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# OBSERVATION OF QUADRATIC SPATIAL SOLITONS IN PERIODICALLY POLED LITHIUM NIOBATE

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**Abstract :**

We report the first observation and characterization of quadratic spatial solitary waves in a long PPLN crystal. It is the first time a spatial soliton was excited in a nonlinear crystal designed for

second harmonic generation with a QPM technique. Self-trapped propagation was obtained on more than six diffraction lengths and for peak power as low as 5 kW.

Spatial Solitary Waves (SSW) corresponding to non-diffracting optical beams that propagate in homogeneous materials, with cubic or quadratic nonlinearity, have been predicted in the early days of nonlinear optics [1,2]. A huge variety of schemes for all-optical processing using optical second and third order nonlinearities and solitons has been proposed and often experimentally verified (see [3] for a review). For many years, however, attention has been mainly devoted to the field of third order nonlinear effects, where stable spatial solitons in pure Kerr media are limited to one dimensional propagation problems [4].

Although, as mentioned above, self-focusing effects and soliton self-trapping accompanying second-harmonic generation were theoretically discussed since the seventies, they have been rediscovered only recently by several authors [3]. Solitons in $\chi^2$ media correspond to the mutual trapping of the fundamental and the second harmonic waves that propagate as a single entity, bound together (symbiotic solitons [5]). However the clear first experimental evidence of the self-trapping of a powerful beam in a quadratic nonlinear crystal was only reported in 1995 by Torruellas and coworkers [6]. The experiments were performed in a 1cm long KTP crystal with short infrared pulses in the vicinity of phase-matched conditions. It has been shown that the output beam size diminished for increasing input intensity until the output width reached a plateau corresponding approximately to the input beam width (about 20 microns ). The observation demonstrated that on the contrary to cubic spatial soliton, two-dimensionnal solitons were stable in quadratic media. Furthermore since the experiments have been carried with a KTP crystal cut for critical type II phase-matching, it was shown that the self-trapping effect cancelled both diffraction and spatial walk-off leading to what has been called a "walking solitary waves" [7,8,9]. A second series of experiments were reported that concerned the observation of 1D-quadratic spatial soliton at 1.32 μm wavelength in a LiNbO3 slab waveguide under type I phase-matching at high temperature (330°C) [10]. It is often argued in papers that one of the motivation for the study and experimentation of spatial solitons in quadratic media is that the intensity threshold for self-trapping can be significantly lower than in cubic material. Up to now unfortunately the intensity required to obtain the self-trapping of beams with about 20 microns radius remained of the order of 10 GW/cm$^2$. This stems from the fact that some nonlinear crystals exhibit very high second order nonlinear coefficients; however these high nonlinear coefficient are not always exploitable for efficient nonlinear interactions, due to the difficulty of achieving phase matching conditions under temperature or angle tuning; it is exactly for this reason that quasi-phase matching (QPM) techniques have been proposed in the seventies [11]; nowadays QPM is not only a nice theoretical approach to phase matching but also a very promising technology to be used and further exploited [12]. The now popular periodically poled lithium niobate is one of this material of choice [13].

Spatial solitary waves in PPLN have been recently predicted theoretically and numerically [14,15], but never observed experimentally. The goal of this letter is to report the first experimental observation and characterization of spatial solitary waves in a PPLN crystal designed for SHG of 1064 nm.

It was already experimentaly confirmed that PPLN, under mismatched SHG conditions, can give rise to strong Kerr-like self-phase modulation effects. An equivalent n2 coefficient as high as +/- 2.35. $10^{-13}$ cm2/W was deduced from Z-scan measurements carried on a short crystal [16]. The main difficulty in our attempt was the preparation of a long, low period grating, PPLN crystal with sufficient transverse homogeneity. The crystal was prepared at ORC using the electric-field poling technique with a patterned electrode of 6.58 microns period.

