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Ladislav Jankovic
*University of Central Florida*

Pierre Aboussouan

Marco Affolter

George Stegeman
*University of Central Florida*

Mordechai Katz

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Quadratic soliton collisions

Ladislav Jankovic, Pierre Aboussouan1, Marco Affolter2, and George Stegeman
School of Optics/CREOL, University of Central Florida
4000 Central Florida Blvd, CREOL Bldg., Orlando, FL 32816-2700, USA
1) Laboratoire de Physique de la Matière Condensée, Université de Nice, 06108 Nice Cedex 2, France
2) Nonlinear Optics Laboratory, Swiss Federal Institute of Technology, Zurich, CH-8093, Switzerland
Ladislav.Jankovic@philips.com
Mordechai Katz
Electro-Optics Div., Soreq NRC, Yavene, 81800, Israel

Abstract: The details of two soliton collision processes were investigated in detail in a 1 cm long periodically poled KTP crystal for the case when the solitons were excited by inputting only the fundamental beam. The effects on the collision outcomes of the distance of the collision into the sample, collision angle and phase mismatch were measured for different relative phases between the input beams. At small angles (around 0.4°) fusion, repulsion and energy transfer processes were observed, while at the collision angles approaching 3.2° the two output soliton beams were essentially unaffected by the interaction. The phase mismatch was varied from 3.5 to -1.5π for the 0.4° collision angle case. The output soliton separation at π input phase difference showed strongly asymmetric behavior with phase mismatch. In general, the measurements indicate a decrease in the interaction strength with increasing phase mismatch. All collision processes were performed in the vicinity of a non-critical phase matching.

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1. Introduction

Some of the most fascinating features of spatial solitons in continuous media stem from their particle-like interactions [1]. It is now well understood that these interactions are generic in nature and apply almost universally to spatial solitons based on all the optical nonlinearities known to date. They do vary in minor details, the most important being that Kerr solitons never fuse together on collision [1]. These generalities have been borne out for solitons in Kerr systems, photorefractive systems, liquid crystals, quadratic media, dissipative systems with gain etc. [2-7]. Of particular interest to this paper are interactions between quadratic solitons because of the way that the solitons are launched [8,9]. Quadratic spatial solitons (QSSs) consist of different spectral components linked via a second order nonlinearity [10]. They have most frequently been investigated under conditions of almost phase-matched second harmonic generation utilizing either birefringent or quasi phase matching. Typically only the fundamental beam (FW) is launched and the QSS is formed some distance into the medium when the generated second harmonic (SH) wave becomes locked in amplitude and phase to the values needed for a spatial soliton. This excitation method for a QSS has proven successful, but has also led to other effects such as multi-soliton generation [11-14]. Here we investigate in detail its effect on QSS interactions.

Interactions between quadratic solitons (for early theoretical considerations of type I $\chi^{(2)}$ soliton interactions see for example ref. 34) have been observed in both 1D (waveguides) and 2D (bulk media) [5,15-18]. The basic results have been confirmed for co-planar interactions, namely attraction for in-phase solitons, repulsion for out-of-phase solitons and energy exchange at other relative phase angles. Furthermore, for the out-of-plane case, rotation about a common axis and even the creation of a third soliton have been observed [16,17]. The experiments have been configured so that the interaction occurred roughly in the middle of the crystal. However, all of these experiments involved excitation by launching the fundamental beam(s) only at the input crystal facet and it has always been assumed that the colliding beams were solitons, and that the output consisted of fully formed solitons. In this paper we examine QSS interactions as a function of distance into the crystal, of relative angle of launch and the variation with phase-mismatch. The results give an insight into the conditions under which the collisions indeed occur between solitons, and whether the output beams are solitons.

