OPTICAL BRIGHT SOLITONS IN LITHIUM NIOBATE
AND THEIR APPLICATIONS

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Abstract. In the present paper we review the physics of soliton formation in lithium niobate by means of photorefractive nonlinearity. Considering the waveguides that such solitonic beams leave in the host material, we summarise some application of such waveguides in terms of integrated photonic circuits.

Key words: spatial solitons, photorefractive nonlinearity, integrated optical circuits, optical sensors, lithium niobate, electro-optics, photonics.

1. INTRODUCTION

With the word “soliton” usually we name a beam self-trapped within a refractive index modification. Such phenomenon was theoretically predicted for the first time almost 50 years ago by Chiao et alii [1], even if experimental demonstrations of a spatial soliton came twenty years latter by A. Barthelemy et alii in a CS\textsubscript{2} cell [2]. Soon after, temporal solitons in optical fibres were also observed by Maneuf et alii [3, 4] due to the fine compensation between self-phase modulation and group-velocity dispersion. Since then, deep and systematic investigations of solitons were carried out. Considering just the activities in the framework of spatial solitons, different materials were investigated, like glass as a pure Kerr medium [5], Kerr semiconductors [6], or photorefractive ones [7].

Solitons became important for the physical modification of the refractive index that they induce in the host medium, phenomenon that induced different specific behaviours when a soliton beam interacts with other light, either shaped as solitons [8, 9] or just linear weak beams [10]. In this last case, solitons can act as
induced waveguides [10, 11], able to trap inside the weak beam and carry it along the whole host medium. Soliton waveguiding was investigated in different materials as semiconductors [12, 13], glass [14], liquid crystals [15] or chalcogenide glasses [16]. However among all, a very important role was played by those solitons and soliton waveguides induced in photorefractive semiconductors.

Photorefractivity was reported for the first time as a dielectric damage of the material in 1966 by Ashkin et alii [17, 18], in 1970 by W.D. Johnston Jr [19] and by Chen [20], whose group used such phenomenon to store holograms [21, 22]. The theory for the photorefractive nonlinearity was developed latter on by Kukhtarev et alii [23] in order to describe the application of such materials in the framework of hologram recording. The application of this model to the propagation of light beams and solitons occurred for the first time in 1993 by Duree et alii [24], even if many experimental and theoretical activities were reported in literature by the same group [25 – 27], by Iturbe-Castillo et alii [28], by Christodoulides and Carvalho [29], by Zozulya and Anderson [30] who formalised the beam propagation in a photorefractive medium, and by many others.

Important phenomena of the soliton propagation were discovered in that period, like for example the beam bending due to the asymmetry of the refractive index modulation by Sheng et alii [31], or the soliton formation in presence of linear and nonlinear optical activity by Vlad, Babin, Bertolotti, Fazio, Zitelli [32, 33], Fazio, Mariani, Bertolotti, Babin, Vlad [34], Fazio, Babin, Bertolotti, Vlad [35], Fazio, Ramadan, Belardini, Bosco, Bertolotti, Petris, Vlad [36], Fazio, Ramadan, Bertolotti, Petris, Vlad [37].

Photorefractive solitons got a very important role in the soliton waveguiding due to the slow dielectric relaxation that in many cases could be very slow. The theory for the soliton fixing was introduced by Klotz et alii [38], who made the hypothesis on ferroelectric domain inversion of the illuminated volume of the photorefractive medium, which remains stable after the soliton writing procedure is switched off. Many papers were published on photorefractive soliton waveguiding starting from the first one by Shih et alii [39], and followed by a very strong activity on solitons and soliton waveguiding by the German group of C. Denz et alii [40] or by the Spanish group of Calvo et alii [41].

In 2004 the first demonstration of spatial solitons and soliton waveguiding in lithium niobate was published by Fazio, Renzi, Rinaldi, Bertolotti, Chauvet, Ramadan, Petris, Vlad [42]. This paper was important because showed that bright solitons in lithium niobate could be indeed realised in this important material using a strong external electric bias to polarise the material. Moreover, as soon as a soliton is reached, it writes a soliton waveguide, which is active for very long time after its writing, and consequently it can be used like a volume waveguide.

