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OPTICAL SOLITONS IN QUADRATIC NONLINEAR MEDIA AND APPLICATIONS TO ALL-OPTICAL SWITCHING AND ROUTING DEVICES

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Chapter 8

Concluding Remarks

In this chapter we summarize the main results obtained within the framework of this Thesis. In short, we have comprehensively investigated the properties of the novel quadratic solitons with emphasis on assessing their potential for performing soliton steering and routing operations.

The study has focused on spatial solitons existing in planar waveguides, i.e. (1+1) configurations, phase matching geometries which involve interaction between one ordinary wave and one extraordinary wave. Using similar tools the analysis can be extended to (2+1) configurations and to Type II and Quasi Phase Matching (QPM) geometries.

In the first chapter we highlighted the main motivations and objectives of this Thesis. In chapter 2 we revised the basic concepts about light propagation leading to the normalized equations for simultaneous pulse/beam propagation of fundamental and second harmonic waves in a quadratic nonlinear, $\chi^{(2)}$, crystal.

In chapter 3 we developed the soliton concept in quadratic nonlinear media and presented the soliton families with a bright shape existing in the absence of Poynting vector walk-off, δ. A bright soliton solution with analytic form exists for a negative value of the wavevector mismatch β, but the whole soliton families are to be found numerically. This has been accomplished here through a shooting method, whose basis have been presented. Bright solitons form one-parametric families for each value of β, defined either by the nonlinear wavenumber, κ_1, or the total energy flow, I. They feature purely tilted phase fronts and the same shape and related properties for any transverse velocity, v, which thus becomes a trivial parameter. For negative β, a threshold energy flow must be exceeded for solitary waves to exist whereas for $\beta \geq 0$

solitons may form with any energy flow value. The cut-off value for negative β solitons was found to be

$$\overline{\kappa}_{1_{CUT-OFF}} = -\frac{\beta}{2}. \tag{8.1}$$

From a practical viewpoint and for a given input beam width, a threshold input power for soliton excitation does exist as well for $\beta \geq 0$, since as the energy flow is lowered the solitons feature increasingly broader beams. On the other side, for the range of power levels of practical interest, the solitons beam for both $\beta > 0$ and $\beta < 0$ is almost constant. As $|\beta|$ increases, the second harmonic energy content of the solitons decreases for $\beta > 0$ and increases for $\beta < 0$. Increases of total energy nonlinearly reduce the effective wavevector mismatch, hence the solitons energy sharing between harmonics behaves accordingly. The case of exact phase matching is characterized by a constant harmonics energy sharing regardless the total energy flow and a constant amplitude$\times$ (width)^2 relation. Through geometric considerations based on energy-hamiltonian, $I - \mathcal{H}$, curves, the families of solitary waves have been found to be stable, except for a narrow band near the cut-off edge for negative β, with limited practical relevance. Analysis of the soliton tails has revealed that at negative β, the linear approximation for the amplitude profiles holds. Namely

$$\begin{aligned} U_1 &\underset{s\longrightarrow\infty}{\longrightarrow} B_1 \exp\left(-\Gamma_1 s\right), \\ U_2 &\underset{s\longrightarrow\infty}{\longrightarrow} B_2 \exp\left(-\Gamma_2 s\right), \end{aligned} \tag{8.2}$$

with B_1, B_2 arbitrary constants and Γ_1 and Γ_2 to be determined by the linearized governing equations (see section 3.4). At positive β, some contribution of nonlinear parametric interaction terms must be considered to yield for the transverse amplitude profiles in tails

$$\begin{aligned} U_1 &\underset{s\longrightarrow\infty}{\longrightarrow} B_1 \exp\left(-\Gamma_1 s\right), \\ U_2 &\underset{s\longrightarrow\infty}{\longrightarrow} \frac{B_1^2}{\beta} \exp\left(-2\Gamma_1 s\right), \end{aligned} \tag{8.3}$$

with B_1 an arbitrary constant. Exploration of the dynamics using again $I - \mathcal{H}$ planes and Stokes parameters has confirmed the robustness of the soliton formation process.

