Complex soliton-like pattern generation in Potassium Niobate due to noisy, high intensity, input beams

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Abstract: We report the generation of complex soliton-like patterns in non-critically-phase-matched potassium niobate which occur in random spatial patterns from shot-to-shot. Up to five spots have been generated at input intensities of 10's GW/cm^2, many times the single soliton threshold. The mechanism which leads to the symmetry breaking required for the complex patterns is interpreted to be random noise imprinted on the input light.

OCIS codes: (190.5530) Pulse propagation and solitons; (190.4410) Nonlinear optics, parametric processes

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1. Introduction

A key property of many optical solitons, that is intrinsically linked to their stability, is their existence as the lowest-energy state of a dynamical system, and hence their ability to emerge from arbitrary initial conditions [1,2]. Quadratic solitons exhibit this property since they can be generated by inputting only a fundamental beam and the harmonic required for a stationary soliton can be generated on propagation into the medium [3,4]. However, because these excitation conditions might be very far from the stationary soliton solutions, the solitons evolve non-adiabatically and large amounts of radiation might be emitted [5]. It has recently been shown that this emitted radiation can lead to the formation of additional solitons, either by their coalescence in certain regions of space or by the fast break-up of the input beams [6-10]. These additional solitons have been predicted to align themselves either along directions dictated by the anisotropy in the diffraction in the crystals, [8] and more typically by dominant elliptical asymmetries in the incident beam [9]. To date the experiments on multi-soliton generation have all reported multi-soliton generation to occur along lines in space [6-10]. However, it was also predicted that in the case of ideal continuous-wave illumination, quasi-random 2D patterns of the generated solitons should be possible due to the amplification of the spatial noise on the input beam. Furthermore, at high input intensities, the presence of temporal noise can also drastically impact the light evolution, as revealed recently in the time-resolved experimental investigation of the properties of quadratic solitons reported by Minardi and co-workers [11]. In this paper we observe the generation of patterns of soliton-like spots in the energy-integrated output images whose spatial distribution changes on a shot-to-shot basis in non-critically-phase-matched (NCPM) potassium niobate ($KNbO_3$).

2. Results and discussion

The current experiments on soliton-like pattern generation were performed in a 1 cm long $KNbO_3$ crystal with propagation along the "b"-axis [6]. For fundamental light polarized along the "a"-axis, the second harmonic is generated via birefringence NCPM polarized along the "c"-axis with an effective nonlinearity of -12pm/V at room temperature at an incident wavelength of 983.5nm [12]. Collinear multi-soliton generation has been reported previously in this sample geometry [6]. An EKSPLA OPG/OPA (optical parametric generator/optical parametric amplifier), pumped by the harmonic of a Nd:YAG laser was used to generate tunable radiation in the 980nm wavelength range with typical shot-to-shot variation in pulse energies of ±7%, rms. The pulses were approximately 22ps in duration with a bandwidth of ≈0.5 nm, with a repetition rate of 10Hz. The output beam was spatially filtered to give a M^2 ≈1.05, where the laser beam quality factor M^2 is defined in terms of w(z) the beam waist at beam propagation position z after the minimum beam waist w_0 and λ the laser source wavelength with $w(z) = w_0\sqrt{1+[M^2\lambda z/(\pi w_0)]^2}$. The energies and spatial distributions of all of the relevant beams were measured and cameras were used to image the input and output intensity distributions. Figure 1 shows a typical measured, color coded, two dimensional intensity distribution of the input beam for a single pulse. The presence of significant spatial noise is clear.

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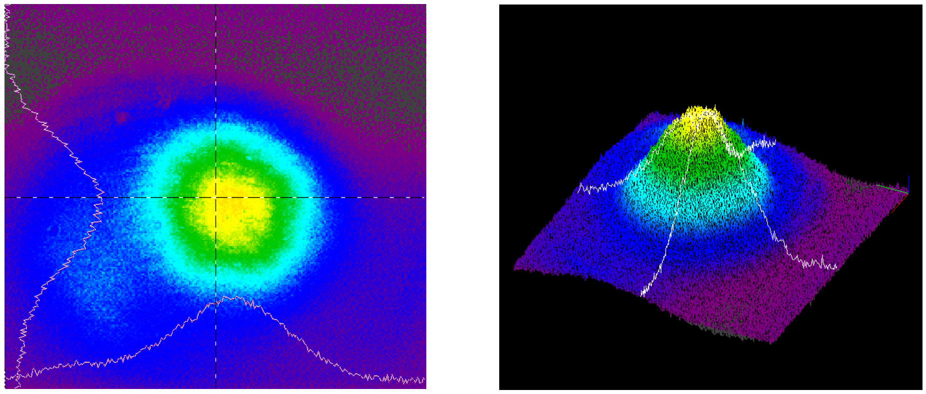

Fig. 1. A typical, experimental intensity distribution of the input beam in 2 and 3D.