2. Relevant properties of quadratic spatial solitons and their interactions

The detailed properties of quadratic solitons can be found in a number of papers [19-23,33]. For quasi-phase-matching (QPM) implemented by periodic poling to periodically reverse the sign of the nonlinearity, the case of interest here, QSSes consist of in-phase, co-polarized FW and SH beams [24,25]. Since QPM along crystal axes implies non-critical phase match (NCPM) in ferroelectrics, the soliton properties are identical for equal incident angles on either side of the NCPM axis.[11,26] The amplitudes (and intensities) of the FW (wavevector $k_1$) and SH (wavevector $k_2$) components near NCPM are determined by the input power and the low power wavevector mismatch $\Delta k = 2k_1-k_2$ [27,28]. When solitons are formed, the effective high power soliton wavevector mismatch $\Delta k_0 =0$ and this is achieved by additional nonlinear phase shifts $\Delta \phi_1$ and $\Delta \phi_2$ that are linear in the propagation distance $z$ so that $\Delta k = (2\Delta \phi_1-\Delta \phi_2)/z=\Delta k_0 =0$ [23,29]. (Note that $\Delta k_0 = \Delta k$ only on phase-match.) As a result, the threshold power needed for stationary solitons is minimum at $\Delta k =0$ where $2\Delta \phi_1=\Delta \phi_2$ [27,28].

These solitons form a two parameter family, one of which is the wavevector mismatch $\Delta k$ and the second is basically a power-width trade-off similar to that in Kerr solitons [23,27]. Thus above the threshold for a given $\Delta k$ there is a continuum of QSSes with their width decreasing with increasing power. For stable QSSes, the ratio of the FW power to SH power decreases with $\Delta k$ decreasing from large positive values, to zero, to large negative values [27,28] As stated previously, QSSes are normally generated by inputting only the FW and relying on propagation distance for the SH component to grow.[9,12,28] Since solitons
are “strong attractors” (i.e. eigenmodes of nonlinear optics), at soliton forming powers the relative phase between the FW and SH evolves towards the in-phase condition $\Delta k_s = 0$. There are two repercussions to FW only excitation for varying $\Delta k$. A larger input FW intensity is needed to generate the required SH for soliton formation as $\Delta k$ decreases, i.e. the soliton generation threshold is higher for FW only excitation. [29,30] Also, this process is not adiabatic and radiation fields are generated at small angles to the soliton propagation axis during the evolution of the soliton. [12] The larger the SH soliton component required, the more radiation is emitted. Therefore the threshold for soliton excitation by FW only input is larger and a more intense radiation background exists for $\Delta k < 0$ than for $\Delta k > 0$. Details on the soliton formation processes in periodically poled KTiOPO₄ (PPKTP), the crystal used in the present experiments, are given in references [12,13,25,26].

The physics of the interactions between QSSes has been explained in simple terms in reference 29. Basically the interaction is a result of the products of the FWs and the FW and SH from different solitons. This leads to attraction for in-phase fields, repulsion for out-of-phase fields and energy exchange between solitons for other relative phase angles.

3. Experimental conditions

The experimental setup was organized as shown in Fig. 1. An EKSPLA, 10Hz, Nd:YAG laser was used as a light source. The 1064nm laser beam, used as the fundamental beam in the soliton processes investigated, was spatially filtered, divided into two beams by a 50:50 beamsplitter, passed through a delay line and a polarizer-halfwave plate combination to control the relative polarization between the input beams. A glass plate (Phase Shifter) was used to introduce a phase shift difference between the beams. Tilt of the glass plate which was positioned in only one arm of the setup was computer controlled. The two beams were directed to a common, 10cm focal length, focusing lens by a beam-combiner and focused down to two separated spots, 16.5$\mu$m FWHM (full width at half maximum). The focal plane of the lens corresponded with the input surface of the sample giving Gaussian shaped beams with planar phasefront inputs, thus facilitating soliton formation. Each input arm generated a separate soliton in the PPKTP sample. After the two beams interacted in the sample and exited through the output facet, the resulting intensity pattern was imaged onto a CCD camera by another lens (4cm focal length). In Fig. 1 the numbers 1 and 2 designate two mirrors which can be inserted into the optical path to image the focal plane of the incident lens onto the CCD camera in order to measure the beam distribution at the sample’s input surface. The collision angle and the collision point were determined from the input and output intensity distributions.
when interaction did not occur as caused by a difference in the timing between the beams (facilitated by the delay line).