In chapter 4 we reviewed the basic concepts about soliton beam steering. The main result obtained can be summarized by the expression

$$v = \frac{\mathcal{J}}{I} - \delta \frac{I_2}{I}, \tag{8.4}$$

stating that in the presence of walk-off the velocity with which a given beam walks the propagation axis off, v, can be controlled through the fraction of energy carried by the second harmonic, I_2/I, being I_2 the second harmonic energy flow. This case has been investigated in first section of chapter 6 through extensive numerical simulations. In configurations with no significant walk-off, the transverse velocity control may be accomplished by introducing some transverse momentum, $\mathcal{J}$, into the system through transversal phase modulations which can simply be angular tilts or sinusoidal phase modulations achieved by input gratings. Numerical analysis of these cases is carried out in second and third sections of chapter 6 respectively.

An analogous result to (8.4) was obtained for type II phase matching configurations. Namely

$$v = \frac{\mathcal{J}}{I} - \delta_2 \frac{I_2}{I} - \delta_3 \frac{I_3}{I}, \tag{8.5}$$

with δ_2, δ_3 respectively the normalized walk-off parameters for fundamental and second harmonic extraordinary waves and I_2, I_3 the respective energy flows.

In chapter 5 we presented the walking solitons which exist in the presence of Poynting vector walk-off. The basic steps for construction of the soliton families with a bright amplitude shape through numerical methods as the Newton-Raphson method have been reviewed. Walking solitons feature curved phase fronts and their shape and related properties do depend upon the transverse velocity v. Hence, they form two-parameter families with v and κ_1, or I, the family parameters. The profiles shape preservation for walking solitons can be viewed as the exact cancellation of local energy exchanges betwen harmonics and transverse points within the same harmonic rather than total absence of energy exchanges, a condition which holds for the non-walking solitons. Under the condition

$$v < \frac{\beta}{2\delta} - \frac{\delta}{2}, \tag{8.6}$$

the linear approximation (8.2) is valid for the amplitude profiles far from the soliton peak, and for the phase profiles one has

$$\phi_{1_s} \xrightarrow[s\to\infty]{} -\frac{v}{r}, \tag{8.7}$$

$$\phi_{2_s} \xrightarrow[s\to\infty]{} -\frac{(v+\delta)}{\alpha}. \tag{8.8}$$

The cut-off value to be exceeded for solitons to exist under the condition (8.6) is

$$\kappa_{1_{CUT-OFF}} = \max\left[\frac{v^2}{2}, -\frac{\beta}{2} - \frac{(v+\delta)^2}{4\alpha}\right]. \tag{8.9}$$

Due to nonlinear terms contribution, when condition (8.6) does not hold, the second harmonic phase and amplitude profiles in tails may have complicate expressions which alter the second term in brackets in expression (8.9). However, for the solitons found through the numerical search, the cut-off was determined by the first term. Discussion of stability through geometrical considerations upon the $I-\mathcal{J}-\mathcal{H}$ surfaces has lead to the conclusion that except for near cut-off solutions with limited practical relevance, all relevant walking solitons are stable. The robustness of the soliton formation has been confirmed through numerical simulations from which representative examples have been presented.

As holding promise for future all-optical operation, quadratic solitons have concentrated a lot of research efforts during the years in which this Thesis work was developed. As a result, many of the concepts gathered in chapters 3-5, at present well-known and established, were progressively discovered while this Thesis work advanced, thus constituting as well part of the results of this Thesis. As original issues we highlight the use of Stokes parameters for monitorization of the dynamics, the results concerning the soliton tails and the properties and applications of walking solitons.

In chapter 6 we gathered all results steaming from extensive numerical simulations carried out to assess the potential of the soliton structures described previously for the design of all-optical switching and routing devices. For typical fundamental wavelengths $\lambda \sim 1\mu m$ and beam widths about $\eta \sim 20\mu m$, the simulations correspond to planar waveguide lengths of about $L \sim 2cm$ made of potassium tytanil phospate (KTP) or type I lithium niobate $(LiNb0_3)$ with input power flows around $P \sim 1GW/cm^2$. In organic materials with large $\chi^{(2)}$, such as dimethyl amino stilbazolium tosylate (DAST), or trough use of Quasi Phase Matching (QPM) techniques in $LiNb0_3$, the power requirements can be lowered down to power levels of $P \sim 1MW/cm^2$ susceptible of being attained with tiny focused laser diodes. The simulations have demonstrated that significant beam steering control is attainable in a variety of configurations with soliton shifts around 5 beam widths and energy efficiencies over 80%.