In the present paper we shall review the main properties of spatial solitons in lithium niobate, showing that such beams can be used to write waveguides and even complex integrated circuits.
2. PHOTOREFRACTIVE NONLINEARITY AND THE SOLITONIC SOLUTION

Photorefractivity is based on light absorption by trap states or defects—impurities or doping atoms in an electro-optic semiconductor. Kukhtarev et alii [23] described this microscopic process by introducing the rate equations for light ionization of donor states \( (N_D^+) \). Let’s consider a laser beam at a photon energy that can be absorbed by donor states of a photorefractive medium; light can excite a free electron plasma in the conduction band, leaving an ionized donor state \( (N_D^-) \):

\[
\frac{\partial N_D^+}{\partial t} = (\beta + \sigma I)(N_D^- - N_D^+) - \xi n_e N_D^+.
\]

(1)

Here \( \beta \) is the thermal photoexcitation probability, \( \sigma \) is the light absorption cross section, \( I \) is the light intensity, \( \xi \) is the probability that one free electron within the density \( n_e \) would recombine at one of the ionized donor states.

In this way, a charge distribution, constituted by free electrons, trapped ionized donors and acceptors (due to impurities or lattice defects), will be present in the material:

\[
\rho = q(N_D^+ - N_A - n_e).
\]

(2)

Part of the distribution in eq. (2) corresponds to fixed charges \( (N_D^+, N_A) \) and part corresponds to both free electrons \( (n_e) \) (that can move inside the medium because of diffusion \( \mu n_e \sqrt{T} \)), because of conduction in a local electric field \( \vec{E} \) \( (q\mu n_e \vec{E}) \) and to hopping holes because of electro-motive photovoltaic force \( \sigma_{pv} I(N_D^- - N_D^+) \hat{c} \). Thus, a current is created inside the material. Its density \( \vec{J} \) depends on these three effects:

\[
\vec{J} = \mu n_e \sqrt{T} \vec{E} + q\mu n_e \vec{E} + \sigma_{pv} I(N_D^- - N_D^+) \hat{c}.
\]

(3)

where \( \mu \) is the electron mobility inside the photorefractive medium, \( k \) is the Boltzmann constant, \( \sigma_{pv} \) is the photovoltaic cross section, and \( \hat{c} \) is the crystallographic optical axis.

The equilibrium between fixed and moving charges is governed by the charge continuity equation:

\[
\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{J}.
\]

(4)
Now the fundamental point is how is generated $\vec{E}$. One component, $\vec{E}_C$, is given by the excited electric charges, and can be calculated by means of the Gauss theorem:

$$\nabla \cdot (\vec{u} : \vec{E}_C) = \rho.$$  \hspace{1cm} (5)

Other component, $\vec{E}_{\text{ext}}$, might be externally applied, while one further term can be represented by the pyroelectric field, $\vec{E}_{\text{py}}$ [43, 44]:

$$\vec{E} = \vec{E}_C + \vec{E}_{\text{ext}} + \vec{E}_{\text{py}}.$$  \hspace{1cm} (6)

The pyroelectric field $E_{\text{py}}$ is given by:

$$E_{\text{py}} = -\frac{P}{\varepsilon_0} \Delta T,$$  \hspace{1cm} (7)

where $P$ is the pyroelectric coefficient, $\varepsilon_0$ is the free space permittivity and $\varepsilon_r$ is the low frequency dielectric permittivity of the material. The pyroelectric field $\vec{E}_{\text{py}}$ is oriented along the lithium niobate optical axis as the pyroelectric tensor of LN has only that correspondent component of non-zero value. The pyroelectric coefficient of lithium niobate has been recently measured by optical methods (Parravicini et alii [45], Popescu, Petris, Vlad [46]).

The dielectric response of the photorefractive material is related to the electric field $\vec{E}$ by the electro-optic effect:

$$e_{ij} = e_{ij,\text{lin}} + \Delta e_{ij} = e_0 \delta_{ij} (1 + \chi_i) - e_0 n_i^2 n_j^2 r_{jk} E_k,$$  \hspace{1cm} (8)

where $i,j,k$ are the indices of the principal crystallographic directions, $\delta_{ij}$ is the Kronecker delta, $\chi_i$ is the linear dielectric susceptibility and $r_{jk}$ is the electro-optic tensor.

The solution of eq. (8) gives indeed an intensity-dependent refractive index: in fact, the electric field $E_k$ responsible for the electro-optic effect depends (see eq. (5)) on the charge distribution $\rho$ excited by light, according to eq.(1). The general expression for the refractive index is [42, 47]:

$$\Delta n = -\frac{1}{2} n_i^2 r_{33} \left[ \left( \frac{I}{I_{\text{tot}}} + \frac{1}{I_{\text{tot}}} \left( \frac{kT}{q} \frac{\partial I_{\text{tot}}}{\partial z} \right) \right) e^{-\frac{I}{I_{\text{tot}}}} + E^2 \frac{I_{\text{dark}}}{I_{\text{tot}}} - \frac{\sigma_{\text{py}} I_B}{q I_{\text{tot}}} \right],$$  \hspace{1cm} (9)
where the light intensity has been divided into beam intensity $I_b = \frac{\sum E|^2}{Z}$ (with $Z$ the optical impedance), dark intensity $I_{dark}$, and total intensity $I_{tot} = I_b + I_{dark}$.

