered input beam increasingly broadens with increasing power in this regime.

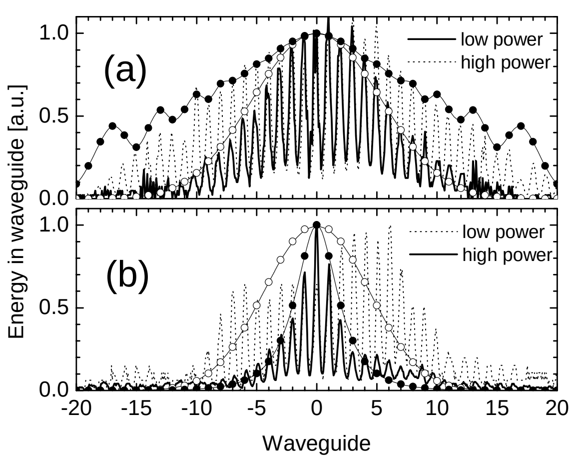

Fig. 2: FH output profiles for negative wave-vector mismatch. (a) Nonlinear beam broadening with unstaggered excitation in an array with l_c = 12.16 mm, input peak power 1.4 kW, $\Delta\beta L$ = -50π. (b) Staggered soliton in an array with l_c = 15.7 mm, 150 W input peak power, $\Delta\beta L$ = -16π. The envelopes show calculated beam profiles.

The dependence of the soliton parameters on variation in the diffraction conditions and the wave-vector mismatch is shown in Fig. 3. In stronger coupled arrays the powers necessary for soliton propagation were larger.

Also for increasing values of $|\Delta\beta L|$ increasing soliton powers were measured for both, the staggered and the unstaggered solitons, a clear indication of the decreasing cascaded quadratic nonlinearity far from phase-matching.

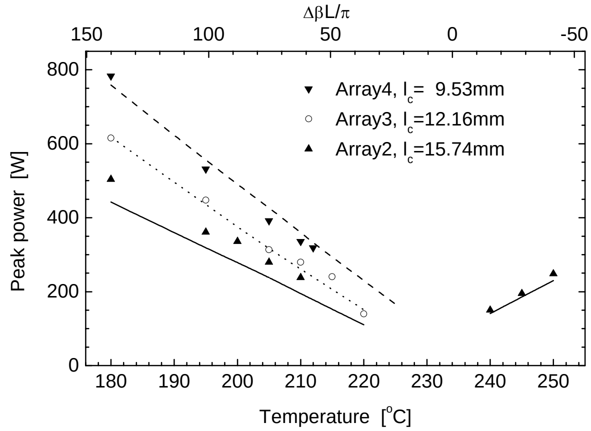

Fig. 3: Soliton FW input peak power versus $\Delta\beta L$ in different arrays. Continuous lines show theory.

Our measurements showed stable soliton output profiles only after careful alignment of the transverse position of the beam. The stable solitons formed when the maximum intensity of the beam incident on the sample was centered on a waveguide (see left insert in Fig. 4). The resulting solitons have maximum energy in the central one of the excited waveguides and are called “odd” solitons. The first nine frames in Fig. 4 show a stable power over time in the three central waveguides guiding the soliton. When the beam maximum hits the sample between two waveguides (Fig. 4, right insert) a strongly flickering output as documented in frames 10 to 19 in Fig. 4 was observed as the peak intensity jumped back and forth between the adjacent channels. This agrees with theory which predicts stable odd and unstable even solitons. The even excitation broke up and evolved, alternating towards odd solitons centered on either the left or right one of the equally excited channels.

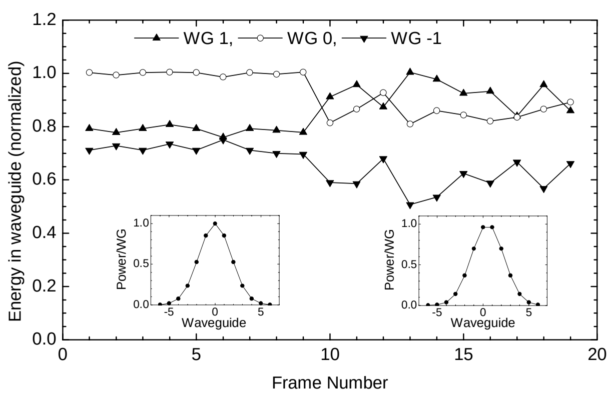

Fig. 4: Stability of unstaggered even and odd solitons, l_c = 15.7 mm, $\Delta\beta L = 140\pi$. The energy in the central waveguides guiding the soliton is plotted versus time. The time between two frames is 200 ms.

4. Conclusion

We have observed the first discrete quadratic optical solitons in waveguide arrays. Staggered and unstaggered solitons have been characterized and the conditions for their existence were experimentally verified. For the wrong sign of the wave-vector mismatch, instead of soliton propagation, nonlinear beam broadening was observed. The stability behavior of quadratic discrete solitons was investigated. The experimental results agree well with theoretical predictions.

4. References

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