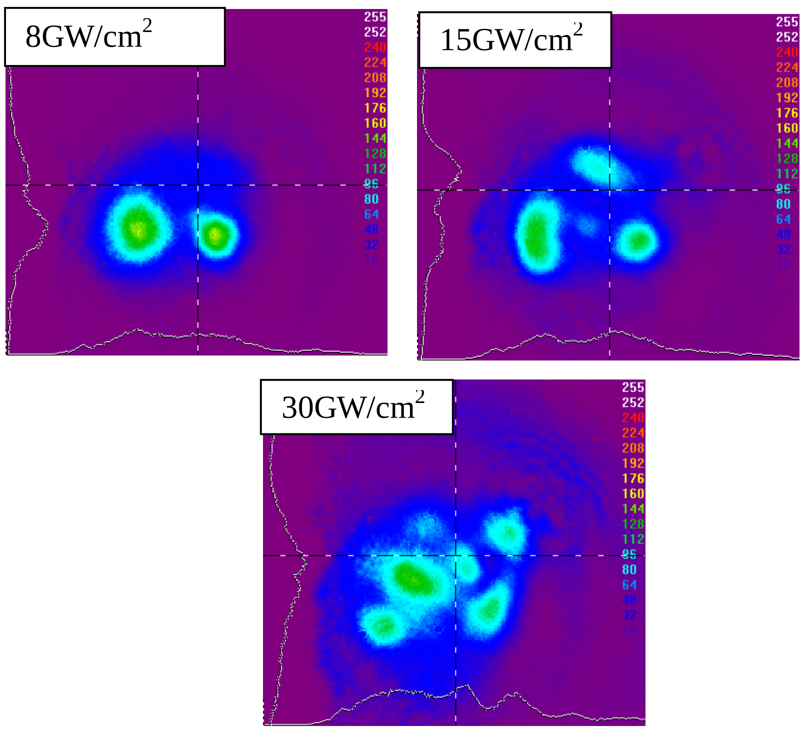

Fig. 2. (Movies 128KB, 288KB and 423KB) Three collages of output beam patterns obtained for peak input fundamental beam intensities of 8 GW/cm^2, 15 GW/cm^2 and 30 GW/cm^2. Successive frames correspond to successive laser pulses at the same peak input intensity.

The evolution obtained for the different patterns observed are shown in Fig. 2 for three different intensities, namely 5, 15 and 30 GW/cm^2. In each case there is a collage of output patterns corresponding to successive laser pulses of nominally the same total energy and pulse width. In fact, as a result of random temporal and spatial noise on the pulses, the successive patterns vary widely from one another. In Fig. 2(a) (5 GW/cm^2 peak intensity input), the predominant pattern consists of two localized beams aligned approximately horizontally. Note that the single soliton threshold for these conditions (i..e, a beam waist ~18µm, with $M^2 \approx 1.0$)

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is about 2.7 GW/cm^2, [7] thus the input peak intensity in Fig. 2(a) is subcritical for two solitons to be formed at these sample lengths. Therefore, the soliton nature of the two spots visible in the plot is questionable. Still, the generation of two well-defined light spots is clearly visible. For fundamental beam inputs of ≈15 GW/cm^2 peak intensity, i.e., 5 times the single soliton threshold (Fig. 2(b)), the output patterns are more complex, exhibiting 2-3 localized spots, frequently non-collinear along a single line. At even higher input intensities, of order 7-10 times the single soliton threshold peak intensity (Fig. 2(c)), the successive output patterns vary widely from shot-to-shot. Up to 5 non-collinear light spots are observed.

In Fig. 3 is shown a variety of interesting patterns observed experimentally, and the conditions under which they were obtained. Notice that in all of the acquired images some of the light spots exhibit irregular shapes and that the different spots carry widely different energies. The former observation is partially attributed to the off-axis overlap produced by the collage of several laser pulses shown in each plot and the latter to the asymmetric input beam break-up. Also, we stress that with increasing input intensity, the differences between the successive output light spots patterns increased, an indication that the observations are driven by the spatio-temporal dynamics mediated by both, the spatial noise imprinted on the beams and the temporal noise imprinted in the light pulses.