The propagation of a light beam inside a photorefractive medium is consequently influenced by the nonlinear response of the material, according to the nonlinear wave equation (here reported for each light polarization component $E_i$):

$$\nabla^2 E_i - \mu_0 e_{i,lin} \frac{\partial^2 E_i}{\partial t^2} = -e_0 n_i^2 \sum_{j,k} n_j^2 r_{ijk} E_k \frac{\partial^2 E_j}{\partial t^2}.$$  (10)

In particular the optical nonlinearity, through the refractive index modulation (eq. (9)), acts like a distributed microlens, whose effect is to self-focus or self-defocus the light that induces it. Bright soliton beams, let’s say “self-confined beams”, are light beams that experience self-focusing due to a positive variation of the refractive index, carrying light down to such a tiny spot where diffraction dominates the beam dynamics. The soliton (or self-confined) regime is reached when self-focusing and diffraction compensate each other, arriving to a stable state for which light propagates without diffraction, as confined in a small refractive channel.

3. BULK SPATIAL SOLITONS

From equations (7–9) it is quite evident that self-focusing cannot be reached simply due to the negative behavior of the electro-optic nonlinearity (eq. (8)) and consequently of the refractive index (eq. (9)). Thus, mainly dark solitons can be reached in LiNbO$_3$. A dark soliton is a shadow propagating without diffraction inside a bright background. Such phenomenon is not assisted by self-focusing but by self-defocusing which clearly occurs when a negative variation in the refractive index is reached. Photorefractive dark solitons were observed in 1995 for the first time by Taya et alii [48]. In order to induce bright solitons special shrewdness must be used: such procedure was adopted nine years latter (2004) by Fazio, Renzi, Rinaldi, Bertolotti, Chauvet, Ramadan, Petris, Vlad [42], who were able to realize bright solitons in LiNbO$_3$ for the first time. In order to induce a positive contrast in the refractive index a very intense bias static electric field must be applied on the sample. Such procedure was previously applied to other crystals than LiNbO$_3$ like for example in BSO [32–37]. Due to the electro-optic effect, the refractive index of the whole medium is reduced from the linear value. When a local illumination is applied, the photoexcited charges can screen up the external bias, realizing a volume of higher refractive index than surrounding, inside which light propagates without diffraction (screening solitonic solution).
In 2004, Fazio et alii [42] applied a static bias higher than 20 kV/cm in order to reach an efficient screening of the external bias and to induce self-focusing. The experimental images of the beam self-focusing for 20kV/cm of bias are shown in Fig. 1. Here the profile of the laser is recorded at the output surface of the crystal: from an initial diffraction (left-side image) the beam starts to be confined along the $c$ optical axis (which is vertical in the images) and only latter on along the orthogonal direction as well, arriving to a perfectly circular beam (right-side image).

![Fig. 1 – The profiles of the laser at the output surface of the crystal. From the linear diffraction (first on the left) the beam experiences self-focusing until a perfectly circular and confined beam is reached (on the right).](image)

Such behavior is clearly shown in Fig. 2 where the fitted output waists are reported for two different values of the static bias. Red points correspond to the waists along the $c$ optical axis (vertical direction in Fig. 1) while the black points along the orthogonal direction (horizontal direction).

![Fig. 2 – The fitted profiles of the output beams. Only above 20 kV/cm of static bias the final soliton becomes circular.](image)

It is evident that a circular soliton is possible only above 20 kV/cm, reference value for future elaborations. It is also evident that the $c$ optical axis is a fast axis because the photorefractive nonlinearity is stronger in this direction. The orthogonal direction is the slow one: in fact the beam is indeed self-focused along the fast direction because of the nonlinear response (Fig. 3). When the total intensity of the beam increases because of the spatial confinement, the nonlinearity
becomes active also for the slow direction, which is somehow dragged by the fast one. This is well described in Fig. 3 where theoretical simulations clearly show this difference in the confinement speed.

Fig. 3 – Numerical simulation of different dynamics for the fast and slow components.