The sample used in the experiment was a 10mm long, periodically poled, b-cut KTP crystal. The periodicity of the poling structure was 9µm, providing quasi-phase matching for 1064nm at 43.6°C. The input fundamental beam (1064nm), polarized vertically (along the c crystal axis) was launched into the sample. The generated second harmonic (SH) polarization was co-parallel with the fundamental beam (FW). For the given crystal configuration the effective nonlinear coefficient was \(d_{eff}=9.5\text{pm/V}\) [31]. Due to the quasi-phase matching the experiment was performed in the vicinity of non-critical phase matching (NCPM) so that the structure of the quadratic solitons changed only weakly with angular tuning [11].

Solitons are generated in these PPKTP samples for intensities above 3GW/cm\(^2\) (soliton threshold) for the given beam parameters.[25]

4. Collision processes and soliton formation

Because with FW input only the required SH and hence the solitons are generated after some propagation distance into the crystal as discussed previously, a soliton collision process should depend on the specific physical collision point inside the sample. The “collision point” designates the distance from the front facet of the sample to the position where the collision occurs based on the input and output beam separation in the absence of interaction, as shown in Fig. 2(a). In the first set of measurements performed, the angle was kept around 0.4° so that soliton interaction area (see Fig. 2(b)) is kept the same. The sample temperature (43.6°C) was set to correspond to NCPM and the input beam intensities, around 3.3GW/cm\(^2\), were kept slightly above the soliton threshold (~3GW/cm\(^2\)) [25,26]. The higher the input intensity, the shorter the distance usually required for soliton formation. Thus by operating just above threshold, it was expected that phenomena connected with incomplete soliton formation would be exaggerated and amenable to investigation.

![Diagram of collision processes performed at the same collision angle and propagation direction]

Fig. 2. Interaction geometries (a) The collision point. (b) The interaction region.

The output patterns from the camera shown in Fig. 3 illustrate the effects of incomplete soliton formation on the collision results. The results for two collision points, 4.1 and 6.6mm into the sample which illustrate the effects of incomplete soliton formation are shown. Clearly there are collision position dependent changes in the output. For a collision distance of ~6.6mm, the results are in good agreement with theory indicating sufficient soliton formation prior to collision.[32] The output beams are around 18µm size corresponding to well-formed solitons. The 0° relative phase case shows at the output a collapse into a single, high intensity beam, around \(\pi\) two well-separated beams result, and at other phase angles energy has been transferred preferentially to one soliton at the expense of the other with a reversal of the energy flow direction occurring in passing through \(\pi\) (see Ref. [29] for a more detailed discussion).
The most prominent differences between the two collision points, 4.1mm versus 6.6mm, occur primarily in the beam shapes at 0 and $\pi$ phase difference. The 4.1mm output beams are up to twice wider than for the 6.6mm case, indicating that the input solitons were not well formed. Note that in the 4.1mm case with 0$^0$ phase difference, a beam leaves the collision with sufficient intensity to eventually evolve into a soliton. However, at $\pi$ relative phase, the output beam is barely visible for the 4.1mm case, representing strongly diffracted beams with a peak intensity value an order of magnitude lower than for the corresponding 6.6mm output. In fact the input beams interfere with each other soon after entering the crystal for the 4.1mm case, resulting in quasi-linear interference effects. Evolving beams, not yet having formed solitons, are strongly influenced by these interference effects. At intermediate phase differences, the effects of the limited soliton formation are smaller. Intermediate collision distances showed results intermediate between the two cases discussed. Clearly, there is a minimum propagation distance before the beams collide required in order to perform “soliton” collisions. For the current case this distance is around 6mm.