First section of chapter 6 has analyzed power dependent soliton steering in configurations with a certain amount of Poynting vector walk-off. Because of its greater practical interest, the study has focused on inputs with only the fundamental field and positive β. It has been verified through the numerics that the larger input power the larger second harmonic content and therefore according to (8.4) the larger the steering angle. Likewise, reduction of the stationary second harmonic energy content has been shown to lead to reduction in the steering angle as β is increased. Injection of significant fractions of the input energy into the second harmonic have appeared to merely slightly improve the energy efficiency with reduced influence upon soliton shift. Slight deviations of the soliton velocity from $v \approx -\delta I_2/I$ due to the asymmetry in radiation, have as well been analyzed. The normalized parameters in the simulations correspond for the above typical experimental conditions, to walk-off angles up to $\rho \sim 1^0 - 2^0$. The effect has been proven robust against variations in the wavevector mismatch value.

Second section of chapter 6 has been devoted to investigation of steering control using input tilted beams. Although results for negative β configurations have as well been presented, the interest has mainly been on positive β setups so that a weak second harmonic beam acts as the control. Both initial angular tilt control and input power control have been investigated. The study has considered maximum input angles of about $\theta \sim 2^0$ for the above experimental conditions. A normalized tilt value for maximum soliton deviation, μ_{opt}, has been identified whose value depends on the radiation emitted (see section 6.2). Increases in β have been shown to lead to reduction of the soliton steering but improvement in energy efficiency. The effect of initial phase differences between the harmonics as well as presence of a moderate Poynting vector walk-off were also analyzed to demonstrate that even though they influence the soliton velocity through adequate setup design, do not significantly restrict the usefulness of the beam steering described for practical realization of steering devices.

In the third section of chapter 6 the effect of input phase gratings arranged perpendicular to the propagation axis upon soliton steering has been analyzed. Three different setups have been considered labelled:

- only FF
- FF+SH
- only SH,
- indicating the harmonic which in any case gets the phase modulation. The inputs contain a fundamental beam and in some cases a weak second harmonic whereupon the setups simulated have positive β. Both the power in the input beams with etched gratings, and switchable, electrically or acoustooptically, gratings have been investigated as mechanisms to control the soliton steering. Optimum grating parameters have been identified to be those giving for the amplitude of the phase modulation and for the spatial grating periodthe values $\phi_A \sim 2.4$,and $\Lambda \sim 5\eta$, with η beam width, respectively. Main results are summarized as follows:
- *Power control:* in first and second configurations, the expression of the expected transverse velocity (8.4) does not depend explicitly upon the beam amplitudes . Hence while small soliton shifts solely due to the different behavior of radiation as the input power is varied are observed, the most relevant soliton deviations correspond to third configuration.
- *Switchable grating:* The numerics have shown agreement with the predicted input phase modulation parameter values for maprintximum steering in a variety of input and system conditions. Relevant soliton steering has been obtained in the three setups considered even though first and second configurations have yielded larger soliton shifts at the output.

The fourth section of chapter 6 has been devoted to study the phenomenon of beam splitting. Clean beam splitting into solitons has been shown to take place in a limited range of input powers when only the fundamental wave is injected in $\beta \leq 0$ configurations and when the second harmonic and a weak fundamental signal are inputs with $\beta > 0$. Energy efficiencies are in the range of 30% in each splitted beam. We showed that injection of a weak tilted signal allows for control of the number of solitons formed and the amount of energy coupled to each through variation of the input tilt.

In chapter 7 we briefly analyzed the beam splitting effect ocurring when optical beams nesting a vortex are input in a quadratic bulk material, and discussed its implications to soliton steering. It has been shown that the number and pattern of the solitons found at the output face of the material is susceptible of being controlled by input and system parameters.

The main results of this Thesis are realized in practice with currently available materials and technological ingredients, therefore they hold promise for experimental demonstration. Work is now in progress along this line in our laboratory, in particularly about vortex beams.