Such dragging of the slow component becomes more and more important increasing the external bias. In figure 4 we have reported the fitting for the fast and slow components, at 20 and 40 kV/cm of bias, respectively. The fast components follow a negative exponential dynamics; the slow components have an initial quasi-linear dynamics due to the nonlinear dragging and only afterwards, when the beam waist is sufficiently small, the negative exponential dynamics takes place.

Fig. 4 – The fast and slow components have different dynamics.
During the dragging the light beam regains its Gaussian shape, while turning into hyperbolic secant when the nonlinearity governs the self-focusing with the exponential dynamics (Fig. 5).

![Gaussian Profile vs Hyperbolic Secant Profile](image)

**Fig. 5** – The Gaussian profile of the light beam during the dragging dynamics of the slow direction and Hyperbolic Secant profile when the nonlinearity is indeed governing the soliton formation, for the fast direction and for the slow one after dragging.

The initial experimental set-up for observing such soliton beams proposed in 2004 and followed until 2009 was a bit elaborated, needing a strong isolation to prevent for electric discharge in air. A big improvement in the experimental technique was introduced in 2009 by J. Safioui et alii [43] who adopted as a static bias the electric field self-generated by the host crystal by means of the pyroelectric effect. Experimentally they heated the crystal few tens of degrees in order to generate a very intense electric bias along the $\hat{c}$ optical axis. The self-confined light beams were called pyrolitons in order to stress the concept of the self-biasing through the pyroelectric effect. This procedure is indeed a big innovation in the direction of the extreme simplification of the experimental apparatus.

A further simplification in the soliton formation was introduced by Popescu, Petris, Vlad [49] in 2012 with the application of blue-violet light. In fact, pushing the light energy towards the lithium niobate band-gap would result in a much more efficient charge pumping and consequently in a speed up of the writing process. In their paper they found a soliton writing time scaling as $t^{-1}$ with a time constant as high as $743 \text{s} \cdot \text{W/cm}^2$, showing in this way that solitons can be formed within few seconds with a sufficient high pumping. This work was also used as reference for the work by Fazio et alii [50] where they used violet illumination on iron doped lithium niobate crystals in order to permanently fix soliton waveguides.
4. SURFACE SOLITONS

The bright spatial solitons described in the previous section were realised in the volume of the LiNbO₃ samples. However, thanks to the pyroelectric technique, it was able to realise solitonic beams at the crystal surface. The pyroelectric effect was indeed fundamental to eliminate the electric contacts for the bias and to get access to the interface.

Surface pyrolitons were observed for the first time by J. Safioui [51] in 2010. When a laser beam focused light propagate inside a crystal, the linear diffraction tends to diverge the beam. If such diffraction takes place close to the interface, the whole beam is formed by both the direct and the reflected portions of the light beams which interfere giving rise to an interference intensity pattern in the crystal depth, with fringes parallel to the reflecting interface.

In the experiment performed in 2010 the surface along which the soliton propagated was (1,1,0) i.e. orthogonal to the \( \hat{c} \) optical axis (large surface in the z-cut configuration). In this case both experiments and numerical simulations showed that the laser beam propagates not exactly at the interface, by lies few micrometers below (Fig. 6).

Such characteristics are indeed logic if we consider that the photorefractive nonlinearity needs to realize a specific spatial charge distribution to modify the refractive index.

![Fig. 6 – Surface soliton formation and numerical simulation. In this case the soliton beam lies few microns below the surface.](image)

This distribution, according to eqs. (2–4) is formed by locked holes and moving electrons which must exit the illuminated volume in order to screen up the bias field. Thus, electrons need some space to accumulate, which is exactly the distance between the soliton beam and the real crystal-air interface. Such phenomenon was already observed and described in the paper by Alfassi et alii [52] where surface solitons were induced in presence of a nonlocal nonlinear response of the material.
Such researches show that the real (1,1,0) interface (i.e. the plane orthogonal to the optical axis of the crystal) is not addressable with solitonic light due to the nonlocal nature of the photorefractivity. A different condition was investigated this year by E. Fazio et alii [53], when surface solitons were observed along the (0,1,1) and (1,0,1) crystallographic interfaces. In such configuration charges move parallel to the interface, addressing the light close to the surface (Fig. 7). Using this small ploy, the nonlinearity is made local, pushing the nonlocality along an orthogonal direction with respect to the characteristic directions of the experiment geometry. The numerical simulations show a refractive index modulation lying exactly at the interface. This result opens such technique to important applications for sensors, as will be described latter on.