For completeness we also show in Fig. 4 the output of a collision in which the input solitons are well-formed, but the collision occurs too close to the end of the sample for the output products to be complete solitons. The most common feature is that the output beams are not circular in shape.
5. Collisions at different phase mismatches

The phase mismatch influences both the SH conversion and soliton generation processes and therefore should also affect soliton collisions. In fact, ref. [6] reported numerical and experimental comparison between the soliton collision process at large and small phase mismatch, 19π and 1.36π respectively. They observed significant differences in the collision outputs as the effective Kerr limit was approached around 19π. For smaller values of Δk, as in our measurements, features associated with Kerr-like effects do not contribute significantly.

The threshold intensity required for the soliton generation increases for Δk≠0 and the generated solitons do not have necessarily the same FW/SH ratio as the ones generated at PM.[27,28] In order to investigate the effects of phase mismatch on the collision processes the soliton collisions need to be performed under nominally the same conditions except for the different sample temperatures (different phase mismatch). The input beam intensities were kept around 1.7 times the soliton threshold, higher than that previously used in order to reduce the distance required for soliton formation. Figure 5 shows the input beam intensities for this case. The steeper slope at the higher temperatures (negative phase mismatch) is consistent with the higher threshold intensity required to generate solitons, especially with FW excitation only.
Fig. 6. Dependence of the output patterns versus relative input FW phase at phase-match (upper set) and a phase-mismatch of 3.5π. Input soliton intensities were 5.2 GW/cm² and 8.0 GW/cm² respectively, both at 1.7x the threshold intensity.

Figure 6 shows the output soliton patterns observed for a collision angle of 0.4° at both PM and a 3.5π phase mismatch. The solitons collided after 5.5mm of propagation through the 10mm long sample. The soliton separation at the input sample surface was ~38µm and the input beams were around 16.5µm in size. The output patterns demonstrate fusion around 0° and repulsion at π for both cases. Note that the solitons are better confined at the higher intensities associated with Δk≠0. However the detailed behavior is different. At a phase mismatch of 3.5π the generated soliton is surrounded by an enhanced radiation pattern (bath)
relative to the PM case, indicating that stronger coupling to radiation fields occurs for collisions with $\Delta k \neq 0$. Furthermore, the separation between output solitons at $\pi$ phase difference is larger on phase mismatch. For phase differences away from 0 or $\pi$, the energy exchange between the two colliding solitons is less efficient away from phase match as evidenced by the existence of the second soliton in many cases. This indicates weaker interactions off phase match.

The interaction strength can be estimated by comparing the solitons’ separation at $\pi$ relative phase at different phase mismatch. Output patterns for collision processes performed under similar conditions (collision angle 0.4°, collision point 6.6mm and input intensity at 1.7 times the relevant phase mismatch dependent threshold) but at different phase mismatch are shown in Fig. 7. The solitons are well formed prior to collision although significantly more radiation (the vertical fringes on the pictures) occurs for large negative phase mismatch ($T > T_{PM}$). The output pictures show significant differences in the soliton separation with temperature. Clearly the separation is the smallest for the phase matched configuration and ranges from ~23μm at the phase match to ~30μm at 27°C. In fact, both the input intensity and the separation increase together with increasing phase mismatch. At negative phase mismatch there is a high intensity background consisting of vertical fringes. The interference comes from the radiation associated with the solitons’ generation. Because of this background the transverse soliton mobility is increased and influences the final distribution of the solitons. Note that in the 50°C result, the fringe separations are larger and that the solitons appear to be “pulled apart” by the fringes on which they “sit”.

