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Multi-channel discrete quadratic solitons in periodically poled lithium niobate waveguide arrays

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Abstract: We report the first observation of quadratic discrete solitons localized in multiple neighboring channels of one-dimensional PPLN waveguide arrays. Measured field profiles for discrete diffraction and solitons versus wave-vector mismatch agree with theory.

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1. Introduction

There is great interest in nonlinear discrete systems because of their unique and fascinating properties. It was predicted by Christodoulides and Joseph in 1988 that light propagating in such arrays with a Kerr nonlinearity could undergo diffractionless propagation and self-focusing [1]. To date, spatial discrete solitons were observed in AlGaAs and photorefractive arrays [2] based on an intensity-dependent refractive index. Theoretical investigations have also predicted the existence of discrete quadratic spatial solitons [3]. In contrast to the Kerr and photorefractive ones observed previously, they consist of two or more different frequency components coupled by the second order nonlinearity $\chi^{(2)}$ near their phase-matching condition. Previously we reported localization of such solitons in a single channel, an event which occurs at high enough powers independent of any imperfections in the channel-to-channel coupling and second harmonic generation (SHG) efficiency [4]. Here we report the first observation of discrete quadratic solitons with fields extending over several channels showing excellent agreement with theory.

2. Sample and experimental setup

Channel waveguide arrays (each consisting of 101 guides) were fabricated on 70mm long z-cut $LiNbO_3$ wafers using standard lithography techniques by diffusing Ti stripes into the substrate. For efficient phase-matching SHG, between the fundamental harmonic (FH – 1550nm) TM_{00} and the second harmonic (SH – 775nm) TM_{00} waveguide modes, a uniform QPM grating was written in the sample by electric field poling. At low powers, only FH fields diffract via evanescent nearest-neighbor field overlap. The center-to-center spacing between the arrays' channels varies from 14 to 16µm, which corresponds to linear coupling lengths for the FH in the range from 9.5 to 25.6mm. The SH field distribution is strongly localized in one channel with a negligible field overlap between the channels and can only grow from the FH in a specific channel. The sample was heated in an oven to temperatures higher than 180°C to prevent photorefractive index disturbances and a resulting inhomogeneity of the linear coupling and the wave-vector mismatch. Low power measurements of the discrete diffraction patterns of single and broad beam excitations confirmed the excellent linear properties of the arrays. They showed the linear coupling inside the array to be very homogenous in the propagation and transverse directions (see discrete linear diffraction output patterns in Fig. 1). This is a crucial requirement for a moderately localized soliton experiment and can be satisfied only by going to the limits of current fabrication technology. Nonlinear characterization showed good SHG efficiency but SH tuning curves were not ideal sinc-like in shape. A non-uniformity of the phase mismatch $\Delta\beta L$ of $\pm 10\pi$ due to a temperature distribution in the oven and sample non-uniformity was found to be the reason.