5. SOLITON FORMATION BY TWO-PHOTON PROCESSES

This is a very hot topic, because it describes a nonlinear process, i.e. two-photon response, within another nonlinear process, i.e. soliton formation.

By two-photon process we shall consider 2 different phenomena: A) nonlinear absorption occurring in two steps, where an intermediate real level is pumped before a second absorption carries charges towards the final state and B) a nonlinear absorption occurring with a 2-photon process, i.e. using an intermediate virtual level to transfer charges directly towards the final energy level.

2-STEP

The two-step process in photorefractive soliton was introduced for the first time by Ramadan, Fazio, Mascioletti, Inam, Rinaldi, Bosco, Vlad, Petris, Bertolotti...
[54] who experimentally demonstrated that solitons can be generated (in this case the experiment was performed in BSO) even when light is very far from the energy gap. In this paper the authors also theoretically described the nonlinear dielectric constant with a new intensity dependent saturating expression:

\[
\delta \epsilon = -k n^2 r E_{\text{bias}} \frac{1 + RI}{1 + R\eta I}.
\]  

In eq. (11), \(k\) is the light wavenumber, \(R\) is a constant that depends on the material cross-section coefficients, and \(\eta\) is the ratio between holes and electron mobilities.

The numerical simulations of this model perfectly fit the experimental results (Fig. 8).

In the same year, Castro-Camus and Magaña [55] arrived at the same theoretical results for a general photorefractive medium. In this paper however, the authors did not consider the soliton formation but just recording of holographic gratings.

This technique was applied in 2006 by Vlad, Petris, Bosco, Fazio, Bertolotti [56] in LiNbO3 in order to observed soliton formation induced by IR femtosecond pulses. IR pulses at 800 and or 1064 nm cannot be absorbed by lithium niobate, because no transitions are available at these energies. In this paper the authors showed that strong two-step absorption was indeed possible if a second green illumination was overlapped to the IR beam. Adopting such procedures efficient
self-focusing was induced on IR pulses until a perfect confinement was indeed reached. We should specify here that the two-step induced self-focusing was just the induction of the whole soliton formation, which was fully assisted by the harmonic generation process in order to complete itself and reach a stable situation, as described latter on.

The full theoretical description of the soliton formation in presence of two-step nonlinearity was formulated in 2007 by Hou et alii [57] who solved analytically the theory arriving to the “classical” hyperbolic secant shape for the bright soliton solution (eq. (27) in the paper).

**2-STEP: LUMINESCENCE**

A 2-step process was also adopted to generate solitons in lithium niobate doped with erbium. This rare earth is generally used as doping for light emission. In fact erbium atoms have efficient light emission for laser and light amplification purposes: among all, the most famous transition corresponds to absorption at 980 nm that can re-emit at 1540 nm, i.e. in the third transparency window of glass fibre. Based on erbium, many laser sources are commercially available in bulk glass [58] or optical fibres [59 – 61], both in CW or femtosecond-pulsed regime.

The research group at the Angewandte Physik in Paderborn University during the nineties performed an intense activity for realising lasing action in waveguides within LiNbO₃ crystals [62 – 65]. They doubly doped the substrates with titanium and erbium in order to write the waveguides (titanium) and to access to light emission-amplification by erbium ions. It was clear that laser emission and amplification were possible in lithium niobate too: with respect to other materials, lithium niobate possesses many different nonlinear properties, like the electro-optic, the acousto-optic, the piezo-electric, the pyro-electric ones, just to cite the most important. We could say that lithium niobate is the most versatile medium in photonics. Thus, laser action within lithium niobate would allow to control the emitter and drive specific behaviours by using one or more nonlinear properties of the material. Thus, light emission in lithium niobate could be very important for active and passive photonic devices. These considerations underlined the important of a fine characterisation of the properties of lithium niobate when doped with erbium [66 – 69]. Clearly the inclusion of erbium inside lithium niobate modifies the lattice structure, influencing in this way both the photovoltaic and electro-optic properties [70]. In fact according to the concentration, erbium can enter in the lattice as a pure interstitial dopant (for relatively low concentrations) or substituting Li ions and forming, consequently, compounds with different compositions and crystalline structures. As a consequence, the nonlinear optical properties of the final material can be strongly modified by the erbium doping whose characteristics nonlinearly depend on the erbium concentration. However, spatial solitons in lithium niobate doped with erbium were still possible [71], with a formation dynamics slightly different from what observed in undoped samples. Taking into
account different erbium concentrations, it was possible to derive the refractive contrast which was possible to induce in such material by a laser beam, both in self-focusing and self-defocusing regimes:

![Graph](image)

*Fig. 9 – Refractive index contrast induce by a laser beam in Erbium doped lithium niobate crystals.*

A very important advancement of knowledge in this framework has been published by Fazio et alii [72] in 2010, when they have realised a soliton beam by using the incoherent luminescence emission to write the photorefractive nonlinearity. In fact for amplification purposes, one could desires to generate solitons and soliton waveguides using the same beam used for the emission pumping, in order to guaranty a good mode overlapping between pumping and amplified light. However, this is not possible in lithium niobate is pumping occurs at 980 nm. Such wavelength is indeed absorbed by erbium but has almost no interaction with the host lithium niobate background.

Is there any possibility to force lithium niobate to interact with 980 nm?

When pumping at 980 nm, electrons in erbium undergo transitions from the $^4I_{15/2}$ ground level to the $^4I_{13/2}$ level. A rapid decay transfers charges to the $^4I_{13/2}$ level from which stimulated emission might occur during decay towards the original $^4I_{15/2}$ ground level. However, if the light pumping is sufficiently high, further transitions from the excited $^4I_{11/2}$ level towards the higher $^4F_{7/2}$ one might happen, from where a rapid decay transfers charges to the $^4S_{3/2}$ one. Such $^4S_{3/2}$ can give direct decay transitions towards the ground state $^4I_{15/2}$ via the emission of 555 nm luminescence. Such green luminescence is now absorbed by the lithium niobate host medium that can modify its refractive index by means of the photorefractive effect. Luminescence has usually isotropic emission; however the
initial strong intensity inside the pump beam forces the medium to modify exactly there. Thus, the photorefractive nonlinearity starts to be efficient below the pump beam and for both luminescence and pump light. As a consequence, confinements of both luminescence and pump light occur, which soon evolve towards a stable solitonic state. Both simulations and experiments showed confinement of the pump beam induced by its self-generated luminescence. At the end, due to the nonlinear regime of the two-step pumping of luminescence, an almost perfect overlapping between pump and luminescence beams take place, as shown in Fig. 10.

![Fig. 10 – Perfect overlapping between pump and luminescence beams in erbium doped lithium niobate crystals.](image)

Such solitons have been called L.I.S.S.: Luminescence Induced Spatial Solitons. The use of LISS as waveguides for generating or amplifying light has been finely investigated by Passier et alii [73]. In this paper high refractive contrasts were indeed estimated, as high as 10^3, showing that LISS waveguides are indeed multimode. However due the relatively low contrast, LISS waveguides becomes single mode above 1200 nm, with a strong optimisation exactly at the erbium emission (around 1540 nm) for which the propagation losses of the structure become very low, around 10^3 dB/cm or even lower (Fig. 11).

![Fig. 11 – Propagation losses in a LISS waveguide.](image)
Second Harmonic Generation

Lithium niobate is a nonlinear medium even in the framework of second harmonic generation.

OO-E phase-matching can be reached at wavelengths above 1078 nm. Below such threshold no phase-matching between fundamental and second harmonic signals can be found. However due to the electro-optic properties, the refractive index as well as the phase-matching can be slightly tuned, arriving to significant improvements of the harmonic generation efficiency. This effect becomes more and more efficient if induced inside self-assembled waveguides as the solitonic ones. Pettazzi et alii [74] in fact demonstrated that nonlinear phase-matching occurs inside solitonic waveguides. Working at 1064 nm, no phase-matching is indeed reached and also no interation between light and lithium niobate is possible because the material has not absorptive transitions at these light energies. However, even without phase-matching, a small part of second harmonic with low efficiency is generated, this time at an absorbed wavelength. As a consequence, the second harmonics starts to modify the refractive index of host lithium niobate, that develops a refractive channel inside which both fundamental and second harmonic are trapped. As a consequence, the system gains phase-matching and the generation process becomes more and more ongoing. Efficient frequency-doubling was experimentally demonstrated in presence of beam self-trapping. The self-trapping was induced by the generated second harmonic beam via photorefractive effect with and without an external applied bias, showing fast tuning of phase matching conditions in the written waveguide. Efficient conversion even at nW powers was indeed reached (Pettazzi, Alonzo, Centini, Petris, Vlad, Chauvet, Fazio [75]), which was three orders of magnitude lower than previously reported in the literature [76]. In particular, both cases of without (defocusing) and with (focusing) external biases revealed a nonlinear dynamics of the generated harmonics as a consequence of the induced photovoltaic field, that can drive the generation in perfect matching or out of it. Stable self-confined propagation of the second-harmonic generated light was then demonstrated by a fine tuning of the initial phase-matching [77]. The developed numerical model shows that as a general case SHG in a self-focusing PR medium results in mode beating inside the generated waveguide, as experimentally observed.