![Fig. 7. Collage of output beam patterns obtained for a collision angle of 0.4° for different phase-mismatch. Here the PM temperature corresponds to 43.6°C.](image)

The curve in Fig. 8(a) shows in greater detail the soliton separation versus the phase mismatch for a $\pi$ phase difference between the input beams. The measurements were taken under the same conditions as in Fig. 7. As seen from Fig. 8(a), the solitons have the smallest separation for the phase matching case. The separation increases with the phase mismatch reaching its maximum (~30μm) at around ±2$\pi$. The oscillations seem to exhibit a trend to higher separation with increasing $|\Delta k|$ with a superimposed regular periodicity with a $\Delta k L$ of approximately $\pi$. The general trend mirrors the threshold soliton intensity and presumably reflects an increase in interaction strength with increasing $|\Delta k|$ and hence input intensity.
Fig. 8. (a) Separation of output beams versus phase-mismatch (and temperature) for $\pi$ relative phase between the two FW input beams. (b) Separation between the output solitons at various input intensities obtained from numerical simulations of soliton collision processes. The initial relative phase between the beams was fixed at $\pi$.

CW numerical simulations corresponding to the experimental conditions were used to investigate the dependence on input intensity of the soliton separation at $\pi$ relative phase difference. This phase difference was chosen because experimentally it was observed that this case produced the largest observable effects of incomplete soliton formation. Increasing the intensity decreases the parametric gain length for the SH process and hence leads to progressively shorter distances for soliton formation. The calculations were restricted to the phase matching case. As shown in Fig. 8(b), the separation increases by approximately 15% as the input intensity is increased by 50%. However with further intensity increase the separation remains essentially the same until intensity levels at which additional effects associated with strong radiation created during soliton formation come into play. This behavior confirms the conclusions that a certain level of soliton formation is necessary in order to investigate ideal soliton collision processes. Figure 9 shows how the cw intensity profiles develop during the collision processes for a 0.4° collision angle. The beams tend to interact longer at lower intensities, as expected.

Fig. 9. Numerical simulations of the soliton collisions at different intensities and phase mismatch. FW beam profile is shown only.

In Fig. 10 the solitons output separation data versus relative input phase of the fundamental beams is shown for a number of phase mismatch configurations. The collision angle was ~0.4°, the collisions occurred after ~6.6mm of propagation through the PPKTP sample and the intensities used correspond to the values given in Fig. 5. The solitons are well-
separated around the relative phase of $\pi$, as expected (varying from ~23$\mu$m on PM to ~30$\mu$m at 3.5$\pi$ phase mismatch), and soliton fusion occurs around 0° phase difference, again as expected. The small variations of the nearly flat response around $\pi$ phase (typically 3-5$\mu$m variations) occur quite consistently in the data shown and are not understood at this time. The solitons with a relative phase close to 0° undergo strong energy transfer along their propagation. If the energy transfer is strong enough the solitons eventually collapse into one soliton and the remaining energy is either captured by the existing soliton or it appears as radiation. If the solitons do not fuse they propagate along approximately the same paths as those for the $\pi$ phase case. In some cases solitons were observed to perform small spiraling (the 43.6°C case in Fig. 10) indicating non-coplanar interactions. This would be expected to cause only a small deviation.

![Graph showing soliton separation as a function of relative phase.](image)

**Fig. 10.** Output beam separation as a function of relative phase between the two FW input beams for a number of different temperatures, i.e. phase-mismatch.

As indicated in Fig. 10, the range of relative input fundamental phases for which a single output soliton is observed decreases as the phase mismatch increases, believed to be an indication of weakening interaction processes. This contradicts a conclusion of a strengthening obtained from the absolute separation between the output solitons as the phase mismatch is increased when the relative phase between the input beams is kept at $\pi$. This dependence on the phase angle was not expected. Unfortunately the difficulties in clean soliton generation at large negative phase mismatch ($T > 46^\circ$) limited investigation of these features in that region. However, the behavior at $T=46^\circ$ is similar to that for $\Delta k L>0$, indicating suppression of the fusion effect at negative phase mismatch relative to PM. The detailed phase-dependence of the soliton separation is different for $\Delta k L<0$ versus $\Delta k L>0$. Altogether, the phase difference region in which a single soliton is output decreases by about a factor of two from phase-match (43.6°C) to phase mismatch at $T=33^\circ$ and it occurs only in the close proximity of 0° relative phase at $T=27^\circ$.