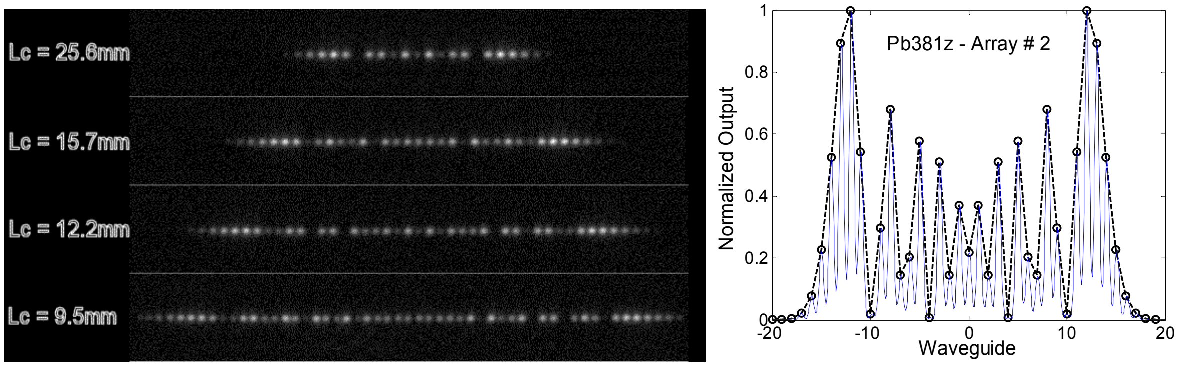

Fig.1. Discrete diffraction patterns of single channel excitation for arrays with different coupling lengths (left) and output intensity distribution for the array with coupling length l_c = 15.7mm (on the right). Circles show theoretical results, solid lines show measured data.

The experiment was performed using a home-made system, operating at λ_{FH} = 1557nm, consisting of a fiber laser by Pritel producing a 5MHz train of bandwidth limited 9ps pulses, stretched in a chirped grating, amplified in a Keopsys large core EDFA, and then recompressed in a bulk compressor to give 4.5kW of peak power in pulses 7.5ps long. Only the FH was launched and the necessary SH of the soliton was generated near the input. An elliptically shaped Gaussian beam with a horizontal FWHM of 62µm was used to excite with 50% coupling efficiency the neighboring waveguides with the same phase for straight propagation inside the array. The output of the sample was observed with cameras for the FH and the SH and with power detectors. At different temperatures with positive and negative ΔβL the output pictures and output powers of FH and SH were measured for varying input power.

In Fig. 2 the FH output for low and high power are compared for two experiments at sample temperatures which produce a positive and a negative phase mismatch (ΔβL) respectively. The 62µm wide input beam excites approximately 4 waveguides and diffracts in the array with a coupling length of l_c= 9.5mm to a 15-waveguide-wide output beam. The maximum of the input beam hits the array at a position centered on a waveguide. For a positive ΔβL at 180°C the output beam width decreases with increasing input power until it reaches the input beam width at a peak power of 700W. In that case a stable "odd" discrete soliton propagates. When the input beam is shifted such that its maximum hits the array between two waveguides a discrete soliton with an "even" profile is excited. The instability of the "even" discrete soliton, as predicted in [3], was observed in strong flickering camera pictures induced by small fluctuations in the input position of the laser beam. For a negative ΔβL at 255°C the nonlinearity supports diffraction and the beam nonlinearly broadens with increasing input power.

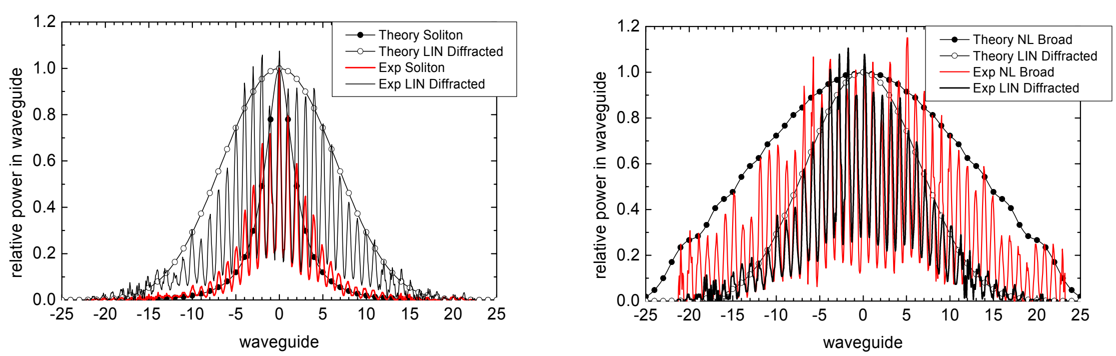

Fig.2. Discrete soliton at 700W input power (left – positive ΔβL) and nonlinearly broadened beam at 1700W input power (right – negative ΔβL) compared to linear diffracted beams for an array with a coupling length l_c = 9.5mm.