Pushing the harmonic generation in a regime of very strong phase-mismatch, usually drops down the conversion efficiency. This is not the case when the harmonic generation occurs inside a self-generated and self-aligning system like a solitonic waveguide. Fazio et alii [78] reported efficient second harmonic generation at 800 nm, where the phase mismatch could be as high as $10^4$ cm$^{-1}$. Such very large differences in both phase- and group-velocities induce the pump and the generated pulses to spatially and temporally separate. However the nonlinear process which cannot be interrupted, forces the generated pulse to suffer a very strong phase-modulation. As a consequence, the second-harmonic pulse remains temporally trapped inside the pump beams, experiencing the same phase-and
group-velocities (Fig. 12). The phase-velocity equality was experimentally demonstrated by means of the same Snell refraction of the fundamental and the second harmonic beams in spite of the index dispersion; the group velocity was instead demonstrated by third harmonic generation due to the beating of the fundamental and second harmonic beams in a suitably matched nonlinear crystal. If now the second harmonic generates a solitonic channel, both fundamental and generated beams can be confined inside, obtaining a perfect overlapping of the two pulses in time and space. Please note that this was not a light bullet, i.e. a solitonic space-time solution, but just a temporal and spatial locking of the pulses that was called “simulton” [79]. Inside a simulton the conversion efficiency can increase of 2-3 orders of magnitude due to the self-aligning nature of solitons (Fig. 13).

Fig. 12 – Numerical simulation second-harmonic process in regime of very-large phase-mismatching. The pump pulse (thick line) generates two second harmonic signals (thin line) one than travels with different group velocity and thus tends to separate, and one that is phase-locked and trapped by the pump.

Fig. 13 – Experimental images of the simulton formation. The second harmonic in simulton can be orders of magnitude more intense than in linear conversion regime.
6. SOLITON WAVEGUIDES

Solitons in LiNbO₃ are important not only from the physical point of view but also from the technological one. In fact, as pointed out in the first demonstration by E. Fazio et alii [42], the very slow dielectric relaxation in this material allows the refractive nonlinearity to remain persistent after the first writing process. Consequently, a light soliton in LiNbO₃ writes a waveguide, which can be used as basic element for integrated photonic circuits. Keeping the written channels in the dark or using them in a spectral band where absorption is absolutely negligible (let’s say with a wavelength above 1 µm) the soliton waveguides were reported to survive for 1 month, even if further tests demonstrate waveguide durability well above several months.

All types of waveguides can be realised with the solitonic writing procedure: planar or channel waveguides, in the volume and at interfaces, perfectly cylindrical of astigmatic ones (i.e. circular in one side and elliptical in the other). Please note that soliton waveguides are basic elements for 3D architectures of integrated circuits. In fact, soliton waveguides can be generated everywhere in a crystal support, without any restriction in position or shape or dimension.

The characteristics of soliton waveguides are very attractive:

<table>
<thead>
<tr>
<th>Specification of soliton waveguides</th>
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<tbody>
<tr>
<td>Writing power</td>
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<tr>
<td>Mode distribution</td>
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<tr>
<td>Typical mode waist</td>
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<tr>
<td>Propagation length</td>
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<tr>
<td>Refractive index contrast</td>
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<td>Refractive index profile</td>
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<tr>
<td>Material group velocity dispersion</td>
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<tr>
<td>Modal group velocity dispersion</td>
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<tr>
<td>Propagation losses</td>
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WAVEGUIDE MODES

Ke-Qing et alii [81] theoretically investigated waveguides induced by screening-photovoltaic solitons in biased photorefractive–photovoltaic crystals. They showed that the number of guided modes increases monotonically with the ratio between the peak intensity of the soliton and the dark irradiance. On the other hand, waveguides induced by dark screening-photovoltaic solitons are always single mode for all intensity ratios and the confined energy near the center of waveguide increases monotonically with the increasing intensity ratio. When the bulk photovoltaic effect is neglectable, the induced waveguides are similar to screening soliton ones, while when the external field is absent, the generated waveguides resemble those induced by photovoltaic solitons. Passier et alii [73] numerically showed a similar phenomenon in LISS.