The experiments were carried with a Q-switched mode-locked Nd :YAG laser delivering 45 ps pulses with as much as few millijoule of energy. The laser beam of gaussian transverse profile was focused onto the entrance face of the uncoated PPLN sample to a spot of 22 μm diameter (FWHMI). The NL crystal was hold in a temperature regulated oven and heated to about 160°C to prevent from photorefractive effects induced by the second harmonic. The 14.5 mm propagation distance in the crystal represented approximately 6.5 diffraction lengths of the gaussian input beam. Like in most of the experiments on quadratic spatial soliton a single infrared pulse was launched in the crystal. The ideal situation for the excitation of a soliton would have required to send simultaneously a pulse at the second harmonic with the suitable relative intensity and phase. However even the simplest case of a single fundamental input leads at high intensity to a fast conversion of the input wave to the second harmonic. It has been calculated that the two fields then reach quickly a steady-state with propagation distance corresponding to the spatial solitary wave. The poled region of the LiNbO3 wafer (0.5 x 0.5 x 14.5 mm) was carefully aligned with the optics axes of the set-up. The ouput face of the PPLN crystal was imaged with magnification onto a CCD camera connected to a beam analyzer. Two filters were alternatively introduced to select either the IR or the green outputs. The first series of recording was carried with the NL crystal tuned to almost perfect SHG phase-matching (T=162°C). We gently increased the input power and for a sufficient intensity we clearly observed a significant narrowing of the output spot at the fundamental as well as at the second harmonic wavelengths. Typical patterns at 1064 nm comparing the input (a) and the outputs respectively at low intensity (b) and above the threshold for soliton waveguiding (c) are reproduced on figure 1. The circular geometry of the input was preserved in the 2D quadratic solitary beam. The complete evolution of the output beam width versus the input intensity for a 22 μm input is shown in figure-2. The fundamental wave started to self-focus at moderate intensity and was completely self-trapped for an intensity of 1.35 GW/cm$^2$. The self-trapping was maintained up to above four times this threshold. The intensities mentionned corresponded to the peak spatial and temporal values. By comparison a KTP crystal for a comparable input required a peak irradiance for reaching soliton propagation about 10 times greater than with PPLN (10 GW/cm$^2$ ). On the other hand the effective nonlinear parameter was measured on our 14 mm long PPLN sample to be approximately 17 pm/V which was more than five time greater than KTP ($d_{eff}$=3.3 pm/V) . From the scaling law of the coupled wave equations one can deduce that the intensity threshold for soliton propagation is proportionnal to $d_{eff}^{-2}$. Consequently on the basis of the previous value published for a QSS in KTP we expected a soliton threshold of only 0.4 GW/cm$^2$ which is three times less than the measured value. The discrepancy should be explained by the strong influence of the longitudinal poling inhomogeneity on the soliton behaviour [14 ?]. We studied the variation in QSS intensity threshold with respect to a change in size of the input spot. The data are reported on figure-3. The threshold was defined here as the intensity giving an output width no larger than 20% to that of the input. As expected the soliton threshold decreased with a broadening of the launched field and the evolution was approximately fitted by a $w^{-4}$ law in agreement with what theory predicted (the w parameter stands for the characteristic beam width) [17]. The experiments were repeted for different phase-matching situations by changing the oven temperature from 140 to 170°C. This temperature range permitted to vary the ?k.L product from + 20.π to - 10.π. On the positive side of the phase-mismatch the QSS intensity threshold increased smoothly and regularly with the detuning. The shape of the plots of the output width versus intensity looked like the one of figure 2. On the contrary, on the negative side of the phase-mismatch the behaviour was slightly different. When we increased the input power level, the fundamental field first undergone a self-defocusing effect that broadened the output pattern. Increasing further the intensity the field evolution turned to self-focusing until quasisoliton propagation was reached. The same features were already reported for QSS in a KTP crystal [6]. When self-trapped, in all cases, the output waves size were comparable to that of the input. The output sizes of the pattern recorded at different phase-matching and for four values of the input irradiance are plotted on figure-4. From the curves we deduced that QSS propagation can be maintained on a broad range of positive phase-mismatches, and can even penetrate in the domain of negative mismatches, provided the intensity is high enough. Numerical integrations of the 2D+1 coupled wave equations were carried using an implicite finite difference scheme. Figure 5 presents the results of our computations on the beam width change at the ouput of the PPLN versus temperature and for four values of the input intensity. By comparing the results in figures 5 and 4 we can see an excellent qualitative agreement between the numerical and the experimental results. Note that for the given experimental conditions the role played by the equivalent (QPM induced) third order nonlinearity (SPM and XPM on the fundamental frequency and XPM on the second harmonic) was only that of slightly increasing the energy threshold for soliton formation on the positive phase-mismatch side and of slightly decreasing the threshold on the negative phase-mismatch side, similarly to what happens to solitons sustained by competing nonlinearities [18].

In conclusion we have prepared a long PPLN crystal designed for SHG of 1064 nm and we have excited self-trapped soliton propagation of narrow beams focused on the entrance face. Quadratic spatial solitons were propagated on up to more than six diffraction lengths. Under perfect phase-matching the intensity thresholds to reach soliton propagation ranged between 0.2 and 1.4 GW/cm2 for beam widths between 32 to 22 microns respectively. These are the lowest observed QSS intensities ever measured. PPLN was thus confirmed as one of the most promising material for the use of quadratic nonlinearities in view of all-optical processing. The additional advantage of QPM is that it may be spatially tailored to realize advanced photonics devices. Transverse effects like the one reported here may be also involved in optical parametric generation, in order to improve the beam quality of the converted radiations, and in the design of OPO as well.

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# Figure captions

Figure 1 : Experimental beam profiles for comparison between the input pattern (a) and the linear diffracted output (b) together with the output picture recorded at high intensity showing a 2D Spatial Solitary Wave (c)

Figure 2 : Evolution of the output beam width versus the input intensity at 1064nm, after normalization to the input size of 22 microns.

Figure 3 : Threshod intensity for SSW propagation in PPLN for different input beam widths. The solid line corresponds to a (width)$^{-4}$ fit normalized to the first experimental point.

Figure 4 : Evolution of the output beam width (normalized to the 22 microns input width) with respect to temperature variation for 0.35 GW/cm2 (dots), 0.7 GW/cm2 (up triangle), 1.3 GW/cm2 (down triangle), 1.9 GW/cm2 (square). Perfect phase matching is at 161.5 °C.

Figure 5 : Theoretical evolution of the output beam width with respect to temperature variation calculated by integration of the 2D+1 coupled wave equations for a gaussian input of 22 microns width. The different curves corresponds respectively to an input intensity of (upper to lower traces) GW/cm2, GW/cm2, GW/cm2 , GW/cm2.