In summary, the details of the features depend on a number of parameters such as the collision point and/or the collision angle, especially for the range over which effectively fusion occurs. In addition, if the input beams are not equal in intensity (not shown here), the measured curves become asymmetric, showing monotonic drop/rise in the soliton separation when going from smaller to higher phase difference. However the abrupt changes from one output soliton (fusion or complete energy transfer) still occur. Finally, the variation with relative phase was richer than expected.
6. Soliton collisions at “small” and “large” angles

It is known from theoretical considerations that as the collision angle increases, for large angles the solitons no longer exchange energy, fuse or repel although there is a lateral displacement in the trajectories [1]. The decrease in the interaction strength with increasing collision angles is dominated by the resulting decrease in interaction region, see Fig. 2(b). The phenomena is somewhat more complicated because of the reduction in the generation efficiency of the SH components of the soliton with increasing relative angles (and hence phase mismatch). However it is known from previous experiments in PPKTP [25] that the soliton generation acceptance bandwidth can be several degrees wide in the vicinity of NCPM and so changes in the soliton composition are small when the relative incidence angle is increased.

Details of the small collision angle case for changes in phase match and relative input phase have already been discussed. Here we concentrate on an experimental investigation of the dependence of the collision processes on changes in the collision angle. The initial experimental setup (Fig. 1), used to perform the small collision angle measurements, was limited by the acceptance angle of the optical imaging system. It limited the collision angles studied to less than ~0.7°. To perform the experiments with larger collision angles the imaging system was modified resulting in ~13 times decrease in the system magnification.

![Fig. 11. Collage of output beam patterns for a variety of relative FW beam input phases and incidence angles.](image)

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The sample temperature was kept at 27°C (ΔkL=3.5π) to operate with positive phase mismatch. The input beam energies were around 9GW/cm², slightly lower than twice the single soliton threshold at the given phase mismatch. As a result of this high intensity the solitons were generated within a short propagation distance into the crystal. The measurements corresponding to the collision angles 0.2, 0.35 1.1 and 3.2 degrees (the collision points are 5.8, 6, 5 and 4mm respectively) are shown in Fig. 11 for a few selected phase differences. The numbers on the left side indicate the relative phase difference between the initially launched FW beams. The large magnification scans for the 0.2° and 0.35° collision angles show features similar to Fig. 6. The fusion and the inter-soliton energy transfer processes are clearly visible at small angles. The output pattern changes dramatically from small to large collision angles even when the difference in magnification is factored in. As the angle increases to 1.1°, the phase dependence decreases significantly. At 0° and 2π relative phase the two beams tend to attract, and as seen from Fig. 11 they collapse towards each other. The resulting beam is elongated and due to the smaller magnification of the imaging system it is not clear if the beams only attract or if they are already partially fused. At the other phase differences the solitons go through the energy exchange processes but their efficiency is significantly smaller than for the small collision angle case. For example, while the weaker output soliton carries around 25% of the total energy for the 0.35° case at the π/2 relative phase, it contains almost 45% of the total energy for the 1.1° case indicating a weak interaction.

At the 3.2° collision angle, the propagating solitons essentially pass through each other, independent of the relative phase. The small changes in the relative solitons’ intensities (below 7%) observed in the output pattern are rather stochastic in nature and do not reflect any significant interactions.