TURNING WAVEGUIDES

A photorefractive screening soliton (i.e. the nonlinearity is dominated by the bias screening) usually does not travel straight but bending due to the charge migration. Such nonlocality was predicted by Christodoulides and Carvalho [29] in 1995, investigated theoretically [82] and experimentally observed [83, 84] many times in literature, mainly in Strontium Barium Niobate crystals (SBN) due to its very high electro-optic coefficient.

Also in lithium niobate bending was observed and experimentally reported by Chauvet et alii [85]. The authors using a numerical model demonstrated that the nonlocality is strictly dependent on the amount of acceptor states present within the photorefractive medium. Large concentrations of acceptors drastically reduce the free-charge free-mean-path, limiting the nonlinear effects in a very small volume around the laser beam. Such acceptors can be naturally present in the medium because of the growing procedure or the purity of the original growing compounds, but can be also artificially modulated but the application of a relatively intense background. In fact, an homogeneous illumination of the whole crystal would result in a large concentration of ionised donors that act as acceptor for free charges. As a consequence, by playing with the background illumination it is possible to control and almost suppress bending of solitons and soliton waveguides too. Using this procedure complex trajectories for integrated circuits can be indeed designed [86]. Using natural soliton bending, curves of several tens of degree’s can be indeed formed in solitonic waveguides with very low losses.

For sharper bending one should consider the total internal reflection of solitons from crystal interfaces. Such procedure was already proposed in literature by Alvarado-Mendez et alii in 1998 [87], but only in 2006 has been efficiently applied in lithium niobate soliton waveguides [88]. In this paper the authors demonstrate efficient propagation inside 90° and 180° turned solitonic waveguides with very low propagation losses, of the order of 0.1 dB/cm, value limited only by the polishing degree of the reflective interface which was relatively poor.
7. INTEGRATED DEVICES BASED ON SOLITON WAVEGUIDES

The soliton procedure is becoming more and more important in the panorama of integrated photonics, being extremely competitive with the other more traditional methods for waveguide realization, in terms of costs, in terms of performances (ultralow propagation losses) and in terms of geometry (soliton waveguides are indeed 3-D basic elements for integrated photonic circuitry).

In 2006 Coda et alii [89] published the first fully solitonic and fully 3-D device. It was 1x2 and 1x4 coupler at the same time, realized by writing 4 solitonic channels, angled one-each-other from the same starting point. The authors demonstrate routing ability over the four gates with very low cross-talk between channels as well as 1-to-2 splitting.

Very recently however Chauvet et alii [90] realised coupling between a solitonic waveguide and an optofluidic circuit. A thin dig (200×200 µm² of cross section) was diced inside a lithium niobate crystal and crossed by a solitonic beam. They showed that self-trapped beams can form even across a relatively large perturbation (dig) if its thickness is smaller or at maximum similar to the diffraction length of the light leaving the solitonic channel. The self-aligning property of the solitonic waveguides provides the re-formation of the soliton channel after the waveguide gap. Such device, constituted of a buried circular optical waveguide crossing the fluidic channel, was employed as a refractive index sensor for liquids.

The last device based on soliton waveguides was proposed by Fiumara and Fazio [91]. In such design paper the authors proposed an integrated device called RISSOR based on surface soliton waveguides, in the configuration described by Fazio et alii [91]. RISSOR is a Refractive-Index Surface Soliton Sensor. Such
device is composed by two semi rib-waveguides connected together by a surface soliton channel. Such device can act like a sensor for the refractive index of the soliton waveguide cladding. In fact variations in the cladding refractive index strongly influence the coupling between rib and soliton waveguides, the coupling via diffraction of the two semi rib-waveguides as well as the solitonic propagation. Changes in transmission could be very large, as shown in figure 13 for 980 nm propagation through a 200 µm long soliton waveguide.

8. CONCLUSIONS

In this review paper we have presented the physics of solitons in lithium niobate and their applications as integrated 3-D waveguides. Soliton waveguide technology is now ripe for pure applications. In fact, we very much know about the physics and consequently the writing procedure is well established and reproducible. Moreover its seems very competitive with traditional methods for realising integrated circuits, in terms of performances, costs and also versatility: in fact such waveguides can take advantage of the self-interacting and self-aligning nature of the photorefractive nonlinearity and solitons, allowing the realisation of complex structures naturally self-aligned, a procedure which cannot be simply realised with more traditional fabrication technologies. Soliton waveguides can really be the possibility to realise custom photonic circuitry with low production costs still maintaining a big application versatility.

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REFERENCES