The typical evolution of the output energy distribution as a function of input peak power for the two different phase-matching conditions at temperatures of 180°C and 255°C are shown in Fig. 3 for the weaker coupled array with

l_c=12.2mm. In the first case the beam initially self-focuses and forms a soliton for the slightly reduced total input power of 575W (due to the decreased linear diffraction in that array). When the input power exceeds the soliton power, the output beam broadens again and eventually breaks up.

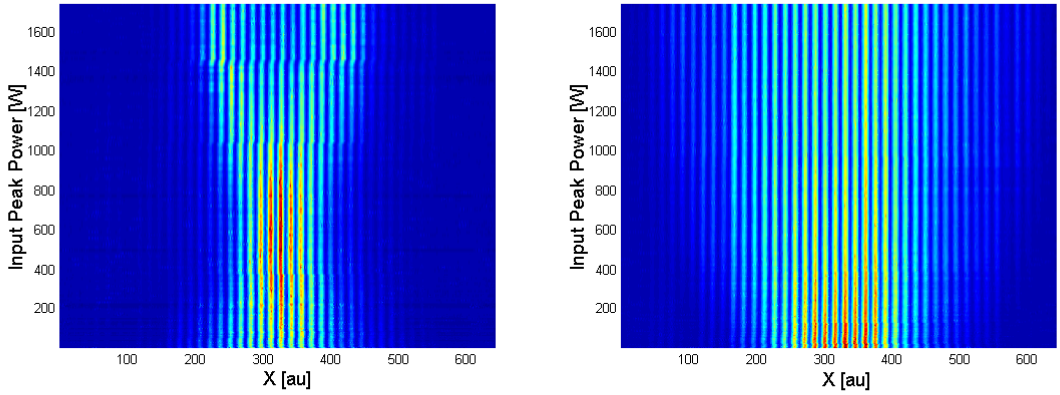

Fig.3. Output energy distribution for two different phase-matching conditions versus input peak power for the array with a coupling length l_c = 12.2mm: at 180°C (positive ΔβL) a discrete soliton formed at 575W peak power (left) and at 255°C (negative ΔβL) nonlinear beam broadening occurs (right).

Reducing the positive ΔβL by increasing the temperature to values closer to the SHG resonance, the necessary power for soliton generation decreases due to the increasing positive cascaded nonlinearity (see Fig.4). This observation together with the nonlinear beam broadening for a negative ΔβL is a strong indication for the quadratic cascaded nonlinearity as the governing effect for the observed solitons. Increasing the diffraction by using a stronger coupled array or by using a narrower input excitation leads to an increase in the soliton power. This general soliton feature together with numerical simulations of the beam propagation inside the array indicate that the observed beams are discrete solitons that have formed shortly after the input and propagate with unchanging shape through the sample.

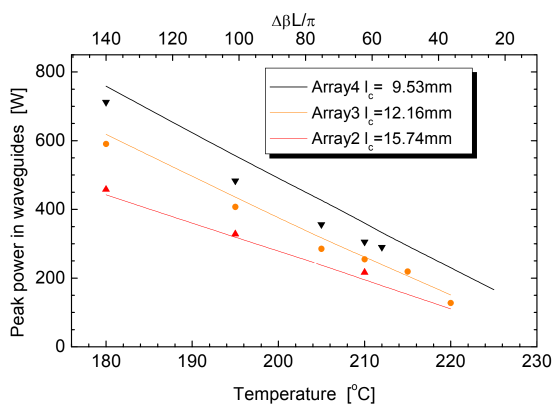

Fig.4. Soliton power as function of phase mismatch for 3 different arrays in four-waveguide-wide solitons (scattered data are measured, lines are theoretical data).

3. Conclusion

We have observed the first discrete quadratic optical solitons in waveguide arrays. The soliton properties have been measured in very good agreement with theoretical predictions.

4. References

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