A summary of the dependence of the output soliton separation on the collision angle is shown in Fig. 12. The graph shows soliton separation versus relative input phase difference for the three characteristic angle regimes. Zero separation indicates a single soliton output corresponding to either soliton fusion or effectively complete energy exchange. For the 0.35° collision angle curve, essentially small collision angle behavior is observed. Fusion occurs in the region around 0° relative phase and repulsion over a wide range of relative phase around π phase difference. The soliton collisions at large angles 1.1° and 3.2° show very different behavior from the 0.35° case. For the 1.1° case there is still a significant drop in the soliton separation at 0° relative phase, indicating that the interaction process still influences the output solitons. The soliton separation achieves approximately a constant value (~100µm) over a very large region of the relative phase. The asymmetric shape is believed to be associated with
the data processing procedure that is limited by the imaging system magnification and resolution. For the 3.2\textdegree configuration the interaction processes have negligible influence on the colliding solitons due to the short interaction distance. The curve is featureless with only small stochastic oscillations around an approximately constant 320\textmu m soliton separation. Finally we note that to first order the plateau separations, \textasciitilde35\textmu m, 100\textmu m and 310\textmu m reflect the increase in collision angles of 0.35\textdegree, 1.1\textdegree and 3.2\textdegree.

7. Radiative losses on collision

In collisions, quadratic solitons interact with each other and due to the nature of this interaction, which has been previously discussed, the outcomes of the collision processes are phase dependent. Well-formed solitons exhibit a specific SHG-FW composition. Once a soliton interaction occurs, the intensity profiles can in some extreme cases change dramatically, varying from a single to a three soliton output. Here we are primarily interested in investigating single soliton outputs when fusion and repulsion occur with two input solitons colliding at around a 0.4\textdegree angle. As discussed previously, in a real experiment when a FW only is launched into a nonlinear medium, a quadratic soliton forms only after a certain minimum propagation distance determined by the input conditions (input beam size, intensity, phase matching, linear and nonlinear properties of the medium). The process of soliton formation is non-adiabatic and therefore energy loss occurs in the form of radiation rings. Once the fields associated with two solitons come close enough to overlap significantly, interactions occur and the solitons eventually can experience very significant transformations dependent on multiple input collision parameters – angle, intensities, soliton composition, etc. An important question is whether the collision causes significant changes in the composition and individual intensities of the output solitons. From some previous studies on soliton collisions in potassium niobate [17], the changes in output soliton intensities with variations in the relative phase between the solitons were measured to be less than 10\%, which was of the same magnitude as the energy fluctuations of the laser used in those experiments.

Here we present measurements of the soliton’s FW and SHG output intensity as function of the relative phase between the solitons (Fig. 13) for three different phase matching conditions. As shown in the Fig. 13, the changes are limited to oscillations of \pm 7\% in the output SH and FW intensity, in agreement with previously measured energy changes in potassium niobate. The measurements show systematic increases (and decreases) in the FW that correlate with decreases (increases) in the SH. However, the limited crystal length prevents a precise evaluation of the final (well after complete separation) SH/FW ratio. Numerical simulations indicate that the complete conversion process requires typically more than 2cm of propagation (double the length of the current sample). Furthermore, we were also limited by the aperture of the detectors and imaging system used. Under current conditions the detectors captured both the solitons and the radiation emitted during the collision and therefore the energy fluctuations measured are probably smaller than those that should be associated with only the output solitons.

Small radiative losses of \textasciitilde7\% were measured in the collision processes investigated here. The 1cm sample does not provide enough propagation distance for the solitons to reach steady state after the collision process. As a result, a more accurate analysis of the radiative losses was not possible in our experimental conditions.
8. Conclusions

An extensive experimental investigation of quadratic soliton collisions was performed in a PPKTP crystal. The collision processes were investigated for various phase mismatches, collision angles and collision points. In addition, the relationship between the collision processes and the relative phase between the solitons was investigated. The recorded patterns and the data extracted from them indicated a weakening of the interaction processes with increase in the phase mismatch at 0° and a strengthening for π relative phase. In addition, at larger collision angles, the interaction efficiency decreased due to reduced interaction length and finally vanished at around 3° collision angle, as expected.

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