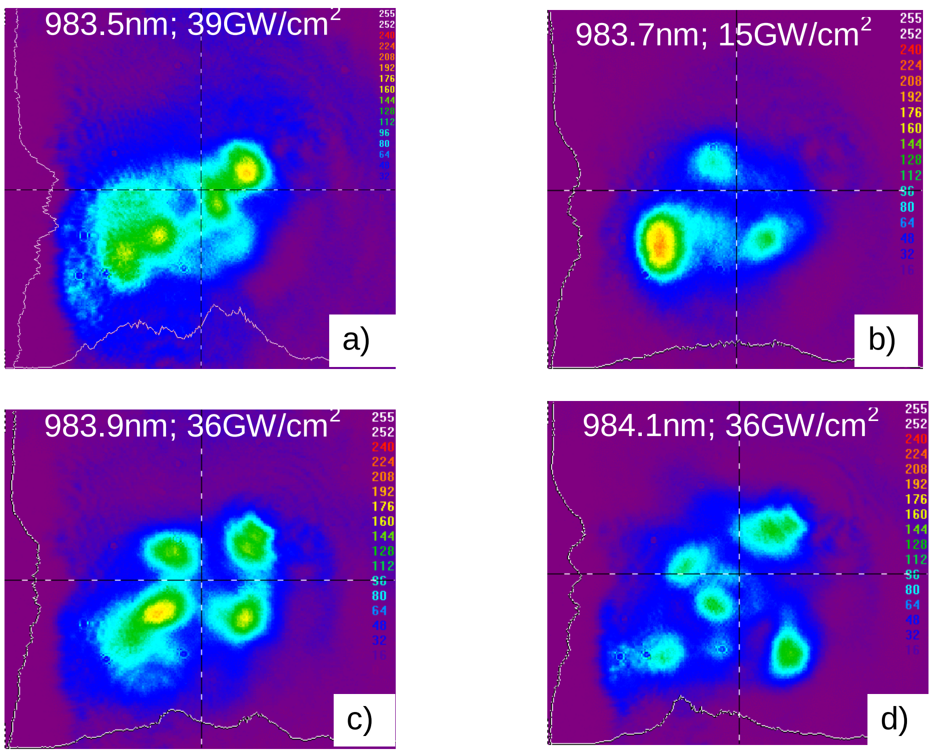

Fig. 3. Selection of four output patterns obtained under different conditions.

A variety of different mechanisms play a significant role in the light evolution under the high-peak power conditions of the current experiments. On one hand, for a given input beam width there is a characteristic threshold for the input intensity required for single soliton generation, and as the input intensity is increased well above this threshold, multiple solitons are generated by the amplification of asymmetries. Such multiple soliton generation can take place even with continuous wave signals, when the input beams contain minute asymmetries, of the order of the wavelength. Such minute asymmetries might be induced by small astigmatisms of the optical components or by random noise added to the input light beams

[9,10]. Note, however, that the laser-OPG-OPA combination used in these experiments also leads to significant temporal noisy pulses. The spatio-temporal dynamics generated in high peak-power up- and down-conversion processes in the soliton regime has recently been shown to lead to pulse break-up in time by Minardi et al [11]. Such temporal break-up and the corresponding spatio-temporal dynamics associated with the presence of temporal noise on the pulsed input beams is believed to also impact the generation of the multiple light-spots described in our experiments, as indicated by the observations described above. This conclusion is also supported by preliminary three-dimensional numerical simulations that were conducted to gain insight into the light evolution inside the potassium niobate crystal. In particular, in the presence of temporal input noise, break-up of the pulses into several sub-pulses, which then add-up into multiple-peak patterns in time-integrated images due to the presence of spatial noise, was observed to occur in spatio-temporal simulations including quadratic nonlinearities and group-velocity-dispersion, conducted under the general conditions of the experiments. Therefore, in the case of noisy input beams and pulses, the full spatio-temporal dynamics mediates the formation of the observed multiple spot light patterns. With regard to the impact of the spatial noise alone, an important conclusion of the simulations, in agreement with previous predictions [9], was that small noise strengths (e.g., 2 %) suffice to lead to multi-soliton generation. The beams used in the current experiments exhibited a significant higher noise, thus the spatial noise on the input beam is critical to the interpretation of the observations.

On the other hand, potassium niobate exhibits a variety of linear and nonlinear properties besides the usual diffraction and purely quadratic nonlinearities, whose combination can also impact the precise outcome of the experiments. First of all, potassium niobate is a biaxial crystal which exhibits anisotropic diffraction, with diffraction ratios, $D_{11}/D_{12} = 0.966$, and $D_{21}/D_{22} = 1.176$, for the fundamental and harmonic beams respectively where D_{11}, D_{12}, D_{21} and D_{22} stand for the diffraction of a fundamental wave (FW, first index is 1) and second harmonic (SH, first index is 2) along the y (second index is 1) and z (second index is 2) axes respectively (see [8] for full details). Second, two-photon absorption (TPA) is large at the harmonic wavelength (TPA coefficient $\alpha_2 \approx 4 \times 10^{-11}$ m/W) at the intensity range used here [13]. Cubic, third-order nonlinearities are small at this wavelength (i.e., $n_2 \approx 6 \times 10^{-6}$ cm^2/GW) [14]. Note, in particular, that the strong TPA reduces the beam intensities very significantly inside the sample, thus weakening or even destroying the soliton-like nature of the output light spots.

It is thus important to stress that elucidation of the detailed origin of the observed multiple-spot light patterns is a complex problem to which several physical effects can contribute and requires extensive, detailed simulations, to be performed in the future. For example, not only are quadratic nonlinearities important, but at high intensities higher-order effects must be also taken into account, especially two photon absorption.

3. Conclusion

In summary, the symmetry of the spatial distribution of the multiple light spots generated for input intensities a few times the single soliton threshold no longer holds at intensities an order of magnitude larger than the single soliton threshold in the presence of noise on the spatial profile and in the temporal pulse envelope. The beam and pulse break-up induced at such conditions dominates the soliton generation process and leads to the generation of non-colinear patterns of multiple light spots. Finally, two-photon- absorption of the harmonic light is an important feature in soliton generation in $KNbO_3$ at high peak powers.

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